BULK SOLID LOAD PROFILES AND LOAD STABILITY DURING BELT CONVEYING

Alan W. Roberts

Emeritus Professor and Director,
Centre for Bulk Solids and Particulate Technologies,
The University of Newcastle, Australia.

SUMMARY

This paper is concerned with the interaction between bulk solids and belt conveyors from the point of view of load profiles on belts during motion and the stability of bulk solids in relation to slip and spillage. Load profiles on belts are examined in relation to bulk density and packing density. A test rig for experimental studies of the load profiles and load stability during conveying around horizontal curves and on inclines is described. A theory is presented to model the behaviour of bulk solids on conveyor belts and predict the conditions under which slip-back and lift-off occur. Dynamic simulations of the inclined conveying action are described and the motions of particles during slip leading to spillage are illustrated.

1. INTRODUCTION

The efficient transport of coal and other bulk solids by belt conveyors depends on many factors, not the least of which is the necessity for the conveying task to be performed without spillage. This requirement becomes particularly important in the case of long overland conveyors which run at increased speeds and which execute combinations of inclines and declines together with vertical and horizontal curves. Slip-back and spillage problems are exacerbated by increases in moisture content of the bulk solid resulting in a reduction in friction at the belt surface. The latter problem often occurs with drift conveyors in coal mines where water sprays are used for dust suppression.

The design of belt conveyors requires information on the load profile, which depends on the surcharge angle, of the bulk solid on the belt. The profile changes along the belt from the load point as the material 'shakes down', and is influenced by such factors as

- vertical and horizontal curves
- idler troughing configuration
- belt inclination
- belt sag and tension
- belt velocity
- belt vibrations

The paper examines the behaviour of bulk solids under such influences. A review is presented of experimental studies involving the measurement of surcharge profiles and settlement of bulk solids during simulated conveying around horizontal curves and on inclines. A theory is presented for the determination of the maximum inclined conveying angles to prevent 'slip back' and 'lift off' as a function of bulk solid properties, conveying speed, idler spacing and belt sag. This allows for a more meaningful approach to this aspect of conveyor design rather than using the present, somewhat empirical methods.

2. PACKING DENSITY OF COAL ON CONVEYOR BELTS

2.1 Load Profile on the Belt

When a bulk solid, such as coal, is loaded onto a conveyor belt, it is loosely packed with a surcharge angle approximating the static angle of repose θ_R. However, the material will soon settle to its equilibrium packing condition as a result of the motion over the idlers. The final surcharge angle is I, as illustrated in Figure 1. There will be segregation occurring within the bulk material with the fines and the moisture migrating to the lower belt surface. Research has indicated that the amount of settling from the loosely packed condition to the equilibrium running condition is normally in the range of 10 - 15%.
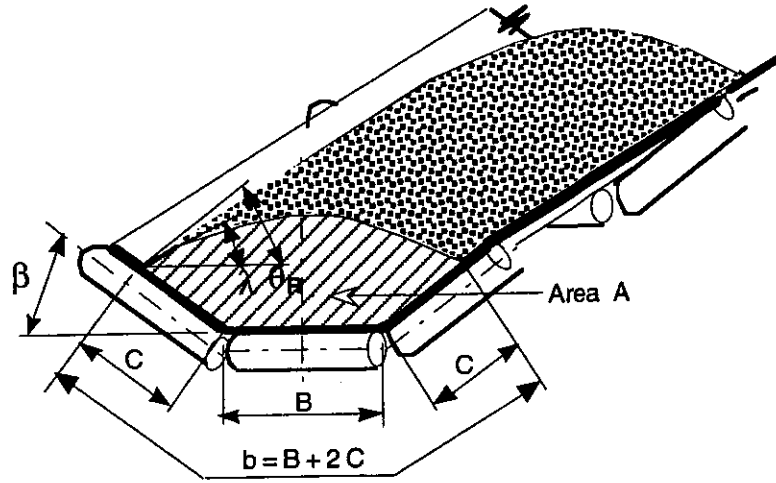
Figure 1. Load Profile on Belt

The carrying capacity of a conveyor depends on the cross-sectional area profile of material on a belt which, as shown by Roberts [1], may be expressed in terms of a non-dimensional load shape factor U and contact perimeter b as follows:

$$A = U\, b^2 \qquad (1)$$

For a three-roll idler system, U is given by

$$U = \frac{1}{(1+2r)^2}\ \{\, r\sin\beta + \frac{r^2}{2}\ \sin2\beta + \frac{\tan\lambda}{6}\ [\,1 + 4\,r\cos\beta + 2\,r^2\,(1+\cos2\beta)]\} \qquad (2)$$

where $\quad r = \dfrac{C}{B} \qquad\qquad \beta$ = troughing angle $\quad\quad \lambda$ = surcharge angle

The surcharge angle will depend on the idler troughing configuration, the static angle of repose of the bulk solid and its degree of cohesiveness. According to CEMA [2], the surcharge angle is usually 5° to 15° less than the angle of repose, although for some bulk solids, it may be as much as 20° less. Colijn [3] gives the following empirical relationship for the surcharge angle

$$\lambda = 1.11\,\theta_R - (0.1\,b + 18^{o}) \qquad (3)$$

For instance, if $\theta_R = 35^{o}$ for coal and $b = 35^{o}$, then from (3), $\lambda = 17.4^{o}$. Based on CEMA, $\lambda = 25^{o}$ which suggests that equation (3) may be a little conservative.

2.2 Load Settlement

On the assumption that, at the instant of loading onto a belt conveyor, the bulk solid is piled loosely at its natural angle of repose, the equivalent cross-sectional area for a three-roll idler configuration is

$$A_i = U_i\, b^2 \qquad (4)$$

where U_i is given by equation (2) with $\theta_R = \lambda$. That is

$$U_i = \frac{1}{(1+2r)^2}\ \{\, r\sin\beta + \frac{r^2}{2}\ \sin2\beta + \frac{\tan\theta_R}{6}\ [\,1 + 4\,r\cos\beta + 2\,r^2\,(1+\cos2\beta)]\} \qquad (5)$$

The reduction in area due to settlement, expressed as a ratio of the loosely packed condition, is

$$A_R = 1 - \frac{U}{U_i} \qquad (6)$$

<u>Example - Conveying of Coal:</u>

The angle of repose for coal is, nominally, 35° and $\lambda = 25°$. For the case when $\beta = 35°$ and $r = 1$,

Equation (2) gives U = 0.176
Equation (5) gives U_i = 0.206
Hence A_R = 0.146

2.3   Bulk Density Considerations

The above example implies a percentage increase in bulk density from the loaded to the running or settled condition of 14.6%. This may be verified by reference to Figure 2 which shows the bulk density as a function of major consolidation pressure for coal of -4mm size fraction. The solids density of the coal has been measured at 1300 kg/m³. Hence the packing density ratio may be computed as the ratio of bulk density to solids density. The packing ratio is indicative of the space occupied by the particles relative to the total space of the particles plus voids.

