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**English version**

# Eurocode 1 - Actions on structures

## Part 4 : Silos and tanks

**Final PT draft (Stage 34)**
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CEN

**European Committee for Standardization**
**Comité Européen de Normalisation**
**Europaisches Komitee für Normung**

**Central Secretariat: rue de Stassart 36, B-1050 Brussels**

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**CONTENTS** **Page**

## Foreword

This European Standard EN 1991-4, General Actions - Actions on silos and tanks, has been prepared on behalf of Technical Committee CEN/TC250/SC1 "Eurocode 1", the Secretariat of which is held by SIS/BST. CEN/TC250/SC1 is responsible for Eurocode 1.

The text of the draft standard was submitted to the formal vote and was approved by CEN as EN 1991-4 on **YYYY-MM-DD**.
No existing European Standard is superseded.

### 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 harmonisation of technical specifications.

Within this action programme, the Commission took the initiative to establish a set of harmonised 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 1980's.

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 |

Eurocode standards recognise 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.

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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).

## Status and field of application of Eurocodes

The Member States of the EU and EFTA recognise 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 harmonised 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 harmonised 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,

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2) According to Art. 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 harmonised ENs and ETAGs/ETAs.

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

give concrete form to the essential requirements by harmonising the terminology and the technical bases and indicating classes or levels for each requirement where necessary ;

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. ;

serve as a reference for the establishment of harmonised 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 harmonised technical specifications (ENs and ETAs) for products

There is a need for consistency between the harmonised technical specifications for construction products and the technical rules for works[4]. 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

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## 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 EN1991-4 through clauses:

2.5 (2)

3.6 (3)

5.4.1 (2)

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[4] see Art.3.3 and Art.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 and shall be used in conjunction with EN 1990: Basis of Design and with 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 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: Basis of Design, 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 limitations apply to the design rules for silos:

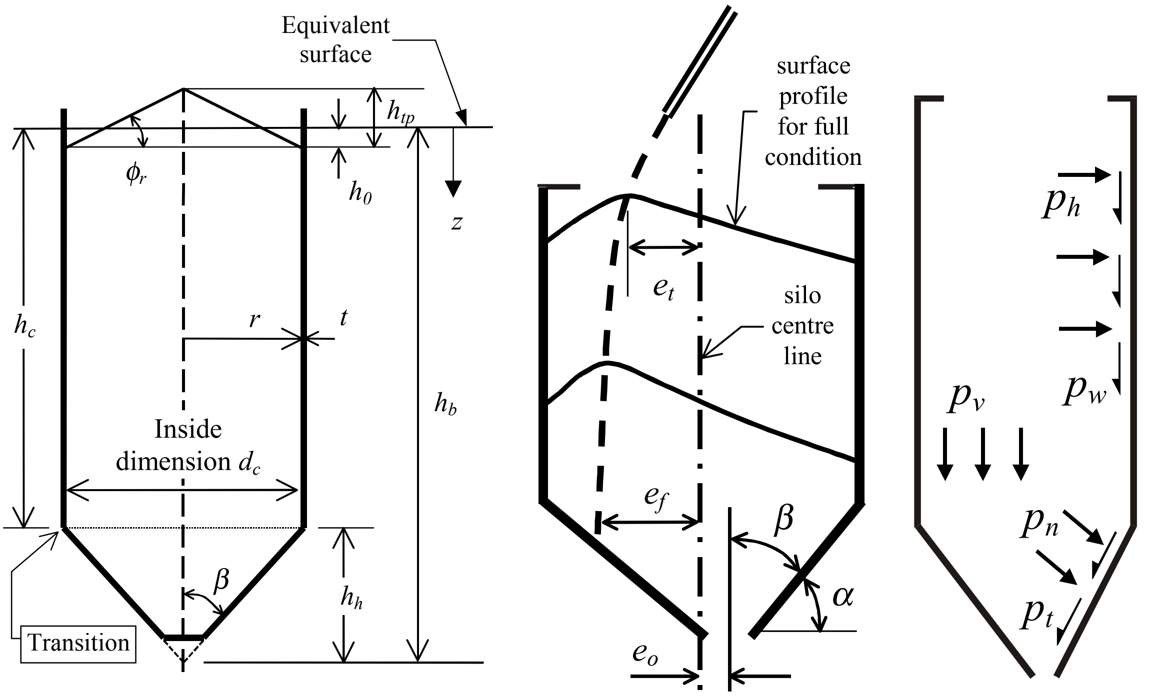
- The silo cross-section shapes are limited to those shown in Figure 1.1d, though minor variations may be accepted provided the structural consequences of the resulting changes in pressure are considered;
- The following geometrical limitations apply:

  $h_b/d_c < 10$
  $h_b < 100$ m
  $d_c < 60$ m

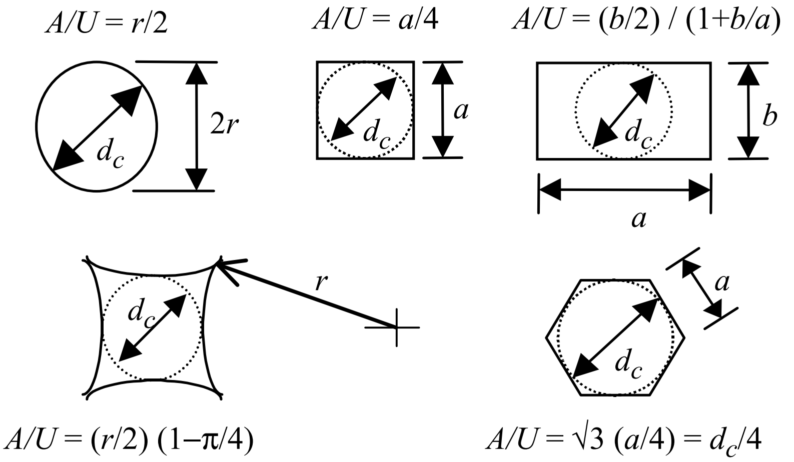
- The transition lies in a single horizontal plane (Figure 1.1a);
- The silo does not contain an internal structure such as a cone or pyramid with its apex uppermost, cross-beams, etc;
- Each silo is designed for a defined range of particulate solids properties;
- The stored solid is free-flowing, or the stored solid can be guaranteed to flow freely within the silo container as designed (see 1.5.12 and Annex C);
- Where discharge devices are used (for example feeders or internal flow tubes) solids flow is smooth and central;
- The maximum particle diameter of the stored solid is not greater than $0{,}03d_c$ (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.

- Filling involves only negligible inertia effects and impact loads.



**a) Geometry** **b) Eccentricities** **c) Pressures and tractions**



**d) Cross-section shapes**

**Figure 1.1: Silo forms showing dimensions and pressure notation**

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

(5) Silo that are subject to pressures that are systematically non-uniform around the silo circumference are not specifically covered by this standard. These cases include a chisel hopper (i.e. a wedge hopper beneath a circular cylinder) and a circular silo with a flat bottom whose outlet extends over the full silo diameter.

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

(7) Actions on the roofs of silos and tanks should be found using EN 1991-1-1, EN 1991-1-3 to EN 1991-1-7 and EN 1991-5 as appropriate.

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

(9) 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 cannot 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 and publications, listed hereafter.

| | |
|---|---|
| EN 1990 | Basis of structural design |
| EN 1991-1-1 | Eurocode 1: Actions on structures<br>Part 1.1: Densities, self-weight and imposed loads |
| EN 1991-1-2 | Eurocode 1: Actions on structures<br>Part 1.2: Actions on structures exposed to fire |
| EN 1991-1-3 | Eurocode 1: Actions on structures<br>Part 1.3: Snow loads |
| EN 1991-1-4 | Eurocode 1: Actions on structures<br>Part 1.4 Wind loads |
| EN 1991-1-5 | Eurocode 1: Actions on structures<br>Part 1.5: Thermal actions |
| EN 1991-1-6 | Eurocode 1: Actions on structures<br>Part 1.6: General actions. Actions during execution |
| EN 1991-1-7 | Eurocode 1: Actions on structures<br>Part 1.7: Accidental actions from impact and explosions |
| EN 1991-2 | Eurocode 1: Actions on structures<br>Part 2: Traffic loads on bridges |
| EN 1991-3 | Eurocode 1: Actions on structures<br>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<br>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 1993-1-7 | Eurocode 3: Design of steel structures: General rules: Part 1.7: Supplementary rules for the strength and stability of transversely loaded planar plated 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: Earthquake resistant design of structures |
| EN 1999 | Eurocode 9: Design of aluminium alloy structures |

## 1.3 Assumptions

(1)P The assumptions listed in EN 1990 may be applied in design to this Part 4 of EN 1991.

## 1.4 Distinction between principles and application rules

(1) Depending on the character of the individual clauses, 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 recognised 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 clause.

## 1.5 Definitions

For the purposes of this standard, a basic list of definitions is provided in EN 1990, ‘Basis of design’ 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 (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 (Figure 1.1d).

**1.5.3**
**circular silo:**
A silo whose plan cross-section is circular (Figure 1.1d).

**1.5.4**
**conical hopper:**
A hopper in which the sloping sides converge towards a single point intended to produce axisymmetric flow in the stored solid.

**1.5.5**
**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 (Figures 3.2c and d, 3.3b and c), but can be caused by other unsymmetrical phenomena (Figure 3.4d).

**1.5.6**
**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 (Figure 1.1b).

**1.5.7**
**equivalent surface:**
Level surface giving the same volume of stored solid as the actual surface (Figure 1.1a).

**1.5.8**
**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 (Figure 3.5d). This expedient arrangement reduces the hopper height whilst assuring reliable discharge.

**1.5.9**
**flat bottom:**
The internal base of a silo, when it has an inclination to the horizontal less than 5°.

**1.5.10**
**flow pattern:**
The form of flowing solid in the silo when flow is well established (Figures 3.1-3.4). The silo is close to the full condition.

**1.5.11**
**fluidised 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 fluidised when only part of the weight of particles is supported by the interstitial air pressure gradient.

**1.5.12**
**free flowing granular solid:**
A granular solid whose flowing behaviour is not significantly affected by cohesion.

**1.5.13**
**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.

**1.5.14**
**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 (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).

**1.5.15**
**granular solid:**
A particulate solid with particles are so large that interstitial air plays a small role in determining the pressures and flow of large masses of the solid.

**1.5.16**
**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.

**1.5.17**
**homogenising fluidised silo:**
A silo in which the particulate solid is fluidised to assist blending.

**1.5.18**
**hopper:**
A silo bottom with inclined walls.

**1.5.19**
**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.

**1.5.20**
**intermediate slenderness silo:**
A silo where $1{,}0 < h_c/d_c < 2{,}0$ (except as defined in 3.3).

**1.5.21**
**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 (Figures 3.1 and 3.2).

**1.5.22**
**lateral pressure ratio *K*:**
The ratio of the horizontal pressure on the vertical wall of a silo to the mean vertical stress in the solid at the same level.

**1.5.23**
**low cohesion:**
A particulate solid sample has low cohesion if the cohesion *c* is less than 4% of the preconsolidation stress $\sigma_r$. (A method for determining cohesion is given in Annex C.9).

**1.5.24**
**mass flow:**
A flow pattern in which all the stored particles are simultaneously in motion during discharge (Figure 3.1a).

**1.5.25**
**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 (Figures 3.1c and 3.3).

**1.5.26**
**non-circular silo:**
A silo whose plan cross-section is in any shape that is not circular (Figure 1.1d).

**1.5.27**
**particulate solid:**
A solid in the form of many discrete and independent particles.

**1.5.28**
**patch load:**
A local load taken to act over a specified zone on any part of the vertical wall of a silo.

**1.5.29**
**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 (Figures 3.1b and 3.2). Flow may occur against the silo wall if the outlet is eccentric (Figures 3.2c and d) or if specific factors cause the channel location to move from above the outlet (Figure 3.4d).

**1.5.30**
**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.

**1.5.31**
**powder:**
For the purposes of this standard, a solid whose mean particle size is less than 0.05mm is classed as a powder.

**1.5.32**
**pressure:**
Force per unit area normal to a wall of the silo.

**1.5.33**
**retaining silo:**
A silo whose bottom is flat and where $h_c/d_c \leq 0,4$.

**1.5.34**
**shallow hopper:**
A hopper in which the full value of wall friction is not mobilised after filling the silo.

**1.5.35**
**silo:**
Containment structure used to store particulate solids (i.e. bunker, bin or silo).

**1.5.36**
**slender silo:**
A silo where $h_c/d_c \geq 2,0$ or that meets the additional conditions defined in 3.3.

**1.5.37**
**slenderness:**
The aspect ratio $h_c/d_c$ of the silo vertical section.

**1.5.38**
**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.

**1.5.39**
**steep hopper:**
A hopper in which the full value of wall friction is mobilised after filling the silo.

**1.5.40**
**stress in the stored solid:**
Force per unit area within the stored solid.

**1.5.41**
**tank:**
Containment structure used to store liquids.

**1.5.42**
**thick-walled silo:**
A silo with a characteristic dimension to wall thickness ratio less than $d_c/t = 200$.

**1.5.43**
**thin-walled circular silo:**
A circular silo with a diameter to wall thickness ratio greater than $d_c/t = 200$.

**1.5.44**
**traction:**
Force per unit area parallel to the wall of the silo (vertical or inclined).

**1.5.45**
**transition:**
The intersection of the hopper and the vertical wall.

**1.5.46**
**vertical walled segment:**
The part of a silo or a tank with vertical walls.

**1.5.47**
**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 'Basis of design', 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) |
| $U$ | 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 (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 |
| $a_\gamma$ | modification coefficient for bulk unit weight |
| $a_\phi$ | modification coefficient for internal friction angle |
| $a_\mu$ | modification coefficient for wall friction coefficient |
| $b$ | width of a rectangular silo (Figure 1.1d) |
| $b$ | empirical coefficient for hopper pressures |
| $c$ | cohesion of the solid |
| $d_c$ | characteristic dimension of inside of silo cross-section (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 (Figure 5.4) |
| $e_f$ | maximum eccentricity of the surface pile during the filling process (Figure 1.1b) |
| $e_{f,cr}$ | maximum filling eccentricity for which simple rules may be used ($e_{f,cr}$=0,25$d_c$) |
| $e_i$ | effective eccentricity for filling calculations |
| $e_o$ | eccentricity of the centre of the outlet (Figure 1.1b) |
| $e_{o,cr}$ | maximum outlet eccentricity for which simple rules may be used ($e_{o,cr}$=0,25$d_c$) |
| $e_t$ | eccentricity of the centre of the top surface pile when the silo is full (Figure 1.1b) |

| | |
|---|---|
| $e_{t,cr}$ | maximum top surface eccentricity for which simple rules may be used ($e_{t,cr}$=0,25$d_c$) |
| $h_b$ | overall height of silo from the hopper apex to the equivalent surface (Figure 1.1a) |
| $h_c$ | height of vertical-walled segment of silo from the transition to the equivalent surface (Figure 1.1a) |
| $h_h$ | height of hopper from the apex to the transition (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 (Figures 1.1a, 5.5 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 (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 (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 |
| $p_{he}$ | horizontal pressure during discharge |
| $p_{he,u}$ | 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 (Figure 1.1c) |
| $p_{ne}$ | 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 |
| $p_{pf}$ | patch pressure after filling |
| $p_{pfi}$ | inverse complementary patch pressure after filling |
| $p_{p,sq}$ | patch pressure in squat silos |
| $p_{pes}$ | patch pressure at circumferential coordinate $\theta$ (thin walled circular silos) during discharge |
| $p_{pfs}$ | patch pressure at circumferential coordinate $\theta$ (thin walled circular silos) after filling |
| $p_t$ | hopper frictional traction (Figure 1.1c) |
| $p_{te}$ | hopper frictional traction during discharge |
| $p_{tf}$ | hopper frictional traction after filling |
| $p_v$ | vertical stress in stored solid (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 solid after filling at the transition (base of the vertical walled segment) |
| $p_{vho}$ | vertical pressure evaluated at the base of the top pile using expression 5.78 with $z = h_o$ |
| $p_{vsq}$ | vertical pressure acting on the flat bottom of a squat or intermediate slenderness silo |
| $p_{vtp}$ | 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) (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 ($r$=0,5$d_c$) |
| $r_c$ | radius of eccentric flow channel |
| $s$ | dimension of the zone affected by the patch load ($s = \pi d_c/16$ □ $0{,}2d_c$) |

| | |
|---|---|
| $t$ | silo wall thickness |
| $x$ | vertical coordinate in hopper with origin at cone or pyramidal apex (Figure 6.2) |
| $z$ | depth below the equivalent surface of the solid in the full condition (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 (Figures 5.6 and 5.7) |
| $z_V$ | depth measure used for vertical stress assessment in squat silos |

### 1.6.3 Greek upper case letters

| | |
|---|---|
| $\Delta T$ | temperature differential between the stored solid and the silo wall |

### 1.6.4 Greek lower case letters

| | |
|---|---|
| $\alpha$ | mean angle of inclination of hopper wall measured from the horizontal (Figure 1.1b) |
| $\alpha_w$ | thermal expansion coefficient for silo wall |
| $\beta$ | angle of inclination of hopper wall measured from the vertical (Figures 1.1a and 1.1b), or the steepest slope on a square or rectangular pyramidal hopper |
| $\gamma$ | upper characteristic value of the bulk unit weight of liquid or particulate solid |
| $\gamma_1$ | bulk unit weight of fluidised stored particulate solid |
| $\theta$ | circumferential angular coordinate |
| $\theta_c$ | eccentric flow channel wall contact angle (circumferential coordinate of the edge of the low pressure zone under eccentric discharge (Figure 5.4) |
| $\psi$ | eccentric flow channel wall contact angle measured from flow channel centre |
| $\mu$ | characteristic value of coefficient of wall friction for a vertical wall |
| $\mu_{heff}$ | effective or mobilised friction in a shallow hopper |
| $\mu_h$ | coefficient of wall friction for hopper |
| $\mu_m$ | mean value of coefficient of wall friction between a particulate solid and the wall |
| $\nu$ | Poisson's ratio for the stored solid |
| $\phi_c$ | characteristic value of unloading angle of internal friction of a particulate solid measured under increasing loads |

| | |
|---|---|
| $\phi_i$ | characteristic value ofloading angle of internal friction of a particulate solid measured under increasing loads |
| $\phi_{im}$ | mean value of the angle of internal friction |
| $\phi_r$ | angle of repose of a particulate solid (conical pile) (Figure 1.1a) |
| $\phi_{wh}$ | hopper wall friction angle (=$\tan^{-1}(\mu_h)$) between a particulate solid and the wall |
| $\sigma_r$ | 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 |
| $p$ | patch load |
| $t$ | tangential to the wall |
| $v$ | vertical |
| $w$ | wall frictional |

| | |
|---|---|
| $\gamma$ | bulk unit weight |
| $\phi$ | angle of internal friction |
| $\mu$ | wall friction coefficient |

# Section 2 Representation and classification of actions

## 2.1 Representation of actions on silos

(1)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.

