Bauforschung

Vorentwurf zu ENV 1991-4
Eurocode 1: Basis of Design and Actions on Structures
Part 4: Actions on Silos and Tanks

T 2571

Fraunhofer IRB Verlag

T 2571

Dieser Forschungsbericht wurde mit modernsten Hochleistungskopierern auf Einzelanfrage hergestellt.

Die in dieser Forschungsarbeit enthaltenen Darstelungen und Empfehlungen geben die fachlichen Auffassungen der Verfasser wieder. Diese werden hier unverändert wiedergegeben, sie geben nicht unbedingt die Meinung des Zuwendungsgebers oder des Herausgebers wieder.

Die Originalmanuskripte wurden reprotechnisch, jedoch nicht inhaltlich überarbeitet. Die Druckqualität hängt von der reprotechnischen Eignung des Originalmanuskriptes ab, das uns vom Autor bzw. von der Forschungsstelle zur Verfügung gestellt wurde.

Fraunhofer IRB Verlag
Fraunhofer-Informationszentrum Raum und Bau

Postfach 80 04 69
70504 Stuttgart

Nobelstraße 12
70569 Stuttgart

Telefon (07 11) 9 70 - 25 00
Telefax (07 11) 9 70 - 25 08

E-Mail irb@irb.fraunhofer.de

www.baufachinformation.de

Massivbau
Baustofftechnologie
Karlsruhe

Schlußbericht zum Forschungsvorhaben
IV 1-5-690/92

Vorentwurf zu ENV 1991-4

Eurocode 1: Basis of Design and Actions on Structures

Part 4: Actions on Silos and Tanks

von
Prof. Dr.-Ing. J. Eibl

Universität Karlsruhe
Institut für Massivbau und Baustofftechnologie
Abteilung Massivbau
Leitung Prof. Dr.-Ing. J. Eibl
1993

Vorbemerkung:

Im Rahmen der Mitarbeit als Experte bei der europäischen Arbeitsgruppe EC1/SC1/PT8, die einen Vorschlag für ein Normpapier zur Lastnorm im Bereich 'Silos und Tanks' ausformulieren sollte, sind umfangreiche Arbeiten für die Entwicklung von Textfassungen und für Vergleichs- und Kontrollrechnungen angefallen, die freundlicherweise durch das Institut für Bautechnik, Berlin, im Rahmen des Forschungsvorhabens

Ergänzende Untersuchungen für einen Vorentwurf zu
Eurocode 1, Basis of Design and Actions on Structures
Teil 4, 'Silos und Tanks'

unter der Kennziffer IV - 1 - 5 - 690/92 unterstützt wurden.

Für die Förderung dieser Untersuchungen sei dem Institut für Bautechnik, Berlin, unser besonderer Dank ausgesprochen.

Forschungsvorhaben

Ergänzende Untersuchungen für einen Vorentwurf zu Eurocode 1,
'Basis of Design and Actions on Structures'
Part 4, 'Actions on Silos and Tanks'
IV - 1 - 5 - 690/92

Zur Vorbereitung des gemeinsamen europäischen Binnenmarktes waren vom Europäischen Normen Comitee (CEN) für die Entwicklung einer gemeinsamen europäischen Regelung der Lastnorm EC1 'Basis of Design and Actions on Structures' eine Reihe von Expertengruppen zur Bearbeitung der dabei angesprochenen verschiedenen Teilgebiete ins Leben gerufen.

In der Arbeitsgruppe EC1/SC1/PT 8 'Silos and Tanks', in die der Verfasser als deutscher Experte berufen wurde, sollte ein Entwurf für die Lasten in Silozellen und für Tanklasten ausgearbeitet werden.

Der nunmehr vorliegende Entwurf basiert auf einer Normvorlage der International Standardisation Organization (ISO) ''Loads due to bulk materials'' (ISO/DIS 11697) sowie auf dem Arbeitspapier ''Silo-Design'' der Féderation International de la Précontrainte (FIP), die in gleichnamigen Arbeitsgruppen bereits vorher unter der Leitung des Verfassers erarbeitet worden war.

Der nunmehr vorliegende ca. 40 seitige Entwurf beinhaltet die spezifischen prinzipiellen Regelungen der Lastannahmen für allgemein übliche Silo- und Tankanlagen, das sind im wesentlichen offene Tanks bzw. Silos mit begrenzten Füll- und Entleerungsexzentrizitäten für relativ frei fließende granulare Schüttgüter.

Ein erster erarbeiteter Textentwurf auf der Basis der bereits erwähnten ISO-Normvorlage wurde an die zuständigen Normstellen der verschiedenen Länder mit der Bitte um Stellungnahme geschickt. Die daraufhin eingegangenen Einwände und Einsprüche mußten geprüft, erörtert und schließlich kommentiert bzw. eingearbeitet werden.

Der vorliegende Textentwurf mußte mit dem Text der Gesamtnorm abgestimmt werden und in die relevanten Sicherheitskonzepte der Eurocodes eingebunden werden.

Maßgebliche Lastkombinationen wurden zusammengestellt und diskutiert. Eine Regelung mit entspechenden Kombinationsbeiwerten wurde in den informativen Teil der Anlage zur Normvorlage aufgenommen.

Zum Teil aus der Prüfung und Diskussion der Einwände und Einsprüche heraus sowie begründet durch die erforderliche Einbindung in das Sicherheitskonzept der Eurocodes waren eine Reihe ergänzender Untersuchungen zu verschiedenen Fragestellungen durchzuführen, die im Rahmen dieser Forschungsvorhabens dankenswerterweise durch das Institut für Bautechnik, Berlin, unterstützt wurden:

- zu Füll- und Entleerungslasten in Silotrichtern
  - Vergleich und Abstimmung mit Lastansätzen anderer internationaler Normen;
  - Vergleich mit aus der Literatur bekannten theoretischen und experimentellen Untersuchungen;
  - Vergleich mit FEM-Berechnungen, durchgeführt mit unserem Rechencode 'SILO';
- zum Bodendruck in Silos mit flachen Böden
  - Vergleich und Abstimmung mit aus der Literatur bekannten experimentellen Untersuchungen;
  - Vergleich mit FEM-Berechnungen mit Hilfe des Rechencodes 'SILO;'
- zur Festlegung geeigneter Schüttgutkennwerte
  - Vergleichende Berechnungen mit DIN 1055/6 und ISO/DIS 11697;
  - Kontrolle der Auswirkung auf die Horizontal- und Bodendrücke und die aufsummierten Wandreibungslasten;
- Zu den Erdbebenbeanspruchungen von Silobauwerken mit den speziellen Fragestellungen:
  - Gefährdung von Dachkonstruktionen bei flachen Silos durch Abrutschen von aufgeschütteten Schüttgutböschungen;
  - Unterstützungkonstruktionen;
  - Erhöhung der horizontalen Silodrücke.

Über die Vorlage des ISO/DIS 11697 hinaus mußten ergänzende Textvorschläge u.a. zu den Themenkomplexen Temperaturlasten, Lasten infolge Erdbebeneinwirkungen, Lasten auf Tankanlagen und Lasten aus Staubexplosionen ausgearbeitet werden.

Über die Mitarbeit des Verfassers in der Expertengruppe konnten die Ergebnisse dieser ergänzenden Untersuchungen direkt in die laufenden Arbeiten zur Ausformulierung des Normenvorschlages eingebracht und berücksichtigt werden.

Dieser Vorentwurf ist in seiner Strukturierung und Formulierungen mit den Vorgaben der anderen Teilgebiete des EC1 "Basis of Design" abgestimmt (Guidelines for Project Teams CEN TC 250/SC1/91/N42).

Der Vorentwurf wurde zwischenzeitlich in seiner englischen Fassung (vorliegenden Textentwurf CEN/TC 250/SC 1/1993/N 108) in der CEN/TC 250/SC1 Sitzung in Berlin beraten und soll nach letzten Korrekturen als ENV 1991-4 verabschiedet werden.

Summary:

Created in 1993 the European Common Market strives for balanced national regulations and demands harmonised European Standards. This anticipating the Committee for European Standardization (CEN) had established a series of working groups with various responsibilities in order to develop common European standards with regard to basis of design and actions on structures among others.

The working group EC1/SC1/PT8 'Actions on Silos and Tanks', which the author as German expert had been appointed to, was charged to draft the corresponding part of a common European standard. Though experience and corresponding national regulations and a first multinational sketch were already available, nevertheless there had to be done a series of additional investigations in order to elaborate a well grounded and balanced standard draft. These studies have been supported by the Institut für Bautechnik, Berlin, which we would like to thank for its gratitude.

Studies had to be performed with regard to filling and discharge loads in hoppers as well as to bottom pressures of flat bottomed silos. Checking the influence of material properties on horizontal wall pressures, vertical bottom pressures and wall frictional pressures a lot of numerical comparisons had to be done to select proper values. For seismic actions on silos and tanks a series of special problems had to be treated generally by numerical simulations. Finally the general concept had to be adapted to the relevant safety regulations.

The results of these additional investigations could be directly used during the ongoing work on formulating the draft of ENV 1991-4. In the mean time the english version of this prestandard has been discussed and after some further amendments will become valid soon.

Résumé:

Le marché commun européen réalisé depuis 1993 impose certains équilibrages et requiert des normes européennes élargies. Un certain nombre de groupes de travail furent crées pour les différentes sections par le Comité des Normes Européennes (CEN), entre outres, afin de développer une norme européenne commune pour le béton armé et le béton précontraint.

Le groupe de travail EC1/SC1/PT8 "Actions on Silos and Tanks", dans lequel l'auteur fut nommé comme expert allemand, élaborâ un projet pour la partie correspondante d'une norme européenne élargie.

Même s'il y avait déjà des normes nationales, une première norme commune et également l'expérience, qui en résulte, pour l'élaboration d'une proposition de norme qui soit fondée et bien ponderée, une série d'études complémentaires furent necéssaires, qui grace à l' Institut für Bautechnik, Berlin, ont pu être accompliées.

En plus des études concernant les actions, qui apparaissent dans les trémies des silos pendant le remplissage respectivement la vidange, des investigations numériques sur les pressions dans la plaque de fond ont été effectuées.

Dans le but d'établir des valeurs appropriées pour les charactéristiques des matériaux emmagasinés et de controler l'effet, qu'ils peuvent l'avoir sur les pressions horizontales, sur la plaque de fond et sur les charges provoquées par le frottement du mur, des volumineux calcules comparatifs ont été faits.