The packing ratio, also shown in Figure 2, approaches, asymptotically, a value of around 73% to 74 %. It is noted that this is similar to the maximum possible packing ratio of equal size spheres, the geometrical packing model being represented by a rhombohedral array. While noting that the coal particles are neither uniform in size nor spherical, nonetheless, there is a very good degree of correlation.
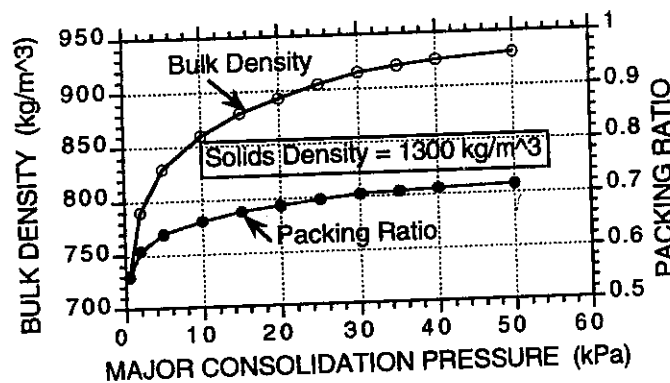

Figure 2   Bulk Density and Packing Ratio for Coal

The maximum likely static pressure at the belt surface due to the loaded product may be estimated as

$$\sigma_1 = \rho g h$$

The consolidation pressures under dynamic conditions will be higher. This is due to the acceleration of the material in the direction normal to the belt as the belt moves from the maximum sag position to the zero sag position at each idler. Thus the major consolidation pressure under dynamic conditions is

$$\sigma_1 = \rho g h \left(1 + \frac{a_v}{g} \right) \tag{7}$$

From the analysis presented in Section 5, the maximum acceleration may be estimated as follows:

$$a_v = \frac{2 \pi^2 V^2 K_s}{X} \tag{8}$$

where   V   = belt velocity
         K_s = sag ratio
         X   = idler spacing

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Assuming, for example, a maximum depth of coal on the belt h = 0.5 m, a belt speed V = 5 m/s, idler spacing = 1.5 m and the sag ratio K_s = 2%, then the acceleration is a_v = 6.6 m/s^2. Assuming, also, that the bulk density is ρ = 850 kg/m^3, then the total maximum consolidation pressure is

$$\sigma_1 = \frac{850 \times 9.81 \times 0.5}{1000} (1 + \frac{6.6}{9.81}) = 7.0 \text{ kPa}$$

Checking the bulk density from Figure 2, for σ_1 = 7.0 kPa, ρ = 850 kg/m^3. The initial assumption for ρ was correct.

Referring to Figure 2, the bulk density at the load point may be assumed to be 740 kg/m^3. Thus the percentage increase in bulk density due to load settlement is

$$\Delta\rho = \frac{850 - 740}{740} = 15\%$$

This corresponds, approximately, to the value of $\Delta\rho$ = 14.6% previously predicted from the load profile.

3.   CONVEYOR SIMULATION TEST RIG

The interaction of bulk materials with belt conveyors has been an ongoing research interest of the University of Newcastle for several years.   This work has involved a series of experimental studies using a specially designed conveyor simulation test rig. The essential details of this rig are illustrated in Figure 3. The rig was originally designed and constructed for the purpose of examining the stability of iron ore on the horizontal curved section of the Channar conveyor of Hamersley Iron. The initial work using this rig was described in a paper by Bennett and Roberts [4] in 1989.
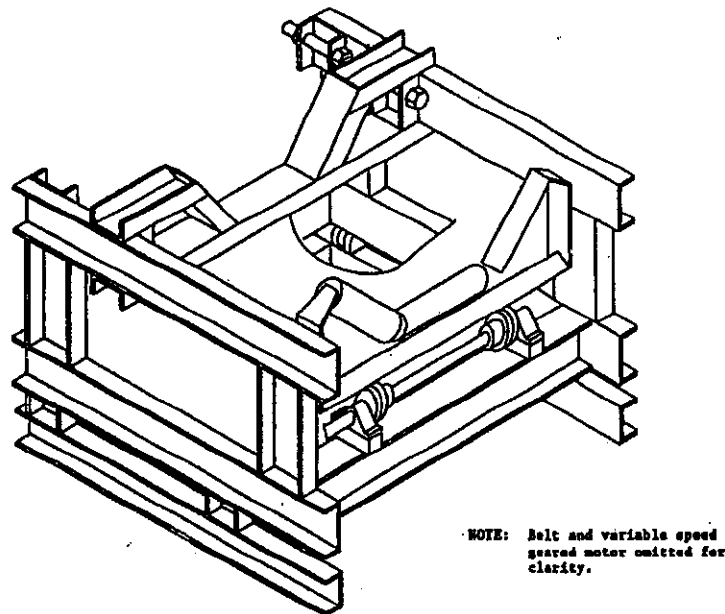

NOTE: Belt and variable speed
geared motor omitted for
clarity.

Figure 3.   Schematic isometric drawing of the conveyor simulation test rig. (Left half shown,
Right half similar - Belt and variable speed geared motor omitted for clarity).

The test rig comprises three main components:

(i)   Conveyor belt clamping and tensioning mechanism

(ii)   Cam driven troughing idler unit to simulate the belt and material passing over consecutive idler sets; and

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(iii)   Main support frame incorporating a two-way tilting base to accommodate vertical inclines and/or the superelevation of horizontally curved conveyor belts.

3.1   Test Rig Specifications

The general specifications of the test rig are:

(i)   All belt types can be accommodated with belt widths up to 1050 mm;

(ii)   Carry idlers to any diameter and specification. Idler types include flat carry idlers, 3 roll in-line and offset troughing idlers (20, 30, 35 and 45°), and 3 roll and 5 roll suspended troughing idlers. Idler spacing is variable from 1000 - 2000 mm.

(iii)   Simulated belt speeds ranging from 0 - 15 m/s are possible via a 3 hp A.C. geared motor unit fed by a variable frequency electronic drive.

(iv)   Belt sag and/or belt tension is controlled through two hydraulic jacking cylinders. The cylinders allow the belt to be adjusted to a present tension, or until a required percentage sag (either for coasting or loaded) is achieved.

(v)   Frequency and amplitude of belt vibration is to simulate material on an actual belt passing from a position on top of an idler set down to the maximum sag position (midway between consecutive idler sets) and finally to the top of the next idler set.

(vi)   The frame is hinged so that it may be set at various superelevation angles for simulation of motion around horizontal curves.

The cam drive which controls the amplitude of vibration is adjusted so that the loaded belt moves between the maximum sag position to level with the belt clamping and tensioning brackets (that is, the top of the next idler set). The frequency of vibration is set to the idler passing frequency which is a function of belt speed and idler spacing. Although the rig does not currently allow the idler rotating frequency to be superimposed it is believed that whilst the frequencies are higher, the amplitudes are so small that the effect of the rotating idlers will be negligible compared to the idler passing motion described above.

