CHAPTER 4.1

Screens

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The classification of particles based on their size is an important step in almost all mineral processing flow sheets. Although the technical focus in plant design, control, and optimization is most often on the comminution (e.g., size control or mineral liberation) and/or separation equipment (e.g., recovery/yield and grade), classification plays a critical role in optimizing process efficiency. This chapter focuses on screens, and in particular on vibrating screens in coarser classification applications.

Peripheral topics such as feeders (Metso 2009, chapter 2), sumps, pumps (Metso 2009, chapter 3.3), slurry pipelines, conveyors (Metso 2009, chapter 3.2), and so on, which are all critically important to the proper operation of screens, are covered elsewhere in this handbook.

To borrow from Matthews (1985), "Screening is defined precisely as a mechanical process which accomplishes a separation of particles on the basis of size and their acceptance or rejection by a screening surface. Particles are presented to the apertures in a screening surface and are rejected if larger than the opening, or accepted and passed through if smaller." The screening process has been a part of mineral processing flow sheets for a very long time, and like many other unit operations, it has seen some interesting mechanical and process developments over the past few years.

Across all the process industries, there are many different kinds of screens and applications. However, as this is a reference source for mineral processing engineers, the discussion is restricted to the most common applications in the mining industry. Figure 1 is a generic graphical representation of the major applications of screening in mining: scalping, size control, and sorting. Table 1 provides more amplification on the type of screen one might find in given applications.

Screen types can generally be categorized as follows:

- **Fixed types:** grizzlies, riffles, sieve bends, and so forth
- **Moving (linear) types:** vibrating, reciprocating, and resonance
- **Moving (rotating) types:** cylindrical trommels and probability

Figures 2, 3, 4, 5, and 6 provide pictures of a grizzly screen, a vibrating screen, a trommel screen for a mill discharge, a Stack Sizer, and a sieve bend, respectively. In general, these are the workhorses of the mining industry, with the vibrating screen standing out as the most widely employed screening unit operation. For this reason, most of this chapter is devoted to the vibrating screen. For the reader with interests in other screening technologies and/or looking for more detail than is presented here, there are many good reference sources, including: basic texts on mineral processing (e.g., Wills and Finch 2016; and numerous SME publications, such as Mular 2003, Bothwell and Mular 2002, Matthews 1985, and Nichols 1982). The latter two sources have companion articles on other aspects of screening as well as associated processes such as bins, feeders, and stockpiles. Original equipment manufacturers (OEMs) also publish handbooks that contain very useful information on the selection and operation of their screen products (e.g., Metso 2009).

VIBRATING SCREEN BASICS

The vibrating screen is ubiquitous in mineral processing plants. One would imagine that with this breadth and history of application, and the screen's apparent simplicity, there would be few remaining unknowns in the screening process. However, the design and operation of screening systems remains a blend of art and science—a statement used by many other authors over the past two decades (e.g., Matthews 1985). It is interesting to note that the screening process is enjoying something of a renaissance today, as new simulation tools offer a closer examination of the physics of the process, providing quantitative insights into mechanisms and their relation to design variables. In addition, new instrumentation offers real-time modulation and measurement of mechanical and process conditions. This chapter deals with vibrating screen basics and applications, and introduces some of the latest tools and techniques in the design, analysis, control, and optimization of vibrating screens.

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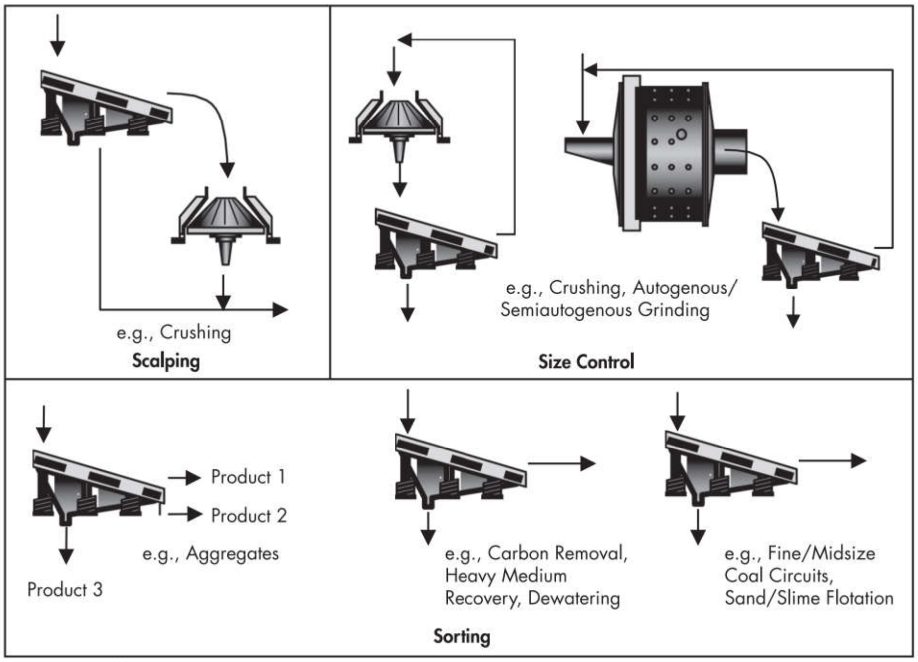


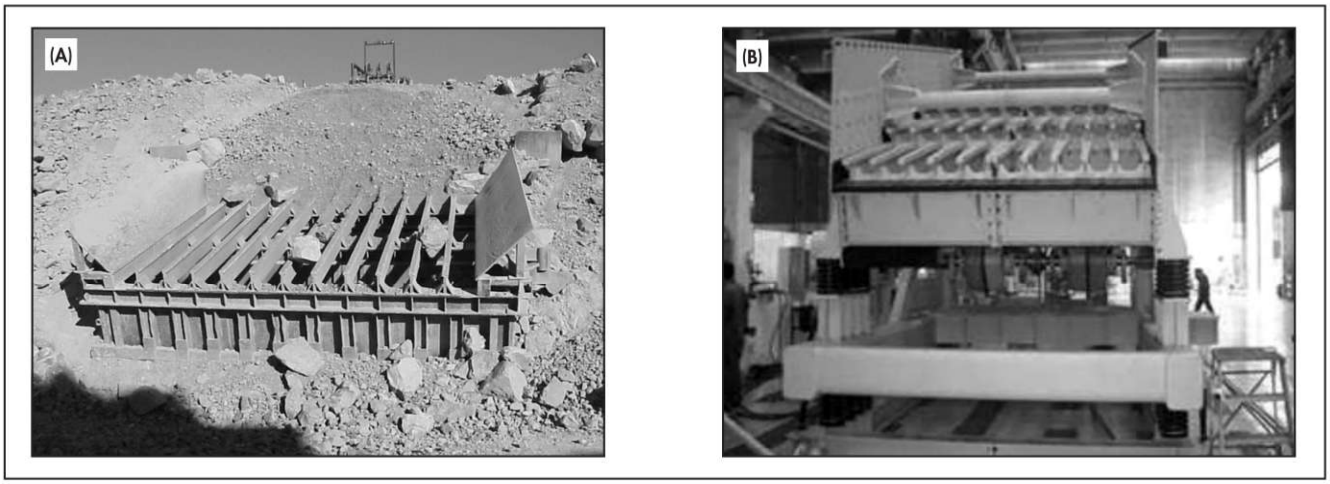
Source: Flintoff and Kuehl 2011

Figure 1 Examples of the application classes for screening in mining

Table 1 Types of screening operations

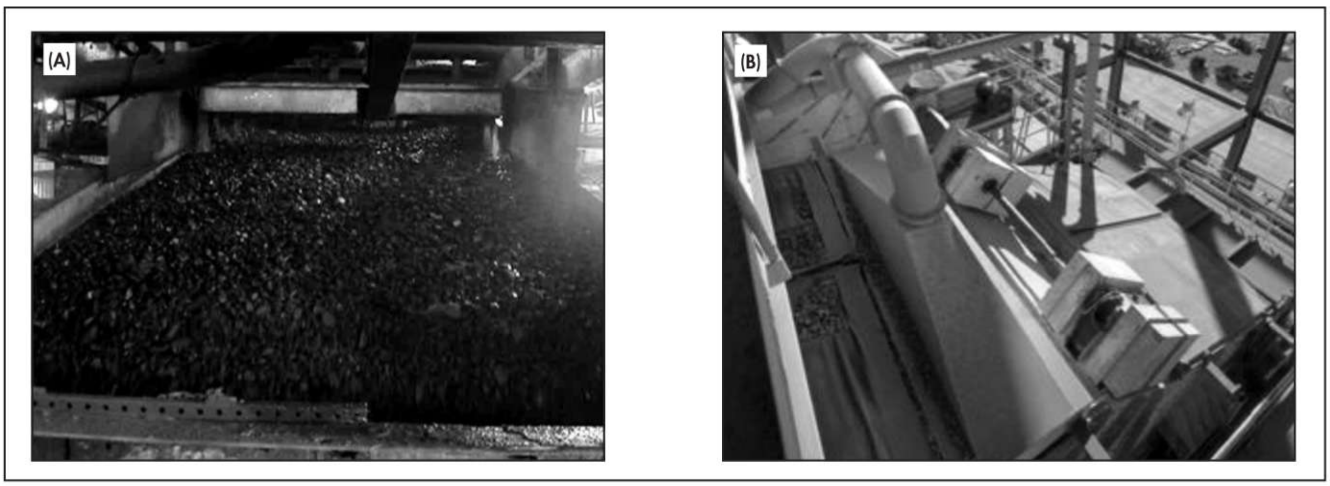
Operation and Description	Type of Screen Commonly Employed
Scalping: Scalping is strictly the removal of an amount of oversize from a feed that is predominantly fines. Scalping typically consists of the removal of oversize from a feed with a maximum of 5% oversize and a minimum of 50% half size. Practically, it is often used in cases where there is a significant oversize material (e.g., in crushing where there is a desire to remove fines to better utilize the volumetric capacity of the crusher). Coarse scalping is typically smaller than 150 mm and larger than 75 mm.	Coarse (grizzly); fine (same as fine separation); ultrafine (same as ultrafine separation). *Example:* Grizzlies are usually used to scalp oversize material from primary crusher feed or to scalp fines from the feed to crushers or grinding rolls.
Coarse separation: Consists of making a size separation smaller than 75 mm and larger than 5 mm (~4 mesh).	Vibrating screens (banana, incline, or horizontal), and trommel screens. *Examples:* The removal of pebbles from a semiautogenous grinding discharge stream, sizing material for the next crushing stage, and sizing material for leach pile or product pile.
Fine separation: Consists of making a size separation smaller than 5 mm (~4 mesh) and larger than 0.3 mm (48 mesh).	Vibrating screens (banana, incline, or horizontal), which are typically set up with a high speed and low amplitude or stroke; sifter screens; static sieves; and centrifugal screens. *Examples:* Sorting coal into ±0.6 mm fractions for washing, and iron ore processing.
Ultrafine separation: Consists of making a size separation smaller than 0.3 mm (48 mesh).	High-frequency, low-amplitude vibrating screens; sifter screens; static sieves; centrifugal screens. *Example:* Size control on grinding circuit product
Dewatering: Consists of the removal of free water from a solid–water mixture and generally limited to 4.8 mm (4 mesh) and above	Uphill inclined vibrating screens (typically –5°), horizontal vibrating screens, incline vibrating screens (about 10°), and centrifugal screens. *Example:* Wet quarrying operations
Trash removal: Consists of the removal of extraneous foreign matter. This is essentially a form of scalping operation, and the type of screen depends on the size range of processed material.	Vibrating screens (horizontal or incline), sifter screens, static sieves, and centrifugal screens. *Example:* The removal of extraneous organic and other matter from the leach feed in a gold plant.
Other applications: Other applications include desliming (the removal of extremely fine particles from wet material by passing it over a screening surface), difficult-to-screen material; conveying (in some instances transport of a material may be as important as the screen operation), dense media recovery, a combination washing and dewatering operation, and concentration.	Vibrating screens (banana, incline, or horizontal), oscillating screens, and centrifugal screens. *Example:* Dense medium recovery in a coal washing plant, flip-flop screens or a wobbler feeder for conveying, and classifying sticky materials to a crusher.

Adapted from Matthews 1985



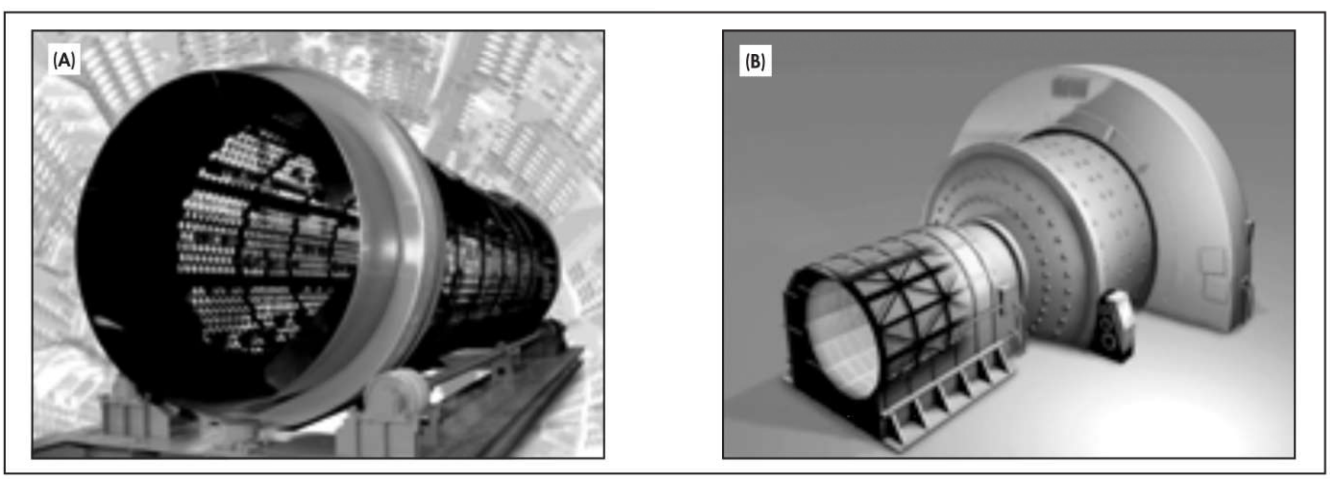
Source: Flintoff and Kuehl 2011

Figure 2 (A) Static grizzly (scalping oversize from a primary jaw crusher feed) and (B) vibrating grizzly screen



Source: Flintoff and Kuehl 2011

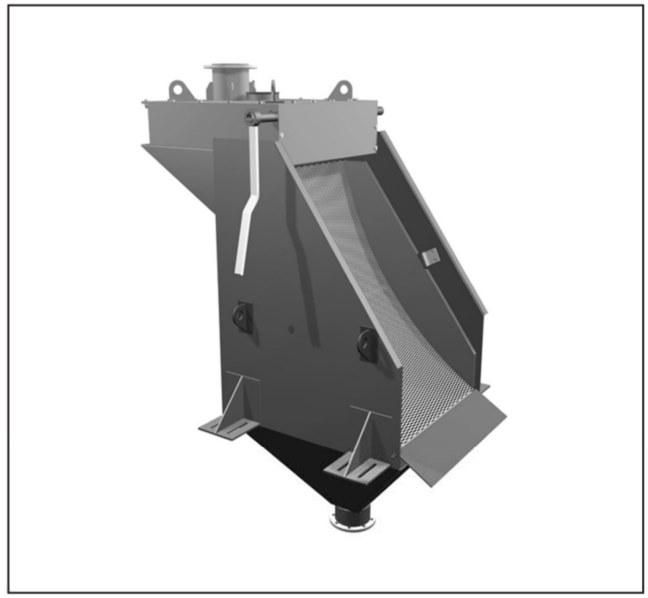
Figure 3 Vibrating screen with a dust collection system



