5.2.4 Discharge loads for circular silos with large outlet eccentricities

5.2.4.1 General

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

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

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

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

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

5.2.4.2 Method for Action Assessment Class 2

5.2.4.2.1 Flow channel geometry

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

$$\theta_c = 35° \qquad \text{... (5.46)}$$

5.2.4.2.2 Wall pressures under eccentric discharge

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

$$p_{hce} = 0 \qquad \text{... (5.47)}$$

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

$$p_{hse} = p_{hf} \qquad \text{... (5.48)}$$

$$p_{hae} = 2p_{hf} \qquad \text{... (5.49)}$$

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

$$p_{wse} = p_{wf} \qquad \text{... (5.50)}$$

$$p_{wae} = 2p_{wf} \qquad \text{... (5.51)}$$

where:

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

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

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

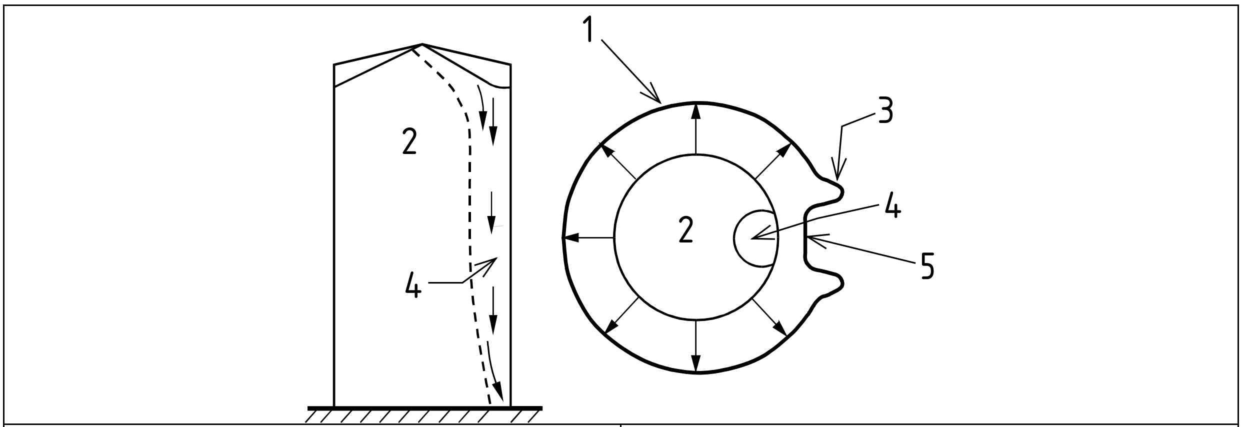
(3) The method of 5.2.4.3.2 may alternatively be used.

