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A Hydrodynamic Approach for Sizing and Selection of Hydrocyclone—Parametric Scaling and Process Optimization

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ABSTRACT

A hydrocyclone is a piece of equipment commonly used as a classifier in mill circuit operations. Traditionally, hydrocyclone performance is characterized by the classification efficiency parameter, such as cut size (d50c), sharpness of separation (α) and bypass (Rf). A plethora of endeavors have already been made to develop parametric models to determine hydrocyclone performance that correlate design and process variables. In contrast to those studies, we made an attempt to develop an approach to derive required design parameters purely from hydrodynamic principles that provides a platform to optimize the operation of a hydrocyclone for a given application. In this selection methodology, we calculated the differential pressure at the air core, as well as the tangential velocity at the boundary of the air core from the vortex principle in a confined geometry at different operating regimes. A series of experiments were conducted using Weir's Cavex® hydrocylone where process variables—such as solids concentration and feed flowrates—were experimentally studied to determine the key classification parameters. For the validation of the current approach we used the same process variables to derive design parameters and compared them with the existing design. The current approach can provide insights towards the selection of design parameters and can be useful for mining industry professionals to optimize different operating parameters of hydrocyclones to achieve the best performance.

INTRODUCTION

The hydrocyclone separator is a popular unit operating in industrial processing; it utilizes the incipient centrifugal forces in the rotating fluid domain to separate suspended particles. The solid- fluid mixture is introduced through the inlet at high pressure that generates a swirling motion inside the cyclone. Research towards understanding the inherent flow behaviours of the fluid and the particles inside the hydrocyclone have gained popularity amongst the numerical and experimental fluid mechanics communities [1–5].

However, industrial friendly mathematical models are yet to be developed based on the existing research. Since the physics of particle and fluid flow behaviour inside a hydrocyclone is still a complex aspect to realize, the empirical models are normally used for evaluation of its performance. Two frequently used models for predicting industrial hydrocyclone performance are Plitt's model

[6] and Nageswararao's model [7]. Moreover, as the models are empirical, the coefficients against each variable have to be determined experimentally when either the material to be processed or the basic design of hydrocyclone are changed even marginally. As this is impractical in many

situations, the performance of industrial scale hydrocyclones is mostly compromised [8–9] .

An attempt has, therefore, been made in this article to demonstrate the theoretical approach to solve the Rankine vortex equation to quantify the flow and pressure variations. A series of experiments were conducted using Weir's Cavex® hydrocyclone where process variables, such as solids concentration and feed flowrate, are experimentally studied to determine the key classification parameters. From the present theoretical paradigm, we estimate the centrifugal force intensity (*u2/Rg*) and correlate it with performance parameters, like split factor and separation cut size (d_{50c}). For validation of the current approach, we used the same process variables to derive the design parameter and compared this parameter with the existing design. The current approach can provide good insights towards the selection of the design parameters and can be useful for an industrial professional to optimize the different operating parameters of the hydrocyclone to achieve the best performance.

MATERIALS AND METHOD

The tests were conducted on a pilot scale, feeding the Cavex® hydrocyclone with silica sand with solids density of 2.65 t/m^3. The details of hydrocyclone geometry used for pilot scale testing are shown in Table 1. Figure 1 shows the particle size distribution of the silica sand sample with an F80 of 60 microns on average. The pilot scale test setup consisted of a pump-sump assembly in a closed loop circuit attached with a Cavex® 100CVX hydrocyclone. The required pressure to obtain a good performance in the hydrocyclones depends upon the cyclone size and of the process conditions. The testing was performed at three pressure levels (68.9 kPa, 103.4 kPa and 137.9 kPa). A variable frequency drive (VFD) was connected with the slurry pump, allowing for the maintenance of the target operating pressure and flowrate. For each operating condition, samples of hydrocyclone feed, overflow and underflow were obtained during the testing. The samples were analyzed for solids concentration and particle size distribution. Mass flow of solids and water at the feed was back calculated from the measured mass of overflow and underflow samples.