> 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.

> NOTE: The structural form of the silo should be selected to give low sensitivity to load deviations.

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

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

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

(5)P Load magnifiers *C* shall be used to represent unfavourable additional loads.

(6)P For silos in Reliability Classes 2 and 3, the load magnifiers *C* shall be used to represent only unfavourable additional loads associated with solids flow during discharge.

(7)P For silos in Reliability Class 1, the load magnifiers *C* shall 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 Reliability Class 1, the load magnifier also accounts for the inherent variability of the properties of the stored solid. For silos in Reliability 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 $\gamma$, $\mu$, $K$ and $\phi_i$ and not in the load magnifiers *C*.

(8)P For silos in Reliability Class 1, the unsymmetrical load shall be represented by an increase in the symmetrical load, using a discharge load magnifying factor *C*.

(9) For silos in Reliability Class 2, the unsymmetrical patch load 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 filling of liquids shall be represented by a symmetrical hydrostatic distributed load.

## 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 Reliability management

(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 one of the following three classes of reliability used in this Part (see Table 2.1), 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)): Classes 1, 2 and 3. The boundaries of the Reliability Classes should be chosen as indicated in Table 2.1.

NOTE 1: The class boundaries may be set by the National Annex. The values in Table 2.1 are the recommended values.

**Table 2.1: Classification of design situations**

| Reliability Class | Description |
|---|---|
| Reliability Class 3 | Silos with capacity in excess of 10000 tonnes<br>Silos with capacity in excess of 1000 tonnes in which any of the following design situations occur:<br>a) eccentric discharge with $e_o/d_c > 0{,}25$ (see Figure 1.1b)<br>b) squat silos with top surface eccentricity with $e_t/d_c > 0{,}25$ |
| Reliability Class 2 | All silos covered by this Standard and not placed in another class |
| Reliability Class 1 | Silos with capacity below 100 tonnes |

NOTE 2: The above reliability 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 Reliability Classification of the structural Eurocodes EN 1992 and EN 1993.

(3) A higher Reliability Class than that required in Table 2.1 may always be adopted. Any part of the procedures for a higher Reliability Class may be adopted whenever it is appropriate.

(4) The choice of minimum Reliability Class should be agreed between the designer, the client and the relevant authority.

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

(6) Where several silos are structurally connected together, the appropriate reliability class for each silo should be determined by the conditions of the individual storage unit, not that of the entire battery of silos.

# Section 3 Design situations

## 3.1 General

(1)P Actions in 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 clauses and values specified for buildings and bridges in EN 1990 Annex A1 and A2 are applied to silos and tanks.

(2)P Selected design situations shall be considered and critical load cases identified. For each critical load case the design values of the effects of actions in combination shall be determined.

(3)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.

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

(5) 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.

(6) 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 can be used 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 $\gamma$ 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 $\mu$, $K$ and $\phi_i$, 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 $\mu$, $K$ and $\phi_i$ 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 $\mu$ | Lateral pressure ratio $K$ | Angle of internal friction $\phi_i$ |
| **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 |
| | | | |
| **For the hopper wall** | | Hopper pressure ratio $F$ | |
| Maximum hopper pressures on filling | Upper value for hopper | Lower | Lower |
| Maximum hopper pressures on discharge | Lower value for hopper | Upper | Upper |

(7) Notwithstanding the above, silos in Reliability Class 1 may be designed for the single value of the mean wall friction coefficient $\mu_m$, the mean lateral pressure ratio $K_m$ and the mean internal friction angle $\phi_{im}$ 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 (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).

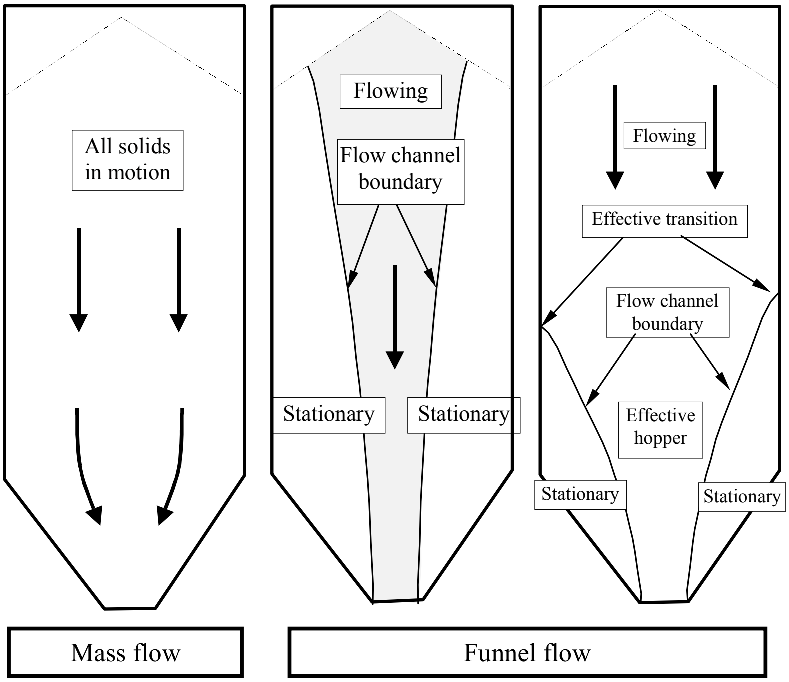
(3) The design should consider the consequences of the flow pattern during discharge, which may be described in terms of the following categories (Figure 3.1).

- mass flow
- pipe flow
- mixed flow

(4) Where pipe flow occurs and is always internal to the solid, (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 (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.

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



a) Mass flow b) Pipe flow c) Mixed flow

**Figure 3.1: Basic flow patterns**

(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 (Figure 3.2c and d and Figure 3.3b and c) (see 5.2.4).

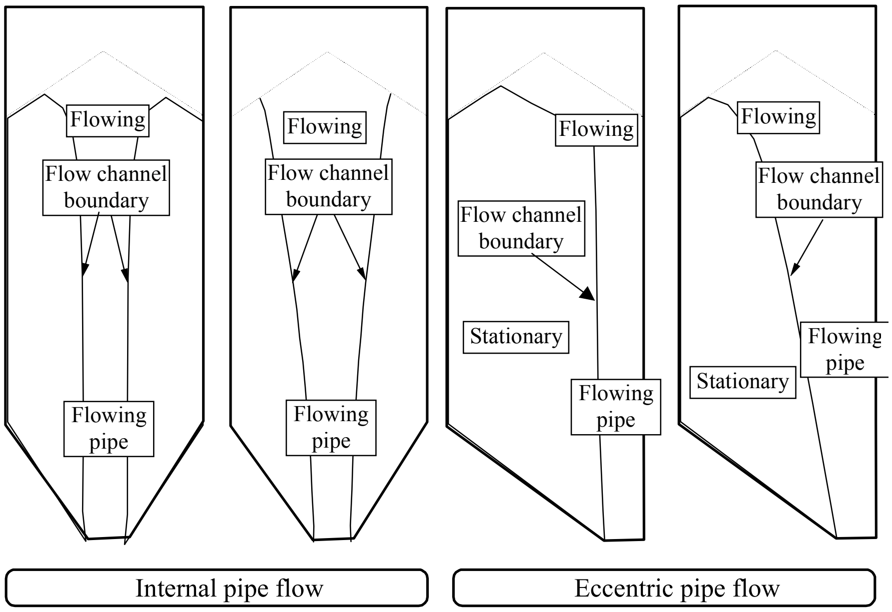
(7) Where a silo has multiple outlets, the design should consider the possibility that either any outlet alone, or any combination of outlets simultaneously, may be opened when the silo is in the full condition.

(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

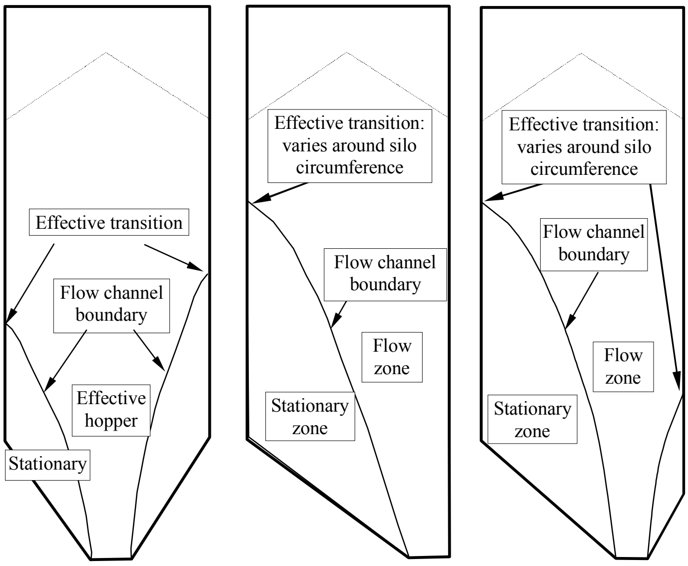
Section 6.4.3.2 of EN 1990. The term “accidental load case” refers to an Accidental Design Situation in Section 6.4.3.3 of EN 1990.

(9) Where a very slender silo is filled eccentrically, or where segregation in a very slender silo can lead to either 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 (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.



a) Parallel pipe flow b) Taper pipe flow c) Eccentric parallel pipe flow d) Eccentric taper pipe flow

**Figure 3.2: Pipe flow patterns**



a) Concentric mixed flow b) Fully eccentric mixed flow c) Partially eccentric mixed flow

**Figure 3.3: Mixed flow patterns**

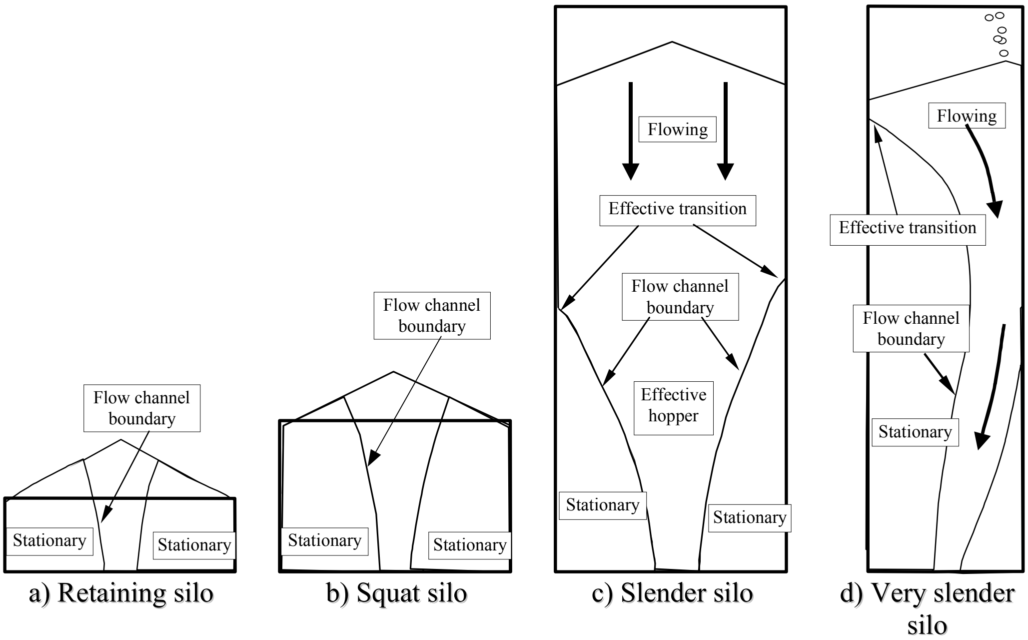


**Figure 3.4: Aspect ratio (slenderness) effects in mixed and pipe flow patterns**

(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 (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 (Figure 3.5b), the whole bottom may be fluidised, 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 (Figure 3.5b), it may be that only a limited zone of powder is fluidised, causing an eccentric pipe flow (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 fluidised zone, and not relative to the location of the outlet.

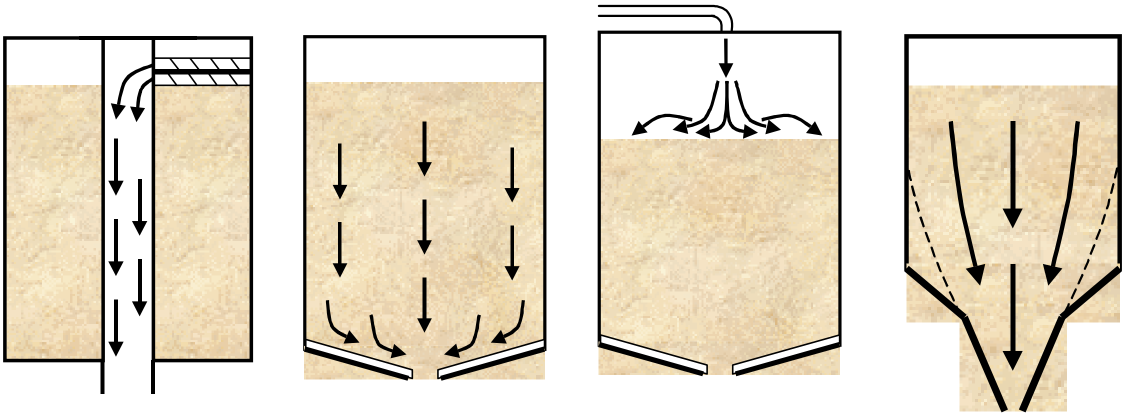
(13) The vertical walls of a silo with an expanded flow discharge hopper (Figure 3.5d) may be subject to mixed flow conditions that may cause unsymmetrical pressures during discharge. The evaluation of the slenderness of a silo of this type should be based on $h_b/d_c$ in place of $h_c/d_c$ (Figure 1.1a).

(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 discharge of the solid from the silo, its design affects the flow pattern in the silo. This can lead to either mass flow, fully eccentric mixed flow or fully eccentric pipe flow.



a) mechanical discharge with concentric pressures

b) air injection and air slides promote mass flow

c) pneumatic filling of powders causes almost flat top surface

d) expanded flow hopper gives mass flow only in bottom hopper

**Figure 3.5: Special filling and discharge arrangements**

## 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 recognises that the unsymmetrical loads may occur anywhere on the silo wall (see 5.2.1.4 (4)).

(3) 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 (Figure 3.5b), a complete sequence (rotation) of aerated sectors. The effects of fatigue shall also be considered in silos affected by vibrating machinery.

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

(5) 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 2x 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.

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

(7) 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 ☐ 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.

(8) 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.

(9) 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 when the tank is in the full condition.

## 3.6 Design considerations 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 E1 in Annex E.

(2) Rules for design for explosions may be found in EN 1991-1-7.

NOTE: Useful advice for the determination of explosion pressures is given in Annex I.

(3) The pressure exerted on structures near a silo as a result of an explosion with 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.

