# Design Principles for Chutes to Handle Bulk Solids[1]

by

**D. Stuart Dick**
**and**
**T. A. Royal**

## Introduction

Chutes are used to direct the flow of bulk solids, *e.g.,* from one conveyor belt to another. Unfortunately, chutes all too often "fail" to perform reliably. Such failures can be costly, particularly where large tonnages of bulk materials are handled such as in most mining and quarrying operations, ship and railcar loading and unloading facilities.

Some of the problems associated with failed chute designs are plugging of chutes, wear on chute surfaces, unacceptable dust generation, excessive belt wear, and particle attrition. By far the most severe of these problems is plugging. Wear on chute surfaces is often dealt with by providing rock boxes, dusting by providing a dust collection system, and excessive belt wear by providing skirts to control bouncing of large lumps. In fact all of these problems can usually be eliminated, or at least minimized, by judicious use of certain chute design principles.

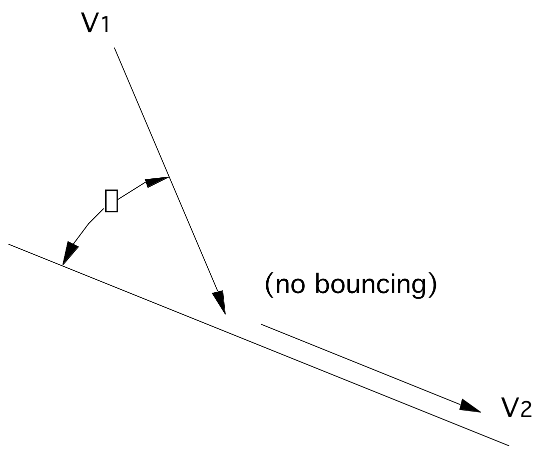
A comprehensive bibliography regarding chute design has been prepared by *Roberts* and *Scott* [1]. Using the terminology in their paper, we will only consider the *fast* (*i.e.,* accelerated) flow mode in which material flows in contact with the chute bottom and side walls without contact with the top.

## Design Principle #1 - Prevent Plugging at Impact Points

A chute must be sufficiently steep and smooth to permit sliding and cleanoff of the most frictional bulk solid that it handles. This is particularly important at impact points such as after a free fall or where the chute changes direction. However, chutes should be no steeper than necessary for cleanoff, to keep material velocities and wear to a minimum.

[1] Source: Stuart-Dick, D. and Royal, T.A.: Design Principles for Chutes to Handle Bulk Solids. Bulk Solids Handling, Vol. 12, No. 3, Sept. 1992, pp 447-450. Used with permission of the publisher.

Fig. 1: Velocity of a particle after impact on a chute




Referring to Fig. 1, the velocity of a stream of particles (assuming no bouncing) after impacting a chute, $V_2$, relative to its velocity before impact, $V_1$, is:

$$\frac{V_2}{V_1} = \cos\theta - \sin\theta \tan\phi'$$

where:

$\theta$ = angle of incoming stream relative to chute surface (see Fig. 1)
$\phi'$ = wall friction angle between particles and chute surface

There is a particular combination of $\theta$ and $\phi'$ that will reduce $V_2$ to zero ($\theta + \phi' = 90°$). The smoother the chute surface, the lower the value of $\phi'$, hence the larger the critical value of impact angle $\theta$ before $V_2$ goes to zero. At this and larger angles of $\theta$, there is no sliding of the bulk solid on the chute surface. At least a part of the flowing stream will "stall" on the surface, and the angle $\phi'$ is no longer useful in analyzing the chute.

The impact pressure, $\sigma$, can be approximated as follows:

$$\sigma = \frac{\gamma V_1^2 \sin^2\theta}{g}$$

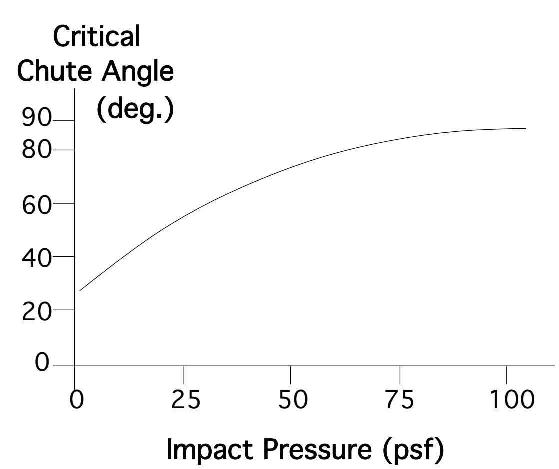
where:

$\gamma$ = bulk weight density
$g$ = acceleration due to gravity

If $V_2$ is zero at an impact point, the material may adhere to the chute surface. A chute angle test developed at Jenike & Johanson, Inc. can be used to measure critical chute angles for adhesion as a function of impact pressure. These angles can be used to determine the minimum chute angle required at an impact point to overcome adhesion. The test consists of loading a sample of the bulk solid on a representative coupon of the chute surface with a range of loads to represent different impact pressures. After each load is applied for a few seconds, the load is removed and the coupon is inclined about a distant pivot point. The angle at which the bulk solid slides is plotted as a function of impact pressure. A typical plot of the test results is shown in Fig. 2.