THEORETICAL MODELING

In-depth review of the inherent flow field inside a hydrocyclone reveals the existence of a force- vortex flow near the central region and free-vortex flow otherwise [10–11]. The swirling flow in a hydrocyclone creates an air core along the axis, normally connected to the atmosphere

Table 1. Cavex® hydrocyclone geometry used for pilot scale testing

Parameter	Dimension
Hydrocyclone diameter (mm)	100
Inlet diameter (mm)	40
Vortex finder diameter (mm)	35
Spigot diameter (mm)	17.5
Cone angle	6°

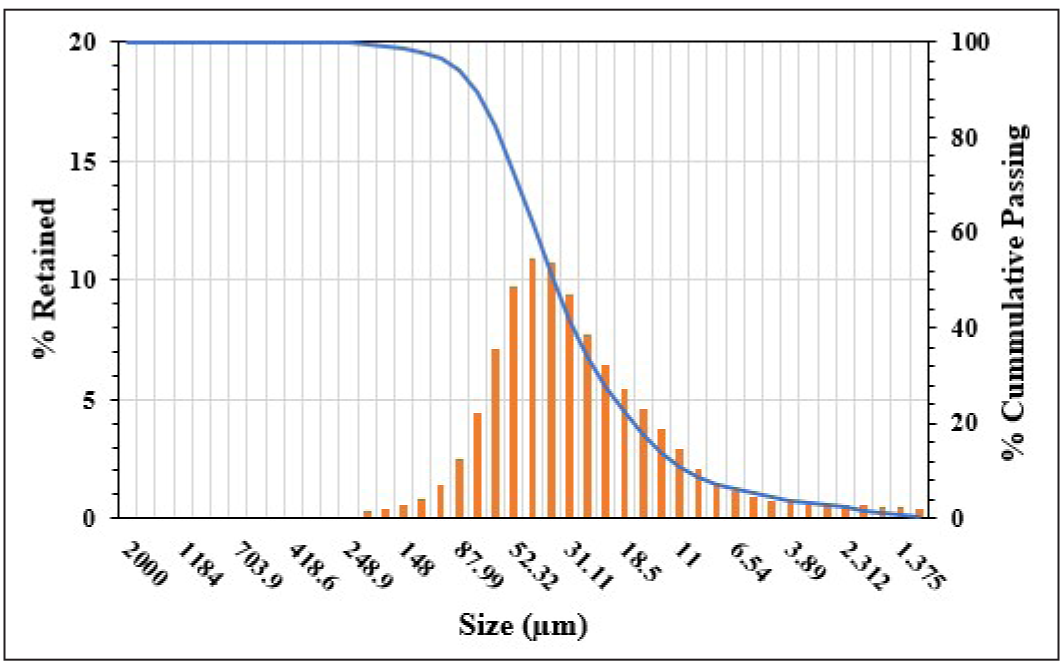

Figure 1. Feed size distribution for silica sand sample

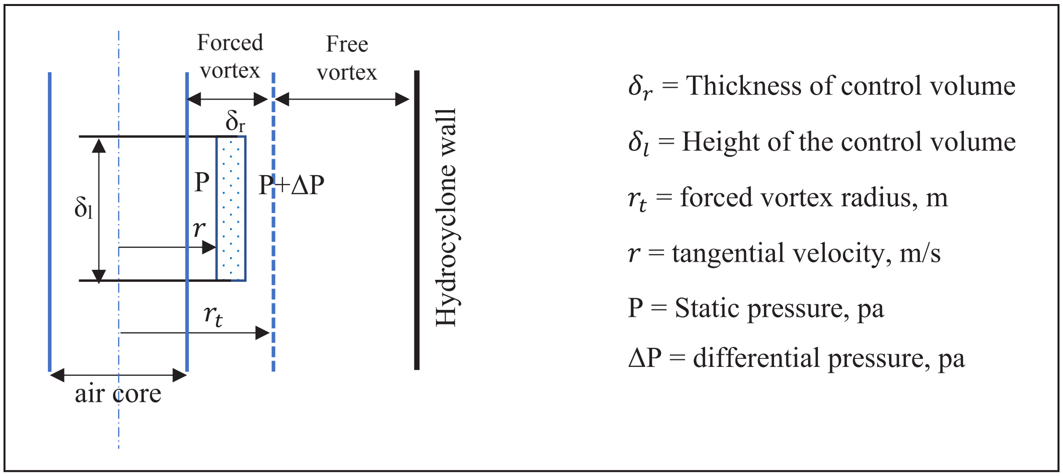

Figure 2. Schematic diagram of pressure variation in composite vortex flow

through the spigot opening. Previous researchers showed that the axial position of the air core diameter depends on the fluctuating operating conditions at the inlet [12]. The major driving force for the separation of solid particles in a hydrocyclone is the centrifugal force generated by the rotational flow of slurry. Centrifugal force generated by the incipient swirling motion drives the coarser particles to the vortex free zone and are collected through the underflow. The forced vortex zone at the vicinity of the air core transports the finer particles upward and they are collected through the overflow. In this paper, low pressure required to achieve the classification of the particles for a particular d50 size in the hydrocyclone and other operational and geometrical parameters associated with the throughput to be processed are calculated. Below is the schematic diagram of the hydrodynamic representation for the pressure distribution considering the composite vortex flow inside the hydrocyclone.

The differential pressure should be such that it should generate potential thrust to carry the particles and fluid along the forced vortex to the overflow of the hydrocyclone [13]. Modelling the vortex equation:

$$P\delta A - \left(P + \frac{dp}{dr}\right)\delta A = \delta mg \tag{1}$$

