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Bases for design of structures — Loads due to bulk materials

Bases du calcul des constructions — Charges dues aux produits en vrac

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Contents

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

International Standard ISO 11697 was prepared by Technical Committee ISO/TC 98, *Bases for design of structures*, Subcommittee SC 3, *Loads, forces and other actions*.

Annex A of this International Standard is for information only.

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Bases for design of structures — Loads due to bulk materials

1 Scope

This International Standard deals with pressure conditions in hoppers, bunkers, bins and silos constructed using normal structural engineering materials. For the purposes of definition, the term silo is used throughout this International Standard to represent all forms of storage.

The methods given in clause 3 for the determination of loads are intended for use with the practical range of containment structures subject to the following limitations:

a) filling is a continuous process involving small inertia effects and inconsequential impact loads;

b) the maximum particle size of the ensiled bulk material is not greater than $0,1R$ (R = hydraulic radius);

c) where discharge devices are used (e.g. feeders, internal flow tubes, etc.), material flow is effectively continuous and centric within the eccentricity limitation given in e):

d) in bottom-discharging silos, the bulk material is free-flowing and has a low cohesion [i.e. $d_a \leqslant 1,0R$ (see annex A)];

e) the eccentricity e of the filling or discharge process, relative to the silo centreline, is less than $0,25d$ for cylindrical silos, and less than $0,25a$ in the case of rectangular silos;

f) the ratio of height to diameter is not greater than 10; the height is not greater than 100 m and the diameter is not greater than 50 m.

Loads determined using this International Standard consider

— a defined range of bulk material properties;

— variations in the surface friction conditions;

— the geometry of the structure;

— attachment to or loading by other structures and/or equipment;

— the methods of filling, storage and discharge.

All the above parameters shall be agreed with the client and written into all contract documents. Design of the silo shall be checked if any of the above criteria are changed.

2 Symbols and units

2.1 Symbols

a	Width of short side of a rectangular silo
A	Cross-sectional area of parallel section
c	Cohesion
C	Overpressure coefficient, load magnifier
C_z	Factor
d	Internal diameter
d_a	Material flow parameter
d_b	Maximum grain size
e	Eccentricity of discharge outlet
h	Overall height of silo
l	Length of long side of a rectangular silo

p_h Lateral pressure due to stored material

p_{he} Lateral pressure during discharge

p_{hf} Lateral wall pressure after filling

p_{h0} Lateral wall pressure in parallel section after filling

p_{ni} Pressure normal to inclined hopper wall ($i = 1, 2, 3$)

p_s Kick or switch pressure

p_t Shear stress on the hopper wall due to friction

p_v Vertical pressure due to stored material

p_w Shear stress on the vertical wall due to friction

P_w Resulting vertical force in silo wall

R Hydraulic radius of parallel section ($= A/u$)

s Length of side of square zone effected by patch load

t Wall thickness

u Cross-section perimeter of parallel section

z Vertical depth measured from effective horizontal surface

α Angle of inclination of hopper wall from horizontal

β Increasing factor for patch load

γ Weight per unit volume of stored material

γ_1 Weight per unit volume of aerated stored material

λ Horizontal/vertical pressure ratio

μ Coefficient of friction between stored material and wall ($=$ tan ϕ_w)

σ_r Reference stress

σ_v Vertical stress in a shear test specimen

σ_w Preload (vertical) in a shear test specimen

σ_{w1} Actual load (vertical) in a shear test specimen

φ Effective angle of internal friction

φ_c Angle of internal friction in a test specimen

φ_w Angle of wall friction

τ_{fi} Maximum friction measured in a shear test specimen ($i = 0$ or 1)

2.2 Units

The units of measurement used in this International Standard are the International System of Units (SI).

3 Silo pressures

Load and pressures in this International Standard are nominal values substituting relevant fractiles during the design life of the structure or the permanency of the design.

3.1 Principles of silo pressure

The filling pressures of bulk materials depend mainly on the material properties and the silo geometry. However, discharge pressures are also influenced by the flow patterns which arise during the process of emptying. Therefore an assessment of material flow behaviour shall be made for each silo design.

