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Solve Solids Flow Problems in Bins, Hoppers, and Feeders[1]

by
J. Marinelli
and
Dr. John W. Carson

Good plant designs provide reliable flow of powders and other bulk materials.

Look at these solids flow problems and ask yourself what they have in common.

Case History #1. A fiberglass manufacturer in the Midwest handles glass batch (a mixture of dry chemical ingredients having a variety of particle sizes and densities) in a surge bin just upstream of its furnace. The contents of this bin are discharged to the furnace continuously, but the level in the bin usually does not change much because fresh mixtures are being continually produced and conveyed into the bin. Every so often, this mixing and conveying system breaks down and, before the problem can be corrected, the bin level drops considerably. Operators have found that when this occurs, the viscosity of the glass in the furnace changes dramatically, creating significant operational problems.

Case History #2. A coal-fired power plant, also in the Midwest, collects fly ash in a bin and meters it into a conditioner. Periodically, fly ash floods uncontrollably through the outlet of this bin, overloading the screw feeder and the inclined screw conveyor. The result is lost production and significant costs for cleanup.

Case History #3. A chemical manufacturer in the Southeast stores cellulose acetate in two large silos, each having a design capacity of approximately one million pounds. Sometime ago plant personnel discovered large regions of stagnant material when they attempted to empty the silos, so a contractor was hired to clean them out. After several weeks of work, 600,000 lb of

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flake were removed from one silo and 400,000 lb from the other. All of this material must be scrapped since it has deteriorated by sitting stagnant in the silos for a prolonged period of time.

Case History #4. A pet food manufacturer in the Southwest has a series of bins to store various raw ingredients used to make dog food. Several of these bins have a capacity of 100,000 lb of material. However, the actual useable capacity of these bins is, in several cases, less than half their design capacity. There are large stagnant regions in these bins, which prevent them from being emptied completely.

What do these case histories have in common? All involve a storage container (bin, silo, bunker), which is exhibiting a *funnel-flow* pattern. This is characterized by a condition in which the walls of the hopper section at the bottom of the container are too shallow or rough for the bulk material to slide along them. As a result, material flows preferentially through a funnel-shaped channel located directly above the outlet while material outside this flow channel is stagnant, as shown in Figure 1. This resulting first-in last-out flow often leads to *particle segregation* and *spoilage. Ratholing* is a common occurrence, which can lead to *flooding* of fine powders or *reduced useable capacity.*

While the four case histories cited above all involve problems with funnel-flow bins and silos, there is a large class of bulk materials which are well-suited to being handled in such structures. These generally have the following characteristics:

- coarse particles – usually a quarter inch in size and larger;
- free flowing materials – materials which do not stick to each other;
- non-degrading particles – materials which do not cake, spoil, or oxidize when sitting for

Figure 1. Bulk material flowing down a storage container becomes stagnant along the bottom due to either shallow wall angle or wall roughness.

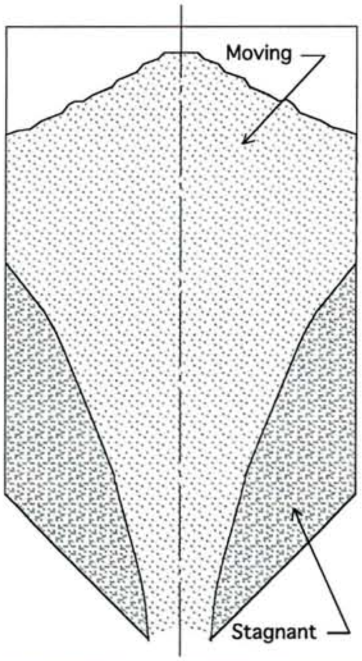


Figure 2. Mass-flow design in action: all the material is moving to prevent operations and maintenance problems.