As density is an explicit parameter assuming the change is linear, density variation in the hydrocyclone can be given by:

$$\rho = \rho_a + \left(\frac{\rho_s - \rho_a}{r_s}\right) \tag{2}$$

Solving and integrating equation 1 and re-arranging the terms we get:

$$-(P_1 - P_2) = \left[\frac{\rho_s - \rho_a}{r_s}\int r\,dr + \int d\rho\, dr\right]\frac{\delta_l}{r_s}g \tag{3}$$

$$-(P_1 - P_2) = \delta_l g\left(\frac{\rho_s + \rho_a}{2}\right) \tag{4}$$

Minimum required tangential velocity of the slurry at the air core boundary is given by:

$$u_\theta = \sqrt{\frac{2(P_1 - P_2)}{\rho_m}} \tag{5}$$

P1—P2 is the differential pressure

Hydrocyclone inlet feed velocity is always at higher pressure, hence the entry flow velocity:

$$v_{in} = \sqrt{u_\theta^2 - \frac{2P_{in}}{\rho_m}} \tag{6}$$

The feed inlet diameter can be calculated through a continuity equation at a defined throughput (Q), neglecting friction losses at the inlet diameter:

$$d_{cy} = \sqrt{\frac{Q}{\pi v_{in}}} \tag{7}$$

The vortex finder diameter can be calculated through the hydrocyclone diameter, minimum thickness and d_{cy} from Equation 7.

The dynamic behavior of the slurry boundary and air interaction, relating surface tension of liquid in the slurry to the strain rate of the liquid, leads to the potential thrust that drives the slurry flow to the overflow of the hydrocyclone. Considering the air impingement on the slurry boundary and attributing the dynamic interaction with Griffith and Rabinowicz's equation [14] on liquid impingement, it is possible to calculate the overflow slurry flow rate through slurry diffusion in the air core. Salama and Venkatesh [15] used this equation to calculate liquid impingement erosive wear in oil well applications.

$$h = \frac{Kq\rho_a v_{in}^2}{2pg}\left(\frac{2\rho_a v_{in}^2}{27gp\epsilon_c^2}\right) \quad (8)$$

Thus, using the above set of equations and adjusting them for a hydrocyclone operation, the base design of a hydrocyclone can be obtained and optimized through fine tuning of the critical parameters.