3.1.1 Flow patterns (see figure 1)

In the assessment of bulk-material flow it is necessary to distinguish between three main flow patterns.

a) **Mass flow** [see figure 1 a)]: A flow profile in which all the stored particles are mobilized during silo discharge.

b) **Funnel flow** (or **core flow**) [see figure 1 b) to f)]: A flow profile 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 can intersect the wall of the parallel section or extend to the top surface. In the latter case, the pattern is called internal flow [see figure 1 c) to e)].

c) **Expanded flow** [see figure 1 f)]: A flow profile in which mass flow develops within a steep-bottom hopper, combining with a stationary zone in an upper less-steep hopper at the bottom of the parallel section. The mass flow zone then extends up the wall of the parallel section.

Different pressure distributions are associated with each of the above flow patterns.

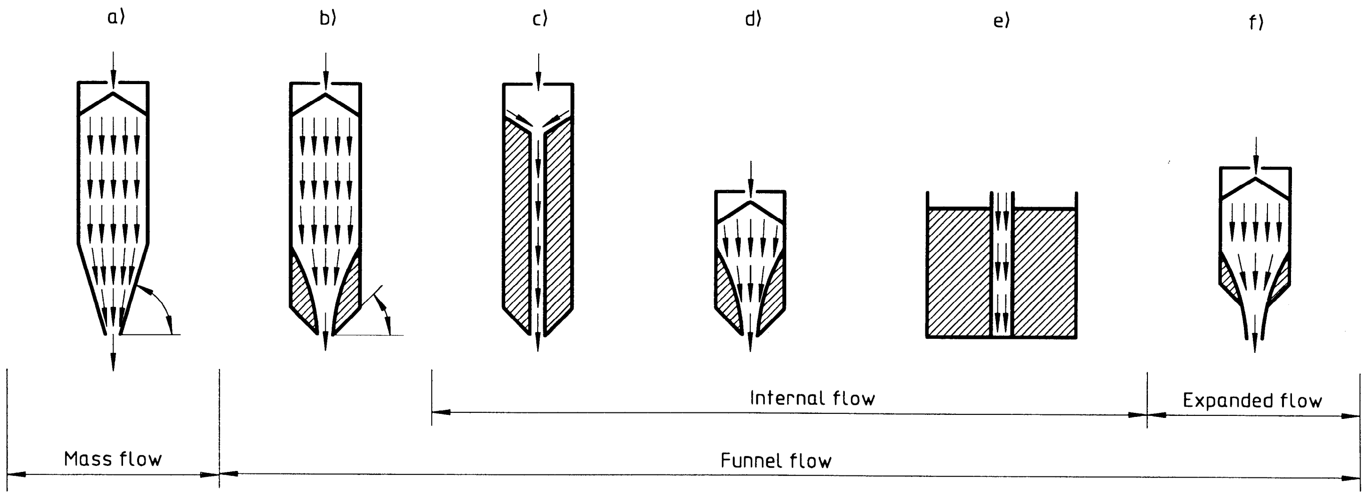

Figure 1 — Flow patterns

The conditions necessary for mass flow depend on the inclination of the hopper wall and the wall friction coefficient. They may be estimated using figure 2 for conical and axisymmetrical hoppers, and figure 3 for configurations producing plane flow. The transition regions shown in figures 2 and 3 represent conditions in which the flow pattern can change abruptly between mass and funnel flow, thereby producing unsteady flow with pressure oscillations. If such conditions cannot be avoided, the silo shall be designed for both mass flow and funnel flow.

A silo may be designed for funnel flow only if figure 2 or figure 3 establishes that this is the only possible flow pattern.

Top-unloading bins may be designed as always operating in internal flow.

3.1.2 Pressure analysis

In this International Standard, the calculation of silo pressures is based on Janssen's theory with the following assumed conditions:

a) static vertical equilibrium;

b) a uniform vertical pressure acts upon any horizontal section;

c) in cylindrical silos, the lateral pressures are symmetrically distributed around the wall circumference;

d) wall friction depends only on the lateral pressure;

e) a constant wall friction coefficient (i.e. Coulomb friction).