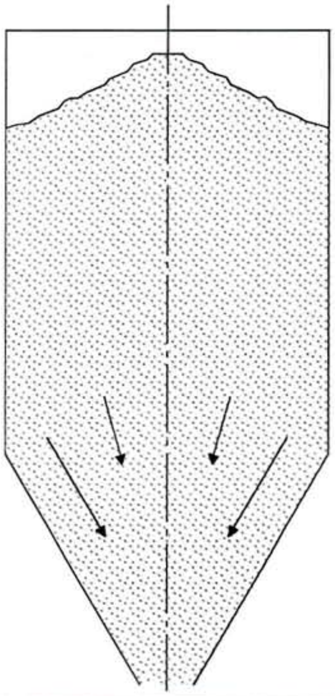
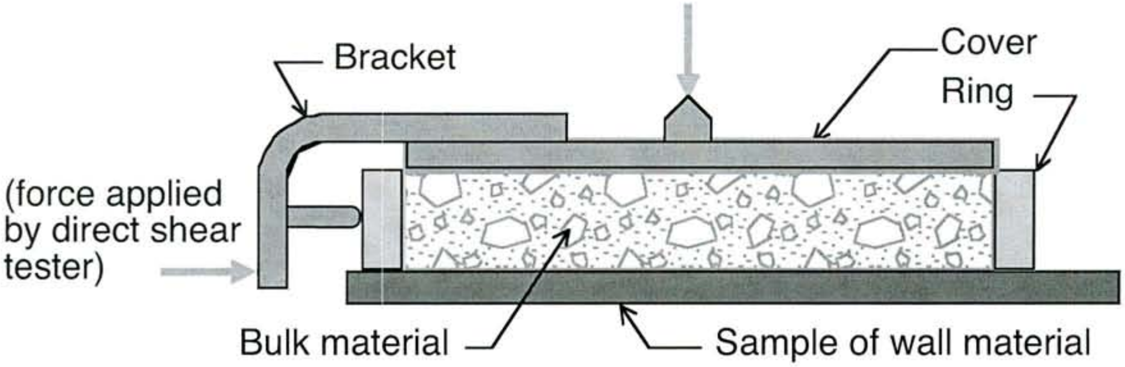


Figure 3. Test setup design allows shear stress (see horizontal arrow) to be measured as a result of applied weights (see vertical downward arrow).



long periods of time without movement; and

- segregation is not a problem – either the material is non-segregating or, if it does segregate, it will not affect downstream processes (for example, if operated on a batch basis).

Provided that the bulk material meets **all four** of these characteristics, a funnel-flow bin or silo is the most economical storage device. One reason is that the sloping hopper walls can be shallow which results in savings in overall headroom for the bin as well as the cost of elevating material into the bin. In addition, by not having particles sliding along the hopper walls, abrasive wear is minimized.

If the bulk material being handled is not coarse, free flowing, non-degrading, and non-segregating, a funnel flow pattern is no longer suitable. Most such materials can be reliably handled using a *mass-flow* design, that is, one in which all of the material is in motion whenever any is withdrawn, as shown in Figure 2. This eliminates ratholing and the associated problems of flooding of fine powders as well as reduced useable bin capacity. In addition, caking, spoilage, and oxidation of the bulk material is minimized because of the first-in first-out flow pattern. Segregation is also minimized for the same reason.

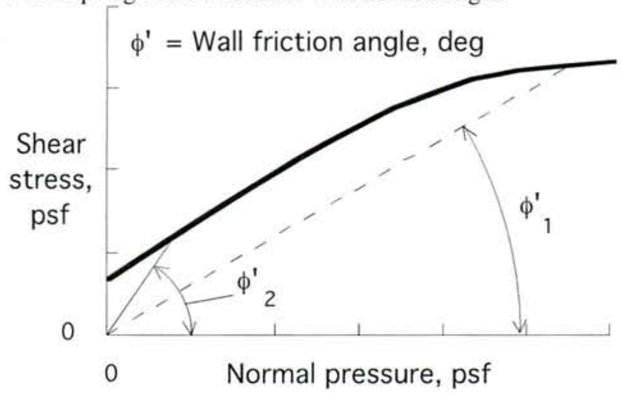
Mass flow bins are suitable for fine powders, cohesive (that is, non-free flowing) bulk materials, materials that tend to degrade when stored for extended periods of time without movement, and when segregation is important. Indeed all four problems described in the case histories above could have been avoided if a mass-flow pattern had been used. How can mass flow be achieved?