Pour les questions spéciales, qui sont impliquées par les actions sismiques dans les silos, de simulations numériques ont été également faites. Finalement le concept général a été assorti et lié avec la théorie de la securité correspondante.

Grace à la collaboration dans le cadre du groupe de travail, les résultats de ces études complémentaires purent être directement insérés dans la formulation actuelle du projet de norme ENV 1991-4, qui entretemps apparut déjà dans sa version anglaise.

CEN/TC250/SC1/1993/N108

ENV 1991-4

EUROCODE 1: Basis of Design and Actions on Structures

Part 4: Actions on Silos and Tanks

CEN/TC250/SC1
Technical Secretariat
June 1993

EUROCODE 1: PART 4

ACTIONS C' SILOS AND TANKS

CONTENTS Page No.

1. INTRODUCTION

1.1 Scope

(1) The following subjects are dealt with in this Part 4 of ENV 1991 Eurocode 1.

Chapter 2	General principles and rules
Chapter 3	Design situations
Chapter 4	Loads on silos from particulate materials
Chapter 5	Loads on tanks from liquids
Annex A	Combination values
Annex B	Test methods for particulate material properties
Annex C	Seismic actions in silos

1.2 Field of Application

(1) Part 4 of ENV 1991 provides general principles and actions for the structural design of tanks and silos including some geotechnical aspects and shall be used in conjunction with Part 1 of ENV 1991 "Basis of Design" other parts of ENV 1991 and ENV 1992-1999.

(2) Part 4 may also be used as a basis for the design of structures not covered in ENV 1992-1999 and where other materials or other structural design actions are involved.

(3) Part 4 also covers structural design during execution and structural design for temporary structures relating to the subjects mentioned in 1.1(1). It relates to all circumstances in which a structure is required to give adequate performance.

(4) Part 4 of ENV 1991 is not directly intended for the structural appraisal of existing construction in developing the design of repairs and alterations or assessing changes of use.

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

- The silo cross section shapes are limited to those shown in Figure 1.1.
- Filling involves only negligible inertia effects and impact loads.
- The maximum particle diameter of the stored material is not greater than $0,03d_c$.

- The stored material is free-flowing.
- The eccentricity e_i of the stored material due to filling is less than $0,25d_c$.
- The eccentricity e_o of the centre of the outlet is less than $0,25d_c$ and no part of the outlet is at a distance greater than $0,3d_c$ from the centre plane of silos with plane flow or the centre line of other silos (Figure 1.1).
- Where discharge devices are used (for example, feeders or internal flow tubes), material flow is smooth and central within the eccentricity limits given above.
- The transition is on a single horizontal plane.
- The following geometrical limits apply:

$$h/d_c < 10$$
$$h < 100 \text{ m}$$
$$d_c < 50 \text{ m}$$

- Each silo is designed for a defined range of particulate material properties.

1.3 Distinction between Principles and Application Rules

(1) Depending on the character of the individual clauses, distinction is made in this Part 4 of ENV 1991 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 preceded by the letter P.

(4) The Application Rules are generally recognized rules which follow the Principles and satisfy their requirements.

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

(6) In this Part 4 of ENV 1991 the Application Rules are identified by a number in brackets e.g. as this clause.

1.4 Notations

(1) Unless defined otherwise in the following, the notation used in International Standard ISO 3839:1987 is adopted.

(2) A comprehensive list of notations is provided in Part 1 'Basis of design' of ENV 1991 and the additional notations below are specific to Part 4.

A	cross-sectional area of vertical walled section
C	wall load magnifier
C_0	maximum wall load magnifier
C_b	bottom load magnifier
C_h	horizontal load magnifier
C_w	wall frictional traction magnifier
C_z	Janssen coefficient
d_c	characteristic cross-section dimension (Figure 1.1)
e	the larger of e_i and e_o
e_i	eccentricity due to filling (Figure 1.1)
e_o	eccentricity of the centre of the outlet (Figure 1.1)
F_p	total horizontal force due to patch load on thin walled circular silo
h	distance from outlet to equivalent surface (Figure 1.1)
h_1,h_2	parameters used in the determination of vertical pressures in squat silos
K_s	design value of horizontal/vertical pressure ratio
$K_{s,m}$	mean value of horizontal/vertical pressure ratio
l_h	hopper wall length (Figure 4.3)
p	hydrostatic pressure

p_h	horizontal pressure due to stored material
p_{he}	horizontal pressure during discharge (Figure 1.1)
$p_{he,s}$	horizontal pressure during discharge calculated using the simplified method
p_{hf}	horizontal pressure after filling
$p_{hf,s}$	horizontal pressure after filling calculated using the simplified method
p_{ho}	horizontal pressure after filling at the base of the vertical walled section
p_n,p_{ni}	pressure normal to inclined hopper wall, i = 1, 2 and 3
p_p	patch pressure
$p_{p.sq}$	patch pressure in squat silos
p_{ps}	patch pressure (thin walled circular silos)
p_s	kick pressure
p_t	hopper frictional traction (Figure 1.1)
p_v	vertical pressure due to stored material (Figure 1.1)
p_{vi}	vertical pressure components used to determine the vertical pressure in squat silos, i = 1, 2, 3
p_{ve}	vertical pressure during discharge
p_{vf}	vertical pressure after filling
$p_{vf,sq}$	vertical pressure after filling in squat silos
p_{vo}	vertical pressure after filling at the base of the vertical walled section
p_w	wall frictional pressure on the vertical section (figure 1)

p_{we} wall frictional pressure during discharge

$p_{we,s}$ wall frictional traction during discharge calculated using the simplified method

p_{wf} wall frictional pressure after filling

$p_{wf,s}$ wall frictional traction after filling calculated using the simplified method

P_w resulting vertical load per unit perimeter of the vertical walled section.

s dimension of the zone affected by the patch load ($s=0,2d_c$)

t wall thickness (Figure 1.1)

U internal perimeter of the vertical walled section

w width of a rectangular silo

x parameter used to calculate hopper loads

z depth below the equivalent surface at maximum filling

z_0 parameter used to calculate loads

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

β patch load magnifier

γ bulk weight density of liquid or stored material

γ_1 bulk weight density of fluidised stored material

θ circumferential angular coordinate

μ design value of coefficient of wall friction for pressure calculation

μ_m mean value of coefficient of wall friction for pressure calculation

φ effective angle of internal friction

φ_w angle of hopper wall friction for flow evaluation

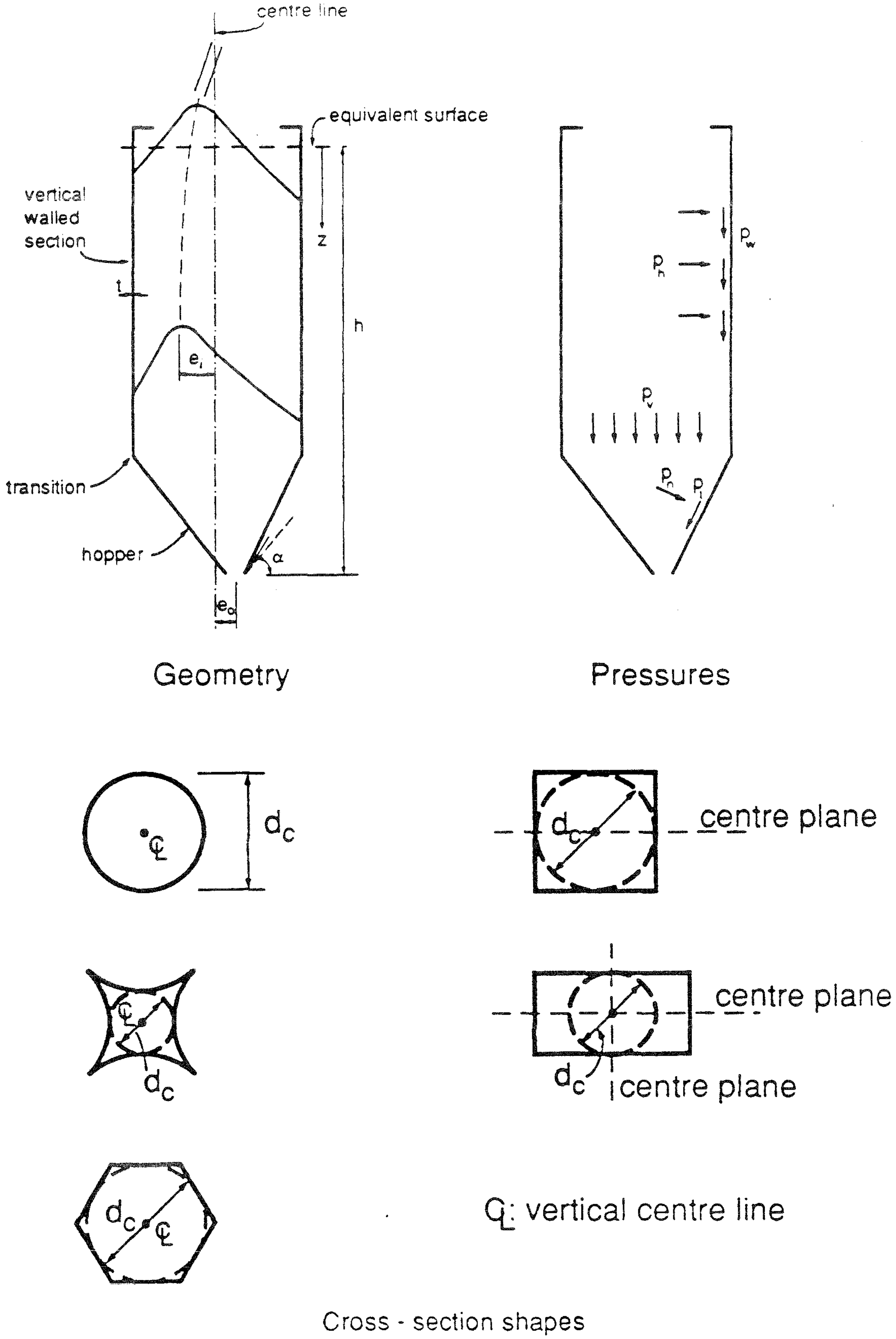


Figure 1.1 Silo forms showing dimensions and pressure notation

1.5 Definitions

(1) A comprehensive list of definitions is provided in Part 1 'Basis of Design' of ENV 1991, and the additional definitions in part 4 of ENV 1991 are specific to this part.

