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Transverse bulk solid behaviour during discharge from troughed belt conveyors

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ABSTRACT

Guidelines for the calculation of bulk solid material cross sectional dimensions and the influence of the belt conveyor transition length on the inclination of the trajectory at discharge are well established. However, not a great deal of research has been conducted on the influence of bulk solid material properties and conveyor belt transition geometry on the bulk solid material cross section at discharge. As such, assessment of cross section break-up associated with cohesive materials and transverse spreading of free flowing materials is missing. Conversely, the majority of discharge trajectory analysis techniques focus on analysis in a single vertical plane along the length of the belt.

This paper presents an analysis of high speed conveyor discharge trajectories in three dimensions, taking into account transverse spreading of free flowing materials and shearing, or cross section discontinuity, exhibited by cohesive materials. Transverse bulk solid material behaviour and trajectory discharge is evaluated using a combination of experimental laboratory tests, a continuum mechanics approach incorporating CAD and Discrete Element Modelling (DEM). The work presented shows that bulk solid material behaviour at discharge is directly influenced by material characteristics and interactions resulting from the geometry of the belt conveyor transition zone.

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1. Introduction

An accurate determination of the burden profile at discharge is essential for effective transfer chute design, specifically the geometry and position of the deflector/impact plate. The approach to analysing the geometrical shape of the bulk solid material cross section during conveying and at discharge is presented. The findings of this work build on those presented previously in Ilic [1] and comprehensively documented in Ilic [2] and the reader is referred to the latter for explanation of any details not presented.

1.1. Material profile at discharge

Immediately prior to the point of tangency of the conveyor belt and head pulley, the material load shape on a troughed belt conveyor can be closely approximated by a segment of a circle, as defined by CEMA [3]. On the other hand, Roberts [4,5] assumes a parabolic cross sectional profile, related to that at the last fully troughed idler set prior to discharge. The parabolic profile is expressed as a function of the material properties and belt geometry at the idler set, including a non dimensional cross-sectional area factor. For high speed discharge, it is generally accepted that the burden moves fast enough from the last idler roll set to discharge for only limited settling to occur. Consequently, the burden head height at discharge is assumed equal to the head height, at the last fully troughed idler roll set.

1.2. Transverse behaviour and relevance to earth pressure theory

The geometry of the bulk solid material cross section prior to discharge changes due to the variation in the profile of the conveyor belt – from a trapezoidal shape governed by the geometry of the last fully troughed idler set, to a flat profile at the head pulley. In this transition zone, the behaviour of the bulk solid is a function of its physical properties and transition time, which in turn depends on transition length and belt speed. Here, bulk solids have a tendency to shear and spread laterally as the belt troughing angle decreases from the last fully troughed idler set to a flat profile at discharge. The motion is similar to that depicted in theory of active stress states associated with a retaining wall pivoting about its base as described in soil mechanics by Terzaghi and Peck [6], Terzaghi [7] and Reimbert [8,9], Nedderman [10], and as found in

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the application to belt conveying by Krause and Hettler [11] and Wheeler [12,13]. Mentioned previously, the analysis of active and passive stress states within the material burden cross section on belt conveyors has been studied in detail by Ilic [1,2].

In earth pressure theory published in 1776, Coulomb derived the orientation of the failure plane as a function of the internal friction of the bulk solid and friction between the wall and the bulk solid. Krause and Hettler [11] applied a modified version of this theory to assess burden on a troughed belt conveyor. The corresponding active state slip plane angle, θ_a, is depicted in Fig. 1.

For the active stress state, the shear plane angle θ_a to the horizontal as a function of the idler inclination angle β, bulk solid internal friction angle θ_i, belt and bulk solid friction angle ϕ_w and conveyor surcharge angle λ, is given by:

$$\theta_a = \tan^{-1}\left[\frac{\left(\frac{\sqrt{\lambda_a \sin(\beta-\phi_w)}}{\sin(\beta+\lambda)}\right)\sin\lambda - \sin\phi_1}{\left(\frac{\sqrt{\lambda_a \sin(\beta-\phi_w)}}{\sin(\beta+\lambda)}\right)\cos\lambda - \cos\phi_1}\right] \quad (1)$$

where the active pressure factor λ_a, is given by:

$$\lambda_a = \left[\frac{\sin(\beta+\phi_i)}{\sqrt{\sin(\beta-\phi_w)} + \sqrt{\frac{\sin(\phi_w+\phi_i)\sin(\phi_i-\lambda)}{\sin(\beta+\lambda)}}}\right] \quad (2)$$

The above equations are valid provided that:

$$\theta_a \geq \theta_c,\ \lambda \leq \phi_i \text{ and } \beta \geq \phi_w \quad (3)$$

1.3. Discharge trajectory

Following transverse effects in the transition zone, the burden moves from a troughed belt profile at the last idler roll set to a flat belt profile at the head pulley and then discharges from the conveyor. Transition length, idler roll inclination and geometry, belt speed and head pulley diameter are all of influence on the discharge trajectory path. Similarly, bulk solid properties influencing the trajectory and the burden cross section at discharge include particle size, bulk density, moisture content, internal angle of friction, adhesion and friction with the belt.