Hopper slope and smoothness

The first step is to make sure that the hopper walls are sufficiently steep and smooth to force the bulk material to slide along them. The required steepness and smoothness is determined by first testing to measure wall friction and then using a set of design charts.

Wall friction measurement. For a bulk material to slide on a surface, friction between the two must be overcome. This friction can be measured by use of a test apparatus such as the one shown in Figure 3. First, the bulk material is placed in a retaining ring on a flat piece of wall material. Then, using weights, various forces are applied to the material in a direction normal (perpendicular) to the wall surface. Material in the ring is forced to slide along the stationary wall material, and the resulting shear

Figure 4. Typical results of the test setup shown in Figure 3 to help engineers determine wall friction angle.



force is measured as a function of the applied normal force.

Figure 4 shows the results of a typical wall friction test. Along the horizontal axis are values of normal pressure (force per unit area acting perpendicular to surface) applied to the material, while the vertical axis represents the measured shear stresses required to overcome friction with the wall sample.

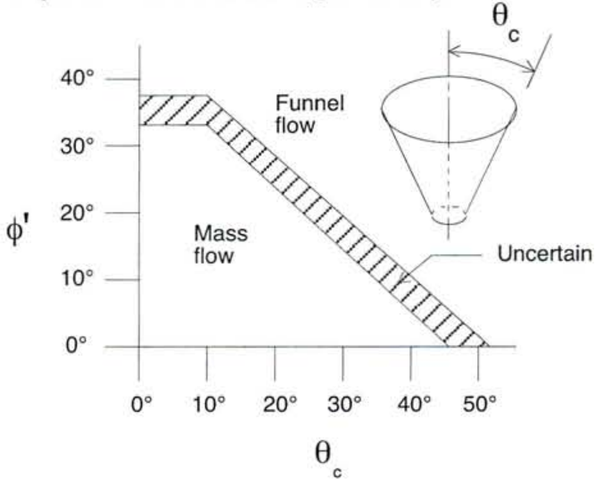
Wall friction angle, designated as ϕ', is defined as the angle formed by a line drawn from the origin to a point on the curve. For a given bulk material and wall surface this angle is not necessarily a constant but often varies with normal pressure, usually decreasing as normal pressure increases.

Factors that influence wall friction. For a given bulk material, wall friction can be affected by:

- **Wall material**. Generally, the smoother the wall surface, the lower the wall friction angle. As a result, less steep hopper angles are needed to ensure mass flow.
- **Temperature**. Both the wall temperature and the bulk material temperature can affect the wall friction angle that develops.
- **Moisture**. Changes in moisture of the bulk material can affect wall friction angles. In some cases, moisture can migrate to the wall surface when warm material is deposited on cold bin walls.
- **Corrosion**. If a hopper is fabricated from carbon steel, it may corrode, creating a more frictional surface than anticipated.
- **Abrasive wear**. As a surface wears, it often becomes polished. Thus, a design based on an unpolished surface is often conservative. In other cases, the surface becomes rougher, which can upset mass flow.
- **Time at rest**. Some bulk materials adhere to wall surfaces while remaining at rest under pressure. As a result, the wall friction angle becomes larger, and steeper hopper angles are needed for mass flow.

Once the wall friction angle for a given bulk material and wall surface has been determined, the next step is to determine what hopper angles are compatible with mass flow. The two types of hopper geometries that have been studied most are cones and wedges.

Figure 5. Design chart for a conical hopper allows the designer to know whether mass-flow or funnel-flow will take place. It has a built-in margin of safety.