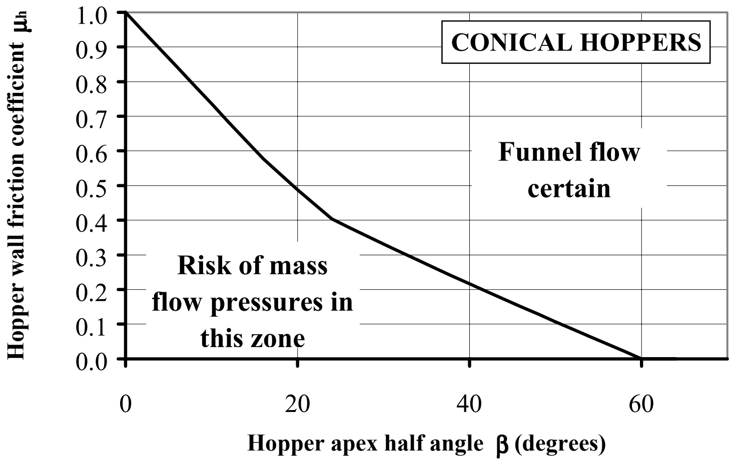
# Section 4 Properties of particulate solids

## 4.1 General

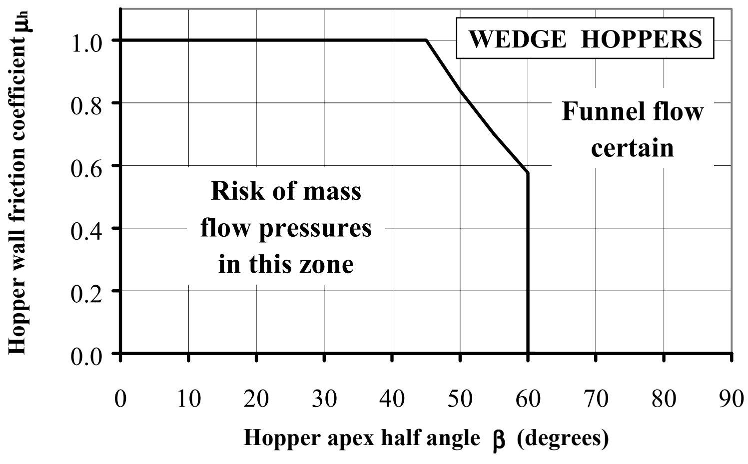
(1)P The load evaluation on a silo shall take account of:

- 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

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) Differences in solids properties indicated in (3)P can be due to the following factors:

- 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) Differences in wall frictional properties indicated in (3)P can be due to the following factors:

- 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 recognised 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)P The characteristic value of a material parameter shall be selected as a cautious estimate of the value affecting the occurrence of the load.

(9) Reference may be made to EN1990, for provisions concerning the interpretation of test results.

NOTE: Refer also to Annex D of EN 1990.

**Table 4.1 – Wall surface definitions**

| **Category** | **Descriptive title** | **Typical wall materials** |
|---|---|---|
| D1 | Low friction<br>or<br>Slippery | Cold-rolled stainless steel<br>Polished stainless steel<br>Coated surface designed for low friction<br>Polished aluminium<br>Ultra high molecular weight polyethylene ‡ |
| D2 | Moderate friction<br>or<br>Smooth | Smooth mild carbon steel (welded or bolted construction)<br>Mill finish stainless steel<br>Galvanised carbon steel<br>Oxidised aluminium<br>Coated surface designed for corrosion resistance or abrasive wear |
| D3 | High friction<br>or<br>Raspy | Off form, steel finished or aged concrete<br>Aged (corroded) carbon steel<br>Abrasion resistant steel<br>Ceramic tiles |
| D4 | Irregular | Horizontally corrugated walls<br>Profiled sheeting with horizontal ribs<br>Non-standard walls with large aberrations |

‡ The roughening effect of particles being impressed into the surface should be considered carefully for these surfaces.

NOTE: The descriptive titles in Table 4.1 are given in terms of friction rather than roughness because there is a poor correlation between measures of roughness and measured wall friction between a sliding granular solid and the surface.

### 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 Reliability 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 E1 in Annex E.

(5) The value adopted in design of the wall friction coefficient $\mu$ for a given particulate solid should take account of the frictional character of the surface on which it slides. The classes of frictional surfaces used in this standard are defined 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 Annex D.2.

(7) The patch load solid reference factor $C_{op}$ should be obtained from Table E1 in Annex E 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 E1 in Annex E. The values shown correspond to the upper characteristic value for the unit weight $\gamma$, but the values of $\mu_m$, $K_m$ and $\phi_{im}$ are mean values.

(2) Where the solid to be stored cannot be clearly identified as similar to one of the descriptors in Table E1 in Annex E, testing according to 4.3 should be undertaken.

(3) To determine the characteristic values of $\mu$, $K$ and $\phi_i$, the tabulated values of $\mu_m$, $K_m$ and $\phi_{im}$ should be multiplied and divided by the conversion factors $a$ given in Table E1 in Annex E. Thus in calculating maximum loads the following combinations should be used:

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

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

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

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

$$\text{Upper characteristic value of } \phi_i = a_\phi \phi_{im} \qquad \ldots (4.5)$$

$$\text{Lower characteristic value of } \phi_i = \phi_{im} / a_\phi \qquad \ldots (4.6)$$

(4) For silos in Reliability Class 1, the mean values of $\mu_m$, $K_m$ and $\phi_{im}$ 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 4.1-4.6 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 Annex 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 $\gamma$

(1) The bulk unit weight $\gamma$ 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 5.78, as appropriate, for the depth at the bottom of the vertical section.

(2) The test method for the measurement of bulk unit weight $\gamma$ described in Annex C.6 may be used.

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

### 4.3.3 Coefficient of wall friction $\mu$

(1) Tests to determine the wall friction coefficient $\mu$ 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 5.70 as appropriate.

(2) The test method for the measurement of $\mu$ described in Annex C.7 should be used.

(3) The mean value $\mu_m$ 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 Annex C.11.

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

### 4.3.4 Angle of internal friction $\phi_I$

(1) The loading angle of internal friction $\phi_I$ (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 5.78 as appropriate.

(2) The test method for the measurement of $\phi_I$ described in Annex C.9 should be used.

(3) The mean value $\phi_{Im}$ of the loading angle of internal friction 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 Annex C.11.

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

### 4.3.5 Lateral pressure ratio *K*

(1) The lateral pressure ratio $K$ (ratio of 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 5.78 as appropriate.

(2) The test method for the measurement of $K$ described in Annex 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 Annex 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 $\phi_{im}$ (4.3.4) as:

$$K_\mathrm{m} = 1{,}1\,(1 - \sin\phi_{im}) \qquad \ldots (4.7)$$

NOTE: the factor 1,1 in expression 4.7 is used to give an approximate representation of the difference between the value of $K$ ($=K_o$) 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 of Annex 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 (Annex 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 5.78 as appropriate.

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

NOTE: Alternatively the cohesion $c$ may be estimated from the flow function *ff* for a solid, measured using a Jenike shear cell. A method for determining the cohesion from the flow function is given in Annex C.9.

### 4.3.7 Patch load solid reference factor $C_{op}$

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 for the parameter $C_{op}$ has not yet been developed. This factor is based on experiments and experience. It applies to silos with conventional filling and discharge systems and built to standard engineering tolerances.

(1) The value of the patch load solid reference factor $C_{op}$ for well-known solids should be taken from Table E1 in Annex E.

(2) For solids not listed in Table E1 in Annex E, 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 $a_\mu$ as:

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

where:

$a_\mu$ is the variability factor for the wall friction coefficient.

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

(3) 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;
- silo hoppers and bottoms.

(2)P The loads on silo vertical walls shall be evaluated according to the slenderness of the silo, 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 $h_c/d_c \leq 0{,}4$;
- silos containing solids with entrained air.

(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)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.

(6) 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. Rules for additional load cases that should be considered for silos in which air entrained into the solid may make it fully or partially fluidised in the silo are given in 5.5.

(7) 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 (Figure 5.1) should be calculated using expressions 5.1 to 5.6.

(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:

$$p_{hf}(z) = p_{ho}\ Y_J(z) \qquad \text{… (5.1)}$$

$$p_{wf}(z) = \mu\, p_{ho}\ Y_J(z) \qquad \text{… (5.2)}$$

$$p_{vf}(z) = \frac{p_{ho}}{K}\ Y_J(z) \qquad \text{… (5.3)}$$

in which:

$$p_{ho} = \gamma K z_o \qquad \text{… (5.4)}$$

$$z_o = \frac{1}{K\mu}\frac{A}{U} \qquad \text{… (5.5)}$$

$$Y_J(z) = 1 - e^{-z/z_o} \qquad \text{… (5.6)}$$

where:

$\gamma$ is the characteristic value of the unit weight

$\mu$ 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

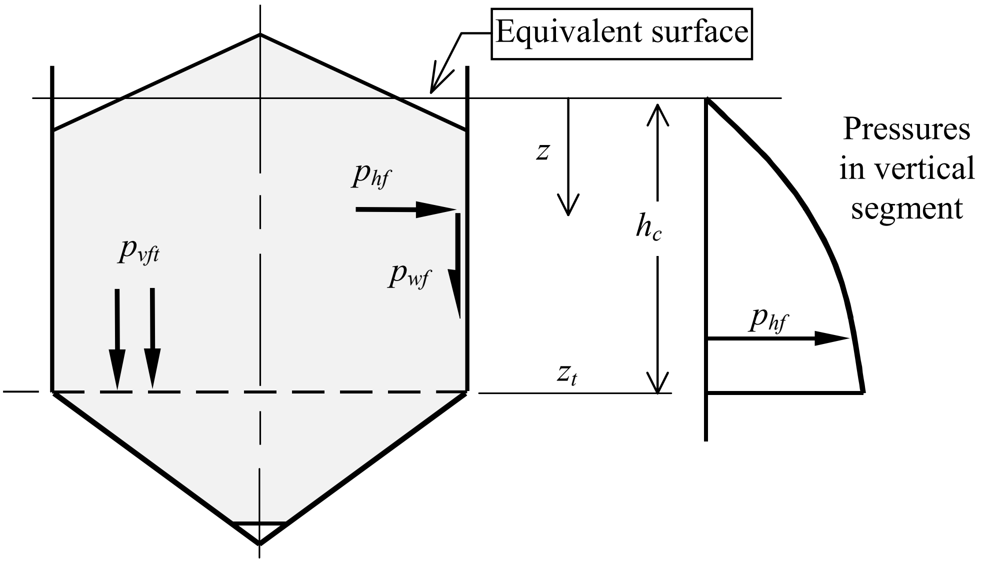


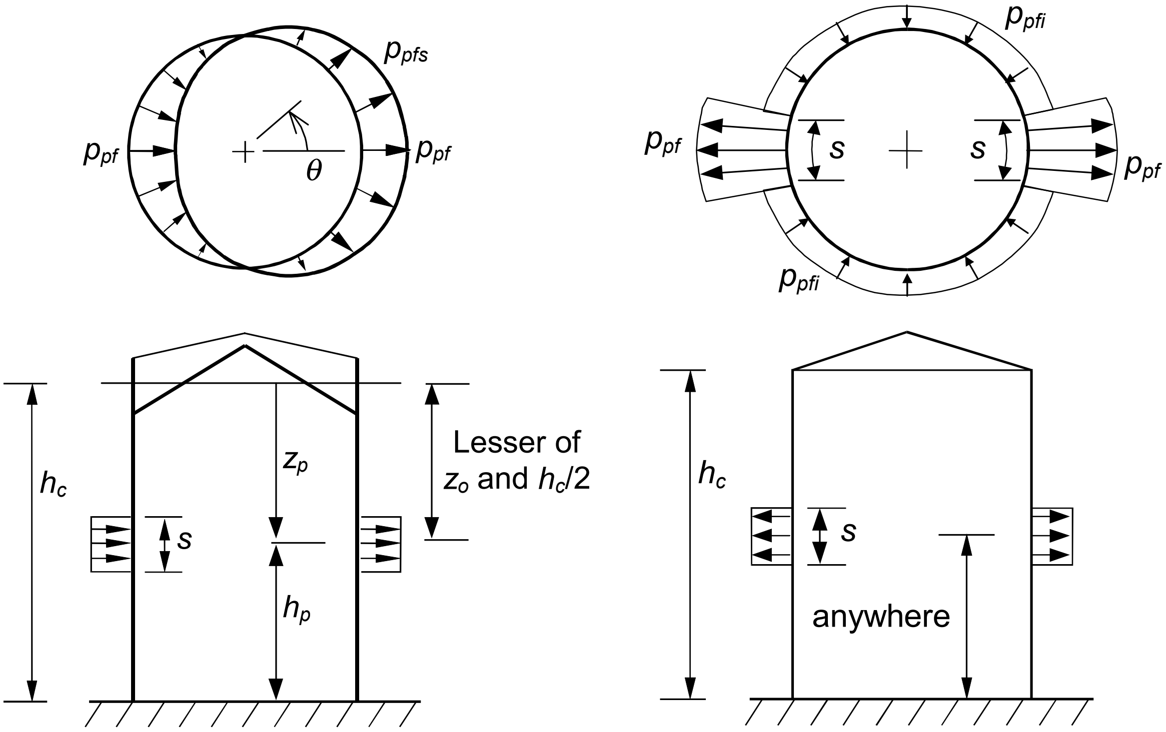
**Figure 5.1 Symmetrical filling pressures in the vertical-walled segment**

(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:

$$n_{zSk} = \int_0^z p_{wf}(z)\, dz = \mu\, p_{ho}\, [z - z_o\, Y_J\, (z)] \qquad \ldots (5.7)$$

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 $\gamma$, wall friction $\mu$, and lateral pressure ratio $K$).



**a) thin-walled welded circular silo** **b) other silo**

**Figure 5.2: 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 Reliability 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:

$$p_{pf} = C_{pf}\ p_{hf} \qquad \ldots (5.8)$$

in which:

$$C_{pf} = 0{,}21\ C_{op}\ [1+2E^2]\ (1 - \exp\{ -1.5\ [(h_c/d_c) - 1]\ \}) \qquad \ldots (5.9)$$

$$E\ =\ 2\ e_f\ /\ d_c \qquad \ldots (5.10)$$

but $C_{pf}\ \geq\ 0$ … (5.11)

where:

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

$p_{hf}$ is the local value of the filling pressure (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 E1 in Annex E)

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

$$s = \pi d_c/16\ \square\ 0{,}2d_c \qquad \ldots (5.12)$$

(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 clauses 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:

$$p_{pfi}\ =\ p_{pf}\ /\ 7 \qquad \ldots (5.13)$$

where:

$p_{pf}$ is the reference magnitude of the filling patch pressure acting outwards (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 Reliability 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 ($d_c/t > 200$), 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:

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

where:

$p_{pf}$ is the outward patch pressure (expression 5.8)

$\theta$ 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:

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

(3) For welded silos in Reliability 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:

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

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

(4) For bolted and riveted silos in Reliability 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, the filling patch load, which represents unsymmetrical loads, may always be represented by an increase in the symmetrical pressure.

(2) The outward patch pressure should be taken to act on the silo wall at any level, over a vertical height $s$ (Figure 5.2b) given by expression 5.12.

(3) The magnitude of the uniform patch pressure $p_{pf,u}$ should be taken as

$$p_{hf,u} = 0.36\, p_{pf} \qquad \dots (5.17)$$

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 $p_{hf,u}$ is chosen so that the bending moments induced in a rectangular silo 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.

### 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 Reliability Classes, the symmetrical discharge pressures $p_{he}$ and $p_{we}$ should be determined as:

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

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

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 Reliability 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:

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

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

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

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

where:

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

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

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

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

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

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 E1 in Annex E)

(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:

$$n_{zSk} = \int_0^z p_{we}\, dz = C_w\ \mu\, p_{ho}\, [z - z_o\, Y_J\, (z)] \qquad \text{… (5.26)}$$

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 (as shown in Figure 1.1b).

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

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

(4) For silos in Reliability Classes 2 and 3, where either of the following conditions apply, the procedure for large discharge eccentricities in slender silos (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:

$$p_{pe} = C_{pe}\ p_{he} \qquad \text{… (5.27)}$$

in which:

$$C_{pe} = 0{,}42\ C_{op}\, [1+2E^2]\, (1 - \exp\{-1.5\, [(h_c/d_c) - 1]\, \}) \qquad \text{… (5.28)}$$

$$E = 2\, e\, /\, d_c \qquad \text{… (5.29)}$$

but $C_{pe} \geq 0$ … (5.30)

$$e = \max(e_f,\, e_o) \qquad \text{… (5.31)}$$

where:

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

$e_o$ is the eccentricity of the centre of the outlet;

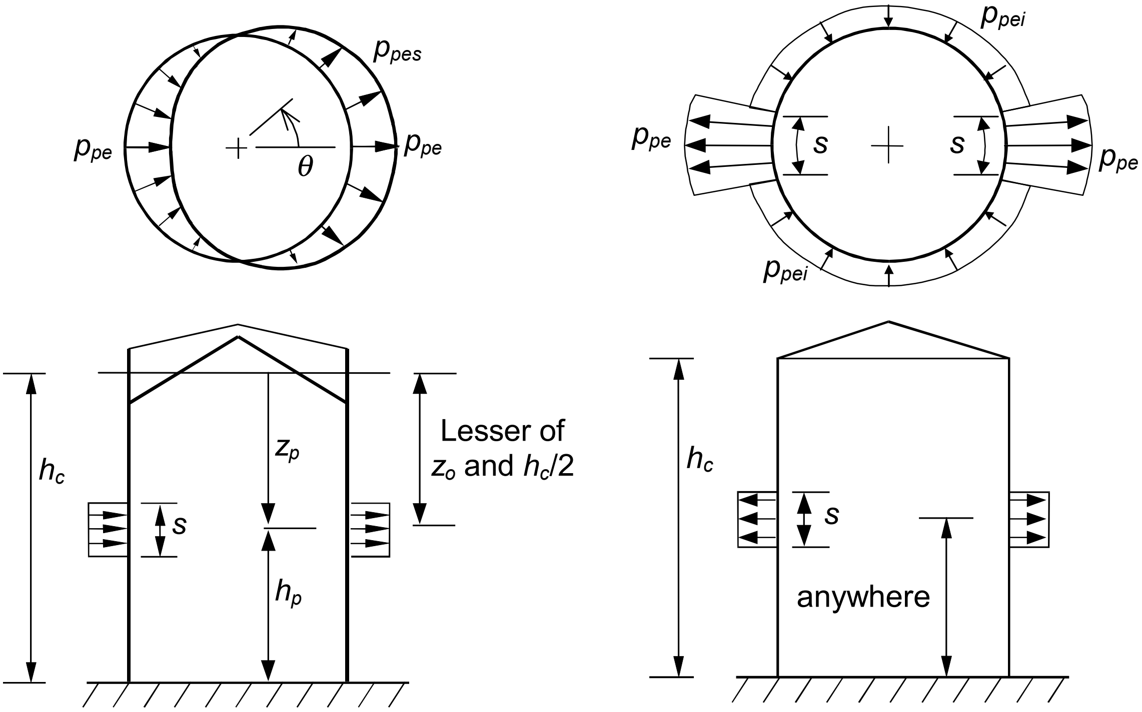
$p_{he}$ is the local value of the discharge pressure at the height at which the patch load is applied (expression 5.18);

$C_{op}$ is the patch load solid reference factor for the solid (see Table E1 in Annex E).

