

The European Union

EDICT OF GOVERNMENT

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EN 1991-4 (2006) (English): Eurocode 1: Actions on structures - Part 4: Silos and tanks [Authority: The European Union Per Regulation 305/2011, Directive 98/34/EC, Directive 2004/18/EC]



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English Version

Eurocode 1 - Actions on structures - Part 4: Silos and tanks

Eurocode 1 - Actions sur les structures - Partie 4: Silos et réservoirs

Eurocode 1 - Grundlagen der Tragwerksplanung und Einwirkungen auf Tragwerke - Teil 4: Silos und Flüssigkeitsbehälter

This European Standard was approved by CEN on 12 October 2005.

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. Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Central Secretariat or to any CEN member.

This European Standard exists 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 Central Secretariat has the same status as the official versions.

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EUROPEAN COMMITTEE FOR STANDARDIZATION
COMITÉ EUROPÉEN DE NORMALISATION
EUROPÄISCHES KOMITEE FÜR NORMUNG

Management Centre: rue de Stassart, 36 B-1050 Brussels

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Foreword

This document (EN 1991-4:2006) has been prepared by Technical Committee CEN/TC250 “Structural Eurocode”, the secretariat of which is held by BSI.

This document shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by November 2006, and conflicting national standards shall be withdrawn at the latest by March 2010.

This document supersedes ENV 1991-4:1995.

According to the CEN/CENELEC Internal Regulations, the national standards organizations of the following countries are bound to implement this European Standard: Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland and the United Kingdom.

Background of the Eurocode programme

In 1975, the Commission of the European Community decided on an action programme in the field of construction, based on Article 95 of the Treaty. The objective of the programme was the elimination of technical obstacles to trade and the harmonization of technical specifications.

Within this action programme, the Commission took the initiative to establish a set of harmonized technical rules for the design of construction works which, in a first stage, would serve as an alternative to the national rules in force in the Member States and, ultimately, would replace them.

For fifteen years, the Commission, with the help of a Steering Committee with Representatives of Member States, conducted the development of the Eurocodes programme, which led to the first generation of European codes in the 1980s.

In 1989, the Commission and the Member States of the EU and EFTA decided, on the basis of an agreement¹⁾ between the Commission and CEN, to transfer the preparation and the publication of the Eurocodes to the CEN through a series of Mandates, in order to provide them with a future status of European Standard (EN). This links *de facto* the Eurocodes with the provisions of all the Council’s Directives and/or Commission’s Decisions dealing with European standards (e.g. the Council Directive 89/106/EEC on construction products CPD and Council Directives 93/37/EEC, 92/50/EEC and 89/440/EEC on public works and services and equivalent EFTA Directives initiated in pursuit of setting up the internal market).

The Structural Eurocode programme comprises the following standards generally consisting of a number of parts:

EN1990	Eurocode:	Basis of structural design
EN1991	Eurocode 1:	Actions on structures
EN1992	Eurocode 2:	Design of concrete structures
EN1993	Eurocode 3:	Design of steel structures
EN1994	Eurocode 4:	Design of composite steel and concrete structures
EN1995	Eurocode 5:	Design of timber structures
EN1996	Eurocode 6:	Design of masonry structures
EN1997	Eurocode 7:	Geotechnical design
EN1998	Eurocode 8:	Design of structures for earthquake resistance
EN1999	Eurocode 9:	Design of aluminium structures

¹⁾ Agreement between the Commission of the European Communities and the European Committee for Standardisation (CEN) concerning the work on Eurocodes for the design of building and civil engineering works (BC/CEN/03/89).

Eurocode standards recognize the responsibility of regulatory authorities in each Member State and have safeguarded their right to determine values related to regulatory safety matters at national level where these continue to vary from State to State.

Status and field of application of Eurocodes

The Member States of the EU and EFTA recognize that Eurocodes serve as reference documents for the following purposes:

- as a means to prove compliance of building and civil engineering works with the essential requirements of Council Directive 89/106/EEC, particularly Essential Requirement N°1 Mechanical resistance and stability and Essential Requirement N°2 Safety in case of fire;
- as a basis for specifying contracts for construction works and related engineering services;
- as a framework for drawing up harmonized technical specifications for construction products (ENs and ETAs).

The Eurocodes, as far as they concern the construction works themselves, have a direct relationship with the Interpretative Documents²⁾ referred to in Article 12 of the CPD, although they are of a different nature from harmonized product standards³⁾. Therefore, technical aspects arising from the Eurocodes work need to be adequately considered by CEN Technical Committees and/or EOTA Working Groups working on product standards with a view to achieving full compatibility of these technical specifications with the Eurocodes.

The Eurocode standards provide common structural design rules for everyday use for the design of whole structures and component products of both a traditional and an innovative nature. Unusual forms of construction or design conditions are not specifically covered and additional expert consideration will be required by the designer in such cases.

National Standards implementing Eurocodes

The National Standards implementing Eurocodes will comprise the full text of the Eurocode (including any annexes), as published by CEN, which may be preceded by a National title page and National foreword, and may be followed by a National Annex.

The National Annex may only contain information on those parameters which are left open in the Eurocode for national choice, known as Nationally Determined Parameters, to be used for the design of buildings and civil engineering works to be constructed in the country concerned, i.e.:

- values and/or classes where alternatives are given in the Eurocode,
- values to be used where a symbol only is given in the Eurocode,
- country specific data (geographical, climatic, etc), e.g. snow map,
- the procedure to be used where alternative procedures are given in the Eurocode.

It may also contain:

²⁾ According to Article 3.3 of the CPD, the essential requirements (ERs) shall be given concrete form in interpretative documents for the creation of the necessary links between the essential requirements and the mandates for harmonized ENs and ETAGs/ETAs.

³⁾ According to Article 12 of the CPD the interpretative documents shall:

- a) give concrete form to the essential requirements by harmonizing the terminology and the technical bases and indicating classes or levels for each requirement where necessary;
- b) indicate methods of correlating these classes or levels of requirement with the technical specifications, e.g. methods of calculation and of proof, technical rules for project design, etc.;
- c) serve as a reference for the establishment of harmonized standards and guidelines for European technical approvals.

The Eurocodes, *de facto*, play a similar role in the field of the ER 1 and a part of ER 2.

- decisions on the application of informative annexes,
- references to non-contradictory complementary information to assist the user to apply the Eurocode.

Links between Eurocodes and harmonized technical specifications (ENs and ETAs) for products

There is a need for consistency between the harmonized technical specifications for construction products and the technical rules for works⁴⁾. Furthermore, all the information accompanying the CE Marking of the construction products which refer to Eurocodes shall clearly mention which Nationally Determined Parameters have been taken into account.

Additional information specific to EN1991-4

EN 1991-4 gives design guidance for the assessment of actions for the structural design of silos and tanks.

EN 1991-4 is intended for clients, designers, contractors and relevant authorities.

EN 1991-4 is intended to be used in conjunction with EN 1990, with the other parts of EN 1991, with EN 1992 and EN 1993, and with the other parts of EN 1994 to EN 1999 relevant to the design of silos and tanks.

National Annex for EN1991-4

This standard gives alternative procedures, values and recommendations for classes with notes indicating where national choices may have to be made. Therefore the National Standard implementing EN 1991-4 should have a National Annex containing all Nationally Determined Parameters to be used for the design of buildings and civil engineering works to be constructed in the relevant country.

National choice is allowed in EN 1991-4 through:

- 2.5 (5)
- 3.6 (2)
- 5.2.4.3.1 (3)
- 5.4.1 (3)
- 5.4.1 (4)
- A.4 (3)
- B.2.14 (1)

⁴⁾ See Article 3.3 and Article 12 of the CPD, as well as clauses 4.2, 4.3.1, 4.3.2 and 5.2 of ID 1.

Section 1 General

1.1 Scope

1.1.1 Scope of EN 1991 - Eurocode 1

(1)P EN 1991 provides general principles and actions for the structural design of buildings and civil engineering works including some geotechnical aspects and shall be used in conjunction with EN 1990 and EN 1992-1999.

(2) EN 1991 also covers structural design during execution and structural design for temporary structures. It relates to all circumstances in which a structure is required to give adequate performance.

(3) EN 1991 is not directly intended for the structural appraisal of existing construction, in developing the design of repairs and alterations or for assessing changes of use.

(4) EN 1991 does not completely cover special design situations which require unusual reliability considerations such as nuclear structures for which specified design procedures should be used.

1.1.2 Scope of EN 1991-4 actions on structures: silos and tanks

(1)P This part provides general principles and actions for the structural design of silos for the storage of particulate solids and tanks for the storage of fluids and shall be used in conjunction with EN 1990, other parts of EN 1991 and EN 1992 to EN 1999.

(2) This part includes some provisions for actions on silo and tank structures that are not only associated with the stored solids or liquids (e.g. the effects of thermal differentials, aspects of the differential settlements of batteries of silos)

(3) The following geometrical limitations apply to the design rules for silos:

- the silo cross-section shapes are limited to those shown in Figure 1.1d, though minor variations may be accepted provided the structural consequences of the resulting changes in pressure are considered;
- the following dimensional limitations apply:

$$h_b/d_c < 10$$

$$h_b < 100 \text{ m}$$

$$d_c < 60 \text{ m}$$

- the transition lies in a single horizontal plane (see Figure 1.1a);
- the silo does not contain an internal structure such as a cone or pyramid with its apex uppermost, cross-beams, etc. However, a rectangular silo may contain internal ties.

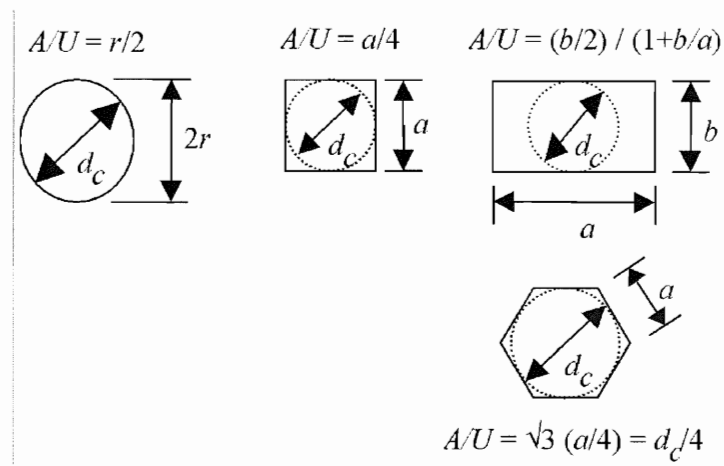
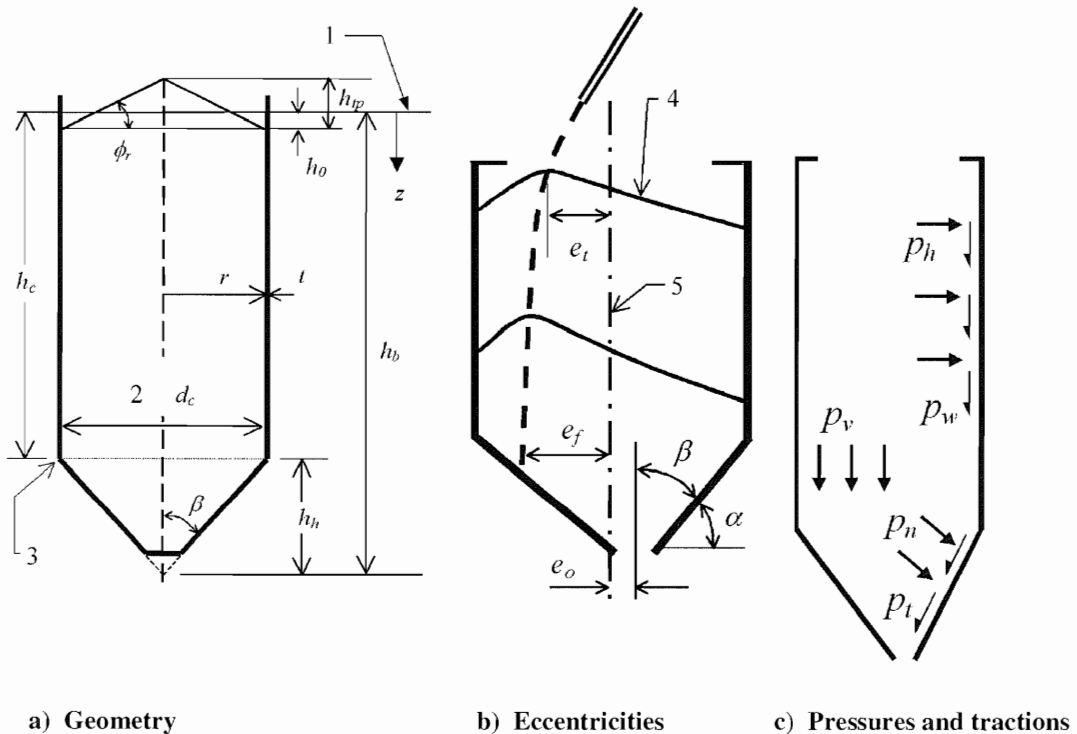
(4) The following limitations on the stored solids apply to the design rules for silos:

- each silo is designed for a defined range of particulate solids properties;
- the stored solid is free-flowing, or the stored solid can be guaranteed to flow freely within the silo container as designed (see 1.5.12 and Annex C);
- the maximum particle diameter of the stored solid is not greater than $0,03d_c$ (see Figure 1.1d).

NOTE: When particles are large compared to the silo wall thickness, account should be taken of the effects of single particles applying local forces on the wall.

(5) The following limitations on the filling and discharge arrangements apply to the design rules for silos:

- filling involves only negligible inertia effects and impact loads;
- where discharge devices are used (for example feeders or internal flow tubes) solids flow is smooth and central.



d) Cross-section shapes

Key

- 1 Equivalent surface
- 2 Inside dimension
- 3 Transition
- 4 Surface profile for full condition
- 5 Silo centre line

Figure 1.1: Silo forms showing dimensions and pressure notation

(6) Only hoppers that are conical (i.e. axisymmetric), square pyramidal or wedge-shaped (i.e. with vertical end walls) are covered by this standard. Other hopper shapes and hoppers with internals require special considerations.

(7) Some silos with a systematically non-symmetric geometry are not specifically covered by this standard. These cases include a chisel hopper (i.e. a wedge hopper beneath a circular cylinder) and a diamond-back hopper.

(8) The design rules for tanks apply only to tanks storing liquids at normal atmospheric pressure.

(9) Actions on the roofs of silos and tanks are given in EN 1991-1-1, EN 1991-1-3 to EN 1991-1-7 and EN 1991-3 as appropriate.

(10) The design of silos for reliable solids discharge is outside the scope of this standard.

(11) The design of silos against silo quaking, shocks, honking, pounding and silo music is outside the scope of this standard.

NOTE: These phenomena are not well understood, so the use of this standard does not guarantee that they will not occur, or that the structure is adequate to resist them.

1.2 Normative references

This European Standard incorporates, by dated or undated reference, provisions from other publications. These normative references are cited at the appropriate places in the text and the publications are listed hereafter. For dated references, subsequent amendments to or revisions of any of these publications apply to this European Standard only when incorporated in it by amendment or revision. For undated references the latest edition of the publication applies (including amendments).

ISO 3898:1997 Basis of design for structures: Notation. General symbols

NOTE: The following European Standards which are published or in preparation are cited at the appropriate places in the text:

EN 1990 Basis of structural design

EN 1991-1-1 Eurocode 1: Actions on structures: Part 1.1: Densities, self-weight and imposed loads

EN 1991-1-2 Eurocode 1: Actions on structures: Part 1.2: Actions on structures exposed to fire

EN 1991-1-3 Eurocode 1: Actions on structures: Part 1.3: Snow loads

EN 1991-1-4 Eurocode 1: Actions on structures: Part 1.4: Wind actions

EN 1991-1-5 Eurocode 1: Actions on structures: Part 1.5: Thermal actions

EN 1991-1-6 Eurocode 1: Actions on structures: Part 1.6: General actions. Actions during execution

EN 1991-1-7 Eurocode 1: Actions on structures: Part 1.7: Accidental actions

EN 1991-2 Eurocode 1: Actions on structures: Part 2: Traffic loads on bridges

EN 1991-3 Eurocode 1: Actions on structures: Part 3: Actions induced by cranes and machinery

EN 1992 Eurocode 2: Design of concrete structures

EN 1992-4 Eurocode 2: Design of concrete structures: Part 4: Liquid retaining and containment structures

EN 1993 Eurocode 3: Design of steel structures

EN 1993-1-6 Eurocode 3: Design of steel structures: General rules: Part 1.6: Supplementary rules for the strength and stability of shell structures

EN 1993-4-1	Eurocode 3: Design of steel structures: Part 4.1: Silos
EN 1993-4-2	Eurocode 3: Design of steel structures: Part 4.2: Tanks
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 alloy structures

1.3 Assumptions

(1)P The general assumptions given in EN 1990, 1.3 apply.

1.4 Distinction between principles and application rules

(1) Depending on the character of the individual paragraphs, distinction is made in this part between principles and application rules.

(2) The principles comprise:

- general statements and definitions for which there is no alternative, as well as
- requirements and analytical models for which no alternative is permitted unless specifically stated.

(3) The principles are identified by the letter P following the paragraph number.

(4) The application rules are generally recognized rules which follow the principles and satisfy their requirements.

(5) It is permissible to use alternative rules different from the application rules given in this Eurocode, provided it is shown that the alternative rules accord with the relevant principles and have at least the same reliability.

(6) In this part the application rules are identified by a number in parentheses, e.g. as this paragraph.

1.5 Definitions

For the purposes of this standard, a basic list of definitions is provided in EN 1990, 1.5 and the additional definitions given below are specific to this part.

1.5.1

aerated silo bottom

a silo base in which air slides or air injection is used to activate flow in the bottom of the silo (see figure 3.5b)

1.5.2

characteristic dimension of inside of silo cross-section

the characteristic dimension d_c is the diameter of the largest inscribed circle within the silo cross-section (see Figure 1.1d)

1.5.3

circular silo

a silo whose plan cross-section is circular (see Figure 1.1d)

1.5.4

cohesion

the shear strength of the stored solid when the normal stress on the failure plane is zero

1.5.5

conical hopper

a hopper in which the sloping sides converge towards a single point intended to produce axisymmetric flow in the stored solid

1.5.6

eccentric discharge

flow pattern in the stored solid arising from moving solid being unsymmetrically distributed relative to the vertical centreline of the silo. This normally arises as a result of an eccentrically located outlet (see Figures 3.2c and d, 3.3b and c), but can be caused by other unsymmetrical phenomena (see Figure 3.4d)

1.5.7

eccentric filling

a condition in which the top of the heap at the top of the stored solids at any stage of the filling process is not located on the vertical centreline of the silo (see Figure 1.1b)

1.5.8

equivalent surface

level surface giving the same volume of stored solid as the actual surface (see Figure 1.1a)

1.5.9

expanded flow hopper

a hopper in which the lower section of the hopper has sides sufficiently steep to cause mass flow, while the upper section of the hopper has shallow sides and funnel flow is expected (see Figure 3.5d). This expedient arrangement reduces the hopper height whilst assuring reliable discharge

1.5.10

flat bottom

the internal base of a silo, when it has an inclination to the horizontal less than 5°

1.5.11

flow pattern

the form of flowing solid in the silo when flow is well established (see Figures 3.1-3.4). The silo is close to the full condition

1.5.12

fluidized solid

a state of a stored fine particulate solid when its bulk contains a high proportion of interstitial air, with a pressure gradient that supports the weight of the particles. The air may be introduced either by aeration or by the filling process. A solid may be said to be partially fluidized when only part of the weight of particles is supported by the interstitial air pressure gradient

1.5.13

free flowing granular solid

a granular solid whose flowing behaviour is not significantly affected by cohesion

1.5.14

full condition

a silo is said to be in the full condition when the top surface of the stored solid is at the highest position considered possible under operating conditions during the design life-time of the structure. This is the assumed design condition for the silo

1.5.15**funnel flow**

a flow pattern in which a channel of flowing solid develops within a confined zone above the outlet, and the solid adjacent to the wall near the outlet remains stationary (see Figure 3.1). The flow channel can intersect the vertical walled segment (mixed flow) or extend to the surface of the stored solid (pipe flow)

1.5.16**granular solid**

a particulate solid in which all the particles are so large that interstitial air plays a small role in determining the pressures and flow of large masses of the solid

1.5.17**high filling velocity**

the condition in a silo where the rapidity of filling can lead to entrainment of air within the stored solid to such an extent that the pressures applied to the walls are substantially changed from those without air entrainment

1.5.18**homogenizing fluidized silo**

a silo in which the particulate solid is fluidized to assist blending

1.5.19**hopper**

a silo bottom with inclined walls

1.5.20**hopper pressure ratio F**

the ratio of the normal pressure p_n on the sloping wall of a hopper to the mean vertical stress p_v in the solid at the same level

1.5.21**intermediate slenderness silo**

a silo where $1,0 < h_c/d_c < 2,0$ (except as defined in 3.3)

1.5.22**internal pipe flow**

a pipe flow pattern in which the flow channel boundary extends to the surface of the stored solid without contact with the wall (see Figures 3.1 and 3.2)

1.5.23**lateral pressure ratio K**

the ratio of the mean horizontal pressure on the vertical wall of a silo to the mean vertical stress in the solid at the same level

1.5.24**low cohesion**

a particulate solid sample has low cohesion if the cohesion c is less than 4 % of the preconsolidation stress σ_f (a method for determining cohesion is given in C.9)

1.5.25**mass flow**

a flow pattern in which all the stored particles are simultaneously in motion during discharge (see Figure 3.1a)

1.5.26**mixed flow**

a funnel flow pattern in which the flow channel intersects the vertical wall of the silo at a point below the solid surface (see Figures 3.1c and 3.3)

1.5.27

non-circular silo

a silo whose plan cross-section is in any shape that is not circular (see Figure 1.1d)

1.5.28

particulate solid

a solid in the form of many discrete and independent particles

1.5.29

patch load

a local load taken to act over a specified zone on any part of the vertical wall of a silo

1.5.30

pipe flow

a flow pattern in which the particulate solid in a vertical or nearly vertical channel above the outlet is in motion, but is surrounded by stationary solid (see Figures 3.1b and 3.2). Flow may occur against the silo wall if the outlet is eccentric (see Figures 3.2c and d) or if specific factors cause the channel location to move from above the outlet (see Figure 3.4d)

1.5.31

plane flow

a flow profile in a rectangular or a square cross-section silo with a slot outlet. The slot is parallel with two of the silo walls and its length is equal to the length of these walls

1.5.32

powder

for the purposes of this standard, a solid whose mean particle size is less than 0,05 mm is classed as a powder

1.5.33

pressure

force per unit area normal to a wall of the silo

1.5.34

retaining silo

a silo whose bottom is flat and where $h_c/d_c \leq 0,4$

1.5.35

shallow hopper

a hopper in which the full value of wall friction is not mobilized after filling the silo

1.5.36

silo

containment structure used to store particulate solids (i.e. bunker, bin or silo)

1.5.37

slender silo

a silo where $h_c/d_c \geq 2,0$ or that meets the additional conditions defined in 3.3

1.5.38

slenderness

the aspect ratio h_c/d_c of the silo vertical section

1.5.39

squat silo

a silo where $0,4 < h_c/d_c \leq 1,0$ or that meets the additional conditions defined in 3.3. Where $h_c/d_c \leq 0,4$, the silo is squat if there is a hopper, but a retaining silo if the bottom is flat

1.5.40**steep hopper**

a hopper in which the full value of wall friction is mobilized after filling the silo

1.5.41**stress in the stored solid**

force per unit area within the stored solid

1.5.42**tank**

containment structure used to store liquids

1.5.43**thick-walled silo**

a silo with a characteristic dimension to wall thickness ratio less than $d_c/t = 200$

1.5.44**thin-walled circular silo**

a circular silo with a diameter to wall thickness ratio greater than $d_c/t = 200$

1.5.45**traction**

force per unit area parallel to the wall of the silo (vertical or inclined)

1.5.46**transition**

the intersection of the hopper and the vertical wall

1.5.47**vertical walled segment**

the part of a silo or a tank with vertical walls

1.5.48**wedge hopper**

a hopper in which the sloping sides converge only in one plane (with vertical ends) intended to produce plane flow in the stored solids

1.6 Symbols used in Part 4 of Eurocode 1

A list of elementary symbols is provided in EN 1990. The following additional symbols are specific to this part. The symbols used are based on ISO 3898: 1997.

1.6.1 Roman upper case letters

- A plan cross-sectional area of vertical walled segment
- A_c plan cross-sectional area of flow channel during eccentric discharge
- B depth parameter for eccentrically filled squat silos
- C load magnifying factor
- C_o discharge factor (load magnifying factor) for the solid
- C_{op} patch load solid reference factor (load magnifying factor) for the stored solid
- C_b bottom load magnifying factor

C_h	horizontal pressure discharge factor (load magnifying factor)
C_{pe}	discharge patch load factor (load magnifying factor)
C_{pf}	filling patch load factor (load magnifying factor)
C_S	slenderness adjustment factor for intermediate slenderness silos
C_T	load multiplier for temperature differentials
C_w	wall frictional traction discharge factor (load magnifying factor)
E	flow channel eccentricity to silo radius ratio
E_s	effective elastic modulus of stored solid at relevant stress level
E_w	elastic modulus of silo wall
F	ratio of normal pressure on hopper wall to mean vertical stress in the solid
F_e	hopper pressure ratio during discharge
F_f	hopper pressure ratio after filling
F_{pe}	total horizontal force due to patch load on thin walled circular silo during discharge
F_{pf}	total horizontal force due to patch load on thin walled circular silo after filling
G	ratio of radius of flow channel to radius of circular silo
K	characteristic value of lateral pressure ratio
K_m	mean value of lateral pressure ratio
K_o	value of K measured for zero horizontal strain, under horizontal and vertical principal stresses
S	hopper geometry factor (=2 for conical, =1 for wedge)
T	temperature
U	internal perimeter of the plan cross-section of the vertical walled segment
U_{sc}	internal perimeter of flow channel to static solid contact under eccentric discharge
U_{wc}	internal perimeter of flow channel wall contact under eccentric discharge
Y	depth variation function
Y_J	Janssen pressure depth variation function
Y_R	squat silo pressure depth variation function

1.6.2 Roman lower case letters

a side length of a rectangular or hexagonal silo (see Figure 1.1d)

- a property modification coefficient to give upper and lower characteristic values from mean values
- a_K modification coefficient for lateral pressure ratio
- a_γ modification coefficient for bulk unit weight
- a_ϕ modification coefficient for internal friction angle
- a_μ modification coefficient for wall friction coefficient
- b width of a rectangular silo (see Figure 1.1d)
- b empirical coefficient for hopper pressures
- c cohesion of the solid
- d_c characteristic dimension of inside of silo cross-section (see Figure 1.1d)
- e the larger of e_f and e_o
- e_c eccentricity of the centre of the flow channel in highly eccentric flow (see Figure 5.5)
- e_f maximum eccentricity of the surface pile during the filling process (see Figure 1.1b)
- $e_{f,cr}$ maximum filling eccentricity for which simple rules may be used ($e_{f,cr} = 0,25d_c$)
- e_o eccentricity of the centre of the outlet (see Figure 1.1b)
- $e_{o,cr}$ maximum outlet eccentricity for which simple rules may be used ($e_{o,cr} = 0,25d_c$)
- e_t eccentricity of the centre of the top surface pile when the silo is full (see Figure 1.1b)
- $e_{t,cr}$ maximum top surface eccentricity for which simple rules may be used ($e_{t,cr} = 0,25d_c$)
- h_b overall height of silo from the hopper apex to the equivalent surface (see Figure 1.1a)
- h_c height of vertical-walled segment of silo from the transition to the equivalent surface (see Figure 1.1a)
- h_h height of hopper from the apex to the transition (see Figure 1.1a)
- h_o depth below the equivalent surface of the base of the top pile (lowest point on the wall that is not in contact with the stored solid (see Figures 1.1a, 5.6 and 6.3))
- h_{tp} total height of the top pile of solid (vertical distance from lowest point on the wall that is not in contact with the stored solid to the highest stored particle (see Figures 1.1a and 6.3))
- n power in hopper pressure relationship
- n_{zSk} characteristic value of vertical stress resultant per unit perimeter in the vertical walled segment
- p pressure
- p_h horizontal pressure due to stored particulate solid (see Figure 1.1c)
- p_{hae} horizontal pressure in static solid adjacent to the flow channel during eccentric discharge

- p_{hce} horizontal pressure in flow channel during eccentric discharge
- p_{hco} asymptotic horizontal pressure at great depth in flow channel during eccentric discharge
- p_{hc} horizontal pressure during discharge
- $p_{hc,u}$ horizontal pressure during discharge calculated using the simplified method
- p_{hf} horizontal pressure after filling
- p_{hfb} horizontal pressure after filling at the base of the vertical walled segment
- $p_{hf,u}$ horizontal pressure after filling calculated using the simplified method
- p_{ho} asymptotic horizontal pressure at great depth due to stored particulate solid
- p_{hse} horizontal pressure in static solid distant from the flow channel during eccentric discharge
- p_{hT} horizontal increase in pressure due to a temperature differential
- p_n pressure normal to hopper wall due to stored particulate solid (see Figure 1.1c)
- p_{nc} pressure normal to hopper wall during discharge
- p_{nf} pressure normal to hopper wall after filling
- p_p patch pressure
- p_{pe} patch pressure during discharge
- p_{pei} inverse complementary patch pressure during discharge
- $p_{pe,nc}$ uniform pressure on non-circular silo to represent patch load effects during discharge
- p_{pf} patch pressure after filling
- p_{pfi} inverse complementary patch pressure after filling
- $p_{pf,nc}$ uniform pressure on non-circular silo to represent patch load effects after filling
- $p_{p,sq}$ patch pressure in squat silos
- p_{pes} patch pressure at circumferential coordinate θ (thin walled circular silos) during discharge
- p_{pfs} patch pressure at circumferential coordinate θ (thin walled circular silos) after filling
- p_t hopper frictional traction (see Figure 1.1c)
- p_{te} hopper frictional traction during discharge
- p_{tf} hopper frictional traction after filling
- p_v vertical stress in stored solid (see Figure 1.1c)