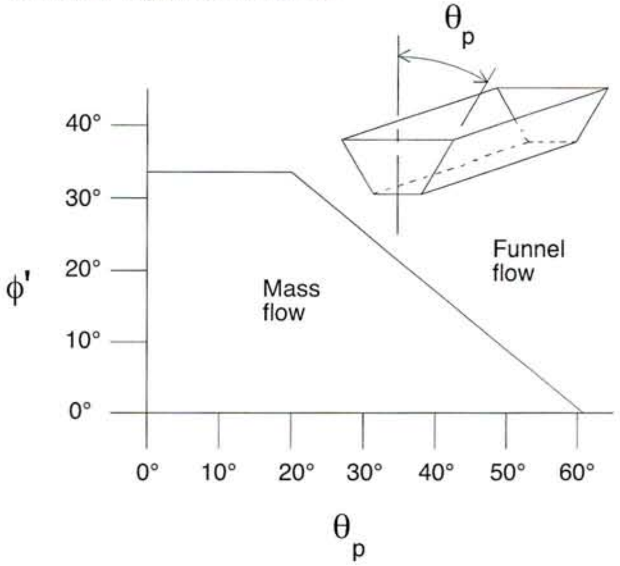
Conical hoppers. Design charts were originally developed by Dr. Andrew Jenike and published in his classic handbook, "Storage and Flow of Solids" [1]. These charts indicate allowable hopper angles for mass flow for given values of wall friction angle. Figure 5 shows a typical chart. On the horizontal axis are values of hopper angles (θ_c) measured in degrees from vertical while the vertical axis contains wall friction angles, ϕ'.

There are several ways to use such a chart. One way is to determine the type of flow pattern that will develop in an existing bin given a certain combination of wall friction angle and hopper angle. For example, if the wall friction angle is 15° and the hopper is 20° from vertical (70° from horizontal), the combination of these two values lies within the mass flow region of the design chart. On the other hand, a wall friction angle of 15° and a hopper angle of 35° will result in funnel flow.

Another way to use such a chart is to determine the maximum (that is, shallowest) hopper angle that will allow mass flow for a certain wall friction angle. To do this, first select a measured value of ϕ' (wall friction angle), then read over to the edge of the mass flow region and down to the appropriate hopper angle. This is the shallowest recommended angle for mass flow.

Notice that there is a region labeled *uncertain* which lies between funnel flow and mass flow. In actuality, this represents a margin of safety to cover slight differences in material properties and hopper design. If the combination of hopper angle and wall friction angle lies too close to the funnel flow line, a switch between mass flow and funnel flow can occur causing bin vibrations and other problems.

Figure 6. This typical design chart for a wedge hopper is used similarly to the one in Figure 5, except note that an "uncertain" region is not needed.



Wedge hoppers. Different design charts are used for wedge hoppers than for conical hoppers. Figure 6 shows a typical chart. Values of hopper angle (measured from vertical) are on the horizontal axis (called in this case θ_p), and wall friction angles ϕ' are on the vertical axis. Notice that there is no uncertain region in the wedge hopper charts. This is because there is no sharp boundary line between mass flow and funnel flow. In fact, mass flow can occur to the right of the design line, even though this labeled as the funnel flow region. This means that a wedge geometry is more forgiving and capable of handling materials with a wider range of flowability than a conical geometry.

This chart is used in the same way as the conical design chart. As an example, if ϕ' is 15°, the resulting maximum wedge hopper angle for mass flow is 40° from vertical. This is 12° less steep than the required conical hopper angle. Hence, mass-flow wedge-shaped configurations require significantly less headroom than conical hoppers.

Figure 7. Dashed trapezoidal shape indicates the second hopper inside the existing hopper.