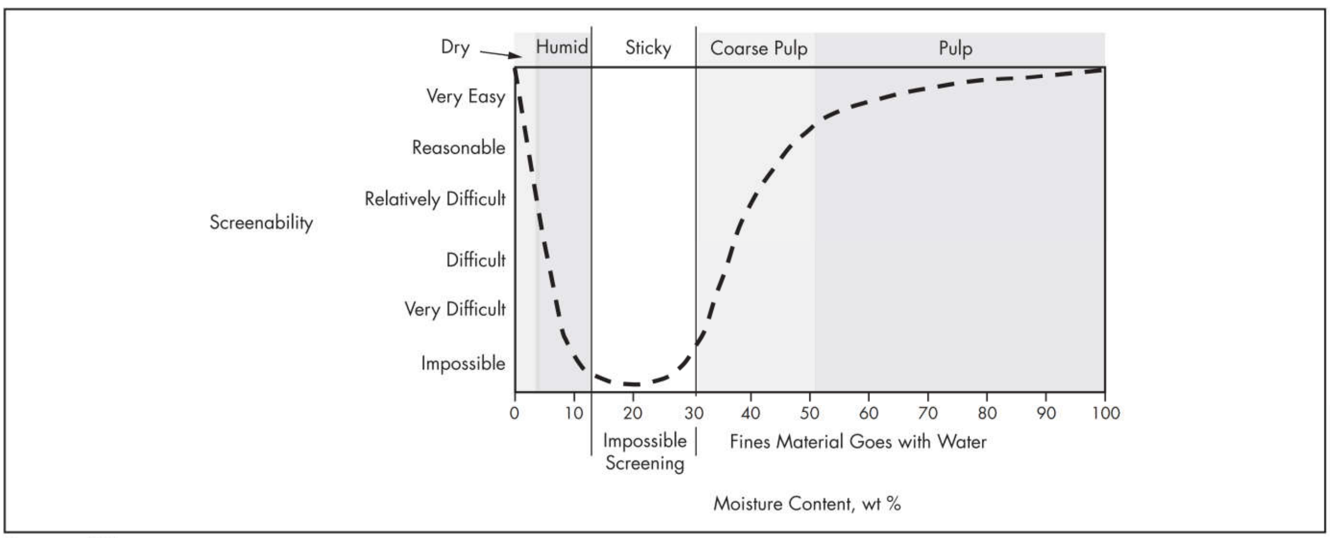
Source: Flintoff and Kuehl 2011

Figure 4 (A) Trommel screen and (B) mill discharge trommel screen

Courtesy of Derrick Corporation
Figure 5 Derrick Stack Sizer



Courtesy of Multotec Process Equipment
Figure 6 Sieve bend



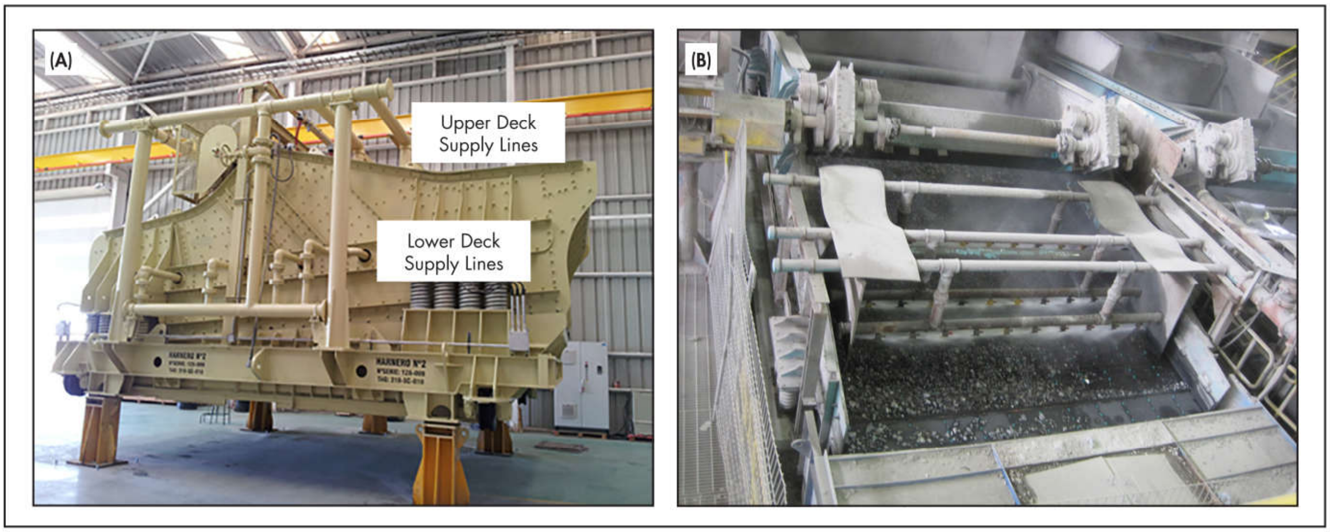
Courtesy of Metso
Figure 7 Screenability as a function of the feed moisture level

Principles of Operation

The vibrating screen is used here as a proxy for all other screens, as the basic operating principles are similar or the same. In the screening process, a feed material comprising particles of varying sizes is presented to the screen media (collectively, the screen deck) in such a way that those particles finer than the screen aperture fall through to the undersize stream, and those that are larger than the screen aperture continue moving along the screen surface to eventually report to the oversize stream.

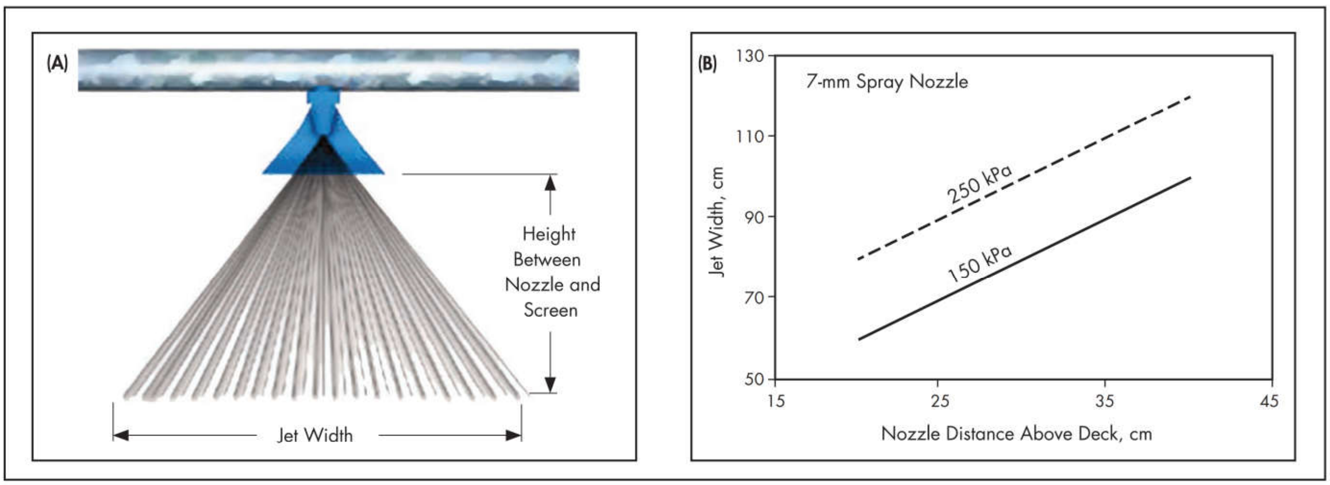
Screening can be carried out with wet or dry feeds, although coarser particle separation (greater than a 5-mm aperture) is usually performed dry (at the surface moisture of the feed) where possible. Wet screening is not to be confused with dewatering screening, as the process aim remains solids size classification for the former. In dry applications, some combination of vibration ("throwing" the particles off the deck) and gravity is responsible for particle transportation. In wet applications, some form of vibrating mechanisms dictates the movement of material. However, hydrodynamic (drag) and gravitational forces are also at work. Wet screening usually involves either sticky/clay-rich feeds or finer particle sizes where the solid material has been slurried to facilitate transportation and processing (e.g., semiautogenous grinding [SAG] discharge screens). Figure 7 is a graphical illustration of the anticipated degree of difficulty ("screenability") introduced when dealing with moist feeds.

There are many similarities between wet and dry screening, starting with the machines themselves. Figure 8A shows a double-deck, low-head, slightly inclined (~5°) SAG discharge



Courtesy of Metso

Figure 8 Use of water sprays in screening: (A) SAG discharge screen equipped with water sprays and (B) typical water spray deployment on a screen deck



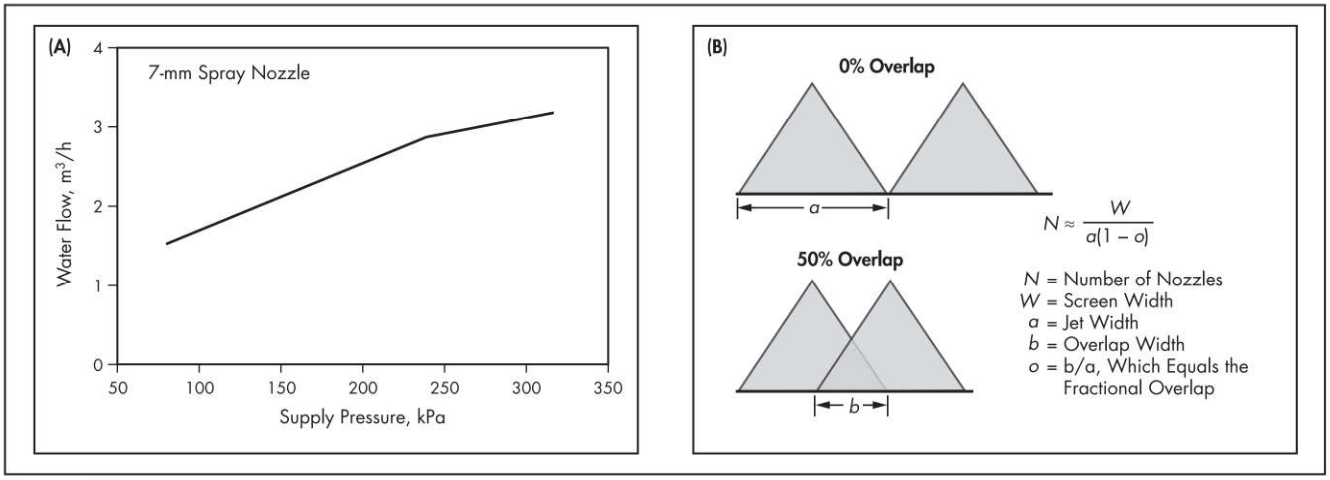
Courtesy of Metso

Figure 9 Water spray geometry: (A) basic dimensional info, and (B) jet width for a particular nozzle opening at different pressures and position above the deck

screen; the additional water supply assembly for the deck sprays is highlighted.

Water can be added to the screen feed in the slurry box feeding the screen, or on the deck through flood boxes or water sprays, the latter being more common. A general rule of thumb is that water added to the feed is more effective than water sprayed on the deck in improving the classification of fines. Spray selection is chosen based on two criteria. One must decide whether the goal is to flush material through the deck or wash off the fines. (In the case of high-pressure grinding roll [HPGR] circuits, water sprays can also be helpful in breaking up the cakes formed in crushing.) For flushing, the nozzles on the spray bar generally operate at lower pressure and higher volumes with the water falling vertically onto the deck. For washing, it is common to operate the nozzles at higher pressure and lower volume, and normally they are oriented to spray against the flow of the solids (e.g., Figure 8B). This is thought to be helpful in "cleaning" fines from the coarser rock surfaces.

The design of the spray water systems is usually in the OEM's purview and depends on the application (e.g., sticky fines, such as magnetite on coal in dense medium circuits) and the water requirements. As Figure 8 indicates, there are often three or more spray bars per deck, and each spray bar is equipped with several nozzles. This is to ensure some overlap in the spray jet from each nozzle and to deliver the required water flow. It is common to try to leave 2–3 m between the last spray bar and the discharge point to allow for dewatering of the oversize materials. From a design perspective, Figure 9 provides typical OEM information relative to the water-jet geometry as a function of the position and operating pressure of the nozzle, here for a 7-mm opening. Nozzle openings typically range from ~4 mm to ~12 mm.



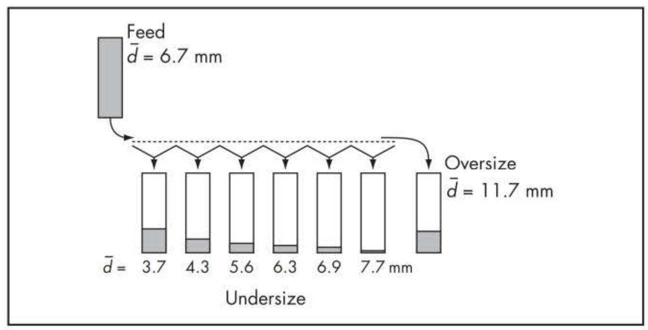
Courtesy of Metso

Figure 10 Water spray flow: (A) water flow for a particular nozzle opening at different pressures and (B) estimating the number of nozzles per spray bar

The companion design information is shown in Figure 10, where the water flow as a function of pressure is illustrated, again for a 7-mm nozzle. The calculation of the number of nozzles relates in part to achieving desired overall water flow to the deck and in part to ensuring efficient operation. For the latter, Figure 10B indicates a couple of options. Since these water sprays use process water, plugging is a possibility and some overlap is generally a good idea. A 50% overlap doubles the number of nozzles and the water flow.

For washing fines (sometimes known as desliming), water is normally sprayed at pressures ranging from 100 to 300 kPa and the volume ranges from 0.7 to 1 m^3/t of solids in the feed. Lower values are possible for relatively clean materials, and higher values are possible for materials with clay or very fine particle content. In the case of treating dry or pit wet feed material, it is common to add 0.3–0.5 m^3 of water per ton of feed to the feed slurry box. For the removal of sticky fines, the spay water addition is usually 0.3–0.5 m^3/t of feed. Again, if the feed is dry or pit wet, it is common to add 0.20.5 m^3 of water to the feed slurry box.

Focusing more on dry screening, Figure 11 is a schematic representation of the results of an experiment with a small horizontal vibrating screen having a square screen aperture of 10 mm. (This screen and test from Hilden [2007] is referenced throughout the text.) The shaded bars depict the relative mass flows, and the annotations show the mass mean size ($\bar{d}$) for each stream. As the feed is introduced onto the deck, it forms a bed that is usually several times the screen aperture in thickness. The bed moves under the influence of gravitation and vibrational motion, and in the process, the particles stratify as the finer materials move quickly through the interstices of the larger particles and find their way to and then through the screen apertures. In this initial zone on the screen, *rapid stratification* (sometimes referred to as segregation) means there is always enough fine material in the layer next to the screen deck that the flow through the screen apertures is more or less constant. This is said to be typical of crowded or saturation screening. However, as the fines are depleted, the bed height is reduced, and at some point the particles begin to act more or less as individual entities. This point is the zone of separated or statistical screening; that is, each time the particle approaches the deck, it has a chance (or a statistical trial) to pass through the aperture. (This notion of repetitive trials underpins many semi-empirical screen models.)

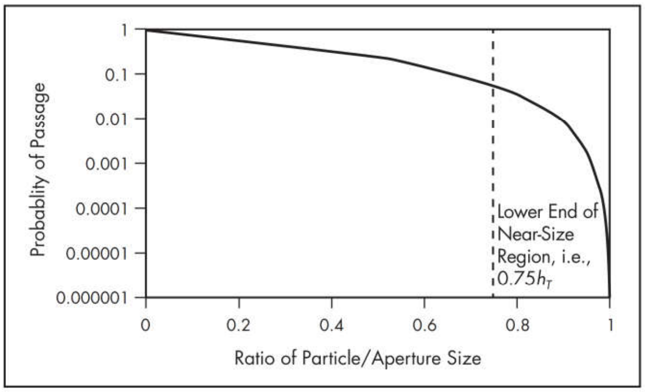


Adapted from Hilden 2007

Figure 11 Relative mass flows and mean particle sizes for a horizontal vibrating screen

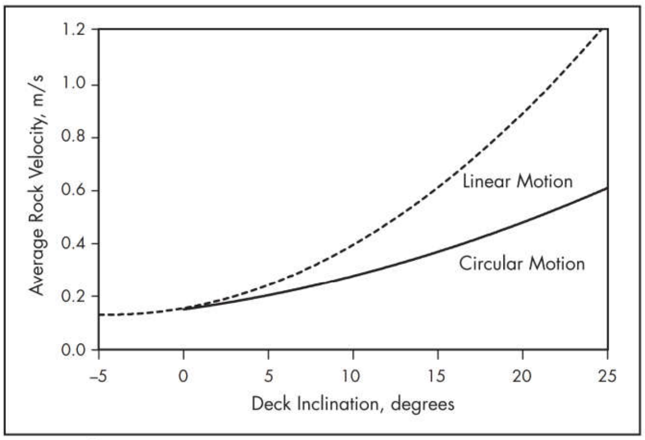
Figure 11 shows that the greatest flow of material to the undersize stream occurs closest to the feed end, typical of crowded screening. Stratification ensures that these particles presented to the apertures are small enough that the probability of passage to the undersize stream is ~1.0. The mass flow to the undersize stream decreases along the length of the deck, which is typical of the transition to separated screening, and more typical of the coarser particles that remain in the bed. (These coarser particles are so-called *near-size*, because they are near to the size of the aperture. Formally, near-size is the fraction of the feed material in the size interval 0.75–1.25 h_T, where h_T is defined later in Figure 17.) For these particles, the probability of passage on any one trial is significantly less than 1.0. This probability is a complex function of many parameters (particle size/shape/density, screen deck motion, aperture geometry, etc.), but for illustrative purposes, Taggart (1945) worked out the probability of passage of a spherical particle falling onto a square aperture, and his data are presented in Figure 12. The probability of passage falls very quickly as the size ratio enters the near-size region and approaches 1.