3.2   Review of Previous Test Results

A range of tests were conducted over a period of time to simulate the motion of bulk materials, coal and iron ore. In the case of the latter, one series of tests was concerned with the stability of iron ore on the horizontally curved section of an overland conveyor. By way of illustration, a typical set of results are shown in Figure 4.
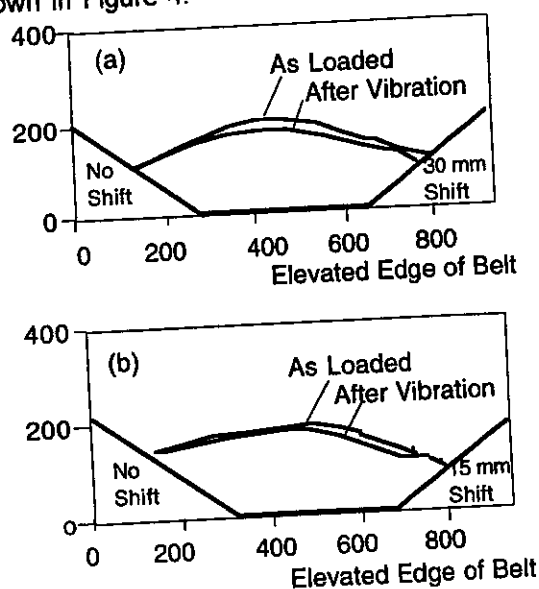

Figure 4.   Change in Surcharge Profile during Simulated Conveying Motion

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The results relate to a 35 deg. idler set, the conveyor rig being set at a horizontal curve super-elevation angle of 8 deg. The iron ore was at a moisture content 0.8% (wet basis) and of a particle size of 90% minus 16 mm. As the results show, there was very little movement of the iron ore. The results indicated that the due to settlement, the decrease in volume of iron ore on the belt was in the order of 8% indicating a corresponding increase in bulk density from loading to running.

4. SIMULATION OF LOAD SETTLEMENT DURING HORIZONTAL AND INCLINED CONVEYING

Follow up work has been performed using the rig of Figure 5 to simulate both horizontal and inclined conveying. This subsequent work, undertaken initially by Guomin and Roberts [5], was concerned with both load settlement and the determination of limiting conveyor slope angles for inclined or declined conveying. The test set-up is shown schematically in Figure 5. Other tests involved the measurement of the amount of settlement or migration, during simulated conveying, of coal fines and moisture to the surface of the belt. The latter information is of particular interest to the determination of carry-back after discharge.
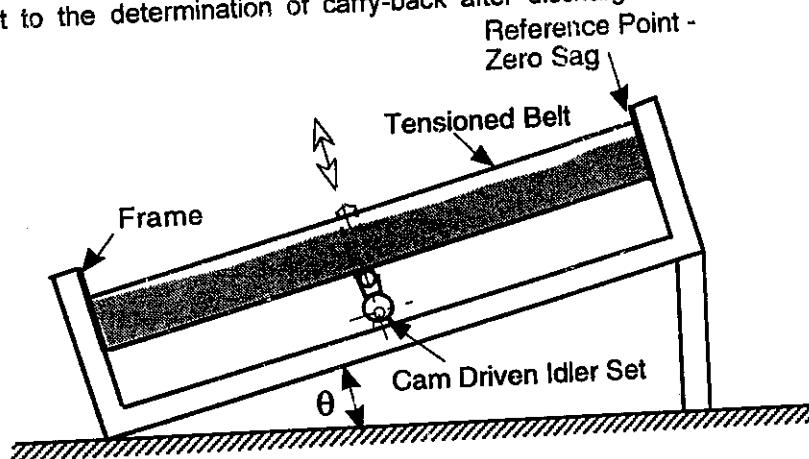

Figure 5. Test Set-Up for Simulated Inclined Conveying

To study the effect of the settlement of coal during conveying, tests performed with both coal and wheat. Noting that coal is a cohesive material, wheat was chosen in order to provide comparative results with a free flowing, non cohesive bulk solid. The test rig loaded with coal is shown in Figure 6
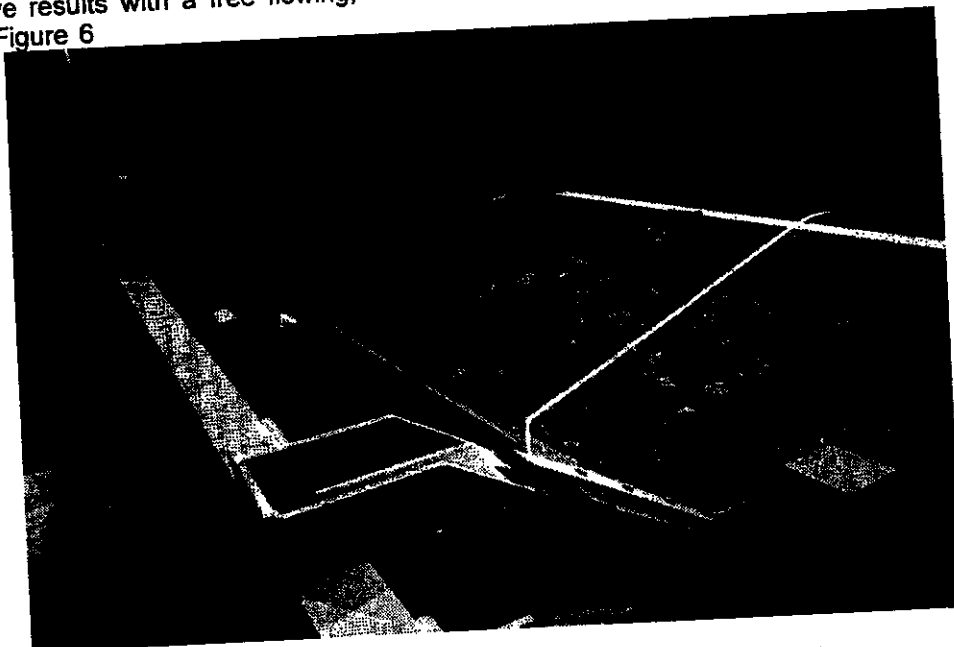

Figure 6. Photograph of Test Rig Loaded with Coal

4.1 Settlement of Bulk Solid - Horizontal Conveying

The settlement of wheat and coal due to horizontal conveying was simulated using a three-roll idler set with 35° troughing angle. The simulated conveying distance was 1000 m with the conveyor speed being simulated by the frequency of the cam drive of the test rig. The sag was set at ± 8 mm, that is, a total of 16 mm or 1% of the idler spacing. A sample of the test results is shown in Figure 7.