Usually a factor of safety of 5° to 10° is added to these minimum values to ensure cleanoff.

Fig. 2: Typical result of chute angle test



Adhesion of the material to the chute surface is not a consideration if $V_2$ can be kept greater than zero. In this case, the rate of changing the direction of a flowing stream will significantly affect the stream's velocity. Assuming that one wants to avoid reducing the velocity to zero, consider an arrangement where a stream of material must be deflected through an angle $\theta$. If the chute can be arranged so that the stream is deflected twice through half angles as shown in Fig. 3, we get:

$$\frac{V_I}{V_1} = \cos\frac{\theta}{2} - \sin\frac{\theta}{2}\tan\phi'$$

at the first impact, and

$$\frac{V_{II}}{V_I} = \cos\frac{\theta}{2} - \sin\frac{\theta}{2}\tan\phi'$$

at the second impact. The ratio of the velocity after the double deflection to the original velocity is:

$$\frac{V_{II}}{V_1} = \cos^2\frac{\theta}{2} - \sin\theta\tan\phi' + \sin^2\frac{\theta}{2}\tan^2\phi'$$

For one single deflection through the angle $\theta$, the ratio of velocities after and before impact is:

Fig. 3: Velocity of a particle after two impacts to deflect through angle $\theta$

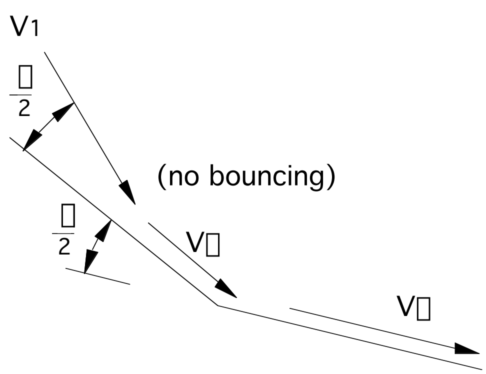
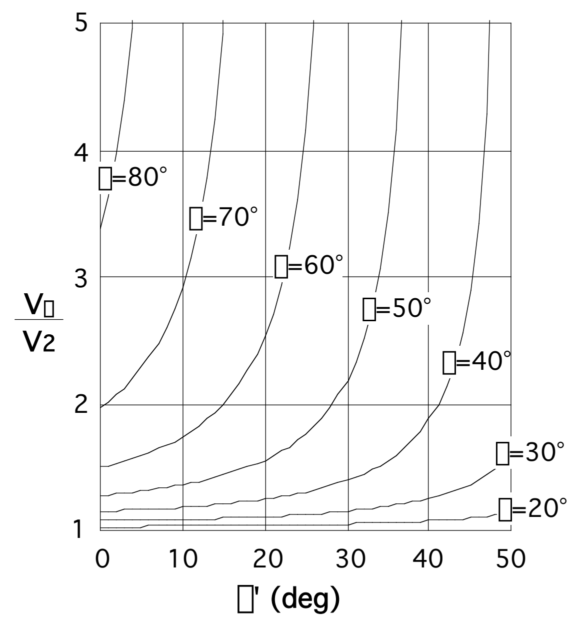



Fig. 4: Velocity of particle after impacting two half angles as a ratio of velocity after one impact




$$\frac{V_2}{V_1} = \cos\theta - \sin\theta\tan\phi'$$

The ratio $V_{II}/V_2$, obtained by dividing the above equations, shows the advantage (in terms of maintaining velocity) of a stepped deflector over a single deflector. Fig. 4 shows a family of curves of $V_{II}/V_2$ for values of $\theta$ as a function of $\phi'$. As the graph shows, the advantage is dramatic when the deflection angle $\theta$ is greater than 30°.

For example, if the angle of sliding friction is 28° and the stream must be deflected through an angle of 50°, the stream velocity after two deflections of 25° each, will be twice what it would be after a single deflection of 50°. At twice the velocity, the stream will have half the cross-sectional area.