- p_{vb} vertical pressure evaluated at the level of the base in a squat silo using Expression (6.2)
- p_{vf} vertical stress in stored solid after filling
- p_{vft} vertical stress in the stored solid at the transition after filling (base of the vertical walled segment)
- p_{vho} vertical pressure evaluated at the base of the top pile using Expression (5.79) with $z = h_o$
- p_{vsq} vertical pressure acting on the flat bottom of a squat or intermediate slenderness silo
- p_{vip} geostatic vertical pressure at the base of the top pile
- p_w wall frictional traction on the vertical wall (frictional shear force per unit area) (see Figure 1.1c)
- p_{wae} wall frictional traction in static solid adjacent to the flow channel during eccentric discharge
- p_{wce} wall frictional traction in flow channel during eccentric discharge
- p_{we} wall frictional traction during discharge
- $p_{we,u}$ wall frictional traction during discharge calculated using the simplified method
- p_{wf} wall frictional traction after filling
- $p_{wf,u}$ wall frictional traction after filling calculated using the simplified method
- p_{wse} wall frictional traction in static solid adjacent to the flow channel during eccentric discharge
- r equivalent radius of silo ($r = 0,5d_c$)
- r_c radius of eccentric flow channel
- s dimension of the zone affected by the patch load ($s = \pi d_c / 16 \cong 0,2d_c$)
- t silo wall thickness
- x vertical coordinate in hopper with origin at cone or pyramidal apex (see Figure 6.2)
- z depth below the equivalent surface of the solid in the full condition (see Figure 1.1a)
- z_o Janssen characteristic depth
- z_{oc} Janssen characteristic depth for flow channel under eccentric discharge
- z_p depth below the equivalent surface of the centre of the thin-walled silo patch load
- z_s depth below the highest solid-wall contact (see Figures 5.7 and 5.8)
- z_v depth measure used for vertical stress assessment in squat silos

1.6.3 Greek upper case letters

- Δ horizontal displacement of the upper part of a shear cell

Δ incremental operator, which appears in the following composite symbols:

Δp_{sq} difference between vertical pressures assessed by two methods for squat silos

ΔT difference between temperature of the stored solid and the silo wall

Δv increment of vertical displacement measured during materials testing

$\Delta \sigma$ increment of stress applied to a cell during materials testing

1.6.4 Greek lower case letters

α mean angle of inclination of hopper wall measured from the horizontal (see Figure 1.1b)

α_w thermal expansion coefficient for silo wall

β angle of inclination of hopper wall measured from the vertical (see Figures 1.1a and 1.1b), or the steepest slope on a square or rectangular pyramidal hopper

γ upper characteristic value of the bulk unit weight of liquid or particulate solid

γ_1 bulk unit weight of fluidized stored particulate solid

δ standard deviation of a property

θ circumferential angular coordinate

θ_c eccentric flow channel wall contact angle (circumferential coordinate of the edge of the low pressure zone under eccentric discharge (see Figure 5.5))

ψ eccentric flow channel wall contact angle measured from flow channel centre

μ characteristic value of coefficient of wall friction for a vertical wall

μ_{heff} effective or mobilized friction in a shallow hopper

μ_h coefficient of wall friction for hopper

μ_m mean value of coefficient of wall friction between a particulate solid and the wall

ν Poisson's ratio for the stored solid

ϕ_c characteristic value of unloading angle of internal friction of a particulate solid (see C.9)

ϕ_l characteristic value of loading angle of internal friction of a particulate solid (see C.9)

ϕ_{lm} mean value of the loading angle of internal friction (see C.9)

ϕ_r angle of repose of a particulate solid (conical pile) (see Figure 1.1a)

ϕ_w wall friction angle (= $\arctan(\mu)$) between a particulate solid and the silo wall

ϕ_{wh} hopper wall friction angle (= $\arctan(\mu_h)$) between a particulate solid and the hopper wall

σ_r reference stress level for solids testing

1.6.5 Subscripts

d	design value (adjusted by partial factor)
e	discharge (emptying) of solids
f	filling and storing of solids
h	hopper
h	horizontal
K	lateral pressure ratio
m	mean value
n	normal to the wall
nc	non-circular silo
p	patch load
t	tangential to the wall
u	uniform
v	vertical
w	wall frictional
γ	bulk unit weight
ϕ	angle of internal friction
μ	wall friction coefficient

Section 2 Representation and classification of actions

2.1 Representation of actions on silos

(1)P Actions on silos shall be determined taking account of the silo structure, the stored solid properties, and the discharge flow patterns that arise during the process of emptying.

(2)P Uncertainties concerning the flow patterns, the influence of the eccentricities of inlet and outlet on the filling and discharge processes, the influence of the form of the silo on the type of flow pattern, and the time-dependent filling and discharge pressures shall be taken into account.

NOTE: The magnitude and distribution of the design loads depend on the silo structure, the stored solid properties, and the discharge flow patterns that arise during the process of emptying. The inherent variability of stored solids and simplifications in the load models lead to differences between actual silo loads and loads given by the design rules in Sections 5 and 6. For example, the distribution of discharge pressures varies around the wall as a function of time and no accurate prediction of the mean pressure or its variance is possible at this time.

(3)P Loads on the vertical walls of silos due to filling and discharge of particulate solids with small eccentricities shall be represented by a symmetrical load and an unsymmetrical patch load. Where larger eccentricities occur, the loads shall be represented by unsymmetrical pressure distributions.

(4) The characteristic value of actions on silos defined in this standard are intended to correspond to values that have a probability of 2 % that they will be exceeded within a reference period of 1 year.

NOTE: The characteristic values are not based on a formal statistical analysis because such data is not currently available. Instead they are based on historical values used in earlier standards. The above definition corresponds to that given in EN 1990.

(5) If the structural form selected for the silo is likely to be sensitive to deviations in load patterns, a sensitivity analysis should be performed.

(6) Symmetrical loads on silos should be expressed in terms of a horizontal pressure p_h on the inner surface of the vertical silo wall, a normal pressure p_n on an inclined wall, tangential frictional tractions on the walls p_w and p_t , and a vertical pressure p_v in the stored solid.

(7) Unsymmetrical loads on the vertical walls of silos with small eccentricities of filling and discharge should be represented by patch loads. These patch loads should be expressed in terms of a local horizontal pressure p_h on the inner surface of the silo.

(8) Unsymmetrical loads on the vertical walls of silos with larger eccentricities of filling and discharge should be represented by unsymmetrical distributions of horizontal pressure p_h and wall frictional traction p_w .

(9) Load magnifiers C should be used to represent unfavourable additional loads.

(10) For silos in Action Assessment Classes 2 and 3 (see 2.5), the load magnifiers C should be used to represent only unfavourable additional loads associated with solids flow during discharge.

(11) For silos in Action Assessment Class 1, load magnifiers C should be used to represent both unfavourable additional loads associated discharge flow and the effects of variability of the stored solid.

NOTE: The load magnifiers C are intended to account for uncertainties concerning the flow patterns, the influence of the eccentricities of inlet and outlet on the filling and discharge processes, the influence of the form of the silo on the type of flow pattern, and the approximations used in transforming the time-dependent filling and discharge pressures into time-independent models. For silos in Action Assessment Class 1, the load magnifier also accounts for the inherent variability of the properties of the stored solid. For silos in Action Assessment Classes 2 and 3, the variability of the design parameters used to represent the stored solid is taken into account in the adopted characteristic values for the stored material properties χ , μ , K and ϕ_1 and not in the load magnifiers C .

(12) For silos in Action Assessment Class 1, unsymmetrical loads should be represented by an increase in the symmetrical load, using a discharge load magnifying factor C .

(13) For silos in Action Assessment Class 2, unsymmetrical patch loads may be alternatively represented by a substitute increase in the symmetrical load that is related to the unsymmetrical patch load magnitude.

2.2 Representation of actions on tanks

(1)P Loads on tanks due to liquids shall be represented by a hydrostatic distributed load.

(2) The characteristic value of actions on tanks defined in this standard are intended to correspond to values that have a probability of 2 % that they will be exceeded within a reference period of 1 year.

NOTE: The characteristic values are not based on a formal statistical analysis because such data is not currently available. Instead they are based on historical values used in earlier standards. The above definition corresponds to that given in EN 1990.

2.3 Classification of actions on silos

(1)P Loads due to stored particulate solids in silos shall be classified as variable actions, see EN 1990.

(2)P Symmetrical loads on silos shall be classified as variable fixed actions, see EN 1990.

(3)P Patch loads associated with filling and discharging processes in silos shall be classified as variable free actions.

(4)P Eccentric loads associated with eccentric filling or discharge processes in silos shall be classified as variable fixed actions.

(5)P Gas pressure loads attributable to pneumatic conveying systems shall be classified as variable fixed actions.

(6)P Loads due to dust explosions shall be classified as accidental actions.

2.4 Classification of actions on tanks

(1)P Loads on tanks shall be classified as variable fixed actions, see EN 1990.

2.5 Action assessment classification

(1) Different levels of rigour should be used in the design of silo structures, depending on the reliability of the structural arrangement and the susceptibility to different failure modes.

(2) The silo design should be carried out according to the requirements of the following three Action Assessment Classes used in this part, which produce designs with essentially equal risk in the design assessment and considering the expense and procedures necessary to reduce the risk of failure for different structures (see EN 1990, 2.2 (3) and (4)):

- Action Assessment Class 1 (AAC 1);
- Action Assessment Class 2 (AAC 2);
- Action Assessment Class 3 (AAC 3).

(3) A higher Action Assessment Class than that required in 2.5 (2) may always be adopted. Any part of the procedures for a higher Action Assessment Class may be adopted whenever it is appropriate.

(4) For silos in Action Assessment Class 1, the simplified provisions of this standard for that class may be adopted.

(5) The Action Assessment Class for a silo should be determined by the conditions of the individual storage unit, not on those of an entire silos battery or group of silos that may be situated in a complete facility.

NOTE 1: The National Annex may define the class boundaries. Table 2.1 shows recommended values.

Table 2.1: Recommended classification of silos for action assessments

Action Assessment Class	Description
Action Assessment Class 3	Silos with capacity in excess of 10 000 tonnes Silos with capacity in excess of 1000 tonnes in which any of the following design situations occur: a) eccentric discharge with $e/d_c > 0,25$ (see figure 1.1b) b) squat silos with top surface eccentricity with $e/d_c > 0,25$
Action Assessment Class 2	All silos covered by this standard and not placed in another class
Action Assessment Class 1	Silos with capacity below 100 tonnes

NOTE 2: The above differentiation has been made in relation to the uncertainty in determining actions with appropriate precision. Rules for small silos are simple and conservative because they have an inherent robustness and the high cost of materials testing of stored solids is not justifiable. The consequences of structural failure and the risk to life and property are covered by the Action Assessment Classification of EN 1992 and EN 1993.

NOTE 3: The choice of Action Assessment Class should be agreed for the individual project.

Section 3 Design situations

3.1 General

(1)P Actions on silos and tanks shall be determined using the general format for each relevant design situation identified in accordance with EN 1990.

NOTE: This does not mean that the paragraphs and values specified for buildings and bridges in EN 1990, A.1 and A.2 are applicable to silos and tanks.

(2)P Selected design situations shall be considered and critical load cases identified. For silos, the design situations shall be based on the flow characteristics of the stored particulate solid, as determined in accordance with Annex C.

(3)P For each critical load case the design values of the effects of actions in combination shall be determined.

(4)P The combination rules depend on the verification under consideration and shall be identified in accordance with EN 1990.

NOTE: Relevant combination rules are given in Annex A.

(5) The actions transferred from adjoining structures should be considered.

(6) The actions from feeders and gates should be considered. Special attention should be paid to unattached feeders that may transfer loads to the silo structure through the stored solid.

(7) The following accidental actions and situations should be considered where appropriate:

- actions due to explosions;
- actions due to vehicle impact;
- seismic actions;
- fire design situations.

3.2 Design situations for stored solids in silos

(1)P Loads on silos from the stored solid shall be considered when the silo is in the full condition.

(2)P Load patterns for filling and discharge shall be used to represent design situations at the ultimate and serviceability limit states.

(3) The design for particulate solids filling and discharge should address the principal load cases that lead to different limit states for the structure:

- maximum normal pressure on the silo vertical wall;
- maximum vertical frictional drag (traction) on the silo vertical wall;
- maximum vertical pressure on a silo bottom;
- maximum load on a silo hopper.

(4) The upper characteristic value of the bulk unit weight γ should be used in all load calculations.

(5) The evaluation of each load case should be made using a single set of consistent values of the solids properties μ , K and ϕ_j , so that each limit state corresponds to a single defined stored solid condition.

(6) Because these load cases each attain their most damaging extreme values when the stored solid properties μ , K and ϕ_j take characteristic values at different extremes of their statistical range, different property extremes

should be considered to ensure that the design is appropriately safe for all limit states. The value of each property that should be adopted for each load case is given in Table 3.1.

Table 3.1: Values of properties to be used for different wall loading assessments

Purpose:	Characteristic value to be adopted		
	Wall friction coefficient μ	Lateral pressure ratio K	Angle of internal friction ϕ_i
For the vertical wall or barrel			
Maximum normal pressure on vertical wall	Lower	Upper	Lower
Maximum frictional traction on vertical wall	Upper	Upper	Lower
Maximum vertical load on hopper or silo bottom	Lower	Lower	Upper
Purpose:	Wall friction coefficient μ	Hopper pressure ratio F	Angle of internal friction ϕ_i
For the hopper wall			
Maximum hopper pressures on filling	Lower value for hopper	Lower	Lower
Maximum hopper pressures on discharge	Lower value for hopper	Upper	Upper
<p>NOTE 1: It should be noted that $\phi_{wh} \leq \phi_i$ always, since the material will rupture internally if slip at the wall contact demands a greater shear stress than the internal friction can sustain. This means that, in all evaluations, the wall friction coefficient should not be taken as greater than $\tan \phi_i$ (i.e. $\mu = \tan \phi_w \leq \tan \phi_i$ always).</p> <p>NOTE 2: Hopper normal pressure p_n is usually maximized if the hopper wall friction is low because less of the total hopper load is then carried by wall friction. Care should be taken when choosing which property extreme to use for the hopper wall friction to ensure that the structural consequences are fully explored (i.e. whether friction or normal pressures should be maximized depends on the kind of structural failure mode that is being considered).</p>			

(7) Notwithstanding the above, silos in Action Assessment Class 1 may be designed for the single value of the mean wall friction coefficient μ_m , the mean lateral pressure ratio K_m and the mean internal friction angle ϕ_{im} for the stored particulate solid.

(8) General expressions for the calculation of silo wall loads are given in Sections 5 and 6. They should be used as a basis for the calculation of the following characteristic loads:

- filling loads on vertical walled segments (Section 5);
- discharge loads on vertical walled segments (Section 5);
- filling and discharge loads on flat bottoms (Section 6);
- filling loads on hoppers (Section 6);
- discharge loads on hoppers (Section 6).

3.3 Design situations for different silo geometrical arrangements

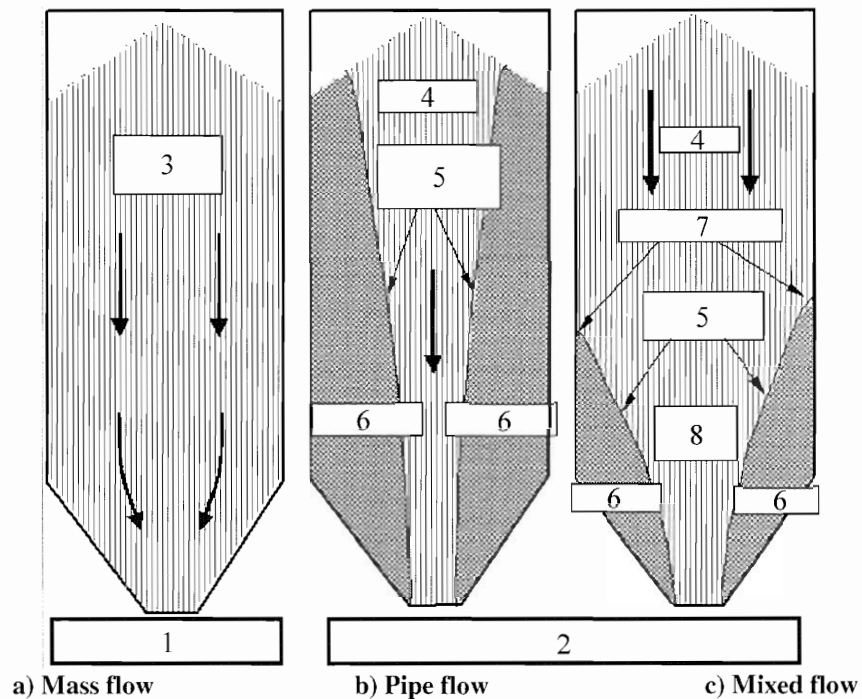
(1)P Different silo aspect ratios (slendernesses), hopper geometries and discharge arrangements lead to different design situations that shall be considered.

(2) Where the trajectory of the solid falling into a silo leads to an eccentric pile at some level (see Figure 1.1b), different packing densities can occur in different parts of the silo that induce unsymmetrical pressures.

The largest eccentricity in the solids trajectory e_f should be used to assess the magnitudes of these pressures (see 5.2.1.2 and 5.3.1.2).

(3) The design should consider the consequences of the flow pattern during discharge, which may be described in terms of the following categories (see Figure 3.1):

- mass flow;
- pipe flow;
- mixed flow.



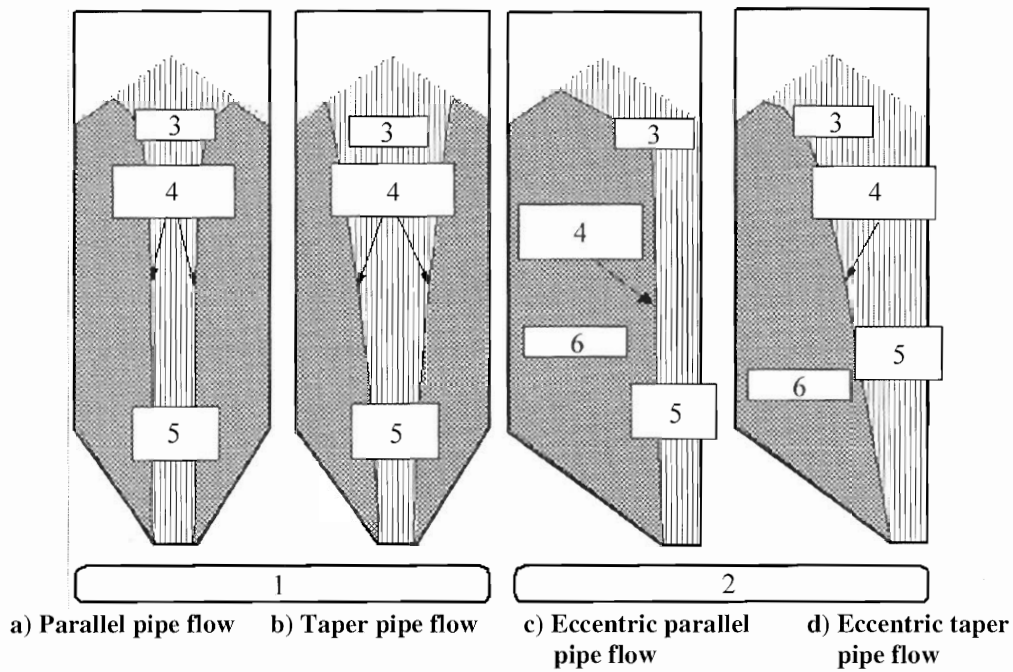
Key

- 1 Mass flow
- 2 Funnel flow
- 3 All solids in motion
- 4 Flowing
- 5 Flow channel boundary
- 6 Stationary
- 7 Effective transmission
- 8 Effective hopper

Figure 3.1: Basic flow patterns

(4) Where pipe flow occurs and is always internal to the solid, (see Figures 3.2a and b) discharge pressures can be ignored. Squat silos with concentric gravity discharge and silos with top-surface mechanical discharge systems that ensure internal pipe flow (see Figures 3.4a and b and 3.5a) satisfy these conditions (see 5.1 (7) and 5.3.2.1 (2) and (4)).

NOTE: An anti-dynamic tube of appropriate design may also satisfy the conditions for internal pipe flow.



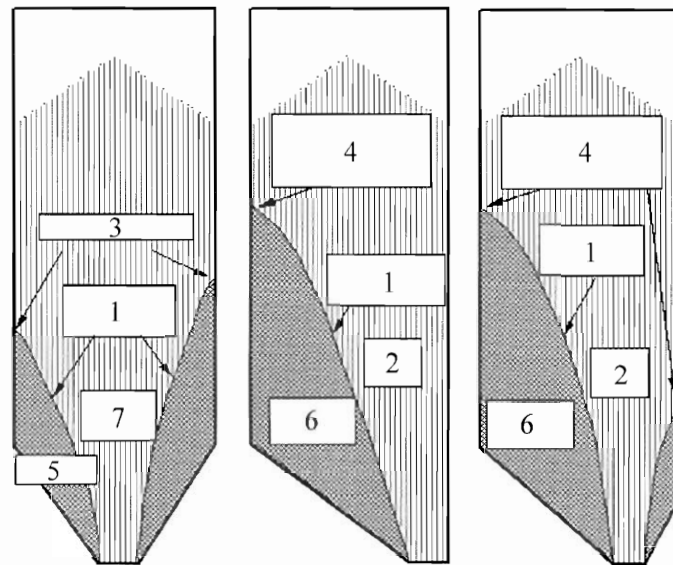
Key

- 1 Internal pipe flow
- 2 Eccentric pipe flow
- 3 Flowing
- 4 Flow channel boundary
- 5 Flowing pipe
- 6 Stationary

Figure 3.2: Pipe flow patterns

(5) Under symmetrical mass or mixed flow (see Figure 3.1), the design should consider the unsymmetrical pressures that may develop (see 5.2.2.2 and 5.3.2.2).

(6) Where pipe flow or mixed flow occurs with partial contact with the silo wall, the design should consider special provisions for the unsymmetrical pressures that may arise (see Figure 3.2c and d and Figure 3.3b and c) (see also 5.2.4).



a) Concentric mixed flow

b) Fully eccentric mixed flow

c) Partially eccentric mixed flow

Key

- 1 Flow channel boundary
- 2 Flow zone
- 3 Effective transition
- 4 Effective transition: varies around silo circumference
- 5 Stationary
- 6 Stationary
- 7 Effective hopper

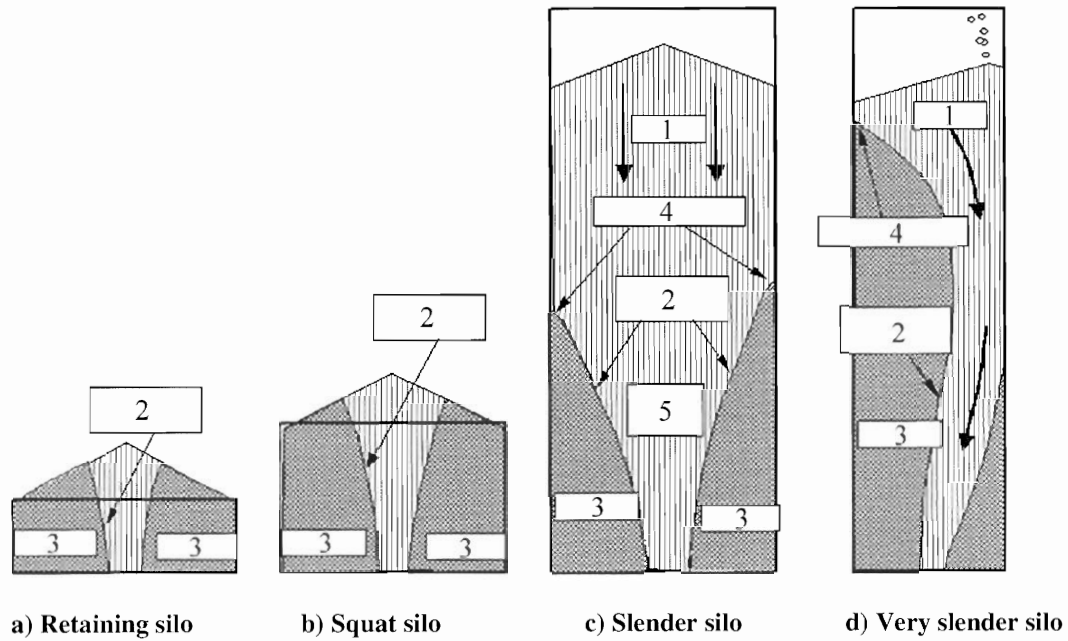
Figure 3.3: Mixed flow patterns

(7) Where a silo has multiple outlets, the design should consider the possibility that either any outlet alone, or any combination of outlets simultaneously, may be opened when the silo is in the full condition.

(8) Where a silo has multiple outlets and the operational design has arranged for it to operate in a particular manner, this manner should be treated as an ordinary design situation. Other outlet opening conditions should be treated as accidental design situations.

NOTE: The term "ordinary design situation" above refers to a Fundamental Combination in EN 1990, 6.4.3.2. The term "accidental load case" refers to an Accidental Design Situation in EN 1990, 6.4.3.3.

(9) Where a very slender silo is filled eccentrically, or where segregation in a very slender silo can lead either to different packing densities in different parts of the silo or to cohesiveness in the solid, the asymmetry of the arrangement of particles may induce unsymmetrical pipe or mixed flow (see Figure 3.4d), with flow against the silo wall that may cause unsymmetrical pressures. The special provisions that are required for this case (see 5.2.4.1 (2)) should be used.



Key

- 1 Flowing
- 2 Flow channel boundary
- 3 Stationary
- 4 Effective transition
- 5 Effective hopper

Figure 3.4: Aspect ratio (slenderness) effects in mixed and pipe flow patterns

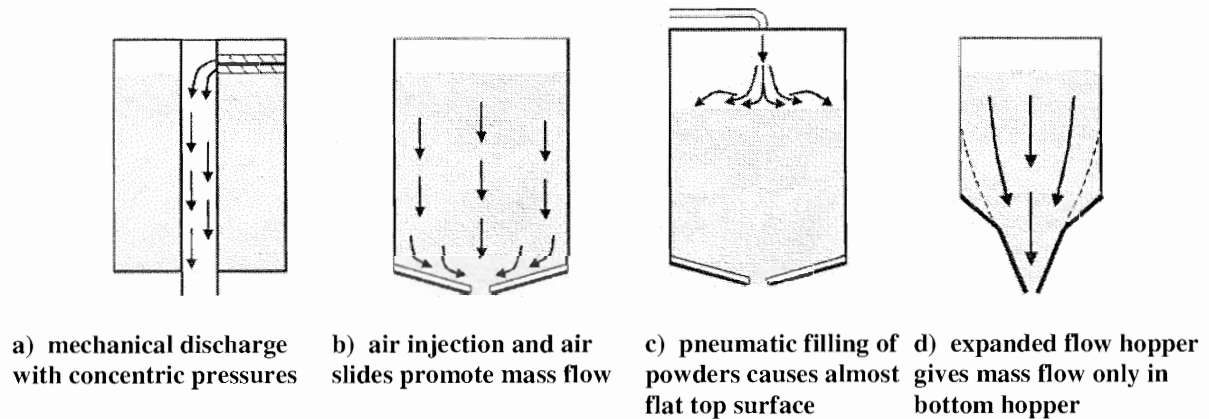


Figure 3.5: Special filling and discharge arrangements

(10) Where a silo is filled with powder that has been pneumatically conveyed, two design situations for the full condition should be considered. First, the stored solid may form an angle of repose, as for other solids. Second, consideration should be given to the possibility that the top surface may be horizontal (see Figure 3.5c), irrespective of the angle of repose and the eccentricity of filling. If this is the case, the eccentricities associated with filling e_f and e_t may be taken to be zero, and the filling level should be taken at its maximum possible value.

(11) Where a silo storing powder has an aerated bottom (see Figure 3.5b), the whole bottom may be fluidized, causing an effective mass flow even in a squat silo geometry. Such a silo should be designed according to the provisions for slender silos, irrespective of the actual slenderness h_c/d_c .

(12) Where a silo storing powder has an aerated bottom (see Figure 3.5b), it may be that only a limited zone of powder is fluidized, causing an eccentric pipe flow (see Figure 3.3b) which should also be considered. The eccentricity of the resulting flow channel and the resulting value of e_o should be evaluated with respect to the fluidized zone, and not relative to the location of the outlet.

(13) The vertical walls of a silo with an expanded flow discharge hopper (see Figure 3.5d) may be subject to mixed flow conditions that may cause unsymmetrical pressures during discharge. The evaluation of the slenderness of a silo of this type should be based on h_b/d_c in place of h_c/d_c (see Figure 1.1a).

(14) Where a silo has a slenderness h_c/d_c less than 0,4, it should be classified as squat if it has a hopper at its base, but classed as a retaining silo if it has a flat bottom.

(15) Where the silo has a hopper that is not conical, pyramidal or wedge shaped, a rational method of analysis of the pressures should be used. Where a hopper contains internal structures, the pressures on both the hopper and the internal structure should be evaluated using a rational method.

(16) Where the silo has a chisel hopper (a wedge shaped hopper beneath a circular cylinder), a rational method of analysis of the pressures should be used.

NOTE: Elongated outlets present special problems. Where a feeder is used to control the discharge of the solid from the silo, its design may affect the solids flow pattern in the silo. This may produce either mass flow or fully eccentric mixed flow, or fully eccentric pipe flow in the silo.

3.4 Design situations for specific construction forms

(1) In concrete silos being designed for the serviceability limit state, cracking should be limited to prevent water ingress at any time. The crack control should comply with the crack width limitations of EN 1992 appropriate for the environment in which the silo is situated.

(2) In metal silos that are assembled using bolted or riveted construction, the provision for unsymmetrical loads (patch loads) should be interpreted in a manner that recognizes that the unsymmetrical loads may occur anywhere on the silo wall (see 5.2.1.4 (4)).