The graphs show the ratio of cross-sectional area of the wheat and coal on the belt as a function of conveying distance. In the case of the wheat, the reduction in area due to settlement is similar for the conveying speeds of 3 m/s and 6 m/s. The results indicate that the wheat settles to a substantially constant profile after 200 m of travel, while for the coal the settlement distance is about 600 m. Since the coal is cohesive and the wheat is not, the coal takes longer to settle than the wheat. Translating the settlement into a bulk density increase from the load point, the increase of bulk density of the wheat is about 12% and the increase in bulk density of the coal is about 14%. These results compare favourably with those predicted in Section 2.
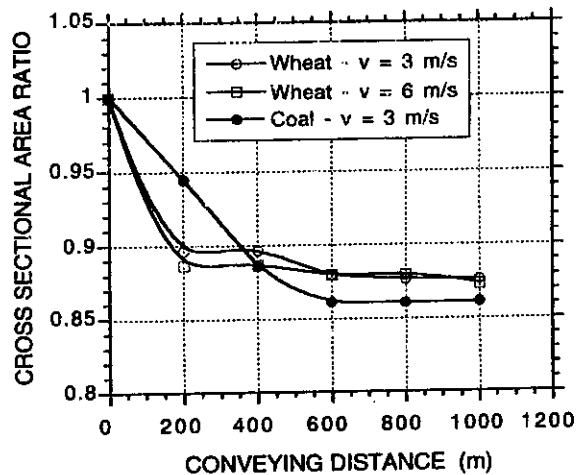

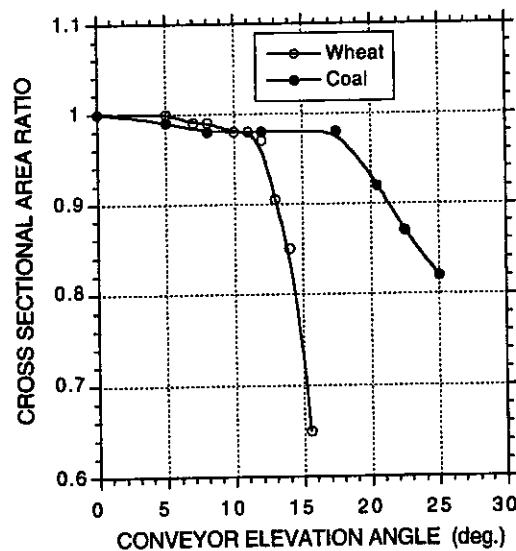Figure 7. Settlement of Wheat and Coal due to Horizontal Conveying

Figure 8. Simulated Slope Conveying of Wheat and Coal
35° Idlers; Simulated Conveying Speed = 3 m/s

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4.2 Limitations to Inclined Conveying

Simulation tests were performed to examine the conveying on inclined slopes. A typical set of results are shown in Figure 8 for wheat and coal at a simulated belt speed of 3 m/s in 35^0 troughing idlers and with a simulated sag of 1%.
The graphs depict the ratio of the cross-sectional area at the maximum sag point to the reference area at nominally zero sag. In the case of the wheat, the load starts to slip back at an elevation angle of 12^0, while for the coal, the slip back occurs at an elevation angle of approximately 18^0. These limiting conveying angles compare favourably with the values given in the CEMA Handbook [1]. CEMA quotes the limiting conveying angle of 12^0 for wheat and 16^0 to 22^0 for coal.

4.3 General Comments

The foregoing shows that the simulation test rig of Figures 3 and 6 provides a satisfactory way of experimentally determining the conveying characteristics of bulk solids. While the test allows the influence of belt speed to be examined as far as the settling of the material on the belt is concerned, it does not allow the slip velocity to be determined. When slip occurs, the bulk solid moves at a relative velocity opposite to that of the belt, but still moves forward at an absolute velocity less than that of the belt. Hence, slightly greater elevation angles may be possible than those measured using the test rig. The test rig predictions may be somewhat conservative, but this is not seen as a disadvantage.

5. DESCRIPTION OF THE INCLINED CONVEYING PROBLEM

In order to provide a greater insight into the mechanism of slip and fall back, an analysis of the problem is now undertaken.

Figure 9 shows a section of an inclined conveyor belt. As the bulk solid is conveyed, transverse cyclical type motion is imparted to the bulk solid as a result of the belt sag and the forward motion of the belt over the idlers. As a consequence, there will be cyclical variations in the contact and drag forces between the belt and the bulk solid which may cause the bulk solid to slip back relative to the belt. If the belt velocity is high enough, there may be zones where the bulk solid loses contact with the belt and actually lifts off.
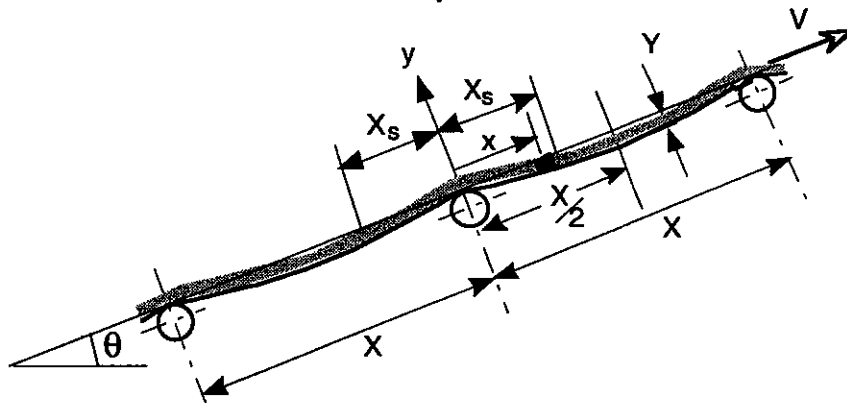

Figure 9. Motion of Bulk Solid on Conveyor Belt

Referring to Figures 9 and 10, the following variables are defined:

X	=	Idler spacing
θ	=	Conveyor slope angle
Y	=	Maximum belt sag
x	=	Coordinate defining a location point on the belt
V	=	$\dfrac{dx}{dt}$ = Belt velocity
x_r	=	Coordinate defining the position of particle of mass "Δm" on belt

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$$V_r \quad = \quad \frac{dx_r}{dt} \quad = \text{Relative velocity of mass particle during slip}$$

y = Belt deflection at location x

Δm = Mass of element

X_s = Section of belt over which slip may occur

Considering a bulk solid mass segment at location 'x', the forces acting are illustrated in Figure 10. The variable shown are

Δmg = Weight of element

N = Normal force between the mass and the belt surface

F_R = Drag force

F_A = Adhesive force between bulk solid and belt

$\ddot{y}$ = Transverse acceleration of belt

$\Delta m\,\ddot{y}$ = Inertia force due to acceleration $\ddot{y}$

$\ddot{x}_r$ = Relative acceleration of mass when slip occurs

$Dm\,\ddot{x}_r$ = Inertia force due to relative acceleration $\ddot{x}_r$
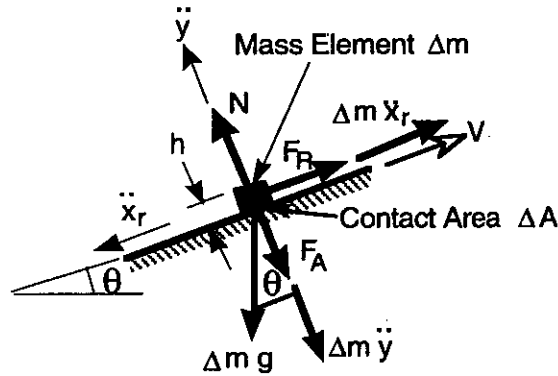

