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Best Practices for Design of Slurry Flow Distributions

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Best Practices for Design of Slurry Flow Distributions

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Abstract: A critical structure in a modern mineral process plant is the slurry distribution box that may receive inflows from different streams and distributes the outflow to downstream unit operations in fixed proportions. The design of these structures is based on traditional hydraulic engineering considerations that apply to structures transporting or handling water. However, additional design considerations specific to slurries include settling of solid particles, the highly abrasive characteristics of the slurry and, occasionally, non-Newtonian rheology of the mixtures. For operational simplicity, and due to the abrasive nature of the slurry, orifices are principally used to distribute the flow. Lessons learned over the years from operation of these structures have resulted in various best practices that are applied during design, construction and operation. These include a receiving chamber for mixing of incoming flows, internal baffles between the receiving and distribution chambers to ensure even distribution, replaceable wear rings or plates to manage wear due to abrasion, and outflow chambers hydraulically independent from upstream conditions to feed downstream processes. This paper describes a number of design criteria and design adjustments made over time to ensure robust and reliable performance of these structures across a range of flow rates and operating conditions. One key aspect discussed is the way in which the receiving chamber should be fed, based on actual feedback received from operations and depending on the metallurgical sampling system used.

Keywords: Mining, slurry, distribution, best practices, design criteria.

1. Introduction

Hydraulic structures such as pump sumps, open channels, drop/collection boxes, weirs, distribution boxes and energy dissipaters are used extensively in the mining industry for the transport, distribution and general handling of slurry flows. These slurries consist of crushed ore that is mixed with water and chemical additives to allow grinding to finer sizes and subsequent extraction of the target mineral (copper, alumina, iron, etc.) through processes such as flotation, leaching and digestion (SME 2002). Modern mineral process plants such as copper concentrators can process an excess of 150,000 tonnes per day of ore, resulting in slurry mixture flow rates of up to 7 m\textsuperscript{3}/s (and higher in facilities where recirculating loads are included).

The design of these structures is based on traditional hydraulic engineering considerations that apply to structures transporting or handling water such as those of the USFHWA (2012). However, additional design considerations specific to slurries include settling of solid particles, the highly abrasive characteristics of the slurry and, occasionally, non-Newtonian rheology of the mixtures (see Abulnaga 2002). Also, a few differences in the design approach are considered depending on how frequently the hydraulic structure is used. As an example, Table 1 shows some key characteristics of two types of slurry present in copper concentrator plants designed by Bechtel: ‘Rougher feed’ and ‘Tailings’. The former is the feed into the flotation circuit, and the latter corresponds to the waste stream downstream of the mineral extraction process (see also Figure 1 for better understanding). The tailings are sent to thickeners for the purpose of dewatering and increasing the solids concentration of (or ‘thickening’) the slurry before deposition in a final tailings storage facility.

<table>
<thead>
<tr>
<th>Type of slurry</th>
<th>Rougher feed</th>
<th>Tailings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range of Flow Rate (m\textsuperscript{3}/s)</td>
<td>2 – 7</td>
<td>2 – 7</td>
</tr>
<tr>
<td>Solids relative density (dimensionless)</td>
<td>2.6 – 2.7</td>
<td>2.6 – 2.7</td>
</tr>
<tr>
<td>Solids concentration by weight (%)</td>
<td>35</td>
<td>33</td>
</tr>
<tr>
<td>Dynamic viscosity (cP)</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Particle size d\textsubscript{50} and d\textsubscript{max} (μm)</td>
<td>75 and 600</td>
<td>105 and 600</td>
</tr>
</tbody>
</table>

In addition to the published design references such as USFHWA (2012) and Abulnaga (2002), design approaches are also based on practical experience and feedback received from operators as described further in this paper.
Within a copper concentrator plant, sometimes slurry flows need to be divided and sometimes collected. Figure 1 shows a simplified sketch with a typical copper concentrator plant process arrangement, illustrating different stages at which slurry flows are divided and collected according to practical requirements and equipment limitations.

Figure 1. Simplified sketch of slurry flow through a copper concentrator plant (flow left to right).