(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 clauses 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.



**a) thin-walled circular silo** **b) other silo**

**Figure 5.3: Side elevation and plan view of the discharge patch load**

### 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 5.3) 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 5.3) should be subjected to an inward discharge patch pressure $p_{pei}$ given by:

$$p_{pei} = p_{pe} / 7 \qquad \ldots (5.32)$$

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.

(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 Reliability 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, 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 (Figure 5.3). The circumferential variation should be taken as:

$$p_{pes} = p_{pe} \cos\theta \qquad \dots (5.33)$$

where:

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

$\theta$ is the circumferential coordinate (see Figure 5.3).

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

$$F_{pe} = \frac{\pi}{2}\, s\, d_c\, p_{pe} \qquad \dots (5.34)$$

(3) For welded silos in Reliability 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:

$$z_p = z_o \quad \text{and} \quad z_p = 0{,}5\, h_c \qquad \dots (5.35)$$

where:

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

(4) For bolted and riveted silos in Reliability 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, the discharge patch load, which represents unsymmetrical loads, may always be represented by an increased symmetrical pressure.

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

(3) The magnitude of the uniform patch pressure $p_{pe,u}$ should be taken as:

$$p_{he,u} = 0{,}36\, p_{pe} \qquad \ldots (5.36)$$

where $p_{pe}$ is the reference discharge patch load pressure (expression 5.27).

NOTE: the value and the extent of the uniform pressure $p_{he,u}$ is chosen so that the bending moments induced in a rectangular silo 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 Reliability 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 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).

(3) 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:

$$p_{hf,u} = p_{hf}\,(1 + \zeta C_{pf}) \qquad \ldots (5.37)$$

$$p_{he,u} = p_{he}\,(1 + \zeta C_{pe}) \qquad \ldots (5.38)$$

in which:

$$\zeta = 0{,}5 + 0{,}01\,(d_c/t) \qquad \ldots (5.39)$$

with $\zeta \geq 1.0$ … (5.40)

where:

$p_{hf}$ is the horizontal symmetrical filling pressure (expression 5.1)

$p_{he}$ is the horizontal symmetrical discharge pressure (expression 5.18)

$C_{pf}$ is the filling patch load factor (expression 5.9)

$C_{pe}$ is the discharge patch load factor (expression 5.28)

(4) 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:

$$p_{hf,u} = p_{hf}\,(1 + 0{,}5 C_{pf}) \qquad \ldots (5.41)$$

$$p_{wf,u} = p_{wf}\,(1 + C_{pf}) \qquad \ldots (5.42)$$

$$p_{he,u} = p_{he}\,(1 + 0{,}5C_{pe}) \qquad \ldots (5.43)$$

$$p_{we,u} = p_{we}\,(1 + C_{pe}) \qquad \ldots (5.44)$$

where:

$p_{wf}$ is the filling symmetrical wall frictional traction (expression 5.2)

$p_{we}$ is the discharge symmetrical wall frictional traction (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 Reliability 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 5.4a).

(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 Reliability 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 5.4a).

(3) Where appropriate, the procedures of 5.2.4.2 and 5.2.4.3 should be used as a separate load case, in addition to the patch load treatment of 5.2.2 and 5.2.3.

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

#### 5.2.4.2 Method for Reliability 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:

$$\theta_c = 35° \qquad \ldots (5.45)$$

##### 5.2.4.2.2 Wall pressures under eccentric discharge

(1) The pressure on the vertical wall in the flowing zone (Figure 5.4c) should be taken as:

$$p_{hce} = 0 \qquad \ldots (5.46)$$

(2) The pressures at depth $z$ on the vertical wall in the zone in which the solid remains static (see Figure 5.4c) should be taken as:

$$p_{hse} = p_{hf} \qquad \ldots (5.47)$$

$$p_{hae} = 2\,p_{hf} \qquad \ldots (5.48)$$

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

$$p_{wse} = p_{wf} \qquad \text{… (5.49)}$$

$$p_{wae} = 2\, p_{wf} \qquad \text{… (5.50)}$$

where:

$p_{hf}$ is the horizontal filling pressure (expression 5.1)

$p_{wf}$ is the filling wall frictional traction (expression 5.2)

NOTE: This simplified method relates to an empty rathole and is sometimes rather conservative.

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

### 5.2.4.3 Method for Reliability 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.

(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:

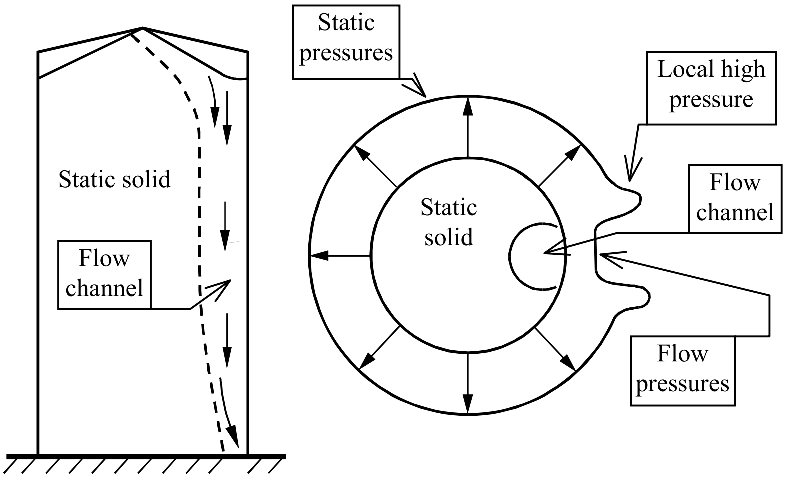
$$r_c = 0{,}2\, r \qquad \text{… (5.51)}$$

$$r_c = 0{,}35\, r \qquad \text{… (5.52)}$$

$$r_c = 0{,}5r \qquad \text{… (5.53)}$$

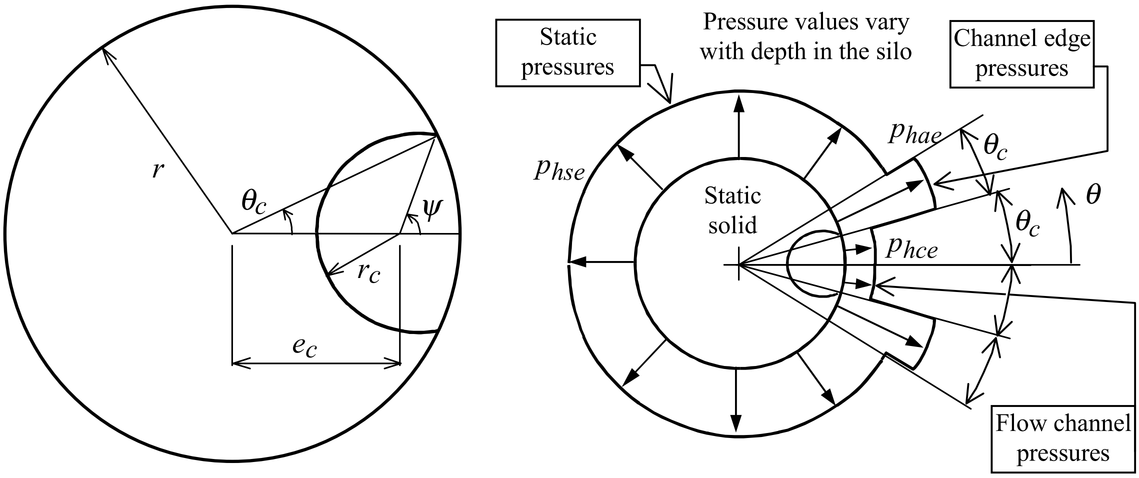
where:

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



a) Elevation b) Cross-section

a) flow channel and pressure pattern



**b) channel geometry** **c) pressures**

**Figure 5.4: Eccentric discharge flow channel and pressure distribution**

(4) The flow channel eccentricity $e_c$ (see Figure 5.4) should be determined as:

$$e_c = r\{\eta\,(1 - G) + (1{-}\eta)\sqrt{1 - G}\,\} \quad \ldots (5.54)$$

in which:

$$G = \frac{r_c}{r} \quad \ldots (5.55)$$

$$\eta = \frac{\mu_m}{\tan\phi_{im}} \quad \ldots (5.56)$$

where:

$\mu_m$ is the mean wall friction coefficient for the vertical wall

$\phi_{im}$ is the mean angle of internal friction of the stored solid

$r_c$ is the design radius of the flow channel (expressions 5.51 to 5.53).

NOTE: the flow channel eccentricity $e_c$ may vary, as indicated in Fig. 3.4d, and does not solely depend 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.

NOTE: This evaluation of the location and radius of the flow channel is based on a minimisation 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 (Fig. 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:

$$\cos\theta_c = \frac{r^2 + e_c^2 - r_c^2}{2\,r\,e_c} \qquad \text{… (5.57)}$$

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

$$U_{wc} = 2\,\theta_c\,r \qquad \text{… (5.58)}$$

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

$$U_{sc} = 2\,r_c\,(\pi - \psi) \qquad \text{… (5.59)}$$

in which:

$$\sin\psi = \frac{r}{r_c}\sin\theta_c \qquad \text{… (5.60)}$$

where the angles $\theta_c$ and $\psi$ are both expressed in radians.

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

$$A_c = (\pi - \psi)r_c^2 + \theta_c r^2 - r\,r_c\sin(\psi - \theta_c) \qquad \text{… (5.61)}$$

### 5.2.4.3.2 Wall pressures under eccentric discharge

(1) The pressure on the vertical wall in the flowing zone (Figure 5.4c) depends on the distance $z$ below the equivalent solid surface and should be determined as:

$$p_{hce} = p_{hco}\left(1 - e^{-z/z_{oc}}\right) \qquad \text{… (5.62)}$$

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

$$p_{wce} = \mu\,p_{hce} = \mu\,p_{hco}\left(1 - e^{-z/z_{oc}}\right) \qquad \text{… (5.63)}$$

in which:

$$p_{hco} = \gamma K z_{oc} \quad \text{… (5.64)}$$

$$z_{oc} = \frac{1}{K}\left(\frac{A_c}{U_{wc}\,\mu + U_{sc}\tan\phi_i}\right) \quad \text{… (5.65)}$$

where:

$\mu$ 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 (Figure 5.4c) should be taken as:

$$p_{hse} = p_{hf} \quad \text{… (5.66)}$$

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

$$p_{wse} = p_{wf} \quad \text{… (5.67)}$$

where:

$p_{hf}$ is the horizontal filling pressure (expression 5.1)

$p_{wf}$ is the filling wall frictional traction (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 (Figure 5.4c) 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:

$$p_{hae} = 2p_{hf} - p_{hce} \quad \text{… (5.68)}$$

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

$$p_{wae} = \mu\, p_{hae} \quad \text{… (5.69)}$$

## 5.3 Squat and intermediate slenderness silos

### 5.3.1 Filling loads on vertical walls

#### 5.3.1.1 Symmetrical load

(1) The symmetrical filling load (Figure 5.5) should be calculated using expressions 5.70 to 5.79.

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

$$p_{hf} = p_{ho}\, Y_R \quad \text{… (5.70)}$$

$$p_{wf} = \mu\, p_{hf} \quad \text{… (5.71)}$$

in which:

$$p_{ho} = \gamma K z_o = \gamma \frac{1}{\mu}\frac{A}{U} \quad \text{… (5.72)}$$

$$Y_R = \left(1 - \left\{\left(\frac{z - h_o}{z_o - h_o}\right) + 1\right\}^n\right) \qquad \text{… (5.73)}$$

$$z_o = \frac{1}{K\mu}\frac{A}{U} \qquad \text{… (5.74)}$$

$$n = -(1 + \tan\phi_r)(1 - h_o/z_o) \qquad \text{… (5.75)}$$

where

$h_o$ is the value of $z$ at the highest solid-wall contact (Figures 1.1a and 5.5).

For a symmetrically filled circular silo of radius $r$, $h_o$ should be determined as:

$$h_o = \frac{r}{3}\tan\phi_r \qquad \text{… (5.76)}$$

and for a symmetrically filled rectangular silo of characteristic dimension $d_c$, $h_o$ should be determined as:

$$h_o = \frac{d_c}{4}\tan\phi_r \qquad \text{… (5.77)}$$

where:

$\gamma$ is the characteristic value of the unit weight

$\mu$ 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

$\phi_r$ is the angle of repose of the solid (see Table E1 in Annex E).

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

$$p_{vf} = \gamma z_V \qquad \text{… (5.78)}$$

in which:

$$z_V = h_o - \frac{1}{(n+1)}\left(z_o - h_o - \frac{(z + z_o - 2h_o)^{n+1}}{(z_o - h_o)^n}\right) \qquad \text{… (5.79)}$$

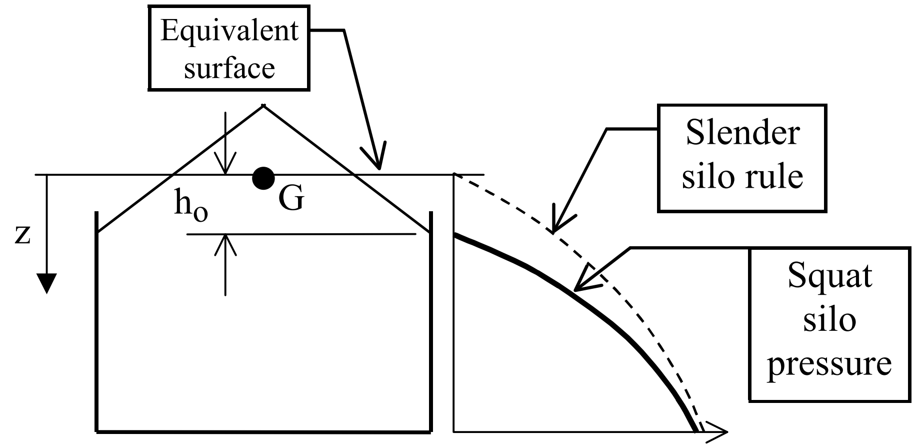


**Figure 5.5 Filling pressures in a squat or intermediate slenderness silo**

(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:

$$n_{zSk} = \int_0^z p_{wf}(z)\, dz = \mu\, p_{ho}\, (z - z_V) \qquad \ldots (5.80)$$

where $z_V$ is given by expression 5.79.

NOTE: The stress resultant defined in expression 5.80 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 5.71. 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 Patch load

(1) For squat silos ($h_c/d_c \leq 1{,}0$), the filling patch load need not be considered ($C_{pf} = 0$).

(2) For silos of intermediate slenderness ($1{,}0 < h_c/d_c < 2{,}0$) the filling patch pressure $p_{pf}$, taken from 5.2.1, may be used to represent accidental asymmetries of loading and small eccentricities of filling $e_f$ (as shown in Figure 1.1b). Where the eccentricity of filling $e_f$ exceeds the critical value $e_{f,cr} = 0{,}25d_c$, the procedure for large filling eccentricities in squat silos should be used (5.3.3).

(3) The filling patch load should be considered to act on any part of the silo wall.

(4) 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.

(5) For silos of intermediate slenderness ($1{,}0 < h_c/d_c < 2{,}0$), the rules set out in 5.2.1 should be used to define the form, location and magnitude of the patch load.

### 5.3.2 Discharge loads on vertical walls

#### 5.3.2.1 Symmetrical load

(1)P 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 $p_{he}$ and $p_{we}$ should be determined as:

$$p_{he} = C_h \; p_{hf} \qquad \ldots (5.81)$$

$$p_{we} = C_w \, p_{wf} \qquad \ldots (5.82)$$

where:

$C_h$ and $C_w$ are discharge factors according to expressions 5.83 to 5.88 as appropriate.