Figure 10.   Forces Acting on Bulk Solid Mass Element in Contact with the Belt

Analysing the forces in the transverse and longitudinal directions

$$N \ = \Delta m \left(g\cos\theta + \ddot{y} + \frac{F_A}{\Delta m} \right) \tag{9}$$

$$F_R = \Delta m \left(g\sin\theta - \ddot{x}_r \right) \tag{10}$$

The adhesive force F_A is given by

$$F_A = \sigma_0 \, \Delta A = \Delta m \, \frac{\sigma_0}{\rho h} \tag{11}$$

where σ_0 = Adhesive stress between the bulk solid and the belt surface

ρ = Bulk density

h = Effective height of bulk solid on belt

While the adhesive stress effect is often negligible, it is included in the analysis for the sake of completeness.

The transverse motion of the bulk solid on the belt is governed by the 'static' sag profile of the belt and the belt velocity, plus any additional transverse vibrations of the belt due to its stiffness, distributed mass and tension.   For a loaded belt, it is reasonable to assume that the latter effect is, in many cases, negligible.   Hence, for the present case, it is assumed that the transverse motion of the bulk solid is due to the sag and forward velocity.

It is also assumed that the sag profile of the belt can be approximated by the cosine curve,

$$y = \frac{Y}{2} \left[\cos\left(\frac{2\pi x}{X} \right) - 1 \right] \tag{12}$$

The frequency of the cyclical transverse motion of point on the belt is

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Frequency $\quad f = \dfrac{V}{X}$ (13)

Noting that $\dot{y} \quad = \dfrac{dy}{dt} \quad = \dfrac{dy}{dx}\dfrac{dx}{dt} \quad = \dfrac{dy}{dx} \ V \ $ and $\ddot{y} = \dfrac{d^2y}{dx^2} \ V^2$

Also defining the sag ratio K_S as

$$K_S = \dfrac{Y}{X}$$ (14)

then (11) becomes

$$y = \dfrac{K_S \, X}{2} \quad [\cos(\dfrac{2\pi x}{X}) - 1]$$ (15)

and

$$\dot{y} \quad = - p \, K_S \, V \, \sin(\dfrac{2\pi x}{X})$$ (16)

then

$$\ddot{y} = - \dfrac{2 \, p^2 \, V^2 \, K_S}{X} \quad \cos(\dfrac{2\pi x}{X})$$ (17)

6.   SLIP OF BULK SOLID RELATIVE TO BELT

6.1 Equivalent Friction

Slip will commence when the drag force F_D equals the force due to limiting friction. Once slip occurs, the drag force reduces slightly to the force corresponding to kinetic friction. For the slip condition,

$$F_D = \mu_E \, N$$ (18)

μ_E is an 'equivalent' friction coefficient which takes into account the actual friction coefficient between the bulk solid and the belt surface and the load configuration of the bulk solid on the belt.   Figure 11 (a) shows the cross-section of bulk solid on a conveyor belt.   A parabolic shaped surcharge is assumed.

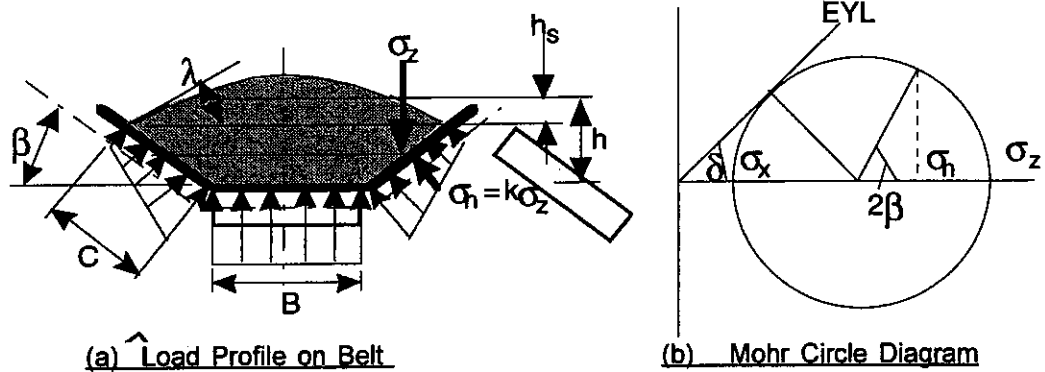(a)   Load Profile on Belt   (b)   Mohr Circle Diagram

Figure 11.   Pressure Distribution Around Belt

Referring to the Mohr Circle diagram of Figure 11 (b), it may be shown that the pressure ratio k is given by

$$k = \dfrac{\sigma_n}{\sigma_z} = \dfrac{1 + \sin\delta \, \cos 2\beta}{1 + \sin\delta}$$ (19)

From Figure 11 (a) it may be shown that

$$\mu_E = \mu \, [\, \dfrac{B \, h + C \, k \, (h_s + h)}{B \, h + C \, \cos\beta \, (h + h_s)} \,]$$ (20)

$$\mu_E \geq \mu$$

Approximate Form of μ_E

As an alternative to the above, μ_E may be approximated by

$$\mu_E = \mu \left(1 + k \frac{h}{B + C} \right) \tag{21}$$

where

h = mean height of bulk solid on belt
k = factor to account for internal friction and the belt cross sectional profile and degree of compaction
μ = friction coefficient between the bulk solid and the belt

The mean height "h" is given by

$$h = C \sin\beta + \frac{(B + 2 C \cos\beta) \tan\lambda}{6} \tag{22}$$

where

β = troughing angle, and λ = surcharge angle

Normally k is such that $0.4 < k < 1.0$, the higher values being relevant when the bulk solid is loosely packed.