(3) In metal silos that have a rectangular planform and contain internal ties to reduce the bending moments in the walls, the provisions of 5.7 should be used.

(4) The effects of fatigue should be considered in silos or tanks that are subjected to an average of more than one load cycle a day. One load cycle is equal to a single complete filling and emptying, or in an aerated silo (see Figure 3.5b), a complete sequence (rotation) of aerated sectors. The effects of fatigue should also be considered in silos affected by vibrating machinery.

(5) Prefabricated silos should be designed for actions arising during handling, transport and erection.

(6) Where a manhole or access opening is made in the wall of a silo structure, the pressure acting on the cover should be assessed as two times the highest value of the local design pressure on the adjacent wall. This pressure should be used only for the design of the opening cover and its supports.

(7) Where the roof supports dust filter assemblies, cyclones, mechanical conveying equipment or other similar items, these should be treated as imposed loads.

(8) Where pneumatic conveying systems are used to fill or empty the silo, the resulting gas pressure differentials should be considered.

NOTE: These pressures are usually <10 kPa, but significant vacuum (e.g. 40 kPa \cong 0,4 bar) can be applied, usually where a conveying process design or operational error occurs. Silos should have appropriate relief protection for such unexpected events, or the silo designer should ensure that they cannot occur.

(9) Where vibrators, air cannons or gyrating live bottoms form part of the silo installation, the alternating loads caused by them should be considered with respect to the limit state of fatigue. The vibrations caused by pneumatic conveying systems should also be considered.

(10) Where it is proposed to modify an existing silo by the insertion of a wall liner, the consequences of the modified wall friction for the structural design should be investigated, including possible structural consequences of changes in the solids flow patterns.

3.5 Design situations for stored liquids in tanks

(1)P Loads on tanks from the stored liquid shall be considered both when the tank is in operation and when it is full.

(2) Where the operational liquid level is different from the level when the tank is full, the latter should be considered as an accidental design situation.

3.6 Principles for design for explosions

(1) Where tanks or silos are used to store liquids or particulate solids that are susceptible to explosion, potential damage should be limited or avoided by appropriate choice of one or more of the following:

- incorporating sufficient pressure relief area;
- incorporating appropriate explosion suppression systems;
- designing the structure to resist the explosion pressure.

Some of the solids that are prone to dust explosions are identified in Table E.1.

NOTE: Advice on the determination of explosion pressures is given in Annex H.

(2) The pressure exerted on structures near a silo as a result of an explosion within it should be determined.

NOTE: The National Annex may give guidance on the pressure exerted on structures near the silo as a result of an explosion within it.

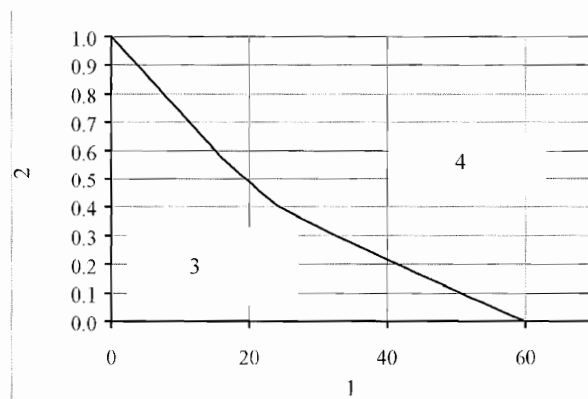
Section 4 Properties of particulate solids

4.1 General

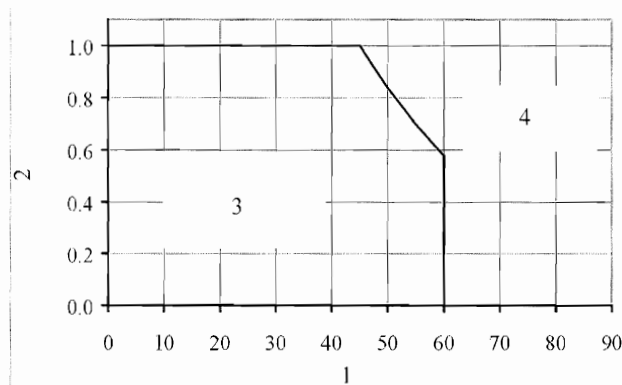
(1)P The evaluation of actions on a silo shall take account of:

- the range of particulate solid properties;
- the variation in the surface friction conditions;
- the geometry of the silo;
- the methods of filling and discharge.

(2) The stiffness of the particulate solid should not be assumed to provide additional stability to the silo wall or to modify the loads defined within this standard. The effects of in-service wall deformations on the pressures developed in the stored solid should be ignored unless a rational verified method of analysis can be applied.



a) Conical hoppers



b) Wedge hoppers

Key

- 1 Hopper apex half angle β (degrees)
- 2 Hopper wall friction coefficient μ_h
- 3 Risk of mass flow pressure in this zone
- 4 Funnel flow certain

Figure 4.1: Conditions in which mass flow pressures may arise

(3) Where necessary, the type of flow pattern (mass flow or funnel flow) should be determined from Figure 4.1. Figure 4.1 should not be used for the functional design of a silo to achieve a mass flow pattern, because the influence of the internal friction angle is ignored.

NOTE: Design for guaranteed mass flow is outside the scope of this standard (see 1.1.2 (5)). Powder and bulk solids handling procedures should be used for this purpose.

4.2 Particulate solids properties

4.2.1 General

(1)P Properties of stored particulate solids, as quantified for load calculations by material parameters, shall be obtained either from test results or from other relevant data.

(2)P Values obtained from test results and other data shall be interpreted appropriately for the load assessment considered.

(3)P Account shall be taken of the possible differences between the material parameters obtained from test results and those governing the behaviour of the solids stored in silos.

(4)P In evaluating the differences in solids properties indicated in (3)P, the following factors shall be considered:

- many parameters are not true constants but depend on the stress level and mode of deformation;
- particle shape, size and size distribution can play different roles in the test and in the silo;
- time effects;
- moisture content variations;
- effect of dynamic actions;
- the brittleness or ductility of the stored solid tested;
- the method of filling into the silo and into the test apparatus.

(5)P In evaluating the differences in wall frictional properties indicated in (3)P, the following factors shall be considered:

- corrosion and chemical reaction between the particles, moisture and the wall;
- abrasion and wear that may roughen the wall;
- polishing of the wall;
- accumulation of greasy deposits on the wall;
- particles of solid being impressed into the wall surface (usually a roughening effect).

(6)P When establishing values of material parameters, the following shall be considered:

- published as well as recognized information relevant to the use of each type of test;
- the value of each parameter compared with relevant published data and general experience;
- the variation of the parameters that are relevant to the design;
- the results of any large scale field measurements from similar silos;
- any correlation between the results from more than one type of test;
- any significant variation in material properties that may be contemplated during the lifetime of the silo.

(7)P The selection of characteristic values for material parameters shall be based on derived values resulting from laboratory tests, complemented by well-established experience.

(8) The characteristic value of a material parameter should be selected as a cautious estimate of the appropriate value, either the upper or the lower characteristic value, depending on its influence on the load being evaluated.

(9) Reference may be made to EN 1990, for provisions concerning the interpretation of test results.

NOTE: Refer also to Annex D of EN 1990.

4.2.2 Testing and evaluation of solids properties

(1)P The values of solid properties adopted in design shall take into account potential variations due to changes in composition, production method, grading, moisture content, temperature, age and electrical charge due to handling.

(2) Particulate solid properties should be determined using either the simplified approach presented in 4.2.3 or by testing as described in 4.3.

(3) For silos in Action Assessment Class 3, particulate solids properties should be obtained by testing as described in 4.3.

(4) The properties of any particulate solid may be taken as represented by the default stored solid given in Table E.1.

Table 4.1: Wall surface definitions

Category	Descriptive title	Typical wall materials
D1	Low friction classed as "Slippery"	Cold-rolled stainless steel Polished stainless steel Coated surface designed for low friction Polished aluminium Ultra high molecular weight polyethylene ^a
D2	Moderate friction classed as "Smooth"	Smooth mild carbon steel (welded or bolted construction) Mill finish stainless steel Galvanized carbon steel Oxidized aluminium Coated surface designed for corrosion resistance or abrasive wear
D3	High friction classed as "Raspy"	Off form concrete, steel finished concrete or aged concrete Aged (corroded) carbon steel Abrasion resistant steel Ceramic tiles
D4	Irregular	Horizontally corrugated walls Profiled sheeting with horizontal ribs Non-standard walls with large aberrations
NOTE: The descriptive titles in this table are given in terms of friction rather than roughness because there is a poor correlation between measured wall friction between a sliding granular solid and the surface and measures of roughness.		
^a The roughening effect of particles being impressed into the surface should be considered carefully for these surfaces.		

(5) The value adopted in design of the wall friction coefficient μ for a given particulate solid should take account of the frictional character of the surface on which it slides. The Wall Surface Categories used in this standard are defined in 4.2.1 and are listed in Table 4.1.

(6) For silos with walls in Wall Surface Category D4, the effective wall friction coefficient should be determined as set out in D.2.

(7) The patch load solid reference factor C_{op} should be obtained from Table E.1 or determined from Expression (4.8).

4.2.3 Simplified approach

(1) The values of the properties of well-known solids should be taken from Table E.1. The values in Table 4.1 correspond to the upper characteristic value for the unit weight γ but the values of μ_m , K_m and ϕ_{1m} are mean values.

(2) Where the solid to be stored cannot be clearly identified as similar to one of the descriptors in Table E.1, testing according to 4.3 should be undertaken.

(3) To determine the characteristic values of μ , K and ϕ_1 , the tabulated values of μ_m , K_m and ϕ_{1m} should be multiplied and divided by the conversion factors a given in Table E.1. Thus in calculating maximum loads the following combinations should be used:

$$\text{Upper characteristic value of } K = a_K K_m \quad \dots (4.1)$$

$$\text{Lower characteristic value of } K = K_m / a_K \quad \dots (4.2)$$

$$\text{Upper characteristic value of } \mu = a_\mu \mu_m \quad \dots (4.3)$$

$$\text{Lower characteristic value of } \mu = \mu_m / a_\mu \quad \dots (4.4)$$

$$\text{Upper characteristic value of } \phi_1 = a_\phi \phi_{1m} \quad \dots (4.5)$$

$$\text{Lower characteristic value of } \phi_1 = \phi_{1m} / a_\phi \quad \dots (4.6)$$

(4) For silos in Action Assessment Class 1, the mean values of μ_m , K_m and ϕ_{1m} may be used for design, in place of the range of values associated with the upper and lower characteristic values.

4.3 Testing particulate solids

4.3.1 Test procedures

(1)P Testing shall be carried out on representative samples of the particulate solid. The mean value for each solid property shall be determined making proper allowance for variations in secondary parameters such as composition, grading, moisture content, temperature, age, electrical charge due to handling and production method.

(2) The mean test values should be adjusted using Expressions (4.1) to (4.6) with the relevant conversion factor a to derive characteristic values.

(3) Each conversion factor a should be carefully evaluated, taking proper account of the expected variability of the solid properties over the silo life, the possible consequences of segregation and of the effects of sampling inaccuracies.

(4) Where sufficient test data exists to determine the standard deviation of a property, the relevant conversion factor a should be determined as set out in C.11.

(5) The margin between the mean and the characteristic values for the solid property is represented by the conversion factor a . Where a single secondary parameter alone accounts for more than 75 % of the value of a , that value should be increased by multiplying it by 1,10.

NOTE: The above provision is made to ensure that the value of a is chosen to represent an appropriate probability of occurrence for the deduced loads.

4.3.2 Bulk unit weight γ

(1) The bulk unit weight γ should be determined at a particle packing density and at a stress level corresponding to the position in the stored solid in the silo where the maximum vertical stress after filling occurs. The vertical stress p_{vft} in the silo may be assessed using Expression (5.3) or (5.79), as appropriate, for the depth at the bottom of the vertical section.

(2) The test method for the measurement of bulk unit weight γ described in C.6 should be used.

(3) The conversion factor to obtain the characteristic value from the measured value should be found using the procedure given in C.11. The conversion factor a_γ should not be taken as less than $a_\gamma = 1,10$ unless a smaller value can be justified by testing and assessment (see C.11).

4.3.3 Coefficient of wall friction μ

(1) Tests to determine the wall friction coefficient μ for the calculation of loads should be determined at a particle packing density and at a stress level corresponding to the position in the stored solid in the silo where the maximum assessed horizontal filling pressure p_{hfb} on the vertical wall after filling occurs. The filling pressure p_{hfb} at the base of the vertical wall may be assessed using Expression (5.1) or (5.71) as appropriate.

(2) The test method for the measurement of μ described in C.7 should be used.

(3) The mean value μ_m of the wall friction coefficient and its standard deviation should be deduced from the tests. Where only the mean value can be found, the standard deviation should be assessed using the procedure given in C.11.

(4) The conversion factor to obtain the characteristic value from the mean value should be found using the procedure given in C.11. The conversion factor a_μ should not be taken as less than $a_\mu = 1,10$ unless a smaller value can be justified by testing and assessment (see C.11).

4.3.4 Angle of internal friction ϕ_1

(1) The loading angle of internal friction ϕ_1 (arctan of the ratio of shear stress to normal stress at failure during virgin loading) should be determined at a particle packing density and at a stress level corresponding to the position in the stored solid in the silo where the maximum vertical stress after filling occurs. The vertical stress may be assessed using Expression (5.3) or (5.79) as appropriate.

(2) The test method for the measurement of ϕ_1 described in C.9 should be used.

(3) The mean value ϕ_{1m} of the loading angle of internal friction and its standard deviation δ should be deduced from the tests. Where only the mean value can be found, the standard deviation should be assessed using the procedure given in C.11.

(4) The conversion factor to obtain the characteristic value from the mean value should be found using the procedure given in C.11. The conversion factor a_ϕ should not be taken as less than $a_\phi = 1,10$ unless a smaller value can be justified by testing and assessment (see C.11).

4.3.5 Lateral pressure ratio K

(1) The lateral pressure ratio K (ratio of mean horizontal to mean vertical pressure) should be determined at a particle packing density and at a stress level corresponding to the position in the stored solid in the silo where the maximum vertical stress after filling occurs. The vertical stress in the solid p_{vf} may be assessed using Expression (5.3) or (5.79) as appropriate.

(2) The test method for the measurement of K described in C.8 should be used.

(3) The mean value K_m of the lateral pressure ratio and its standard deviation should be deduced from the tests. Where only the mean value can be found, the standard deviation should be assessed using the procedure given in C.11.

(4) An approximate value for K_m may alternatively be obtained from the mean value of the measured loading angle of internal friction ϕ_{im} (see 4.3.4) as:

$$K_m = 1,1 (1 - \sin\phi_{im}) \quad \dots (4.7)$$

NOTE: The factor 1,1 in Expression (4.7) is used to give an approximate representation of the difference between the value of $K (=K_0)$ measured under conditions of almost zero wall friction and the value of K measured when wall friction is present (see also 4.2.2 (5)).

(5) The conversion factor to obtain the characteristic value from the measured value should be found using the procedure in C.11. The conversion factor a_K should not be taken as less than $a_K = 1,10$ unless a smaller value can be justified by testing and assessment (see C.11).

4.3.6 Cohesion c

(1) The cohesion c of the solid varies with the consolidating stress that has been applied to the solid. It should be determined at a particle packing density and at a stress level corresponding to the position in the stored solid in the silo where the maximum vertical stress occurs after filling. The vertical stress in the solid p_{vf} may be assessed using Expression (5.3) or (5.79) as appropriate.

(2) The test method for the measurement of c described in C.9 should be used.

NOTE: Alternatively the cohesion c may be estimated from the results of a Jenike shear cell test (ASTM Standard D6128). A method for determining the cohesion from the test results is given in C.9.

4.3.7 Patch load solid reference factor C_{op}

(1)P The patch load solid reference factor C_{op} shall be determined on the basis of appropriate test records.

NOTE 1: The discharge factors C account for a number of phenomena occurring during discharge of the silo. The symmetrical increase in pressures is relatively independent of the solid being stored, but the unsymmetrical component is quite material dependent. The material dependency of the unsymmetrical component is represented by the patch load solid reference factor C_{op} . This parameter is not easily measured in a control test on the solid.

NOTE 2: An appropriate laboratory test method to determine the parameter C_{op} from a control test on the solid alone has not yet been developed. This factor is based on silo discharge experiments and on experience. It applies to silos with conventional filling and discharge systems and built to standard engineering tolerances.

(2) The value of the patch load solid reference factor C_{op} for well-known solids should be taken from Table E.1.

(3) For solids not listed in Table E.1, the patch load solid reference factor C_{op} may be estimated from the material variability factors for the lateral pressure ratio a_K and the wall friction coefficient a_μ as:

$$C_{op} = 3,5 a_\mu + 2,5 a_K - 6,2 \quad \dots (4.8)$$

where:

a_μ is the variability factor for the wall friction coefficient μ ,

a_K is the variability factor for the lateral pressure ratio K for the solid.

- (4) Appropriate patch load solid reference factors C_{op} for specific silos with specified stored solids may also be derived from full-scale tests performed on silos of the same type.

Section 5 Loads on the vertical walls of silos

5.1 General

(1)P The characteristic values of the filling and discharge loads, which are prescribed in this section for the following types of silo, shall be used:

- slender silos;
- intermediate slenderness silos;
- squat silos;
- retaining silos;
- silos containing solids with entrained air.

(2)P The loads on silo vertical walls shall be evaluated according to the slenderness of the silo (see figure 1.1a and 5.1) determined according to the following classes:

- slender silos, where $2,0 \leq h_c/d_c$ (except as defined in 3.3);
- intermediate slenderness silos, where $1,0 < h_c/d_c < 2,0$ (except as defined in 3.3);
- squat silos, where $0,4 < h_c/d_c \leq 1,0$ (except as defined in 3.3);
- retaining silos, where the bottom is flat and $h_c/d_c \leq 0,4$.

(3) A silo with an aerated bottom should be treated as a slender silo, irrespective of its slenderness h_c/d_c .

(4)P The load on vertical walls is composed of a fixed load, called the symmetrical load, and a free load, called the patch load, which shall be taken to act simultaneously.

(5) Detailed rules for the calculation of filling loads and discharge loads are given for each silo slenderness in 5.2, 5.3 and 5.4.

(6) Additional load cases should be considered for silos with special conditions as follows:

- where air may be entrained into the solid and may make it fully or partially fluidized, see 5.5;
- where thermal differentials may develop between the stored solid and the silo structure, see 5.6;
- where the silo has a rectangular planform, see 5.7.

(7)P Where large eccentricities of filling or discharge occur, special different load cases are defined. These shall not be taken to act simultaneously with the symmetric and patch loads, but each shall represent a separate and distinct load case.

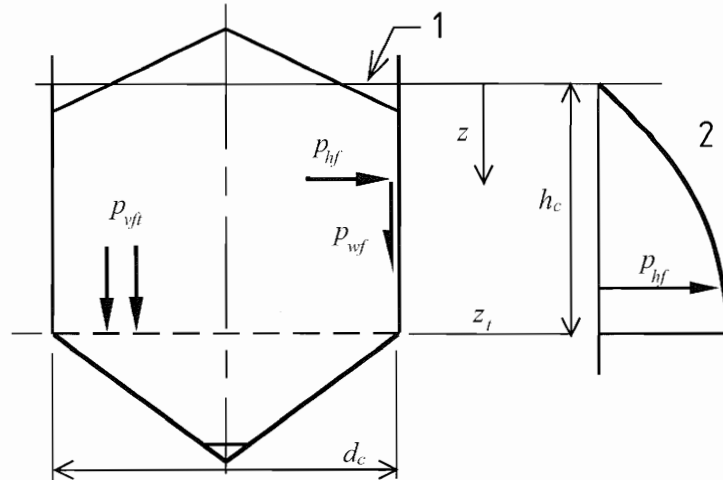
(8) Where internal pipe flow can be guaranteed (see 3.3 (3)), the design may be based on filling loads alone, including the filling patch load where appropriate.

5.2 Slender silos

5.2.1 Filling loads on vertical walls

5.2.1.1 Symmetrical filling load

(1) The symmetrical filling load (see Figure 5.1) should be calculated using Expressions (5.1) to (5.6).



Key

- 1 Equivalent surface
- 2 Pressures in vertical segment

Figure 5.1: Symmetrical filling pressures in the vertical-walled segment

(2) The values of horizontal pressure p_{hf} , wall frictional traction p_{wf} and vertical pressure p_{vf} at any depth after filling and during storage should be determined as:

$$p_{hf}(z) = p_{ho} Y_J(z) \quad \dots (5.1)$$

$$p_{wf}(z) = \mu p_{ho} Y_J(z) \quad \dots (5.2)$$

$$p_{vf}(z) = \frac{p_{ho}}{K} Y_J(z) \quad \dots (5.3)$$

in which:

$$p_{ho} = \gamma K z_0 \quad \dots (5.4)$$

$$z_0 = \frac{1}{K \mu} \frac{A}{U} \quad \dots (5.5)$$

$$Y_J(z) = 1 - e^{-z/z_0} \quad \dots (5.6)$$

where:

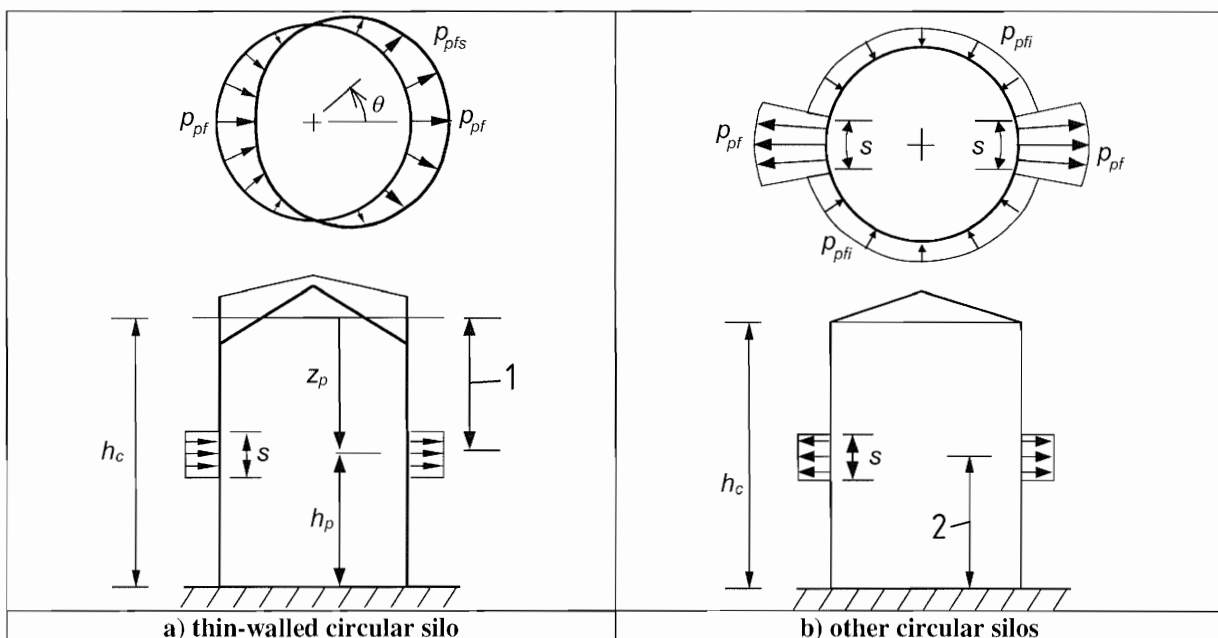
- γ is the characteristic value of the unit weight
- μ is the characteristic value of the wall friction coefficient for solid sliding on the vertical wall
- K is the characteristic value of the lateral pressure ratio
- z is the depth below the equivalent surface of the solid
- A is the plan cross-sectional area of the silo
- U is the internal perimeter of the plan cross-section of the silo

(3) The resulting characteristic value of the vertical force (compressive) in the wall n_{zSk} per unit length of perimeter after filling at any depth z should be determined as:

$$n_{zSk} = \int_0^z p_{wf}(z) dz = \mu p_{ho} [z - z_0 Y_J(z)] \quad \dots (5.7)$$

NOTE: The stress resultant defined in Expression (5.7) is a characteristic value. Care is required when using this result to ensure that the appropriate partial factor on actions is not omitted, since this expression is a result of a structural analysis (using the membrane theory of shells). The expression is included here to assist designers in the integration of Expression (5.2). It is also noted that other loads (e.g. patch loads) may induce additional vertical forces in the wall.

(4) The methods given in 4.2 and 4.3 should be used to determine the characteristic values of the required properties of the particulate solid (unit weight γ ; wall friction μ , and lateral pressure ratio K).



Key

- 1 For welded silos in Action Class 2: the lesser of z_0 and $h_c/2$
- 1 For other thin-walled silos in Action Classes 2 and 3: anywhere
- 2 Anywhere

Figure 5.2: Circular silos: side elevation and plan view of the filling patch load

5.2.1.2 Filling patch load: general requirements

- (1)P The filling patch load, or an appropriate alternative, shall be used to represent accidental asymmetries of loading associated with eccentricities and imperfections in the filling process.
- (2) For silos in Action Assessment Class 1, the filling patch load may be ignored.
- (3) For silos used for the storage of powders that become aerated during the filling process, the filling patch load may be ignored.
- (4) The magnitude of the filling outward patch pressure p_{pf} should be determined from the maximum eccentricity of the top pile throughout the filling process, which is shown as e_f in Figure 1.1b.

(5) The reference magnitude of the filling patch pressure p_{pf} should be taken as:

$$p_{pf} = C_{pf} p_{hf} \quad \dots (5.8)$$

in which:

$$C_{pf} = 0,21 C_{op} [1 + 2E^2] (1 - e^{\{-1,5 [(h_c/d_c) - 1]\}}) \quad \dots (5.9)$$

$$E = 2 e_f / d_c \quad \dots (5.10)$$

but if Expression 5.9 produces a negative value, C_{pf} should be taken instead as:

$$C_{pf} = 0 \quad \dots (5.11)$$

where:

e_f is the maximum eccentricity of the surface pile during filling (see Figure 1.1b);

p_{hf} is the local value of the filling pressure (see Expression (5.1)) at the height at which the patch load is applied;

C_{op} is the patch load solid reference factor for the solid (see Table E.1).

(6) The height of the zone on which the patch load is applied (see Figure 5.2) should be taken as:

$$s = \pi d_c / 16 \cong 0,2 d_c \quad \dots (5.12)$$

(7) The patch load consists of a pattern of normal pressures only. No changes to the frictional traction associated with the changed normal pressure should be considered in design.

(8) The form of the filling patch pressure depends on the form of silo construction. The following construction forms are identified and the patch pressures should be determined using the paragraphs stated below:

- for thick-walled circular silos, see 5.2.1.3 (concrete silos);
- for thin-walled circular silos, see 5.2.1.4 (metal silos);
- for non-circular silos, see 5.2.1.5.

5.2.1.3 Filling patch load: thick-walled circular silos

(1) For thick-walled circular silos, the reference magnitude of the filling patch pressure p_{pf} should be taken to act outwards on two opposite square areas with side length s given by Expression (5.12) (the horizontal distance s is measured on the curved surface where appropriate) (see Figure 5.2b).

(2) In addition to the outward patch pressure p_{pf} , the remainder of the silo circumference over the same height of wall (see Figure 5.2b) should be subjected to an inward patch pressure p_{pfi} given by:

$$p_{pfi} = p_{pf} / 7 \quad \dots (5.13)$$

where:

p_{pf} is the reference magnitude of the filling patch pressure acting outwards (see Expression (5.8)).

NOTE: The value and the extent of the inward pressure p_{pfi} is chosen so that the mean pressure at that level remains unchanged by the patch load.

(3) The filling patch load should be considered to act on any part of the silo wall, but this may be interpreted in the manner described in 5.2.1.3 (4).

(4) In thick-walled circular silos in Action Assessment Class 2, a simplified approach may be used. The most unfavourable load arrangement may be taken as that found by applying the patch at the mid-height of the silo and using the results to deduce approximate values for the stress resultants throughout the wall. The percentage increase in the membrane stress resultants in the wall at that level may be used to scale all the membrane stress resultants on the vertical wall. The calculated bending stress resultants at any level may be found by scaling the values at the patch load level according to the ratio of the filling pressure at that level to the filling pressure at the patch load level.

5.2.1.4 Filling patch load: thin-walled circular silos

(1) For thin walled circular silos ($d_c/t > 200$) in Action Assessment Classes 2 and 3, the filling patch pressure should be taken to act over a height s , given by Expression (5.12), but to extend from a maximum outward pressure on one side of p_{pf} to an inward pressure p_{pf} on the opposite side (see Figure 5.2a). The circumferential variation should be taken as:

$$p_{pfs} = p_{pf} \cos \theta \quad \dots (5.14)$$

where:

p_{pf} is the outward patch pressure (see Expression (5.8))

θ is the circumferential coordinate (see Figure 5.2a).

(2) The total horizontal force F_{pf} due to the filling patch load on a thin-walled circular silo should be determined as:

$$F_{pf} = \frac{\pi}{2} s d_c p_{pf} \quad \dots (5.15)$$

(3) For welded silos in Action Assessment Class 2, the patch load may be taken to act at a depth z_p below the equivalent surface, where z_p is the lesser of:

$$z_p = z_o \quad \text{and} \quad z_p = 0,5 h_c \quad \dots (5.16)$$

where

h_c is the height of the vertical walled segment (see Figure 1.1a).

(4) For bolted and riveted silos in Action Assessment Class 2, the patch load should be considered to act at any depth, but the normal pressure at any level may be taken as a uniform percentage increase throughout the height of the silo.

5.2.1.5 Filling patch load: non-circular silos

(1) For non-circular silos in Action Assessment Classes 2 and 3, the filling patch load, which represents unsymmetrical loads, may be represented by an increase in the symmetrical pressure as defined in (2) and (3).

(2) The outward patch pressure should be taken to act on a horizontal band on the silo wall at any level, over a vertical height s (see Figure 5.3a) given by Expression (5.12).