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

$$C_w = C_h = 1,0 \qquad \ldots (5.83)$$

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

$$C_h = 1,0 + 0,15 \; C_S \qquad \ldots (5.84)$$

$$C_w = 1,0 + 0,1 \; C_S \qquad \ldots (5.85)$$

$$C_S = h_c/d_c - 1,0 \qquad \ldots (5.86)$$

where $C_S$ is the slenderness adjustment factor.

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

$$C_h = 1,0 + 1,5 \,(1 + 0,4 \; e/d_c) \;\; C_{op} \, C_S \qquad \ldots (5.87)$$

$$C_w = 1,4 \,(1 + 0,4 \; e/d_c) \; C_S \qquad \ldots (5.88)$$

$$e \;=\; \max(e_f, \, e_o) \qquad \ldots (5.89)$$

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 E1 in Annex E);

$C_S$ is the slenderness adjustment factor (expression 5.86).

#### 5.3.2.2 Patch load

(1) For silos in all Reliability Classes that are squat ($h_c/d_c \leq 1{,}0$) and with discharge eccentricity $e_e$ less than $e_{e,cr} = 0{,}1d_c$, the discharge patch load should not be considered ($C_{pe} = 0$).

(2) For silos of intermediate slenderness ($1{,}0 < h_c/d_c < 2{,}0$) in Reliability Class 1, the discharge patch load may be ignored.

(3) For silos in Reliability Classes 2 and 3 that are of intermediate slenderness ($1{,}0 < h_c/d_c < 2{,}0$), the provisions of 5.3.2.3 should be adopted.

(4) For silos in Reliability Classes 2 and 3 that are squat ($h_c/d_c \leq 1{,}0$) with discharge eccentricity greater than $e_{e,cr} = 0{,}1d_c$, the provisions of 5.3.2.3 should be adopted.

(5) The discharge patch pressure $p_{pe}$ may be used to represent accidental asymmetries of loading and small eccentricities of filling $e_f$ (as shown in Figure 1.1b).

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

(7) 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, the provisions of 5.3.4 should be adopted.

#### 5.3.2.3 Substitute uniform pressure increase for filling and discharge

(1) For silos in Reliability 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 load values obtained from 5.3.1.2 and 5.3.2.2, using expressions 5.37 to 5.44 as appropriate.

### 5.3.3 Large eccentricity filling loads in squat and intermediate circular silos

(1)P For silos of circular planform in Reliability 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 $e_{t,cr} = 0{,}25d_c$ (Figure 5.6), 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 5.90 to those evaluated for symmetrical filling or discharge 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.

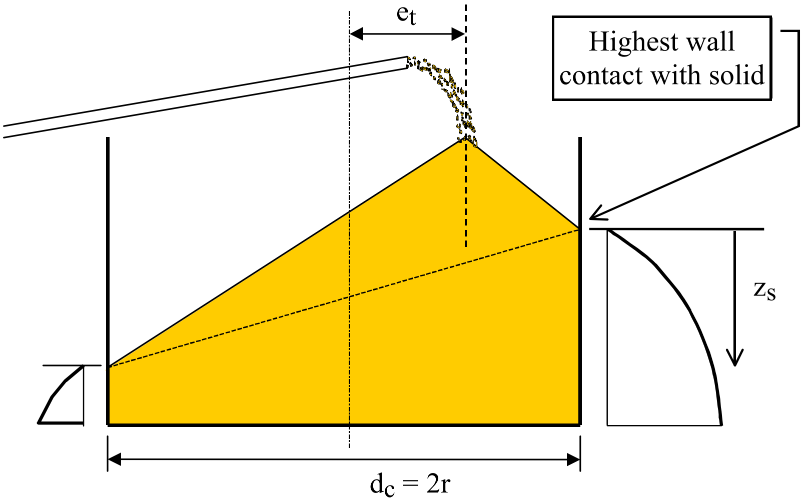


**Figure 5.6 Filling pressures in an eccentrically filled squat or intermediate slenderness silo**

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

(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:

$$n_{zSk} = 0{,}04\, p_{ho}\, z_s\, \tan\phi_r\, (e_t / r)\,(6 + 7Z - Z^2) \quad \ldots (5.90)$$

in which:

$$p_{ho} = \frac{\gamma}{\mu}\frac{A}{U} = \frac{\gamma r}{2\mu} \quad \ldots (5.91)$$

$$Z = \frac{z_s}{B} \quad \ldots (5.92)$$

$$B = \frac{r}{2\mu K} - h_o \quad \ldots (5.93)$$

$$h_o = r \tan\phi_r \left[1 - (e_t / r)^2\right] / 3 \quad \ldots (5.94)$$

where

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

$\phi_r$ 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 5.6)

NOTE: The stress resultant defined in expression 5.90 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 5.90 should be added to the force arising from wall friction, which may be taken from expression 5.80.

### 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 Reliability 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. The evaluation of the lateral pressure ratio shall take account of the restraint to radial expansion provided by the wall (i.e. at rest pressure condition).

(2) The normal pressure $p_h$ on a vertical wall (see Figure 5.7) should be determined as:

$$p_h = \gamma K (1 + \sin\phi_r)\, z_s \qquad \text{… (5.95)}$$

where:

$z_s$ is the depth below the highest stored solid contact with the wall (Figure 5.7);

$\gamma$ 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;

$\phi_r$ is the angle of repose of the stored solid.

NOTE: The National Annex may give an alternative method for determining $p_h$. The recommended expression is expression 5.95.

NOTE: Expression 5.95 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.

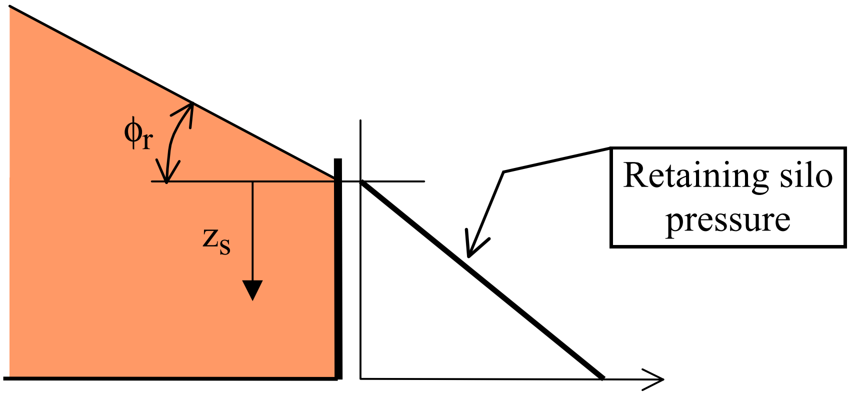


Figure 5.7 Filling pressures in a retaining silo

(3) 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 as:

$$n_{zSk} = \gamma \frac{\mu K}{2} (1 + \sin\phi_r) z_s^2 \qquad \text{… (5.96)}$$

where $\mu$ is the upper characteristic value of the wall friction coefficient of the solid.

(4) 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 $\gamma$ 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)P With regard to 5.4.2 (1), the evaluation of the conditions of discharge shall 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 fluidised as a consequence of the entrainment of air shall be designed for the additional pressures that may arise due to fluidisation and air pressure.

(2)P Homogenising fluidised 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 fluidised;
- the stored solid not fluidised.

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

### 5.5.2 Loads in silos containing fluidised solids

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

NOTE: the conditions under which a stored powder can become fluidised 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 homogenising fluidised silos (see 1.5.17) storing powders (see 1.5.31) that are being recirculated, it should be assumed that the stored solid can become fluidised.

(3) The pressure on the silo walls $p_h$ from fluidised solids should be calculated as follows:

$$p_h = \gamma_1 z \qquad \text{… (5.97)}$$

where:

$\gamma_1$ is the fluidised unit weight.

(4) The fluidised unit weight of a powder $\gamma_1$ may be taken as equal to:

$$\gamma_1 = 0{,}8\ \gamma \qquad \dots (5.98)$$

where:

$\gamma$ 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:

$$p_{hT} = C_T\, \alpha_w\, \Delta T\, \frac{E_w}{[(r/t) + (1-\nu)(E_w/E_{sU})]} \qquad \dots (5.99)$$

where:

$C_T$ is the temperature load multiplier;

$\alpha_w$ is the coefficient of thermal expansion of the silo wall;

$\Delta T$ 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;

$v$ is Poisson's ratio for the particulate solid ($v$ = 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 Annex 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.

## 5.7 Loads in rectangular silos

### 5.7.1 Rectangular silos

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

(2) The value of pressure defined in 5.2 at each level should be taken as the mean pressure at that level, but the local pressure at any point on the wall may differ from this value.

(3) 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 Reliability 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.

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

### 5.7.2 Silos with internal ties

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

(2)P The forces applied by the ties to the walls of the structure shall 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 Reliability 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 ENV 1993-4-1 Chapter 9.

# 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.

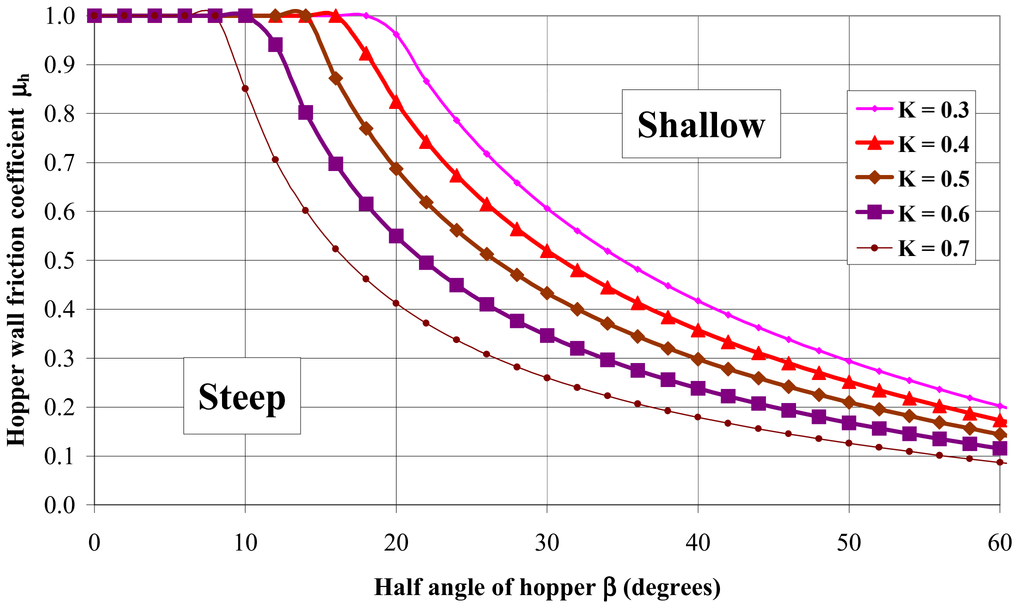


**Figure 6.1 The boundary between steep and shallow hoppers**

(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 $\alpha$ 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 (Figures 6.1 and 6.2):

$$\tan\beta < \frac{(1-K)}{2\mu_h} \qquad \text{… (6.1)}$$

where:

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

$\beta$ is the hopper apex half angle

$\mu_h$ 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 mobilised 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 mobilised). 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 mobilised).

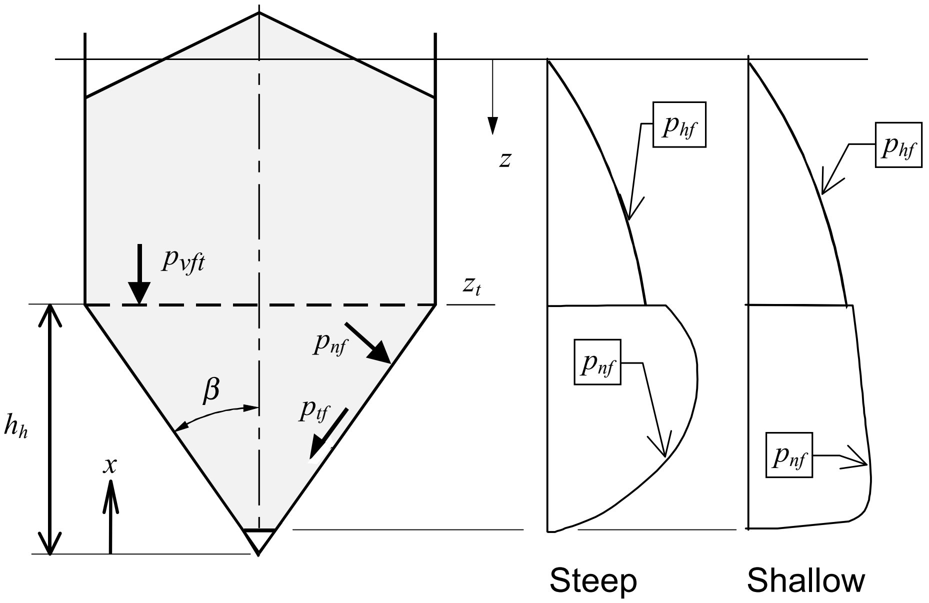


**Figure 6.2 Distributions of filling pressures in steep and shallow hoppers**

### 6.1.2 General rules

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

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

where:

$p_{vf}$ is the filling value of the vertical pressure calculated using expression 5.3 or 5.78 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: Figure 1.1a) and using the values of solids properties that induce maximum hopper loading (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.

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

$C_b = 1{,}0$ except under the conditions defined in (4) below … (6.3)

(3) For silos in Reliability Class 1 where the mean value of the material properties $K$ and $\mu$ have been used for design, the bottom load magnifier should be determined as:

$C_b = 1{,}3$ except under the conditions defined in (4) below … (6.4)

(4) Where there is a significant probability that the stored solid can develop dynamic loading conditions (see (5)), higher loads are applied to the hopper or silo bottom, the bottom load magnifier should be taken as:

$$C_b = 1{,}2 \quad \text{for Reliability Classes 2 and 3} \qquad \ldots (6.5)$$

$$C_b = 1{,}6 \quad \text{for Reliability Class 1} \qquad \ldots (6.6)$$

(5) The conditions of (4) 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 1: the evaluation of the cohesion $c$ of a solid is given in Annex C.9. The cohesion is classed as low if, following consolidation to a normal stress level $\sigma_r$, the assessed cohesion $c$ exceeds $c/\sigma_r = 0{,}04$ (see 1.5.23).

NOTE 2: the pressures on the walls of hoppers may alternatively be determined as set out in Annex H.

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

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

in which:

$$n = S\,(F\,\mu_{heff}\cot\beta + F) - 2 \qquad \ldots (6.8)$$

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

$$S = 1 \text{ for wedge hoppers} \qquad \ldots (6.10)$$

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

where:

$\gamma$ is the upper characteristic value of the solid unit weight

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

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

$\mu_{heff}$ is the effective or mobilised 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)

$\beta$ is the hopper apex half angle (=90° – $\alpha$), 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 (Figure 1.1d)

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

(7) 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.

(8) The determination of the value of the effective or mobilised hopper wall friction coefficient $\mu_{heff}$ 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 $\alpha \leq 5°$) 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 acting on a flat bottom should be determined as:

$$p_v = p_{vft} \qquad \ldots (6.12)$$

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 (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:

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

in which:

$$\Delta p_{sq} = p_{vtp} - p_{vho} \qquad \ldots (6.14)$$

$$p_{vtp} = \gamma h_{tp} \qquad \ldots (6.15)$$

where:

$p_{vb}$ is the uniform component of pressure, obtained from expression 6.2 with $z = h_c$ and adopting characteristic values for the solids properties that induce maximum hopper loading (Table 3.1).

$p_{vho}$ is the Janssen vertical pressure at the base of the top pile, obtained from expression 5.78 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 (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 (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 $\gamma z$ ($z$=$h_o$) 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.

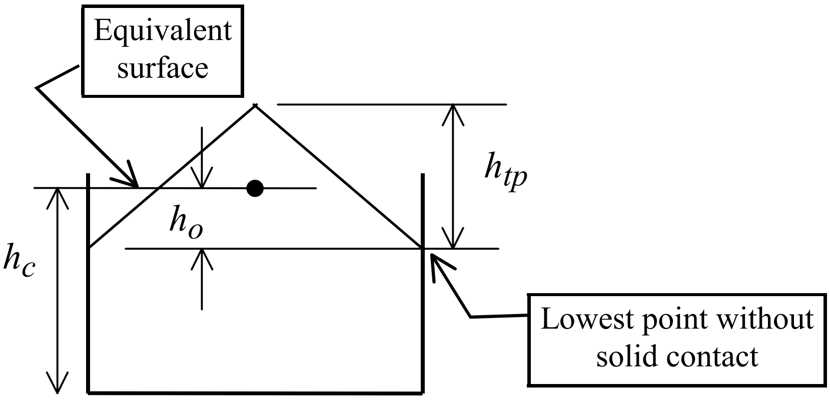


**Figure 6.3 Pressures on the bottom of a squat or intermediate silo**

(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 Mobilised friction

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

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

where:

$\mu_h$ 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 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:

$$F_f = 1 - \frac{b}{\left(1 + \frac{\tan\beta}{\mu_h}\right)} \qquad \text{… (6.17)}$$

The parameter *n* in expression 6.7 is given by:

$$n = S\,(1-b)\,\mu_h \cot\beta \qquad \text{… (6.18)}$$

where:

$b$ is an empirical coefficient $b = 0{,}2$.