6.2 Condition for Slip to occur

Noting the condition that $\ddot{x}_r \geq 0$, the general case for slip with acceleration $\ddot{x}_r$ is obtained from equations (9) to (11).

$$\ddot{x}_r = g \sin\theta + \mu_E \left[\frac{2\pi^2 V^2 K_s}{X} \cos\left(\frac{2\pi x}{X}\right) - g \cos\theta - \frac{\sigma_0}{\rho h} \right] \tag{23}$$

The slip acceleration $\ddot{x}_r$ has a maximum value when $\cos\left(\frac{2\pi x}{X}\right) = 1$, that is, when $x = 0$ or $x = X$. It will have a minimum positive value when $\cos\left(\frac{2\pi x}{X}\right) = 0$, that is, when $x = \frac{X}{4}$ or $x = \frac{3X}{4}$. If the bulk solid is slipping backward relative to the belt with acceleration $\ddot{x}_r$, the corresponding belt velocity is

$$V = \sqrt{\frac{X}{2\pi^2 K_s \cos\left(\frac{2\pi x}{X}\right)} \left[g \left(\cos\theta - \frac{1}{\mu_E \sin\theta} \right) + \frac{\sigma_0}{\rho h} + \frac{\ddot{x}_r}{\mu_E} \right]} \tag{24}$$

When slip is pending, $\ddot{x}_r = 0$ and the corresponding belt velocity is

$$V = \sqrt{\frac{X}{2\pi^2 K_s \cos\left(\frac{2\pi x}{X}\right)} \left[g \left(\cos\theta - \frac{1}{\mu_E} \sin\theta \right) + \frac{\sigma_0}{\rho h} \right]} \tag{25}$$

6.3 Relative Motion

Noting that $x = V t$, then (23) becomes

$$\ddot{x}_r = g \sin\theta + \mu_E \left[\frac{2\pi^2 V^2 K_s}{X} \cos\left(\frac{2\pi V}{X} t\right) - g \cos\theta - \frac{\sigma_0}{\rho h} \right] \tag{26}$$

Letting $V_r = \dot{x}_r$, then by integration,

$$V_r = \left[g \sin\theta - \mu_E \left(g \cos\theta + \frac{\sigma_0}{\rho h} \right) \right] \frac{x}{V} + \mu_E \pi V K_s \sin\left(\frac{2\pi x}{X}\right) \tag{27}$$

and

$$x_r = [g \sin\theta - \mu_E(g \cos\theta + \frac{\sigma_0}{\rho h})] \frac{x^2}{2 V^2} - m_E \frac{X K_S}{2} \sin(\frac{2 p x}{X})$$ (28)

6.4 Net Velocity of Bulk Solid

The net velocity of the bulk solid on the belt is

$$V_{net} = V - V_r$$

Slip will occur if the belt speed is greater than that given by equation (24) and $V_r \geq 0$. For slip to cease, V_r becomes zero and from equation (27)

$$\sin (\frac{2 \pi x}{X}) = \frac{x}{\mu_E \pi V^2 K_S} [\mu_E (g \cos\theta + \frac{\sigma_0}{\rho h}) - g \sin\theta]$$ (29)

This has to be solved to find $x = X_S$ (see Figure 10). An approximate solution may be obtained by considering the first three terms of the series expansion of $\sin (\frac{2 \pi x}{X})$.

$$\sin (\frac{2 \pi x}{X}) \approx (\frac{2 \pi x}{X}) - \frac{1}{6} (\frac{2 \pi x}{X})^3$$

Hence, equation (29) becomes

$$X_S \approx \sqrt{\frac{3 X^3}{4 p^3} \{\frac{2 p}{X} - \frac{1}{\mu_E \pi V^2 K_S} [\mu_E (g \cos\theta + \frac{\sigma_0}{\rho h}) - g \sin\theta]\}}$$ (30)

6.5 Restriction to Slip

The foregoing analysis defines the conditions under which slip can occur. In many cases slip is prevented by the constraints imposed by the upstream material on the belt as illustrated in Figure 12. Slip will be prevented if the restraining force due to friction $F_1 \geq F_2 \cos \theta$.
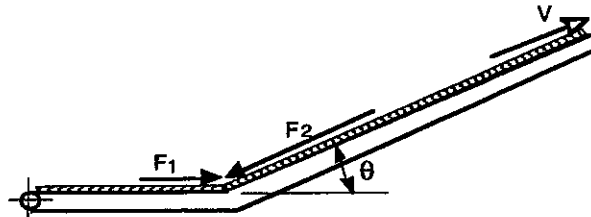

Figure 12. Restriction to Slip by Upstream Material on Belt

7. FALL BACK DUE TO LIFT OFF

7.1 Condition for Lift Off

Lift off occurs when the normal force becomes zero. From the foregoing analysis, it may be shown that the belt velocity for lift off to occur is given by

$$V = \sqrt{\frac{X}{2 \pi^2 K_S \cos(\frac{2 \pi x}{X})} [g \cos\theta + \frac{\sigma_0}{\rho h}]}$$ (31)

The minimum belt velocity for lift off to occur corresponds to $x = 0$ or $x = X$ for which the particles on the belt attain a maximum downward (negative) acceleration.

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7.2   Fall Back of Material during Free Flight

When lift off occurs, the particles move in free flight as indicated in Figure 13. Assuming lift off begins at point P, the particles move in free flight making contact with the belt again at point P_1 which is located at a distance x_f from point P. The time of flight is designated t_f. During this time, the point on the belt travels a distance x_b from P to P_2. In this simplified analysis, inter-particle contacts during free flight are not considered and it is assumed that the coefficient of restitution is zero at the point where contact is again made with the belt. This is a reasonable assumption for cohesive bulk solids.
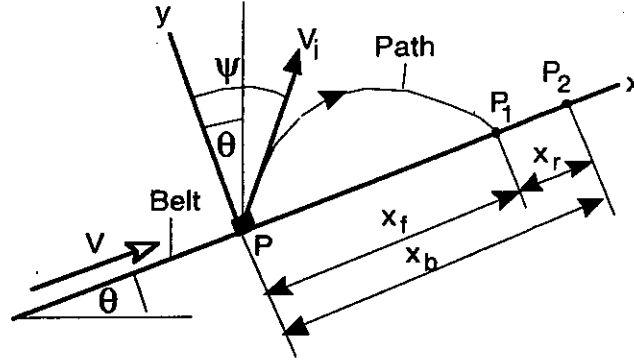

Figure 13. Fall-Back During Lift Off

The velocity of a bulk solid particle at lift off is V_i and is inclined at angle $(\psi-\theta)$ to the vertical. V_i is composed of two components $\dot{x}_i$ and $\dot{y}_i$ in the 'x' and 'y' directions respectively.   For the 'x' direction, $\dot{x}_i$ is equal to the belt velocity minus the relative velocity $V_r = \dot{x}_r$. That is,

$$\dot{x}_i = V - V_r$$

For convenience, let $\dot{x}_i = C_x V$ (32)

where $C_x = 1 - \dfrac{V_r}{V}$ (33)

V_r is given by equation (27). For the 'y' direction, the velocity of the material on the belt is given by equation (16). That is,

$$\dot{y} = - \pi K_s V \sin(\frac{2\pi x}{X})$$

$\dot{y}$ is positive each cycle for the range $\dfrac{X}{2} < x \leq X$. While the lift off velocity component $\dot{y}$ will vary in magnitude from zero to a maximum $\pi K_s V$ and then to zero again, for convenience, the maximum lift off velocity is used in the analysis. That is

$$\dot{y} = \pi K_s V$$ (34)

Hence, the initial velocity is

$$V_i = V \sqrt{(\pi K_s)^2 + C_x^2}$$ (35)

and $y = \tan^{-1} [\dfrac{C_x}{\pi K_s}]$ (36)