All the above assumptions are idealizations or simplifications.

In practice, silo pressures are known to be unsymmetrical due to the effects of segregation during filling, geometric wall imperfections and eccentric filling or discharge, even if these are nominally concentric. Pressures in silos are not only governed by static phenomena but also involve dynamic responses with probabilistic characteristics.

Eccentric filling or eccentric discharge of a silo can cause highly unsymmetrical loadings on the wall, floor and supporting elements.

Nevertheless, pressures calculated using the methods proposed in this International Standard are in good overall agreement with measurements, provided all aspects of the design which are specific to each individual silo, such as inherent material variability, etc., are considered.

During filling and storage, an elastic or active state of stress is developed within the stored mass. When a silo discharges in funnel flow, this stress state is disturbed to varying degrees over the height of the silo. In the region where the flow channel intersects the wall, a position which varies in both a vertical and horizontal plane, the stress state changes towards a passive condition with a corresponding increase in the ratio of lateral to vertical pressure. To deal with this situation, a multiplying overpressure factor C has been introduced into the pressure calculation. This factor is derived from experience and experimental measurements using different bulk materials (see clause 5). This factor also accounts for local pressure increases due to imperfections in the wall geometry, inhomogeneity of the bulk material, slip/stick properties and small discharge eccentricities.

Silo design shall consider unfavourable parameter combinations in determining the design loadings.

For the calculation of lateral and vertical pressures, the value of the vertical coordinate z is taken from a fictitious horizontal surface representing the actual mass of the stored bulk material and its assumed density. The surface level of the stored bulk solid can be changed by the actions of aeration, pneumatic filling, vibration of silo walls, or mechanical spreading of the material during filling.

In this International Standard, the calculated pressures are assumed to be continuous. In situations where particle sizes are large in comparison with the wall thickness, the need for special provisions shall be investigated.

3.2 Basic equations

The pressures at a depth z in the cylindrical section are as follows:

$$p_{\mathrm{wf}}(z) = \gamma R \times C_z(z) \qquad \ldots (1)$$

$$p_{\mathrm{hf}}(z) = \frac{\gamma R}{\mu} \times C_z(z) \qquad \ldots (2)$$

$$p_{\mathrm{vf}}(z) = \frac{\gamma R}{\lambda \mu} \times C_z(z) \qquad \ldots (3)$$

The factor C_z is given by:

$$C_z(z) = 1 - e^{(-z/z_0)} \qquad \ldots (4)$$

The depth z_0 is given by:

$$z_0 = \frac{R}{\lambda \mu} \qquad \ldots (5)$$

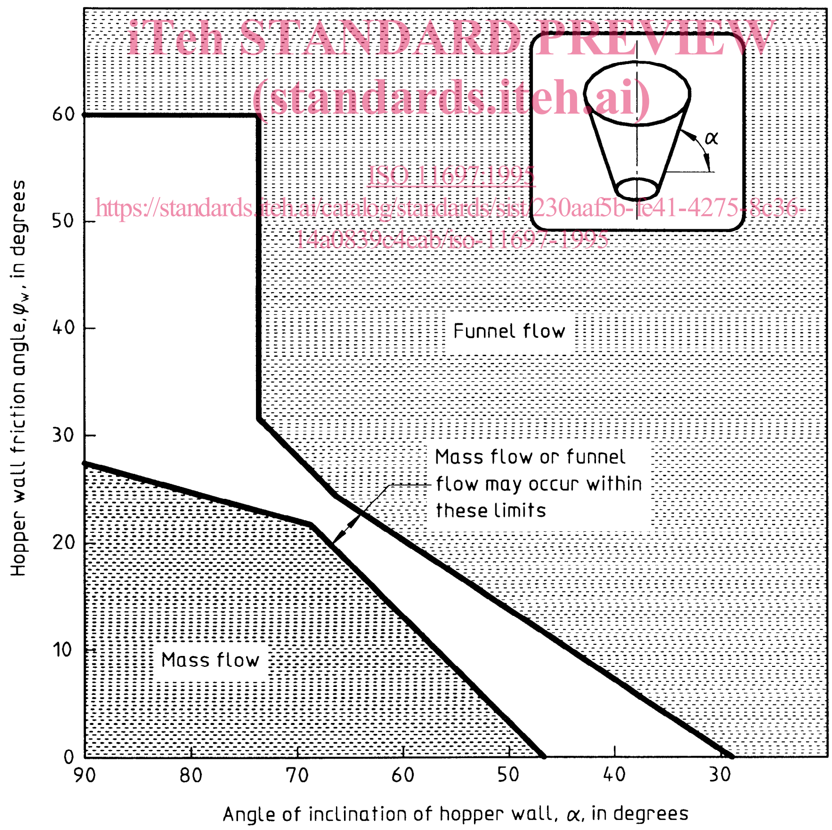

Figure 2 — Limit between mass flow and funnel flow for circular hoppers

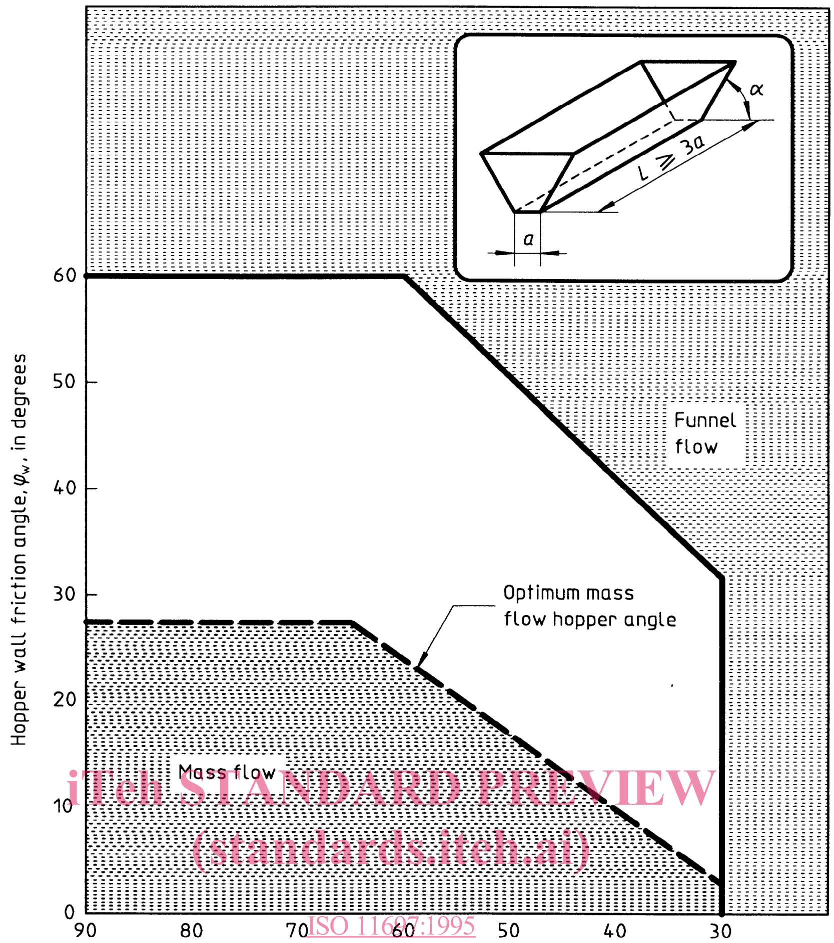

Figure 3 — Limit between mass flow and funnel flow for wedge-shaped hoppers

The friction forces p_w acting on the wall may be integrated vertically to calculate the resulting vertical force in the wall, $P_w(z)$, per unit circumference acting at the depth z, using following equation:

$$P_w(z) = \int_0^z p_{wf}(z)\,dz = \gamma[z - z_0 C_z(z)] \qquad \ldots (6)$$

The bulk materials properties γ, μ and λ are given in clause 4.

