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A continuum model of stresses in a vertical silo with a flow channel in the vicinity of the wall, using the principal stress cap surface approach for the bulk solids

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ABSTRACT

Eurocode 1 (2006) gives design equations for eccentric stresses in silos, including flow channels adjacent to the wall. This has been modelled using the approach of Matchett et al. (2015, 2016).

A three zone model was developed, consisting of:

- The flow channel.
- The transition zone.
- The bulk of the solids.

The flow channel and the transition zone were modelled by Janssen-type equations. The bulk was modelled by the principal stress cap approach.

The transition zone is a complex region and has several purposes:

1. To shelter the low stress flow channel from the high stresses around.
2. To allow high principal stresses at the transition/bulk interface, within the yield locus.
3. To form a transition between the dynamic flow channel and the static bulk.
4. To allow transition from passive stress in the flow channel to active stress in the bulk.

The model was calibrated against the data of Chen et al. (2007) for a full-scale silo, and described the data reasonably well, scaling axially and azimuthally.

Large experimental data sets are required to calibrate a model. Unfortunate data points cannot be arbitrarily rejected.

Further extensive, experimental data are needed to calibrate models.

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1. Introduction

Matchett et al. (2015, 2016) describe how eccentric stresses in vertical, cylindrical silos were modelled. They used a "principal stress cap surface" approach, in which the geometry of the principal stress cap and principal stress paths in 3-dimensional space were assumed "a priori"—see Fig. 1.

Seen from above, the principal stresses in the azimuthal direction describe circular stress paths in the horizontal plane.

In a symmetrical system, the circle would be centred about the centre of the silo, of radius r_2, creating a series of concentric circles. In an asymmetrical system, the centre of the core, radius r_1, was displaced a distance h, causing the circular stress paths to be compacted in the direction of displacement and expanded in the opposite direction. The

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Nomenclature

The notation used in Matchett et al. (2015, 2016) is used in this paper. Additional notation used specifically in this paper is given below.

A_f	Flow channel zone cross section area (m^2)
A_t	Transition zone cross section area (m^2)
$b_{Janssen}$	Janssen coefficient (m^{-1})
CYFI	Conical Yield Function Index
d	Silo diameter (m)
K_f	Flow channel zone stress ratio: horizontal/vertical
K_t	Transition zone stress ratio: horizontal/vertical
K_{tb}	Transition zone stress ratio: horizontal/vertical, used in horizontal force balance
l	Half chord length subtended by angle θ (m)
l_o	Half chord length subtended by angle $\theta_{\bigcirc}$: transition zone (m)
l_f	Flow channel half (m)
P_f	Flow channel half perimeter (m)
P_{fw}	Flow channel perimeter
r_3	Flow channel radius (m)
θ	Angle subtended between the silo centre and a point at the bulk solid zone/transition zone boundary
θ_o	Angle subtended between the silo centre and the point where the bulk solid zone boundary meets the silo wall
μ	Internal coefficient of friction
μw	Coefficient of wall friction
μtw	Transition zone coefficient of wall friction
σfh	Flow channel horizontal stress (Pa)
σfv	Flow channel vertical stress (Pa)
σth	Transition zone horizontal stress (Pa)
σthw	Transition zone horizontal wall stress (Pa)
σtv	Transition zone vertical stress (Pa)
$\sigma 2b$	Principal stress σ_2 transmitted across the transition/bulk interface: boundary condition for the bulk zone (Pa)
τf	Flow channel internal shear stress (Pa)
τfw	Flow channel wall shear stress (Pa)