(2) **Equivalent surface.** Level surface giving the same volume of stored material as the actual surface (Figure 1.1).

Flat bottom. A flat silo bottom or a silo bottom with inclined walls where

$\alpha \leq 20°$.

Flow pattern. The form of flowing material in the silo when flow is well established. (Figure 1.2). The silo is close to its maximum filling condition.

Fluidised material. A stored material injected with air, which significantly changes the behaviour of the stored material.

Free flowing material. A material with a low cohesion.

Funnel Flow (or **Core Flow**) (Figure 1.2). A flow pattern in which a channel of flowing material develops within a confined zone above the outlet, and the material adjacent to the wall near the outlet remains stationary. The flow channel may intersect the vertical walled section or extend to the surface of the stored material.

Homogenizing silo. A silo containing a fluidised material.

Hopper. A silo bottom with inclined walls where $\alpha > 20°$.

Internal Flow (Figure 1.2). A funnel flow pattern in which the flow channel extends to the surface of the stored material.

Kick load. A local load that occurs at the transition during discharge.

Low cohesion. A material sample has low cohesion if the cohesion is less than 4kPa when the sample is preconsolidated to 100kPa. (A method for determining cohesion is given in Annex B).

Mass Flow (Figure 1.2). A flow pattern in which all the stored particles are mobilised soon after the start of discharge.

Patch Load. A local load taken to act over a specified zone on any part of a silo wall.

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.

Silo. Containment structure used to store particulate materials (i.e. bunkers, bins, and silos).

Slender silo. A silo where $h/d_c \geq 1,5$.

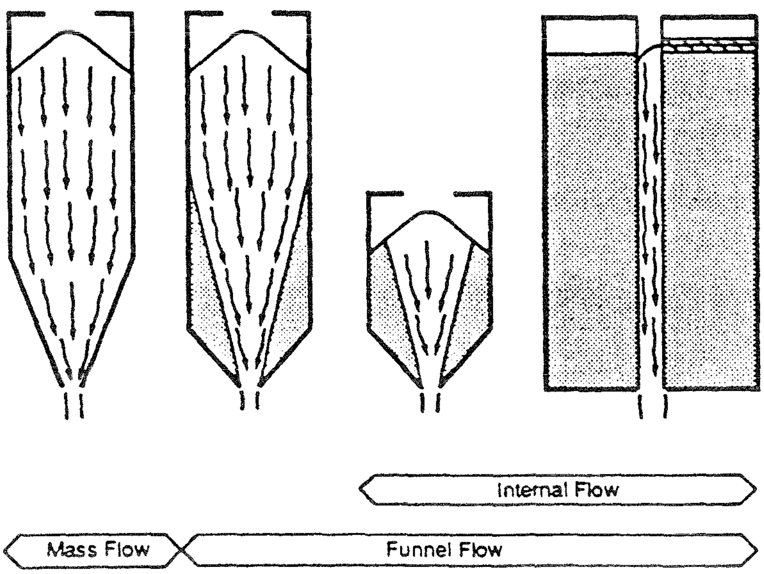
Squat silo. A silo where $h/d_c < 1,5$.

Tank. Containment structure used to store liquids.

Thin walled circular silo. A silo with a circular cross section, no stiffeners and where $d_c/t > 200$.

Transition The intersection of the hopper and the vertical walled section.

Vertical walled section. The part of a silo or a tank with vertical walls.



2 GENERAL PRINCIPLES AND RULES

P(1) Loads due to stored materials are classified as variable actions, see ENV 1991-1

P(2) The structural form of the silo shall be selected to give low sensitivity to load deviations.

P(3) Loads due to particulate materials shall be calculated for filling and for discharge. The magnitude and distribution of the design loads depend on the silo structure, the stored mateial properties and the flow patterns which arise during the process of emptying.

(4) The inherent variability of stored materials and simplifications in the load models lead to differences between actual silo loads and loads given by the design rules in Section 4. 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.

(5) Simplified rules for the prediction of flow patterns (Figure 4.1) may be used for the calculation of actions in silos.

(6) Simplified rules for the prediction of flow patterns (Figure 4.1) should not be used for the design of silos for flow.

P(6) The actions from adjoining structures shall be considered.

P(7) The design rules for tanks apply only to tanks storing liquids at normal atmospheric pressure.

3 ASSESSMENT OF ACTIONS

3.1 General

P(1) The relevant silo loads shall be determined for each design situation identified in accordance with part 1 "Basis of Design" of ENV 1991 and ANNEX A of this document. The arrangement of silo loads for load cases in a particular design situation are indicated below.

(2) The partial factors for the ultimate limit states can be taken as for buildings from table 3 in Basis of Design.

3.2 Ultimate limit state.

Persistent and transient situations

P(1) The load cases which have to be considered for ultimate limit state verifications are in general caused by a persistant or transient design situation.

(2) Thermal actions can include climatic effects and the effects of hot materials. Design situations that shall be considered include:

- Hot material filled into a partly filled silo or tank. The effects of heated air above the stored material shall be considered.
- Resistance to silo wall contraction from the stored material during cooling.

(3) 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.

P(4) Prefabricated silos shall be designed for actions due to handling, transport and erection.

P(5) Loads arising from the maximum possible filling shall be considered.

Accidental situations

P(6) The following accidental actions shall be considered

- actions due to explosions (3.2(7), 3.2(8) and 3.2(9))
- actions due to vehicle impact (refer to chapter 1 "Accidental actions" of ENV 1991-2)
- seismic actions (refer to Annex C and ENV 1998)
- actions due to fire (refer to chapter 1 of "Accidental actions from fire" of ENV 1991-2.)

(7) Tanks and silos may be used to store liquids or particulate materials that may cause explosions. Some of the materials that may lead to dust explosions are listed in table 4.1.

(8) The potential dama ge from dust explosions should be limited or avoided by appropriate choice of one or more of the following:

- incorporating sufficient pressure relief area,
- designing the structure to resist the explosion pressure.

(9) The explosion pressure in a silo without adequate relief area may be as high as 1 MPa.

(10) Prevention of dust explosions should be considered during design by appropriate choice of one or more of the following:

- prescribing proper maintainance and cleaning routines,
- avoiding ignition by safe selection of electronic equipment,
- careful use of welding equipment.

3.3 Serviceability limit state.

P(1) Where design limits for deflections or damage (including cracking) have to be verified the rare frequent or quasi-pemanent load combination shall be used, depending on the requirements concerning the performance of the structure.

(2) For assesing the effects of creep the quasi-permanent value of the load shall be used.

(3) Cracking shall be limited to prevent water penetration when designing silos for water sensitive materials at the serviceability limit state.

3.4 Fatigue

P(1) The effects of fatigue shall 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 filling and emptying. The effects of fatigue shall also be considered in silos affected by vibrating machinery.

4 LOADS DUE TO PARTICULATE MATERIALS

4.1 General

(1) Loads due to particulate materials depend on:

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

(2) The flow pattern (mass flow or funnel flow) may be determined from Figure 4.1.

(3) For the determination of the flow pattern, the angle of wall friction shall be obtained either by testing as described in 4.5.2, or by using the approximate values of coefficient of wall friction given in table 4.1 and shall be calculated as follows:

$$\varphi_w = \arctan \mu_m \qquad \text{... (4.1)}$$

P(4) Loads due to particulate materials in silos shall be considered as variable actions.

(5) Load patterns for filling and discharge can be used at the ultimate and serviceability limit states.

(6) Characteristic values for the filling and discharge loads are prescribed for the following types of silo:

- slender silos (Section 4.2),
- squat silos (Section 4.3),
- homogenizing silos and silos with a high filling velocity (Section 4.4).

(7) Any support given to the silo wall by the stiffness of the particulate material may be ignored in load calculations. This means that interaction of wall deformation and load from the stored material may be ignored.

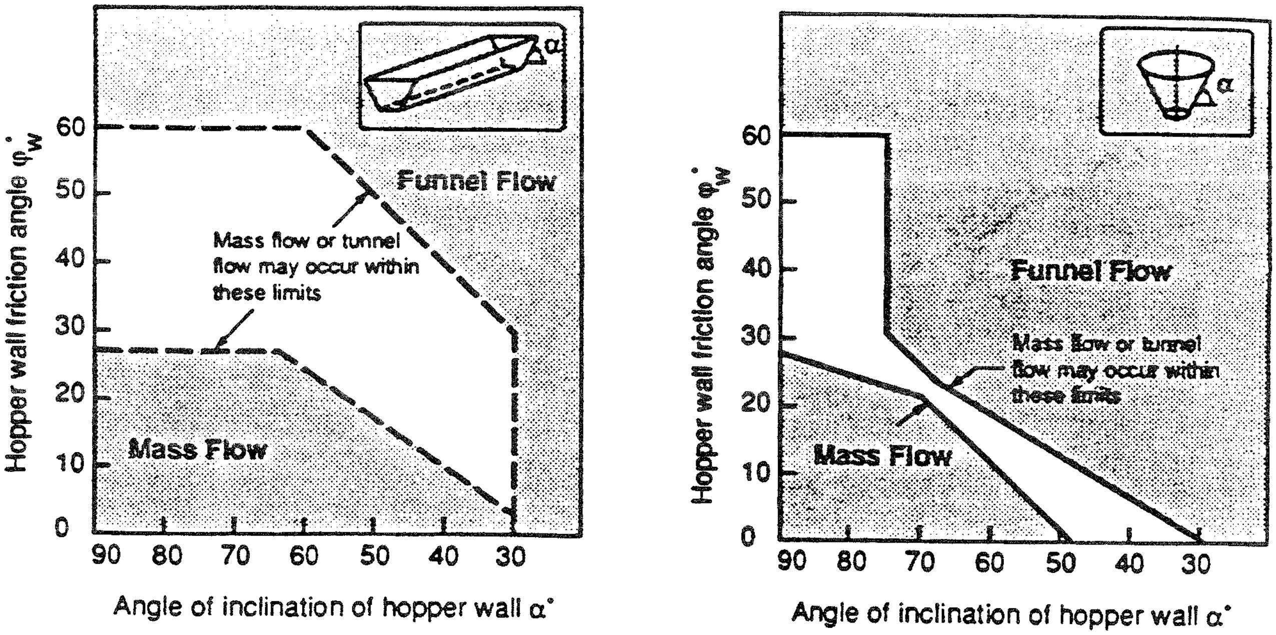


Figure 4.1 Limit between mass flow and funnel flow for conical and wedge-shaped hoppers

4.2 Slender silos

(1) Detailed rules for the calculation of filling loads are given in 4.2.1 and for discharge loads in 4.2.2. Simplified rules for filling and discharge are given in 4.2.3.