Extending this argument, it is easy to see that in the limit, a curved deflector will slow down a stream the least, and further, the larger the radius of curvature, the better the stream's velocity will be maintained.

**Design Principle #2 - Ensure Sufficient Cross-Sectional Area**

While a bulk solid is sliding on a straight chute surface it will accelerate or decelerate, as a function of $\theta$ and $\phi'$ (see Fig. 5) under the influence of gravity alone:

$$a = g\,(\sin\theta - \cos\theta \tan\phi')$$

On a curved surface (in a vertical plane), centrifugal forces will add to the normal forces between the material and the chute, (see Fig. 6). This introduces another term to the acceleration equation:

$$a = g(\sin\theta - \cos\theta \tan\phi') - \frac{V^2}{R}\tan\phi'$$

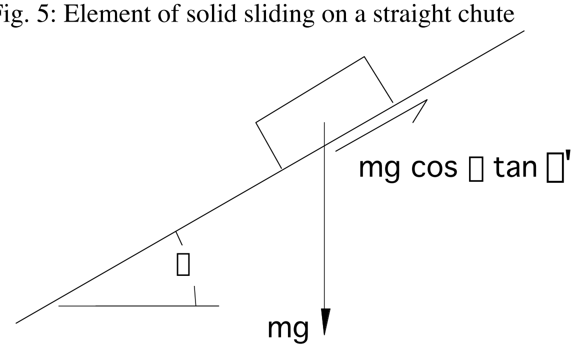
$R$ is positive as shown in Fig. 6 and the material is assumed to be in contact with the chute at all times.

It is interesting to note the angle at which the terms in the above equation cancel. Take values of 25° for $\phi'$ and 3 m for $R$. When $V$ = 5 m/s (a free fall drop of 1.3 m) the acceleration is zero when the chute angle is 46° from horizontal. When $V$ = 7.5 m/s (a free fall drop of 2.9 m) the acceleration is zero when the chute angle is 79° from horizontal!

As the material accelerates and decelerates through the chute, its cross-sectional area changes. This affects the mass of the element being considered and should be taken into account in the calculations.

It is essential in designing a chute to know what the velocity of the flowing stream is at any point. The concept of a "throat" in a chute is of no practical significance unless the velocity is known, since the mass flow rate is proportional to velocity and cross-sectional area. At any distance, $S$, along a chute surface, the stream velocity, $V$, is given by:

Fig. 5: Element of solid sliding on a straight chute



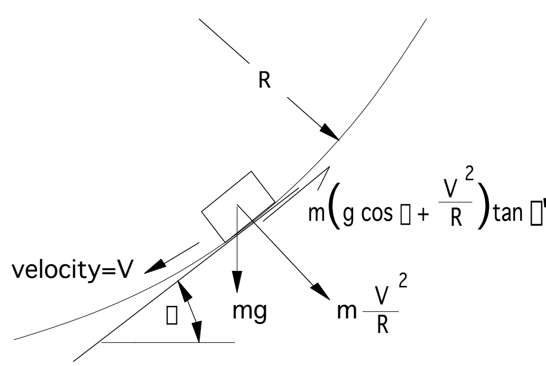

$$V = \sqrt{V_0^2 + 2aS}$$

where:

$V_0$ = velocity at starting point ($S$=0)
a = acceleration along chute surface

This assumes, of course, that the chute cross-section does not decrease along its length. Such a condition is usually desirable since a converging chute may slow down the stream so much that particles come into contact with the chute's top surface. *Roberts* and *Scott* [1] describe this as a *slow* flow mode. When this

Fig. 6: Element of solid sliding on a curved chute



occurs, bulk solid flow within the chute becomes similar to that which occurs in a hopper. In the slow flow mode the possibility of flow stoppage due to arching must be considered.

A good rule of thumb is that a chute should be sized such that it is no more than one-third full at the point of minimum velocity. In going through this calculation it is important to assume a conservative (*i.e.,* low) value of the bulk density of the bulk solid.

**Design Principle #3 - Control Stream of Particles**

In order to control the velocity of a stream through a chute (both magnitude and direction) it is often advantageous to slope the chute rather than allow the particles to free-fall in a vertical section.