3.3 Wall pressure

Filling pressure acting on the wall of the cylindrical section are calculated directly from equations (1), (2), (4) and (5).

In silos where the flow zone intersects the wall (i.e. all flow patterns except internal flow), the design discharge pressures shall be obtained by multiplying the filling loads by an overpressure coefficient C. The value of C shall be related to the silo aspect ratio h/d:

for	$h/d \leqslant 1{,}0$	$C = 1{,}0$
for	$1{,}0 < h/d < 1{,}5$	$C = 1{,}0 + 0{,}7(h/d - 1{,}0)$
for	$h/d \geqslant 1{,}5$	$C = 1{,}35$

These values apply only to materials which conform to the classes defined in table 1. For other materials, the value of C can be calculated from equation (A.3) of annex A.

In silos having an internal flow pattern [i.e. in figure 1 c), d) and e)], the design discharge pressures shall be taken as equal to the filling and storage pressures.

3.3.1 Patch load

Unsymmetrical pressures are unavoidable even where concentric filling of axisymmetrical silos is involved, and are dependent on both the characteristics of the bulk material and the imperfections in the as-built silo geometry. Inhomogeneities and probabilistic changes within the bulk material can also contribute to fluctuations in the flow zone. For these reasons, silos should be designed to resist unsymmetrical loads, with special attention to the induced bending moments.

To account for such actions, an additional patch load of magnitude $0{,}2p_{he}$ shall be taken to act on any part of the silo wall over a square zone of side length $s = 0{,}8A/u$ (see figure 4). Any possible support given to the silo wall by the bulk material shall be ignored in this calculation.

3.3.2 Eccentric discharge

Discharge through an eccentric outlet or outlets results in an unsymmetrical pressure distribution around the circumference of the silo, inducing bending moments in the wall. It can also initiate buckling of the wall of a steel silo. Silo walls shall be designed to resist these loads.

An examination of many published pressure distributions for eccentric discharge, having their origins in both theoretical and experimental studies, has shown little consistency. The following simplification is therefore proposed for estimating the maximum pressures.

For discharge eccentricities smaller than $0{,}25d$ in the case of circular silos, and less than $0{,}25a$ for rectangular silos, the patch load (see 3.3.1) should be increased by a factor β, given in the following equation:

$$\beta = 1{,}0 + 4{,}0e/d$$

This expression does not apply to eccentricities in excess of $0{,}25d$.

It should be noted that where eccentricities are large (i.e. e approaches $0{,}5d$), lateral wall pressures during discharge, p_{he}, can approach zero on the side of the opening.

3.4 Bottom loads

Values of vertical pressures acting on flat or shallow silo bottoms under filling and discharge conditions (inclinations $\alpha \leqslant 20°$) shall be calculated using equation (3) increased by the empirical factor 1,35. This does not allow for impact loads during filling or the possibility of dynamic loads due to unreliable flow.

For vertical pressures on the floor of a squat silo, see 3.7.

3.5 Hopper loads

Theories for the calculation of pressures in silo hoppers are available in the literature, but the phenomenon is still not fully understood and agreement between different calculation methods is poor. Therefore a simple, semi-empirical method for the computation of hopper pressures is recommended.

The normal wall pressure, p_n, under filling and discharge conditions in hoppers having $\alpha \geqslant 20°$ shall be calculated as the sum of loads due to hopper filling [equation (9)] and loads resulting from the vertical surcharge directly above the transition [equations (7) and (8)]. (See figure 5.)

$$p_{n1} = 1{,}5p_{h0}\left(\frac{1}{\lambda}\cos^2\alpha + \sin^2\alpha\right) \quad \ldots (7)$$

$$p_{n2} = \frac{1{,}5}{\lambda}p_{h0}\cos^2\alpha \quad \ldots (8)$$

$$p_{n3} = 3{,}0\frac{A}{U}\frac{\gamma\lambda}{\sqrt{\mu}}\sin^2\alpha \quad \ldots (9)$$

where p_{h0} is the lateral wall pressure acting on the vertical wall immediately above the hopper in the filling condition, as calculated from equation (1).