The other parameters are defined in 6.1.2 (6).

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

$$p_{nf} = F_f\, p_v \qquad \text{… (6.19)}$$

$$p_{tf} = \mu_h\, F_f\, p_v \qquad \text{… (6.20)}$$

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:

$$F_e = \frac{1 + \sin\phi_i \cos\varepsilon}{1 - \sin\phi_i \cos(2\beta + \varepsilon)} \qquad \text{… (6.21)}$$

in which:

$$\varepsilon = \phi_{wh} + \sin^{-1}\left\{\frac{\sin\phi_{wh}}{\sin\phi_i}\right\} \qquad \text{… (6.22)}$$

$$\phi_{wh} = \tan^{-1} \mu_h \qquad \text{… (6.23)}$$

where:

$\mu_h$ is the lower characteristic value of wall friction coefficient in the hopper

$\phi_i$ is the angle of internal friction of the stored solid

NOTE: 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 Annex H.10, may alternatively be used.

(2) The normal pressure and frictional traction (Figure 6.4) at any point on the wall of a steep hopper during discharge should be determined as:

$$p_{ne} = F_e \; p_v \qquad \text{… (6.24)}$$

$$p_{te} = \mu_h F_e \; p_v \qquad \text{… (6.25)}$$

where $F_e$ is given by expression 6.21.

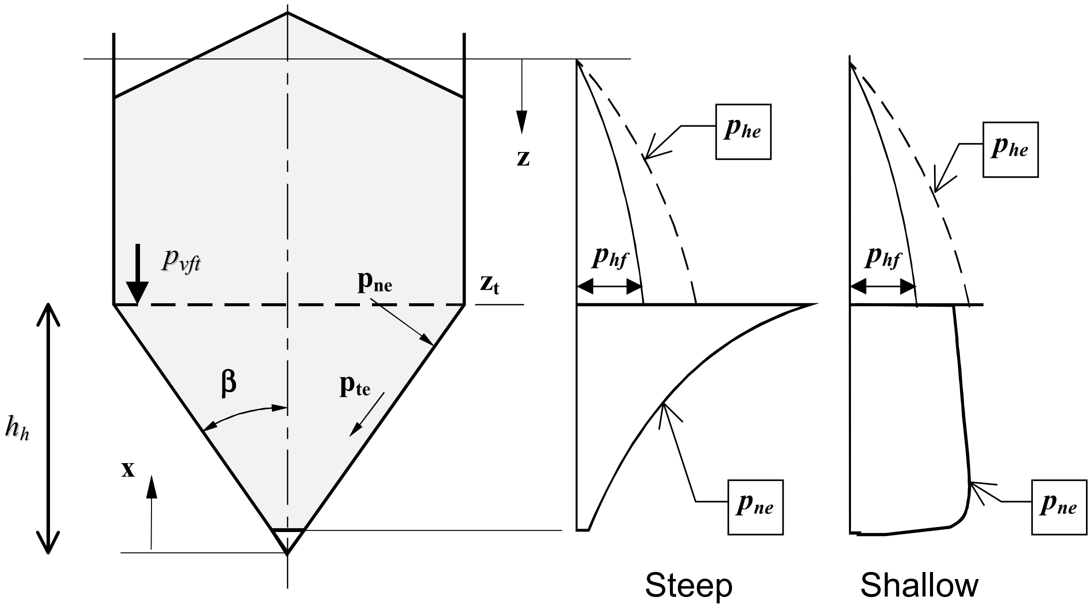


**Figure 6.4 Discharge pressures in steep and shallow hoppers**

## 6.4 Shallow hoppers

### 6.4.1 Mobilised friction

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

$$\mu_{heff} = \frac{(1-K)}{2\tan\beta} \qquad \text{… (6.26)}$$

where:

$K$ is the characteristic value of lateral pressure ratio for the vertical section, chosen for maximum hopper loading (Table 3.1)

$\beta$ is the half angle of the hopper (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:

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

The parameter $n$ in expression 6.7 is given by:

$$n = S\,(1-b)\,\mu_{heff} \cot\beta \qquad \text{… (6.28)}$$

where:

$\mu_{heff}$ is the mobilised or effective wall friction coefficient in the shallow hopper (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 and frictional traction at any point on the wall of a shallow hopper after filling (Figure 6.2) should be determined as:

$$p_{nf} = F_f \; p_v \qquad \text{… (6.29)}$$

$$p_{tf} = \mu_{heff} F_f \; p_v \qquad \text{… (6.30)}$$

where:

$F_f$ is given by expression 6.27.

### 6.4.3 Discharge loads

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

# 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 comprehensive 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:

$$p(z) = \gamma z \quad \text{… (7.1)}$$

where:

$z$ is the depth below the liquid surface

$\gamma$ is the unit weight of the liquid

## 7.3 Liquid properties

(1) The densities given in EN 1991-1-1 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 should consider the possible adiabatic nature of the process.

# Annex A

(Informative)

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

*EDITORIAL NOTE: This annex should be incorporated into EN 1990 'Basis of structural design'.*

### 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 ($\gamma_F$ factors) and on combinations on silos and tanks with other actions; and the relevant $\psi$ 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 $\gamma$

(1) The values given in Annex 1 of EN 1990 'Basis of structural design' 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 $\gamma_F$ may be reduced from 1,50 to 1,35.

#### A.2.2 Combination factors $\psi$

(1) The combination factors $\psi$ for silo loads and tank loads and combination factors with other actions are given in Table A1-A5.

### 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)

### A.4 Design situations and action combinations for Reliability 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 $\psi$ to account for the

reduced probability of simultaneous occurrence in accordance with EN 1990. The combinations given in Tables A1, A2, A3, A4 and A5 should be used, with Accompanying Actions 2 and 3 reduced by their appropriate combination factors $\psi$.

(2) The combination factor $\psi_{0,1}$ shall 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 $\mu_m$, 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 $\psi$ may be set by the National Annex. The values in this table are recommended values.

**Table A1**

**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 | Self weight | Solids filling | 1,0 | | |
| WE | Wind and empty | 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 | 0,3 | Imposed loads or deformation | 0,3 |

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

NOTE: The subscripts of $\psi$ 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 A2

## "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 | $\xi_1$ | (See next column, "main") | | Description | $\psi_{0,1}$ | Description | $\psi_{0,2}$ | Description | $\psi_{0,3}$<br>$\psi_{0,4}$<br>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 A2 should be used with expressions 6.10a and 6.10b in Section 6.4.3.2 of EN 1990.

### Table A3

## "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 A3 should be used with expression 6.11b in Section 6.4.3.3 of EN 1990.

### Table A4

## "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 A4 should be used with expression 6.12b in Section 6.4.3.4 of EN 1990 and those of EN 1998-1 and EN 1998-4.

### Table A5

### 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 | $\psi_{0,2}$ or $\psi_{2,2}$ | Description | $\psi_{0,3}$ $\psi_{0,4}$ or $\psi_{2,3}$ $\psi_{2,4}$ 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 | 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 A5 should be used with expressions 6.14b, 6.15b and 6.16b in Section 6.5.3 of EN 1990 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 Reliability Class 1

The following simplified design situations may be considered for silos in Reliability Class 1:

- Filling
- Discharge
- Wind when empty
- Filling with wind
- Snow (for the roof)

A simplified treatment of wind loading is permitted according to rules of EN 1991-1-4.

# Annex B

(Normative)

# Actions, partial factors and combinations of actions on tanks

## 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.

### 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.

### 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.

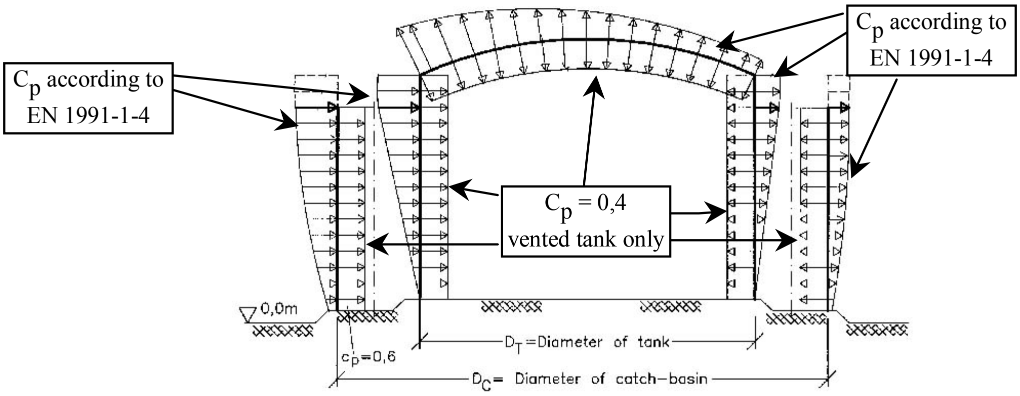
(2) In addition, the following pressure coefficients may be used for circular cylindrical tanks, see Figure B.1:

a) internal pressure of open top tanks and open top catch basin: $c_p = -0,6$.

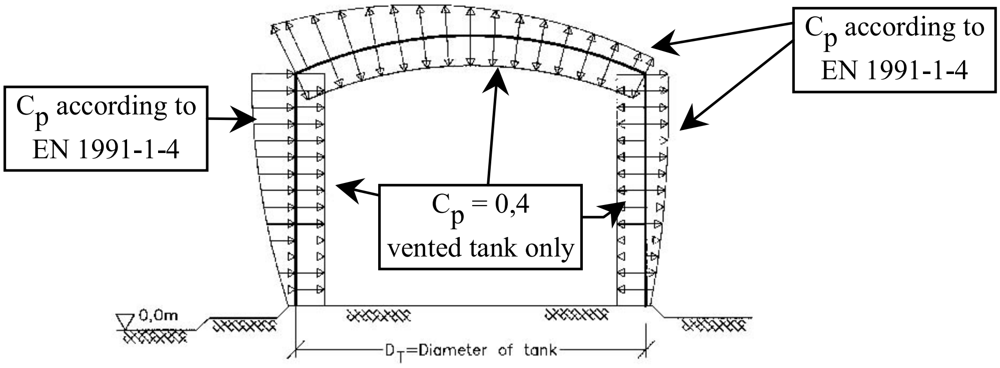
b) internal pressure of vented tanks with small openings: $c_p = -0,4$.

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**

**Figure B1: 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 minimise 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 Emergency loadings

(1) The loads should include loadings from events such as external blast, impact, adjacent external fire, explosion, leakage of inner tank, roll over, overfill of inner tank.

NOTE: These loads may be specified in the National Annex, or by the client for the particular 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 partial factor for the liquid induced loads during operation (B.2.1(1)) should be taken as $\gamma_F = 1{,}20$.

(3) The partial factor for the liquid induced loads during test (B.2.1(2)) should be taken as $\gamma_F = 1{,}00$.

(4) For accidental design situations, the partial factors for the variable actions should be taken as $\gamma_F = 1{,}00$.

### B.4 Combination of actions

(1)P The general requirements of Section 6 of EN 1990 shall be followed.

(2) Imposed loads and snow loads need not be considered to act simultaneously. The National Annex may specify a different approach where appropriate.

(3) Seismic actions need not be considered to act during test conditions.

(4) Emergency actions need not be considered to act during test conditions. The combination rules for accidental actions given in EN 1990 should be applied to emergency situations.

# 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. For load assessment, 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 there are other significant differences. As a result, the sample preparation differs in some key ways from that appropriate to the measurement of flow properties.

(2) 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 Reliability Class 3, or for a stored solid that is not listed in Table E1 in Annex E, or as an alternative to the simplified values given in Table E1 in Annex E. 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 (C.6, C.8 and C.9): reference stress $\sigma_r$ = 100 kPa

b) to represent the horizontal pressure (C.7.2): reference stress $\sigma_r$ = 50 kPa

### C.3 Notation

For the purpose of this annex the following notation applies:

| | |
|---|---|
| $a$ | property modification coefficient |
| $c$ | cohesion (Figure C4) |
| $D$ | cell internal diameter |
| $F_r$ | residual shear force at end of wall friction test (Figure C2b) |
| $K_{mo}$ | mean lateral pressure ratio for smooth wall conditions |
| $\Delta$ | displacement of top part of shear cell during test |
| $\phi_l$ | angle of internal friction measured during loading of the sample |
| $\phi_c$ | angle of internal friction measured under decreasing normal stresses |
| $\mu$ | coefficient of friction between the sample of solid and the sample of wall |

| | |
|---|---|
| $\sigma_r$ | reference stress |
| $\tau_a$ | final shear stress measured in a shear test after increasing the normal stress (Figure C4) |
| $\tau_b$ | peak shear stress measured in a shear test after decreasing the normal stress (Figure C4) |
| $\tau$ | 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 $\sigma_r$ 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 $\sigma_r$ 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: Reference may be made to the ASTM Standard D6128 concerning this procedure.
NOTE: 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 Consolidated bulk unit weight $\gamma$

### C.6.1 Principle of the test

(1) The bulk unit weight $\gamma$ 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.

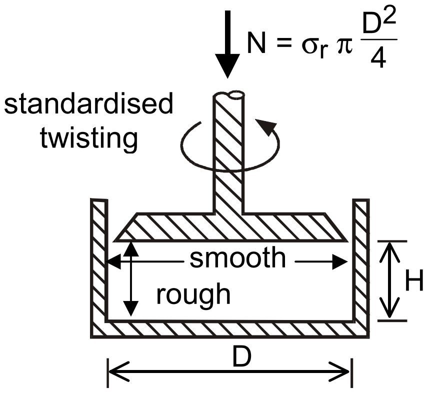


Figure C1: Device for the determination of $\gamma$

### C.6.2 Apparatus

(1) The cell shown in Figure C1 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 0,3*D* and 0,4*D*.

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 recognised 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 $\sigma_r$ 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)P A distinction should be made between the two parameters:

- Coefficient of wall friction $\mu_m$ for the determination of pressures;
- Angle of wall friction $\phi_{wh}$ 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 $\mu_m$ 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 characterise 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 $\mu_m$ 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 C2. 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 0,15$D$ and 0,20$D$. 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 recognised 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 $\sigma_r$ 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 0,04mm/s.

(5) The residual friction force $F_r$ (Figure C2), attained at large deformations, should be used in the calculation of the coefficient of wall friction $\mu$ for action calculations.

(6) The sample value of the coefficient of wall friction $\mu$ for action calculations should be determined as

$$\mu = \frac{F_r}{N} \qquad \text{… (C.1)}$$

where:

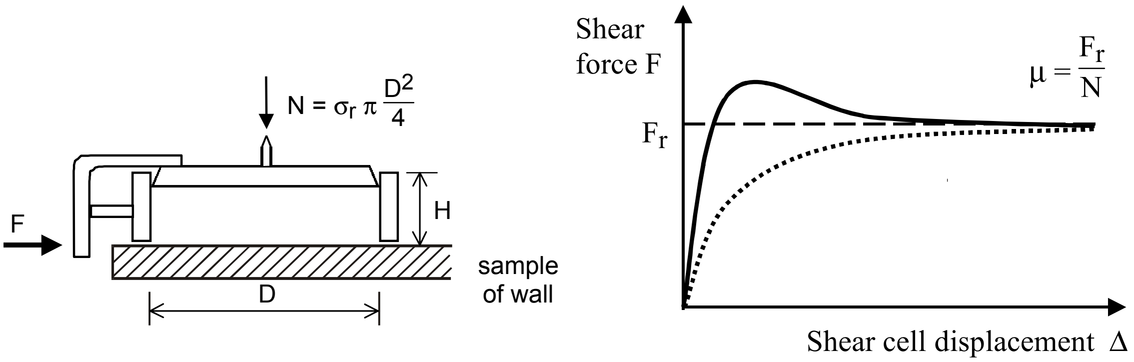
$F_r$ is the final or residual value of the shear force (Figure C2 b);
$N$ is the applied vertical load on the cell.

### C.7.3 Angle of wall friction $\phi_{wh}$ for the evaluation of flow

(1) Where it is necessary to obtain the angle of wall friction $\phi_{wh}$ 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.



**a) Cell for measuring wall friction** **b) Typical shear-displacement curves**

**Figure C2: 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 $\sigma_1$ should be applied to a sample constrained against horizontal deformation. The induced horizontal stress $\sigma_2$ should be measured and the secant value of the lateral pressure ratio $K_o$ determined.

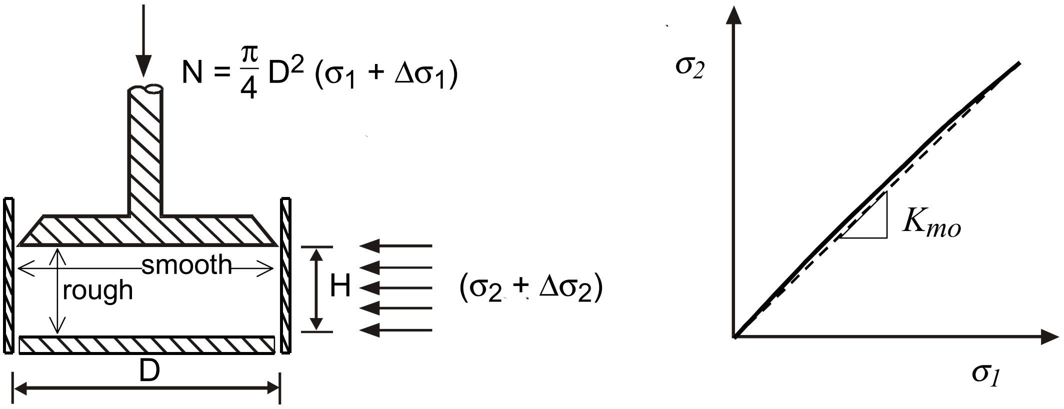
NOTE: The magnitude of the coefficient $K_0$ is influenced by the direction of the principal stresses in the test sample. The horizontal and vertical stresses are approximately principal stresses in the test sample whereas they may not be in the silo.