P(2) General equations for the calculation of silo wall loads are given in Section 4.2.1. They shall be used as a basis for the calculation of the following design loads:

- filling loads on vertical walled sections (see 4.2.1)
- filling loads on flat bottoms (see 4.2.1)
- filling loads on hoppers (see 4.2.1)
- discharge loads on vertical walled sections (see 4.2.2)
- discharge loads on flat bottoms and hoppers (see 4.2.2)

4.2.1 Filling loads

P(1) After filling, the values of wall frictional traction p_{wf}, horizontal pressure p_{hf} and vertical pressure p_v at any depth z shall be taken as:

$$p_{wf}(z) = \gamma \frac{A}{U} C_z(z) \qquad \text{... (4.2)}$$

$$p_{hf}(z) = \frac{\gamma A}{\mu U} C_z(z) \qquad \text{... (4.3)}$$

$$p_v(z) = \frac{\gamma A}{K_s \mu U} C_z(z) \qquad \text{... (4.4)}$$

where:

$$C_z(z) = 1 - e^{(-z/z_0)} \qquad \text{... (4.5)}$$

$$z_0 = \frac{A}{K_s \mu U} \qquad \text{... (4.6)}$$

P(2) The resulting vertical force in the wall $P_w(z)$ per unit length of perimeter acting at any depth z is:

$$P_w(z) = \int_0^z p_{wf}(z) dz = \gamma \frac{A}{U} [z - z_0 C_z(z)] \qquad \text{... (4.7)}$$

(3) Methods for determining the particulate material properties weight density γ, wall friction μ and conversion factor K_s are given in Section 4.5.

Vertical walled section

P(4) The filling load is composed of a fixed load and a free load, called a patch load.

P(5) The fixed load shall be calculated from equ (4.2) and (4.3).

(6) The patch pressure p_p shall be considered to act on any part of the silo wall and is taken as:

$$p_p = 0,2\beta\ p_{hf} \qquad \text{... (4.8)}$$

where:

$$\beta = 1 + 4\, e_f/d_c \qquad \text{... (4.9)}$$

(7) For concrete silos, silos with stiffeners and silos with non circular cross-section shapes, the patch pressure shall be taken to act on two opposite square areas with side length s (Figure 4.2), equal to:

$$s = 0.2d_c \qquad \text{... (4.10)}$$

(8) In many silos a simplified approach can be used to apply the patch load. The most unfavourable load arrangement can be designed for by applying the patch at the mid-height of the silo and using the percentage increase in the wall stresses at that level to increase the wall stresses throughout the silo.

(9) For thin walled circular silos the patch pressure shall be taken to act over a height s, but to extend from a maximum outward pressure on one side of p_p to an inward pressure p_p on the opposite side (Figure 4.2). The variation shall be taken as:

$$p_{ps} = p_p \cos\theta \qquad \text{... (4.11)}$$

where: θ is given in Figure 4.2.

(10) The total horizontal force F_p due to the patch load on thin walled circular silos is given by:

$$F_p = \frac{\pi}{2} s d_c p_p \qquad \text{... (4.12)}$$

(11) A simplified method can be used for applying the patch load to thin walled circular silos. The patch load may be taken to act at a depth z_o below the equivalent surface, or at the mid-height of the vertical walled section, whichever gives the higher position of the load.

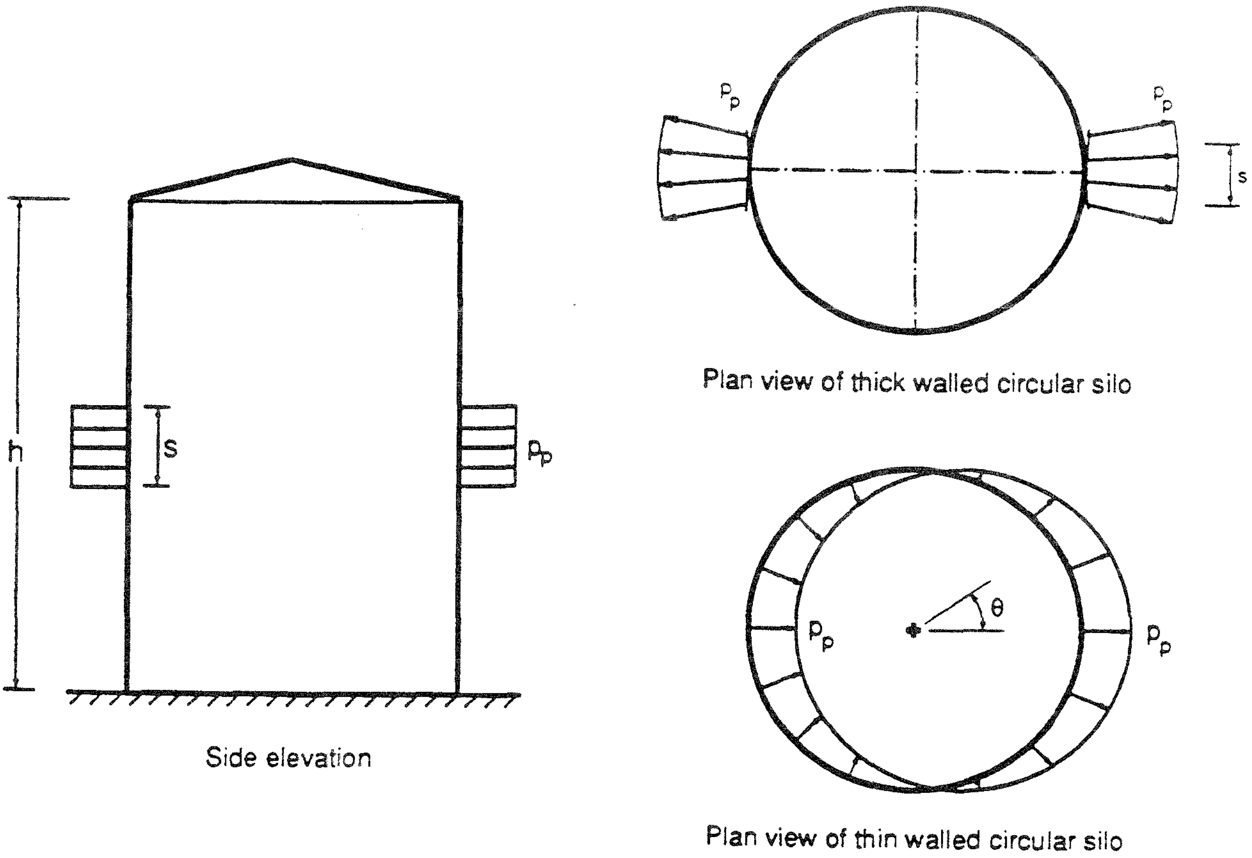


Figure 4.2 Side elevation and plan view of the patch load

Flat bottoms

(12) Vertical loads acting on flat or shallow silo bottoms (inclinations $\alpha \leq 20°$) shall be calculated as follows:

$$p_{vf} = C_b p_v \qquad \text{... (4.13)}$$

where: p_v shall be calculated using equ (4.4)

C_b is a bottom load magnifier to account for the uneven load distribution calculated using equ (4.14).

$$C_b = 1{,}2 \qquad \text{... (4.14)}$$

Hoppers

(13) The pressure normal to the inclined hopper wall p_n in hoppers where $\alpha > 20°$ shall be calculated from equ (4.15) as the sum of the pressure due to hopper filling p_{n1}, p_{n2} and the pressure due to the vertical pressure in the stored material directly above the transition. (p_{n3} Figure 4.3).

$$p_n = p_{n3} + p_{n2} + (p_{n1} - p_{n2})\frac{x}{l_h} \qquad \text{... (4.15)}$$

where: x is a length between 0 and l_h (Figure 4.3) and p_{n1}, p_{n2}, p_{n3} are calculated as follows:

$$p_{n1} = p_{v0}(C_b \cos^2\alpha + K_s \sin^2\alpha) \qquad \text{... (4.16)}$$

$$p_{n2} = C_b p_{v0} \cos^2\alpha \qquad \text{... (4.17)}$$

$$p_{n3} = 3{,}0\,\frac{A}{U}\,\frac{\gamma\, K_s}{\sqrt{\mu}}\,\sin^2\alpha \qquad \text{... (4.18)}$$

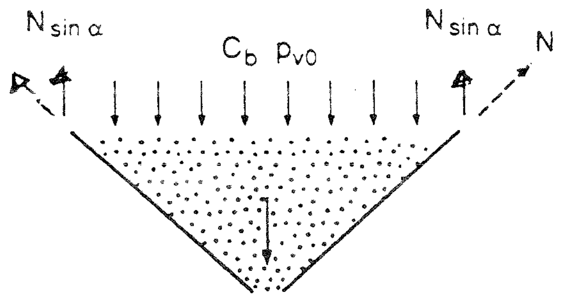
where: C_b is the bottom load magnifier taken from equ (4.14)

p_{v0} is the vertical pressure acting at the transition calculated using equ (4.4).

P(14) The value of the wall frictional traction, p_t , is given by:

$$p_t = p_n\, \mu \qquad \text{... (4.19)}$$

where: p_n is calculated using equ (4.15).