A critical structure in a modern mineral process plant is the slurry distribution box which may receive inflows from different streams and distributes the outflow to downstream unit operations in fixed proportions as described in Figure 1. It is critical to ensure an even distribution of slurry in terms of volumetric flow rate, mass flow rate and particle size distribution so downstream unit operations work efficiently under appropriate (design) loads.

A slurry distribution box with uneven distribution could cause significant impact both in business and environmental aspects. For instance, following the sketch in Figure 1, if the rougher feed distribution box works inefficiently so that flotation cells in row #2 receive more flow than intended, then the retention time in each cell (cell volume/flow rate) will be less than the design value, and a fraction of recoverable copper will be wasted. In other words, flotation cells in row #2 will be overloaded, resulting in loss of copper and earnings opportunity. On the other hand, flotation cells in rows #1 and #3 will have higher retention times but not enough mass flow rate to recover all the copper intended, i.e. they will be underloaded and underused, resulting in reduced capital efficiency.

Similarly, using Figure 1 as a guide, if the tailings distribution box works inefficiently so that thickener #2 receives more flow than intended, then thickeners #1 and #3 receive less flow. Thickener #2 will be overloaded, resulting in potential electrical and mechanical overload, i.e. increased wear and failure rates of some mechanisms and electrical motors. In addition, the outflowing reclaimed water from the thickener overflow will have concentration of suspended solids higher than expected which can require additional mitigation measures downstream to treat it for reuse in the process. Simultaneously, thickeners #1 and #3 will be underloaded which could result in the inability to reach the targeted tailing’s solids concentration in the thickener underflow. This is critical since the practical consequence of this is that more water than intended would discharge to the tailings storage facility and would not be totally recovered for reuse in process. Also, sometimes tailings storage facilities are not prepared for receiving tailings containing excess water. All this could bring complex and unforeseen environmental and operational challenges which would demand ‘non-productive’ attention.

2. Hydraulic Design of a Slurry Distribution Box

2.1. General Concepts

Distribution boxes are designed with a number of chambers and hydraulic controls to ensure thorough mixing of the incoming slurry streams and even distribution to each outlet of volumetric flow rate, solids concentration and particle size while maintaining stable flow conditions. Figure 2 shows a typical arrangement for a distribution box that consists of the following key elements:

1. Incoming feed, either open channel flow launder or a vertical feed pipe;
2. Receiving chamber for collecting and mixing the incoming streams;
3. Internal baffle and orifice under the baffle;
4. Distribution chamber with upward flow orifice and dart valve to allow flow shut-off;
5. Outlet chambers, prior to discharge from the distribution box;
6. Outlet pipes to downstream operation;
7. Emergency overflow chamber and outlet pipe.
Figure 2. Conceptual design of a distribution box (flow right to left). (a) & (c) Plan and elevation view, respectively: box is fed by a sloped open channel launder. (b) & (d) Plan and elevation view respectively: box is fed by a vertical pipe.

Hydraulic calculations for sizing of the elements of the distribution box are performed from downstream to upstream by verifying satisfactory operation for the maximum and minimum fluid levels in each chamber over a range of flow rates and always checking for hydraulic independence between each element.

The general design concepts of a slurry distribution box are as follows:

1. Maintain hydraulic independence between the incoming slurry feed and the hydraulics within the box to avoid generating a backwater effect and potential overflows in the upstream system. This independence is achieved by ensuring that a minimum vertical drop height is always maintained between the incoming pipe or launder and the maximum fluid level in the receiving chamber.

2. Similarly, maintain hydraulic independence between the downstream operations and the distribution box to avoid the potential of siphon action or backwater from downstream impacting the performance and flow distribution within the box.

3. Dissipate the energy of the incoming flow jets to avoid these impinging on the walls or base of the distribution box, which would lead to accelerated wear.

4. Maintain a high turbulent environment through the distribution box to ensure mixing of the slurry, even distribution of flow, momentum and solids particles, and avoid settling of solids.
Figure 3 shows extracts from a 3D model of a distributor, illustrating the size (see person for reference) and location within the process plant (elevated above the floor to allow gravity flow to downstream unit operations).