NOTE: 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.

### C.8.1.2 Apparatus

(1) The geometry of the test apparatus is shown in Figure C3. 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: It is generally necessary to have a separate bottom plate, to make both horizontal and vertical strain measurements, to site the strain measurement devices distant from the specimen ends, and to verify that the measured strains are related to the internal horizontal stress by the assumed factor (bending of the apparatus wall may affect this relationship).



**(a) Test apparatus**

**(b) Typical development of $\sigma_2$ with increasing $\sigma_1$**

**Figure C3: Test method for determining $K_o$**

#### C.8.1.3 Procedure

(1) The reference stress $\sigma_r$ 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) The horizontal stress $\sigma_2$ in the sample that results from application of a vertical stress $\sigma_1$ equal to the reference stress $\sigma_r$ should be observed. The value of $K_o$ should be calculated from these stresses (Figure C3) as:

$$K_o = \frac{\sigma_2}{\sigma_1} \qquad \text{… (C.2)}$$

(4) The value of $K$ should be taken as:

$$K = 1{,}1\,K_o \qquad \text{… (C.3)}$$

NOTE: the factor 1,1 in expression C.2 is used to give an approximate representation of the difference between the lateral pressure ratio (=$K_o$) 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 $\phi_I$, 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 $\phi_I$.

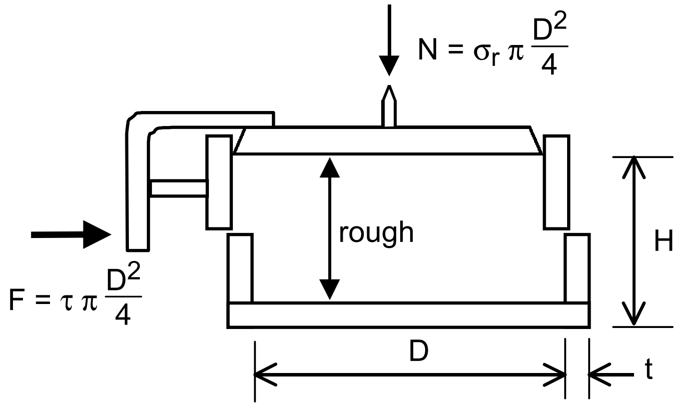
## C.9 Strength parameters: cohesion $c$ and internal friction angle $\phi_i$

### C.9.1 Direct measurement

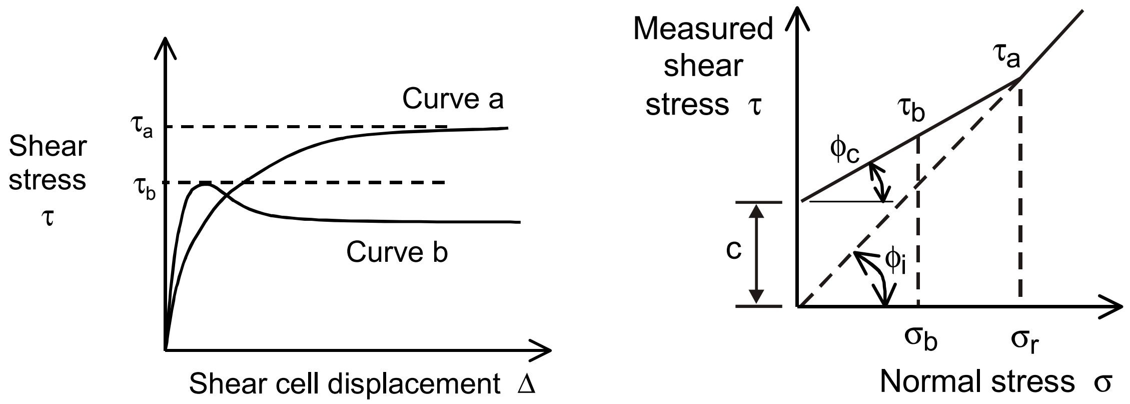
#### C.9.1.1 Principle of the test

(1) The strength of a stored solid sample may be determined from shear cell tests. Two parameters $c$ and $\phi_I$ 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.



**a) Shear cell**



**b) Typical shear – displacement curves**

**c) Typical shear stress – normal stress relations for measured shear stresses**

**Figure C4: Test Method for determining the angles of internal friction $\phi_i$ and $\phi_c$ and the cohesion $c$ based on the preconsolidation stress $\sigma_r$**

### C.9.1.2 Apparatus

(1) The test apparatus should consist of a cylindrical shear cell, as shown in Figure C4. 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 recognised 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 $\sigma_r$ 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 0,04mm/s.

(3) The shear stress $\tau$ developed at or before a horizontal displacement of $\Delta = 0.06\ D$ should be used to calculate the strength parameters for the solid, where $D$ is the internal diameter of the cell (Figure C4).

(4) At least two tests should be carried out (Table C2 and Figure C4) as defined in (5) and (6) below.

(5) The first sample should be sheared under a normal load causing the reference stress $\sigma_r$ to obtain the failure shear stress $\tau_a$.

(6) The second sample should first be pre-loaded under a normal load causing the reference stress $\sigma_r$ 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 ($\sigma_b \square \sigma_r/2$) and sheared again to obtain the failure shear stress $\tau_b$. Stresses determined from the two tests are named in Table C1).

**Table C1 - Recommended tests**

| Test | Pre-load value of normal stress | Test load value of normal stress | Maximum measured shear stress |
|---|---|---|---|
| No. 1 | $\sigma_r$ | $\sigma_r$ | $\tau_a$ |
| No. 2 | $\sigma_r$ | $\sigma_b \square \sigma_r/2$ | $\tau_b$ |

### C.9.1.4 Interpretation

(1) The loading angle of internal friction $\phi_l$ for the stored solid should be calculated as:

$$\phi_l = \arctan\left(\tau_a / \sigma_r\right) \qquad \text{… (C.4)}$$

(2) The cohesion $c$ that develops in the stored solid under the reference stress $\sigma_r$ should be calculated as:

$$c = \tau_a - \sigma_r \tan \phi_c \qquad \text{… (C.5)}$$

in which:

$$\phi_c = \arctan\left(\frac{\tau_a - \tau_b}{\sigma_r - \sigma_b}\right) \qquad \text{… (C.6)}$$

where:

$\phi_c$ is the unloading internal friction angle for an overconsolidated material

NOTE: The value of cohesion $c$ depends strongly on the consolidation stress $\sigma_r$, 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 angle of internal friction $\phi_l$ (which is then is equal to $\phi_c$).

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 have been undertaken, and the flow function and effective angle of internal friction obtained, 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 $\sigma_{vft}$, which is defined in C.2.

(3) The "major principal consolidating stress" $\sigma_c$ should be taken as equal to the maximum mean vertical stress in the silo after filling $\sigma_{vft}$.

(4) The unconfined yield stress $\sigma_u$ corresponding to this consolidation stress should be determined from the flow function. The effective angle of internal friction $\delta$ (determined under the corresponding stress conditions) should also be found.

(5) An approximate value for the cohesion $c$ should then be determined as:

$$c = \sigma_c \left( \frac{\sin\delta - \sin\phi_c}{\cos\phi_c \, (1+\sin\delta)} \right) \quad \ldots \text{(C.7)}$$

in which:

$$\phi_c = \sin^{-1} \left( \frac{2 \sin\delta - k}{2 - k} \right) \quad \ldots \text{(C.8)}$$

$$k = \left( \frac{\sigma_c}{\sigma_u} \right) (1 + \sin\delta) \quad \ldots \text{(C.9)}$$

where:

$\sigma_c$ is the major principal consolidating stress found in a Jenike shear cell test

$\sigma_u$ is the unconfined yield strength found in a Jenike shear cell test

$\delta$ is the effective angle of internal friction found in a Jenike shear cell test

$\phi_c$ is the unloading angle of internal friction (Figure C4 c)

NOTE: It should be noted that the value of cohesion $c$ depends strongly on the consolidation stress $\sigma_r$, so this cannot be regarded as a fixed property of the solid.

NOTE: It should be noted that the major principal consolidating stress $\sigma_c$ is usually referred to as $\sigma_1$ in the bulk solids handling literature.

(6) An approximate value for the loading angle of internal friction $\phi_i$ may be found from this test as

$$\phi_i = \tan^{-1} \left( \frac{\sin\delta \cos\phi_c}{1 - \sin\phi_c \sin\delta} \right) \quad \ldots \text{(C.10)}$$

NOTE: It should be noted that the two parameters $c$ and $\phi_i$ are used in this standard only to define the effects of a stored solid's strength on silo pressures.

## C.10 Effective elastic modulus $E_s$

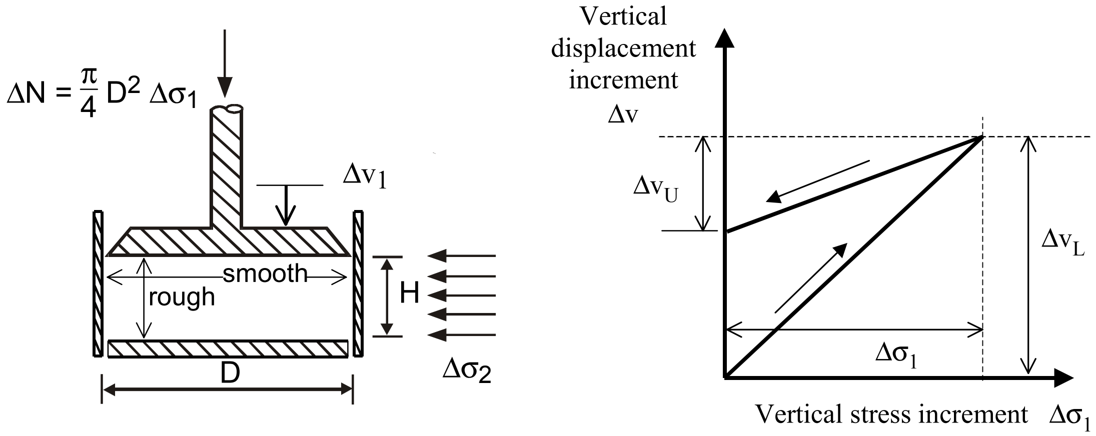
### C.10.1 Direct measurement

#### C.10.1.1 Principle of the test

(1) A vertical stress $\sigma_1$ 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 $\Delta v_1$ 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 $\Delta v_1$ should be measured. The unloading effective elastic modulus $E_{sU}$ should be deduced from these measurements.

NOTE: 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: 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.



**(a) Test apparatus**

**(b) Typical vertical displacements for increments of vertical stress $\Delta\sigma_1$**

**Figure C5: Test Method for determining the loading and unloading elastic moduli**

#### C.10.1.2 Apparatus

(1) The geometry of the test apparatus that should be used is shown in Figure C5 and is similar to the apparatus described in C.8 for the measurement of lateral pressure ratio *K*.

(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 $\sigma_r$ 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 $\sigma_1$ equal to the reference stress $\sigma_r$, 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 $\sigma_1$.

(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 $\Delta v$. The loading incremental value of $K$ should then be determined as $K_L$:

$$K_L = \frac{\Delta\sigma_2}{\Delta\sigma_1} \qquad \text{... (C.11)}$$

(6) The loading effective elastic modulus $E_{sL}$ should then be determined as:

$$E_{sL} = H\frac{\Delta\sigma_1}{\Delta v}\left(1 - \frac{2K_L^2}{1 + K_L}\right) \qquad \text{... (C.12)}$$

(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 $\sigma_1$.

(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 $\Delta v$ (both negative) The unloading incremental value of $K$ should then be determined as $K_U$

$$K_U = \frac{\Delta\sigma_2}{\Delta\sigma_1} \qquad \text{... (C.13)}$$

(9) The unloading effective elastic modulus $E_{sU}$ should then be deduced as:

$$E_{sU} = H\frac{\Delta\sigma_1}{\Delta v}\left(1 - \frac{2K_U^2}{1 + K_U}\right) \qquad \text{... (C.14)}$$

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

$$E_{sU} = \chi\, p_{vft} \qquad \text{... (C.15)}$$

where:

$p_{vft}$ is the vertical stress at the base of the vertical walled section (expression 5.3 or 5.78)

$\chi$ 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 $\chi$ may be estimated as

$$\chi = 7\,\gamma^{3/2} \qquad \text{… (C.16)}$$

where:

$\gamma$ is the unit weight of the stored solid in kN/m$^3$.

(3) The value of $\chi$ 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 should 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) 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 EN1990 Basis of Design, Annex D “Design assisted by testing”, recommends a different value from 1,28. As stated in the above clause, 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.

(4)P Both upper and lower characteristic values of the relevant properties shall be used to obtain the relevant loading conditions.

(5) 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 E1 in Annex E represent a mixture of judgement based on experience and available experimental data.

(6) 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 $\overline{x}$, should be determined from test data.

(3) Where possible, the coefficient of variation $\delta$ 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 C2 may be used as a guide.

(5) The upper characteristic value for the property ($x_u = x_{0,90}$) should be determined as:

$$x_{0,90} = \overline{x}\,(1 + 1{,}28\,\delta) \qquad \text{… (C.17)}$$

(6) The lower characteristic value for the property ($x_\ell = x_{0,10}$) should be determined as:

$$x_{0,10} = \overline{x}\,(1 - 1,\,28\,\delta) \qquad \text{… (C.18)}$$

(7) The conversion factor $a_x$ for the property should be determined as:

$$a_x = \sqrt{\frac{1 + 1{,}28\,\delta}{1 - 1{,}28\,\delta}} \approx 1 + 1{,}28\delta + \delta^2 \qquad \text{… (C.19)}$$

(8) Where the values must be estimated, the coefficient of variation $\delta$ 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 C2.

### Table C2 Typical values of the coefficient of variation of particulate solids properties

| | **Coefficient of variation δ** | | | | |
|---|---|---|---|---|---|
| **Bulk solid** | **Lateral pressure ratio ($K$)** | **Angle of internal friction ($\phi_i$)** (degrees) | **Wall friction coefficient ($\mu$)** | | |
| | | | Wall friction category | | |
| | | | Type Dl | 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

(1) 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

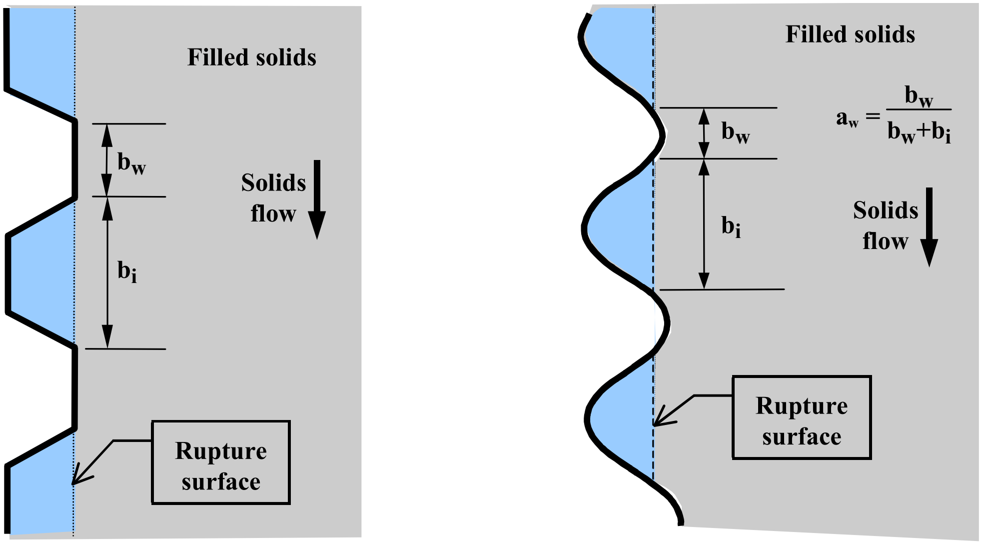
(1) For wall Type D4 (corrugated or profile steel sheeting or walls with horizontal ribs), the effective wall friction should be determined as:

$$\mu_{eff} = (1 - a_w) \tan\phi_i + a_w \mu_w \qquad \text{... (D.1)}$$

where:

$\mu_{eff}$ is the effective wall friction coefficient;
$\phi_i$ is the angle of internal friction;
$\mu_w$ is the wall friction coefficient (against a flat wall surface);
$a_w$ is the wall contact factor.