The increase in the mass mean size along the deck in Figure 11 also reflects the fact that the remaining material on



Data from Taggart 1945

Figure 12 Probability of passage as a function of particle size



Courtesy of Metso

Figure 13 Rock velocity estimates for an inclined screen as a function of deck motion

the deck becomes coarser as it moves from the feed end to the discharge. This helps to explain why screen length governs efficiency. On the other hand, screen width is related to the amount of material that can be fed to the screen and be effectively separated, and therefore this is the major factor governing capacity.

On this latter point, a rule of thumb for good dry screen operation is for the maximum bed depth at the discharge point to be 3:1 → 4:1 screen apertures in thickness, although operation at 2:1 is quite common. A rule of thumb for wet screening is to design for a maximum bed depth of 4:1–6:1 times the opening. At larger targets, the efficiency of removal of the particles close to the aperture size is reduced, as stratification is more difficult. Such a situation suggests a wider screen, higher transport speeds (increased inclination), or that multiple screen decks probably should be considered, using a larger aperture size on the top deck to scalp out much of the larger oversize and reduce the loading on the lower deck for the final classification. At less than the target bed depths given earlier, these particles will probably bounce excessively, reducing the number of trials and the screen efficiency.

Designers estimate the bed depth using the following equation:

$$B = \frac{(M/\rho_b)}{3.6Wv} \quad \textbf{(EQ 1)}$$

where

B = bed depth, mm
M = solids mass flow, t/h, discharge (or feed) end of the screen (e.g., usually taken as the flow of oversize material in the feed)
ρ_b = bulk density of the solids, t/m^3
W = screen width, m
v = rock velocity across the screen, m/s

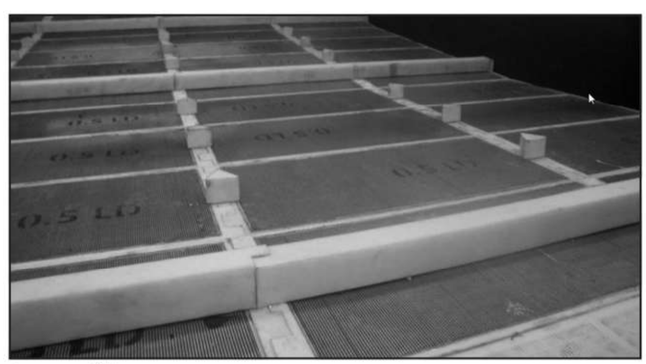
The value for the rock velocity, v, usually comes from general correlations developed by the OEMs. Figure 13 shows typical values of rock velocity for inclined screens, as a function of both inclination and the general shape of the orbit. For example, in the case of the screen in Figure 11, the feed rate is 15.7 t/h; the fraction of material coarser than the 10-mm aperture in the feed is 18.7%; the bulk density is 1.62 t/m^3; the screen width is 0.34 m; and, given that the deck is horizontal with linear motion, the estimated rock velocity from Figure 13 is ~0.16 m/s. From this, the calculated bed depth is 9.3 mm, which gives an aperture ratio less than 1 when compared the screen aperture, meaning the screen is underloaded. One would therefore expect some efficiency issues with this screen, and this will be apparent in the discussion on performance assessment later in this chapter.

It is also sometimes useful to install weirs (or dams) on the deck surface, which hold back the flow as an aid to sustaining an active bed and/or facilitating better water removal. These weirs are typically 30–50 mm high and have a maximum spacing of ~1.2 m. Figure 14 is a rather extreme example showing the dams or weirs installed on a screen deck.

Screen design and operation is about matching the screen characteristics to the (range of) feed conditions. Table 2 provides a summary of the important variables for each.

When focusing on design variables, screen area is important because capacity is proportional to width (W) and efficiency is proportional to length (L). It is common for $L \approx 2W$ to $3W$. Because of the mechanical fittings on and around the screen decks, the effective area is often approximated as 90%–95% of the actual (= LW) area. Screens are standard products, so the OEMs dictate the actual sizes. Therefore, it is common to require more than one screen, operating in parallel, to effectively separate a feed.

Open area (OA) is expressed as the ratio of the total area of the apertures over the total active area of the screen deck. Figure 15 illustrates this for a square aperture of 10 mm in a wire mesh screen with a wire diameter of 2 mm, for the screen



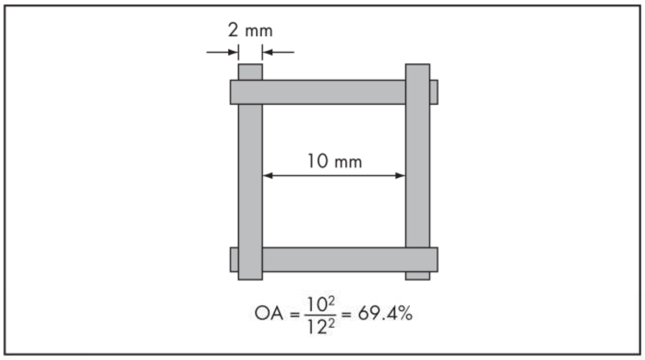
Courtesy of Metso

Figure 14 Weirs on a screen deck

Table 2 Design and operating variables for vibrating screens

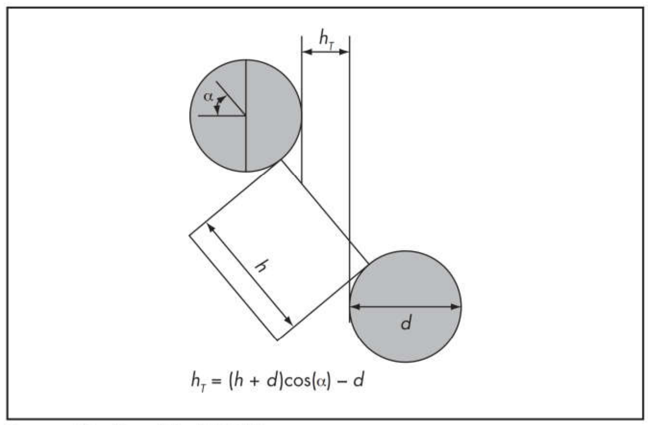
Design Variables	Operating Variables
Screen area and open area	Particle size, shape, and distribution
Aperture size and shape	Solids feed rate, feed distribution across the deck, and bed depth
Slope of screen deck	Feed moisture content
Speed	Clay content
Magnitude of stroke	
Type of motion	
Feed arrangement	

Source: Bothwell and Mular 2002



Source: Flintoff and Kuehl 2011
Figure 15 Computing open area

Source: Flintoff and Kuehl 2011
Figure 16 Blinding on a screen deck



Source: Flintoff and Kuehl 2011
Figure 17 Relation between the throughfall size (h_T) and the aperture size (h)

in Figure 11. From the earlier explanations of screening mechanism, clearly the greater the OA, the greater the capacity of the screen. In practice, OA is limited by the need for sufficient mechanical strength and wear resistance of the deck, and is a function of the media materials of construction (e.g., wire mesh versus perforated plate).

This is a good point to introduce some common, and occasionally confusing, jargon associated with phenomena that act to reduce the OA, and hence capacity. The first is *pegging* (also called clogging or plugging), which occurs when a near-size particle becomes firmly lodged in an aperture, effectively eliminating it from the screening process. The second is *blinding* (also called bridging), which is the phenomena whereby smaller particles aggregate in such a way that they combine to block up the aperture, having the same overall effect as pegging, as shown in Figure 16. Blinding is more of a problem with moist or sticky materials and small aperture sizes.

The aperture size is, by convention, the minimum linear measurement in an opening, for example, the diameter for a round hole, the width (where width ≤ length) for a slot or a square, and so on. (Because screen performance assessments start with sieving samples of process streams, and because the sieve has square apertures, the best correlations occur with square apertures in the screen media.) What is perhaps more important is the so-called throughfall size, h_T, which accounts for the change in effective opening as the screen is inclined. This is illustrated in Figure 17, where the angle of inclination is exaggerated to show the difference between the aperture size, h, and the throughfall size, h_T, for a wire mesh screen surface. (There is a similar effect for rectangular slots.)

Although square apertures may be the most common, there is a multitude of aperture shapes. Some of the more common shapes are illustrated in Figure 18. Square or round shapes generally allow for better control of the separation size, although circular apertures are most often used in coarse screening applications. Longitudinal slotted apertures allow slabby particles into the undersize stream, so they increase capacity and reduce pegging and blinding. (Aperture shape can have a significant influence on capacity; see, for example, Q2 factor later in Table 6.) Transverse slots are mainly used in dewatering applications. (For steel or polymeric screen media, it is possible to design tapers and other forms of relief into the apertures to minimize pegging.) Finally, the screen deck or panel is designed to withstand the load and maximize wear life, so in the case of a large spread in feed particle sizes and/or some large particles in the feed, it is common to use multiple screen decks to satisfy both mechanical and process requirements.

As observed earlier in Figure 13, inclining a screen deck causes the feed material to move more quickly on the deck, reducing the residence time and increasing capacity and sometimes efficiency. Vibration motion on a horizontal screen deck usually means material velocities of 10–16 m/min, while an inclination of about 20° will increase this to the range of 25–30 m/min. Generally, inclinations range from horizontal to as high as 30°, although ~20° is the usual limit. This led to the evolution of the multislope screen (commonly known as

FR - Square apertures - The most common type of aperture. Normally resulting in the most accurate separation.

FS - Square apertures in staggered pattern. Same applications as FR but apertures are arranged to prevent "tracking" of fines.

SLS - Rectangular apertures with the flow typically recommended for screening material with high content of fines or if there are signs of pegging.

SL - Rectangular apertures with the flow typically recommended for screening material with high content of fines or if there are signs of pegging.

STS - Rectangular apertures across the flow. Normally recommended for dewatering applications.

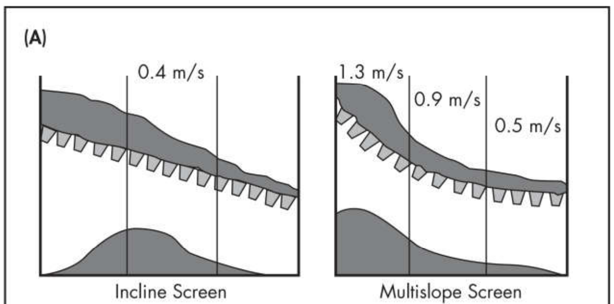
ST - Rectangular apertures across the flow in staggered pattern. Can be used as an alternative in dewatering applications.

C - Round apertures have similar applications to FR openings. Traditionally used in applications such as primary screening.

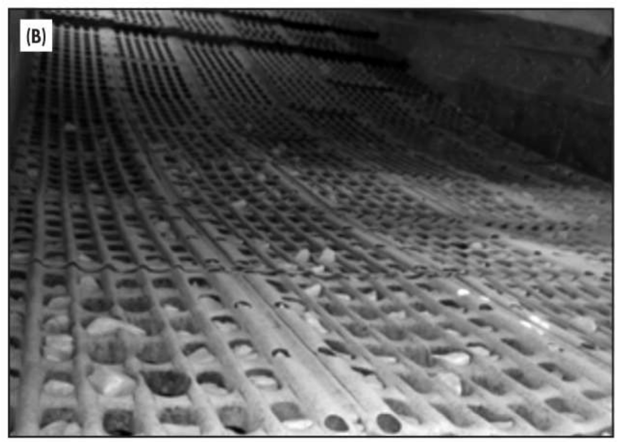
CS - Round apertures in staggered pattern. Same applications as C but arranged to prevent "tracking" of fines.

Courtesy of Metso

Figure 18 Common screen aperture shapes



Slope, degrees	35	30	25	20	15	10	5	0
Velocity, m/s	2.00	1.66	1.23	0.84	0.58	0.46	0.40	0.30



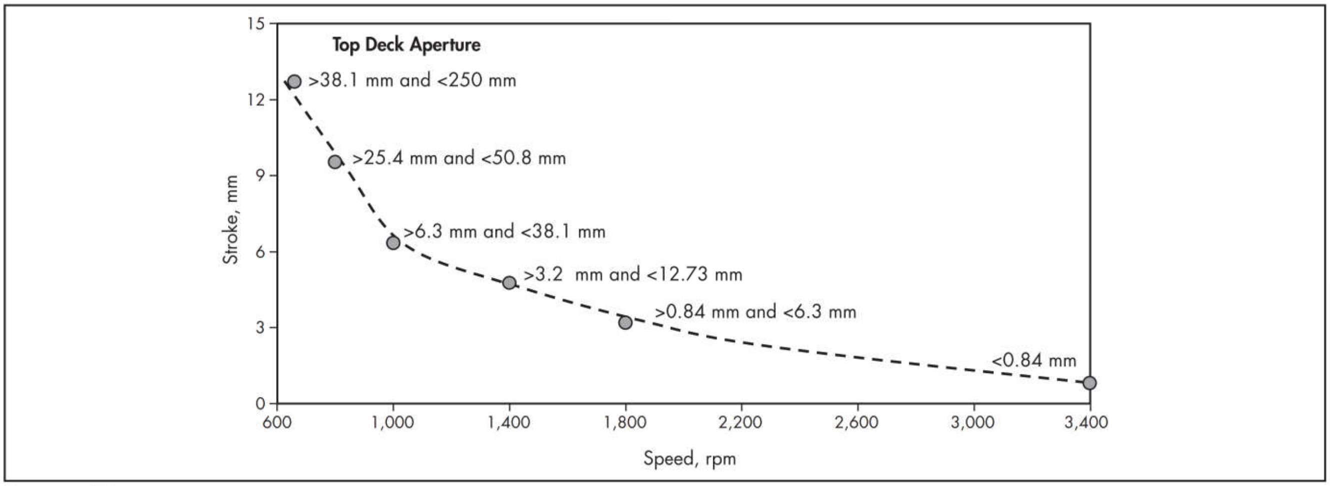
Source: Flintoff and Kuehl 2011

Figure 19 Banana screen deck

the banana screen). The banana screen (see Figure 19) has a relatively high slope in the initial screening zone, which takes advantage of the fast kinetics of fine particle removal. The slope then decreases, which slows particle movement and offers an additional g-force to accelerate removal of the larger fine or near-size material. In the final section, the slope is relatively flat, yielding minimal velocity and maximum residence time, for finer near-size particle removal to the undersize stream.

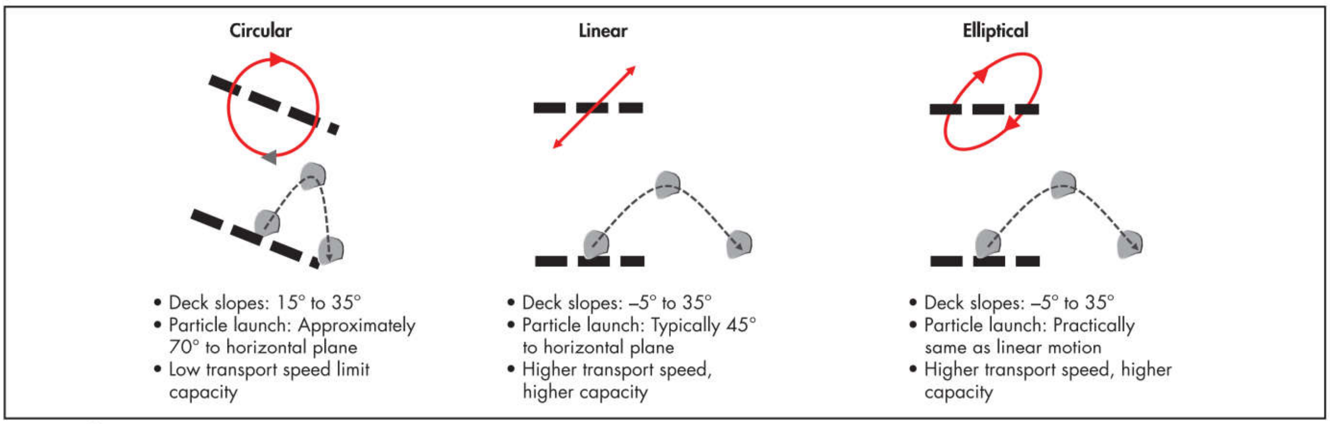
Vibrating screen deck motion (or orbit) is circular, elliptical, or linear, with the vibrating mechanism rotating in the direction of the flow or counter to the flow. In coarser classification operations, strokes are usually in the range of 6–15 mm, and speed ranges from 650 to 950 rpm. Figure 20, for inclined screens treating a material of a specific bulk density, attempts to illustrate the general relationship between stroke and speed. The annotations, for example, ">25.4 mm and <50.8 mm," refer to the top deck aperture range that one would expect with screens operating at or near this combination of stroke and speed. There is overlap—that is, a smaller-stroke, higher-speed machine can also be used in applications up to 38.1 mm. In practice, the OEM will choose the stroke to facilitate the separation at the selected aperture size and then select the speed that will keep the machine within mechanical limitations. However, when the resulting speed is close to the natural frequency, the process is reversed. The main points of Figure 19 are that (1) as stroke increases, speed must decrease; (2) finer cuts require smaller strokes and higher speeds; and (3) aperture changes, especially larger ones (e.g., where a screen is repurposed) should be approached with caution. An OEM's screen offering will generally appear along this curve but not in a continuous fashion. Things like natural frequencies must be avoided.