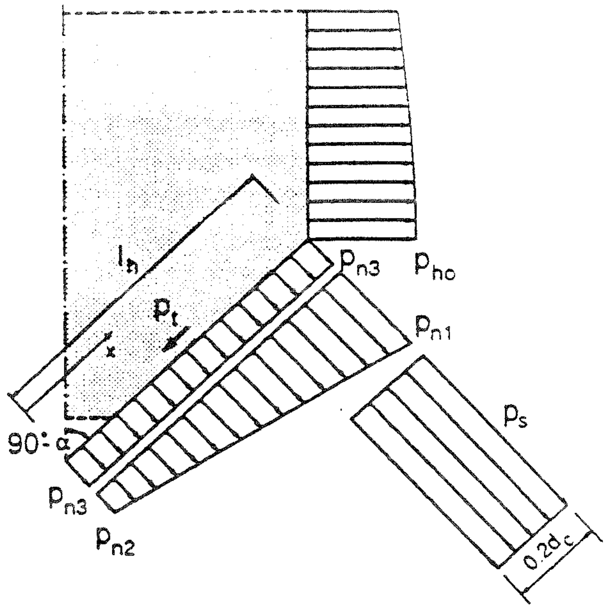


Figure 4.3 Hopper loads and tensile force at the top of the hopper

(15) For silo design the vertical component of the tensile force at the top of the hopper may be required (for example, for the design of silo supports or a ring beam at the transition level). The vertical component shall be determined from force equilibrium incorporating a vertical surcharge $C_b p_{v0}$ calculated at the transition level and the weight of the hopper contents (Figure 4.3).

4.2.2 Discharge loads

Vertical walled section

P(1) The discharge loads are composed of a fixed load and a free load, called a patch load.

(2) The fixed loads p_{we}, p_{he} shall be obtained by multiplying the corresponding filling fixed loads p_{wf}, p_{hf} by the load magnifiers C_w and C_h :

$$p_{we} = C_w \; p_{wf} \qquad \text{... (4.20)}$$

$$p_{he} = C_h \; p_{hf} \qquad \text{... (4.21)}$$

where: C_w and C_h shall be taken as 1,0 for silos that are unloaded from the top (no flow).

In other slender silos the wall frictional traction magnifier and the horizontal load magnifier shall be equal to:

$$C_w = 1{,}1 \qquad \text{... (4.22)}$$

$$C_h = C_0 \qquad \text{... (4.23)}$$

Values of the maximum load magnifier C_0 are given in 4.5.

(3) The magnitude of the discharge patch pressure shall be taken as:

$$p_p = 0{,}2\beta p_{he} \qquad \text{... (4.24)}$$

where: p_{he} shall be calculated using equ (4.21).

β depends on the greater of the filling and discharge eccentricities.

β shall be taken as:

$$\beta = 1 + 4e/d_c \qquad \text{... (4.25)}$$

(4) The application of patch loads for discharge shall be carried out using the guidance given for patch loads for filling (4.2.1 (7) to (11)).

Flat bottom and hopper

(5) For funnel flow silos, the discharge loads on bottoms and hoppers shall be calculated using the guidance for filling loads (4.2.1(12)(15)).

(6) For mass flow silos, an additional fixed load, the kick load, shall be applied.

The kick load is given by a uniform normal pressure p_s extending over an inclined distance of $0{,}2d_c$ along the hopper wall below the transition (Figure 4.3) and around the perimeter.

$$p_s = 2\, p_{h0} \qquad \text{... (4.26)}$$

where: p_{h0} is the horizontal filling pressure at the transition.

4.2.3 Simplified method for filling and discharge

(1) For silos where d_c<5m, the patch loads described in 4.2.1 and 4.2.2 may be replaced by increases in other wall loads as follows.

(2) For concrete silos, silos with stiffeners, and silos with non circular cross-section shapes, the horizontal pressures for filling $p_{hf,s}$ and discharge $p_{he,s}$ are increased as follows:

$$p_{hf,s} = p_{hf}(1+0,2\beta) \quad \text{... (4.27)}$$

$$p_{he,s} = p_{he}(1+0,2\beta) \quad \text{... (4.28)}$$

where: p_{hf} is calculated using equ (4.3)

p_{he} is calculated using equ (4.21)

β is calculated using equ (4.9) or (4.25).

(3) For thin walled circular silos, the horizontal pressures for filling $p_{hf,s}$ and discharge $p_{he,s}$ and the vertical traction for filling $p_{wf,s}$ and discharge $p_{we,s}$ are increased as follows:

$$p_{hf,s} = p_{hf}(1+0,1\beta) \quad \text{... (4.29)}$$

$$p_{he,s} = p_{he}(1+0,1\beta) \quad \text{... (4.30)}$$

$$p_{wf,s} = p_{wf}(1+0,2\beta) \quad \text{... (4.31)}$$

$$p_{we,s} = p_{we}(1+0,2\beta) \quad \text{... (4.32)}$$

where: p_{hf} is calculated using equ (4.3)
p_{he} is calculated using equ (4.21)
p_{wf} is calculated using equ (4.2)
p_{we} is calculated using equ (4.20)

β is calculated using equ (4.9) or (4.25).

4.3 Squat silos

(1) Wall loads in squat silos shall be calculated as for slender silos (Section 4.2) with the following modifications:

- the load magnifiers C_h (equ (4.21)) and C_w (equ (4.20)) are related to the ratio of height to diameter h/d_c of the silo.

For silos where $h/d_c \leq 1{,}0$

then $C_w = C_h = 1{,}0$ ... (4.33)

and the patch pressure may be neglected.

For silos where $1{,}0 < h/d_c < 1{,}5$

then
$$C_w = 1{,}0+0{,}2(h/d_c-1{,}0)$$
$$C_h = 1{,}0+2(C_0-1{,}0)(h/d_c-1{,}0) \qquad \text{... (4.34)}$$

and the patch pressure $p_{p,sq}$ shall be calculated in this case as follows:

$$p_{p,sq}=2p_p(h/d_c-1{,}0) \qquad \text{... (4.35)}$$

where: p_p is determined using the guidance for slender silos (4.2.1. P(6) to (11) and 4.2.2. (3) and (4))

The lateral pressure p_h at the point at which the upper surface of the stored material meets the silo wall may be reduced to zero. Below this point, a linear pressure variation may be assumed (Figure 4.4), calculated using $K_s = 1{,}0$, until this linear pressure reaches the pressure determined from equ (4.3) or equ (4.21) as appropriate.

(2) The vertical pressures during filling and discharge acting on the flat bottom $p_{vf,sq}$ shall be calculated as follows:

$$p_{vf,sq} = C_b \left(p_{v1} + (p_{v2} - p_{v3}) \frac{1,5D - h}{1,5D - h_1} \right) \quad \text{... (4.36)}$$

where: p_{v1} is calculated from equ (4.4) and $z = h$.

p_{v2} varies across the section and is $p_{v2} = \gamma h_2$, where h_2 is the varying distance from the surface to a horizontal plane at the level of the lowest point of the wall not in contact with the stored material (Figure 4.4).

p_{v3} is calculated from equ (4.4) and $z = h_1$.

(3) Hopper loads during filling shall be calculated using equ (4.15).

(4) Hopper loads during discharge shall be calculated using the guidance given in 4.2.3 (2) for flat bottoms and hoppers.

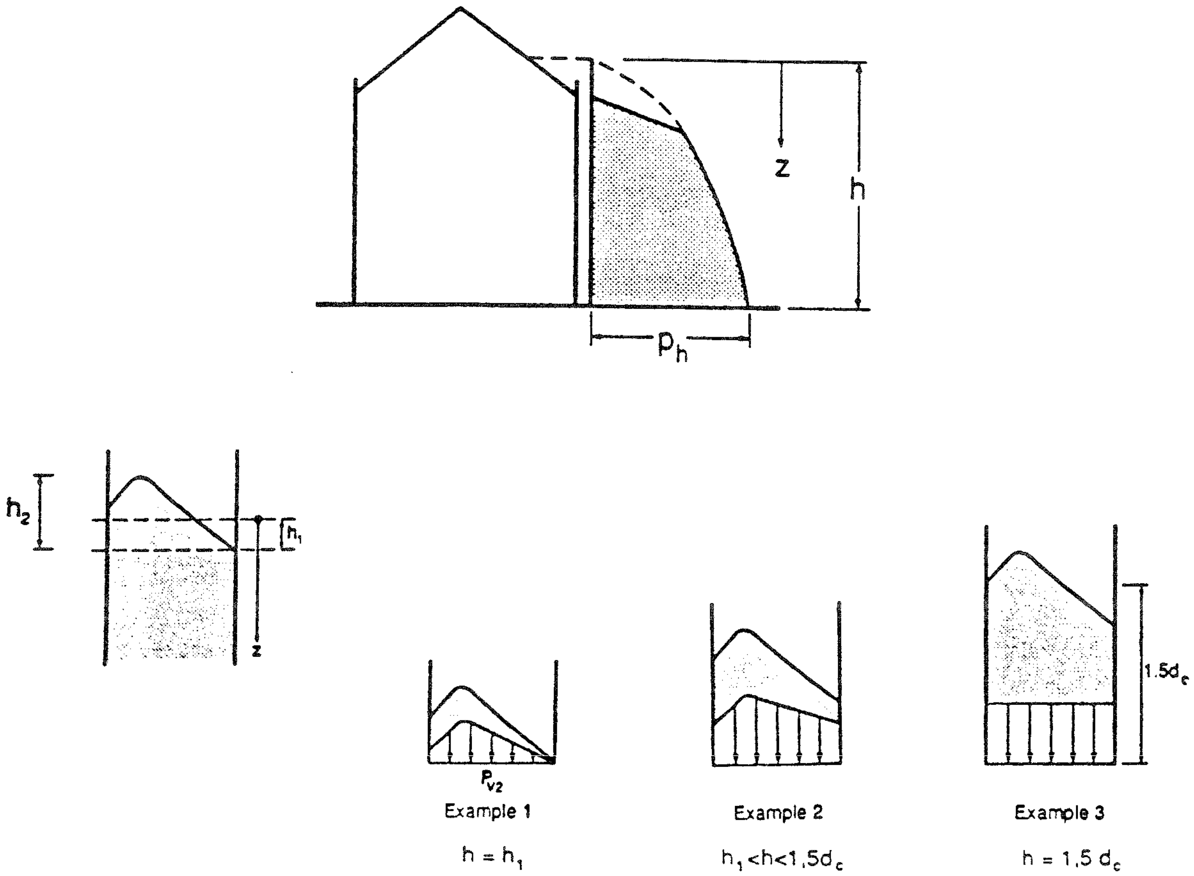


Figure 4.4 Wall loads and flat bottom loads in squat silos

4.4 Homogenizing silos and silos with a high filling velocity

P(1) Homogenizing silos and silos with a high filling velocity shall be designed for the following load cases:

- the stored material fluidised
- the stored material not fluidised.

P(2) In silos storing powders where the velocity of the rising surface of the stored material exceeds 10 m/h it is assumed that the stored material is fluidised.