RESULTS AND DISCUSSION

This pressure difference is essentially symbolized by the energy loss when the fluid rotates under the action of high turbulence force field. Since the inner vortex, mainly occupied by the air core, behaves like a solid body, the transport of water and slurry through the overflow stream is mainly controlled by the induced shear created by the inner vortex. In connection to the above theoretical interpretation on the Rankine vortex flow, one can appreciate a radial pressure drop essentially takes place both in the cylindrical section and the conical section, as well due to the prevailing swirling flow. Figure 4 represents the radial distribution of static pressure obtained through the theoretical analysis. With increasing inlet pressure (or flow rate), the separation efficiency increases, which is possibly due to the increase in centrifugal force that causes an inflation of static pressure drop. Figure 5 presents the radial distribution of the tangential velocity profile inside the hydrocyclone. Specifically, near the central region (the region close to r =0), a high magnitude of u_θ signifies the presence of a strong forced vortex zone. Subsequently, the magnitude of u_θ reduces to very low value towards the wall. This feature is similar to a free vortex zone.

The magnitude of centrifugal intensity, Γ (defined as u^2/Rg) is very sensitive to the pressure drop between the free and forced vortex regions. It is imperative to note that the increase in Γ_c results in an increase in the magnitude of Γ_{max} (defined as $u^2/R_m g$). The magnitude of Γ_{max} decides whether a particle will move towards the wall or not and thereby creates a graded distribution of particles inside the hydrocyclone. The variation of the cut size and split factor with Γ_{max} is depicted in Figure 6 which shows an inverse power relationship between the Γ_{max} and the cut size and the split ratio. Figure 6(a) explains the enhancement in Γ_{max} leads to a finer cut size. Thus, to achieve a finer cut size for a given diameter hydrocyclone we have to select the design or operating parameters, which can increase the magnitude of Γ_{max}. The variation of centrifugal intensity has a strong influence on the swirl flow transition from the forced to the free vortex zones, which causes an induced drag to drive the slurry through the periphery of the inner vortex to the overflow outlet. Increase in the magnitude of Γ_{max} is, therefore, increasing the overflow slurry flowrate and thereby causing a decrease in the split ratio (defined as underflow slurry flowrate with respect to feed flowrate) as shown in Figure 6(b).