It may be shown that the distance x_f is given by

$$x_f = \frac{2 V_i^2 \sin(y-\theta) \cos\psi}{g \cos^2\theta}$$ (37)

The corresponding time of flight is

$$t_f = \frac{x_f \cos\theta}{V_i \sin(\psi-\theta)} \qquad (38)$$

The total distance of fall back is

$$x_r = x_b - x_f = V t_f - x_f \qquad (39)$$

The average relative velocity during fall back is

$$V_{rb} = \frac{x_r}{t_f} \qquad (40)$$

Depending on the distance x_f, there may be more than one lift-off or bounce per cycle. For a single lift-off per cycle, the average net fall-back velocity per cycle is

$$V_{rav} = \frac{x_r}{X} V_{rb} \qquad (41)$$

Hence, the net velocity of bulk solid during conveying is

$$V_{bs} = V - V_{rav} \qquad (42)$$

8. SOME PLOTTED RESULTS

8.1 Slip and Lift Off

Figure 14 shows belt velocities for lift-off and slip, computed using equations (31) and (25) respectively, for the condition when the adhesive stress $\sigma_o = 0$, sag is 2% and the equivalent friction coefficient $\mu_E = 0.5$. It is noted that at $\theta = 0$, the belt velocities for slip and lift-off are the same. For a given angle θ, provided the belt speed is less than V_S, slip will not occur. Also, provided the belt speed is less than V_L, lift-off will not occur.

Figure 15 shows the corresponding influence of belt sag on lift-off and slip for the belt speed $V = 5$ m/s.
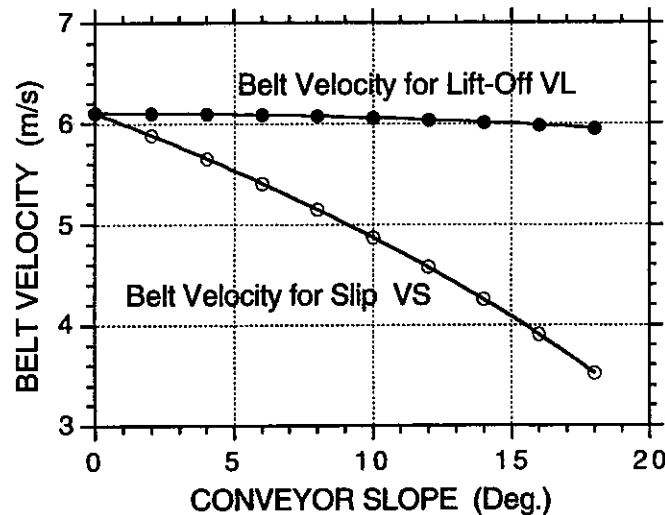

Figure 14. Belt Velocities for Slip and Lift Off
$\mu_E = 0.5$; $K_s = 2\%$; Idler Spacing $X = 1.5$ m; $\sigma_o = 0$
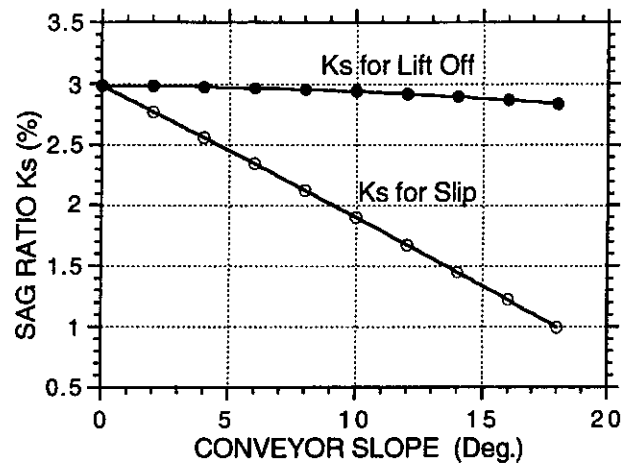
Figure 15.   Sag Ratios for Slip and Lift Off
Belt Speed V = 5 m/s: μ_E = 0.5: X = 1.5 m: σ_0= 0

8.2   Influence of Belt Friction

In the case of coal drift conveyors, the use of water sprays for dust suppression can greatly reduce the friction between the coal and the belt, causing slip and spillage.   The influence of friction at the belt surface is illustrated in Figure 16.   As the friction decreases, the slope angle at which slip commences is significantly reduced.   For example, if the equivalent friction μ_E = 0.2 and the conveyor runs at 4 m/s, slip and possible spillage will occur if the conveyor slope angle is greater than 7^0.   This applies to an idler spacing of X = 1.5 m and a sag ratio of K_S = 0.02 (that is 2%).
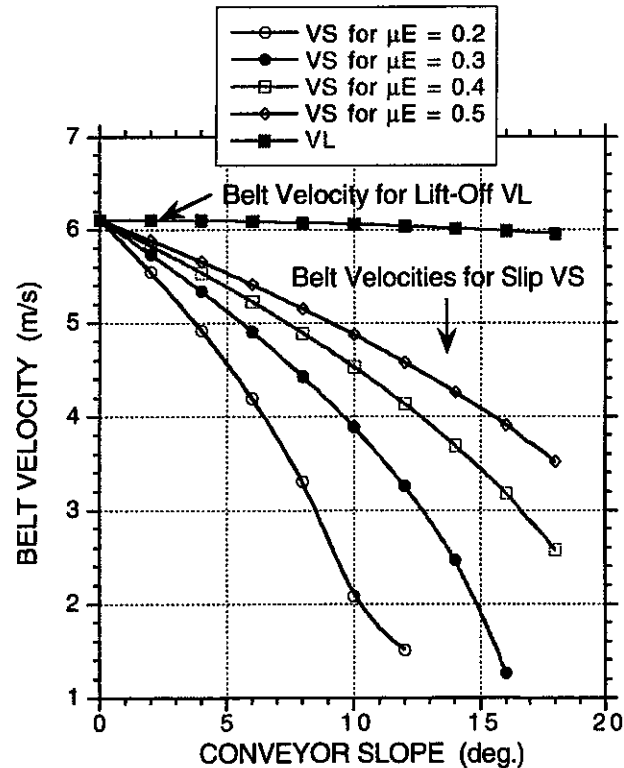

Figure 16.   Equivalent Friction Coefficients for Slip
K_S = 2%: Idler Spacing X = 1.5 m: σ_0= 0

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8.3 Relative Motion During Slip

As indicated by equation (30), there is a limited distance X_S over which slip can occur. As an example, Figure 17 shows this distance as a function of conveyor slope angle for the case when $V = 5$ m/s, $X = 1.5$ m, $K_S = 0.02$ and $\mu_E = 0.5$. Figure 18 shows the relative and net conveying velocities during slip for the case when $\mu_E = 0.5$; $X = 1.5$ m; $V = 5$ m/s; $\theta = 15^O$.