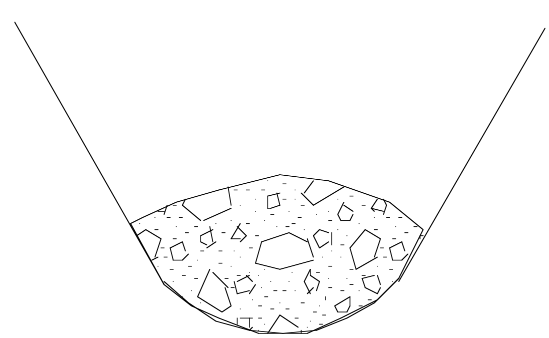
Once particles are on a chute, their direction should be controlled at all times independent of the type of bulk solid being handled. In addition, this control should be gained as soon as possible after impact. This is best accomplished by a curved surface that directs the material to a single path or point independent of the initial place or direction of impact with the chute. Consequently, chutes should generally be composed of conical surfaces, cylindrical pipes, or flat plates arranged to closely approach these geometric configurations. A shape like that shown in Fig.□ concentrates and controls the stream very well. *Carson* [2] described another chute configuration that utilizes these concepts. It consists of a conical collecting chute and standard pipe spout, both of which can be rotated periodically about their axis of symmetry to distribute wear. The smooth curvature of the conical collecting chute gently redirects the stream of particles without the high impact pressures associated with flop gates. Except for the free-fall distance from the in-feed conveyor to the collecting chute, the bulk solid stays in contact with the chute surface, thus controlling aeration and impact pressures. The lower pipe spout can be rotated 360° about the vertical axis to direct the outgoing stream of material.

Most chutes in use today have square or rectangular cross sections. There are many valid reasons for doing this, such as:

- Square or rectangular sections are made from flat plates, which are easy to visualize, draw, fabricate, modify, line, and replace when sections wear.
- Flat plates can be easily flanged and bolted.
- It is easy to mount inspection ports, blocked chute detectors, etc.

However, when the material being handled is sticky and prone to plug the chute, there are significant advantages to having curved surfaces on which the material slides. In fact, some of the advantages of a curved chute cross-section can be argued for other chute problems as well (*e.g.,* dusting or bouncing of large lumps on a receiving belt).

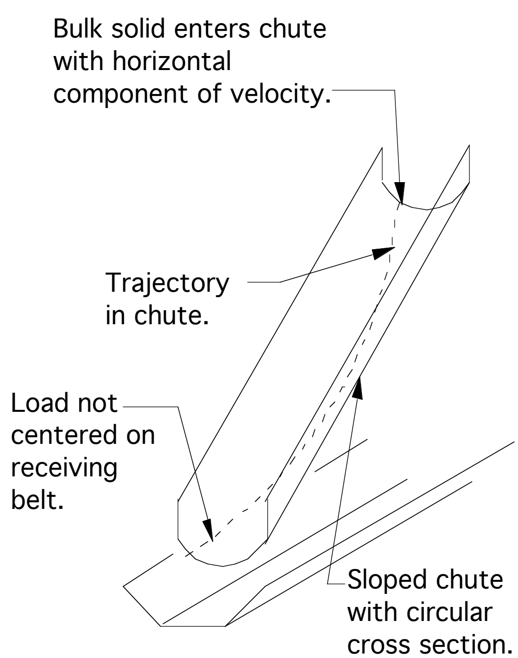
Fig. 7: Cross-sectional shape of chute to concentrate stream



A curved cross-section can be used to center the load, whereas a square or rectangular section may allow the load to concentrate in a corner or to disperse and entrain air. Concentrating the load in the center of a curved chute allows the momentum of the moving material to keep the chute clean, whereas concentrating it in the corner of a square or rectangular cross-section often results in buildup and plugging.

If a flowing material enters a section of chute with horizontal momentum, it is necessary to deal with this momentum or run the risk of not having the load centered at the chute exit. The path that material will follow can vary with material properties and flow rate (see Fig. 8). There are various ways to dissipate the horizontal momentum including rubber curtains, chains, ribs in the chute, *etc.* Which method is best depends on the material and the chute layout. In these situations, experience is often more useful than mathematical models; however, models are being developed that can predict flow through various geometries fairly accurately.

Fig. 8: Trajectory of bulk solid on sloped chute




The problems of excessive belt wear and lack of control of material landing on a belt are often due to the same phenomenon. Large lumps, which are being accelerated by the belt, bounce and roll after impacting the belt normal to its surface. This increases belt wear and requires extended skirts in the acceleration zone to contain the material. By giving the material a velocity in the direction of the belt, both problems can be reduced or eliminated. Material should be centered on the belt, and, if possible, at a speed slightly greater than that of the belt.

**Design Principle #4 - Minimize Abrasive Wear of Chute Surface**

Free fall height and abrupt changes in the direction of material flow should be minimized in order to control solids impact pressures that can lead to high chute wear as well as problems of attrition, dusting, and fluidization of fine materials. Whenever a variety of materials must be handled, design details that must be tuned to a single material (such as bang plates to slow or redirect material flow), must be avoided.