![Figure 3](image1.png)

**Figure 3.** 3D model extract of a distribution box fed by an open channel flow launder (flow right to left). (a) 3D view, showing incoming launder entering from top right of the figure. (b) Side elevation view showing dart valves and bottom outlet on left of figure.

When considering the conceptual design for controlling flow through and out of the distribution box, this can be achieved in a number of different ways: using active devices such as gates and valves or using passive devices such as weirs or orifices. Passive devices are typically preferred, where at all possible, to reduce maintenance requirements and complexity of control systems and generally provide for a more robust operation.

When deciding between weirs and orifices, a key consideration is the sensitivity of the outflow to fluctuations in fluid levels and internal pressures within the distribution box. Since flow rate through an orifice is a function of $H^{0.5}$ (where $H$ is the pressure head differential), while flow rate over a weir is a function of $H^{1.5}$, the resulting discharge curves have very different shapes. Figure 4 illustrates the difference in sensitivity in flow, $Q$ (vertical axis), to fluctuations in pressure head, $H$ (horizontal axis). For the same pressure head fluctuation, $\Delta H$, the flow fluctuation, $\Delta Q$, through an orifice is less than $\Delta Q$ over a weir. Therefore, orifices provide greater stability to the outflow, especially in the highly-turbulent environment where the hydraulic head is continuously changing over time.
2.2. Receiving Chamber

As the name implies, the receiving chamber is the first chamber in the distribution box that receives the incoming flow streams. The main objective of the receiving chamber is to ensure thorough mixing of these incoming streams to allow even distribution to each of the outlets of volumetric flow rate, solids concentration, mass flow rate, and solids particle size distribution. Design of the receiving chamber is a trade-off between being compact enough to maintain a highly-turbulent environment to avoid excessive solids settlement, to promote good mixing of incoming flows, and to avoid having bottom and walls exposed to high velocities of the incoming jets, which would result in excessive wear. Past experience has demonstrated that ‘conservative’ (i.e. larger than required) designs of receiving chambers are in fact prone to operational problems due to excessive solids deposition and uneven flow and solids distribution. Conversely, chambers that are too small, and where the incoming jet’s impact with the walls are subject to very high rates of wear, needing repair and/or replacement after a short period of time.

Although high-tech materials exist to withstand the abrasiveness of high velocity slurry flows, these are generally very expensive to install and maintain, hence the preferred method of protecting the walls and bottom of the chamber from excessive wear is to use the fluid within the chamber as a ‘cushion’ to dissipate the energy of the incoming jets.

The first aspect in sizing the receiving chamber is to establish the range of the incoming flow jets. Janssen (2013) presents an assessment of the parabolic trajectory of incoming jets from open channel launders to estimate the drop length of jets for different flow conditions and determine the location at which the incoming jets impact the fluid surface. Once the location of impact of the jets is established, the dispersion of the energy and momentum of the jet is estimated. Palavecino and Adriasola (2012) present an analysis of the design criteria used for estimating the energy dissipation within the receiving chamber. An example of typical design criteria used for sizing of the receiving chamber, based on many years of operational experience, is illustrated in Figure 5.

The shape of the receiving chamber is driven by requirements for avoiding low turbulent zones within the chamber, achieving symmetry to help ensure even flow distribution, and physical constraints within the confines of a congested process plant. A semi- or fully- circular plan shape (see Figure 2 above) is the preferred shape as it maintains symmetry towards each of the outlets. However, even with this ideal shape, operational problems can be experienced, as described in more detail in section 3.