To elaborate on orbits, circular motion provides for a launch angle of about 70°–80° relative to the screen media



Courtesy of Metso

Figure 20 Example stroke and speed relationship for inclined vibrating screens



Courtesy of Metso

Figure 21 Particle launch characteristics as a function of deck motion

surface, while linear motion results in a launch angle of 40°–55°. With the high launch angle in circular motion, to achieve a reasonable transport speed (capacity), the deck should have an inclination of 10°–12°. Linear motion screens can function even with a negative deck inclination (e.g., up to –7°). Elliptical motion has the same launching properties as linear motion, and this is summarized in Figure 21.

The advantage of circular motion is that it subjects the particles to forces in all directions, which minimizes the risk of pegging, as shown in Figure 22. Elliptical motion can be thought of as an intermediate to circular and linear motions—it combines the anti-pegging features of circular motion with the ability to work at any screen inclination, as is the case for linear motion.

A commonly referenced screen operating parameter here is the g-force, computed as

$$G = \frac{N^2 S}{1{,}789{,}129} \quad \textbf{(EQ 2)}$$

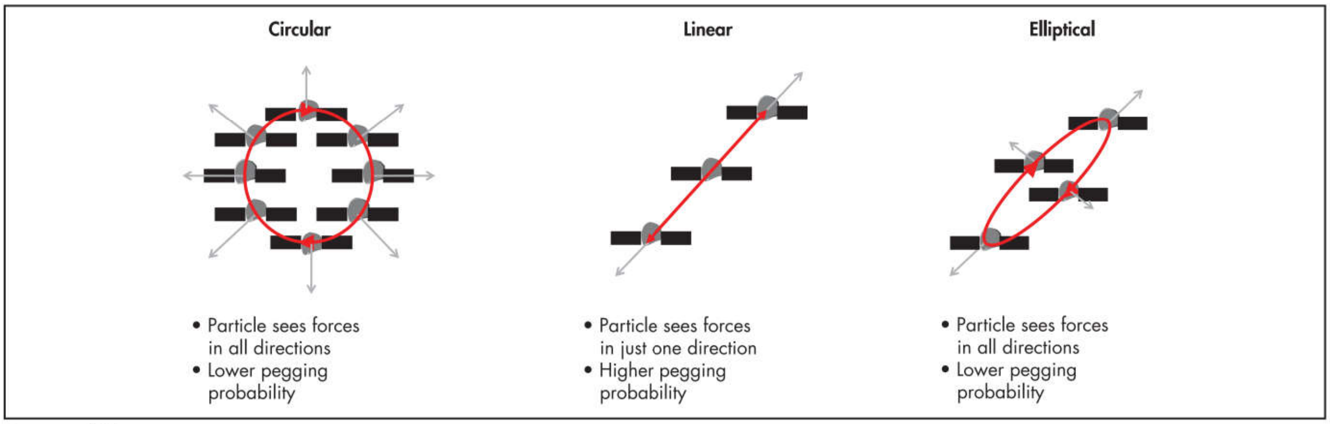
where

G = g-force (also known as the throw number)
N = speed, rpm
S = stroke, mm

Typical g-forces are in the 3.0–5.0 range, tending to higher values with heavy loads, sticky materials, or where pegging and blinding are issues. The g-force is usually higher in a horizontal screen, as it must provide the means for both stratification and material movement. (For example, with the horizontal test screen in Figure 11, the speed was 981 rpm and the stroke 5 mm, giving $G = 2.69$. As an aside, this would be considered a low value, as horizontal; screens usually run in the range of $4 \leq G \leq 4.7$.) The target acceleration or g-force is usually 3–3.5, perpendicular to the deck. As Figure 23 shows, this requires that a linear screen run at G value of ~5 to achieve 3.5 in the perpendicular plane. OEMs tend to use g-force data mainly for diagnostic purposes, for example, for assessing machine mechanical issues and limitations, understanding pegging and blinding issues, and so on. Table 3 details the conditions prevalent over a broad range of g-forces.

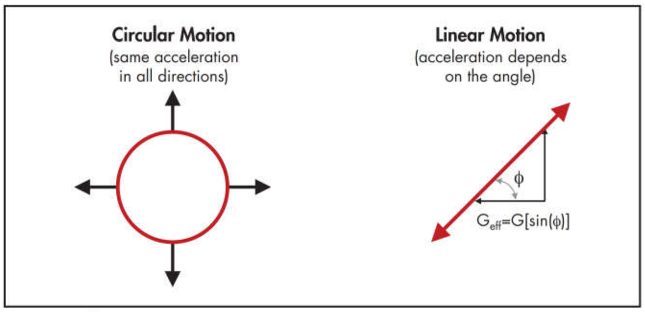
Figure 24 is a simplified graphic of particle motion with different forces and orbits, and Figure 25 shows how deck motion can be induced using weights on the shaft. Of course, there are other methods to induce motion and other more complex orbits.

The stroke angle, measured relative to the length of the deck and in the direction of flow, can affect efficiency and



Courtesy of Metso

Figure 22 Forces at work on particles as a function of deck motion



Courtesy of Metso

Figure 23 Resolving the G_{eff} force perpendicular to the screen deck

capacity. Very low (~0°) or high (~180°) angles do little other than accelerate wear. For other angles there is a component of vertical movement (aiding stratification) and a horizontal component aiding (<90°) or retarding (>90°) material flow. (For the screen in Figure 11, the stroke angle was 50°.)

To summarize, the designer for the screening application chooses the orbit motion (circular, elliptical, or linear) based on a compromise between material movement (capacity), which emphasizes linear motion, and efficiency, which emphasizes circular motion. The ellipse is an optimized solution. All give good stratification with the correct stroke angle. For horizontal and banana screens, linear motion is the de facto standard because material movement is critical. For inclined screens, circular or elliptical orbits are more common.

Finally, there is the matter of feeding the screen. Here are three general rules:

1. The feed must be uniformly distributed (at least 75%) across the width of the screen for the unit to achieve rated capacity.
2. The feed rate must be modulated where possible (e.g., using belt feeders) to ensure the screen works efficiently in the face of changing feed conditions.
3. Where possible, it is good to introduce the feed having a motion opposite to the eventual material flow, which helps in distribution and avoids flooding in the initial zone of the screen deck.

Table 3 G-force implications in inclined vibrating screens

G-Force Perpendicular to the Deck	Comment
<1.5	Practically no movement on the deck, so of no use
1.5–2.5	The stratification is limited and relative velocity between the particle and the deck is low. These parameters are suitable for soft screening and where size degradation is problematic and there is a low tolerance to impact.
3.0–3.5	The particle is presented to the screen deck at its maximum relative velocity and offers the best screening condition for inclined screens. The stratification is adequate.
4.0–5.0	The stratification is good, but the relative velocity between the deck and particle is low, offering poor screening efficiency. Bearing life is shortened.
5–6	The stratification is good, but the particle projection exceeds the pitch (particles are in flight too long) and screening opportunities are lost. The relative velocity of screen and particle is low, combining to give poor parameters for efficient inclined screening. The high acceleration forces can act negatively on the screen structure, and bearing life is further shortened.

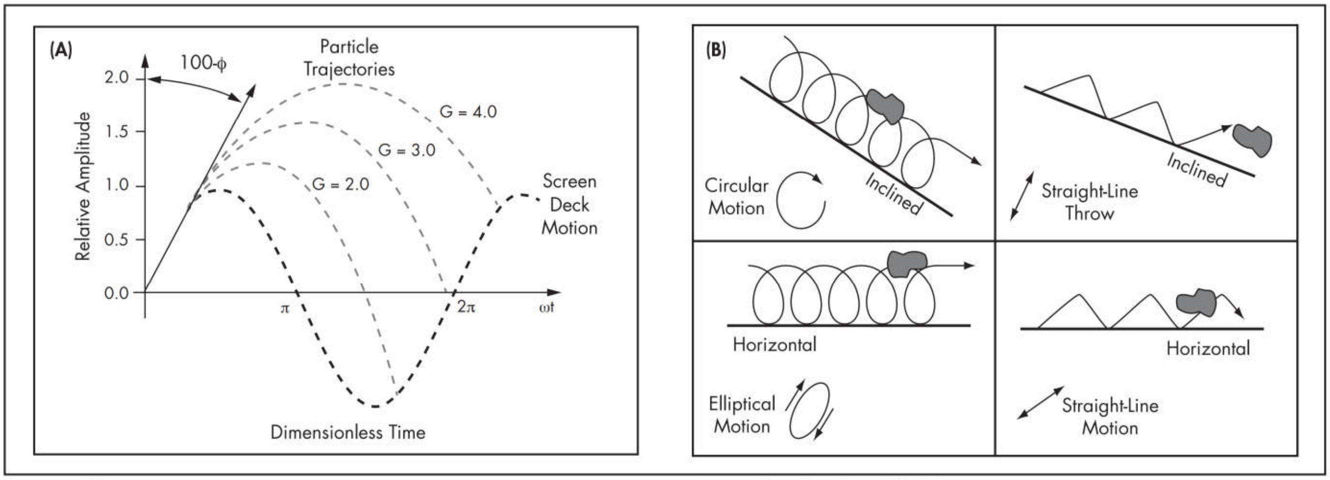
Source: Moon 2003

This brief synopsis, summarized in Table 4, provides a review of the major design variable of a vibrating screen and indicates usual design ranges where appropriate. Of course, this "one-variable-at-a-time" approach does not always consider the myriad interactions among these variables.

Screen Media

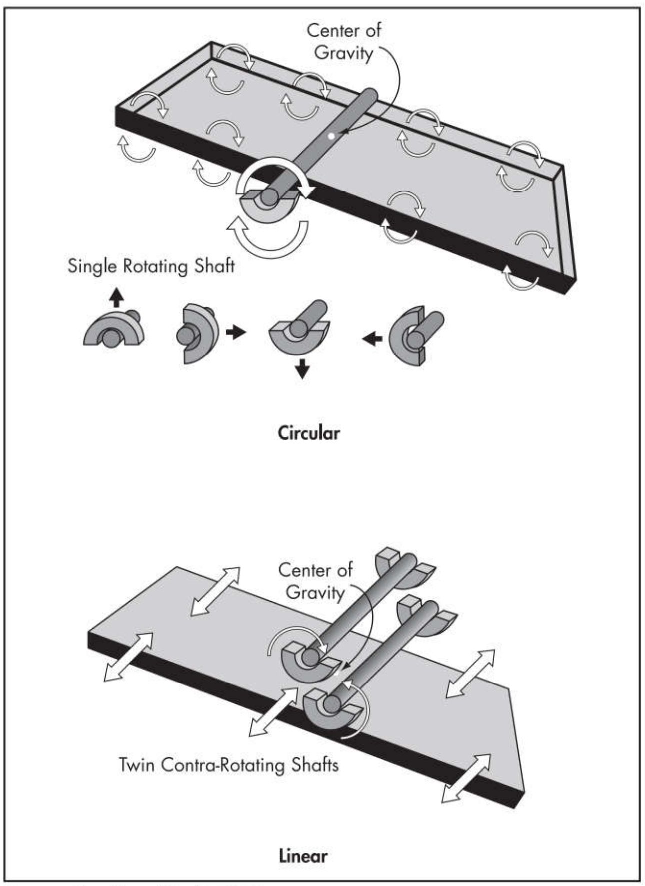
Since screen media is often the single biggest operational expense for a vibrating screen, this chapter would be incomplete without a brief introduction to this topic. The governing objective here is absolute lowest total cost, which implies that availability, cost, wear life, downtime, and so on must all be considered in making the final media selection. OEMs do publish handbooks on this topic, which can be very helpful (e.g., Metso, n.d.).

There are three major materials of construction for screen media: steel (punched plate or wire mesh), rubber, and polyurethane. The polymeric compounds of rubber and polyurethane are usually more expensive but tend to exhibit superior



Courtesy of Metso Source: Flintoff and Kuehl 2011

Figure 24 Particle motion (A) relative to screen deck as a function of g-force and (B) as a function of the deck orbit



Source: Flintoff and Kuehl 2011

Figure 25 Using weights to induce specific orbits

Table 4 Process matrix for a vibrating screen*

Design Variable	Screen Capacity	Screen Efficiency	Undersize Mean Size	Pegging/ Blinding
Screen area	+	+	0	0
Open area	+	+ or 0	0	0
Aperture size	+	+	+	–
Aperture shape (increasing nonuniformity)	+	+ or 0	+	–
Deck inclination	+	– or 0	–	– or 0
Speed	+	+	0	–
Stroke angle	–	+	0	– or 0
Stroke	+	+	0	–
Orbit (from linear toward circular)	–	+	0	–

Source: Flintoff and Kuehl 2011

*All other factors being equal, an increase in the design parameter will cause an increase (+), decrease (–), or no change (0) in the performance metric.

wear performance in applications that permit alternatives. Service life can be extended by factors of more than four through eight with polymerics but is ore dependent.

Figures 26 through 28 show wire mesh, rubber, and polyurethane media, respectively. Media specialists often break down applications as scalping, standard production (size control and sorting), and washing (sorting).

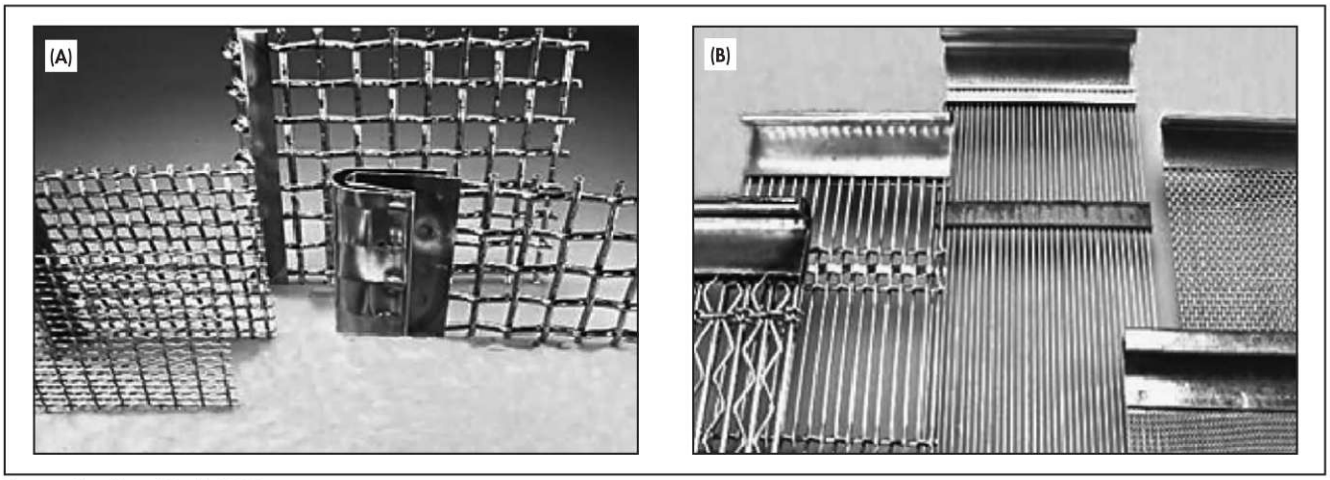
Wire mesh can have standard weaves, as shown in Figure 26A, or slotted anti-blinding or even custom weaves as shown in Figure 26B. The wires are usually high-carbon or stainless steels.