A number of different models for the determination of discharge trajectories exist, including those of CEMA [3], Dunlop Conveyor Manual [14], Korzen [15], Golka [16,17] and Booth [18].

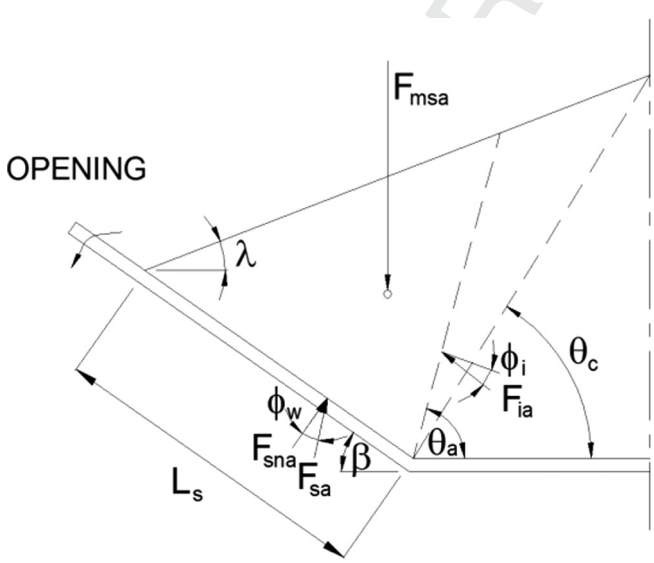

Fig. 1. Krause and Hettler's active stress state.

Experimental validation to assess accuracy, implement combinations of and differentiate between these models has been studied in detail by Arnold and Hill [19], Huque and McLean [20] and Hastie [21]. While such methods and guidelines exist, unfortunately, the general extent thus far has been limited to two dimensional analyses. The exception is Golka [16,17] who proposes a coefficient of divergence for the flow commencing at the head pulley centreline, however, that approach does not provide a relationship to the properties of the bulk solid material handled.

Discharge trajectories fall into two categories; slow speed trajectories and high speed trajectories, with determination of category dependent on the belt velocity, V_b and head pulley radius, R. For slow speed trajectories, the bulk solid material will wrap around the head pulley by some angle prior to discharge, while for fast speed trajectories, the material will discharge at the point of tangency between the conveyor belt and the head pulley. It is the latter, high speed trajectories, which are the focus of this study.

Prior to plotting the trajectory, the angle of discharge is first evaluated. In the absence of conveyor belt transition geometry, the inclination of the belt transition, ϵ, may be estimated by the guidelines such as CEMA [3], Apex Fenner [22] and Dunlop [14]. In general, the inclination at discharge is slightly higher than the general inclination of the conveyor, α, due to the transition from a troughed profile at the last idler roll set to a flat profile at the head pulley. The trajectory model used in this study, based on projectile motion, was adopted from Roberts [4,5], however, the approach presented may easily be modified to incorporate any alternative trajectory model available.

2. Transition zone analysis and DEM simulation

An experimental laboratory test apparatus was utilised to investigate lowering belt sides at a drop time slower than gravity. This was achieved with the use of a pneumatic cylinder as shown in Fig. 2. The apparatus geometry was modelled on a 600 mm wide conveyor belt (500 mm in length). The experimental procedure consisted of pouring a number of bulk solid materials into the middle of the apparatus and then shaping manually in order to produce a parabolic profile (head height of 120 mm). The sides were then lowered over a time interval of 0.5 s.

All tests were captured with a high-speed video camera from which the material cross sectional profile was assessed. Experimental results were compared to existing theory and to results obtained from DEM (Rocky Particle Simulator) simulations. The physical properties and sets of calibrated DEM simulation parameters utilised in the study are summarised in Table 1 and Table 2. The calibration procedure is necessary to specify accurate, virtual particle parameters used in the DEM, reflective of physical bulk properties of the real granular materials. As the procedure is thorough and not the focus of this paper, a detailed account is not presented. Briefly, the procedure involved the use of angle of repose, slump plane (internal shear), direct shear, inclining wall friction experimental tests and iteration via numerical simulations as a means of virtual parameter specification. Other parameters, not reported herein such as loading stiffness and coefficient of restitution, were selected based on existing literature. Furthermore, the contact model used in the simulations is a hysteretic linear spring (no damping in the tangential direction), with elastic plastic spring/dashpot rolling friction. The cohesion/adhesion model utilises a simple on-off switch and is based on particle weight and an acting distance. A comprehensive description of the testing and calibration regime to determine the physical and simulation parameters and other parameters selected from literature, as well as the DEM contact model implemented, may be found in Ilic [2]. In the DEM results presented in this section, modelling was per-

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