In recent years, computation fluid dynamics (CFD) analysis of receiving chambers has been used to provide semi-quantitative design data to support the design criteria approach and help optimize the size and shape of the chamber. Design using CFD model results will be the subject of a future paper.
2.3. Flow Sampling

Continuous sampling of slurries at different stages of the overall mineral extraction process is a vital activity of plant operators for maintaining control and improving performance. The samples are needed to conduct metallurgical analyses from which the concentrations of different components can be measured several times per day. Based on the results, operators can judge whether they are operating correctly or if adjustments are required and predict production rates. Sampling typically takes place at distribution boxes as these are key collection and distribution nodes within the process network, and they are also convenient locations to install the sampling device. The arrangement for obtaining a representative composite sample of the slurry flow depends on the vendor proprietary design of the sampler (for example, see Outotec 2017 and FLSmidth 2017), and vendor selection is often dictated by owner/operator preferences. There are two main types of samplers used on distribution boxes: travelling linear samplers and static box samplers.

The travelling linear sampler is a device that is located over the rectangular launder feeding the distribution box. The green box on top of the distribution box in Figure 3(a) houses a travelling linear sampler. The primary sample is taken by a thin cutter device that travels across the whole width of the inflowing slurry jet to collect a representative sample. The inflow must be a parabolic slurry jet with a given depth, width and mean velocity, as illustrated in Figures 2(a) and 2(c), which continues to feed the receiving chamber of the distribution box without significant interference.

The static box sampler is a fixed device where the flow enters horizontally into a receiving chamber with an internal overflow weir to collect a representative primary sample across the whole cross section of the flow. By having the internal weir, the static box sampler creates a restriction to the flow, often generating a hydraulic jump in the launder upstream of the sampler. In this case, the main slurry flow stream is discharged vertically through an outlet flange located at the bottom of the sampler, connecting to a vertical pipe feeding the distribution box, similar to the arrangement shown in Figures 2(b) and 2(d).

2.4. Flow Control and Distribution

For operational simplicity, and due to the abrasive nature of the slurry, orifices are principally used as hydraulic controls to distribute the flow from the receiving chamber to the outlet chamber, avoiding the use of valves or gates to control the flow. As discussed above, orifices are preferred over weirs as the sensitivity of flow to fluctuation in pressure head is significantly less for orifice flow. Flow velocities through the orifices are typically maintained between approximately 0.5 m/s and 2.5 m/s, for minimum and maximum flow conditions. Even at these velocities, the abrasive nature of the slurry results in wear on the edges of the orifices, hence sacrificial wear rings or edging is installed within each orifice, to allow replacement at regular maintenance intervals.

Typically, two orifices are used in series for each outlet stream. The first is a rectangular orifice formed by the internal baffle, forcing the slurry flow downwards into the distribution chamber. The intention of the baffle is to
force turbulent re-circulation within the receiving chamber, encourage mixing of the slurry, and prevent preferential flow paths to any distribution chamber (see lesson learned in Section 3). The typical vertical opening of the baffle is approximately 300 to 500 mm, but this is always reviewed on a case-by-case basis.

From the distribution chamber, another typical arrangement is for the slurry to pass through an upward flow circular orifice before dropping into the outlet chamber. These orifices can be sealed closed by lowering the dart valves into the orifice seat (see Figure 2). During normal operation, these dart valves are maintained, raised above the fluid level, and typically only used in an on/off mode. This has proven to be very efficient from an operational and maintainability standpoint, limiting wear on operational parts of the box.

Hydraulic design of the upward flow distribution chamber typically involves an iterative design approach, checking a number of key criteria along with operational considerations such as:

- Maintaining a minimum upward flow velocity for transporting solids particles, allowing for hindered settling velocities of solids particles in the high-density slurry;
- Limiting the size of the orifice, and therefore, the size of the dart valve for cost and operability;
- Checking the height of the upward flow jet to avoid impinging on the fully raised dart valve and limiting the height to which this valve needs to be raised;
- Limiting the maximum flow velocity to avoid excessive wear and/or use of expensive ceramic wear rings and orifice seats.

2.5. Flow Outlet

Flow from the outlet chamber to the downstream unit operations can either be through a vertical bottom outlet, as shown in Figure 2, or through horizontal outlets. In either case, sizing of the hydraulic control is performed such that a minimum drop is always maintained from the upward flow orifice from the distribution chamber to the maximum level in the outlet chamber. The outlet pipes, whether vertical or horizontal, are typically vented to avoid surging flow conditions due to air entrainment.