For shallow hopper angles ($\alpha < 20°$), the normal pressure p_n shall be taken as equal to the bottom loads calculated in 3.4.

The frictional tractions on the hopper wall are given by the following equation:

$$p_t = \mu p_n \quad \ldots (10)$$

where p_n is the sum of p_{n1}, p_{n2} and p_{n3} [equations (7) to (9)].

Loads resisted by silo supports shall be determined from force equilibrium using a vertical surcharge p_{vf}, acting on a horizontal surface directly above the hopper, increased by the empirical factor of 1,35.

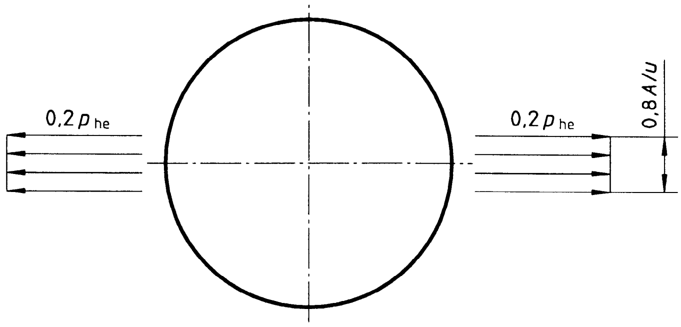

Figure 4 — Patch load

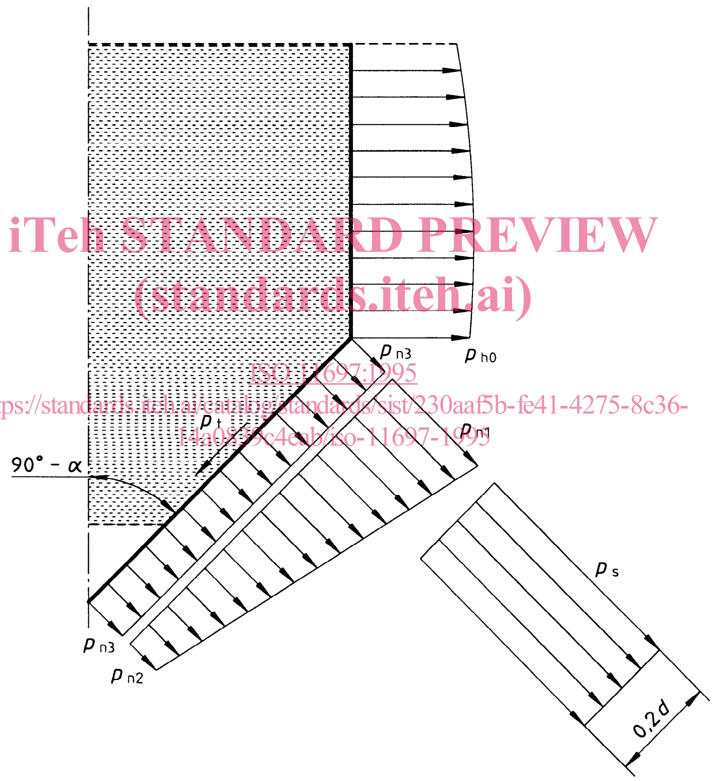

Figure 5 — Hopper loads

3.6 Kick pressure in mass-flow bins

At the transition between the vertical wall and the hopper in a mass-flow silo, the normal wall pressure during discharge becomes considerably larger than the filling pressure. This phenomenon is commonly referred to as the "switch" or "kick" pressure.[1)]

For mass-flow silos, a uniform normal pressure, p_s, extending over an inclined distance of 0,2d below the transition (see figure 5) shall be added to the pressures calculated in accordance with section 3.5.

$$p_s = 2p_{h0} \quad \ldots (11)$$

where p_{h0} is the horizontal filling pressure in the parallel section.

1) Various methods for the calculation of the peak "switch" pressure have been proposed but for the purpose of design calculations, a simplified approach is recommended.