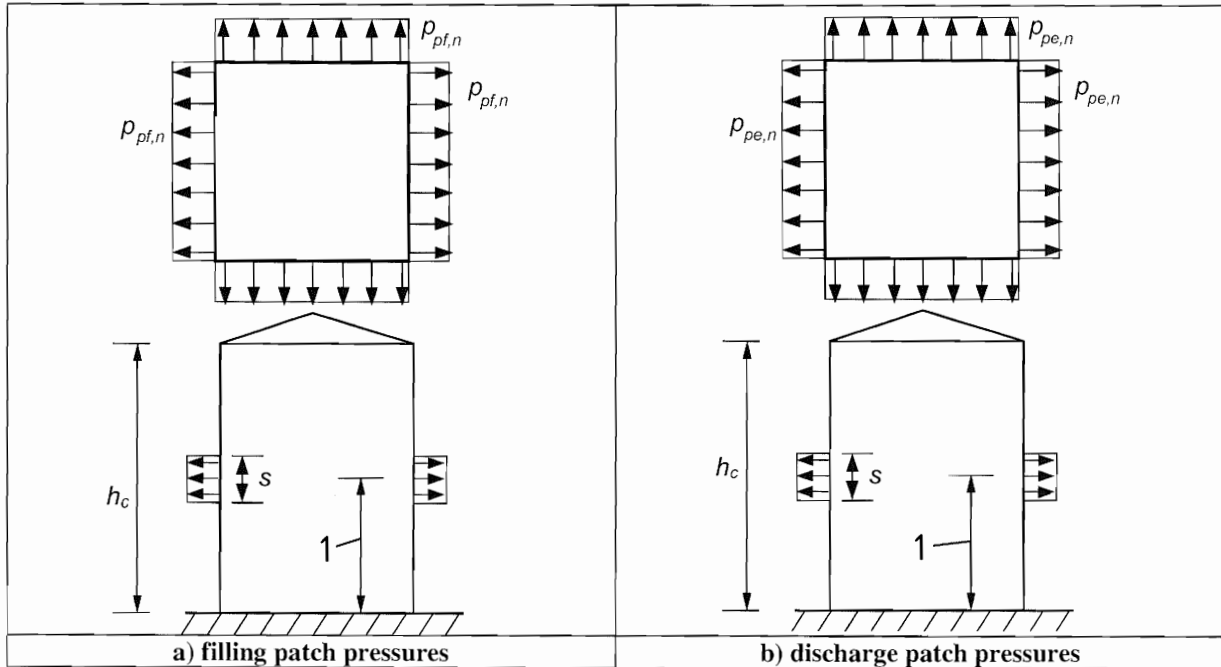
(3) The magnitude of the uniform symmetrical pressure increase on the non-circular wall $p_{pf,nc}$ should be taken as

$$p_{pf,nc} = 0,36 p_{pf} \quad \dots (5.17)$$

where:

p_{pf} is the reference filling patch load pressure (Expression (5.8)) and the appropriate dimension d_c should be found using Figure 1.1d.

NOTE: The value and the extent of the uniform pressure $p_{pf,nc}$ is chosen so that the bending moments induced in a rectangular silo without internal ties are approximately the same as those that would be induced by a local patch load with pressure p_{pf} placed at the centre of the wall.



Key

1 Anywhere

Figure 5.3: Non-circular silos: side elevation and plan view of patch loads

5.2.2 Discharge loads on vertical walls

5.2.2.1 Symmetrical discharge load

(1)P Symmetrical increases in the discharge load shall be used to represent the possible transitory increases in pressure that occur on silo walls during the discharge process.

(2) For silos in all Action Assessment Classes, the symmetrical discharge pressures p_{he} and p_{we} should be determined as:

$$p_{he} = C_h p_{hf} \quad \dots (5.18)$$

$$p_{we} = C_w p_{wf} \quad \dots (5.19)$$

where:

C_h is the discharge factor for horizontal pressure

C_w is the discharge factor for wall frictional traction.

The discharge factors C_h and C_w should be determined according to Expressions (5.20) to (5.24) as appropriate.

(3) For silos in all Action Assessment Classes that are unloaded from the top (no flow within the stored solid), the values of C_h and C_w may be taken as:

$$C_h = C_w = 1,0 \quad \dots (5.20)$$

(4) For slender silos in Action Assessment Classes 2 and 3, the discharge factors should be taken as:

$$C_h = C_o = 1,15 \quad \dots (5.21)$$

$$C_w = 1,10 \quad \dots (5.22)$$

where:

C_o is the discharge factor for all solids ($C_o = 1,15$).

(5) For slender silos in Action Assessment Class 1, where the mean value of the material properties K and μ have been used for design, the discharge factors should be taken as:

$$C_h = 1,15 + 1,5 (1 + 0,4 e/d_c) C_{op} \quad \dots (5.23)$$

$$C_w = 1,4 (1 + 0,4 e/d_c) \quad \dots (5.24)$$

$$e = \max(e_f, e_o) \quad \dots (5.25)$$

where:

e_f is the maximum eccentricity of the surface pile during filling;

e_o is the eccentricity of the centre of the outlet;

C_{op} is the patch load solid reference factor for the solid (see Table E.1).

(6) The resulting characteristic value of the vertical force (compressive) in the wall n_{zSk} per unit length of perimeter during discharge at any depth z should be determined as:

$$n_{zSk} = \int_0^z p_{we} dz = C_w \mu p_{ho} [\bar{z} - z_o Y_J(z)] \quad \dots (5.26)$$

NOTE: The stress resultant defined in Expression (5.26) is a characteristic value. Care should be taken when using this result to ensure that the appropriate partial factor on actions is not omitted, since this expression is a result of a structural analysis (using the membrane theory of shells). The expression is included here to assist designers in the integration of Expression (5.19). It should also be noted that other loads (e.g. patch loads) may induce additional vertical forces in the wall.

5.2.2.2 Discharge patch load: general requirements

(1)P The discharge patch load shall be used to represent accidental asymmetries of loading during discharge, as well as inlet and outlet eccentricities (see Figure 1.1b).

(2) For silos in Action Assessment Class 1, the discharge patch load may be ignored.

(3) For silos in Action Assessment Classes 2 and 3, the method of this section should be used to assess discharge loads.

(4) For circular silos in Action Assessment Classes 2 and 3, where either of the following conditions apply, the procedure for large discharge eccentricities in slender circular silos (see 5.2.4) should be used as a separate load case (see 5.1 (5)) in addition to the method of this section:

- the eccentricity of the outlet e_o exceeds the critical value $e_{o,cr} = 0,25d_c$ (see Figure 3.3c);
- the maximum filling eccentricity e_f exceeds the critical value $e_{f,cr} = 0,25d_c$ and the slenderness of the silo is greater than the limiting value $(h_c/d_c)_{lim} = 4,0$ (see Figure 3.4d).

(5) The reference magnitude of the discharge outward patch pressure p_{pe} should be determined as:

$$p_{pe} = C_{pe} p_{he} \quad \dots (5.27)$$

in which:

for $h_c/d_c > 1,2$, C_{pe} is given by Expression 5.28

$$C_{pe} = 0,42 C_{op} [1+2E^2] (1 - \exp\{-1,5 [(h_c/d_c) - 1]\}) \quad \dots (5.28)$$

for $h_c/d_c \leq 1,2$, C_{pe} is given by the greatest of the values given by Expressions 5.28, 5.29 and 5.30

$$C_{pe} = 0,272 C_{op} \{(h_c/d_c - 1 + E)\} \quad \dots (5.29)$$

$$C_{pe} = 0 \quad \dots (5.30)$$

in which:

$$E = 2 e / d_c \quad \dots (5.31)$$

$$e = \max(e_f, e_o) \quad \dots (5.32)$$

where:

e_f is the maximum eccentricity of the surface pile during filling;

e_o is the eccentricity of the centre of the outlet;

p_{he} is the local value of the discharge pressure at the height at which the patch load is applied (Expression (5.18));

C_{op} is the patch load solid reference factor for the solid (see Table E.1).

(6) The discharge patch load consists of a pattern of normal pressures only. No changes to the frictional traction associated with the changed normal pressure should be considered in design.

(7) The form of the discharge patch pressure depends on the form of silo construction. The following construction forms are identified and the patch pressures should be determined using the paragraphs stated below:

- for thick-walled circular silos, see 5.2.2.3 (concrete silos);
- for thin-walled circular silos, see 5.2.2.4 (metal silos);
- for non-circular silos, see 5.2.2.5.

5.2.2.3 Discharge patch load: thick-walled circular silos

(1) For thick-walled circular silos, the outward patch pressure p_{pe} should be taken to act on two opposite square areas with side length s (see Figure 5.4b) given by Expression (5.12) (the horizontal distance s is measured on the curved surface where appropriate).

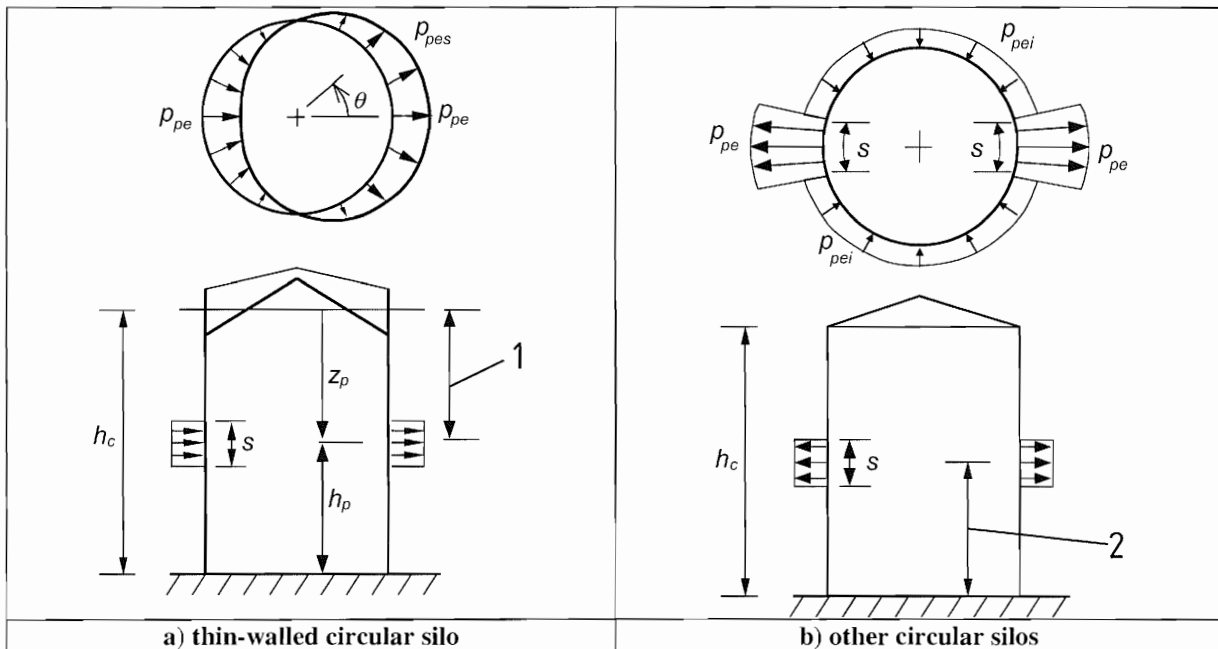
(2) In addition to the outward patch pressure p_{pe} , the remainder of the silo circumference over the same height of wall (see Figure 5.4b) should be subjected to an inward discharge patch pressure p_{pei} given by:

$$p_{pei} = p_{pe} / 7 \quad \dots (5.33)$$

where:

p_{pe} is the outward patch pressure (Expression (5.27)).

NOTE: The value and the extent of this inward pressure is chosen so that the mean pressure at that level remains unchanged by the patch load.



Key

- 1 For welded silos in Action Class 2: the lesser of z_0 and $h_c/2$
- 1 For other thin-walled silos in Action Classes 2 and 3: anywhere
- 2 Anywhere

Figure 5.4: Circular silos: side elevation and plan view of the discharge patch load

(3) The discharge patch load should be considered to act on any part of the silo wall, but this may be interpreted in the manner described in 5.2.2.3 (4).

(4) In thick-walled silos in Action Assessment Class 2, a simplified approach may be used. The most unfavourable load arrangement may be taken as that found by applying the patch at the mid-height of the silo and using the results to deduce approximate values for the stress resultants throughout the wall. The percentage increase in the membrane wall stress resultants at that level may be used to scale all the membrane wall stress resultants on the vertical wall. The calculated bending stress resultants at each level may be found by scaling the values at the patch load level according to the ratio of the filling pressure at that level to the filling pressure at the patch load level.

5.2.2.4 Discharge patch load: thin-walled circular silos

(1) For thin walled circular silos in Action Assessment Classes 2 and 3, the discharge patch pressure should be taken to act over a height s , given by Expression (5.12), but to extend from a maximum outward pressure on one side of p_{pe} to an inward pressure p_{pe} on the opposite side (see Figure 5.4a). The circumferential variation should be taken as:

$$p_{pes} = p_{pe} \cos \theta \quad \dots (5.34)$$

where:

p_{pe} is the outward patch pressure (Expression (5.27))

θ is the circumferential coordinate (see Figure 5.4a).

(2) The total horizontal force F_{pe} due to the discharge patch load on a thin-walled circular silo should be determined as:

$$F_{pe} = \frac{\pi}{2} s d_c p_{pe} \quad \dots (5.35)$$

(3) For welded silos in Action Assessment Class 2, the discharge patch load may be taken to act at a depth z_p below the equivalent surface, where z_p is the lesser of:

$$z_p = z_o \quad \text{and} \quad z_p = 0,5 h_c \quad \dots (5.36)$$

where:

h_c is the height of the vertical walled segment (see Figure 1.1a).

(4) For bolted and riveted silos in Action Assessment Class 2, the discharge patch load should be considered to act at any depth, but the normal pressure at any level may be taken as a uniform percentage increase throughout the height of the silo (the procedures of 5.2.3 may alternatively be used).

5.2.2.5 Discharge patch load: non-circular silos

(1) For non-circular silos in Action Assessment Classes 2 and 3, the discharge patch load, which represents unsymmetrical loads, may be represented by an increase in the symmetrical pressure as defined in (2) and (3).

(2) The outward patch pressure should be taken to act on a horizontal band on the silo wall at any level, over a vertical height s (see Figure 5.3b) given by Expression (5.12).

(3) The magnitude of the uniform symmetrical pressure increase on the non-circular wall $p_{pe,nc}$ should be taken as:

$$p_{pe,nc} = 0,36 p_{pe} \quad \dots (5.37)$$

where

p_{pe} is the reference discharge patch load pressure (see Expression (5.27)).

NOTE: The value and the extent of the uniform pressure $p_{pe,nc}$ is chosen so that the bending moments induced in a rectangular silo without internal ties are approximately the same as those that would be induced by a patch load placed at the centre of the wall.

5.2.3 Substitute uniform pressure increase for filling and discharge patch loads

(1) For silos in Action Assessment Class 2, a uniform increase in the symmetrical load may be substituted for the patch load method of 5.2.1 and 5.2.2 to account for asymmetries in the filling and discharge processes.

(2) For non-circular silos, the uniform increases are defined in 5.2.1.5 and 5.2.2.5.

(3) For circular silos, the following procedures may be used only if the base and the top of the vertical wall are restrained to retain their horizontal shape by appropriate stiffeners (the circular silo must be held circular at the top and bottom by a structurally connected roof or a ring stiffener).

(4) For thick-walled circular silos, the resulting total symmetrical horizontal pressures for filling ($p_{hf,u}$) and discharge ($p_{he,u}$) should be determined as:

$$p_{hf,u} = p_{hf} (1 + \zeta C_{pf}) \quad \dots (5.38)$$

$$p_{he,u} = p_{he} (1 + \zeta C_{pe}) \quad \dots (5.39)$$

in which:

$$\zeta = 0,5 + 0,01 (d_c/t) \quad \dots (5.40)$$

with $\zeta \geq 1,0$... (5.41)

where:

p_{hf} is the horizontal symmetrical filling pressure (see Expression (5.1));

p_{he} is the horizontal symmetrical discharge pressure (see Expression (5.18));

C_{pf} is the filling patch load factor (see Expression (5.9));

C_{pe} is the discharge patch load factor (see Expression (5.28)).

(5) For thin-walled circular silos, the resulting total symmetrical horizontal pressures for filling $p_{hf,u}$ and discharge $p_{he,u}$ and the resulting total symmetrical frictional traction for filling $p_{wf,u}$ and discharge $p_{we,u}$ should be determined as:

$$p_{hf,u} = p_{hf} (1 + 0,5 C_{pf}) \quad \dots (5.42)$$

$$p_{wf,u} = p_{wf} (1 + C_{pf}) \quad \dots (5.43)$$

$$p_{he,u} = p_{he} (1 + 0,5 C_{pe}) \quad \dots (5.44)$$

$$p_{we,u} = p_{we} (1 + C_{pe}) \quad \dots (5.45)$$

where:

p_{wf} is the filling symmetrical wall frictional traction (see Expression (5.2));

p_{we} is the discharge symmetrical wall frictional traction (see Expression (5.19))

and the parameters p_{hf} , p_{he} , C_{pf} and C_{pe} are calculated as indicated in (3).

5.2.4 Discharge loads for circular silos with large outlet eccentricities

5.2.4.1 General

(1) Where the outlet eccentricity e_o exceeds the critical value $e_{o,cr} = 0,25d_c$ and the silo is in Action Assessment Class 2 or 3, the following procedures should be used to determine the pressure distribution during eccentric discharge in a pipe flow channel above the outlet (see Figure 5.5a).

(2) Where the maximum filling eccentricity e_f exceeds the critical value $e_{f,cr} = 0,25d_c$ and the slenderness of the silo exceeds $h_c/d_c = 4,0$, and the silo is in Action Assessment Class 2 or 3, the following procedures should be also used to determine the pressure distribution that may occur as a result of the formation of an eccentric pipe flow channel (see Figures 3.4d and 5.5a).

(3) Where they are applicable (see (1) and (2)), the procedures of 5.2.4.2 and 5.2.4.3 should be used as a separate independent load case. This is an additional load case that is separate from that defined by filling and discharge pressures with the patch load treatment of 5.2.2 and 5.2.3.

(4) The calculation should be performed using the lower characteristic value of μ and the upper characteristic value of ϕ_f for the solid.

(5) A simplified procedure is permitted for silos in Action Assessment Class 2, as given in 5.2.4.2. For silos in Action Assessment Class 3, the procedure given in 5.2.4.3 should be implemented.

5.2.4.2 Method for Action Assessment Class 2

5.2.4.2.1 Flow channel geometry

(1) Calculations are required for only one size of flow channel contact with the wall, which should be determined for:

$$\theta_c = 35^\circ \quad \dots (5.46)$$

5.2.4.2.2 Wall pressures under eccentric discharge

(1) The pressure on the vertical wall in the flowing zone (see Figure 5.5c) should be taken as:

$$p_{hce} = 0 \quad \dots (5.47)$$

(2) The pressures at depth z on the vertical wall in the zone in which the solid remains static (see Figure 5.5c) should be taken as:

$$p_{hse} = p_{hf} \quad \dots (5.48)$$

$$p_{hae} = 2p_{hf} \quad \dots (5.49)$$

and the frictional traction on the wall at depth z as:

$$p_{wse} = p_{wf} \quad \dots (5.50)$$

$$p_{wae} = 2p_{wf} \quad \dots (5.51)$$

where:

p_{hf} is the horizontal filling pressure (see Expression (5.1));

p_{wf} is the filling wall frictional traction (see Expression (5.2)).

NOTE: This simplified method relates to an empty rathole (empty flow channel), and the method may therefore sometimes be rather conservative.

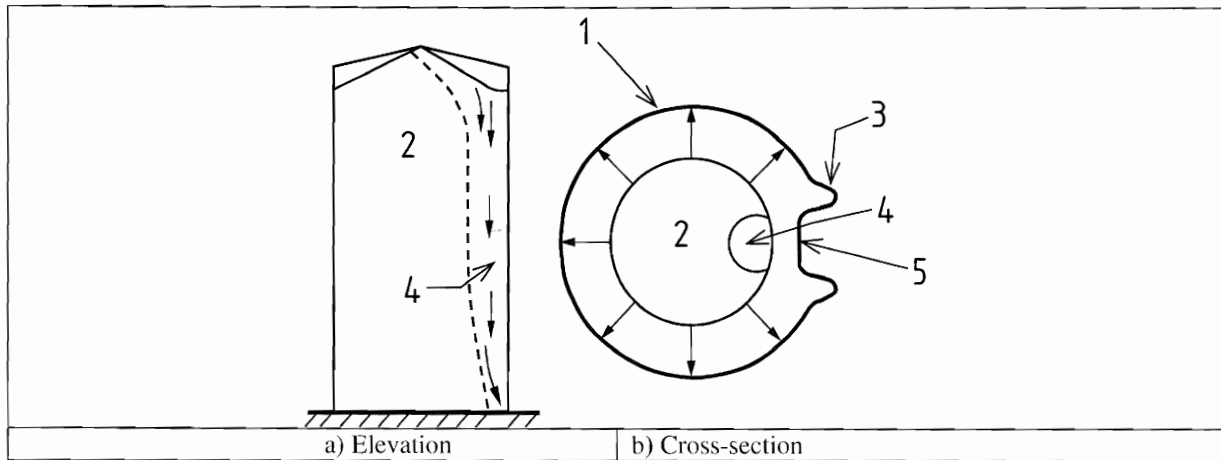
(3) The method of 5.2.4.3.2 may alternatively be used.

5.2.4.3 Method for Action Assessment Class 3

5.2.4.3.1 Flow channel geometry

(1)P The geometry of the flow channel and its location shall be chosen to reflect the geometry of the container, the discharge arrangements and the properties of the stored solid.

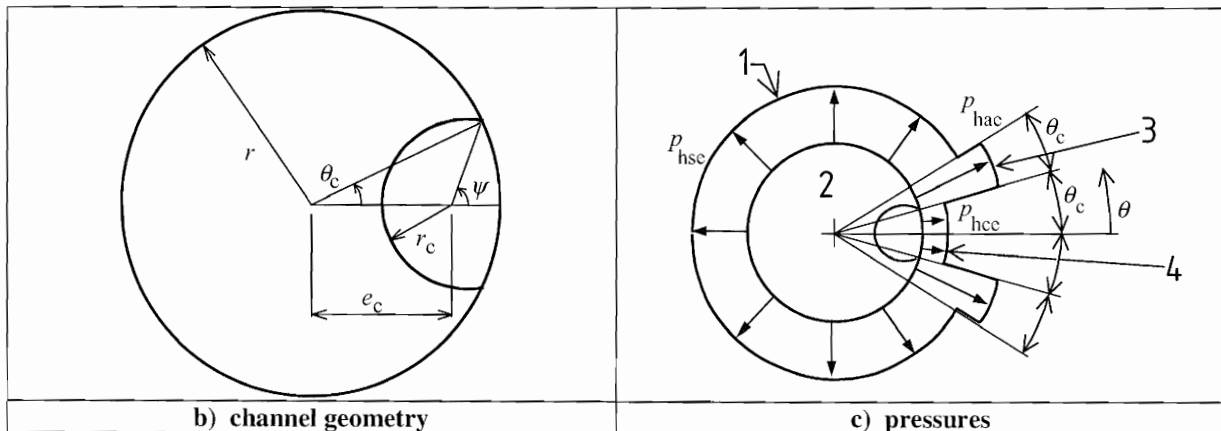
(2) Where the discharge arrangement leads to a flow channel of well defined geometry and location, the appropriate parameters for this flow channel should be adopted.



Key

- 1 Static pressures
- 2 Static solid
- 3 Local high pressure
- 4 Flow channel
- 5 Flow pressure

a) flow channel and pressure pattern



Key

- 1 Static pressures
- 2 Static solid
- 3 Channel edge pressures
- 4 Flow channel pressures

Figure 5.5: Eccentric discharge flow channel and pressure distribution

(3) Where the geometry of the flow channel cannot be directly deduced from the discharge arrangements and silo geometry, calculations should be performed for no less than three values of the radius of the flow channel r_c , to allow for random variations in the size of the flow channel from time to time. These three values should be taken as:

$$r_c = k_1 r \quad \dots (5.52)$$

$$r_c = k_2 r \quad \dots (5.53)$$

$$r_c = k_3 r \quad \dots (5.54)$$

where:

r is the radius of the circular silo ($= d_c/2$).

NOTE: The values of k_1 , k_2 and k_3 may be given in the National Annex. The recommended values are 0,25, 0,4 and 0,6 respectively.

(4) The flow channel eccentricity e_c (see Figure 5.5) should be determined as:

$$e_c = r \{ \eta (1 - G) + (1 - \eta) \sqrt{1 - G} \} \quad \dots (5.55)$$

in which:

$$G = \frac{r_c}{r} \quad \dots (5.56)$$

$$\eta = \frac{\mu}{\tan \phi_i} \quad \dots (5.57)$$

where:

μ is the lower characteristic wall friction coefficient for the vertical wall;

ϕ_i is the upper characteristic angle of internal friction of the stored solid;

r_c is the design radius of the flow channel (see Expressions (5.52) to (5.54)).

NOTE 1: It should be noted that $\phi_w \leq \phi_i$ always, since the material will rupture internally if slip at the wall contact demands a greater shear stress than the internal friction can sustain. This means that $\eta \leq 1$ in all evaluations.

NOTE 2: The flow channel eccentricity e_c may vary, as indicated in Figure 3.4d, and does not depend solely on the outlet eccentricity e_o . This procedure is intended to identify conditions that are close to the most demanding for each silo geometry and structural arrangement. The flow channel eccentricity may consequently be less than both the critical value of the outlet eccentricity $e_{o,cr}$ and the critical value of the inlet eccentricity $e_{f,cr}$.

NOTE 3: This evaluation of the location and radius of the flow channel is based on a minimization of the total frictional drag at the channel perimeter on the solid in the channel, assuming the periphery of the channel to be a circular arc. Other methods of predicting flow channel dimensions may be used.

(5) Notwithstanding the above requirements concerning the assumed flow channel radius, where an expanded flow hopper is used (see Figure 3.5d), the radius of the flow channel r_c should be taken as the radius of the top of the expanded flow hopper.

(6) The angular length of the wall contact with the flowing channel should be found, bounded by the circumferential coordinates $\theta = \pm \theta_c$, where:

$$\cos \theta_c = \frac{r^2 + e_c^2 - r_c^2}{2 r e_c} \quad \dots (5.58)$$

(7) The arc length of the contact between the flow channel and the wall should be determined as:

$$U_{wc} = 2 \theta_c r \quad \dots (5.59)$$

and the arc length of the contact between the flow channel and static solid as:

$$U_{sc} = 2 r_c (\pi - \psi) \quad \dots (5.60)$$

in which:

$$\sin \psi = \frac{r}{r_c} \sin \theta_c \quad \dots (5.61)$$

where the angles θ_c and ψ are both expressed in radians.

(8) The cross-sectional area of the flowing channel should be determined as:

$$A_c = (\pi - \psi)r_c^2 + \theta_c r^2 - r r_c \sin(\psi - \theta_c) \quad \dots (5.62)$$

5.2.4.3.2 Wall pressures under eccentric discharge

(1) The pressure on the vertical wall in the flowing zone (see Figure 5.5c) depends on the distance z below the equivalent solid surface and should be determined as:

$$p_{hce} = p_{hco} \left(1 - e^{-z/z_{oc}}\right) \quad \dots (5.63)$$

and the frictional traction on the wall at level z as:

$$p_{wce} = \mu p_{hce} = \mu p_{hco} \left(1 - e^{-z/z_{oc}}\right) \quad \dots (5.64)$$

in which:

$$p_{hco} = \gamma K z_{oc} \quad \dots (5.65)$$

$$z_{oc} = \frac{1}{K} \left(\frac{A_c}{U_{wc} \mu + U_{sc} \tan \phi} \right) \quad \dots (5.66)$$

where:

μ is the wall friction coefficient for the vertical wall;

K is the lateral pressure ratio for the solid.

(2) The pressure at depth z on the vertical wall far from the flowing channel in the zone where the solid remains static (see Figure 5.5c) should be taken as:

$$p_{hse} = p_{hf} \quad \dots (5.67)$$

and the frictional traction on the wall at depth z as:

$$p_{wse} = p_{wf} \quad \dots (5.68)$$

where:

p_{hf} is the horizontal filling pressure (see Expression (5.1));

p_{wf} is the filling wall frictional traction (see Expression (5.2)).

(3) A higher pressure p_{hae} is exerted on the vertical wall in the zone of static solid adjacent to the flow zone (see Figure 5.5c) and depends on the depth z below the equivalent solid surface. The pressure at depth z in the static zone near to the flowing channel should be determined as:

$$p_{hae} = 2p_{hf} - p_{hce} \quad \dots (5.69)$$

and the frictional traction on the wall at depth z as:

$$p_{\text{waf}} = \mu p_{\text{hae}} \quad \dots (5.70)$$

5.3 Squat and intermediate slenderness silos

5.3.1 Filling loads on vertical walls

5.3.1.1 Filling symmetrical load

- (1) The symmetrical filling load (see Figure 5.6) should be calculated using Expressions (5.71) to (5.80).
- (2) The values of horizontal pressure p_{hf} and wall frictional traction p_{wf} at any depth after filling should be determined as:

$$p_{\text{hf}} = p_{\text{ho}} Y_{\text{R}} \quad \dots (5.71)$$

$$p_{\text{wf}} = \mu p_{\text{hf}} \quad \dots (5.72)$$

in which:

$$p_{\text{ho}} = \gamma K z_{\text{o}} = \gamma \frac{1}{\mu} \frac{A}{U} \quad \dots (5.73)$$

$$Y_{\text{R}} = \left(1 - \left[\left(\frac{z - h_{\text{o}}}{z_{\text{o}} - h_{\text{o}}} \right) + 1 \right]^n \right) \quad \dots (5.74)$$

$$z_{\text{o}} = \frac{1}{K \mu} \frac{A}{U} \quad \dots (5.75)$$

$$n = - (1 + \tan \phi_{\text{r}}) (1 - h_{\text{o}}/z_{\text{o}}) \quad \dots (5.76)$$

where

h_{o} is the value of z at the highest solid-wall contact (see Figures 1.1a and 5.6).