Typical applications for rubber screen decks (Figure 27) include high-impact scalping type duty or situations where abrasion and/or blinding is a serious concern. The decks are manufactured by punching or molding.

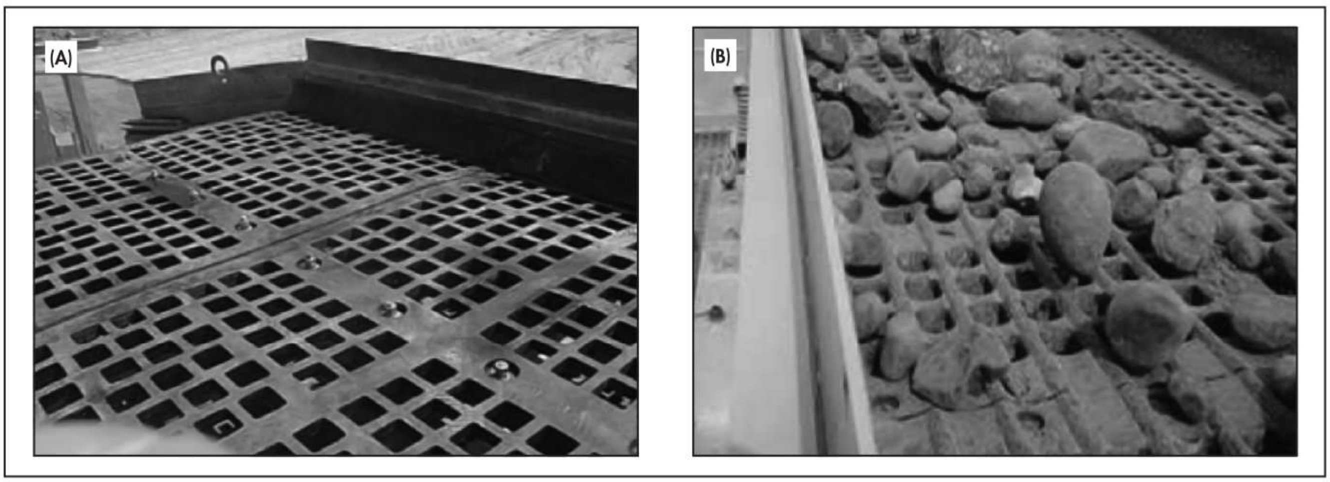
Polyurethane decks (Figure 28) are usually found in standard production applications and in washing or dewatering applications. They are manufactured by casting or injection molding processes.

The polymeric materials lend themselves to modular installation or paneling. Table 5 weighs the advantages and disadvantages of steel versus the polymerics.

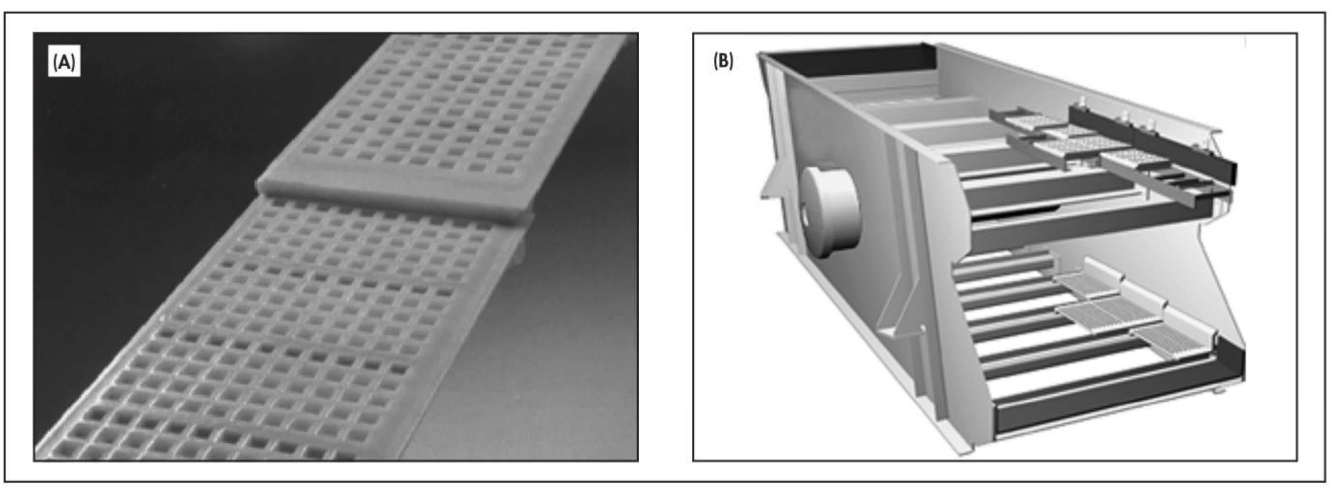
As a cautionary note, although there might be a tendency to choose thicker panels to increase wear life, this will reduce capacity and accuracy and will induce higher levels of pegging and blinding. Media suppliers familiar with best practices can be very helpful in these selections, and it is also recommended that the screen OEM is consulted when changing the design of media.



Source: Flintoff and Kuehl 2011
Figure 26 Wire mesh media



Source: Flintoff and Kuehl 2011
Figure 27 Rubber screen decks



Source: Flintoff and Kuehl 2011
Figure 28 Polyurethane decks

Screen Applications

This section provides more detail on three of the more common applications of screens in mineral processing flow sheets.

Traditional Crushing and Screening Circuit

The more traditional three-stage crushing and screening circuit is illustrated in Figure 29. For open pit operations, the primary crusher would be a gyratory, whereas for underground mining operations, a jaw crusher would most likely be employed. Except for heap leach operations, this type of circuitry has been supplanted by SAG or HPGR circuits. However, there are still quite a few older operations around the world that employ three- or four-stage crushing plants, for example, the iron ore industry in the Commonwealth of Independent States and South American countries. As the figure shows, the traditional three-stage crushing circuit can employ grizzly, scalping, and sizing screens.

Grizzly Screen

In plants where run-of-mine (ROM) ore has a high fines content, vibrating grizzly screens are used to increase the primary crushing capacity by scalping the fines. Grizzly screens are essentially very robust scalping screens. They are most commonly applied with jaw crushers, as gyratory crushers are normally high-capacity machines and can accommodate fines in the ROM feed.

Standard grizzly screens are available in sizes up to 2.4 × 4.8 m and can handle a volumetric capacity up to 1,200 m^3/h (depending on the feed size distribution). (To calculate the mass flow capacity, multiply the volumetric capacity of the screen by the bulk density of the solids.) For higher capacities, custom-made grizzlies can be designed and constructed. When designing a custom-made grizzly, important information includes the feed top size (mechanical robustness considerations), the fines content (OA considerations), and the feeder width (usually an apron feeder for large capacity). The grizzly width must be compatible with the feeder to reduce the drop height of the feeder discharge to the grizzly feedbox, as it can handle large lumps, and the impact provides high stress to the machine body. The use of rubber liners in the feedbox is strongly recommended to absorb the higher impact of the large lumps.

Grizzly machines are usually assembled with grizzly rail bars or with perforated plates, manufactured with abrasion-resistant steel (Figure 30). The grizzly rail bars have a tapered profile and high OA and are assembled in steps with an open end, which minimizes pegging and provides high capacity. Perforated plates have a lower OA, and therefore lower capacity, but are attractive because they reduce the risk of belt damage from large slab-like particles with sharp edges.

In high-capacity mines with finer ROM feed (e.g., Brazilian iron ore mines) that employ larger truck-shovel operations, it is very difficult for the shovel operator to separate the large lumps prior to delivery to the primary gyratory crusher. To avoid grizzly machine mechanical failures, a static grid (Figure 31) is recommended at the truck discharge to remove large lumps (>1,200 mm). Coarse particles remaining on the grid can be broken with a hydraulic rock breaker.

Scalping Screen

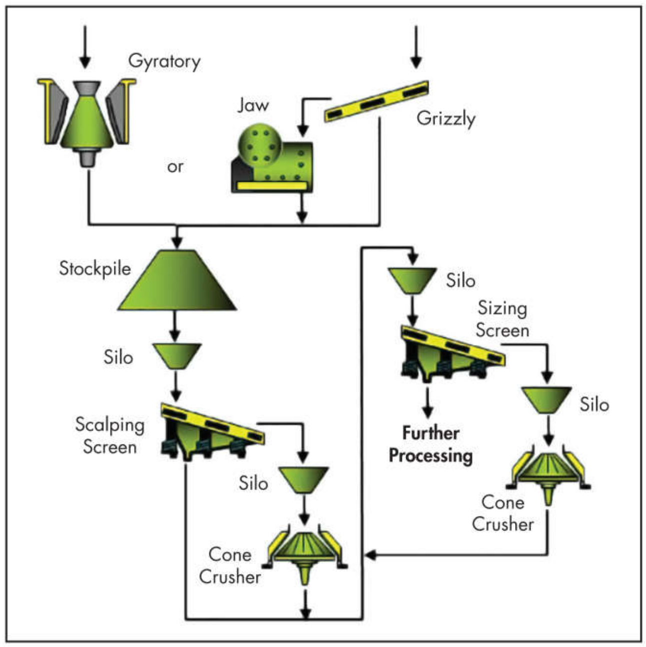
Scalping screens are usually intended to remove the fine particles in the crusher feed to avoid packing and the development of extreme forces in the crushing cavity. The aperture size is typically selected to be just smaller than the design crusher closed side setting (CSS), and the usual range is 50 to 120 mm. Because scalping screens are commonly applied in open circuit, efficiencies of 85%–90% are acceptable.

When treating primary crusher discharge, the feed top size to the scalping screens is in the range of 250 to 400 mm, depending on the primary crusher open side setting. To properly handle this top size while ensuring long service life, the use of strong rubber panels on the top deck (Figure 32) is highly recommended. The rubber absorbs the impact of the large lumps, preventing low panel life because of structure bending. In addition, riding bars are used to improve the impact absorption of large lumps. For lower abrasion index ores, perforated plates built with abrasion-resistant steel are also used.

Table 5 Advantages and disadvantages of steel versus polymeric screen decks

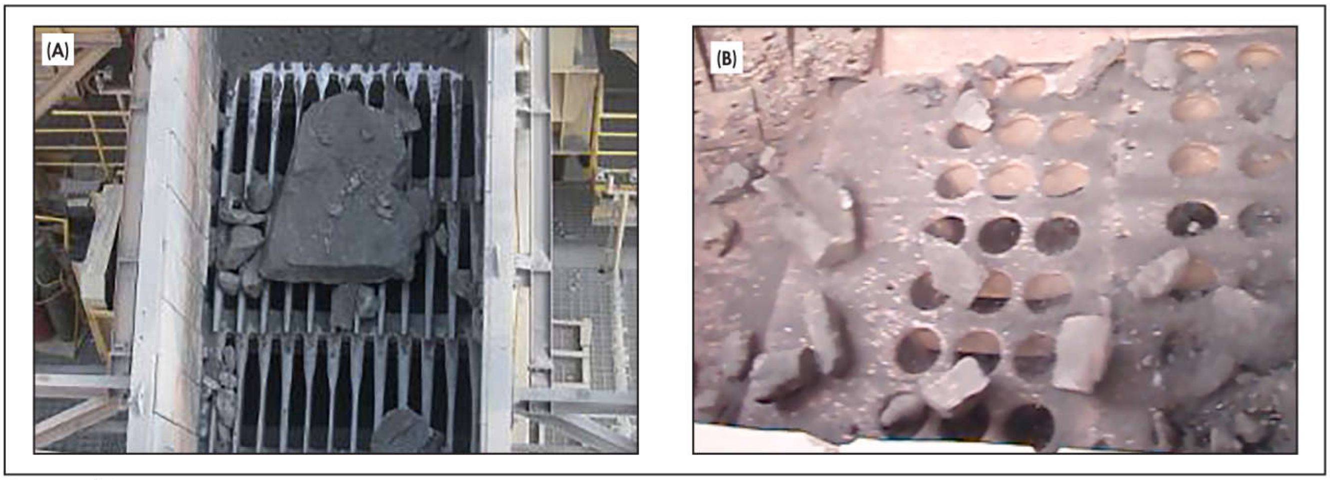
Wire	Rubber/Polyurethane
Advantages • Price • Accuracy of cut • Open area is high (on installation)	Advantages • Longer life • Less downtime • Shock resistance • Accuracy • Reduced pegging • Reduced blinding • Open area (in operation) • Noise reduction
Disadvantages • Shorter life • More downtime • Pegging problems • Blinding problems • Reduces open area (in operation) • Noise levels	Disadvantages • Price • Open area (on installation) (e.g., although these screens tend to have lower open areas out of the manufacturing process than wire mesh, they retain open area much better)

Source: Flintoff and Kuehl 2011



Courtesy of Metso

Figure 29 Traditional crushing and screening circuit



Courtesy of Metso

Figure 30 Grizzly screens with (A) bars and (B) perforated plates

Courtesy of Metso

Figure 31 Static grid at primary crushing dump point

Courtesy of Metso

Figure 32 Rubber panels with riding bars for scalping screening application

The screen types recommended for scalping are the banana (linear motion) and the inclined (circular motion) double-deck type, where the top deck usually performs a relief/protection function. Because the impacts of the large particles are absorbed by the top deck, it is possible to use common modular panels in the lower deck for high abrasion index ores, and wire mesh for low abrasion index ores.

To avoid pegging at large media apertures and to optimize the screening efficiency, the scalping screen stroke must be higher than common sizing screens. The stroke cannot be too large, as that will decrease the screen performance (excessive bounce and lower probability of passage); and it cannot be too small, as that will increase the pegging tendency. A practical way to detect if a scalping screen is operating with an incorrect stroke or speed setting is if the particles pegging the screen deck can be easily removed by hand when the machine stops. If so, the screen has insufficient force to dislodge these particles. Generally, the preferred stroke and speed combination for scalping screens is 6 mm and 820 rpm.

Based on current market trends for large screen selection, and their ability to handle feeds with high fines content, banana screens are the most common scalping machine in new projects. The banana screen shape is the latest screening development, and the screens are designed to maximize the screening capacity as described earlier. The higher the fines content in the feed, the higher the "banana factor" gain in both dry and wet screening. The banana shape starts to exhibit a capacity gain against the more traditional screens when the feed is more than 40% passing the aperture size. As a rule of thumb, banana screens offer 30% higher capacity than a traditional inclined circular motion screen, in about the same footprint.

As larger and larger equipment is required (the economies of scale), the banana screen is a popular choice because it is does not have the same scaling constraints as more traditional screens. Because of roller bearing constraints, inclined circular motion screens are restricted to a 3.0 × 6.1 m size for scalping. Banana screens can be built with sizes up to 4.8 × 8.5 m in the double-deck configuration.

Horizontal screens can be applied in scalping, but this makes sense only when there is a height restriction in the building. Because of the horizontal deck, the pegging tendency for

Courtesy of Metso

Figure 33 (A) Banana screen, (B) inclined screen, and (C) horizontal screen

large apertures is high. Good practice is to consider a maximum aperture of 50–75 mm for horizontal screens.

Sizing Screen

Sizing screens, as the name implies, are used to screen out an end product (e.g., aggregate plants) or to deliver a finer product for further processing (e.g., mining plants). The most common application is in closed circuit with a final crushing stage in a wet or dry process, and where the oversize is recirculated to the crusher feed. Efficiencies of 90%–95% are usually required in these applications. In mining applications, the typical apertures for separation are from 3 to 75 mm in dry processes, and from 0.5 to 75 mm in wet processes.

Recommended screens for sizing applications (Figure 33) are the banana (linear motion) and inclined (circular motion) double-deck type. As is the case for scalping screen selection, horizontal screens are recommended only when there is a building height restriction and for fine wet screening (<2-mm separation).

In the past, the "standard" screen size for large mining plants was 2.4 × 6.1 m. However, with the development of engineering tools such as finite element analysis (FEA, which emerged around 1990) and strain gauging and vibration measurements to validate these FEA models, larger screens (e.g., 3.6 m and 4.2 m wide) have been designed and manufactured and perform to expectations. For large greenfield projects, the 3.6 × 7.3 m screen size is becoming the new standard. For some projects, 4.2 × 8.5 m screens are being implemented. To use the full capacity of large screens, it is very important to ensure the correct feed distribution (the feed must cover at least 75% of the width of the deck at the feed end) to avoid significant loss of available screening area. When feeding screens with a width of 3.6 m or 4.2 m from a conveyor belt, it is usually necessary to design a feed chute with rock boxes to distribute the feed properly, as the conveyor generally is much narrower than the screen. The best solution to correctly spread the feed for large screens in dry processes is to use a divergent vibrating feeder (Figure 34). These feeders generally operate with a linear motion and a stroke of ~6 mm. For wet processes, the feed chute must be carefully designed, using the turbulence of the pulp flow to spread the slurry.