5.2.4.3 Method for Action Assessment Class 3

5.2.4.3.1 Flow channel geometry

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

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

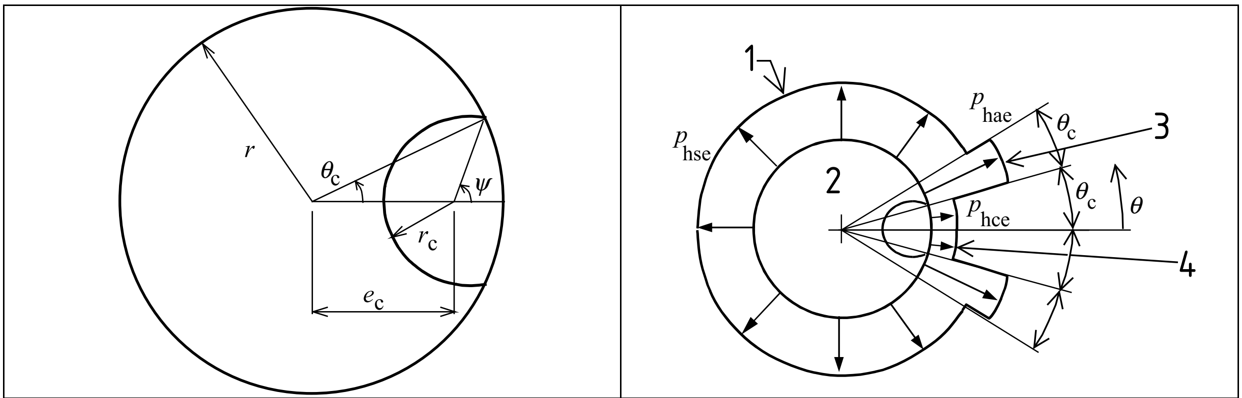


a) Elevation	b) Cross-section

Key

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

a) flow channel and pressure pattern



b) channel geometry	c) pressures

Key

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

Figure 5.5: Eccentric discharge flow channel and pressure distribution

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

$$r_c = k_1\, r \qquad \ldots (5.52)$$

$$r_c = k_2\, r \qquad \ldots (5.53)$$

$$r_c = k_3\, r \qquad \ldots (5.54)$$

where:

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

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

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

$$e_c = r\,\{\eta\,(1 - G) + (1-\eta)\sqrt{1-G}\,\} \qquad \ldots (5.55)$$

in which:

$$G = \frac{r_c}{r} \qquad \ldots (5.56)$$

$$\eta = \frac{\mu}{\tan\phi_i} \qquad \ldots (5.57)$$

where:

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

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

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

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

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

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

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

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

$$\cos\theta_c = \frac{r^2 + e_c^2 - r_c^2}{2\,r\,e_c} \qquad \ldots (5.58)$$

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

$$U_{wc} = 2\theta_c\,r \qquad \ldots (5.59)$$

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

$$U_{sc} = 2\,r_c\,(\pi - \psi) \qquad \ldots (5.60)$$

in which:

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

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

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

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

5.2.4.3.2 Wall pressures under eccentric discharge

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

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

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

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

in which:

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

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

where:

μ is the wall friction coefficient for the vertical wall;

K is the lateral pressure ratio for the solid.

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

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

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

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

where:

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

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

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

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

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

$$p_{wae} = \mu \, p_{hae} \qquad \text{… (5.70)}$$

5.3 Squat and intermediate slenderness silos

5.3.1 Filling loads on vertical walls

5.3.1.1 Filling symmetrical load

(1) The symmetrical filling load (see Figure 5.6) should be calculated using Expressions (5.71) to (5.80).

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

$$p_{hf} = p_{ho} \, Y_R \qquad \text{… (5.71)}$$

$$p_{wf} = \mu \, p_{hf} \qquad \text{… (5.72)}$$

in which:

$$p_{ho} = \gamma K z_o = \gamma \frac{1}{\mu} \frac{A}{U} \qquad \text{… (5.73)}$$

$$Y_R = \left(1 - \left\{ \left(\frac{z - h_o}{z_o - h_o} \right) + 1 \right\}^n \right) \qquad \text{… (5.74)}$$

$$z_o = \frac{1}{K \mu} \frac{A}{U} \qquad \text{… (5.75)}$$

$$n = -(1 + \tan\phi_r)(1 - h_o/z_o) \qquad \text{… (5.76)}$$

where

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

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

$$h_o = \frac{r}{3} \tan\phi_r \qquad \text{… (5.77)}$$

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

$$h_o = \frac{d_c}{4} \tan\phi_r \qquad \text{… (5.78)}$$

where:

γ is the characteristic value of the unit weight;

μ is the characteristic value of the wall friction coefficient for solid sliding on the vertical wall;

K is the characteristic value of the lateral pressure ratio;

z is the depth below the equivalent surface of the solid;

A is the plan cross-sectional area of the silo;

U is the internal perimeter of the plan cross-section of the silo;

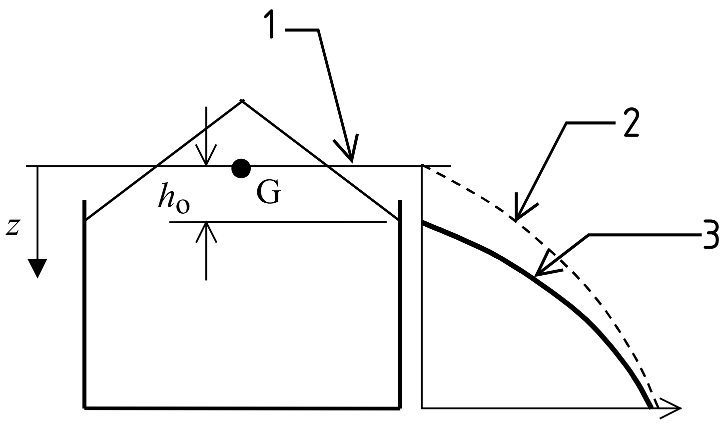
ϕ_r is the angle of repose of the solid (see Table E.1).