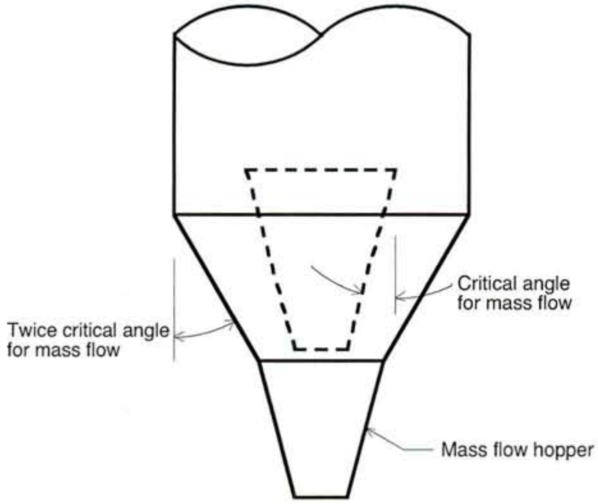
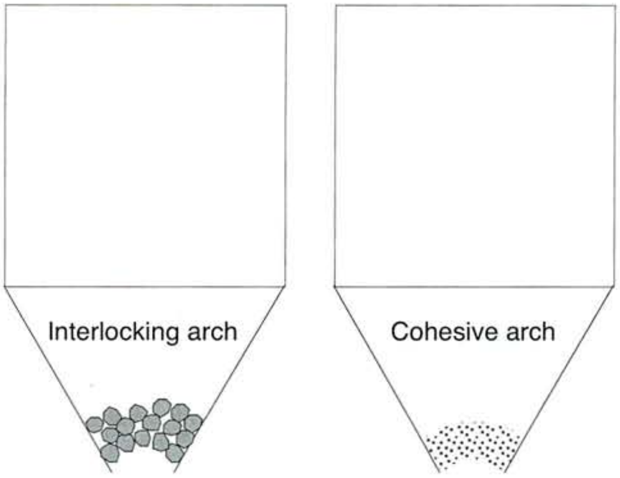


Figure 8. Knowing the characteristics of these two types of flow obstructions will help determine outlet size.



Other designs. Mass flow can also be achieved by the use of inserts, such as a BINSERT®. The latter can convert a funnel-flow bin to mass flow by use of a second hopper inside an existing hopper. Figure 7 shows a typical design. Material is forced to flow along the walls of the shallow (formerly funnel flow) outer cone.

Outlet size determination

How large does the outlet of a mass-flow bin need to be? This is the second consideration for proper design of such a bin.

There are two types of flow obstructions that can occur with bulk materials, as shown in Figure 8. The first is *particle interlocking* where particles lock together mechanically. The minimum outlet size required to prevent an interlocking arch is directly related to the size of the particles, provided that the particles are at least 1/4 in. or larger. As a rule of thumb, a circular outlet must be sized about six to eight times the largest particle size. Wedge hoppers must have an opening width that is at least three to four times the largest particle size.

If most of the particles are less than about 1/4 in. in size, flow obstructions can occur by *cohesive arching*. Particles can bond together physically, chemically, or electrically. In order to characterize this bonding tendency (called *cohesiveness* of a bulk material), its *flow function* must be determined. This can be generated in a testing laboratory by measuring the cohesive strength of the bulk material as a function of consolidation pressure applied to it. Such strength is directly related to the ability of the bulk material to form arches and ratholes in bins and hoppers.

The strength/pressure relationship (flow function) is usually measured using a direct shear tester. Consolidation values are easily controlled, and the cohesive strength of the bulk material is determined by measuring interparticle shear stresses while the consolidation pressure is being applied.

Once a flow function has been developed, minimum opening sizes to prevent arching can be calculated by the use of the hopper's *flow factor*. Flow factors can be obtained from Jenike's design charts [1]. Comparing the flow factor and flow function yields the minimum opening required to prevent a cohesive arch from forming.

Typically, the requirement for a circular opening is about twice that of a slotted opening. For example, if a 12 in. diameter opening is required to prevent arching in a cone, the minimum slot requirement would be about 6 in. wide. Note that the length of a slot should be at least three times its width.