P(3) Loads on the silo walls from fluidised materials shall be calculated as follows:

$$p = \gamma_1 z \qquad \text{... (4.37)}$$

where:

γ_1 is the fluidised density.

(4) The fluidised density of powders may be taken as equal to:

$$\gamma_1 = 0{,}8\,\gamma \qquad \text{... (4.38)}$$

where: γ is the bulk weight density of the powder determined from 4.5.

P(5) Design loads when the stored material is not fluidised shall be calculated for slender silos according to Section 4.2 and for squat silos according to 4.3.

4.5 Particulate material properties

(1) Particulate material properties shall be determined using either the simplified approach presented in 4.5.1 or by testing as described in 4.5.2. The maximum load magnifier C_0 is given in Table 4.1 or may be assessed from 4.5.3.

4.5.1 Simplified approach

(1) The material properties are defined in Table 4.1. Values given for γ are upper bound values whereas values of μ_m and $K_{s,m}$ are mean values.

(2) To account for the inherent variability of particulate material properties and to

obtain values that represent extremes of the material properties, the values of μ_m and $K_{s,m}$ shall be increased by the conversion factor 1,15 or decreased by the factor 0,9. These factors shall be selected to produce the most unfavourable combination of loadings on the structure. Thus, in calculating the maximum design loads, the following combinations of the parameters K_s and μ shall be considered:

Max p_h for $K_s = 1{,}15\,K_{s,m}$ and $\mu = 0{,}9\,\mu_m$ ... (4.39)

Max p_v for $K_s = 0{,}9\,K_{s,m}$ and $\mu = 0{,}9\,\mu_m$ ... (4.40)

Max P_w for $K_s = 1{,}15\,K_{s,m}$ and $\mu = 1{,}15\,\mu_m$ ... (4.41)

Table 4.1 - Particulate material properties

Particulate material	Density[3] γkN/m	pressure ratio $K_{s,m}$	Coefficient of wall friction, μ_m Steel[4]	Concrete	Maximum load magnifier C_0
barley[1]	8,5	0,55	0,35	0,45	1,35
cement	16,0	0,50	0,40	0,50	1,40
cement clinker	18,0	0,45	0,45	0,55	1,40
dry sand[2]	16,0	0,45	0,40	0,50	1,40
flour[1]	7,0	0,40	0,30	0,40	1,45
fly ash[2]	14,0	0,45	0,45	0,55	1,45
maize[1]	8,5	0,50	0,30	0,40	1,40
sugar[1]	9,5	0,50	0,45	0,55	1,40
wheat[1]	9,0	0,55	0,30	0,40	1,30
coal[1,2]	10,0	0,50	0,45	0,55	1,45

Note:

- [1] Dust explosions may occur with this material.
- [2] Care should be taken because of the possible range of material properties.
- [3] Densities are given for the calculation of loads and should not be used for volume calculations. Densities given in chapter 1 "Densities of building Materials and Stored Materials" of ENV 1991-2-1 may be used for volume calculations.
- [4] Not applicable to corrugated walls

4.5.2 Testing particulate materials

P(1) Testing shall be carried out on representative samples of the particulate material. The mean value for each material 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.

P(2) The mean test values shall be adjusted by conversion factors to derive extreme values. The conversion factors shall be selected to allow for variability of the material properties over the silo life and for sampling inaccuracies.

P(3) The conversion factors for a material property shall be adjusted if the effect of one of the secondary parameters accounts for more than **75%** of the margin introduced for the material property by the conversion factors.

Bulk weight density γ

(4) The bulk weight density shall be determined at a stress level corresponding to the maximum vertical pressure in the silo. The vertical pressure p_v in the silo may be assessed using equ (4.4).

(5) A test method for the measurement of bulk weight density is described in Annex B.

(6) The conversion factor shall be not less than 1,15.

Coefficient of wall friction μ_m

(7) Two values of μ_m shall be measured. One shall be used for the determination of flow patterns and the other for the calculation of wall loads.

(8) Tests to determine μ_m for the evaluation of flow patterns shall be carried out at a low stress level corresponding to the stress level found during flow in the lower part of the hopper.

(9) Tests to determine μ_m for the calculation of loads shall be carried out at a stress level corresponding to the maximum horizontal pressure p_{hf} in the vertical part of the silo. p_{hf} may be assessed by using equ (4.3).

(10) Test methods for the measurement of the two values of μ_m are described in Annex B.

(11) The conversion factor shall not be less than 1,15 for the upper bound value or greater than 0,9 for the lower bound value.

Horizontal to vertical pressure ratio $K_{s,m}$

(12) The horizontal to vertical pressure ratio $K_{s,m}$ shall be determined at a vertical stress level corresponding to the maximum vertical pressure in the silo. The test specimen shall be confined laterally. The vertical pressure may be assesed by using equ (4.4).

(13) A test method is given in Annex B.

(14) An alternative test method based on the measurement of the internal angle of friction is also given.

(15) The conversion factors shall not be less than 1,15 for the upper bound value or greater than 0,9 for the lower bound value.

4.5.3 Maximum load magnifier

P(1) The load magnifier C accounts for a number of phenomena occurring during discharge of the silo. The magnitude of the load magnifier increases with increasing material strength.

(2) An appropriate test method for the parameter C has not yet been developed. The load magnifiers are based on experience and apply to silos with conventional filling and discharge systems and built to standard engineering tolerances.

(3) For materials not listed in Table 4.1, the maximum wall load magnifier may be obtained using:

$$C = 1{,}35 + 0{,}02\ (\varphi - 30°) \quad \text{and} \quad C > 1{,}35 \qquad \text{... (4.42)}$$

where: φ is measured in degrees.

(4) A test method to determine φ is given in Annex B.

(5) Appropriate load magnifiers for specific silos with specified stored materials can be estimated based on full scale tests performed with such silos.

5 LOADS ON TANKS FROM LIQUIDS

P(1) Loads due to liquids shall 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

P(2) Loads in tanks are variable actions.

P(3) The characteristic value of pressure p, at depth z for a full tank is:

$$p(z) = \gamma z \qquad \text{... (4.43)}$$

(4) Densities given in Chapter 1 "Densities of building materials and stored materials" of ENV 1991-2-3 may be used.

ANNEX A COMBINATION VALUES (Informative)

(1) The combination factors ψ for silo loads and tank loads and combination factors with other actions are given in Table A.1.

(2) Silos and tanks are different to many other structures because they may be subjected to the full design loads from particulate materials or liquids for most of their life.

(3) Detailed rules on combinations of actions are given in ENV 1991-1 Eurocode 1, Basis of Design.

(4) If the maximum depth of liquid and the density of the heaviest stored liquid are well defined, the value of the partial coefficient γ may be reduced from 1,50 to 1,35.

Table A1: ψ factors for silo loads and tank loads

Action	ψ_0	ψ_1	ψ_2
Silo Loads due to particulate materials	1.0	0.9	0.8
Tank Loads due to liquids	1.0	0.9	0.8
Imposed loads Imposed deformation	0.7	0.5	0.3
Snow loads	0.6[1]	0.2[1]	0
Wind loads	0.6[1]	0.5[1]	0
Temperature	0.6[1]	0.5[1]	0

Note:

- [1] Values applicable except for some geographical regions where modification may be required.

ANNEX B TEST METHODS FOR PARTICULATE MATERIAL PROPERTIES (Informative)

B1 Object

This Annex describes test methods for the determination of the stored material parameters introduced in ENV 1991-4.

B2 Field of application

The test methods may be used for a specific silo design where the stored material is not listed in Table 4.1 or as an alternative to the simplified values given in Table 4.1. Reference stresses in the tests are either vertical or horizontal and they shall be representative of the stored material stresses after filling at the silo transition.

The test methods may also be used for the preparation of general values of material properties. Tests to determine general values shall be carried out, where applicable, at the following reference stress levels:

100 kPa to represent the vertical silo pressure (B8, B9 and B10)
50 kPa to represent the horizontal silo pressure (B7.2)

B4 Notation

c	cohesion
F_1	shear force (Figure B1)
$K_{s,m0}$	horizontal/vertical pressure ratio for smooth wall conditions
σ_r	reference stress
φ_c	angle of internal friction measured for a consolidated test specimen
τ_{fi}	maximum shear stress measured in a shear test specimen, i=1,2

B5 Definitions

Secondary parameter Parameters that may influence stored material properties. Secondary parameters include material composition, grading, moisture content, temperature, age, electrical charge due to handling and production method. For the determination of general values at reference stresses as mentioned in B2, variations in these stress levels shall be considered a secondary parameter.

Sampling The selection of representative samples of stored material or silo wall material.

Reference stress Stress levels at which the measurements of stored material properties are carried out. The reference stress is selected to correspond to the stress level in the silo after filling.

B6 Sampling and preparation of samples

Testing shall be carried out on representative samples of the particulate material. The mean value for each material property shall be determined making proper allowance for variation of secondary parameters.

The following method of sample preparation shall be used for the tests described in B7.2, B8, B9.1 and B10:

- The sample shall be poured into the test box, without vibration or other compacting forces and the reference stress σ_r applied. A top plate shall be rotated backwards and forwards three times through an angle of 10 degrees to consolidate the sample (Figure B1).

The mean test values shall be adjusted by conversion factors to derive extreme values. The conversion factors shall be selected to allow for the influence of secondary parameters, the variability of the material properties over the silo life, and for sampling inaccuracies.

The conversion factors for a material property shall be adjusted if the effect of one secondary parameter accounts for more than 75% of the margin introduced for the material property by the conversion factor.

B7 Wall friction

Two parameters shall be used:

- Angle of wall friction φ_w for the evaluation of flow
- Coefficient of wall friction μ_m. for the determination of pressures.

B 7.1 Angle of wall friction φ_w for the evaluation of flow

Principle of the test

A sample of the particulate material is sheared along a surface representing the hopper wall and the friction force at the sheared surface is measured. The reference pressure is kept low to simulate the low pressures occurring during discharge near the outlet of the silo.

Apparatus and test procedure

The test may be carried out using the apparatus described in B 7.2 and in accordance with the test procedure given in "International Standard Shear Testing Technique", Report of the European Federation of Chemical Engineering, EFCE, Working Party on the Mechanics of Particulate Solids, The Institution of Chemical Engineers, 1989 (or revisions).