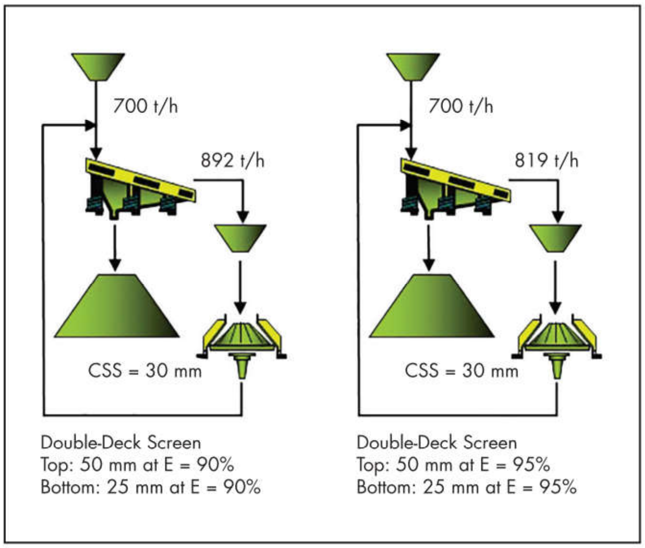
In the past, sizing screens were usually sized to reach 90% efficiency, but now engineering companies typically ask for screen designs that offer 95% efficiency. (Screening efficiency will be discussed in more detail later in this chapter. These numbers refer to E_u as defined later by Equation 4.) When doing sizing calculations for a closed circuit, this requirement must be carefully analyzed. For example, to go from 90% to 95% efficiency, the screen may require ~20% more area, which means a larger and more expensive screen. A critical element of this analysis relates to the determination of expected recirculating load (i.e., if the screening efficiency drops from 95% to 90%, the increase in the circulating load must be accommodated by the crusher). Figure 35 illustrates the potential impact of screen efficiency on circulating load.

Courtesy of Metso

Figure 34 Large screen fed by a divergent vibrating feeder

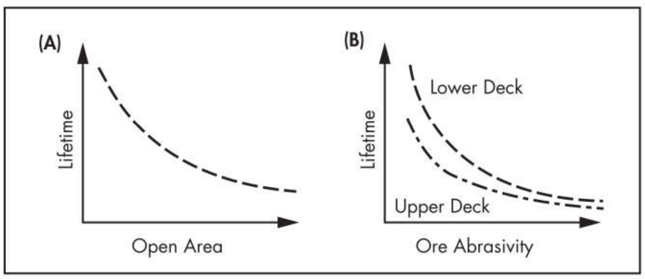
Although some small mines still use wire mesh because of its lower cost, most modern and larger mining operations use modular panels fabricated from polymeric media (rubber and polyurethane). Panels provide better service life and are easier to handle. In general, due its higher flexibility (impact absorption), rubber media is recommended when the wear is caused by impact or high load, and polyurethane when the wear is caused by abrasion.

When pegging and blinding is a problem, flexibility helps to keep the media clean. Rubber panels can usually be manufactured in 40 and 60 shore A (a hardness measure based on indentation testing). Polyurethane is usually manufactured in 90 shore A, which is hard. It can also be manufactured in lower hardnesses, although this is not common. To mitigate pegging,



Courtesy of Metso

Figure 35 Closed-circuit load at 90% and 95% efficiency

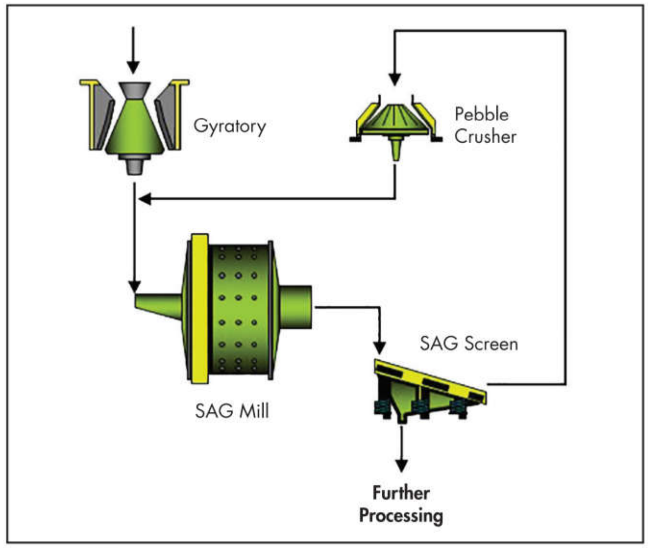


Courtesy of Metso

Figure 36 Relative media lifetime: (A) as a function of open area and (B) as a function of ore abrasivity

polyurethane panels can be manufactured in a zigzag design (e.g., Polydeck Screen Corporation's VR panels). A problem with a zigzag design is that the separation precision is slightly compromised. Some quarry operators choose to use flexible rubber screening media to minimize pegging and blinding in their dry screening operations. In mining sizing applications, separation precision is not as strict a requirement; therefore, both rubber and polyurethane can be employed for an anti-pegging solution.

In terms of the capacity–service life trade-off, the higher the OA of the media, the higher the screening capacity. However, the higher the OA, the shorter the service life, since there is less material to wear and the panel design is weaker (see Figure 36, which also includes ore abrasivity effects). Media suppliers usually have a standard media design that has a good balance of life and OA, and one that emphasizes OA design to maximize capacity. The correct media design is determined by the application. For greenfield projects, where a new screening building must be erected, it is safer to select the screen size and media based on standard panels, but for a revamp of existing plants, where capacity must be maximized, high OA media is probably the best solution. The preferred stroke and speed combination for sizing screens is generally around 5 mm and 900 rpm.



Courtesy of Metso

Figure 37 SAG circuit

SAG Circuit

In a semiautogenous, ball mill, and pebble crusher (or SABC) SAG circuit (see Figure 37), vibrating screens are used to screen the pebbles from the SAG discharge for recirculation to the pebble crusher. The SAG mill may be equipped with a trommel screen, in which case the trommel oversize is the screen feed, and the trommel undersize is combined with the screen undersize.

Because the SAG foundation is expensive and it is usually required to remove the fines adhered to the pebbles, horizontal screen types are often the best compromise for SAG discharge screens (see Figure 38). Horizontal screens offer a low profile and slower pebble travel speeds for more effective washing. The slight modification here is that SAG discharge screens are designed to work at an inclination of 5° to provide a higher capacity (see also Figure 8A).

For high feed solids rates (>1,500 t/h), the screen body must be carefully designed, because the SAG rotation tends to bias the discharge to one side or the other of the screen, creating a torque on the machine body. In addition, the screen body must be designed to accept a high volumetric load dropping from height. Generally, the SAG screen mechanical availability is lower than that of the SAG mill itself, and unlike the pebble crusher, there is no option for bypass. To ensure a high availability for the SAG circuit, the screen should be assembled on a trolley for quick replacement by a spare unit (the "cassette" maintenance concept).

The SAG screen can be used with or without a trommel, although to ensure high screening capacity, the combination of a trommel and a SAG discharge screen is widely employed. The use of a trommel can complicate the screen selection, as it is very difficult to predict the mass balance and particle size distributions for the trommel products. Since vibrating screens have a maximum bed depth (mechanical load and separation performance) to work safely, errors in the predicted mass balance could lead to screen overloads and mechanical damage/failures and/or poor separation performance.

The use of single- or double-deck screens in this application depends on the bed depth. Usually, a standard mining

Courtesy of Metso
Figure 38 SAG discharge screen

screen can handle up to 150 mm of bed depth. However, because of the mechanical design precautions mentioned earlier, a SAG screen can usually handle up to 250–300 mm of bed depth. Only a few OEMs have good (mechanical and process) design experience with SAG screens, and it is best to work only with these firms. Such firms include, but are not limited to, Metso, Schenck Process, and FLSmidth–Ludowici.

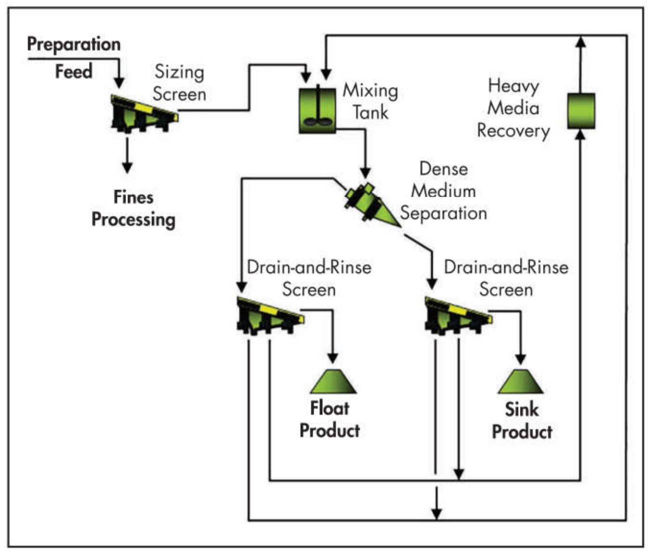
Dense Media Circuit

Dense media circuits are common in coal and diamond beneficiation applications. Using dense media (usually magnetite or ferrosilicon), the "fluid" density can be managed to control the separation of lighter (floats) and heavier (sinks) components in an ore. Figure 39 illustrates a typical coal preparation dense medium cyclone circuit (e.g., treating 50 × 0.5-mm particles) with sizing screens to get the right feed size fractions to the correct circuits, and drain-and-rinse screens for media (and some fines) recovery on both dense medium separation products.

Since the media (magnetite and especially ferrosilicon) is expensive, after the separation in dense medium separation cyclones and drums, the media are recovered in drain-and-rinse screens. The first section of the screen is used to recover most of the media and the remaining part to rinse the particles and remove the media adhered to particle surfaces. There are usually separate screens to drain and rinse the media (and ore fines) from the sink and float products, but in some cases, depending on the flow rates, a single screen with a partition wall can be used for both float and sink products, as illustrated in Figure 40.

Horizontal and banana screens (the latter with a slope combination of 25° at the feed end and 0° at the discharge) are widely used for drain-and-rinse applications. These "desliming"-like applications can have apertures as fine as 0.5 mm, so the 0° inclination at the discharge is important to provide good oversize dewatering. Any inclination of this region of the screen deck in the 0.5- to 2-mm aperture range can result in excess water to the oversize stream.

In older coal preparation plants, the combination of a static sieve bend directly feeding a horizontal screen has been successfully applied in drain-and-rinse applications. The sieve bend (with wedge wire) promotes a quicker drainage of the feed pulp, removing all the easy screening fine particles and most of the media pulp. The horizontal screen then washes the remaining particles and, as a result of its slower particle travel velocity, performs the near-size particles screening. The banana screen achieves the same principle, and with the advantage that the entire deck is vibrating, thereby minimizing pegging problems. The sieve bend is static and can experience some pegging issues. In addition, the sieve bend wedge wire can wear to have very sharp edges (a safety matter), and these machines are usually assembled in one big piece, presenting installation and maintenance handling challenges. The banana screen makes it light and easy to handle during maintenance.

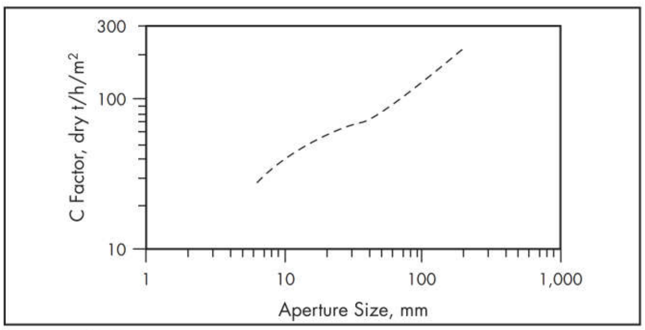


Courtesy of Metso
Figure 39 Dense media circuit

For desliming and drain-and-rinse applications, polyurethane media are usually used because abrasion is the main wear mechanism and rubber media is not generally available with apertures smaller than 2 mm. The preferred stroke and speed combination for desliming and drain-and-rinse screens is the same as the sizing screens: 5 mm and 900 rpm. The OEM list for dense media screening includes, but is not limited to, Metso, Schenck Process, FLSmidth–Ludowici, Joest, Haver and Boecker, Siebtechnik, and Weir–Linatex.

Courtesy of Metso

Figure 40 Drain-and-rinse screen with partition wall



Source: Allis-Chalmers, n.d.

Figure 41 Basic capacity factor (C) as a function of aperture size

Screen Selection

The many opinions and methods of screen selection suggest fertile ground for development and refinement. Three general approaches follow:

- **Class 1:** Empirical methods based on correlations derived from extensive databases of industrial experimental results
- **Class 2:** Lab screening tests with empirical model-based scale-up procedures
- **Class 3:** Fundamental model-based methods (these are relatively new and are described later in more detail)

Class 2 methods have been used sparingly in the past, but recent work (Hilden 2007) suggests there is good scope for improvement and room to combine Class 2 and Class 3 methods very effectively. Despite the potential of using Class 2 and Class 3 methods, most industrial vibrating screens are still selected using Class 1 methods. Because in most cases these screens operate more or less as designed, it is understandable why these methods have survived, with a few improvements, for some 70 years.

Class 1 selection methods employ empirical correlations to deduce screen area. Given the application (e.g., a pebble screen on a SAG mill discharge), the design feed rate of solids, and the typical feed particle size distribution, the design process can begin. Early decisions on numbers of decks, inclination, motion, low-head or high-head screens, and so on, come from the design basis documents and past practices in similar applications. After these parameters are set, the correlations can be used to compute screen area requirements, and the deck with the largest area determines the screen size. The task is then to match one of the standard products to the design. This is often an iterative design process.

Two usual approaches can be used to solve the Class 1 design problem—one based on the total solids feed rate to the screen and the other based on the solids feed rate of undersize material to the screen. Not surprisingly, this is also an area of debate, as the scientific community tends to prefer the latter method, yet the former is very commonly used. The former method is described in an abbreviated way as follows, simply for illustrative purposes. To provide a real example, the data for the screen in Figure 11 is used.

The fundamental equation for determining the screen area required is given in the following equation (Allis-Chalmers n.d.).

$$A = \frac{T}{CMKQ_1Q_2Q_3Q_4Q_5Q_6} \tag{EQ 3}$$

where

A = required screen area
T = mass flow of feed to screen
C = basic capacity factor
M = oversize factor (percent larger than aperture size in feed)
K = undersize factor (percent smaller than ½ aperture size in feed)
Q_1 = bulk density factor (usually ~60% of rock density)
Q_2 = aperture shape factor
Q_3 = particle shape factor
Q_4 = OA correction factor
Q_5 = wet or dry screening factor
Q_6 = surface moisture factor

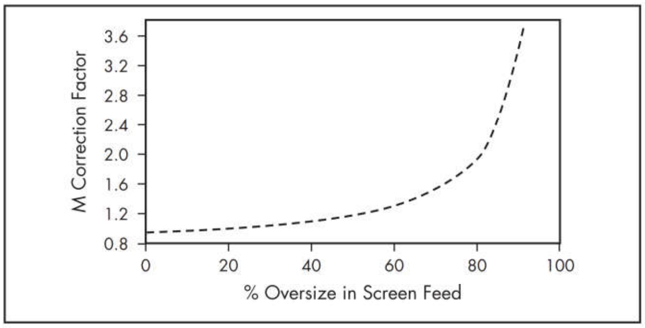
Figures 41 through 43 provide the basis for estimating the factors C, M, and K. Table 6 provides the means of estimating the Q factors (note that OA and aperture shape come from Figure 15). Table 7 presents the summary data for the calculations, showing both the input data required and the empirical corrections, as deduced from Figures 41–43 and Table 6 (which are adapted from Allis-Chalmers [n.d.]). The required area allows for a 6% loss because of mechanical fittings and so on. Following the rough rule that $L = 3W$, this screen would have the approximate dimensions of 0.34 × 1.03 m. In fact, the screen in Figure 11 is 0.34 × 1.67 m. The width is the same, but the test screen has extra length so one would expect an impact on classification efficiency. This topic is discussed the following subsection.