For a symmetrically filled circular silo of radius r , h_{o} should be determined as:

$$h_{\text{o}} = \frac{r}{3} \tan \phi_{\text{r}} \quad \dots (5.77)$$

and for a symmetrically filled rectangular silo of characteristic dimension d_{c} , h_{o} should be determined as:

$$h_{\text{o}} = \frac{d_{\text{c}}}{4} \tan \phi_{\text{r}} \quad \dots (5.78)$$

where:

- γ is the characteristic value of the unit weight;
- μ is the characteristic value of the wall friction coefficient for solid sliding on the vertical wall;
- K is the characteristic value of the lateral pressure ratio;
- z is the depth below the equivalent surface of the solid;

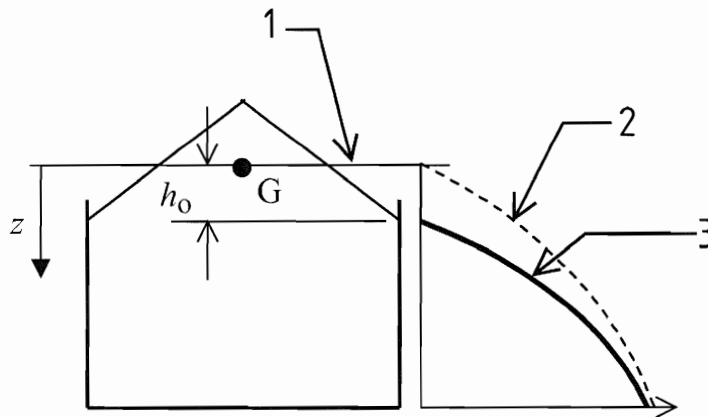
- A is the plan cross-sectional area of the silo;
 U is the internal perimeter of the plan cross-section of the silo;
 ϕ_r is the angle of repose of the solid (see Table E.1).

(3) The value of vertical pressure p_{vf} at any depth after filling should be determined as:

$$p_{vf} = \gamma z_v \quad \dots (5.79)$$

in which:

$$z_v = h_o - \frac{1}{(n+1)} \left(z_o - h_o - \frac{(z + z_o - 2h_o)^{n+1}}{(z_o - h_o)^n} \right) \quad \dots (5.80)$$



Key

- 1 Equivalent surface
- 2 Slender silo rule
- 3 Squat silo pressures

Figure 5.6: Filling pressures in a squat or intermediate slenderness silo

(4) The resulting characteristic value of the vertical force (compressive) in the wall n_{zSk} per unit length of perimeter at any depth z should be determined as:

$$n_{zSk} = \int_0^z p_{wf}(z) dz = \mu p_{ho} (z - z_v) \quad \dots (5.81)$$

where z_v is given by Expression (5.80).

NOTE: The stress resultant defined in Expression (5.81) is a characteristic value. Care should be taken when using this result to ensure that the appropriate partial factor on actions is not omitted, since this expression is a result of a structural analysis (using the membrane theory of shells). The expression is included here to assist designers in the integration of Expression (5.72). It should also be noted that other loads (e.g. patch loads or unsymmetrical filling) may induce additional vertical forces in the wall.

5.3.1.2 Filling patch load

- (1) The filling patch load should be considered to act on any part of the silo wall.
- (2) The patch load consists of normal pressure only. No changes to the frictional traction associated with the changed normal pressure should be considered in design.
- (3) For squat silos ($h_c/d_c \leq 1,0$) in all Action Assessment Classes, the filling patch load need not be considered ($C_{pf} = 0$).
- (4) For silos of intermediate slenderness ($1,0 < h_c/d_c < 2,0$) in Action Assessment Class 1, the filling patch load may be ignored.
- (5) For silos of intermediate slenderness ($1,0 < h_c/d_c < 2,0$) in Action Assessment Classes 2 and 3, the filling patch pressure p_{pf} taken from 5.2.1 should be used to represent accidental asymmetries of loading and small eccentricities of filling e_f (see Figure 1.1b).
- (6) For silos of squat or intermediate slenderness ($h_c/d_c < 2,0$) in Action Assessment Classes 2 and 3, where the eccentricity of filling e_f exceeds the critical value $e_{f,cr} = 0,25d_c$, the additional load case for large filling eccentricities in squat silos should be used (see 5.3.3).

5.3.2 Discharge loads on vertical walls

5.3.2.1 Discharge symmetrical load

- (1) Symmetrical increases in the discharge load shall be used where it is necessary to represent possible transitory increases in pressure during the discharge process.
- (2) For squat silos ($h_c/d_c \leq 1,0$), the symmetrical discharge loads may be taken as identical to the filling loads.
- (3) For silos of intermediate slenderness ($1,0 < h_c/d_c < 2,0$), the symmetrical discharge pressures p_{hc} and p_{wc} should be determined as:

$$p_{hc} = C_h p_{hf} \quad \dots (5.82)$$

$$p_{wc} = C_w p_{wf} \quad \dots (5.83)$$

where:

C_h and C_w are discharge factors according to Expressions (5.84) to (5.89) as appropriate.

- (4) For silos in all Action Assessment Classes that are unloaded from the top (no flow within the stored solid):

$$C_w = C_h = 1,0 \quad \dots (5.84)$$

- (5) For intermediate slenderness silos in Action Assessment Class 2 and 3, the discharge factors should be taken as:

$$C_h = 1,0 + 0,15 C_S \quad \dots (5.85)$$

$$C_w = 1,0 + 0,1 C_S \quad \dots (5.86)$$

$$C_S = h_c/d_c - 1,0 \quad \dots (5.87)$$

where

C_S is the slenderness adjustment factor.

(6) For intermediate slenderness silos in Action Assessment Class 1, where the mean value of the material properties K and μ have been used for design, the discharge factors should be taken as:

$$C_h = 1,0 + \{ 0,15 + 1,5 (1 + 0,4 e/d_c) C_{op} \} C_S \quad \dots (5.88)$$

$$C_w = 1,0 + 0,4 (1 + 1,4 e/d_c) C_S \quad \dots (5.89)$$

$$e = \max(e_f, e_o) \quad \dots (5.90)$$

where:

e_f is the maximum eccentricity of the surface pile during filling;

e_o is the eccentricity of the centre of the outlet;

C_{op} is the patch load solid reference factor for the solid (see Table E.1);

C_S is the slenderness adjustment factor (Expression (5.87)).

(7) The resulting characteristic value of the discharge vertical force (compressive) in the wall n_{zSk} per unit length of perimeter at any depth z should be determined as:

$$n_{zSk} = \int_0^z p_{we}(z) dz = C_w \mu p_{ho} (z - z_v) \quad \dots (5.91)$$

where z_v is given by Expression (5.80).

NOTE: The stress resultant defined in Expression (5.91) is a characteristic value. Care should be taken when using this result to ensure that the appropriate partial factor on actions is not omitted, since this expression is a result of a structural analysis (using the membrane theory of shells). The expression is included here to assist designers in the integration of Expression (5.83). It should also be noted that other loads (e.g. patch loads or unsymmetrical filling) may induce additional vertical forces in the wall.

5.3.2.2 Discharge patch load

(1) The discharge patch pressure p_{pe} should be used to represent accidental asymmetries of loading (see Figure 1.1b).

(2) The rules set out in 5.2.2 should be used to define the form, location and magnitude of the patch load.

(3) For squat or intermediate slenderness silos ($h_c/d_c < 2,0$) in all Action Assessment Classes, where the eccentricity of discharge e_o exceeds the critical value $e_{o,cr} = 0,25d_c$, the additional load case defined in 5.3.4 should also be adopted.

(4) For squat silos ($h_c/d_c \leq 1,0$) in all Action Assessment Classes and with discharge eccentricity e_o less than $e_{o,cr} = 0,1d_c$, the discharge patch load should not be considered ($C_{pe} = 0$).

(5) For squat or intermediate slenderness silos ($h_c/d_c < 2,0$) in Action Assessment Class 1, the discharge patch load should not be considered ($C_{pe} = 0$).

(6) For squat silos ($h_c/d_c \leq 1,0$) in Action Assessment Class 2 and with discharge eccentricity e_o greater than $e_{o,cr} = 0,1d_c$, the provisions of 5.3.2.3 should be adopted.

(7) For silos of intermediate slenderness ($1,0 < h_c/d_c < 2,0$) in Action Assessment Class 2, the provisions of 5.3.2.3 should be adopted.

(8) For squat silos ($h_c/d_c \leq 1,0$) in Action Assessment Class 3 and with discharge eccentricity e_o greater than $e_{o,cr} = 0,1d_c$, the provisions of 5.2.2.2 to 5.2.2.5, as appropriate, should be adopted.

(9) For silos of intermediate slenderness ($1,0 < h_c/d_c < 2,0$) in Action Assessment Class 3, the provisions of 5.2.2.2 to 5.2.2.5, as appropriate, should be adopted.

5.3.2.3 Substitute uniform pressure increase for filling and discharge

(1) For silos in Action Assessment Class 2, a uniform increase in the symmetrical load may be substituted for the patch load method of 5.3.1.2 and 5.3.2.2 to account for asymmetries in the filling and discharge processes.

(2) The provisions of 5.2.3 may be applied to the patch loads obtained from 5.3.1.2 and 5.3.2.2, using Expressions (5.38) to (5.45) as appropriate.

5.3.3 Large eccentricity filling loads in squat and intermediate circular silos

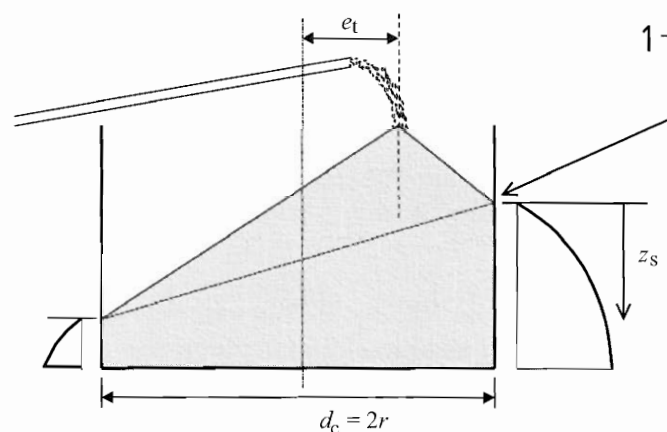
(1)P For silos of circular planform in Action Assessment Class 3 that have a squat or intermediate slenderness ($h_c/d_c < 2,0$) and a top surface filling eccentricity e_t greater than $e_{t,cr} = 0,25d_c$ (see Figure 5.7), the effect of the asymmetry of the normal pressures in inducing vertical forces in the silo wall shall be considered.

(2) Where hand calculations are performed, the requirements of 5.3.3 (1)P may be fulfilled by adding the vertical wall forces n_{zSk} defined by Expression (5.92) to those evaluated for symmetrical filling with a fill level corresponding to filling symmetrically to the highest wall contact (see 5.3.1.1).

(3) The effect of unsymmetrical pressures may be accounted for by an increase in the vertical force in the wall at the circumferential location where the filling height is greatest.

NOTE: The increase in vertical wall force arises from the global bending action of the silo when the normal pressures are absent from the opposite wall. The increase in vertical force is therefore directly additive to the forces arising from friction that are defined for symmetrical load cases above.

(4) The calculation should be performed using the upper characteristic values of the properties K and μ for the solid.



Key

1 Highest wall contact with solid

Figure 5.7: Filling pressures in an eccentrically filled squat or intermediate slenderness silo

(5) The characteristic value of the resulting additional vertical force (compressive) in the wall $n_{zSk}(z_s)$ per unit length of circumference at any depth z_s below the point of highest wall contact should be determined as:

$$n_{zSk} = 0,04 p_{ho} z_s \tan \phi_r \left(\frac{e_t}{r} \right) (6 + 7Z - Z^2) \quad \dots (5.92)$$

in which:

$$p_{ho} = \frac{\gamma}{\mu} \frac{A}{U} = \frac{\gamma r}{2\mu} \quad \dots (5.93)$$

$$Z = \frac{z_s}{B} \quad \dots (5.94)$$

$$B = \frac{r}{2\mu K} - h_o \quad \dots (5.95)$$

$$h_o = r \tan \phi_r [1 - (e_t/r)^2] / 3 \quad \dots (5.96)$$

where

z_s is the depth below the highest point of solid contact with the wall;

ϕ_r is the angle of repose of the particulate solid;

r is the radius of the circular silo wall;

e_t is the radial eccentricity of the top of the filling pile (see Figures 1.1b and 5.7).

NOTE: The stress resultant defined in Expression (5.92) is a characteristic value. Care should be taken when using this result to ensure that the appropriate partial factor on actions is not omitted, since this expression is a result of a structural analysis (using the membrane theory of shells).

(6) The force per unit circumference defined in Expression (5.92) should be added to the force arising from wall friction, which may be taken from Expression (5.81).

5.3.4 Large eccentricity discharge loads in squat and intermediate circular silos

(1) Where the eccentricity of discharge e_o exceeds the critical value $e_{o,cr} = 0,25d_c$ in a silo of squat or intermediate slenderness ($h_c/d_c < 2,0$) in Action Assessment Class 2 or 3, the procedure for large discharge eccentricities in slender silos should be used (5.2.4) as an extra load case separate from the symmetrical and patch load treatment given in 5.3.2.

5.4 Retaining silos

5.4.1 Filling loads on vertical walls

(1)P The filling load on the vertical wall shall consider the effect of the geometry of the pile of stored solid, and where appropriate, the curvature of the silo wall.

(2) The evaluation of the lateral pressure ratio K should take account of the restraint provided by the wall against outward movement of the stored solid (i.e. at rest pressure condition). Where a structural analysis is used to demonstrate that the wall can displace sufficiently in its elastic range, a lower value of K may be adopted.

(3) The characteristic value of the horizontal pressure p_h on a vertical wall (see Figure 5.8) should be determined.

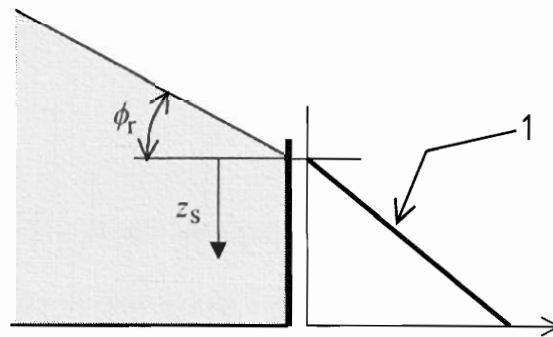
NOTE 1: The method to be used for determining the horizontal pressure p_h may be given in the National Annex. The recommended method is given in Expression (5.97):

$$p_h = \gamma K (1 + \sin\phi_r) z_s \quad \dots (5.97)$$

where:

- z_s is the depth below the highest stored solid contact with the wall (see Figure 5.8);
- γ is the upper characteristic value of the unit weight of the solid;
- K is the upper characteristic value of the lateral pressure ratio for the solid;
- ϕ_r is the angle of repose of the stored solid.

NOTE 2: Expression (5.97) is precise for a straight vertical wall with fully frictional wall contact and the angle of repose equal to the angle of internal friction. It matches the expression given in EN 1997.



Key

- 1 Retaining silo pressure

Figure 5.8: Filling pressures in a retaining silo

(4) The characteristic value of the resulting vertical force n_{zSk} (compressive) in the wall per unit length of circumference at any depth z_s below the point of highest wall contact should be determined in a manner that is consistent with the pressures defined in (3) and the wall friction coefficient μ .

NOTE: The method to be used for determining the resulting vertical force n_{zSk} may be given in the National Annex. The recommended method is given in Expression (5.98):

$$n_{zSk} = \gamma \frac{\mu K}{2} (1 + \sin\phi_r) z_s^2 \quad \dots (5.98)$$

where μ is the upper characteristic value of the wall friction coefficient of the solid.

(5) Notwithstanding other rules within this part of EN 1991, the variability of the properties of the stored solids may be deemed to have been considered for retaining silos by adopting only the upper characteristic values of the unit weight γ and the lateral pressure ratio K of the solid.

5.4.2 Discharge loads on vertical walls

(1) The discharge load on the vertical wall may be taken to be less than the filling load.

(2) With regard to 5.4.2 (1), the evaluation of the conditions of discharge should take account of the possibility of unsymmetrical pressures as a result of uneven removal of solid from within the silo.

5.5 Silos containing solids with entrained air

5.5.1 General

(1)P Silos in which it is possible for the stored solid to be fully or partially fluidized as a consequence of the entrainment of air shall be designed for the additional pressures that may arise due to fluidization and air pressure.

(2)P Homogenizing fluidized silos and silos with a high filling velocity (see 1.5.16 and 1.5.17) shall be designed for the following load cases:

- the stored solid fluidized;
- the stored solid not fluidized.

(3) Load evaluations for conditions when the stored solid is not fluidized should be performed according to 5.2 or 5.3 above.

5.5.2 Loads in silos containing fluidized solids

(1) In silos storing powders (see 1.5.31), it should be assumed that the stored solid can become fluidized if the velocity of the rising surface of the stored solid exceeds 10 m/h.

NOTE: The conditions under which a stored powder can become fluidized depend on many factors and are not simple to define. The above rule provides a simple estimate of whether this may be an important design consideration. Where any doubt exists, it is recommended that specialist advice on the behaviour of the stored solid be sought.

(2) In homogenizing fluidized silos (see 1.5.18) storing powders (see 1.5.32) that are being recirculated, it should be assumed that the stored solid can become fluidized.

(3) The pressure normal to the silo wall p_h from fluidized solids should be calculated as follows:

$$p_h = \gamma_1 z \quad \dots (5.99)$$

where:

γ_1 is the fluidized unit weight.

(4) The fluidized unit weight of a powder γ_1 may be taken as equal to:

$$\gamma_1 = 0,8 \gamma \quad \dots (5.100)$$

where:

γ is the bulk unit weight of the powder determined from Section 4.

5.6 Thermal differentials between stored solids and the silo structure

5.6.1 General

(1)P The design of a silo structure shall consider the consequences of thermal effects (displacements, strains, curvatures, stresses, forces and moments) due to a temperature difference between the stored solid and the silo structure and/or between the external environment and the silo structure.

(2)P Silos in which it is possible for the bulk of the stored solid to be at a different temperature from that of all or part of the wall shall be designed for the additional pressures that may arise due to differential thermal expansion in the presence of a stiff solid.

(3) The thermal conditions should be assessed with reference to EN 1991-1-5.

(4) Differential thermal displacements between the silo and any connected structure should be considered. The following design situations should be considered.

- reduction in ambient temperature relative to the temperature of the silo and stored solid;
- filling of the silo with hot solid;
- differential heating rates between exposed steel members and reinforced concrete;
- restraint to wall displacements from the silo structure.

NOTE: Differential heating between exposed steel members and reinforced concrete is typically found in silo roofs where the roof beams have sliding supports at the wall and provide vertical support to the roof only (i.e. no composite action). The problem stems from short term differential expansion; this reduces with time as the concrete temperature rises to match that in the exposed steel member.

5.6.2 Pressures due to reduction in ambient atmospheric temperature

(1)P Where it is possible for the ambient temperature of the atmosphere to fall considerably within a short period, the design shall consider the pressures induced by differential thermal shrinkage between the external structure and the relatively thermally inert stored solid.

(2) For silos with a circular planform, an additional normal pressure p_{hT} should be taken to act on a silo vertical wall when the container is cooled relative to the stored solid. The additional pressure at each height in the silo should be determined as:

$$p_{hT} = C_T \alpha_w \Delta T \frac{E_w}{[(r/t) + (1-\nu)(E_w/E_{sU})]} \quad \dots (5.101)$$

where:

C_T is the temperature load multiplier;

α_w is the coefficient of thermal expansion of the silo wall;

ΔT is the temperature differential;

r is the silo radius ($=d_c/2$);

t is the wall thickness;

E_w is the elastic modulus of the silo wall;

ν is Poisson's ratio for the particulate solid ($\nu = 0,3$ may be assumed);

E_{sU} is the unloading effective elastic modulus of the stored solid at the depth z .

(3) The assessment of the unloading effective elastic modulus of the solid E_{sU} at the depth z should take account of the vertical stress p_{vf} in the stored solid at that depth after filling.

(4) The unloading effective elastic modulus E_{sU} should be determined using the method described in C.10.

(5) Where materials testing of the solid is used to obtain the unloading effective elastic modulus, the value of the temperature load multiplier should be taken as $C_T = 1,2$. Where the unloading effective elastic modulus is estimated from the density, the value of the temperature load multiplier should be taken as $C_T = 3$.

5.6.3 Pressures due to filling with hot solids

(1)P Where hot solids are placed in a silo, account shall be taken of the temperature differential between the cooler solids that have been there for some time and the hot atmosphere above the solids surface. The effect of such temperature differentials on the differential expansion of the silo wall at different levels shall be considered, together with the bending moments arising from satisfying compatibility between these deformations.

(2) These effects need not be considered for silos in Action Assessment Class 1.

5.7 Loads in rectangular silos

5.7.1 Rectangular silos

(1) The wall loads due to bulk solids in rectangular silos should be taken as defined in 5.2, 5.3 and 5.4, as appropriate.

(2) Notwithstanding the general requirement of 4.1 (2), where the silo is constructed with flexible walls whose stiffness is comparable with the stiffness of the contained solid, silos in Action Assessment Classes 1 and 2 may be designed to take advantage of bulk solid-structure interaction effects that reduce the pressures at the midside of the walls and increase the pressures in the corners.

(3) Where a variation of pressure at a level is assumed, according to (2), the mean pressure at that level should be taken as the value of pressure calculated using 5.2 or 5.3.

(4) With regard to 5.7.1 (3) and where such reduced pressures are used, a rational method of pressure assessment should be used.

5.7.2 Silos with internal ties

(1) The wall loads due to bulk solids in rectangular silos with internal ties should be taken as defined in 5.2, 5.3 and 5.4 as appropriate.

(2) The forces applied by the ties to the walls of the structure should be evaluated taking into account the bulk solids loading on each tie, the location and fixation of each tie, the sag of the tie and the stiffness of the structure in resisting increased sag in the tie as a result of bulk solids loading.

(3) For silos in the Action Assessment Classes 1 and 2 of this standard, the forces applied by the ties to the walls of the structure should be evaluated using the structural analysis according to EN 1993-4-1.

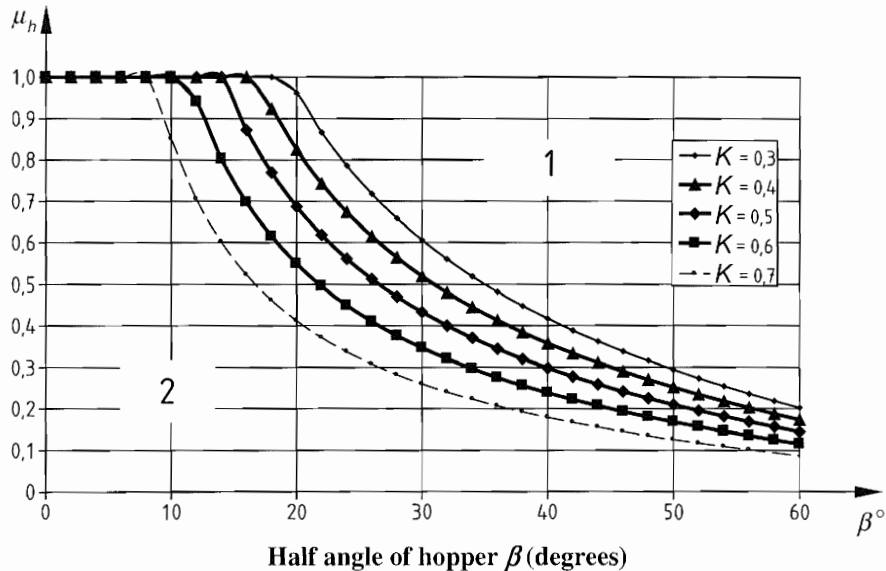
Section 6 Loads on silo hoppers and silo bottoms

6.1 General

6.1.1 Physical properties

(1)P The characteristic values of the filling and discharge loads on silo bottoms, which are prescribed in this section for the following types of silo, shall be used:

- flat bottoms;
- steep hoppers;
- shallow hoppers.



Key

1 Shallow

2 Steep

β Hopper apex half angle (degrees)

μ_h Lower characteristic value of hopper wall friction coefficient

K Lower characteristic value of lateral pressure ratio on vertical walls

Figure 6.1: The boundary between steep and shallow hoppers

(2)P The loads on the walls of silo hoppers shall be evaluated according to the steepness of the hopper, determined according to the following classes:

- a flat bottom shall have an inclination to the horizontal α less than 5°;
- a shallow hopper shall be any hopper not classified as either flat or steep;
- a steep hopper shall be any hopper that satisfies the following criterion (see Figures 6.1 and 6.2):

$$\tan \beta < \frac{1-K}{2\mu_h} \quad \dots (6.1)$$

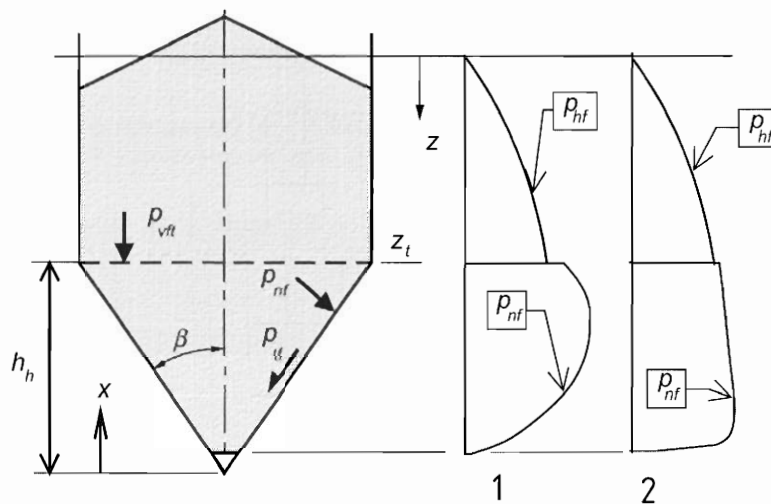
where:

K is the lower characteristic value of the lateral pressure ratio on the vertical walls;

β is the hopper apex half angle;

μ_h is the lower characteristic value of wall friction coefficient in the hopper.

NOTE: A steep hopper is one in which the solid slides down the inclined hopper wall when the silo is filled and the solid above the hopper causes it to be consolidated. The wall frictional shear stress or traction is then related to the normal pressure on the hopper by the wall friction coefficient (fully mobilized wall friction). A shallow hopper is one in which the solid does not slide down the inclined hopper wall when the silo is filled (the slope is too low or the friction too high). The wall frictional shear stress or traction is then not related to the normal pressure on the hopper by the wall friction coefficient, but by a lower value, which depends on the hopper slope and the stress state in the solid (wall friction not fully mobilized). The compressibility of the solid also plays a role in this distinction, but it is less important. The boundary between steep and shallow hoppers is smooth, with the same pressures applied to a hopper that is at the boundary whether it is in either category (wall friction just fully mobilized).



Key

- 1 Steep
- 2 Shallow

Figure 6.2: Distributions of filling pressures in steep and shallow hoppers

6.1.2 General rules

(1) For the calculation of pressures on hopper walls two methods are given. The reference method is given in this clause (6.1.2), and the alternative method is given in Annex G.

(2) The mean vertical pressure at the transition between the vertical walled segment and the hopper or on the silo bottom should be determined as:

$$p_{vft} = C_b p_{vf} \quad \dots (6.2)$$

where:

p_{vf} is the filling value of the vertical pressure calculated using Expression (5.3) or (5.79) according to the slenderness of the silo, with the z coordinate equal to the height of the vertical wall h_c (i.e. at the transition: see Figure 1.1a) and using the values of solids properties that induce maximum hopper loading (see Table 3.1);

C_b is a bottom load magnifier to account for the possibility of larger loads being transferred to the hopper or bottom from the vertical walled segment.

(3) For silos in Action Assessment Classes 2 and 3, the bottom load magnifier should be determined as:

$$C_b = 1,0 \text{ except under the conditions defined in (5) below} \quad \dots (6.3)$$

(4) For silos in Action Assessment Class 1 where the mean value of the material properties K and μ have been used for design, the bottom load magnifier should be determined as:

$$C_b = 1,3 \text{ except under the conditions defined in (5) below} \quad \dots (6.4)$$

(5) Where there is a significant probability that the stored solid can develop dynamic loading conditions, higher loads are applied to the hopper or silo bottom. These conditions should be assumed to occur if either:

- a silo with a slender vertical walled section is used to store solids that cannot be classed as of low cohesion (see 1.5.23);
- the stored solid is identified as susceptible to mechanical interlocking (e.g. cement clinker).

NOTE: The evaluation of the cohesion c of a solid is given in C.9. The cohesion is classed as low if, following consolidation to a normal stress level σ_r , the assessed cohesion c does not exceed $c/\sigma_r = 0,04$ (see 1.5.23).