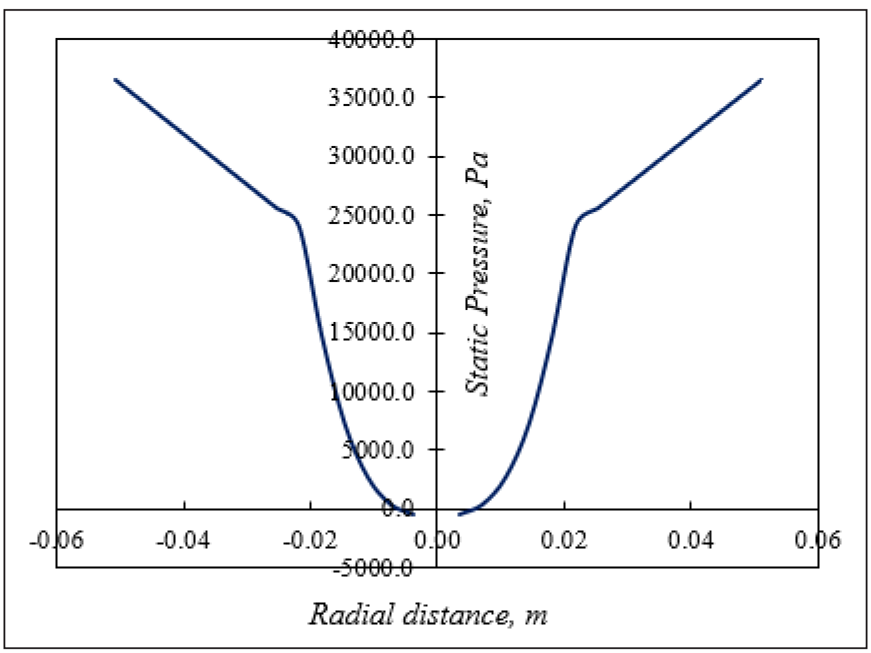

Figure 4: Calculated pressure profile in the hydrocyclone

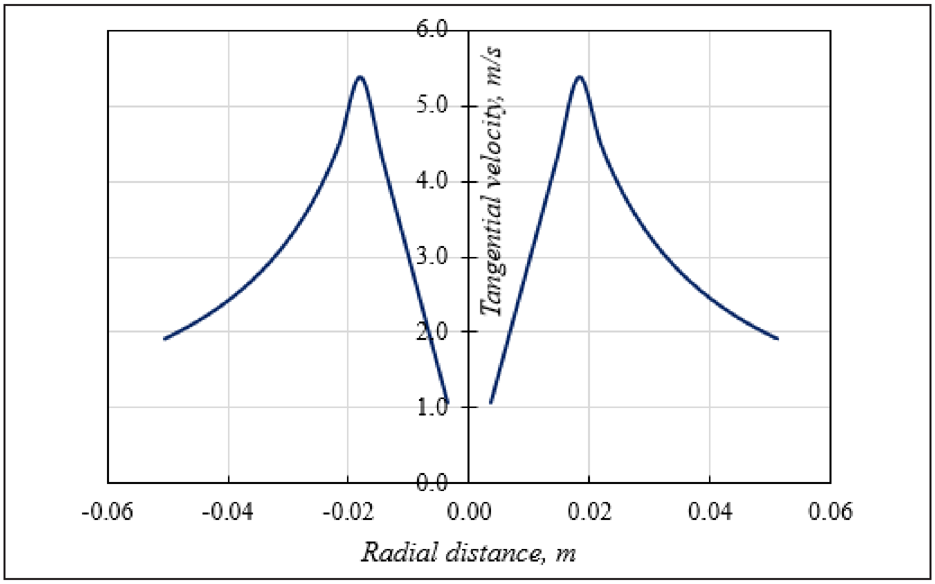

Figure 5. Calculated tangential velocity profile

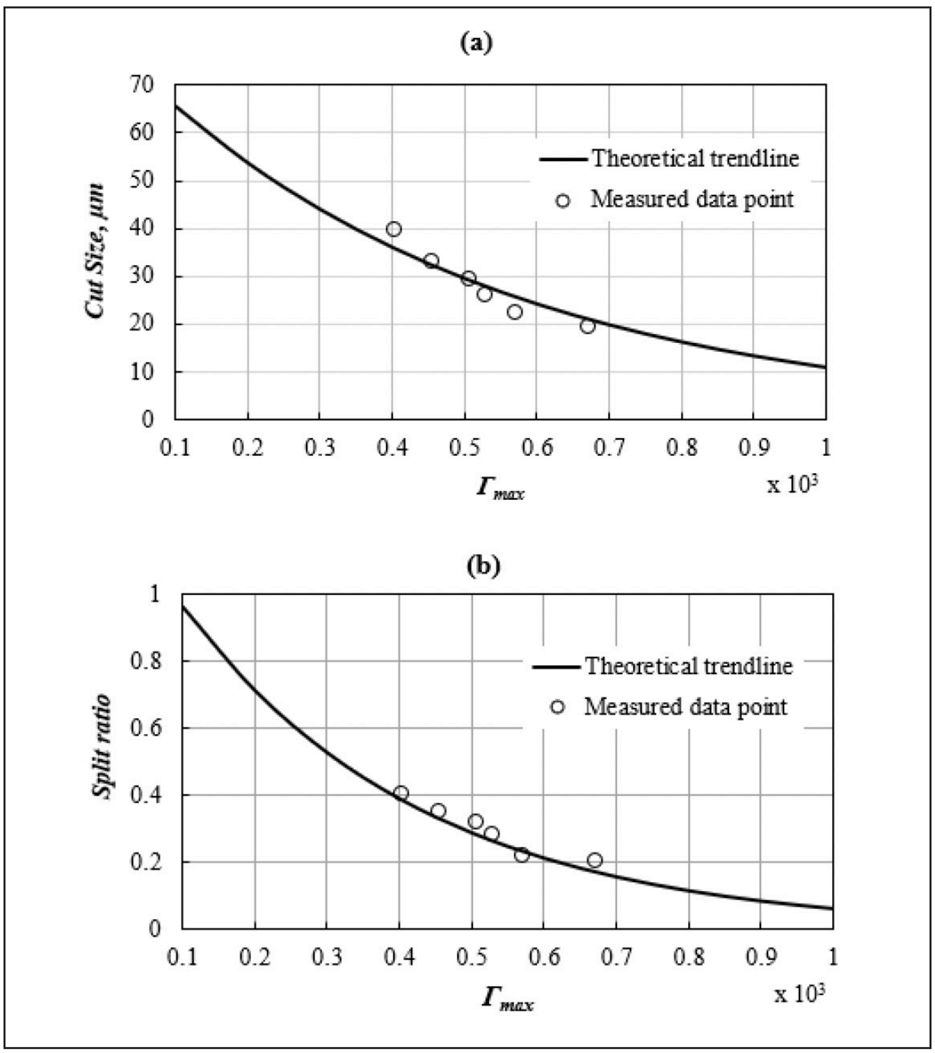

Figure 6. Effect of Γ_{max} on (a) cut size and (b) split ratio

Table 2. Comparison between the actual dimensions and predicted values

Design Parameters	Actual Dimension	Calculated	Error %
Cyclone diameter, mm	100	100	
Feed inlet diameter, mm	38.5	34	11.7 %
Vortex finder Diameter, mm	35	37.5	7.1 %
Spigot Diameter, mm	17.5	16	8.6 %

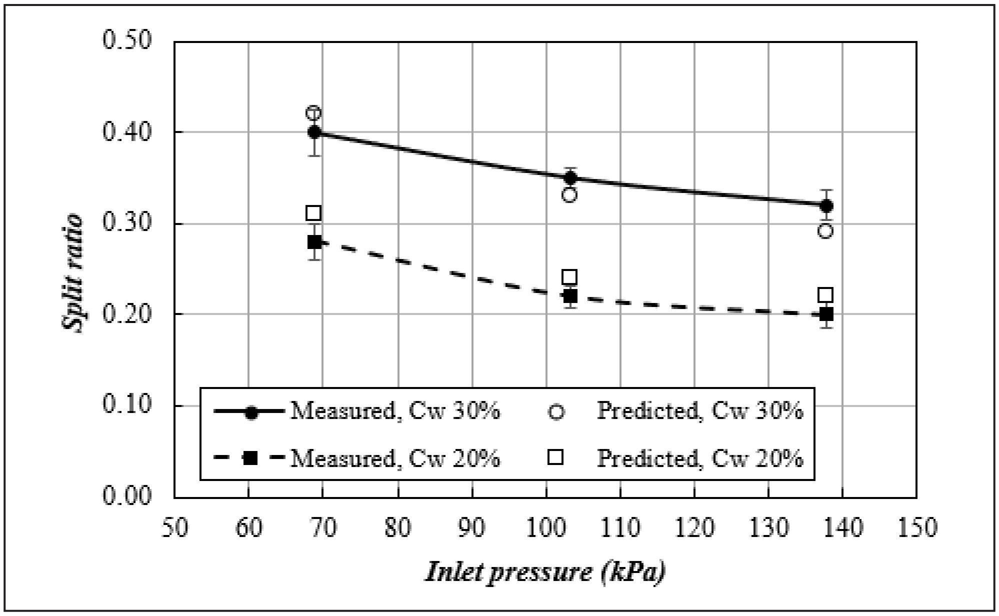

Figure 7. Comparison between experimental and predicted water split at different pressure and feed solids concentration

VALIDATION

The present theoretical approach is applied for the Cavex® hydrocyclone to compare the design parameters, as shown in the Table 2. It is observed that the predicted dimensions obtained from the theoretical calculations show a good agreement with the actual dimensions of the vortex finder spigot, inlet diameter and hydroyclone diameter.

Additionally, we used the present theoretical approach to determine the split ratio at different feed pressure and solids concentration. The comparative plot between experimental data and the predicted values is shown in Figure 7. From the plot it can be observed that the prediction provides a close agreement (error < 10%) against the observed trend of experimental measurements.