Minimum dimensions to prevent cohesive arches are affected by several parameters, including:

- **Particle size and shape**. Generally the finer the particle size the greater its cohesive strength – hence the larger the outlet required. Particle shape is less important, but the more irregular the shape, generally the more difficult to flow.
- **Temperature**. Many bulk materials are sensitive to the temperature at which they are handled. This temperature may either be constant or changing. It is essential that flow property tests be conducted closely simulating the environmental conditions to which the bulk material is (or will be) exposed.
- **Moisture**. Moisture can affect the cohesiveness of a bulk material. Typically, as moisture increases, cohesive strength also increases. Only when saturation moisture is approached, does a solid's strength decrease (becoming slurry-like).
- **Time of storage at rest**. During continuous flow (flow which is initiated as soon as the bin is filled) many bulk materials flow quite easily. However, if flow is stopped because equipment is shut down or breaks down, the material will sit at rest for a period of time: overnight, a weekend, a month, or even longer. When this period has elapsed, the material is expected to flow but often does not because its cohesive strength has increased. The test program must simulate the time of storage at rest that material will experience so that it can be considered during the design stage.
- **Relative humidity**. Since many bulk materials are hygroscopic, the exposure of such materials to humid air causes an increase in moisture and therefore a gain in strength.

Flow rate considerations

A third consideration when designing a mass-flow bin is the discharge rate required. All bulk materials have some maximum rate at which they will discharge through a hopper opening of a given size. Usually this rate is far in excess of the required rate, especially if the bulk material consists primarily of coarse particles. Fine powders, on the other hand, have considerably lower maximum discharge rates when exiting from a bin. This is due to the interaction between air (or gas) and solid particles as reflected in the *permeability* of the material [3]. The following are some of the factors that affect flow rates of fine powders:

- **Particle size and shape**. Generally the finer the particle size and the greater the range of particle sizes, the less permeable it is and hence the lower the flow rate. Shape can also affect permeability but generally to a smaller extent.
- **Level of material in bin**. As the level of material increases, the maximum flow rate will generally decrease. This is because more air or gas within the voids of the material is squeezed out in the cylinder section creating more of a vacuum condition in the lower portion of the hopper.

- **Outlet size**. For fine powders, the maximum flow rate increases in direct proportion to the area of hopper opening. Thus by increasing the opening, flow-rate limitations can sometimes be overcome. However, the size of the feeding device required to control the rate of discharge must also increase.
- **Outlet shape**. Solids can flow at higher rates through slots because they generally have a larger cross-sectional area than circular outlets.
- **Residence time**. This can be both helpful as well as detrimental. Sometimes a minimum residence time is needed to provide some deaeration so that the material does not flood through the bin outlet. However, if this time is too long, the material may become so deaerated that its maximum rate of discharge is dramatically reduced.

Solid/gas interactions are very complex and, in many cases, counter-intuitive. While trial-and-error methods can be used, the results are often disappointing. Proprietary two-phase flow computer programs have been developed that can reliably predict how solids and gases will interact. Problems such as settlement and limiting flow rate can be studied, as well as ways to overcome flow-rate restrictions by the introduction of small, controlled amounts of air.

Outlet area must be fully live

Conditions at and below the hopper outlet are just as important as the outlet size, and the hopper's slope and smoothness. A cut-off gate, feeder, or both may be used. In a subsequent article, we will discuss in more detail how to design feeders to ensure reliable flow. The key to gate and feeder design is that material must be able to flow uniformly over the entire area of the outlet. If a gate is used with a mass-flow bin. it is important that it be used either fully open or fully closed. Modulation of flow rate must be done with a feeder, not a gate. It is usually important that the feeder's capacity increase in the discharge direction, particularly when using a screw or belt feeder under a slotted outlet.

We have discussed basic concepts of solids flow in this article. Subsequent articles will deal specifically with feeder selection and design, and segregation problems and solutions.