(6) Where the conditions of (5) are met, the higher loads on the hopper or silo bottom should be determined using the bottom load magnifier C_b , which should be taken as:

$$C_b = 1,2 \text{ for Action Assessment Classes 2 and 3} \quad \dots (6.5)$$

$$C_b = 1,6 \text{ for Action Assessment Class 1} \quad \dots (6.6)$$

(7) For each condition in a hopper, the mean vertical stress in the solid at height x above the apex of the hopper (see Figure 6.2) should be determined as:

$$p_v = \left(\frac{\gamma h_h}{n-1} \right) \left\{ \left(\frac{x}{h_h} \right) - \left(\frac{x}{h_h} \right)^n \right\} + p_{vft} \left(\frac{x}{h_h} \right)^n \quad \dots (6.7)$$

in which:

$$n = S (F \mu_{heff} \cot \beta + F) - 2 \quad \dots (6.8)$$

$$S = 2 \text{ for conical and square pyramidal hoppers} \quad \dots (6.9)$$

$$S = 1 \text{ for wedge hoppers} \quad \dots (6.10)$$

$$S = (1 + b/a) \text{ for hoppers of rectangular planform} \quad \dots (6.11)$$

where:

γ is the upper characteristic value of the solid unit weight;

h_h is the vertical height between the hopper apex and the transition (see Figure 6.2);

x is the vertical coordinate upwards from hopper apex (see Figure 6.2);

μ_{heff} is the effective or mobilized characteristic wall friction coefficient for the hopper (Expressions (6.16) and (6.26) as appropriate);

S is a hopper shape coefficient;

F is the characteristic value of the hopper pressure ratio (Expressions (6.17), (6.21) or (6.27) as appropriate);

β is the hopper apex half angle ($= 90^\circ - \alpha$), or the steepest slope on a square or rectangular pyramidal hopper;

p_{vft} is the mean vertical stress in the solid at the transition after filling (Expression (6.2));

a is the length of a rectangular planform (see Figure 1.1d);

b is the width of a rectangular planform (see Figure 1.1d).

(8) The determination of the value of the hopper pressure ratio F should take account of whether the hopper is steep or shallow and whether filling or discharge loads are being evaluated. Appropriate values of F should be taken from 6.3 and 6.4.

(9) The determination of the value of the effective or mobilized hopper wall friction coefficient μ_{heff} should take account of whether the hopper is steep or shallow. Appropriate values should be taken from 6.3 and 6.4.

6.2 Flat bottoms

6.2.1 Vertical pressures on flat bottoms in slender silos

(1) The vertical pressure acting on a flat bottom (inclination $\alpha \leq 5^\circ$) may be taken as uniform, except when the silo is squat or of intermediate slenderness. For these cases, 6.2.2 should be used.

(2) The vertical pressure p_v acting on a flat bottom should be determined as:

$$p_v = p_{vft} \quad \dots (6.12)$$

where:

p_{vft} is obtained from Expression (6.2).

(3) The vertical pressure acting on a flat bottom during discharge should be taken as identical to the vertical pressure at the end of filling.

6.2.2 Vertical pressures on flat bottoms in squat and intermediate silos

(1) The potential that pressures higher than those defined in 6.1 (see Expression (6.2)) may occur locally on the flat bottom of a squat or intermediate slenderness silo should be considered.

(2) The vertical pressure p_{vsq} acting on the flat bottom of a squat or intermediate slenderness silo may be taken as:

$$p_{vsq} = p_{vb} + \Delta p_{sq} \left(\frac{2,0 - h_c / d_c}{2,0 - h_{tp} / d_c} \right) \quad \dots (6.13)$$

in which:

$$\Delta p_{sq} = p_{vtp} - p_{vho} \quad \dots (6.14)$$

$$p_{vtp} = \gamma h_{tp} \quad \dots (6.15)$$

where:

p_{vb} is the uniform component of vertical pressure, obtained from Expression (6.2) with $z = h_c$ and adopting characteristic values for the solid's properties that induce maximum hopper loading (see Table 3.1);

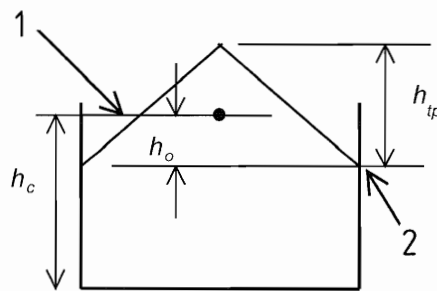
p_{vho} is the Janssen vertical pressure at the base of the top pile, obtained from Expression (5.79) with $z = h_o$;

h_o is the depth below the equivalent surface of the base of the top pile, defined as the lowest point on the wall that is not in contact with the stored solid (see Figure 6.3);

h_{tp} is the total height of the top pile, defined as the vertical distance from lowest point on the wall that is not in contact with the stored solid to the highest stored particle (see Figure 6.3);

h_c is the depth of the silo base below the equivalent surface.

NOTE: The above rule provides a linear transition between the base pressure defined by the Janssen equation for a silo that is just slender, $h_c/d_c = 2,0$, and the pressure γz ($z=h_o$) for the condition where the solids in the silo are only in the form of a heap ($h_c=h_o$) with no contact with the vertical wall. The latter is greater than the true maximum pressure beneath a pile of particulate solid, but the result gives a simple conservative estimate.



Key

- 1 Equivalent surface
- 2 Lowest point without solid contact

Figure 6.3: Pressures on the bottom of a squat or intermediate silo

(3) The vertical pressure p_{vsq} given in Expression (6.13) may be taken to act both after filling and during discharge.

(4) The value of p_{vsq} given by Expression (6.13) represents the vertical pressure near the centre of the silo floor. Where support of the floor slab is not uniform, a rational analysis should be used to determine the floor pressure variation.

6.3 Steep hoppers

6.3.1 Mobilized friction

(1) For both filling and discharge conditions, the effective or mobilized wall friction coefficient in Expression (6.8) should be taken as

$$\mu_{heff} = \mu_h \quad \dots (6.16)$$

where:

μ_h is the lower characteristic value of wall friction coefficient in the hopper.

6.3.2 Filling loads

(1) Under filling conditions, the mean vertical stress p_v in the stored solid at any level in a steep hopper should be determined using Expressions (6.7) and (6.8), with the value of the parameter F given by $F = F_f$, with F_f as:

$$F_f = 1 - \frac{b}{\left(1 + \frac{\tan\beta}{\mu_h}\right)} \quad \dots (6.17)$$

The parameter n (see Expression (6.8)) is then given by:

$$n = S (1-b) \mu_h \cot\beta \quad \dots (6.18)$$

where:

b is an empirical coefficient: $b = 0,2$.

The other parameters are defined in 6.1.2 (6).

(2) The normal pressure p_{nf} and frictional traction p_{tf} at any point on the wall of a steep hopper after filling (see Figure 6.2) should be determined as:

$$p_{nf} = F_f p_v \quad \dots (6.19)$$

$$p_{tf} = \mu_h F_f p_v \quad \dots (6.20)$$

where F_f is given by Expression (6.17).

6.3.3 Discharge loads

(1) Under discharge conditions, the mean vertical stress in the stored solid at any level in a steep hopper should be determined using Expressions (6.7) and (6.8), with the value of the parameter F given by $F = F_e$.

(2) The value of F_e may be calculated either by using the reference method given in Expression (6.21), or by the alternative method given in G.10:

$$F_e = \frac{1 + \sin\phi_1 \cos\varepsilon}{1 - \sin\phi_1 \cos(2\beta + \varepsilon)} \quad \dots (6.21)$$

in which:

$$\varepsilon = \phi_{wh} + \sin^{-1} \left\{ \frac{\sin\phi_{wh}}{\sin\phi_1} \right\} \quad \dots (6.22)$$

$$\phi_{wh} = \tan^{-1} \mu_h \quad \dots (6.23)$$

where:

μ_h is the lower characteristic value of wall friction coefficient in the hopper;

ϕ_1 is the angle of internal friction of the stored solid.

NOTE 1: It should be noted that $\phi_{wh} \leq \phi_1$ always, since the material will rupture internally if slip at the wall contact demands a greater shear stress than the internal friction can sustain.

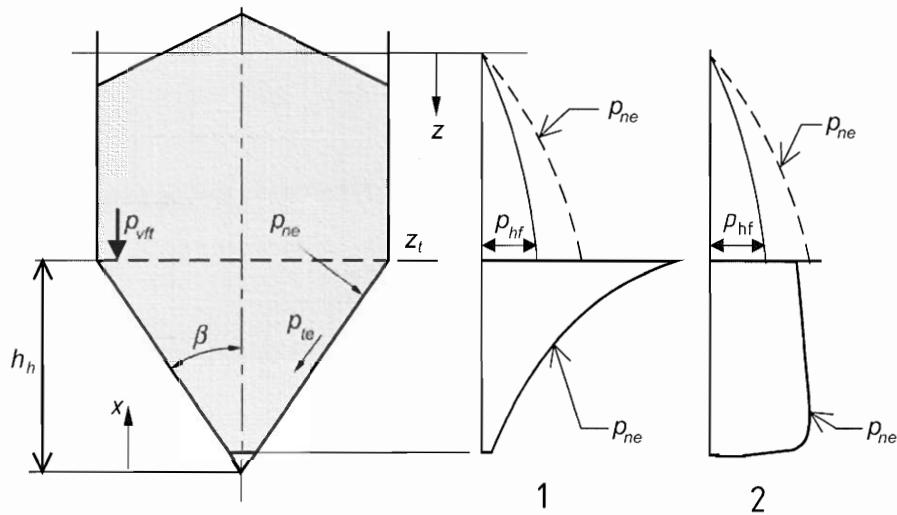
NOTE 2: The above Expression (6.21) for F_e is based on the simple theory of Walker for discharge pressures. The alternative expression of Enstad for F_e , set out in G.10, may alternatively be used.

(3) The normal pressure p_{ne} and frictional traction p_{te} (see Figure 6.4) at any point on the wall of a steep hopper during discharge should be determined as:

$$p_{ne} = F_e p_v \quad \dots (6.24)$$

$$p_{te} = \mu_h F_e p_v \quad \dots (6.25)$$

where F_e is obtained as defined in (2).



Key

- 1 Steep
- 2 Shallow

Figure 6.4: Discharge pressures in steep and shallow hoppers

6.4 Shallow hoppers

6.4.1 Mobilized friction

(1) In a shallow hopper, the wall friction is not fully mobilized. The mobilized or effective wall friction coefficient should be determined as:

$$\mu_{heff} = \frac{(1 - K)}{2 \tan \beta} \quad \dots (6.26)$$

where:

- K is the lower characteristic value of lateral pressure ratio for the vertical section (see table 3.1);
- β is the half angle of the hopper (see Figure 6.2).

6.4.2 Filling loads

(1) Under filling conditions, the mean vertical stress in the stored solid at any level of a shallow hopper should be determined using Expressions (6.7) and (6.8), with the value of the parameter F given by:

$$F_f = 1 - \{b / (1 + \tan\beta / \mu_{\text{heff}})\} \quad \dots (6.27)$$

The parameter n (see Expression (6.8)) is then given by:

$$n = S(1-b) \mu_{\text{heff}} \cot\beta \quad \dots (6.28)$$

where:

μ_{heff} is the mobilized or effective wall friction coefficient in the shallow hopper (see Expression (6.26));

b is an empirical coefficient: $b = 0,2$.

The other parameters are defined in 6.1.2 (6).

(2) The normal pressure p_{nf} and frictional traction p_{tf} at any point on the wall of a shallow hopper after filling (see Figure 6.2) should be determined as:

$$p_{\text{nf}} = F_f p_v \quad \dots (6.29)$$

$$p_{\text{tf}} = \mu_{\text{heff}} F_f p_v \quad \dots (6.30)$$

where:

F_f is given by Expression (6.27).

6.4.3 Discharge loads

(1) In shallow hoppers under discharge conditions (see Figure 6.4), the normal pressure and frictional traction may be taken as identical to the values on filling (see 6.4.2).

6.5 Hoppers in silos containing solids with entrained air

(1)P Hoppers in which it is possible for the stored solid to be fully or partially fluidized as a consequence of the entrainment of air shall be designed for the additional pressures that may arise due to fluidization and air pressure.

(2) The design pressures should be evaluated as defined in 5.5.2 with no frictional traction on the hopper wall.

Section 7 Loads on tanks from liquids

7.1 General

(1)P The following rules shall be used to determine the characteristic values of pressure loads from the liquid stored in tanks.

NOTE 1: These rules are valid for static conditions in all types of tanks, but tanks in which dynamic phenomena may occur are not included.

NOTE 2: A list of relevant actions, partial factors and combinations of actions on tanks may be found in Annex B.

7.2 Loads due to stored liquids

(1) Loads due to liquids should be calculated after considering:

- a defined range of liquids to be stored in the tank;
- the geometry of the tank;
- the maximum possible depth of liquid in the tank.

(2) The characteristic value of pressure p should be determined as:

$$p(z) = \gamma z \quad \dots (7.1)$$

where:

z is the depth below the liquid surface;

γ is the unit weight of the liquid.

7.3 Liquid properties

(1) The densities given in EN 1991-1-1, Annex A should be used.

7.4 Suction due to inadequate venting

(1)P Where the venting system to a tank may be susceptible to blockage or impediment, a rational analysis shall be used to determine the suction pressures arising during tank discharge at the peak rate. This analysis shall consider the possible adiabatic nature of the process.

Annex A

(Informative)

Basis of design - supplementary paragraphs to EN 1990 for silos and tanks

EDITORIAL NOTE: This annex is for information only and will be transferred to EN 1990 after Formal Vote.

A.1 General

- (1) In principle the general format given in EN 1990 for design procedures is applicable. However silos and tanks are different to many other structures because they may be subjected to the full loads from particulate solids or liquids for most of their life.
- (2) This annex provides supplementary guidance applicable to silos or tanks regarding partial factors on actions (γ_F factors) and on combinations on silos and tanks with other actions; and the relevant ψ factors.
- (3) Thermal actions include climatic effects and the effects of hot solids. Design situations that should be considered include:
 - hot solid or liquid filled into a partly filled silo or tank. The effects of heated air above the stored material should be considered;
 - resistance of the stored solid to silo wall contraction during cooling.
- (4) Determination of the effect of differential settlements of batteries of silo or tank cells should be based on the worst combination of full and empty cells.

A.2 Ultimate limit state

A.2.1 Partial factors γ

- (1) The values given in EN 1990, A.1 may be used for the design of silos and tanks.
- (2) If the maximum depth of liquid and the unit weight of the heaviest stored liquid are defined, the value of the partial factor γ_F may be reduced from 1,50 to 1,35.

A.2.2 Combination factors ψ

- (1) For the combination factors ψ for silo loads and tank loads and combination factors with other actions, see A.4.

A.3 Actions for combination

- (1) The following actions should be considered in the ultimate limit state design of the silo:
 - filling and storage of particulate solids (referred to as filling loads in EN 1991-4);
 - discharge of particulate solids (referred to as discharge loads in EN 1991-4);
 - imposed loads (see EN 1991-1-1);
 - snow loads (see EN 1991-1-3);
 - wind action when the silo is either full or empty (see EN 1991-1-4);
 - thermal loads (see EN 1991-1-5);
 - imposed deformations: foundation settlement (see EN 1997);
 - seismic loads (see EN 1998);
 - dust explosion loads.

A.4 Design situations and action combinations for Action Assessment Classes 2 and 3

(1) The dominant action and the permanent action should be taken at their full value in each load case, but the accompanying actions may be reduced by the combination factor ψ to account for the reduced probability of simultaneous occurrence in accordance with EN 1990. Combinations should be chosen in accordance with the rules of EN 1990.

(2) The combination factor $\psi_{0,1}$ should be taken as 1,0 and $\xi_1 = 0,9$ in all the above load combinations.

(3) Where the dominant action is seismic or accidental, the accompanying solids loading may be obtained using the single value of the mean wall friction coefficient μ_m , the mean lateral pressure ratio K_m and the mean hopper pressure ratio F_m for the stored particulate solid provided the appropriate procedures in 5.2, 5.3 and 6.1 are adopted.

NOTE: The values of ψ may be set by the National Annex. The values and combinations given in Tables A.1, A.2, A.3, A.4 and A.5 are recommended values, with Accompanying Actions 2 and 3 reduced by their appropriate combination factors ψ .

Table A.1: Design situations and action combinations to be considered

Short title	Design situation / Dominant action 1	Permanent actions	Accompanying Action 2	$\psi_{0,2}$	Accompanying Action 3	$\psi_{0,3}$
D	Solids discharge	Self weight	Foundation settlement	1,0	Snow or wind or thermal	0,6
					Imposed loads or deformation	0,7
I	Imposed loads or deformation	Self weight	Solids filling	1,0	Snow or wind or thermal	0,6
S	Snow	Self weight	Solids filling	1,0		
WF	Wind and full silo	Self weight	Solids filling	1,0		
WE	Wind and empty silo	Self weight	Solids empty	0,0		
T	Thermal	Self weight	Solids filling	1,0		
F	Foundation settlement	Self weight	Solids discharge	1,0	Snow or wind or thermal	0,6
				$\psi_{2,2}$		$\psi_{2,3}$
E	Explosion	Self weight	Solids filling	0,9	Imposed loads or deformation	0,3
V	Vehicle impact	Self weight	Solids filling	0,8	Imposed loads or deformation	0,3

NOTE 1: This table refers to terms in the load combination rules of Section 6 in EN 1990.

NOTE 2: The subscripts of ψ have the following significance: first subscript is for the type of design situation: normal combination values are 0; frequent values are 1; quasi-permanent values are 2. The second subscript refers to the load number in the combination.

Table A.2: "Ordinary" ultimate limit state ("Ordinary" ULS) - design situations and action combinations to be considered

Short title	Design situation / Leading variable action	Permanent actions		Leading variable action		Accompanying variable action 1 (main)		Accompanying variable action 2		Accompanying variable action 3, 4, etc.	
		Description	ξ_1	(See next column, "main")		Description	$\psi_{0,1}$	Description	$\psi_{0,2}$	Description	$\psi_{0,3}$ $\psi_{0,4}$ etc
D	Solids discharge	Self weight	0,9			Solids discharge	1,0	Foundation settlement	0,7	Snow, wind, thermal	0,6
										Imposed loads, imposed deformation	0,7
I	Imposed deformation	Self weight	0,9			Solids filling	1,0	Imposed deformation	0,7	Snow, wind, thermal	0,6
										Imposed loads	0,7
S	Snow	Self weight	0,9			Solids filling	1,0	Snow	0,6	Imposed loads	0,7
WF	Wind and full silo	Self weight	0,9			Solids filling, full silo	1,0	Wind	0,6	Imposed loads	0,7
WE	Wind and empty silo	Self weight	0,9			Solids, empty silo	0,0	Wind	0,6	Imposed loads	0,7
T	Thermal	Self weight	0,9			Solids filling	1,0	Thermal	0,6	Imposed loads	0,7

NOTE: Table A.2 should be used with Expressions (6.10a) and (6.10b) in EN 1990, 6.4.3.2.

Table A.3: "Accidental" ultimate limit state ("Accidental" ULS) - design situations and action combinations to be considered

Short title	Design situation / Leading variable action	Permanent actions		Leading accidental action		Accompanying variable action 1 (main)		Accompanying variable action 2		Accompanying variable action 3, 4, etc.	
		Description		Description		Description	$\psi_{1,1}$ or $\psi_{2,1}$	Description	$\psi_{2,2}$	Description	$\psi_{2,3}$ $\psi_{2,4}$ etc
E	Explosion	Self weight		Blast pressure		Solids filling	0,9 or 0,8	Imposed deformation	0,3	Imposed loads	0,3
V	Vehicle impact	Self weight		Vehicle impact		Solids filling	0,9 or 0,8	Imposed deformation	0,3	Imposed loads	0,3

NOTE: Table A.3 should be used with Expression (6.11b) in EN 1990, 6.4.3.3.

Table A.4: "Seismic" ultimate limit state ("Seismic" ULS) - design situations and action combinations to be considered

Short title	Design situation / Leading variable action	Permanent actions		Leading seismic action		Accompanying variable action 1 (main)		Accompanying variable action 2		Accompanying variable action 3, 4, etc.	
		Description		Description		Description	$\psi_{2,1}$	Description	$\psi_{2,2}$	Description	$\psi_{2,3}$ $\psi_{2,4}$ etc
SF	Seismic action and full silo	Self weight		Seismic action (earthquake)		Solids filling, full silo	0,8	Imposed deformation	0,3	Imposed loads	0,3
SE	Seismic action and empty silo	Self weight		Seismic action (earthquake)		Solids, empty silo	0,8	Imposed deformation	0,3	Imposed loads	0,3

NOTE: Table A.4 should be used with Expression (6.12b) in EN 1990, 6.4.3.4 and those of EN 1998-1 and EN 1998-4.

Table A.5: Serviceability limit state (SLS) - design situations and action combinations to be considered

Short title	Design situation / Leading variable action	Permanent actions		Leading variable action		Accompanying variable action 1 (main)		Accompanying variable action 2		Accompanying variable action 3, 4, etc.	
		Description		(See next column, "main")		Description	$\psi_{1,1}$ or $\psi_{2,1}$	Description	$\psi_{6,2}$ or $\psi_{2,2}$	Description	$\psi_{0,3}$ or $\psi_{0,4}$ or $\psi_{2,3}$ or $\psi_{2,4}$ etc
D	Solids discharge	Self weight				Solids discharge	0,9 or 0,8	Foundation settlement	0,7 or 0,3	Snow, wind, thermal	0,6 or 0,0
										Imposed loads, imposed deformation	0,7 or 0,3
I	Imposed deformation	Self weight				Solids filling	0,9 or 0,8	Imposed deformation	0,7 or 0,3	Snow, wind, thermal	0,6 or 0,0
										Imposed loads	0,7 or 0,3
S	Snow	Self weight				Solids filling	0,9 or 0,8	Snow	0,6 or 0,0	Imposed loads	0,7 or 0,3
WF	Wind and full silo	Self weight				Solids filling, full silo	0,9 or 0,8	Wind	0,6 or 0,0	Imposed loads	0,7 or 0,3
WE	Wind and empty silo	Self weight				Solids, empty silo	0,0	Wind	0,6 or 0,0	Imposed loads	0,7 or 0,3
T	Thermal	Self weight				Solids filling	0,9 or 0,8	Thermal	0,6 or 0,0	Imposed loads	0,7 or 0,3

NOTE: Table A.5 should be used with Expressions (6.14b), (6.15b) and (6.16b) in EN 1990, 6.5.3 as follows:

Characteristic combination, Expression (6.14b):

The characteristic combination is normally used for irreversible limit states.

Frequent combination, Expression (6.15b):

The frequent combination is normally used for reversible limit states.

Quasi-permanent combination, Expression (6.16b):

The quasi-permanent combination is normally used for long-term effects and the appearance of the structure.

A.5 Action combinations for Action Assessment Class 1

(1) The following simplified design situations may be considered for silos in Action Assessment Class 1:

- filling;
- discharge;
- wind when empty;
- filling with wind;
- snow (for the roof).

(2) A simplified treatment of wind loading is permitted according to rules of EN 1991-1-4.

Annex B

(Informative)

Actions, partial factors and combinations of actions on tanks

EDITORIAL NOTE: This annex is for information only and will be transferred to EN 1990 after Formal Vote.

B.1 General

- (1)P The design shall take account of the characteristic values of the actions listed in B.2.1 to B.2.14.
- (2) The partial factors on actions according to B.3 and the action combination rules according to B.4 should be applied to these characteristic values.

B.2 Actions

B.2.1 Liquid induced loads

- (1)P During operation, the load due to the contents shall be the weight of the *product to be stored from maximum design liquid level* to empty.
- (2)P During test, the load due to the contents shall be the weight of the *test medium from maximum test liquid level* to empty.

B.2.2 Internal pressure loads

- (1)P During operation, the internal pressure load shall be the load due to the specified minimum and maximum values of the internal pressure.
- (2)P During test, the internal pressure load shall be the load due to the specified minimum and maximum values of the test internal pressure.

B.2.3 Thermally induced loads

- (1) Stresses resulting from restraint of thermal expansion may be ignored if the number of load cycles due to thermal expansion is such that there is no risk of fatigue failure or cyclic plastic failure.

B.2.4 Self-weight loads

- (1)P The self-weight loads on the tank shall be considered as those resulting from the weight of all component parts of the tank and all components permanently attached to the tank.
- (2) Numerical values should be taken from EN 1991-1-1, Annex A.

B.2.5 Insulation

- (1)P The insulation loads shall be those resulting from the self-weight of the insulation.
- (2) Numerical values should be taken from EN 1991-1-1, Annex A.

B.2.6 Distributed imposed load

- (1) The distributed imposed load should be taken from EN 1991-1-1 unless specified by the client.

B.2.7 Concentrated imposed load

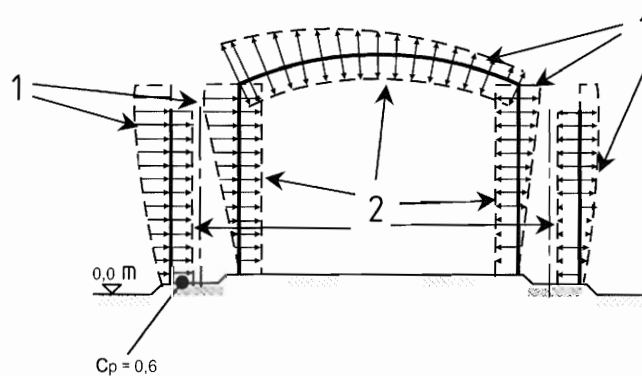
- (1) The concentrated imposed load should be taken from EN 1991-1-1 unless specified by the client.

B.2.8 Snow

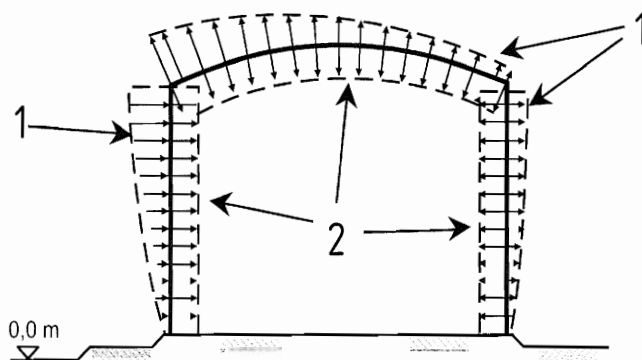
- (1) The loads should be taken from EN 1991-1-3.

B.2.9 Wind

- (1) The loads should be taken from EN 1991-1-4.
- (2) In addition, the following pressure coefficients may be used for circular cylindrical tanks, see figure B.1:
 - a) internal pressure of open top tanks and open top catch basin: $c_p = -0,6$.
 - b) internal pressure of vented tanks with small openings: $c_p = -0,4$.
 - c) where there is a catch basin, the external pressure on the tank shell may be assumed to reduce linearly with height.
- (3) Due to their temporary character, reduced wind loads may be used for erection situations according to EN 1991-1-4 and EN 1991-1-6.



a) Tank with catch basin



b) Tank without catch basin

Key

- 1 C_p according to EN 1991-1-4
- 2 $C_p = 0,4$ vented tank only

Figure B.1: Pressure coefficients for wind loading on a circular cylindrical tank

B.2.10 Suction due to inadequate venting

- (1) The loads should be taken from section 7 of this standard.

B.2.11 Seismic loadings

(1)P The loads shall be taken from EN 1998-4, which also sets out the requirements for seismic design.

B.2.12 Loads resulting from connections

(1)P Loads resulting from pipes, valves and other items connected to the tank and loads resulting from settlement of independent item supports relative to the tank foundation shall be taken into account. Pipework shall be designed to minimize loadings applied to the tank.

B.2.13 Loads resulting from uneven settlement

(1)P Settlement loads shall be taken into account where uneven settlement can be expected during the lifetime of the tank.

B.2.14 Accidental actions

(1) The loads should include the consequences of events such as external blast, impact, adjacent external fire, explosion, leakage from the inner tank, roll over and overfilling of the inner tank.

NOTE: These loads may be specified in the National Annex, or by the client for the individual project.

B.3 Partial factors for actions

(1)P The partial factors according to EN 1990 shall be applied to the actions B.2.2 to B.2.14.

(2) The recommended value of the partial factor for the liquid induced loads during operation (see B.2.1(1)) is $\gamma_F = 1,20$.

(3) The recommended value of the partial factor for the liquid induced loads during test (see B.2.1(2)) is $\gamma_F = 1,00$.

(4) For accidental design situations, the recommended value of the partial factor for the variable actions is $\gamma_F = 1,00$.

B.4 Combination of actions

(1)P The general requirements of EN 1990, Section 6 shall be followed.

(2) It is recommended that imposed loads and snow loads need not be considered to act simultaneously.

(3) It is recommended that seismic actions need not be considered to act during test conditions.

(4) It is recommended that accidental actions need not be considered to act during test conditions, but that the combination rules for accidental actions given in EN 1990 are applied.

Annex C

(Normative)

Measurement of properties of solids for silo load evaluation

C.1 Object

(1) This annex describes test methods for the determination of the stored solids parameters introduced in EN 1991-4 for the purposes of silo load evaluation only. These methods are not intended for use in design for reliable discharge. Where the properties are required for load assessment, the following aspects are important: the relevant stress level is much larger than that for flow assessment, the sample preparation must reflect conditions in highly stressed parts of the stored solid after filling, and the stress history of the material is generally different from that associated with flow stoppages. As a result, the sample preparation differs in some key ways from that appropriate to the measurement of flow properties.

The particle packing arrangements sought in these tests should achieve high densities for the stored solid. All the parameters that affect silo pressures should be evaluated under these conditions because this condition for the solid is the reference state for the upper characteristic values of the actions on the silo structure.

C.2 Field of application

(1) The test methods defined here are for use on silos in Action Assessment Class 3, or for a stored solid that is not listed in Table E.1, or as an alternative to the simplified values given in Table E.1. The reference stresses in the tests are either vertical or horizontal and they should be representative of the stresses in the stored solid at the silo transition when the silo is in the full condition.

(2) The test methods may also be used for the measurement of values of solids properties of general relevance to silo design. Tests to determine such generally relevant values should be carried out, where applicable, using the following reference stress levels:

a) to represent the vertical pressure (see C.6, C.8 and C.9): reference stress $\sigma_r = 100$ kPa

b) to represent the horizontal pressure (see C.7.2): reference stress $\sigma_r = 50$ kPa.

C.3 Notation

For the purpose of this annex the following notation applies:

<i>a</i>	property modification coefficient
<i>c</i>	cohesion (see Figure C.4)
<i>D</i>	cell internal diameter
F_r	residual shear force at end of wall friction test (see Figure C.2b)
K_{mo}	mean lateral pressure ratio for smooth wall conditions
Δ	displacement of top part of shear cell during test
ϕ_1	angle of internal friction measured during loading of the sample
ϕ_c	angle of internal friction measured under decreasing normal stresses
μ	coefficient of friction between the sample of solid and the sample of wall
σ_r	reference stress
τ_a	final shear stress measured in a shear test after increasing the normal stress (see Figure C.4)

- τ_b peak shear stress measured in a shear test after decreasing the normal stress (see Figure C.4)
- τ shear stress measured in a shear test.