B 7.2 Coefficient of wall friction μ_m for the determination of pressures

Principle of the test

A sample of the particulate material is 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 is measured.

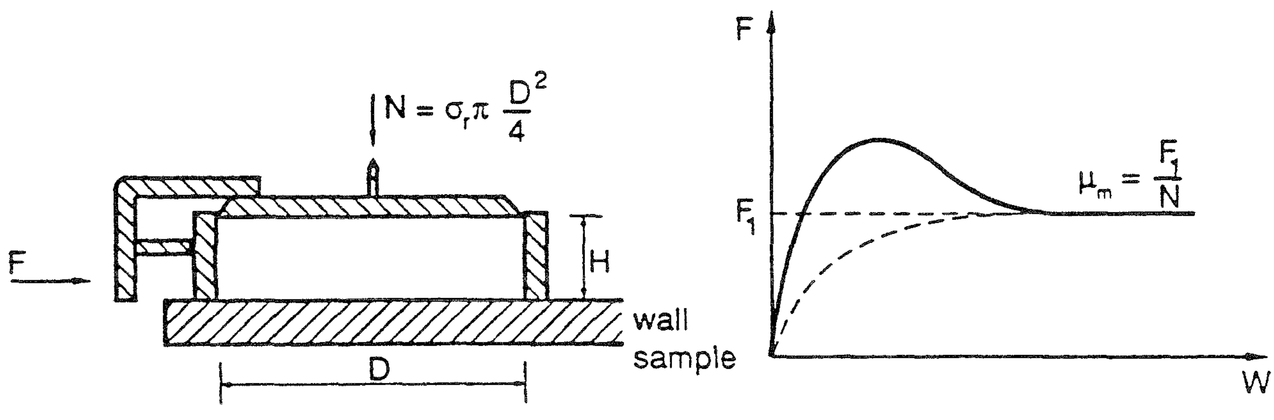


Figure B1 Test method for determination of wall friction coefficient

Apparatus

The test apparatus is shown in Figure B1. The diameter of the box shall be at least 40 times the maximum particle size and the compacted height H of the sample shall be between 0,15D and 0,20D. In the case of wall samples with irregularities such as corrugations the box size shall be selected accordingly.

Procedure

The reference stress shall be equal to the horizontal silo pressure.

Sample preparation shall be carried out according to the guidelines given in B6.

Shearing of the sample shall be carried out at a constant rate of approximately 0,04 mm/sec.

The friction force F_1 attained at large deformations shall be used in the calculation of the coefficient of friction (Figure B1).

B8 Consolidated bulk weight density γ

Principle of the test

The bulk weight density γ is determined from a consolidated sample of the particulate material.

Apparatus

The box shown in Figure B2 shall be used to measure the weight and volume of the material sample. The diameter D of the box shall be at least 40 times the maximum particle size and the compacted height H of the sample shall be between 0,3D and 0,4D.

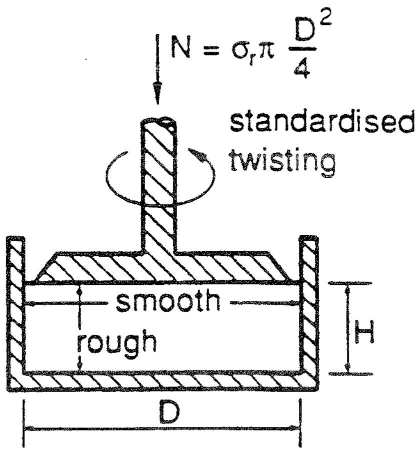


Figure B2 Device for the determination of γ

Procedure

The reference stress shall be equal to the vertical silo pressure.

Sample preparation shall be carried out according to the guidelines given in B6. The bulk weight density is determined by dividing the weight of a consolidated sample of the particulate material by the bulk volume.

B 9 Horizontal to vertical pressure ratio $K_{s,m}$

B 9.1 Direct measurement

Principle of the test

A vertical pressure is applied to a sample constrained against horizontal deformation. The resulting horizontal and vertical stresses are measured and the coefficient $K_{s,m0}$ determined.

Note: The magnitude of the coefficient $K_{s,m0}$ 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.

Apparatus

The geometry of the test apparatus is similar to the apparatus described in B8 for the measurement of bulk weight density γ (Figure B3). To measure the horizontal stress, it is necessary to have a seperate bottom plate.

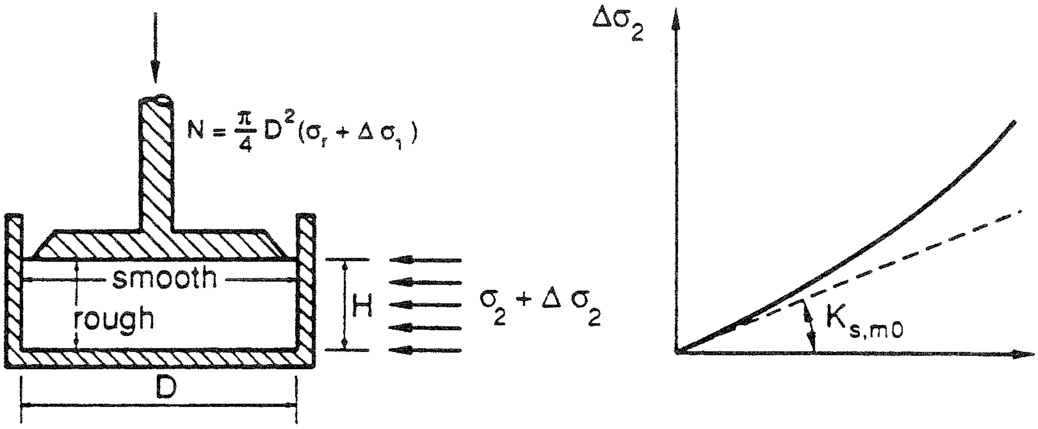


Figure B3 Test method for determining $K_{s,m0}$

Procedure

The reference stress shall be equal to the vertical silo pressure.

Sample preparation shall be carried out according to the guidelines given in B6.

The relationship between the horizontal and vertical load increments, from which $K_{s,m0}$ is calculated, is determined as indicated in Figure B3.

$K_{s,m}$ shall be taken as $K_{s,m} = 1,1\ K_{s,m0}$

B 9.2 Indirect measurement

A value of $K_{s,m}$ appropriate for filling and storing conditions may be calculated indirectly from the measured angle of internal friction φ from:

$$K_{s,m} = 1,1\ (1 - \sin\varphi) \qquad \text{... (B.1)}$$

φ may be determined from either of the methods described in B10 or in a triaxial test apparatus.

B 10 Strength parameters c , φ_c and φ

Principle of the test

The strength of a stored material sample may be determined from shear box tests. Three parameters **c** , φ_c and φ are used to define the stored material strength after silo filling.

Apparatus

The test apparatus consists of a cylindrical shear box, as shown in Figure B4. The shear box diameter, D, shall be at least 40 times the maximum particle size and the height H between 0,3D and 0,4D.

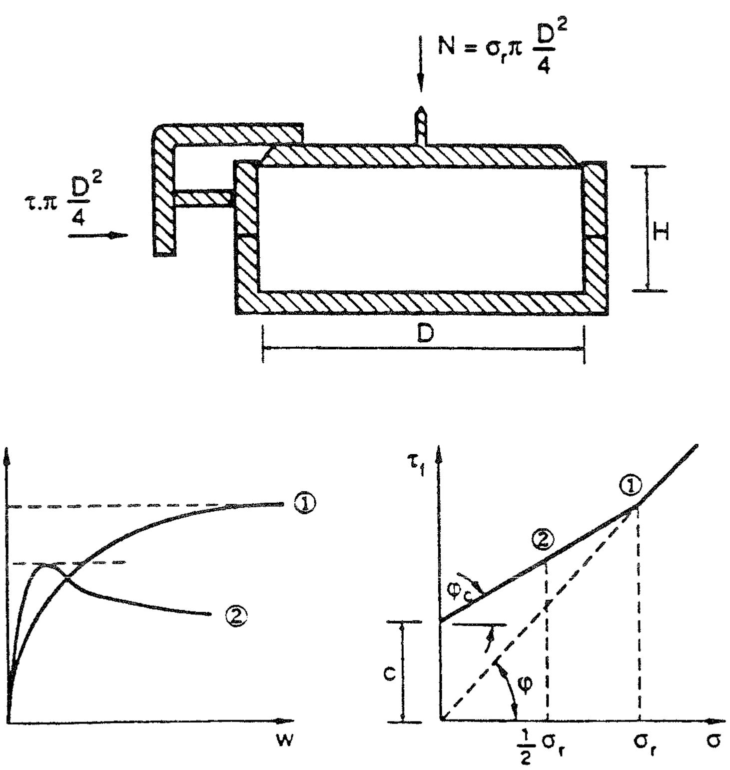


Figure B4 Test method for determining the angles of internal friction φ and φ_c and the cohesion c at the preconsolidation level σ_r

Procedure

The reference stress σ_r shall be equal to the vertical silo pressure. Sample preparation shall be carried out according to the guidelines given in B6.

The maximum shear stress τ_f developed before a horizontal displacement of $w = 0{,}05\ D$ is attained shall be used to calculate the material strength parameters.

At least two tests shall be carried out (table B1 and Figure B4). One sample shall be sheared when loaded at the reference stress, the other shall be sheared at half the reference stress after pre-loading to the reference stress. Stresses determined from the two tests are named in Table B1.

Table B1 - Recommended tests

Test	pre-load	test load	outcome
No.1	σ_r	σ_r	τ_{f1}
No.2	σ_r	$\frac{1}{2}\sigma_r$	τ_{f2}

The stored material strength parameters c , φ_c and φ are calculated as follows:

$$\varphi = \arctan\frac{\tau_{f1}}{\sigma_r} \qquad \text{... (B.2)}$$

$$\varphi_c = \arctan\frac{\tau_{f1}-\tau_{f2}}{0{,}5\ \sigma} \qquad \text{... (B.3)}$$

$$c = \sigma_r\,(\tan\varphi - \tan\varphi_c) \qquad \text{... (B.4)}$$

The strength of cohesionless materials, ($c = 0$), is described by one parameter, the angle of internal friction φ , and is equal to φ_c .

Note: A standard triaxial test may be used in preference to the test described above.