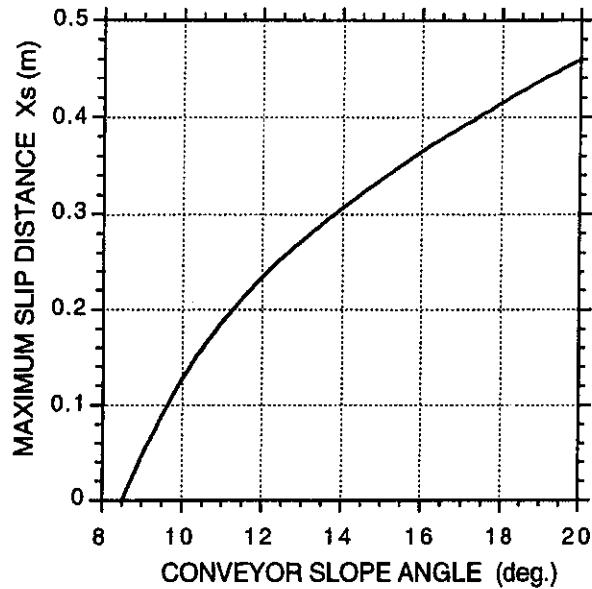Figure 17. Maximum Slip Distance as Function of Slope Angle θ
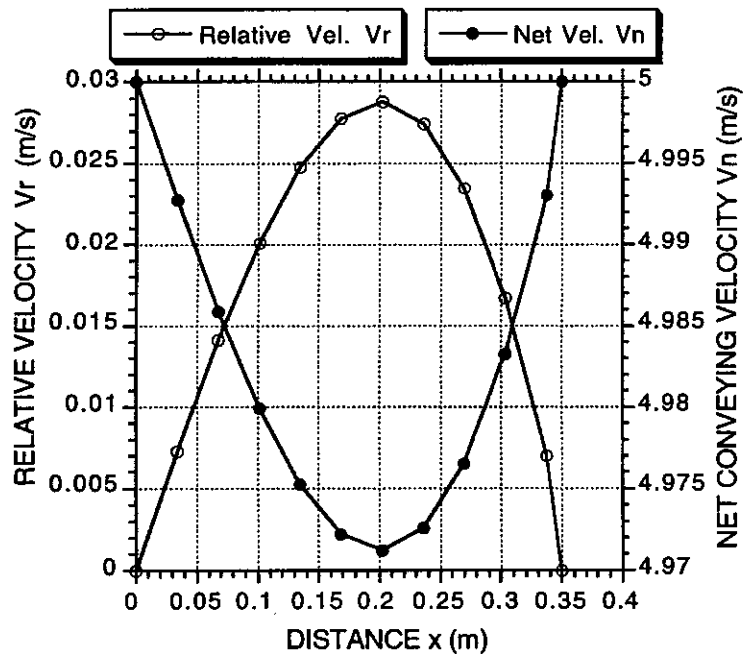$V=5$ m/s; $X = 1.5$; $K_S =2\%$; $\sigma_0= 0$; $\mu_E = 0.5$

Figure 18. Relative and Net Conveying Velocities During Slip
$V=5$ m/s; $X = 1.5$; $K_S =2\%$; $s_0= 0$; $\mu_E = 0.5$; $\theta = 15^O$

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8.4   Relative Motion During Lift-Off

The condition for relative motion during lift off is illustrated in Figure 19.   This applies to the belt velocity of 6.5 m/s.   The graph shows the relative velocity during a single lift-off cycle and the corresponding net conveying velocity.
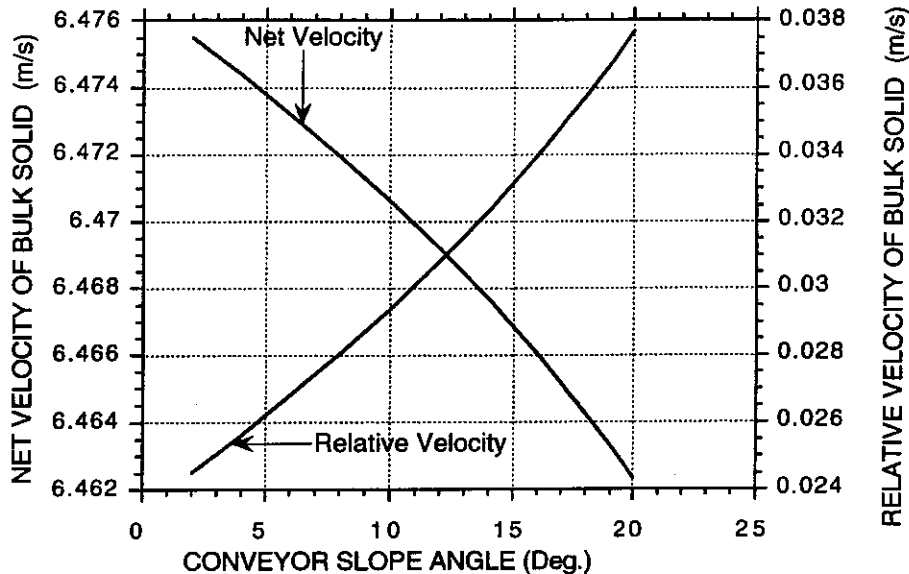

Figure 6.19. Net Conveying Velocity for Single Lift-Off per Cycle
V = 6.5 m/s; K_s = 2 %; X = 1.5 m; C = 0.9

9.   CONCLUDING REMARKS.

This paper has examined the interaction between bulk solids and belt conveyors from the point of view of load profiles on belts during motion and the stability of bulk solids in relation to slip and spillage.   A test rig developed at the University of Newcastle for experimental studies of the load profiles and load stability during conveying around horizontal curves and on inclines has been described.

A theory has been presented to model the behaviour of bulk solids on conveyor belts and predict the conditions under which slip back and lift off occur.   These conditions may lead to spillage. The theory takes into account belt inclination, troughing configuration, belt sag and tension, and belt velocity.   The theory also includes consideration of the relevant properties of the bulk solid such as the friction and adhesion between the bulk solid and the belt.

10.   REFERENCES

1.   Roberts, A.W.   "Belt Conveyors - Review of Conventional Design Procedures". Chapter 2, course notes, "Modern Developments in Belt Conveying",   Centre for Bulk Solids and Particulate Technologies, The University of Newcastle, August, 1996.

2.   "Belt Conveyors for Bulk Materials". Conveyor Equipment Manufacturers Association (CEMA). USA

3.   Colijn, H. "Mechanical Conveyors for Bulk Solids". Elsevier, 1995

4.   Bennett, D.J. and Roberts, A.W.   "Bulk Solid and Conveyor Belt Interaction During Transportation".   Proc. 3rd Intnl. Conf. on Bulk Materials, Storage, Handling and Transporation, I.E. Aust., Newcastle, June 1989. (pp.345-358).

5. Guomin, S. and Roberts, A.W. "Experiment on Area of Load Cross Section and Surcharge Angle of Bulk Material on Belts During Transportation". Research Report, TUNRA Bulk Solids, The University of Newcastle, July, 1990.