C.4 Definitions

For the purpose of this annex the following definitions apply.

C.4.1

secondary parameter

any parameter that may influence stored material properties but is not listed as a primary cause of parameter variation. Secondary parameters include composition, grading, moisture content, temperature, age, electrical charge due to handling, and production method. Variations in the reference stresses mentioned in C.2 should each be considered as a secondary parameter

C.4.2

sampling

the selection of representative samples of stored solids or silo wall material, including variations with time

C.4.3

reference stress

the reference stress is the stress state at which the measurements of stored solid properties are carried out. The reference stress is normally selected to correspond to the stress level in the silo after filling. Sometimes it may be necessary to define the reference stress with more than one principal stress

C.5 Sampling and preparation of samples

- (1) Testing should be carried out on representative samples of the particulate solid.
- (2) The choice of sample should be made with appropriate consideration of the variations that may occur during the lifetime of the structure, the changes that may be caused by variations in ambient conditions, the effects of methods of silo operation, and the effects of segregation of solids within the silo.
- (3) The mean value for each solids property should be determined making proper allowance for variation of secondary parameters.
- (4) The reference stress σ_r for each test should be identified in relation to the stress state in the stored solid after filling. The value of the reference stress need not be accurately defined.

NOTE: A precise evaluation of the reference stress would require the outcome of the test to be known before the test is performed. The precise value of the reference stress is not critical to the tests, but these tests should be performed at stress levels that are appropriate to the purpose to which they will be put.

- (5) The following method of sample preparation should be used for the tests described in C.6, C.7.2, C.8.1 and C.9.
- (6) The sample should be poured into the test cell, without vibration or other compacting forces and the reference stress σ_r applied. A top plate should be rotated clockwise and anticlockwise about the vertical axis several times through an angle of at least 10 degrees to consolidate the sample.

NOTE 1: Reference may be made to the ASTM Standard D6128 concerning this procedure.

NOTE 2: The number of twists that is required depends on the solid being tested.

- (7) The mean test values should be adjusted by conversion factors to derive extreme values. The conversion factors should be selected to allow for the influence of secondary parameters, the variability of the solids properties over the silo life, and for sampling inaccuracies.

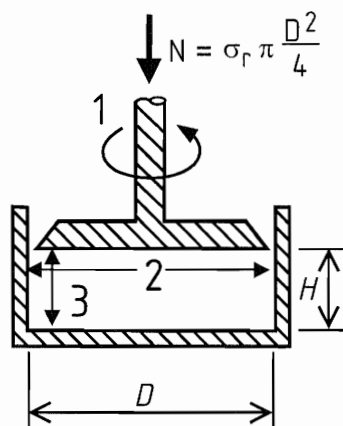
(8) The conversion factors a for the properties of a solid should be adjusted if the effect of one secondary parameter accounts for more than 75 % of the margin introduced for the solids property by the conversion factor.

C.6 Bulk unit weight γ

C.6.1 Principle of the test

(1) The bulk unit weight γ should be determined using a consolidated sample of the particulate solid.

NOTE: The aim of this test is to obtain a good estimate of the maximum density likely to occur in the silo. This aim is achieved by identifying the maximum achievable bulk density at the stress level likely to arise in the silo. To achieve this, it is necessary to pack the solid into the test apparatus with an appropriately densely packed arrangement of the particles before the consolidating stress is applied. This can be achieved either by rain filling of the solid, or by twisting of the lid to achieve a density that is representative of the conditions relevant to silo pressure evaluation. For this reason, a rough lid is chosen, with rotation of the lid to achieve appropriate particle rearrangement. This procedure differs from the ASTM method given in ASTM D6683-01 "Standard test method for measuring bulk density values of powders and other bulk solids" because the latter is chiefly concerned with powders, where the aim is to achieve a loose density.



Key

- 1 Standardised twisting
- 2 Smooth
- 3 Rough

Figure C.1: Device for the determination of γ

C.6.2 Apparatus

(1) The cell shown in Figure C.1 should be used to measure the weight and volume of the solid sample. The diameter D of the cell should be at least 5 times the maximum particle size and not less than 10 times the mean particle size. The compacted height H of the sample should be between $0,3D$ and $0,4D$.

NOTE: The restrictions on particle sizes are chosen for the following reasons. The maximum particle size is limited to ensure that the restrictions on particle arrangements caused by the fixed lines of the walls do not have an inordinate influence on the measured density. In addition, it is recognized that this influence is greater where the particles are all of about the same size than where smaller particles can occupy the interstitial spaces between the larger particles. Thus, for monosized materials the above restriction is at 10 times the particle size, but for solids with a wide particle size distribution, the restriction falls to 5 times the largest particle size.

C.6.3 Procedure

(1) The reference stress σ_r should be equal to the vertical stress in the stored solid in the silo p_v .

(2) Sample preparation should be carried out according to the guidelines given in C.5. The bulk unit weight is determined by dividing the weight of a consolidated sample of the particulate solid by the bulk volume. The height H should be taken as the mean of three measurements at the same radius and at 120° separations around the cell.

NOTE: If the density is measured instead using ASTM Standard D6683, a lower density may be found. The difference is generally small for powders, but it may be significant for coarse grained solids.

C.7 Wall friction

C.7.1 General

(1) A distinction should be made between the two parameters:

- coefficient of wall friction μ_m for the determination of pressures;
- angle of wall friction ϕ_{wh} for the evaluation of flow.

(2) For solids containing a range of particle sizes that may segregate during the filling process, the sample used for the determination of the wall friction coefficient μ_m should be chosen with appropriate consideration of the effects of segregation.

(3) Wall friction tests should be conducted with wall sample coupons that are representative of the wall surface materials that will be used in construction.

NOTE: Although testing laboratories may have sample coupons of a wide range of construction and lining materials, an individual coupon may have a different finish from that which is available at the time of construction. Coupons of nominally identical description may produce wall friction angles that differ by several degrees. Where possible, wall coupons should be obtained from the anticipated source of the construction material (such as a steel mill or vessel fabricator). Painted steel surfaces should be painted with the same type of paint. For major projects, it is recommended that test coupons are retained for later comparison with the construction materials that are actually used. It is not currently possible to characterize a wall coupon surface in a way that reliably predicts its wall friction behaviour.

(4) Wherever the silo wall may later be subject to either corrosion or abrasion, wall friction tests should be conducted on both fresh and used coupons.

NOTE: Wall surface finishes in silos usually change over time. Corrosion may roughen a surface, while abrasive wear may either polish or roughen the surface. Surfaces such as polyethylene may be gouged, and painted surfaces may be scratched. Silo walls may also become smoother due to an accumulation of fine products from the stored solids in small voids (grease, fines etc.). These changes may cause a funnel flow pattern to occur in a silo intended for mass flow, or for mass flow to occur in a silo intended for funnel flow. The filling pressures may increase in a silo with polished walls and the filling wall frictional traction may increase in a silo with a roughened wall.

C.7.2 Coefficient of wall friction μ_m for the determination of pressures

C.7.2.1 Principle of the test

(1) A sample of the particulate solid should be sheared along a surface representing the silo wall (a sample with corrugation in the case of corrugated steel silos) and the friction force at the sheared surface should be measured.

NOTE: Care should be used to ensure that the wall shear data is interpreted appropriately according to whether loading or flow calculations are being performed.

C.7.2.2 Apparatus

(1) The test apparatus is shown in Figure C.2. The diameter of the cell should be at least 20 times the maximum particle size and not less than 40 times the mean particle size. The compacted height H of the sample should be between $0,15D$ and $0,20D$. In the case of wall samples with irregularities such as corrugations the cell size should be selected accordingly.

NOTE: The restrictions on particle sizes are chosen for the following reasons. The maximum particle size is limited to ensure that the restrictions on particle arrangements caused by the fixed lines of the walls do not have an inordinate influence on the measured property. In addition, it is recognized that this influence is greater where the particles are all of about the same size than where smaller particles can occupy the interstitial spaces between the larger particles. Thus, for monosized materials the above restriction is at 40 times the particle size, but for solids with a wide particle size distribution, the restriction falls to 20 times the largest particle size.

C.7.2.3 Procedure

- (1) The reference stress σ_r should be taken as the largest horizontal silo pressure p_h .
- (2) Sample preparation should be carried out according to the guidelines given in C.5.
- (3) After filling the cell and before shearing, the cell should be rotated and lifted slightly off the test surface, so that only friction between the particles and surface is measured.
- (4) Shearing of the sample should be carried out at a constant rate of approximately 0,04 mm/s.
- (5) The residual friction force F_r (see Figure C.2), attained at large deformations, should be used in the calculation of the coefficient of wall friction μ for action calculations.
- (6) The sample value of the coefficient of wall friction μ for action calculations should be determined as:

$$\mu = \frac{F_r}{N} \quad \dots (C.1)$$

where:

- F_r is the final or residual value of the shear force (see Figure C.2b);
- N is the applied vertical load on the cell.

C.7.3 Angle of wall friction ϕ_{wh} for the evaluation of flow

- (1) Where it is necessary to obtain the angle of wall friction ϕ_{wh} for the evaluation of flow, reference may be made to the ASTM Standard D6128.
- (2) The wall friction value needed for flow assessment should be obtained at low stress levels.
- (3) Care should be used to ensure that the wall shear data is interpreted appropriately according to whether loading or flow calculations are being performed.

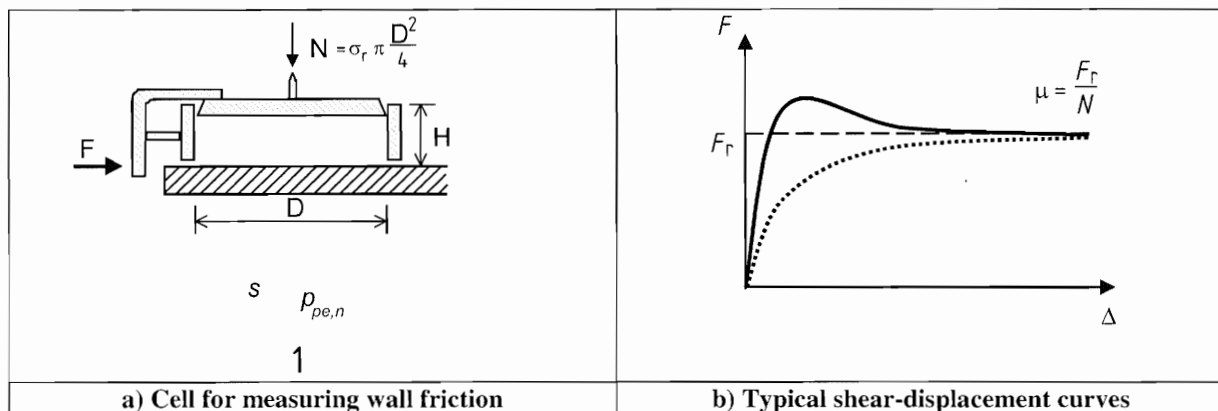


Figure C.2: Test method for determination of wall friction coefficient

C.8 Lateral pressure ratio K

C.8.1 Direct measurement

C.8.1.1 Principle of the test

(1) A vertical stress σ_1 should be applied to a sample constrained against horizontal deformation. The induced horizontal stress σ_2 should be measured and the secant value of the lateral pressure ratio K_0 determined.

NOTE 1: The magnitude of the coefficient K_0 is influenced by the direction of the principal stresses in the test sample. The horizontal and vertical stresses are approximately principal stresses in the test sample whereas they may not be in the silo.

NOTE 2: Where the sample is said to be constrained against horizontal deformation, this means that the horizontal strains in the solid are kept so small that their effect on the stress in the particulate solid sample is minor. Nevertheless these strains are large enough to produce measurable observations in the thin wall of the apparatus, or in special parts of the wall that have been designed to concentrate strains. A mean circumferential strain of the order of 100 microstrains generally meets these criteria of limited strain in the solid with measurable values in the apparatus.

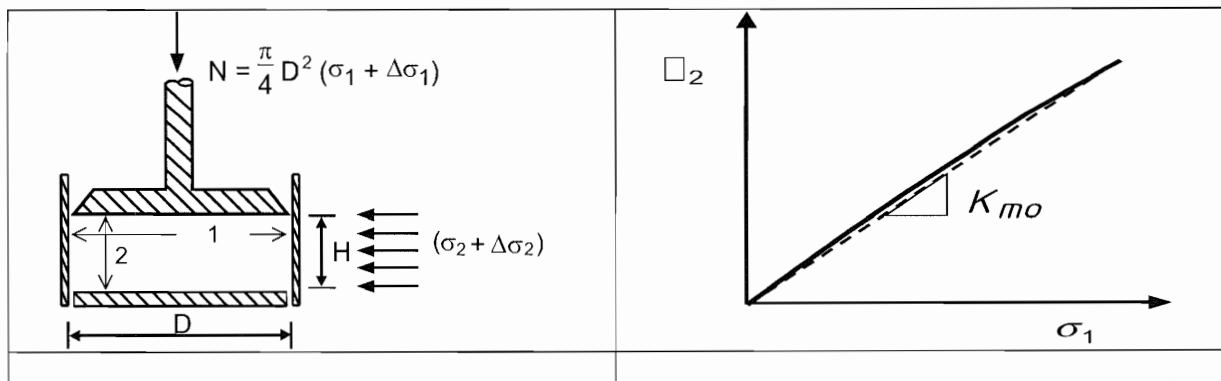


Figure C.3: Test method for determining K_0

C.8.1.2 Apparatus

(1) The geometry of the test apparatus is shown in Figure C.3. The horizontal stress should be deduced from strains measured on the outer surface of the vertical section, but the wall must be thin, and the design must ensure that the stress state in the wall is correctly interpreted.

NOTE: The following features are generally necessary in this apparatus:

- a separate bottom plate that is independent of the walls;
- measurement of both horizontal and vertical strains on the cylindrical walls;
- locating the strain measurement devices distant from the specimen ends; and
- verification that the measured strains are related to the internal horizontal stress by the assumed factor (vertical bending of the cylindrical wall may affect this relationship).

C.8.1.3 Procedure

- The reference stress σ_r should be taken as the highest vertical stress in the stored solid in the silo.
- Sample preparation should be carried out according to the guidelines given in C.5.
- The horizontal stress σ_2 in the sample that results from application of a vertical stress σ_1 equal to the reference stress σ_r should be observed. The value of K_0 should be calculated from these stresses (see Figure C.3) as:

$$K_0 = \frac{\sigma_2}{\sigma_1} \quad \dots \text{ (C.2)}$$

(4) The value of K should be taken as:

$$K = 1,1 K_0 \quad \dots \text{(C.3)}$$

NOTE: The factor 1,1 in Expression (C.3) is used to give an approximate representation of the difference between the lateral pressure ratio ($=K_0$) measured under conditions of almost zero wall friction and the value of K measured when wall friction is present (see also 4.2.2 (5)).

C.8.2 Indirect measurement

(1) An approximate value for K may be deduced from the loading angle of internal friction ϕ_1 , which may be determined either from the method described in C.9 or from a triaxial test. The approximate relationship given in Expression (4.7) should be used to deduce K from ϕ_1 .

C.9 Strength parameters: cohesion c and internal friction angle ϕ_1

C.9.1 Direct measurement

C.9.1.1 Principle of the test

(1) The strength of a stored solid sample may be determined from shear cell tests. Two parameters c and ϕ_1 should be used to define the effects of a stored solid's strength on silo pressures after the silo has been filled.

(2) Reference may be made to the ASTM D6128, but it should be noted that the parameters derived from the test in that standard are not identical to those defined here.

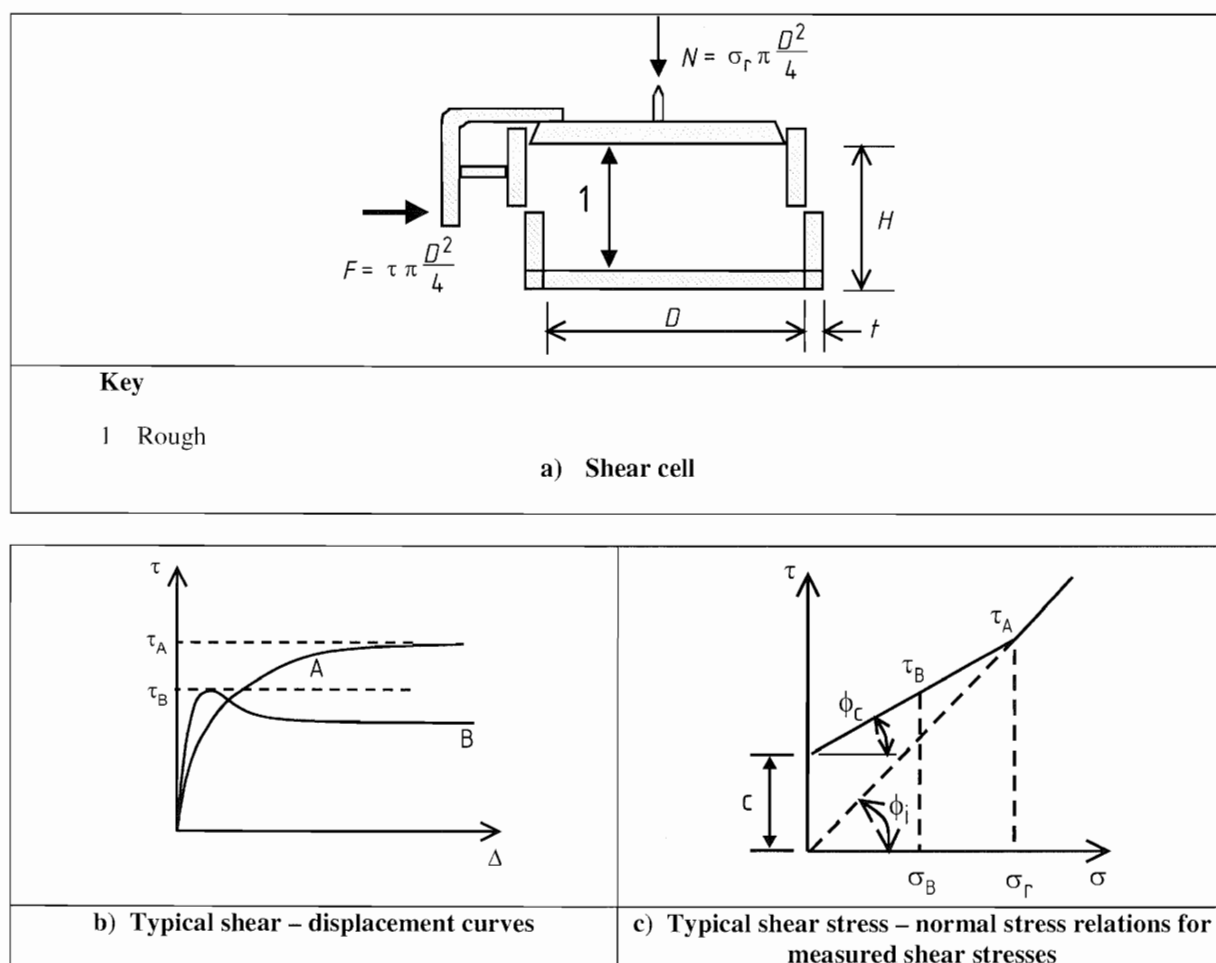


Figure C.4: Test method for determining the angles of internal friction ϕ_i and ϕ_c and the cohesion c based on the preconsolidation stress σ_r

C.9.1.2 Apparatus

(1) The test apparatus should consist of a cylindrical shear cell, as shown in Figure C.4. The shear cell diameter D should be at least 20 times the maximum particle size and not less than 40 times the mean particle size. The height H should be between $0,3D$ and $0,4D$.

NOTE: The restrictions on particle sizes are chosen for the following reasons. The maximum particle size is limited to ensure that the restrictions on particle arrangements caused by the fixed lines of the walls do not have an inordinate influence on the measured property. In addition, it is recognized that this influence is greater where the particles are all of about the same size than where smaller particles can occupy the interstitial spaces between the larger particles. Thus, for monosized materials the above restriction is at 40 times the particle size, but for solids with a wide particle size distribution, the restriction falls to 20 times the largest particle size.

C.9.1.3 Procedure

- (1) The reference stress σ_r should be approximately equal to the vertical stress in the stored solid in the silo defined in C.2. Sample preparation should be carried out according to the guidelines given in C.5.
- (2) Shearing of the sample should be carried out at a constant rate of approximately 0,04 mm/s.
- (3) The shear stress τ developed at or before a horizontal displacement of $\Delta = 0,06D$ should be used to calculate the strength parameters for the solid, where D is the internal diameter of the cell (see Figure C.4).
- (4) At least two tests should be carried out (see Table C.1 and Figure C.4) as defined in (5) and (6) below.

(5) The first sample should be sheared under a normal load causing the reference stress σ_r to obtain the failure shear stress τ_A .

(6) The second sample should first be pre-loaded under a normal load causing the reference stress σ_r and just brought to shear failure as for the first sample. Shearing should be stopped and the applied shear load reduced to zero. The normal load on this second sample should then be reduced to a value causing approximately half the reference stress ($\sigma_B \approx \sigma_r/2$) and sheared again to obtain the failure shear stress τ_B . Stresses determined from the two tests are named in Table C.1).

Table C.1: Recommended tests

Test	Pre-load value of normal stress	Test load value of normal stress	Maximum measured shear stress
No. 1	σ_r	σ_r	τ_A
No. 2	σ_r	$\sigma_B \approx \sigma_r/2$	τ_B

C.9.1.4 Interpretation

(1) The loading angle of internal friction ϕ_1 for the stored solid should be calculated as:

$$\phi_1 = \arctan (\tau_A / \sigma_r) \quad \dots (C.4)$$

(2) The cohesion c that develops in the stored solid under the reference stress σ_r should be calculated as:

$$c = \tau_A - \sigma_r \tan \phi_c \quad \dots (C.5)$$

in which:

$$\phi_c = \arctan \left(\frac{\tau_A - \tau_B}{\sigma_r - \sigma_B} \right) \quad \dots (C.6)$$

where:

ϕ_c is the unloading internal friction angle for an overconsolidated material

NOTE: The value of cohesion c depends strongly on the consolidation stress σ_r , so this cannot be regarded as a fixed property of the solid.

(3) For a cohesionless solid (where $c = 0$), the frictional strength should be described only by the loading angle of internal friction ϕ_1 (which is then equal to ϕ_c).

NOTE: A standard triaxial test may be used as an alternative to the test described above.

C.9.2 Indirect measurement

C.9.2.1 Principle of the test

(1) Where shear cell tests using a Jenike Shear Cell (ASTM Standard D6128) have been undertaken, the cohesion of a stored solid may alternatively be approximately deduced from these results.

(2) The cohesion should be found in relation to the maximum mean vertical stress in the silo after filling σ_{vft} , which is defined in C.2.

(3) The “major principal consolidating stress” σ_c should be taken as equal to the maximum mean vertical stress in the silo after filling σ_{vft} .

(4) The unconfined yield stress σ_u corresponding to this consolidation stress should be determined. The effective angle of internal friction δ (determined under the corresponding stress conditions) should also be found.

(5) An approximate value for the cohesion c should then be determined as:

$$c = \sigma_c \left(\frac{\sin \delta - \sin \phi_c}{\cos \phi_c (1 + \sin \delta)} \right) \quad \dots (C.7)$$

in which:

$$\phi_c = \sin^{-1} \left(\frac{2 \sin \delta - k}{2 - k} \right) \quad \dots (C.8)$$

$$k = \left(\frac{\sigma_u}{\sigma_c} \right) (1 + \sin \delta) \quad \dots (C.9)$$

where:

σ_c is the major principal consolidating stress found in a Jenike shear cell test;

σ_u is the unconfined yield strength found in a Jenike shear cell test;

δ is the effective angle of internal friction found in a Jenike shear cell test;

ϕ_c is the unloading angle of internal friction (see Figure C.4c).

NOTE 1: It should be noted that the value of cohesion c depends strongly on the consolidation stress σ_c , so this cannot be regarded as a fixed property of the solid.

NOTE 2: It should be noted that the major principal consolidating stress σ_c is usually referred to as σ_1 in the bulk solids handling literature.

(6) An approximate value for the loading angle of internal friction ϕ_1 may be found from this test as:

$$\phi_1 = \tan^{-1} \left(\frac{\sin \delta \cos \phi_c}{1 - \sin \phi_c \sin \delta} \right) \quad \dots (C.10)$$

NOTE: It should be noted that the two parameters c and ϕ_1 are used in this standard only to define the effects of a stored solid's strength on silo pressures.

C.10 Effective elastic modulus E_s

C.10.1 Direct measurement

C.10.1.1 Principle of the test

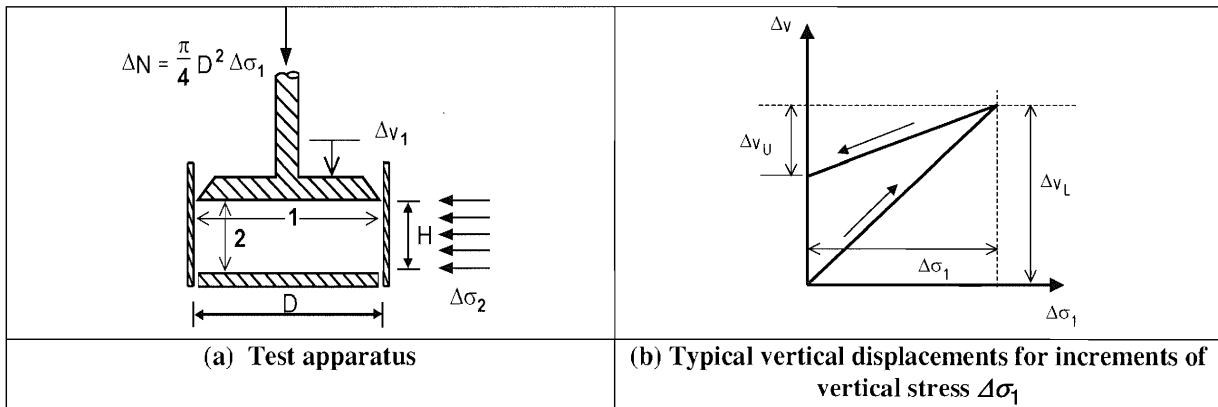
(1) A vertical stress σ_1 should be applied to a sample constrained against horizontal deformation. As the vertical stress increases by $\Delta\sigma_1$, the change in induced horizontal stress $\Delta\sigma_2$ and the change in vertical displacement Δv_1 should be measured. The loading effective elastic modulus E_{sL} should be deduced from these measurements. The vertical stress should then be decreased by $\Delta\sigma_1$, the change in induced horizontal stress $\Delta\sigma_2$ and the change in vertical displacement Δv_1 should be measured. The unloading effective elastic modulus E_{sU} should be deduced from these measurements.

NOTE 1: The magnitude of the coefficient K_0 is influenced by the direction of the principal stresses in the test sample. The horizontal and vertical stresses are approximately principal stresses in the test sample.

NOTE 2: Where the sample is said to be constrained against horizontal deformation, this means that the horizontal strains are kept so small that their effect on the stress in the particulate solid sample is minor, but the strains are large enough to produce measurable observations in the thin wall of the apparatus. Strains of the order of 100 microstrain meet these criteria.

C.10.1.2 Apparatus

(1) The geometry of the test apparatus that should be used is shown in Figure C.5 and is similar to the apparatus described in C.8 for the measurement of lateral pressure ratio K .



Key

- 1 Smooth
- 2 Rough

Figure C.5: Test method for determining the loading and unloading elastic moduli

(2) The horizontal stress should be deduced from strains measured on the outer surface of the vertical section. The wall of the cell should be thin, and the design should ensure that the stress state in the wall is correctly interpreted (it is generally necessary to have a separate bottom plate, to make both horizontal and vertical strain measurements, and to site the strain measurement devices distant from the specimen ends).

(3)P An accurate means of measuring small increments in the vertical displacement of the sample shall be provided.

C.10.1.3 Procedure

- (1) The reference stress σ_r should be taken as the highest vertical stress in the stored solid in the silo.
- (2) Sample preparation should be carried out according to the guidelines given in C.5.
- (3) After application of a vertical stress σ_1 equal to the reference stress σ_r , the measurement systems for observing horizontal stress and vertical displacement should be read. The height of the compressed sample H should also be accurately measured.
- (4) A small additional increment of vertical stress $\Delta\sigma_1$ should be applied, and the horizontal stress and vertical displacement should be measured again. The increment of vertical stress $\Delta\sigma_1$ should be approximately 10 % of the reference stress σ_1 .

(5) The change in horizontal stress (caused by the vertical stress increment $\Delta\sigma_1$) should be determined as $\Delta\sigma_2$ and the change in vertical displacement should be determined as Δv . The loading incremental value of K should then be determined as K_L :

$$K_L = \frac{\Delta\sigma_2}{\Delta\sigma_1} \quad \dots \text{ (C.11)}$$

(6) The loading effective elastic modulus E_{sL} should then be determined as:

$$E_{sL} = H \frac{\Delta\sigma_1}{\Delta v} \left(1 - \frac{2K_L^2}{1 + K_L} \right) \quad \dots \text{ (C.12)}$$

(7) A small incremental reduction of vertical stress $\Delta\sigma_1$ should then be applied (treated as negative quantity), and the horizontal stress and vertical displacement should be measured again. The increment of vertical stress $\Delta\sigma_1$ should again be approximately 10 % of the reference stress σ_1 .