NOTE: For wall Type 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.



a) Trapezoidal corrugated profile b) Sinusoidal corrugated profile

**Fig. D1 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, with an appropriate estimate made of the solid/wall contact regime (Fig. D1):

$$a_w = \frac{b_w}{b_w + b_i} \qquad \text{... (D.2)}$$

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 $a_w$. This proportion cannot be simply defined, and should be estimated according to the sheeting profile.

NOTE: For wall sheeting profiles similar to that shown in Fig, D1b, 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 $\mu$ and the angle of internal friction $\phi_i$ 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 $\phi_i$ should be taken as equal to the angle of repose $\phi_r$. 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 E1.

**Table E1 - Particulate solids properties †**

| Type of particulate solid | Unit weight $\gamma$ | | Angle of repose $\phi_r$ | Angle of internal friction $\phi_i$ | | Lateral pressure ratio $K$ | | Wall friction coefficient ‡ $\mu$ ($\mu = \tan \phi_w$) | | | | Patch load solid reference factor $C_{op}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\gamma_\ell$ | $\gamma_u$ | $\phi_r$ | $\phi_{Im}$ | $a_\phi$ | $K_m$ | $a_K$ | Wall type D1 | Wall type D2 | Wall type D3 | $a_\mu$ | |
| | Lower | Upper | | Mean | Factor | Mean | Factor | Mean | Mean | Mean | Factor | |
| | kN/m³ | kN/m³ | degrees | degrees | | | | | | | | |
| Default material * | 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 |

† Where this table does not contain the material to be stored, testing should be undertaken.

* 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.

‡ Effective wall friction for wall Type D4 (corrugated wall) may be found using the method defined in Annex D2.

∝ Solids in this table that are known to be susceptible to dust explosion are identified by the symbol ∝

☐ Solids that are susceptible to mechanical interlocking are identified by the symbol ☐

NOTE: The unit weight of the solid $\gamma_u$ is the upper characteristic value, to be used for all calculations of actions. The lower characteristic value $\gamma_\ell$ is provided in Table E1 to assist in estimating the required volume of a silo that will have a defined capacity.

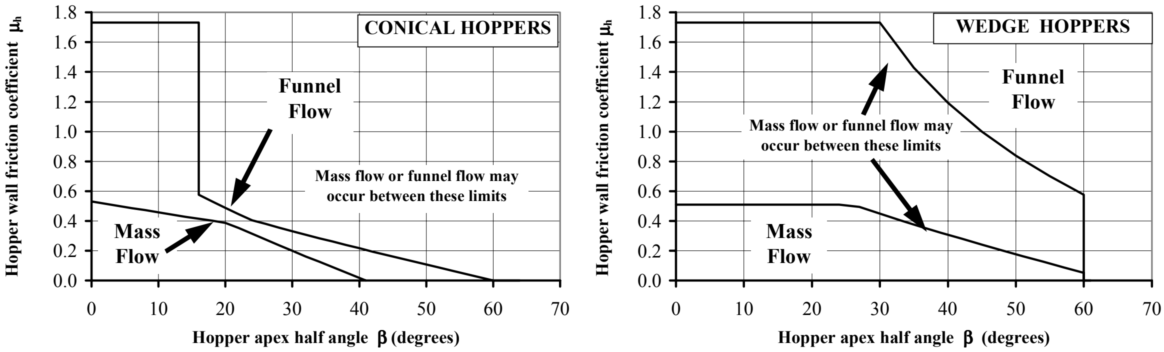
# Annex F

(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 following information 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 H is used.



**a) Conical hoppers** **b) Wedge hoppers**

**Figure F1 The conditions under which mass flow or funnel flow occur in conical and wedge-shaped hoppers**

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.

# Annex G

(Informative)

## Seismic Actions

NOTE: This annex should be removed when this topic is covered in EN 1998.

### G.1 General

(1) This annex gives general guidance for the design of silos for seismic actions. The design rules supplement general rules for the calculation of seismic actions on structures given in EN 1998 and may be incorporated into EN 1998 at a later stage.

(2) The value of the earthquake acceleration for the silo structure is calculated according to EN 1998. The silo and the particulate solid may be regarded as a single rigid mass.

### G.2 Notation

$\alpha$ effective horizontal acceleration due to earthquake, accounting for spectral amplification of the acceleration spectrum, importance factor for the structure and the effects of modal waveform, where appropriate

$\Delta p_{h,so}$ additional horizontal pressure due to seismic actions

### G.3 Design situations

(1) The following design situations should be considered:

- horizontal accelerations and the resulting vertical loads on silo supports and foundations (G.4.1);
- additional loads on the silo walls (G.4.2);
- a rearrangement of the particulate solid at the top of the silo. The seismic action may cause the stored solid to form slip lanes endangering the roof construction and the silo walls in the upper region (Figure G1).

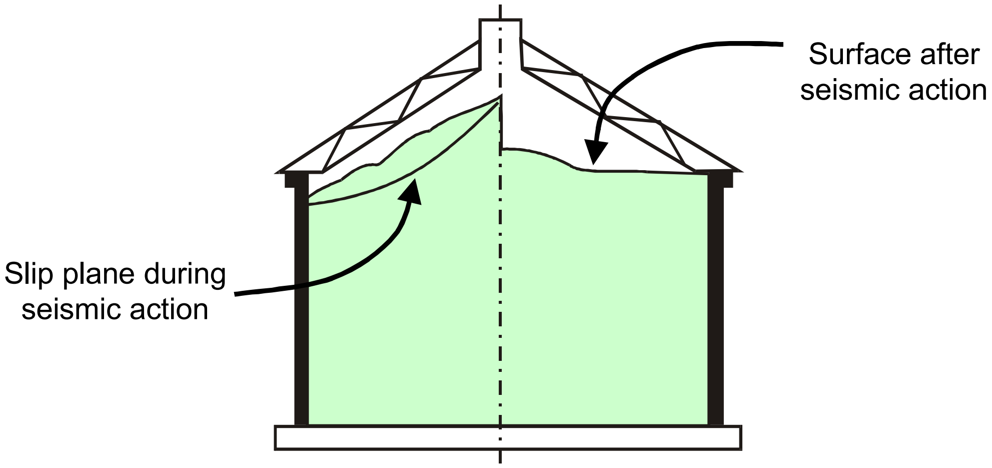


**Figure G1: Redistribution of particulate solids at the top of the silo**

### G.4 Seismic actions

(1) Guidance for calculation of seismic actions on silo supports and silo foundations is given in G.4.1 and guidance on silo walls is given in G.4.2.

#### G.4.1 Silo supports and foundations

(1) Seismic actions due to the weight of the silo and the particulate solid may be regarded as a single force acting at the centre of gravity of the combined structure and particulate solid (Figure G2).

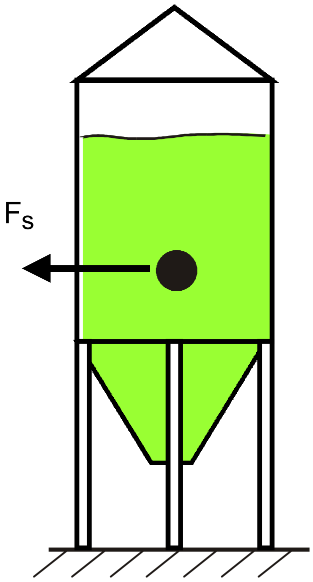


**Figure G2: Seismic action for substructure**

#### G.4.2 Silo walls

(1) A horizontal load should be used to represent the effect of seismic action on the structure, and superposed on the loads due to stored solids defined in Sections 5 and 6. The total load is equivalent to the mass of the particulate solid multiplied by the value of the earthquake horizontal acceleration $\alpha$.

(2) The reference value of the additional normal pressure on the wall due to seismic action for a circular silo of diameter $d_c$ is given by:

$$\Delta p_{h,so} = \gamma \frac{\alpha}{g} \frac{d_c}{2} \qquad \text{… (G.1)}$$

and for a rectangular silo of width $b$ is given by:

$$\Delta p_{h,so} = \gamma \frac{\alpha}{g} \frac{b}{2} \qquad \text{… (G.2)}$$

where:

$\gamma$ is the bulk unit weight

$\alpha$ is the horizontal seismic acceleration

$g$ is the acceleration due to gravity

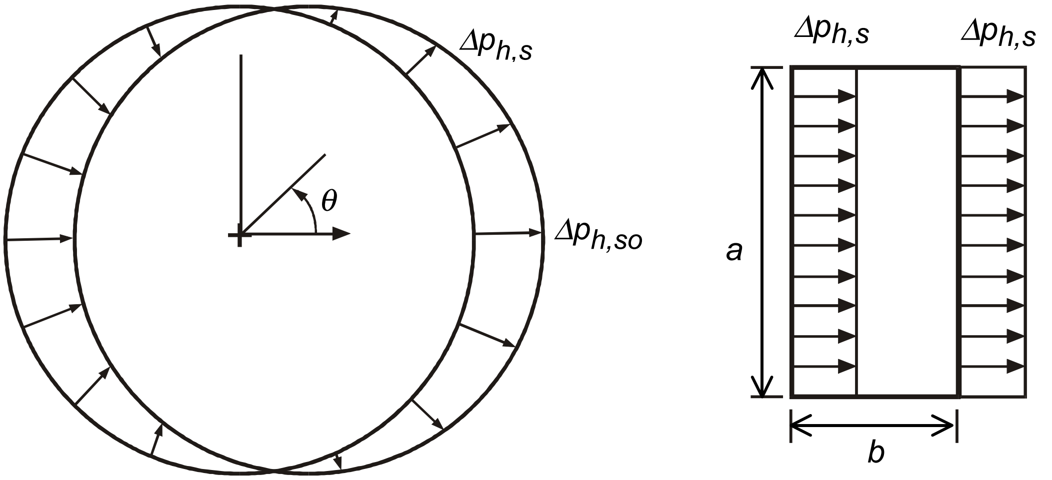
(3) The additional normal pressure may be taken as constant over the height of the silo except near the top of the silo where the resultant of the seismic pressure and the filling or discharge pressure should not be less than zero.

(4) The horizontal distribution of the additional pressure $\Delta p_{h,s}$ is shown in Figure G3. For a circular silo, the additional pressure $\Delta p_{h,s}$ should be taken as:

$$\Delta p_{h,s} = \Delta p_{h,so} \cos\theta \qquad \text{… (G.3)}$$

For a rectangular silo, $\Delta p_{h,s}$ should be taken as:

$$\Delta p_{h,s} = \Delta p_{h,so} \qquad \text{… (G.4)}$$



**a) circular planform silo** **b) rectangular planform silo**

**Figure G3: Plan view of the additional horizontal pressure due to seismic actions on the vertical walled segments of silos**

# Annex H

(Informative)

# Alternative rules for pressures in hoppers

## H.1 General

(1) This annex gives two alternative methods of assessing the pressures in hoppers.

(2) The method defined in H.2 to H.5 may be used to define hopper pressures under both fililng 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 H.10 may alternatively be used in conjunction with those of 6.3 to define the discharge pressures in steep hoppers.

## H.2 Notation

| | |
|---|---|
| $l_h$ | inclined distance from hopper apex to the transition (Figure H1) |
| $p_n$ | 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 |

## H.3 Terminology

### H.3.1

**kick load:**
A local load that can occur at the transition during discharge from a mass flow silo.

## H.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 F1 in Annex F.

(3) Where a silo may flow in either mass flow or funnel flow, the design should account for both possible flow modes.

## H.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:

$$C_b = 1{,}3 \qquad \text{… (H.2)}$$

(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:

$$C_b = 1{,}6 \qquad \text{… (H.3)}$$

(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 Annex C.9. The cohesion is classed as low if, following consolidation to a normal stress level $\sigma_r$, the assessed cohesion $c$ exceeds $c/\sigma_r = 0,04$ (see 1.5.23).

### H.6 Filling pressures on flat and nearly-flat bottoms

(1) Vertical loads acting on flat or nearly-flat silo bottoms (inclinations $\alpha \leq 20°$) should be calculated using:

$$p_{\mathrm{vf}} = C_{\mathrm{b}}\, p_{\mathrm{v}} \qquad \text{… (H.4)}$$

where:

$p_v$ is calculated using expression 5.3 or 5.78 at the relevant depth $z$ below the equivalent surface.

$C_b$ is the bottom load magnifier

### H.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:

$$p_n = p_{n3} + p_{n2} + (p_{n1} - p_{n2})\frac{x}{l_h} \qquad \text{… (H.5)}$$

in which:

$$p_{n1} = p_{v0}\,(C_b \sin^2\beta + \cos^2\beta) \qquad \text{… (H.6)}$$

$$p_{n2} = p_{v0}\, C_b \sin^2\beta \qquad \text{… (H.7)}$$

$$p_{n3} = 3{,}0\,\frac{A}{U}\,\frac{\gamma K_s}{\sqrt{\mu}}\,\cos^2\beta \qquad \text{… (H.8)}$$

where:

$\beta$ is the slope of the hopper to the vertical (see Figure H1)

$x$ is a length between 0 and $l_h$ (see Figure H1)

$p_{n1}$ and $p_{n2}$ define the pressure distribution due to filling

$p_{n3}$ is the hopper pressure due to the vertical pressure in the stored material at the transition.

$C_b$ is the bottom load magnifier

$p_{v0}$ is the vertical pressure acting at the transition after filling, calculated using expression 5.3 or 5.78 as appropriate.

(2) The value of the wall frictional pressure $p_t$, is given by:

$$p_t = p_n \mu \qquad \text{… (H.9)}$$

where:

$p_n$ is calculated from expression H.5.

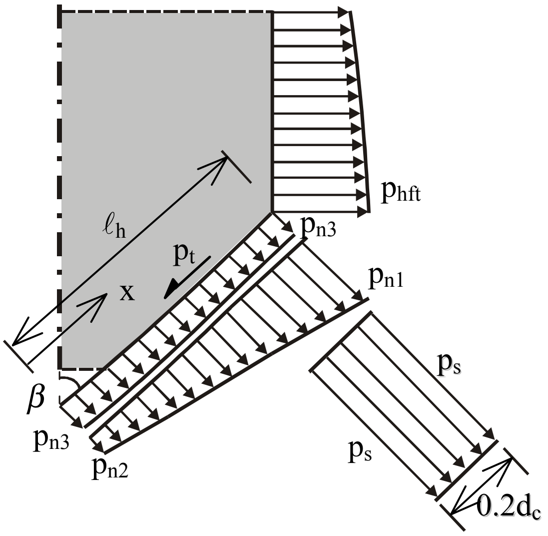


**Figure H1 Alternative rule for hopper loads**

## H.8 Discharge pressures on flat or nearly-flat bottoms

(1) For flat or nearly-flat silo bottoms (inclinations $\alpha \leq 20°$), the discharge load may be calculated using the guidance for filling loads (H.6).

## H.9 Discharge pressures on hoppers

(1) For funnel flow silos, the discharge loads on hoppers may be calculated using the guidance for filling loads (H.7).

(2) For mass flow silos, an additional fixed normal pressure, the kick load $p_s$ (Figure H1) is applied, over an inclined distance of $0{,}2d_c$ down the hopper wall and all around the perimeter.

$$p_s = 2\,K\,p_{vft} \qquad \text{(H.10)}$$

where:

$p_{vft}$ is the vertical pressure acting at the transition after filling calculated using expression 5.3 or 5.78 as appropriate.

## H.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:

$$F_e = \left(\frac{1}{1 + \mu \cot\beta}\right)\left\{1 + 2\left[1 + \left(\frac{\sin\phi_i}{1+\sin\phi_i}\right)\left(\frac{\cos\varepsilon \sin(\varepsilon-\theta)}{\sin\theta}\right)\right]\right\} \qquad \text{… (H.11)}$$

in which:

$$\varepsilon = \beta + \frac{1}{2}\left(\phi_{wh} + \sin^{-1}\left\{\frac{\sin\phi_{wh}}{\sin\phi_i}\right\}\right) \qquad \text{… (H.12)}$$

$$\phi_{wh} = \tan^{-1} \mu_h \qquad \ldots \text{(H.13)}$$

where:

$\mu_h$ is the lower characteristic value of wall friction coefficient in the hopper

$\phi_i$ is the angle of internal friction of the stored solid

NOTE: Where this theory of hopper pressures is adopted, expression H.11 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 I

(Informative)

# Actions due to dust explosions

## I.1 General

(1) This annex gives advice on appropriate design for actions due to dust explosion.

## I.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.

## I.3 Notation

| | |
|---|---|
| $p_{max}$ | maximum overpressure |
| $p_{red}$ | reduced maximum explosion pressure. |
| $p_a$ | initial release pressure |

## I.4 Additional regulations and literature

(1) Additional regulations and useful references can be found in ……

## I.5 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 8-10 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 pressure rise rate (dp/dt).

(5) The design parameters may be found by the methods defined in DIN 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.

### I.6 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.

### I.7 Protecting precautions

(1) The damage due an explosion is minimised 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 minimised.

(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).

(3) 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.

### I.8 Design of structural elements

(1) The design pressure of the explosion should be treated as an accidental load on all structural elements.

### I.9 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.

### I.10 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 design. These effects are associated with the explosion and can result in an underpressure that should be considered in the design.

### I.11 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).

(2) The velocity of moving elements should be calculated by means of design methods given in ---.

### I.12 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.

(2) Simplified rules to evaluate the reaction forces may be found in ---- .