Literature cited

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[Published as sidebar to article]

Steep conical hopper may not be the answer

In order to ensure mass flow a steep hopper is required to overcome friction and promote material sliding on the walls. Hopper steepness, however, is not the only concern. Smoothness of the wall surface is just as important.

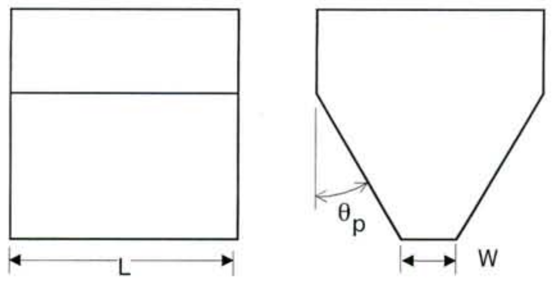
Many people have the mistaken impression that a 70° cone (20° from vertical) ensures mass flow. Nothing could be further from the truth! A 70° cone with a rough wall surface or a frictional bulk material will more than likely flow in a funnel-flow pattern. Both steepness and smoothness of the hopper walls are important.

Wedge hoppers are often better than cones

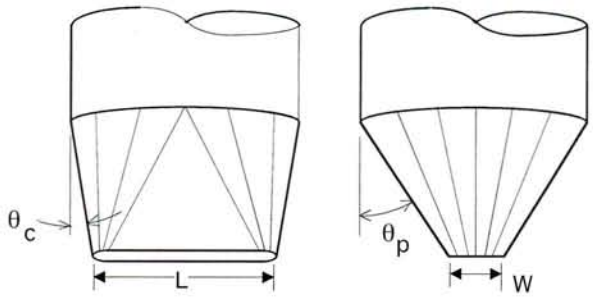
Several advantages to using wedge-shaped configurations over conical configurations are [4]:

- **Less steep hopper angles**. Typically a wedge-shaped hopper can be 10° to 12° less steep than a conical hopper and still promote mass flow. This can provide significant savings in hopper height and cost. In addition, a wedge hopper design is more forgiving than a cone in terms of limiting hopper angles and wall friction. Examples of wedge-shaped hoppers are shown in Figure 9.
- **Smaller outlet sizes**. In order to overcome a cohesive or interlocking arch, a conical hopper has to have twice the diameter as the width of a wedge-shaped hopper. Thus, cones generally require larger, more expensive feeders.

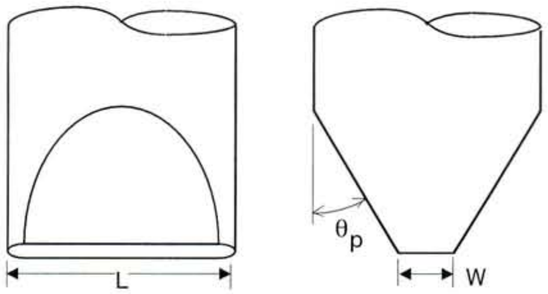
Figure 9. Side and front views of wedge, transition, and chisel hoppers.



Wedge Hopper



Transition Hopper



Chisel Hopper

- **Higher flow rates**. Because of the increased cross-sectional area of a slotted outlet, the maximum flow rate is much greater than that of a conical hopper.

Other considerations:

- **Capital cost**. Each application must be looked at individually. While a wedge-shaped hopper requires less headroom or a less expensive liner than a cone, the feeder and gate (if used) may be more expensive.

- **Headroom**. Here the advantage is clearly with wedge-shaped hoppers. This is particularly important when retrofitting existing equipment in an area of limited headroom.

- **Discharge point**. In many applications, it is important to discharge material along the centerline of the bin, in order to interface with downstream equipment. Generally, conical hoppers are better for these situations, particularly if only a gate is used to stop or start flow.

- **Mating with a standpipe**. If material is being fed into a pressurized environment, a standpipe is often used to take the pressure drop. Either circular or rectangular standpipes can be used, but circular ones are often preferred because they are smaller in cross-sectional area (resulting in less gas leakage) and structurally more robust.