2.6. Overflow Chambers

Distribution boxes include overflow chambers to convey any emergence overflows to a collection sump in a controlled manner for both safety and operations considerations. Due to the occasional use of the overflow chambers and to reduce cost by developing a more 'fit-for-purpose' design, these are typically designed to less stringent criteria than the main chambers in the distribution box, such as:

- Use bare steel instead of rubber or ceramic lining;
- Smaller overflow chamber with incoming flow allowed to impact the base or the walls of the overflow chamber.

3. Feedback Received from Actual Operations

Some actual mining operations have had practical problems with slurry distributions boxes, from which the authors have received feedback (José Adriasola, confidential project and customer communications, 2016 / 2017). Three case studies are presented as examples of relevant feedback and improvements to the existing design practices.

3.1. Distribution Box Feeding Copper Slurry to Parallel Rougher Flotation Cells

The general arrangement of this case study is similar to the one shown in Figures 2(a) and 2(c), with a total of 7 independent outlet chambers, each one fed by a single 36-inch circular opening (dart valve seat). Each outlet chamber is intended to feed one row of rougher flotation cells. The distribution box is fed by a sloped rectangular open-channel launder with a total flow rate varying from 4.2 to 6.5 m³/s.

Typically, flow rates at distribution box outlets are not directly measured. However, there is an indirect way to infer the flow rate through the results obtained in metallurgical samples downstream in each row of flotation cells. In this case study, when the plant started operations, the 7 rows of rougher flotation cells consistently showed uneven copper recovery. The 3 central rows of cells – fed by the 3 central outlet chambers of the distribution box – achieved the expected copper recovery rate while the other 4 (2 at one extreme of the semicircle and 2 at the opposite extreme) achieved low recovery rates. After discarding other potential causes, it was inferred that the distribution box was not working correctly and it was overloading the 3 central rows of flotation cells. From an
indirect estimation of slurry flow rate, it was determined that the 3 central outlets discharged between 15 and 25% more flow per outlet than the other 4 lateral outlets.

This was important feedback because it demonstrated that the baffle provided in the original design was not sufficiently effective to ensure the desired even flow distribution. Conceptually speaking, the horizontal slurry jet feeding the distribution box has a preferential momentum in the direction of the flow towards the 3 central outlets, as shown in Figure 6(a). The intermediate baffle was included to counteract the preferential momentum and maintain the turbulence confined within the receiving chamber, but the facts demonstrated that this was not effective.

To fix the problem, two alternatives were analyzed. In this case, there were no constraints related with the sampling system, so the best alternative from a technical standpoint was switching to a different feeding arrangement with a vertical feed pipe instead of the sloped launder. This was intended to improve the momentum distribution, as shown in Figure 6(b). Unfortunately, since operations could not stop for a sufficiently long time to allow the implementation of this new feeding arrangement, this alternative was discarded.

The other alternative, which was eventually implemented, considered that the 3 central 36-inch circular openings were replaced by 32-inch openings to reduce the discharge capacity of these outlets by approximately 20% to counteract the observed difference in flow. In addition, the dart valves corresponding to these new 32-inch openings were modified to include a flow modulating capacity (atypical) in contrast to the original concept that was only on/off operation. The remaining 4 outlets with 36-inch openings were left the same, operating only on/off. The implementation time was significantly shorter and affordable for operations, and the results were satisfactory.

3.2. Distribution Box Feeding Copper Tailings to Parallel Screening Systems

In this case study, thickened tailings—with approximately 55% solids concentration by weight—were being utilized as a source of coarse sand particles for the continuous wall raising of the earth dam confining the tailings storage facility. These thickened tailings were conveyed several kilometers in a concrete launder to a segregation plant near the dam. The total flow was approximately 3.2 m³/s. A slurry distribution box was built to split the total flow in 10 outlets, each of them feeding one screening system.

