DEPOSITION METHODS FOR CONSTRUCTION OF HYDRAULIC FILL TAILINGS DAMS

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INTRODUCTION

For large scale mining operations the most cost effective method of tailings dam construction is to utilize tailings for hydraulic fill construction. A wide range of deposition methods and dam construction techniques are available. The methods chosen are often related to the scale of the project. Larger operations with higher dams will usually require more sophisticated methods than smaller operations with lower dams. Also construction methods are chosen to suit the preference of the operators and deposition methods will generally evolve as operators gain experience.

This paper reviews the common methods of deposition for hydraulic fill construction of tailings dams, which are:

1) spigotting;

2) cycloning with direct deposition of underflow; and

3) cell construction.

In all cases the methods refer to deposition to a beach above water. Underwater deposition does not result in adequate densities for hydraulic fill construction except for structures with very flat slopes.

The deposition method used also depends on the tailings dam design. The most common typical dam designs, which will be related in the following sections to deposition methods, are upstream, downstream and centreline construction. In practice, most hydraulic fill tailings dams are hybrids of these basic designs.

SPIGOTTING

Spigotting is the technique of discharging tailings from a number of points along a tailings header line to achieve a more or less uniform flow of tailings. Spigotting is used to construct tailings beaches for all types of tailings dams but is most commonly used to construct upstream tailings dams. An advantage over single point discharge is that tailings lines do not have to be moved as often to build the beach. When dusting of beaches is a problem, since it is more easily controlled by spigotting with regular rotation because of discharge points. Spigotting cannot normally be carried out in cold weather because of freezing of tailings on the beaches. Mines in northern Canada which employ spigotting in the summer usually switch to single point discharge in the cold winter months.

In the case of upstream tailings dams, the spigotted beach itself constitutes the dam. In the case of centreline and downstream tailings dams, the spigotted beach may perform a variety of functions including support for the main structural section of the dam and/or reduction in seepage by creation of a long seepage path from the pond. Some upstream tailings dams have failed under earthquake loading and thus are used less frequently for new mines in seismic areas. However, if proper engineering design is carried out, upstream tailings dams can be used in seismic areas. The embankment slope must be relatively flat and must be completely drained by an underdrain that can be relied upon.

Knight and Haile (1983) refer to spigotted beach deposition as subaerial deposition. We do not favour the use of this term. We consider subaerial deposition to be a term used to describe a particular philosophy of tailings deposition (Lighthall, 1987) that is inappropriate for application in most parts of Canada and the United States.

Spigots are small pipes coming off a main tailings line at regular intervals. Spigot intervals must be close enough so that fines do not collect between the spigot points. Spigots are usually positioned at or below the centre point of the header line. The variation of solids concentration in the spigot discharge depends on the header tailings velocity, the initial solids concentration and the position of the spigot point on the header line. The portion of the flow that is not taken by the spigots is usually free discharged out the end of the main line. The end discharge usually has a lower solids concentration because the coarser tailings tend to come out the spigot points. The spacing and diameter of spigot points for some tailings dams are given in Table 1.

Table 1: Typical Dimensions and Spacing of Spigot Pipes

Mine	Ore Type	Header Pipe Diameter (mm)	Spigot Diameter (mm)	Spigot Spacing (m)
Mount Wright	Iron	610 - 24	24	15
Syncrude	Oilsands	610	150	24.4
Bingham Canyon	Copper	610	24	6
Endako	Molybdenum	686 - 762	100	9.8-12.2
Highmont	Copper/Molybdenum	762	150	61
Equity	Silver	450	100	50

In upstream dam construction, the spigot points are raised usually by one of two methods, termed "spigotting down" or "spigotting up" as shown on Figure 1. Spigotting down is employed at the Quebec Cartier Mount Wright and Kennecott Bingham Canyon mines. In these types of operation the tailings header line sits on a berm of coarse tailings, waste rock fill or borrow fill constructed with conventional earthmoving equipment. In some instances the berm is compacted to give better trafficability. The spigots discharge over the upstream crest of the berm until the tailings level reaches the berm crest. A new berm is then constructed on the tailings beach and the header line is moved on to this new berm.