The notation used in the previous papers (Matchett et al., 2015, 2016) is given below:

a_1	Relates projected circle radius R_1 to X $R_1 = a_1 X + a_1'$
a_1'	Constant relating R_1 to X—see a_1 (m)
a_2	Differential of projected circle centre $a_2 = \partial O_X/\partial X$
D	D/DX and D/DZ are differentials along the principal stress paths for changes in X & Z respectively
e_1	Angle used in the calculation of R_2 (rad)
E	Factor relating rotation in the horizontal plane to rotation on the λ-plane
h	Inner circle offset (m)
k	Ratio of wall vertical to normal stress: Janssen model
K_w	Ratio of σ_1/σ_3 at the wall
M	Conical Yield Function parameter
r_1	Inner circle radius (m)
r_2	Outer circle (silo) radius (m)
R_1	Radius of projected horizontal circle of principal stress path (m)
R_2	Radius of principal stress cap at a general point (m)
R_{20}	Value of R_2 at $\varepsilon_1 = 0$ (m)
$R_{2\pi}$	Value of R_2 at $\varepsilon_1 = \pi$ (m)
w_1	Arc length along Ψ_1-line, seen as $\partial w_1/\partial X$ (m)
w_2	Arc length along Ψ_2-line, seen as $\partial w_2/\partial Z$ (m)
x	x-axis co-ordinate (m)
X	Intercept of projected horizontal surface with x-axis (m)
X_o	Minimum value of X (m)
X_{max}	Maximum value of X (m)
x1, x2, x3	Local Cartesian co-ordinates coincident with directions of principal stress
y	y-axis co-ordinate (m)
z	z-axis co-ordinate (m)
Z	Value of z for the inner radius of the principal stress cap (m)
Z_o	Value of Z at the point of boundary conditions (m)
βc	Angle of circular arc to normal at inner core (rad)
βw	Angle of circular arc to normal at wall (rad)
$\varepsilon 1$	Angle from x-axis in the horizontal plane (rad)
$\varepsilon 2$	Angle from the vertical in the x-z plane at $\varepsilon_1 = 0$, rotated along the elliptical, principal stress path (rad)
$\varepsilon 3$	Angle from the vertical—slope of the principal stress cap surface as seen from ε_1 (rad)
$\gamma 1$	Slope of principal stress, σ_3 at the wall (Pa/m)
$\gamma 2$	Slope of principal stress, σ_1 at the wall
$\boldsymbol{\phi}$	Angle of internal friction. A nominal value of 30° has been used (rad)
$\boldsymbol{\lambda}$	Characteristic slope of principal stress path ellipse when projected onto the x-z plane (rad)
μw	Coefficient of wall friction. A nominal value of 0.3 has been used
$\boldsymbol{\eta}$	Surcharge friction factor
θlim	Limiting value of wall arc angle (rad)
ζlim	Limiting value of plane of yield (rad)
$\Psi 1$	Angle of Ψ_1-line to x-axis on the horizontal plane (rad)
$\Psi 2$	Angle of Ψ_2-line to vertical—principal stress path for changes in Z (rad)
$\boldsymbol{\rho}$	Bulk density of the bulk solid in the silo (Kg/m^3)
$\sigma 1$	Principal stress in x_1 direction (Pa)
$\sigma 2$	Principal stress in x_2 direction (Pa)
$\sigma 3$	Principal stress in x_3 direction (Pa)

centre of the core is now the centre of stress, and a Cartesian axis was defined at this point, with x in the direction of displacement and z vertically. The centres of successive, azimuthal principal stress circles were also displaced, and a given circle can be characterised by the value X(upper case x), its value at the point where it crosses the x axis.

The vertical height was characterised by parameter Z(upper case z). This is the value of z at a characteristic point on the principal cap surface—in this case the value of z at the core. The principal stress cap surface describes a circular arc in the x–z plane, along the x-axis, with characteristic radii R_{20} in the positive sense of x and $R_{2\pi}$ in the negative direction of x. A given circle subtends an angle ε_2 to the vertical plane. ε_2 is constant around a line of constant X. Thus, an X-line describes the path of principal stress σ_2 and is a circular projection onto the horizontal plane of an elliptical path in 3 dimensions.

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