ANNEX C SEISMIC ACTIONS (Informative)

C1 Scope and object

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 Eurocode 8 and may be incorprated into Eurocode8 at a later stage.

The value of the earthquake acceleration for the silo structure is calculated according to Eurocode 8. The silo and the particulate material may be regarded as a single rigid mass.

C2 Notation

a horizontal acceleration due to earthquake

p_{hs} horizontal pressure due to seismic actions.

C3 Design situations

The following design situations shall be considered:

- horizontal accelerations and the resulting vertical loads on silo supports and foundations (C4.1),
- additional loads on the silo walls (C4.2),
- a rearrangement of the particulate material at the top of the silo. The seismic action may cause the stored material to form slip planes endangering the roof construction and the silo walls in the upper region (Figure C1).

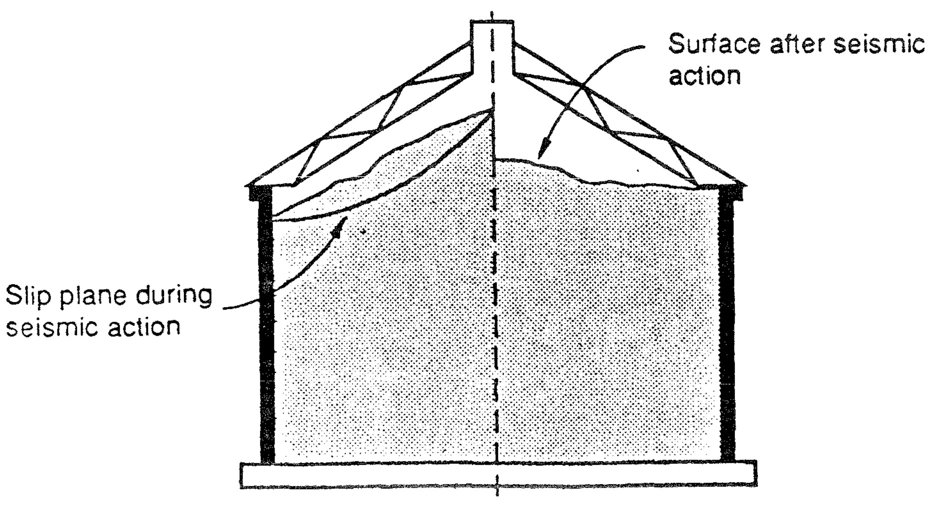


Figure C1 Redistribution of particulate materials at the top of the silo

C 4 Seismic actions

Guidance for calculation of seismic actions on silo supports and silo foundations is given in C4.1 and guidance on silo walls is given in C4.2.

C 4.1 Silo supports and foundations

Seismic actions due to the weight of the silo and the particulate material may be regarded as a single force acting at the centre of gravity of the combined structure and particulate material (Figure C2).

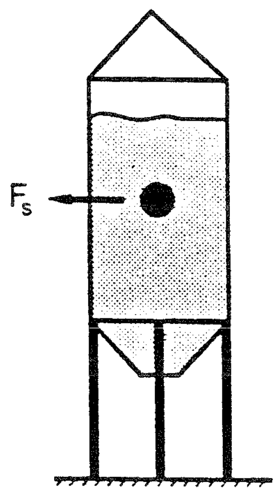


Figure C2 Seismic action for substructures

C 4.2 Silo walls

A horizontal load shall be applied to the silo walls. The load is equivalent to the mass of the particulate material multiplied by the value of the earthquake acceleration. The horizontal distribution of the earthquake load for circular and rectangular silos is shown in Figure C3. The horizontal pressure is 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 shall not be less than zero.

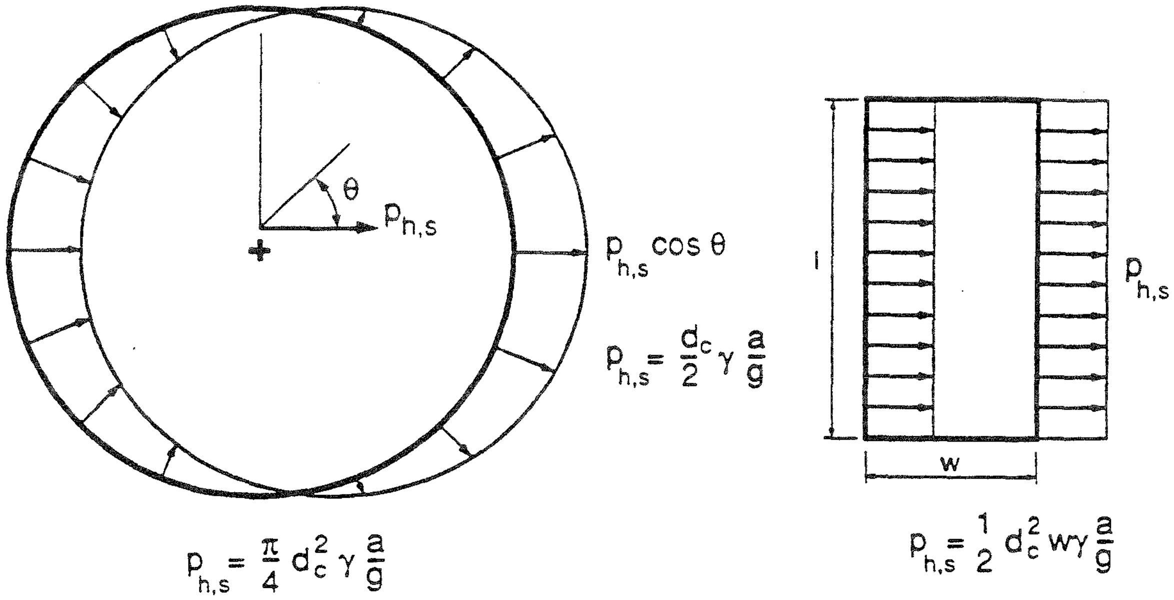


Figure C3 Plan view of the additional earthquake loads on the vertical walled sections of silos with circular and rectangular cross section shapes

Summary on the Final Research Report

Additional Investigations for a First Draft of Eurocode 1, 'Basis of Design and Actions on Structures' Part 4, 'Actions on Silos and Tanks' IV - 1 - 5 - 690/92

Created in 1993 the European Common Market strives for balanced national regulations and demands harmonised European Standards. This anticipating the Committee for European Standardization (CEN) had established a series of working groups with various responsibilities in order to develop common European standards with regard to basis of design and actions on structures among others.

The working group EC1/SC1/PT8 'Actions on Silos and Tanks', which the author as German expert had been appointed to, was charged to draft the corresponding part of a common European standard. Though experience and corresponding national regulations and a first multinational sketch were already available, nevertheless there had to be done a series of additional investigations in order to elaborate a well grounded and balanced standard draft. These studies have been supported by the Institut für Bautechnik, Berlin, which we would like to thank for its gratitude.

Studies had to be performed with regard to filling and discharge loads in hoppers as well as to bottom pressures of flat bottomed silos. Checking the influence of material properties on horizonal wall pressures, vertical bottom pressures and wall frictional pressures a lot of numerical comparisons had to be done to select proper values. For seismic actions on silos and tanks a series of special problems had to be treated generally by numerical simulations. Finally the general concept had to be adapted to the relevant safety regulations.

The results of these additional investigations could be directly used during the ongoing work on formulating the draft of ENV 1991-4. In the mean time the english version of this prestandard has been discussed and after some further amendments will become valid soon.

Postanschrift:
Institut für Massivbau und Baustofftechnologie · Universität Karlsruhe
Abteilung Massivbau · Postfach 6980 · 7500 Karlsruhe 1

Lieferanschrift:
Am Fasanengarten
7500 Karlsruhe 1

Fernsprecher: 07 21-608 22 77
Teletex 72 11 66 = UNIKar
Telefax 07 21-608 42 90

INSTITUT FÜR MASSIVBAU
UND BAUSTOFFTECHNOLOGIE
UNIVERSITÄT KARLSRUHE (TH)

ABTEILUNG MASSIVBAU
PROF. DR.-ING. J. EIBL

MPA
KARLSRUHE

Résumé du rapport final sur le projet de recherche

Études complémentaires concernant un avant-projet pour le Eurocode 1, 'Basis of Design and Actions on Structures' Part 4, 'Actions on Silos and Tanks' IV - 1 - 5 - 690/92

Le marché commun européen réalisé depuis 1993 impose certains équilibrages et requiert des normes européennes élargies. Un certain nombre de groupes de travail furent crées pour les différentes sections par le Comité des Normes Européennes (CEN), entre outres, afin de développer une norme européenne commune pour le béton armé et le béton précontraint.

Le groupe de travail EC1/SC1/PT8 "Actions on Silos and Tanks", dans lequel l'auteur fut nommé comme expert allemand, élaborâ un projet pour la partie correspondante d'une norme européenne élargie.

Même s'il y avait déjà des normes nationales, une première norme commune et également l'expérience, qui en résulte, pour l'élaboration d'une proposition de norme qui soit fondée et bien ponderée, une série d'études complémentaires furent necéssaires, qui grace à l' Institut für Bautechnik, Berlin, ont pu être accompliées.

En plus des études concernant les actions, qui apparaissent dans les trémies des silos pendant le remplissage respectivement la vidange, des investigations numériques sur les pressions dans la plaque de fond ont été effectuées.

Dans le but d'établir des valeurs appropriées pour les charactéristiques des matériaux emmagasinés et de controler l'effet, qu'ils peuvent l'avoir sur les pressions horizontales, sur la plaque de fond et sur les charges provoquées par le frottement du mur, des volumineux calcules comparatifs ont été faits.

Pour les questions spéciales, qui sont impliquées par les actions sismiques dans les silos, de simulations numériques ont été également faites. Finalement le concept général a été assorti et lié avec la théorie de la securité correspondante.

Grace à la collaboration dans le cadre du groupe de travail, les résultats de ces études complémentaires purent être directement insérés dans la formulation actuelle du projet de norme ENV 1991-4, qui entretemps apparut déjà dans sa version anglaise.

Postanschrift:
Institut für Massivbau und Baustofftechnologie · Universität Karlsruhe
Abteilung Massivbau · Postfach 6980 · 7500 Karlsruhe 1

Lieferanschrift:
Am Fasanengarten
7500 Karlsruhe 1

Fernsprecher: 07 21-608 22 77
Teletex 72 11 66 = UNIKar
Telefax 07 21-608 42 90