(8) The change in horizontal stress (caused by the vertical stress increment $\Delta\sigma_1$) should be determined as $\Delta\sigma_2$ and the change in vertical displacement should be measured as Δv (both negative). The unloading incremental value of K should then be determined as K_U :

$$K_U = \frac{\Delta\sigma_2}{\Delta\sigma_1} \quad \dots \text{ (C.13)}$$

(9) The unloading effective elastic modulus E_{sU} should then be deduced as:

$$E_{sU} = H \frac{\Delta\sigma_1}{\Delta v} \left(1 - \frac{2K_U^2}{1 + K_U} \right) \quad \dots \text{ (C.14)}$$

NOTE: The unloading effective elastic modulus is usually much higher than the loading modulus. In assessments where a high elastic modulus may be deleterious to the structure (e.g. thermal differentials), the unloading modulus should be used. Where the elastic modulus of the solid is beneficial to the structure (e.g. in thin-walled rectangular silos) the loading modulus should be used.

C.10.2 Indirect assessment

(1) As an aid to determine whether testing is justified in a particular case, an approximate value for E_{sU} may be estimated from

$$E_{sU} = \chi p_{vft} \quad \dots \text{ (C.15)}$$

where:

p_{vft} is the vertical stress at the base of the vertical walled section (Expression (5.3) or (5.79));

χ is the modulus contiguity coefficient.

NOTE: The unloading effective elastic modulus E_{sU} and the vertical stress p_{vft} are expressed in the same units in Expression (C.15).

(2) In the absence of experimental data from tests according to C.10.1, the modulus contiguity coefficient χ may be estimated as

$$\chi = 7 \gamma^{3/2} \quad \dots \text{ (C.16)}$$

where:

γ is the unit weight of the stored solid in kN/m^3 .

(3) The value of χ may alternatively be taken as 70 for dry agricultural grains, 100 for small mineral particles and 150 for large hard mineral particles.

C.11 Assessment of the upper and lower characteristic values of a property and determination of the conversion factor a

C.11.1 Principle

(1)P The silo shall be designed for the most adverse loading condition which may occur during its design life. This section deals with the assessment of the variability of properties which may occur in samples presented for testing at the time of design.

NOTE: It is likely that the properties of the stored solid will change during the life of the structure, but these are not easy to assess.

(2)P The extreme values of loads for design shall be represented by their characteristic values, which are values with accepted prescribed probabilities of not being exceeded (5 percentile and 95 percentile values normally) during the intended life of the container or the permanency of the design.

(3)P The extreme values of properties needed to achieve these extreme load levels shall be termed characteristic values of the properties.

(4)P Both upper and lower characteristic values of the relevant properties shall be used to obtain the relevant loading conditions.

(5) The simplified treatment defined here should be used, in which the characteristic value is taken as 1,28 standard deviations from the mean.

NOTE 1: The values of properties required to achieve a fixed probability of exceedence of the load levels depend on the geometry and absolute size of the container, the load case being considered, and whether the loads are on vertical or hopper walls. In addition, the moisture content, temperature, potential for segregation and age all affect these values.

NOTE 2: It may be noted that EN 1990, Annex D "Design assisted by testing", recommends a different value from 1,28. As stated in the above paragraph, because several uncorrelated properties contribute to the characteristic load value, a 10 percentile or 90 percentile value of each property is judged to be a reasonable estimate of the value required to give an appropriate probability for the final load. The use of a higher value than this is likely to lead to designs that are considerably more conservative than current practice.

(6) If adequate experimental data is available, the characteristic values should be determined using statistical techniques.

NOTE 1: Test data, although useful as the basis for the assessment of characteristic values, have their limitations (limited sample size, limited sampling technique, etc.). These limitations may cause the data to be unrepresentative of the full range of properties that may occur in the design life of the structure.

NOTE 2: The values given in Table E.1 represent a mixture of judgement based on experience and available experimental data.

(7) If the client or designer has adequate data or experience for a particular design situation, then the client may select characteristic values to represent the range of values of properties that may occur during the design life of the container.

C.11.2 Method of estimation

(1) The following procedure may be used to obtain the characteristic values of any property. In the following, the variable x is used to represent any property.

(2) The mean value of the property \bar{x} , should be determined from test data.

(3) Where possible, the coefficient of variation δ should be determined from the test data.

(4) Where the test data is insufficient to provide a good estimate of the coefficient of variation, an appropriate value should be estimated for the solid. Table C.2 may be used as a guide.

(5) The upper characteristic value for the property ($x_u = x_{0,90}$) should be determined as:

$$x_{0,90} = \bar{x} (1 + 1,28 \delta) \quad \dots \text{(C.17)}$$

(6) The lower characteristic value for the property ($x_\ell = x_{0,10}$) should be determined as:

$$x_{0,10} = \bar{x} (1 - 1,28 \delta) \quad \dots \text{(C.18)}$$

(7) The conversion factor a_x for the property should be determined as:

$$a_x = \sqrt{\frac{1+1,28\delta}{1-1,28\delta}} \approx 1 + 1,28\delta + \delta^2 \quad \dots \text{(C.19)}$$

NOTE: Expression (C.19) is the simplest method of determining a single value for a_x that gives a close approximation for both $x_{0,90}$ and $x_{0,10}$. However, it should be noted that because Expressions (C.17) and (C.18) are additive expressions, but the use of a_x is multiplicative, there will always be a small discrepancy between the characteristic values determined from Expressions (C.17) and (C.18) and those found using the simpler method of this standard based on Expression (C.19) and Expressions (4.1) to (4.6).

(8) Where the values must be estimated, the coefficient of variation δ for unit weight should be taken as 0,10. For other properties, the values may be estimated from those for similar particulate solids using Table C.2.

Table C.2: Typical values of the coefficient of variation of particulate solids properties

Bulk solid	Coefficient of variation δ				
	Lateral pressure ratio (K)	Angle of internal friction (ϕ_1) (degrees)	Wall friction coefficient (μ)		
			Wall friction category		
			Type D1	Type D2	Type D3
Aggregate	0,11	0,11	0,09	0,09	0,09
Alumina	0,14	0,16	0,05	0,05	0,05
Animal feed mixture	0,08	0,06	0,19	0,19	0,19
Animal feed pellets	0,05	0,05	0,14	0,14	0,14
Barley	0,08	0,10	0,11	0,11	0,11
Cement	0,14	0,16	0,05	0,05	0,05
Cement clinker	0,21	0,14	0,05	0,05	0,05
Coal	0,11	0,11	0,09	0,09	0,09
Coal, powdered	0,14	0,18	0,05	0,05	0,05
Coke	0,11	0,11	0,09	0,09	0,09
Flyash	0,14	0,12	0,05	0,05	0,05
Flour	0,08	0,05	0,11	0,11	0,11
Iron ore pellets	0,11	0,11	0,09	0,09	0,09
Lime, hydrated	0,14	0,18	0,05	0,05	0,05
Limestone powder	0,14	0,16	0,05	0,05	0,05
Maize	0,10	0,10	0,17	0,17	0,17
Phosphate	0,11	0,13	0,09	0,09	0,09
Potatoes	0,08	0,09	0,11	0,11	0,11
Sand	0,08	0,07	0,11	0,11	0,11
Slag clinkers	0,08	0,07	0,11	0,11	0,11
Soya beans	0,08	0,12	0,11	0,11	0,11
Sugar	0,14	0,14	0,05	0,05	0,05
Sugarbeet pellets	0,11	0,11	0,09	0,09	0,09
Wheat	0,08	0,09	0,11	0,11	0,11

Annex D (Normative)

Evaluation of properties of solids for silo load evaluation

D.1 Object

This annex describes methods for the evaluation of parameters needed in EN 1991-4 for the purposes of silo load evaluation that cannot be measured directly.

D.2 Evaluation of the wall friction coefficient for a corrugated wall

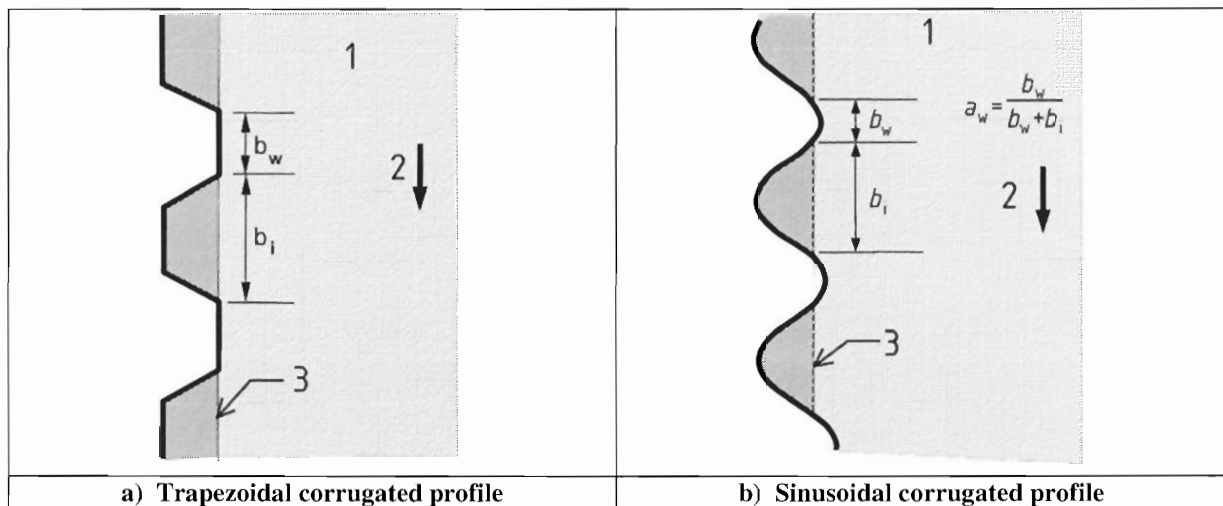
(1) For Wall Surface Category D4 (corrugated or profile steel sheeting or walls with horizontal ribs) (see Figure D.1), the effective wall friction should be determined as:

$$\mu_{\text{eff}} = (1 - a_w) \tan \phi_1 + a_w \mu_w \quad \dots \text{(D.1)}$$

where:

- μ_{eff} is the effective wall friction coefficient;
- ϕ_1 is the angle of internal friction;
- μ_w is the wall friction coefficient (against a flat wall surface);
- a_w is the wall contact factor.

NOTE: For Wall Surface Category D4, the effective wall friction depends on the stored solid's internal friction, the friction coefficient against a flat wall, and the profile of the sheeting.



Key

- 1 Filled solids
- 2 Solid flow
- 3 Rupture surface

Figure D.1: Dimensions of profile steel sheeting

(2) The parameter a_w in Expression (D.1), which represents the extent of solids movement against the wall surface, should be determined from the geometry of the wall sheeting profile (see Figure D.1a):

$$a_w = \frac{b_w}{b_w + b_i} \quad \dots \text{(D.2)}$$

NOTE: The interface between the moving and stationary zones is partly in contact with the wall and partly an internal rupture surface within the solid. The proportion of interface that involves the solid moving against the wall is given by a_w .

- (3) Where necessary, an appropriate estimate should be made of the solid/wall contact regime (see Figure D.1b).

NOTE: For wall sheeting profiles similar to that shown in Figure D.1b, the value of a_w may be taken as 0,20.

D.3 Internal and wall friction for coarse-grained solids without fines

- (1) The wall friction coefficient μ and the angle of internal friction ϕ_1 cannot be easily determined for solids which consist of large particles without a fines content (e.g. lupins, peas, potatoes), so the angle of internal friction ϕ_1 should be taken as equal to the angle of repose ϕ_r of a loose poured heap of solid with an approximately planar surface.

Annex E (Normative)

Values of the properties of particulate solids

E.1 General

(1) This annex provides values of stored solid properties for design.

E.2 Defined values

(1) The values that should be used in design are given in Table E.1.

Table E.1: Particulate solids properties

Type of particulate solid ^{d, e}	Unit weight ^b		Angle of repose ϕ_r	Angle of internal friction ϕ_i			Lateral pressure ratio K		Wall friction coefficient ^c μ ($\mu = \tan \phi_w$)				Patch load solid reference factor C_{op}
	γ_l	γ_u		ϕ_{im}	a_ϕ	K_m	a_K	Wall type D1	Wall type D2	Wall type D3	a_μ		
												Lower kN/m ³	
Default material ^a	6,0	22,0	40	35	1,3	0,50	1,5	0,32	0,39	0,50	1,40	1,0	
Aggregate	17,0	18,0	36	31	1,16	0,52	1,15	0,39	0,49	0,59	1,12	0,4	
Alumina	10,0	12,0	36	30	1,22	0,54	1,20	0,41	0,46	0,51	1,07	0,5	
Animal feed mix	5,0	6,0	39	36	1,08	0,45	1,10	0,22	0,30	0,43	1,28	1,0	
Animal feed pellets	6,5	8,0	37	35	1,06	0,47	1,07	0,23	0,28	0,37	1,20	0,7	
Barley ☼	7,0	8,0	31	28	1,14	0,59	1,11	0,24	0,33	0,48	1,16	0,5	
Cement	13,0	16,0	36	30	1,22	0,54	1,20	0,41	0,46	0,51	1,07	0,5	
Cement clinker †	15,0	18,0	47	40	1,20	0,38	1,31	0,46	0,56	0,62	1,07	0,7	
Coal ☼	7,0	10,0	36	31	1,16	0,52	1,15	0,44	0,49	0,59	1,12	0,6	
Coal, powdered ☼	6,0	8,0	34	27	1,26	0,58	1,20	0,41	0,51	0,56	1,07	0,5	
Coke	6,5	8,0	36	31	1,16	0,52	1,15	0,49	0,54	0,59	1,12	0,6	
Flyash	8,0	15,0	41	35	1,16	0,46	1,20	0,51	0,62	0,72	1,07	0,5	
Flour ☼	6,5	7,0	45	42	1,06	0,36	1,11	0,24	0,33	0,48	1,16	0,6	
Iron ore pellets	19,0	22,0	36	31	1,16	0,52	1,15	0,49	0,54	0,59	1,12	0,5	
Lime, hydrated	6,0	8,0	34	27	1,26	0,58	1,20	0,36	0,41	0,51	1,07	0,6	
Limestone powder	11,0	13,0	36	30	1,22	0,54	1,20	0,41	0,51	0,56	1,07	0,5	
Maize ☼	7,0	8,0	35	31	1,14	0,53	1,14	0,22	0,36	0,53	1,24	0,9	
Phosphate	16,0	22,0	34	29	1,18	0,56	1,15	0,39	0,49	0,54	1,12	0,5	
Potatoes	6,0	8,0	34	30	1,12	0,54	1,11	0,33	0,38	0,48	1,16	0,5	
Sand	14,0	16,0	39	36	1,09	0,45	1,11	0,38	0,48	0,57	1,16	0,4	
Slag clinkers	10,5	12,0	39	36	1,09	0,45	1,11	0,48	0,57	0,67	1,16	0,6	
Soya beans	7,0	8,0	29	25	1,16	0,63	1,11	0,24	0,38	0,48	1,16	0,5	
Sugar ☼	8,0	9,5	38	32	1,19	0,50	1,20	0,46	0,51	0,56	1,07	0,4	
Sugarbeet pellets	6,5	7,0	36	31	1,16	0,52	1,15	0,35	0,44	0,54	1,12	0,5	
Wheat ☼	7,5	9,0	34	30	1,12	0,54	1,11	0,24	0,38	0,57	1,16	0,5	

NOTE Where this table does not contain the material to be stored, testing should be undertaken.

^a For situations where it is difficult to justify the cost of testing, because the cost implications of using a wide property range for the design are minor, the properties of the "default material" may be used. For small installations, these properties may be adequate. However, they will lead to very uneconomic designs for large silos, and testing should always be preferred.

^b The unit weight of the solid γ_u is the upper characteristic value, to be used for all calculations of actions. The lower characteristic value γ_l is provided in Table E.1 to assist in estimating the required volume of a silo that will have a defined capacity.

^c Effective wall friction for wall Type D4 (corrugated wall) may be found using the method defined in Annex D, D.2.

^d Solids in this table that are known to be susceptible to dust explosion are identified by the symbol ☼

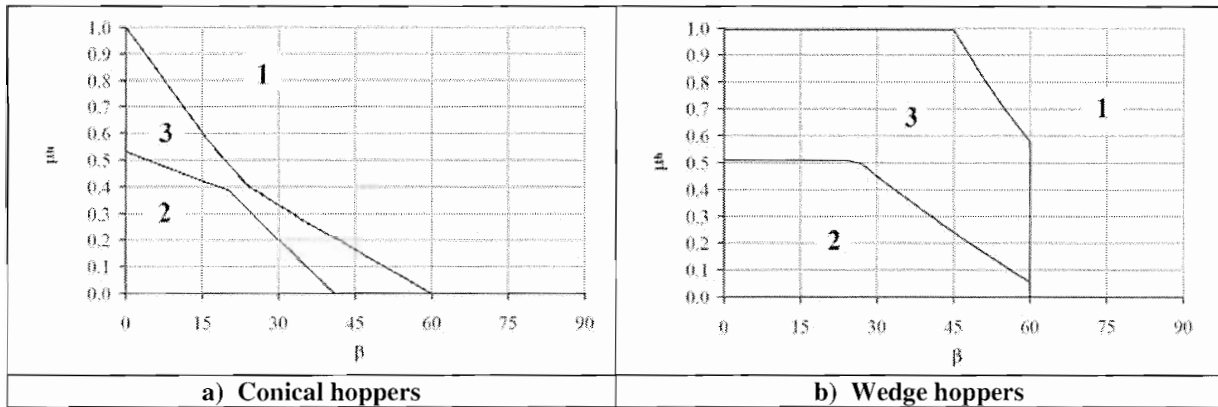
^e Solids that are susceptible to mechanical interlocking are identified by the symbol †

Annex F (Informative)

Flow pattern determination

F.1 Mass and funnel flow

(1) Determination of the flow pattern for the functional design of the silo is outside the scope of this standard. However, the information in Figure F.1 is given to alert the designer to the possibility that mass flow pressures may occur in the silo. This information is also needed when the alternative hopper design method of Annex G is used.



Key

- 1 Funnel flow
- 2 Mass flow
- 3 Mass flow or funnel flow may occur between these limits
- β Hopper apex half angle (degrees)
- μ_h Hopper wall friction coefficient

NOTE: In the zone between the limits of mass flow and funnel flow, the mode of flow depends on parameters not included in this standard.

Figure F.1: The conditions under which mass flow or funnel flow occur in conical and wedge-shaped hoppers

Annex G

(Normative)

Alternative rules for pressures in hoppers

G.1 General

- (1) This annex gives two alternative methods of assessing the pressures in hoppers.
- (2) The method defined in G.3 to G.9 may be used to define hopper pressures under both filling and discharge conditions. However, it should be noted that the integrated pressures do not correspond to the weight of the stored solid, so these expressions should be treated with caution.
- (3) The expressions given in G.10 may alternatively be used in conjunction with those of 6.3 to define the discharge pressures in steep hoppers.

G.2 Notation

- l_h inclined distance from hopper apex to the transition (see Figure G.1)
- p_n pressure normal to inclined hopper wall
- p_{ni} components of pressure normal to inclined hopper ($i = 1, 2$ and 3)
- p_s kick pressure at transition

G.3 Definitions

G.3.1

kick load

a local load that can occur at the transition during discharge from a mass flow silo

G.4 Design situations

- (1) The hopper should be designed for filling and discharge conditions.
- (2) The expected flow mode for the hopper should be determined using Figure F.1.
- (3) Where a silo may flow in either mass flow or funnel flow, the design should account for both possible flow modes.

G.5 Evaluation of the bottom load multiplier C_b

- (1) For silos other than those identified in (2) below, the bottom load magnifier should be determined as:

$$C_b = 1,3 \quad \dots \text{ (G.1)}$$

- (2) Where there is a significant probability that the stored solid can develop dynamic loading conditions (see (3)), higher loads are applied to the hopper or silo bottom, the bottom load magnifier should be taken as:

$$C_b = 1,6 \quad \dots \text{ (G.2)}$$

- (3) Situations under which the conditions of (2) may be deemed to occur include:
 - where a silo with a slender vertical walled section is used to store solids that cannot be classed as of low cohesion (see 1.5.23);
 - where the stored solid is identified as susceptible to mechanical interlocking (e.g. cement clinker).

NOTE: The evaluation of the cohesion c of a solid is given in C.9. The cohesion is classed as low if, following consolidation to a normal stress level σ_p , the assessed cohesion c does not exceed $c/\sigma_p = 0,04$ (see 1.5.23).

G.6 Filling pressures on flat and nearly-flat bottoms

(1) Vertical loads acting on flat or nearly-flat silo bottoms (inclinations $\alpha \leq 20^\circ$) should be calculated using:

$$p_{vfb} = C_b p_{vf} \quad \dots \text{(G.3)}$$

where:

p_{vf} is calculated using Expression (5.3) or (5.79) at the relevant depth z below the equivalent surface;

C_b is the bottom load magnifier.

G.7 Filling pressures in hoppers

(1) When the inclination of the hopper wall to the horizontal is greater than 20° (see Figure 1.1b) the pressure normal to the inclined hopper wall p_n at any level should be calculated as follows:

$$p_n = p_{n3} + p_{n2} + (p_{n1} - p_{n2}) \frac{x}{l_h} \quad \dots \text{(G.4)}$$

in which:

$$p_{n1} = p_{vft} (C_b \sin^2 \beta + \cos^2 \beta) \quad \dots \text{(G.5)}$$

$$p_{n2} = p_{vft} C_b \sin^2 \beta \quad \dots \text{(G.6)}$$

$$p_{n3} = 3,0 \frac{A}{U} \frac{\gamma K}{\sqrt{\mu_h}} \cos^2 \beta \quad \dots \text{(G.7)}$$

where:

β is the slope of the hopper to the vertical (see Figure G.1);

x is a length between 0 and l_h (see Figure G.1);

p_{n1} and p_{n2} define the hopper pressures due to the stored material vertical pressure at the transition;

p_{n3} is the hopper pressure due to solid within the hopper;

C_b is the bottom load magnifier;

p_{vft} is the vertical pressure p_{vf} acting at the transition level after filling, calculated using Expression (5.3) or (5.79) as appropriate;

μ_h is the characteristic value of wall friction coefficient in the hopper (lower characteristic value);

K is the characteristic value of the lateral pressure ratio in the vertical walled segment;

A plan cross-sectional area of vertical walled segment;

U internal perimeter of the plan cross-section of the vertical walled segment.

(2) The value of the wall frictional pressure p_t , is given by:

$$p_t = p_n \mu_h \quad \dots (G.8)$$

where:

p_n is calculated from Expression (G.4).

(3) When evaluating the pressures according to Expressions G.5, G.6 and G.7, the same characteristic value of K should be used. Both the upper and lower characteristic values should be considered.

NOTE: Because the lower characteristic value of K produces the highest value of p_{vft} , but the upper characteristic value of K produces the highest value of p_{n3} , it is not possible to make general statements about which characteristic value will induce the worst loading case for the hopper. Both characteristic values should be examined.

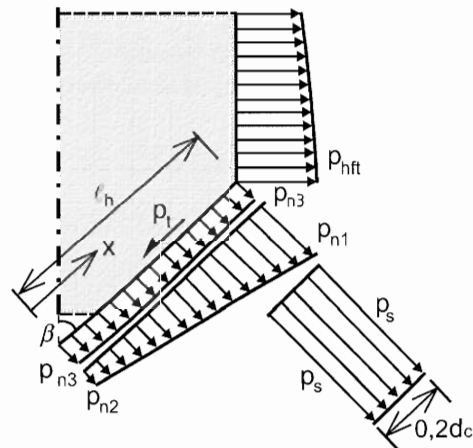


Figure G.1: Alternative rule for hopper loads

G.8 Discharge pressures on flat or nearly-flat bottoms

(1) For flat or nearly-flat silo bottoms (inclinations $\alpha \leq 20^\circ$), the discharge load may be calculated using the guidance for filling loads (see G.6).

G.9 Discharge pressures on hoppers

(1) For funnel flow silos, the discharge loads on hoppers may be calculated using the guidance for filling loads (see G.7).

(2) For mass flow silos, an additional fixed normal pressure, the kick load p_s (see Figure G.1) is applied, over an inclined distance of $0,2d_c$ down the hopper wall and all around the perimeter:

$$p_s = 2 K p_{vft} \quad (G.9)$$

where:

p_{vft} is the vertical pressure acting at the transition after filling calculated using Expression (5.3) or (5.79) as appropriate.

G.10 Alternative expression for the discharge hopper pressure ratio F_e

(1) Under discharge conditions, the mean vertical stress in the stored solid at any level in a steep hopper may be determined using Expressions (6.7) and (6.8), with the alternative value of the parameter F given by:

$$F_e = \left(\frac{1}{1 + \mu \cot \beta} \right) \left\{ 1 + 2 \left[1 + \left(\frac{\sin \phi_1}{1 + \sin \phi_1} \right) \left(\frac{\cos \varepsilon \sin(\varepsilon - \beta)}{\sin \beta} \right) \right] \right\} \quad \dots \text{ (G.10)}$$

in which:

$$\varepsilon = \beta + \frac{1}{2} \left(\phi_{wh} + \sin^{-1} \left\{ \frac{\sin \phi_{wh}}{\sin \phi_1} \right\} \right) \quad \dots \text{ (G.11)}$$

$$\phi_{wh} = \tan^{-1} \mu_h \quad \dots \text{ (G.12)}$$

where:

μ_h is the lower characteristic value of wall friction coefficient in the hopper;

ϕ_1 is the angle of internal friction of the stored solid.

NOTE: Where this theory of hopper pressures is adopted, Expression (G.10) should be used in place of Expression (6.21). This expression for F_e is based on the more complete theory of Enstad for discharge pressures.

Annex H (Informative)

Actions due to dust explosions

H.1 General

(1) This annex gives advice on appropriate design for actions due to dust explosion.

H.2 Scope

(1) This annex is valid for all silos and similar vessels, where combustible or/and explosive non-toxic dusts are stored, produced, handled or discharged in significant quantities.

(2) Where the possibility of dust explosions can be excluded with certainty as a result of special precautions taken in the design of the plant, the provisions of this annex need not be considered.

(3) Where the possibility of dust explosions in existing plants is being assessed, this annex may also be used. In such cases, the actual conditions, rather than the design conditions, should be considered. Where doubt exists, experts should be consulted.

H.3 Notation

p_{\max} maximum overpressure

p_{red} reduced maximum explosion pressure.

p_a initial release pressure.

H.4 Explosive dusts and relevant properties

(1) Many different types of stored solids produce dust that can be explosive. Dust explosions are possible in both organic and inorganic dusts, when the particles are fine enough, distributed homogeneously in the air, and can react with oxygen to produce a continuous exothermic reaction.

(2) During an explosion in the types of solids normally stored in silos, pressures of about 8 to 10 bar can be attained in a closed space without venting.

(3) The key design parameters for dust explosions are:

- the dust value K_{ST} ;
- the maximum overpressure p_{\max} .

(4) The dust value may be determined from the rate of pressure rise (dp/dt).

(5) The design should follow the procedures defined in EN 26184-1.

(6) The most important types of explosive dusts are: cellulose, fertilizer, pea flour, animal feed, rubber, grain, wood, wood dust, coal lignite, synthetic materials, ground corn, maize starch, malt, rye flour, wheat flour, milk powder, paper, pigment, soya flour, cleaning products, sugar.

H.5 Ignition sources

(1) Normally, a small energy source is sufficient to ignite an explosion in the above types of dust. Typical ignition sources in silos or neighbouring rooms and installations include:

- hot surfaces, generated through friction caused by a defect in machinery;
- sparks from welding, grinding and cutting during repair work;
- glowing cinders, carried into the silo with the bulk material;

- sparks from foreign bodies;
- unsuitable or defective electrical products (for example light fixtures);
- heat development during drying processes; and
- self ignition by electrical static discharge.

H.6 Protecting precautions

(1) The damage due to an explosion is minimized by containing the explosion within the space where it originates. It should be prevented from spreading to other parts of the installation. The overpressure of the explosion should also be minimized.

(2) The consequences of the explosion can be limited by taking appropriate preventive measures during the planning stages of the project (e.g. incorporating explosion barriers in a manner similar to fire walls).

The individual plant sections between barriers should, in principle, be designed for one of the following two conditions:

- where no venting is used, capable of resisting the maximum explosion pressure p_{\max} , or
- where appropriate venting is used, capable of resisting a reduced design pressure p_{red} .

(4) The value of the reduced design pressure p_{red} depends on the type of dust, the dimensions of the space to be vented, the venting area, the initial release pressure p_a and the inertia of the venting system.

(5) Design for the consequences of an explosion should consider the effects of the flash of fire leaving a venting outlet. This fire should neither cause any impairment of the surroundings nor initiate an explosion in an adjacent section.

(6) The design should consider limitation of the danger to persons from fragments of glass or other structural elements. Where possible, vent openings should lead directly into open spaces through planned venting outlets that reduce the explosion pressure. In single silos, this may be achieved by use of a vented roof. In the case of nested silos, stairwells or windows high above ground level may be used.

(7) The venting system should be initiated at a low pressure and should have a low inertia.

(8) The possibility should be considered that a rapid initiation of the venting system under a low pressure may cause a larger amount of dust-air mixture to be released. Under such circumstances, consideration should be given to use of a system with greater inertia.

H.7 Design of structural elements

(1) The design pressure of the explosion should be treated as an accidental load on all structural elements.

H.8 Design pressure

(1) All load bearing structural elements and all elements used for the purpose of explosion barriers should be designed to withstand the dust explosion design pressure.

H.9 Design for underpressure

(1) The inertia forces arising from a rapid discharge of gas, followed by cooling of the hot fumes should be considered in the design. These effects are associated with the explosion and can result in an underpressure that should be considered in the design.

H.10 Design of venting devices

(1) All relevant parts of venting devices should be secured against detachment as a consequence of the explosion pressure waves (e.g. explosion relief doors should be fixed at joints; caps should be fastened by ropes or similar fixings).

NOTE: The design may follow the procedures described in DIN Report 140 "Design of silos for dust explosion" published in January 2005 by Beuth-Verlag.

H.11 Reaction forces by venting

(1) When venting is used, the reaction forces must be considered in the design of support systems. These are especially important in lightweight structures with horizontal venting areas and in any venting arrangement that is unsymmetrical in the silo cross section.

NOTE: The design may follow the procedures described in DIN Report 140 "Design of silos for dust explosion" published in January 2005 by Beuth-Verlag.