The first problem with this distribution box was that the size of the receiving chamber was too big and the drainage outlet was too small. Therefore, solid settlement occurred whenever the distribution box was stopped for a short time during commissioning and start-up operations because the time required to drain the box was too long. This problem was fixed by installing a larger bottom drain outlet pipe, thereby significantly reducing the time to drain the box and controlling the solids settlement. Although a basic calculation, a check of the drain time for all chambers was implemented for future designs along with more detailed assessment of commissioning conditions.

Figure 6. Conceptual analysis of slurry flow momentum (flow right to left). (a) Box is fed by a sloped launder. (b) Box is fed by a vertical pipe.
The second problem was that operations personnel had installed a fixed screen to retain large solid particles which were occasionally transported by the tailings flow along the concrete launder. The fixed screen was useful to capture these large solid particles, but it was observed that this screen was dissipating the flow energy that should have reached the receiving chamber to maintain a turbulent environment and promote suspension of solid particles. After evaluation, the fixed screen for capturing large solid particles was removed. This is a good example to learn that resolving a single problem without having a more general vision could lead to worse situations.

3.3. Distribution Box Feeding Copper Tailings to Parallel Tailings Thickeners

In this case study, the focus was on the upward slurry flow through dart valve openings impacting the bottom of the dart valves when they were open, producing vibration and accelerated wear of the rubber plugs. It was evident that the vertical run of the dart valves (from close position to open position) was insufficient.

The lesson learned was to consider the energy of the upward flow through the dart valve seat so the minimum vertical run of the dart valves could be determined (see Figure 7). For this purpose, a conservative calculation is made, considering that a dart valve seat behaves like square-edge circular orifices with a coefficient of contraction equal to 0.61, i.e. fully contracted flow is assumed. The kinetic energy of the upward flow, \( V^2/2g \), is then calculated at the ‘vena contracta,’ located at D/2 downstream of (above) the dart valve seat where the flow lines are parallel. A design margin, \( \delta \), can also be added if required. In general terms, the magnitude of this design margin can be considered to be between 100 and 300 millimeters; however, it will depend on the specific case. Eq. (1) shows the simple formula currently used for this purpose.

\[
Minimum \, vertical \, run = D + \frac{V^2}{2g} + \delta \quad \text{with} \quad V = \frac{q}{0.61\left(\frac{D^2}{4}\right)}
\]

where \( D \) is the internal diameter of the dart valve opening, \( V \) is the mean flow velocity at the ‘vena contracta,’ \( g \) is the acceleration due to gravity, \( \delta \) is the design margin, and \( q \) is the volumetric flow rate through the dart valve opening.

![Figure 7. Dart valve minimum vertical run to avoid upward flow impact (flow right to left).](image)
4. Conclusions

The case studies all illustrate the importance of attention to seemingly small details in the design often addressed with fundamental hydraulic engineering approaches but still requiring careful thought and application. In light of the experiences described in this paper, a number of best practices for designing slurry distribution boxes are recommended.

- Always check what type of slurry sampling system is preferred by the owner. This will determine important layout decisions amongst which the slurry feed arrangement is included. As discussed in this paper, the slurry feed arrangement is fundamental for the hydraulic design of a distribution box, especially because of the distribution of the flow momentum.

- A slurry feed arrangement considering a vertical pipe feeding the receiving chamber is preferred, whenever this is possible, as long as the sampling method permits this.

- The importance of conducting a thorough hazard and operability assessment of any design decisions or changes, considering the holistic operation of the structure in question and not only solving the immediate problems.

- The use of passive flow distribution methods (fixed diameter orifice) is preferred in slurry applications for operational simplicity and robustness. Methods for easily changing the orifice diameter, by inserting different sizes of wear rings and dart valves, provide a degree of flexibility that allows operators to make adjustments to distribution after operation starts.

- The use of CFD models is suggested to better understand the complex fluid dynamics within a slurry distribution box. Nowadays, CFD models can be of much help to understand the turbulence distribution within the receiving chamber to localize potential dead zones in which solids can settle more easily, to identify potential areas subjected to high abrasive action of the slurry, and to ensure an even distribution in terms of mass flow and particle size distribution.

5. References