Abrasive products that are free flowing do not normally present difficult wear problems. The easy solution is to provide rock boxes to eliminate impact of the flowing stream on a chute surface. However, one of the most difficult chute problems to solve is how to design for a high flow rate of a sticky material that is abrasive. Examples are wet ash and abrasive ore being transported from in-pit crushers. One of two approaches may be used. First, if space allows, the stream of material can be controlled with a surface very close to its natural trajectory. Since impact pressure is proportional to the sine of the impact angle □, reducing that angle will reduce wear and maximize the velocity of the material after impact. In addition, the mechanism that causes buildup due to sticking is counteracted in two ways: the impact pressures that cause the problem are reduced, and the momentum of the flowing material keeps the chute surface cleaned off.

An alternative approach is to minimize the amount of chute surface in contact with the material at the impact points. This is done by using ribs in the chute to create mini rock boxes as shown in Fig. 9. When using this approach it is essential to concentrate the stream by using a curved surface and to keep the angle between the trajectory and chute surface small. This approach is recommended when materials, like run-of-mine ore, are being handled where the material consists of large lumps mixed with wet fines. Another example is diamondiferous clayey ore, where even abrasion resistant liners do not provide an adequate wear life.

The abrasion resistant ribs are made integral with the shell, and the shell is divided into elements. The elements are made to simply hook onto a frame, so that replacement of worn elements in the field is simple.

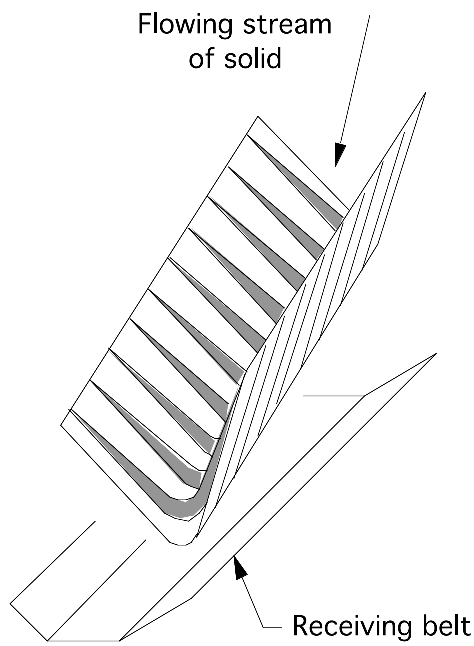
Jenike & Johanson, Inc. engineers pioneered the development of a high speed belt-to-belt transfer chute incorporating these features (U.S. Patent 4,646,910).

**Design Principle #5 - Control Generation of Dust**

Dust is created in a chute when the flowing material entrains air. To avoid dusting, it is essential to:

- keep the material in contact with the chute surface

Fig. 9: Mini rock boxes created by ribs in a chute




- concentrate the material stream
- keep impact angles small
- keep the velocity through the chute as near constant as possible
- if the material must land on a belt conveyor at the chute exit, make sure that the particles leaving the chute are traveling in the direction of and close to, or greater than, the velocity of the belt.

By following these guidelines, the amount of dust generated at a transfer chute can be reduced by orders of magnitude, if not eliminated completely. For example, in a job where plugging and dusting at transfer chutes were causing costly cleanup and maintenance problems at a ship loading facility, engineers at Jenike & Johanson were asked to redesign the chutes. After replacing a particularly troublesome transfer chute where billowing clouds of dust had been generated, air was actually sucked into the chute by the flowing stream of particles. Since the material (a type of fine coal) was kept under control in the chute, there was no dust generated within the chute, and the exit point was also free of dust problems.

## Design Principle #6 - Minimize Particle Attrition

The attrition of a friable product as it flows through a chute will be affected by conditions in the chute. Particle attrition is more likely to occur at impact points where the impact pressures are high, than on a smooth surface where the product is sliding. Therefore, in most cases, attrition can be minimized by designing a chute to:

- minimize the angle between the flowing stream and chute surface at impact points
- keep the flowing stream concentrated and in contact with the chute surface
- keep the velocity of the stream through the chute constant.

## References

[1] *Roberts, A. W.* and *Scott, O. J.*: Flow of bulk solids through transfer chutes of variable geometry and profile; *Bulk Solids Handling*, Vol. 1 (1981), No. 4, pp. 715-727.

[2] *Carson, J. W.:* How to ensure reliable, controlled flow at a bulk terminal; presented at the 4th Bulk Handling & Transport Conference, Amsterdam, June 1983.