Although the symbology is slightly different, equations for the relationships shown graphically in Figures 41 through 43 are available in King (2001).

Performance Assessment

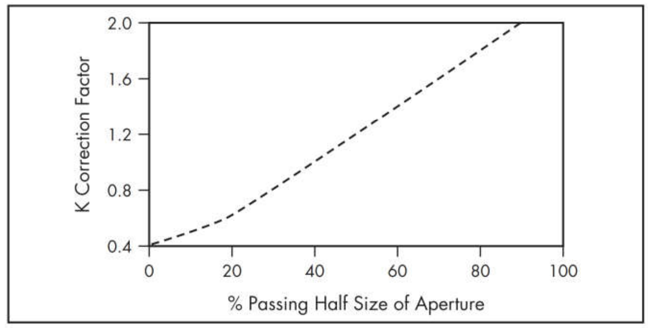
Mechanical and process performance can be distinguished, but this subsection only focuses on the latter.

A single parameter can be calculated in several ways that will quantify screen performance. Among these, the most common are E_u, which is defined as the efficiency of removal of undersize material from the oversize stream, and, R_u, which is the efficiency of undersize removal from the feed stream.



Source: Allis-Chalmers, n.d.

Figure 42 Correction factor (M) as a function of percent oversize



Source: Allis-Chalmers, n.d.

Figure 43 Correction factor (K) as a function of percent half size

Table 6 Q correction factors

Bulk Density Factor	Value
Bulk density, dry t/m^3	Q_1
0.4	0.25
0.8	0.50
1.6	1.00
2.08	1.30
Aperture Shape Factor	
Opening shape	Q_2
Square	1.00
Rounded	0.80
Slotted	
2:1 Slot	1.15
3:1 Slot	1.20
4:1 Slot	1.25
Particle Shape Factor	
Particle shape	Q_3
Cubical	1.00
Slabby	0.90
Open Area Factor	
Open area	Q_4
Calculation	Q_4 = percent open area ÷ 50%
Wet or Dry Screening Factor	
Opening	Q_5
Dry	1.00
Wet	
0.8–3.2 mm	1.25
4.8–6.4 mm	1.40
8–12.7 mm	1.20
14.3–25.4 mm	1.10
Surface Moisture Factor	
Surface moisture	Q_6
≤3%	1.00
3%–6%	0.85
6%–9%	0.70
Wet screen	1.00

Source: Flintoff and Kuehl 2011

Referring to the symbology in Figure 44, Equations 4 and 5 are used to compute numerical values.

$$E_u = \frac{F(1-\hat{f}_u)}{O} = (1-\hat{o}_u) \quad \textbf{(EQ 4)}$$

$$R_u = \frac{U}{F\hat{f}_u} = \frac{(\hat{f}_u - \hat{o}_u)}{\hat{f}_u(1-\hat{o}_u)} \quad \textbf{(EQ 5)}$$

where

F = feed rate
$\hat{f}_u$ = cumulative mass fraction in the feed passing the aperture size
O = oversize mass flow rate
$\hat{o}_u$ = cumulative mass fraction in the oversize stream
U = undersize mass flow rate

To estimate these performance measures, one is required to perform a sampling experiment around the screen while it is running at steady-state conditions. This raises subjects beyond the scope of this chapter (experimental design, sampling theory, sample preparation and analysis, mass balancing, etc.), but these are usually covered in the standard textbooks, such as Wills and Finch (2016). Practical issues, typically associated with sample access as well as the isolation of a screen operating in parallel, tend to make this a challenging experiment. Fortunately, for the screen shown in Figure 11, the balanced data are already available and are summarized in Table 8.

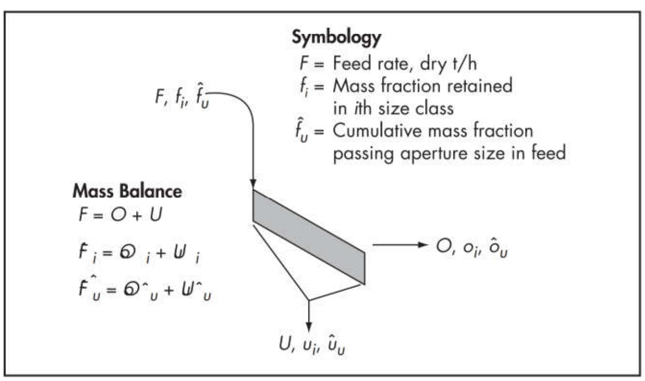
Using these results, E_u = 77.9% and R_u = 93.5%. The data suggest that there is quite a lot of finer (less than the aperture size of 10 mm) near-size material in the oversize stream. In terms of assessing performance, the manufacturers have a curve that relates E_u to the rated capacity of the screen. This is shown in Figure 45, and the rated capacity is the ratio of the actual tonnage (or area) to the calculated tonnage (or area) from Equation 3. The respective area figures for the example are 0.35 and 0.57 m^2, which gives a percentage of rated capacity of 59.9%. This point is plotted on the curve for reference.

This comparison indicates that the test screen in Figure 11 is not performing as well as would be expected at the given operating conditions and further analysis (e.g., low G values,

Table 7 Screen sizing example

Parameter	Value
Feed rate, dry t/h	15.7
Aperture (square), mm	10
Rock density, dry t/m^2	2.7
Application	Dry
C Factor, dry t/h/m^2	40.12
M Factor	0.972
K Factor	0.88
Q Factors	
Q_1	1.00
Q_2	1.00
Q_3	1.00
Q_4	1.39
Q_5	1.00
Q_6	1.00
Adjusted unit capacity, dry t/h/m^2	47.64
Area required, m^2	0.34
Size, mm	**Feed Distribution, %**
13.2	5.6
9.5	16.6
8	11.4
6.7	11.1
4.75	24.1
3.35	10.7
2.8	6.5
Pan	14.0
Percent +10 mm	18.7
Percent –5 mm	34.0

Data from Hilden 2007



Source: Flintoff and Kuehl 2011

Figure 44 Screen performance parameters

extended length, etc.) of the situation would be required to validate the result and improve performance.

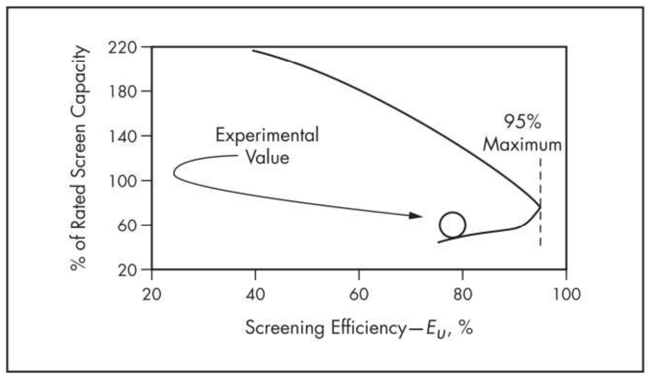
Another very common measure of efficiency is to use the data in Table 8 to compute an experimental partition curve, which can then be modeled to extract performance metrics.

The details related to the estimation and analysis of partition curves are provided in Chapter 4.6, "Partition Curves."

Table 8 Sampled data summary for the horizontal screen in Figure 11

Size	Feed	Oversize	Undersize
13.2	5.6%	20.8%	0.0%
9.5	16.6%	61.8%	0.0%
8	11.4%	13.9%	10.5%
6.7	11.1%	3.5%	13.9%
4.75	24.1%	0.0%	33.0%
3.35	10.7%	0.0%	14.6%
2.8	6.5%	0.0%	8.9%
Pan	14.0%	0.0%	19.1%
Mass fraction	1.00	0.27	0.73
Percent –10 mm	81.3%	22.1%	100.0%
Mass flow, dry t/h	15.7	4.2	11.5

Data from Hilden 2007



Source: Flintoff and Kuehl 2011

Figure 45 Percentage of rated capacity versus E_U

The authors of this chapter assume that the reader is already familiar with this topic or has read this chapter.

In the case of vibrating screens treating dry materials at relatively large aperture sizes (e.g., >5 mm), it is quite common to use Equation 21 in Chapter 4.6, "Partition Curves," to model the experimental partition curve data; that is, the fines bypass to the coarse product in these cases (Rf) is taken to be zero. Figure 46 presents the results for the screen in Figure 11. The sharpness of separation, α, is very high, which may have something to do with the length of the deck. (Recall that this screen is longer—1.67 m—than would be required for the feed conditions it was seeing, 1.03 m from the earlier screen sizing calculation.)

One would normally expect the cut size to be close to the throughfall aperture size, and clearly the value is a little low here. (This is, in part, because of the way the characteristic size was defined for this study.) The sharpness of separation for screens cutting in this aperture size range is usually around 6, so a value of 9.6 suggests that efficiency is relatively high. Taken together, the implication is that the screen is not processing the finer near-size material very well, which would require further investigation.

The data acquired for the screen in Figure 11 permit the calculation of the cumulative partition curve (here using the experimental data) as a function of the position along the length of the deck. The experimental results are shown in

Figure 47. Given the earlier explanation related to crowded and separated screening, it is no surprise to see that the fine material moves quickly through the screen—collectively, particles do not have to progress far down the deck before all of the very fine material has passed through the apertures (and the corresponding $p_i = 0$). For the fine, near-size material, clearly the process is much slower (as illustrated in Figure 12).

The periodic measurement of screen efficiency is as important to the maintenance of process performance as the periodic measurement of, for example, bearing condition is to the maintenance of mechanical performance. Unfortunately, often the process aspects of screens are ignored. However, screens are robust devices and often have a direct impact on the performance of comminution and separation equipment, for which a "systems thinking" approach must be applied.

Recent Developments

This section provides a brief introduction to some of the developments emerging in the vibrating screen market.

Real-Time Condition Monitoring

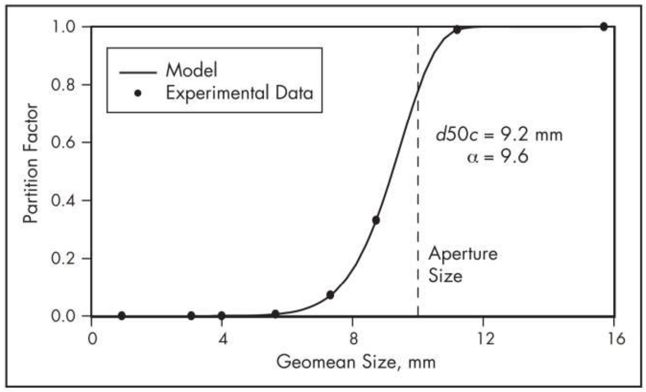
Using vibration, thermographic, and occasionally other specialty sensors to automate the more usual manual inspections of predictive maintenance is becoming increasingly commonplace. Where it is done, this is still usually reserved for the typical applications of monitoring bearing health. Manufacturers such as Metso (ScreenWatch) have taken this a step further by using additional wireless accelerometers to compute screen orbits, which can then be compared with expected values from run-in tests and/or finite element modeling to analyze the mechanical and process health of the screen. (This essentially automates the manual throw-card analysis, making the results available in real time, all the time.) Figure 48 is an example of normal orbits and the kinds of trends that develop when there is a problem with the supporting springs. Loose media on the screen deck and other kinds of serious problems have their own orbit "signature."

In the case of the normal orbits (Figure 48A), both are linear, showing the same stroke and angle. In the case of the abnormal condition (Figure 48B), the orbits are now elliptical and the strokes are different.

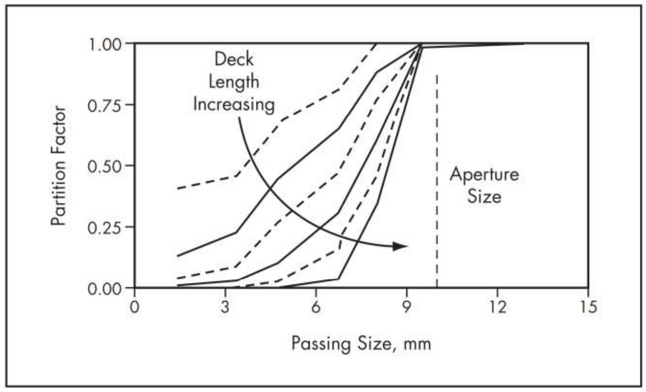
The frequency spectrum of the accelerometers also provides useful information on the mechanical state of the deck, loading, and other interesting performance parameters. Moreover, when these signals are combined with others (from load cells, vision systems, etc.) in a kind of sensor fusion approach, the analytical detail and reliability can be dramatically increased.

Real-Time Deck Motion Modulation

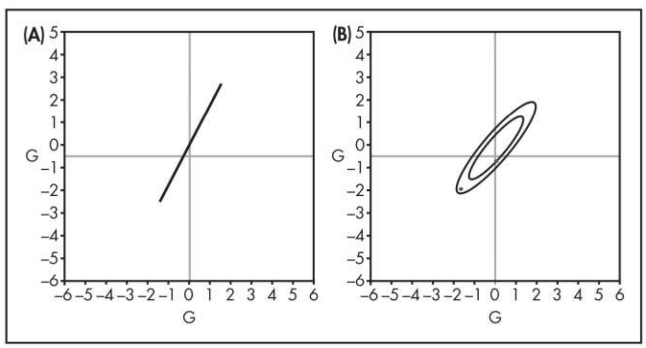
As seen earlier in the process matrix of Table 4, deck motion (stroke, angle, and orbit) all affect performance, and because screen feeds often change (mass flow and particle size distribution), one school of thought says the ability to modulate these parameters online would support real-time screen performance management. Several manufacturers are exploring this kind of solution on selected screen models. For example, Metso has developed a system for controlling stroke angle on its Ellipti-Flo inclined screens. (Ogawa [2010] has discussed the effect of stroke angle on screen performance.) Figure 49 illustrates an application for screens that are subject to pegging. In this particular case, the feed is interrupted and the angle adjusted to maximize G (see Figure 23) perpendicular to the screen deck. This procedure can also be performed with the feed on, although the angle change is not likely to be as large as shown in this figure. One can also conceive of using this feature to control the rate of movement of material across the deck. For example, if the feed rate drops, the angle can change to increase residence time and avoid screen inefficiencies in the discharge region, and the converse.



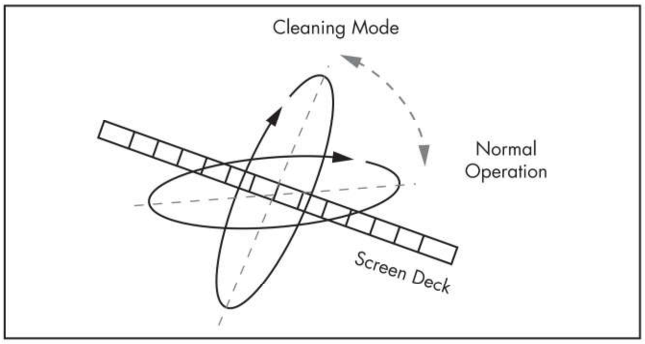
Adapted from Flintoff and Kuehl 2011
Figure 46 Experimental and modeled partition function data



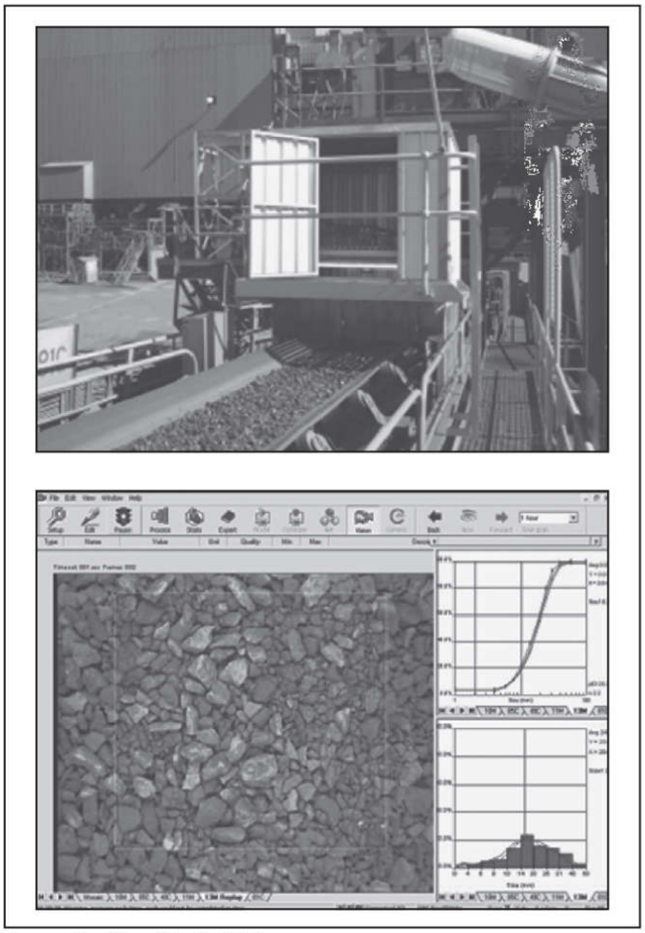
Data from Hilden 2007
Figure 47 Partition factors as function of position on deck



Source: Flintoff and Kuehl 2011
Figure 48 Feed end orbits in (A) normal and (B) abnormal operation



Courtesy of Metso
Figure 49 Controlling stroke angle on a Metso Ellipti-Flo inclined screen



Source: Flintoff and Kuehl 2011
Figure 50 VisioRock installation and typical output display

Instrumentation

One of the exciting areas of potential for performance monitoring is "machine vision," primarily as applied to measuring feed or product size. Typically, dry screening is very dusty and requires hoods covering the entire screening surface for effective dust control. Therefore, applications on the deck itself (oversize velocity, load, etc.) are a challenge. However, in the case where the product streams are discharged onto belts, the standard technology, such as Metso's VisioRock, can be applied. For example, in the production of iron ore, lump size control is very important, and early warning of a problem is essential if, for example, the screen media is broken, thereby producing off-specification material in the undersize stream. One operator is now using machine vision to detect and react to these types of quality assurance events, and Figure 50 shows the VisioRock installation as well as the output from data processing. In this case, images are analyzed at a rate of ~10 per second, which is more than sufficient to monitor everything that passes.