CONCLUSION

Based on the above results, the hydrodynamic approach to arrive at hydrocyclone dimensional parameters appears to be a promising methodology. The key factor that drives the hydrocyclone performance is the pressure at the center. From the study it is observed that the flow entry velocity is a determining factor to achieve the required pressure that develops the air flow field along the length of the hydrocyclone. The higher the inlet feed pressure, the higher the tangential velocity that develops a robust air flow field at the center of the hydrocyclone. Having said that, the change in the hydrocyclone spigot and vortex finder diameter greatly affects the performance of the hydrocyclone. The approach outlined in this paper provides key insights on the required dimensions of the vortex finder, spigot and hydrocyclone height to be maintained for specific requirements with regard to throughput, solids concentration and cut size.

Further development of the methodology is required to derive the radial density distribution, as well as across the hydrocyclone height, and perform design analysis for various operating parameters. The methodology is scalable to be confirmed with testing of various hydrocyclone sizes to ensure the theoretical output aligns with the test results. Future work involves developing a tool that provides reasonable partition curve information for process conditions along with key hydrocyclone dimensions.

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Downstream Improvements on Upstream Dams: An Owner's Perspective of a Paradigm Shift

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ABSTRACT

Mining companies have sharpened their refocus on their tailings management strategies in recent years. Mining companies with tailings storage facilities that use the upstream construction method have been challenged to track the evolution of industry standards, assess risks, revise design, and communicate design revisions with regulators. While many aspects of best practices and industry standards have evolved in recent years as an attribute of continual improvement, the controlling standard in the design of many upstream dams is understanding the foundational strengths of hydraulically deposited tailings. Following best practices and industry standards, Hibbing Taconite Company managed by Cleveland-Cliffs, began the re-evaluation of foundation strengths underlying a system of upstream dams at the company's iron ore mine tailings storage facility in northern Minnesota. Initial steps in the re-evaluation require reanalysis of design parameters and recommendations by the Engineer of Record to the Owner, which was followed by a series of meetings with the Technical Review Board to determine an initial path forward. Once a path forward and preliminary design parameters were determined, the Owner engaged with the State Dam Safety Engineer to discuss and seek approval of the plan. With continuous regulatory engagement throughout the process, further refinement of the design parameters for the hydraulically-placed tailings foundations underlying upstream dams began with field and lab geotechnical investigations. Following a review of risk assessments and trigger actions response plans, Hibbing Taconite revised its tailings storage facility operating plans and budget for the coming years. Based on the findings of the re-evaluation, reanalysis, and refinement of parameters, a paradigm shift was realized with the hydraulically placed tailings foundation strengths underlying the upstream system of dams. This paper explores the path that the Hibbing Taconite Company followed to understand the paradigm shift and construct downstream improvements. The plan involved tailings re-characterization, dam design revisions, operating plan reconciliation, budget revisions, wetland permitting, dam safety permit amendments, storm water prevention plans, borrow materials studies, new concrete decant structures and the pursuit to recognize and be consistent with industry standards.

INTRODUCTION

Cleveland-Cliffs, Inc. is the largest flat-rolled steel producer in North America. Founded in 1847 as an iron mine operator, Cleveland-Cliffs, Inc. also is the largest producer of iron ore pellets in North America. The Company is vertically integrated from raw materials from its Minnesota and Michigan mines, direct reduced iron, and ferrous scrap to primary steelmaking and downstream finishing, stamping, tooling, and tubing. Cleveland Cliffs, Inc. is the largest supplier of steel to the automotive industry in North America and serves a diverse range of markets due to its comprehensive offering of steel products. Cleveland Cliffs, Inc. is headquartered in Cleveland, Ohio with mining, steel and downstream manufacturing operations located across the United States and in Canada (Cleveland-Cliffs, Inc. 2023a). Cleveland-Cliffs, Inc. has a long history of safely operating tailings storage facilities and in 2022, was awarded the Midwest Regional Award in, and presented by the Association of State Dam Safety Officials. Cleveland-Cliffs, Inc. operates five tailings storage facilities, and has implemented proactive and conservative steps have been implemented to ensure the safety of these dams against potential failures. Through regular and rigorous review of the facilities, Cleveland-Cliffs, Inc. updated emergency action plans, reinforced thousands of feet of dam embankment and modified operations to reduce safety risks. Cliffs developed positive working relationships with state dam