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

$$p_{vf} = \gamma z_V \qquad \ldots (5.79)$$

in which:

$$z_V = h_o - \frac{1}{(n+1)}\left(z_o - h_o - \frac{(z + z_o - 2h_o)^{n+1}}{(z_o - h_o)^n} \right) \qquad \ldots (5.80)$$



Key

1 Equivalent surface
2 Slender silo rule
3 Squat silo pressures

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

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

$$n_{zSk} = \int_0^z p_{wf}(z)\, dz = \mu\, p_{ho}\,(z - z_V) \qquad \ldots (5.81)$$

where z_V is given by Expression (5.80).

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

5.3.1.2 Filling patch load

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

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

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

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

(5) For silos of intermediate slenderness ($1{,}0 < h_c/d_c < 2{,}0$) in Action Assessment Classes 2 and 3, the filling patch pressure p_{pf} taken from 5.2.1 should be used to represent accidental asymmetries of loading and small eccentricities of filling e_f (see Figure 1.1b).

(6) For silos of squat or intermediate slenderness ($h_c/d_c < 2{,}0$) in Action Assessment Classes 2 and 3, where the eccentricity of filling e_f exceeds the critical value $e_{f,cr} = 0{,}25 d_c$, the additional load case for large filling eccentricities in squat silos should be used (see 5.3.3).

5.3.2 Discharge loads on vertical walls

5.3.2.1 Discharge symmetrical load

(1)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:

$$p_{he} = C_h \, p_{hf} \qquad \ldots (5.82)$$

$$p_{we} = C_w \, p_{wf} \qquad \ldots (5.83)$$

where:

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

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

$$C_w = C_h = 1{,}0 \qquad \ldots (5.84)$$

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

$$C_h = 1{,}0 + 0{,}15 \, C_S \qquad \ldots (5.85)$$

$$C_w = 1{,}0 + 0{,}1 \, C_S \qquad \ldots (5.86)$$

$$C_S = h_c/d_c - 1{,}0 \qquad \ldots (5.87)$$

where

C_S is the slenderness adjustment factor.

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

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

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

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

where:

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

e_o is the eccentricity of the centre of the outlet;

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

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

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

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

where z_V is given by Expression (5.80).

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

5.3.2.2 Discharge patch load

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

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

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

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

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

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

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

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

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

5.3.2.3 Substitute uniform pressure increase for filling and discharge

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

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

5.3.3 Large eccentricity filling loads in squat and intermediate circular silos

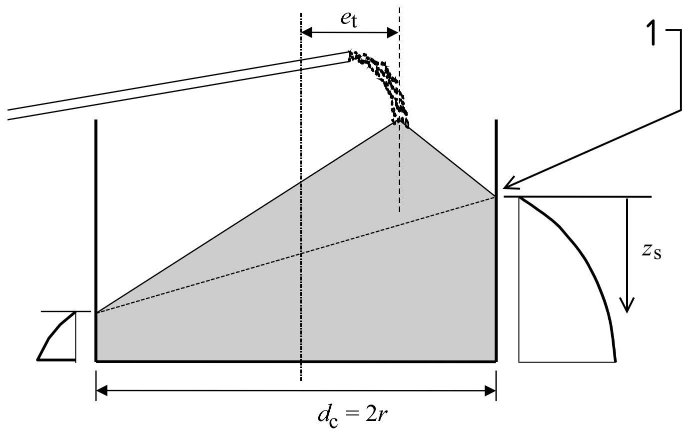
(1)P For silos of circular planform in Action Assessment Class 3 that have a squat or intermediate slenderness ($h_c/d_c < 2{,}0$) and a top surface filling eccentricity e_t greater than $e_{t,cr} = 0{,}25d_c$ (see Figure 5.7), the effect of the asymmetry of the normal pressures in inducing vertical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

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

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

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

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



Key

1 Highest wall contact with solid

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