Acoustics also offer interesting potential for analyzing screen performance, but it is very early for research in this area.

Population Balance Simulation Methods

Population balance methods (PBMs) are not new, having been in use for at least two decades, but as the design and operation needs turn increasingly toward simulation to support these activities, higher and higher fidelity is required. These are an element of the Class 2 methods previously mentioned. Although the industry is moving in this direction, older approaches are still in use in most of the simulation packages. One of these is the model by Karra (1979), which is based on a Class 1 selection method, although in this case it is based on the method of sizing relating to the mass flow rate of undersize in the feed stream.

Using Equation 11 in Chapter 4.6, "Partition Curves," Karra (1979) developed a correlation based on the empirical screen sizing factors used in the screen selection approach. The factors have been modified over time, and their estimation is described elsewhere (e.g., King 2001), but the equation for computing $d50c$ is

$$d50c = \frac{G_c h_T}{[(T_u/H)(ABCDEF)]^{0.148}} \qquad \textbf{(EQ 6)}$$

where

$d50c$ = cut size
G_c = near-size correction factor
h_T = throughfall aperture (see Figure 17)
T_u = tons of undersize in the feed, dry t/h
H = effective screen area, m^2
A = basic capacity factor
B = oversize factor
C = fine size factor
D = deck location factor
E = wet screen factor
F = bulk density factor

Because several properties for the screen in Figure 11 have been given, Table 9 is a shortened summary of the Karra calculation of $d50c$. In this particular case, the authors elected to use data from the screen in Figure 11 based on a screen length of 1.1 m, closer to what was estimated in the screen selection discussion (1.03 m), and not on the total screen length (1.67 m). This would correspond to the first four undersize "bins" (from the left) in Figure 11. As one can see, the extra screen length does affect efficiency, as there is material in the last two undersize bins. The argument is that the Karra model was developed from screens in near-normal operation, and using the data from a shorter screen complies more closely with that condition.

Karra assumes α is a constant in the partition curve model with a value of ~5.9, and in the authors' experience, numbers

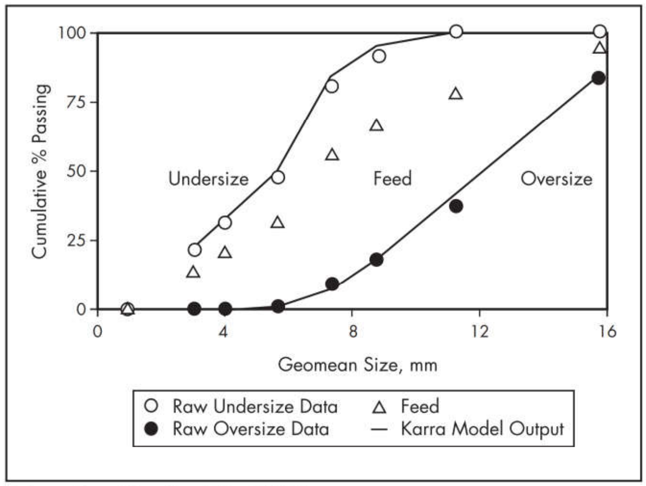
Table 9 Computing Karra's *d*50*c* for the screen in Figure 11

Symbol	Factor	Units	Result
T_u	Feed	dry t/h	15.67
H	Effective screen area	m^2	0.35
h_T	Throughfall aperture	mm	10.00
G_c	Near-size correction factor	—	0.82
A	Basic capacity factor	$t/h/m^2$	17.85
B	Oversize factor	—	1.38
C	Fine size factor	—	1.12
D	Deck location factor	—	1.00
E	Wet screen factor	—	1.00
F	Bulk density factor	—	1.01
$d50$	Cut size	mm	7.85

Source: Flintoff and Kuehl 2011

in the region are pretty typical for coarse screening. The *d*50*c* value in Equation 6 is also in decent agreement with the experimental value of 8.2 mm (based here on the shorter screen length data).

Karra's model can be used to predict the expected size distributions for the undersize and oversize products, and these are shown in Figure 51 along with the actual experimental results. The predictions are good. The calculated mass splits of 0.37 (to oversize) and 0.63 (to undersize) compare well with the experimental results of 0.35 and 0.65.



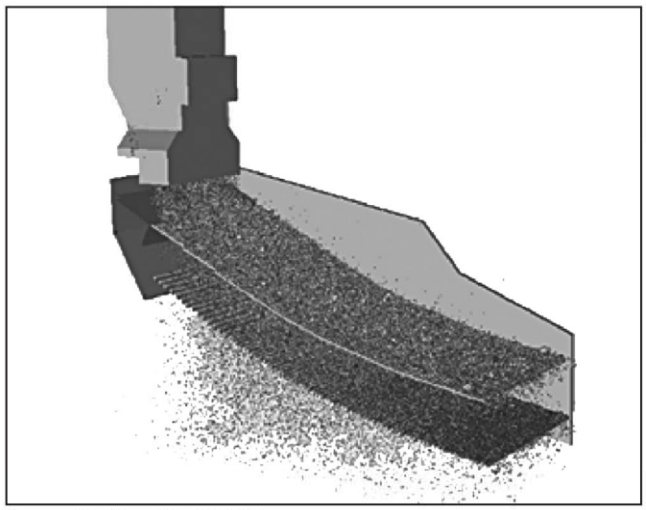
Adapted from Flintoff and Kuehl 2011

Figure 51 Karra's model predictions and actual cumulative size distribution curves for the "shortened" screen in Figure 11

Discrete Element Simulation Methods

In the pursuit of higher fidelity simulation of screen performance, the ultimate tool is probably discrete element modeling (DEM). Very briefly, this approach is based on fundamental models drawn from physics (e.g., Newton's laws of motion). Using a mathematical description of the body and motion of the screen; some typical physical properties; and the feed size distribution, flow rate, and particle shapes, the DEM simulation can be run from only first principles (no correlations, no parameters drawn for experimental data, etc.). Although this sounds simple in concept, solving the problem is onerous, as there are millions of particles, each requiring several differential equations to describe translational and rotational motion in time and space. Because of the interactions of the particles among themselves and with the screen itself, the integration intervals are very short—about one millionth of a second. Simulating several seconds of real-time operation can take hours or days, depending on the problem size, computational capability, and simulation code efficiency. Consequently, the goal is to combine DEM and PBM, the former to work out the real mechanisms and the latter to abstract these and provide speedy calculations.

Because of the vast quantities (gigabytes or even terabytes) of numerical data generated in such simulations, it is common to use visualization techniques to "see the results." However, the numerical data must be used for any calculations. Figure 52 presents a snapshot of visualization, and Figure 53 shows the predicted (lines) and measured (bullets) particle size distributions from a simulation of the banana screen pictured Figure 19B. The agreement in Figure 53 is very good, which provides some insight into the power this tool will bring to screen modeling.



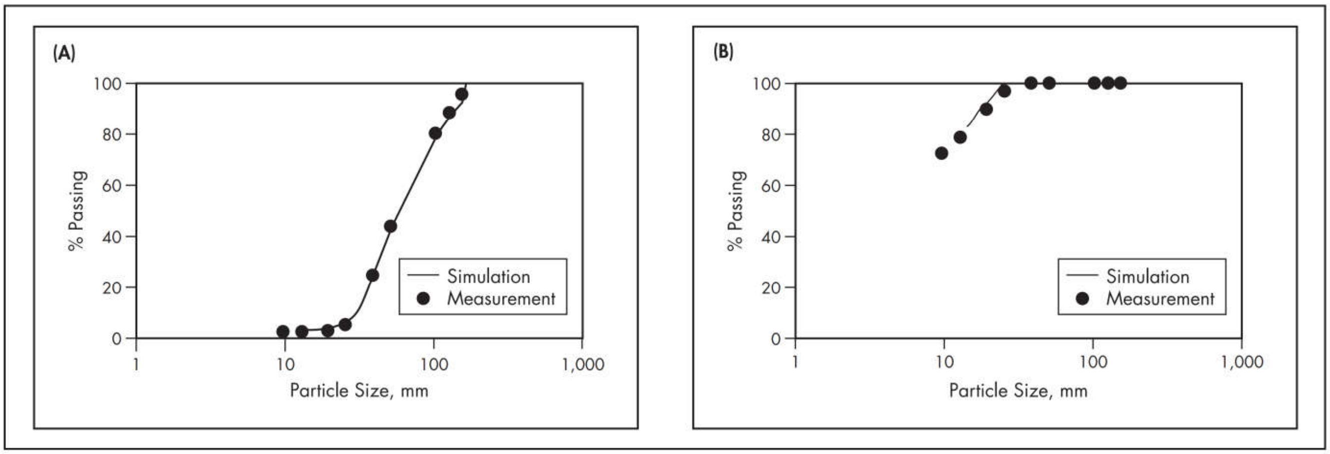
Source: Flintoff and Kuehl 2011

Figure 52 DEM visualization of screen operation

Fine Screening

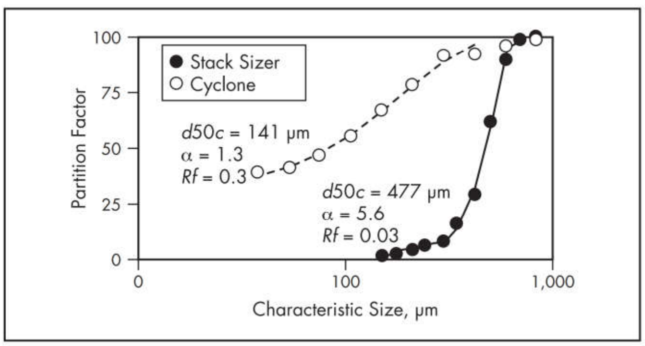
In general, wet fine particle classification is achieved by mechanical/hydraulic means (e.g., rake or spiral/screw classifiers), hydrocyclones, and fine screens. Although the mechanical devices still have their place, fine screens and especially hydrocyclones dominate fine and ultrafine classification. *Fine screening* is the term generally reserved for fine and ultrafine separations, as defined in Table 1. It is performed dry or wet, although in most mining or quarrying applications, this is a wet process, consequently the emphasis is on wet fine screening.

For the most part, the principles described previously for vibrating screens apply to most screening processes. One notable difference is that fine screening generally involves much higher rotational speeds (e.g., ~3,600 rpm) and therefore much smaller strokes. Another major difference for fine screening is that the selection of the appropriate screen is as



Source: Flintoff and Kuehl 2011

Figure 53 DEM predictions of (A) oversize and (B) undersize particle size distributions



Source: Flintoff and Kuehl 2011

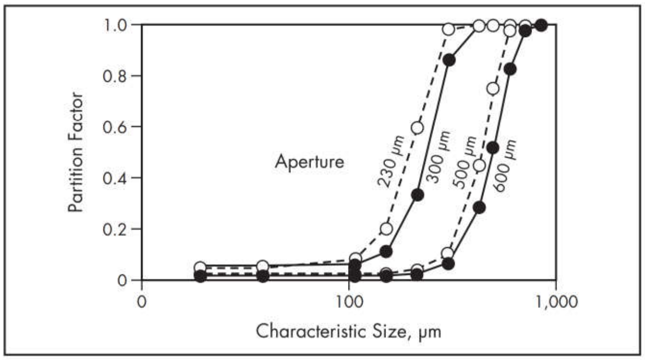
Figure 54 Partition curves for a 10-in. hydrocyclone and a Derrick Stack Sizer

much an art (i.e., past practices in similar applications) as a science (i.e., laboratory testing of specific screens on the expected feed material and supplier databases). This complexity is due in large measure to the critically important aspect of fluid mechanics, as drag forces tend to govern wet fine and ultrafine separations. Suffice it to say that the expertise in fine-screen design generally lies with the major supplier organizations, such as Derrick Corporation, Conn-Weld Industries, Kroosh Technologies, PanSep, Multotec, Wedgewire, and others.

The two most common wet fine screening devices are the sieve bend (i.e., a stationary version of the banana screen, Figure 6) and the more conventional, high-frequency fine screen (i.e., having a more conventional geometry, and represented herein by the Derrick product line, including the Stack Sizer [Figure 5], mulitfeed screen, repulp screen, etc.). Wet fine screening is essentially the only flow-sheet option in several applications, for example, coal preparation desliming, iron ore coarse silica removal. (A more complete review of this topic is available in Valine and Wennen [2002].) There are many other applications where wet screening provides an alternative to hydrocyclones or other mechanical devices, as it offers some significant advantages in classification efficiency (as measured by α or E_u). In some applications, both sieve bends and high-frequency screens are used in conjunction with hydrocyclones to exploit the physical and classification attributes for each type of separator. In other instances, it may also be possible to feed a wet screen by gravity, rather than the pumping systems more commonly associated with hydrocyclone batteries. Nevertheless, in these kinds of trade-off studies, it generally comes down to the footprint advantages of hydrocyclones versus the process efficiency advantages of wet screening. For example, one study (Vince 2007) in coal indicated that purely from a capacity perspective, two to three Derrick Stack Sizers were the equivalent of one 900-mm classifying hydrocyclone. Interestingly, that same study concluded that the Stack Sizer should be considered for coal preparation applications with cut points in the 100- to 350-µm range, while sieve bends could be considered for cut sizes in the 250- to 350-µm range. Of even greater interest was the observation that "similar" equipment made by different suppliers can have quite different performance characteristics—*caveat emptor* (buyer beware).

One area of growing interest for fine screening is to close fine-grinding (ball mill or even stirred mill) circuits (see Wennen et al. 1997). The opportunities to exploit improved efficiency to reduce specific energy and media requirements, and to improve downstream metallurgical efficiency (e.g., by minimizing overgrinding of valuable minerals) are very appealing, both technically and economically. In addition, while hydrocyclones separate based on particle mass (i.e., particle size and density are first-order effects), wet fine screens separate predominantly on size (i.e., density is a higher order effect, mainly related to particle stratification). For example, in iron-ore grinding, the cut size on a screen is the same for the iron minerals and silica, while in a hydrocyclone, the cut size for the iron minerals is about one-third of that for silica, which is to say that a lot of fine liberated iron mineral can be sent back to the grinding mill by a hydrocyclone.

Consider the partition curves shown in Figure 54. Although there are some "apples to oranges" comparisons in terms of the cut sizes, these examples are drawn from the same plant in similar applications (Acquino and Vizcarra 2007); the real interest comes from the comparison of the sharpness of separation (α) and the efficiency (here inversely related to *Rf*, as estimated from the particle size data). The benefits of wet screening are obvious, which makes it a technical option for cut sizes ranging down to 100 µm. For the hydrocyclone



Source: Flintoff and Kuehl 2011

Figure 55 Partition curves for a Derrick Stack Sizer with different screen apertures

partition curve, the inflections and rather poor sharpness of separation are a partial consequence of the existence of liberated heavy and light minerals in the feed (i.e., the particle density effect).

Finally, Figure 55 provides a glimpse of the ability of this fine screen to preserve efficiency over a range of aperture sizes, that is, sharpness of separation is good and bypass is low.

ACKNOWLEDGMENTS

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