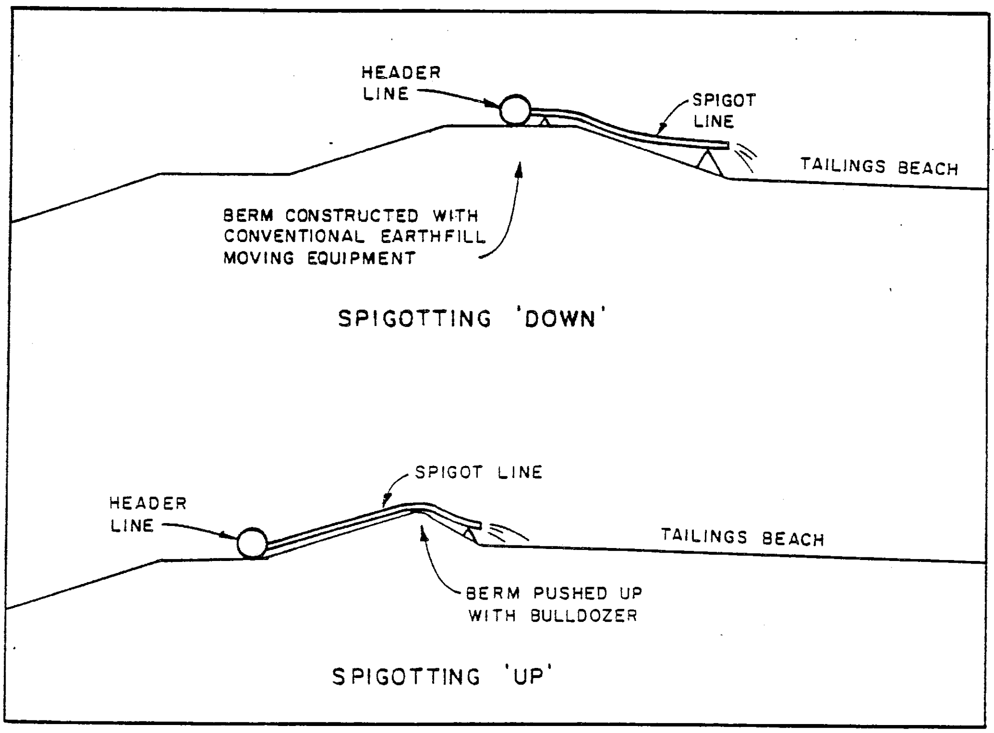

Figure 1: Typical Spigotting Configurations

In the spigotting up procedure employed at the Endako Mine, the tailings header line sits at the downstream toe of a berm pushed up by a bulldozer. A flexible spigot line attached to the spigot point is laid up and over the berm. Tailings are discharged until the level reaches the top of the berm and a new berm is constructed. The advantages of the spigotting up over the spigotting down procedure is that the header line is moved less often and the berm is cheaper to construct. A disadvantage is that to drain the header line tailings must be released on the downstream slope.

The characteristics of a tailings beach deposit depends upon a number of interrelated factors. The slope of tailings beaches is usually concave, steeper near the discharge and flattening towards the pond. Empirical relationships such as those given by Blight (1988) are used to predict tailings beach profiles for planning tailings impoundment layouts. The beach profile depends on the tailings feed gradation and the solids concentration. In general, finer tailings and lower solids concentrations produce flatter beaches.

It is generally observed that the coarsest tailings particles settle first on the beach and fines are transported the greatest distance. This segregation process is anything but uniform and depends on the tailings gradation and the solids concentration. Finer tailings that have only a small percentage of sand in their top end may show little uniform sorting. In these cases the beach is characterized by its nonhomogeneity rather than by some uniform change in grain size. Blight (1988) postulates that if there is an overall reduction in grain size from the spigot point the permeability of the tailings decreases from the spigot point. This depresses the phreatic surface from the isotropic case and reduces the wetted surface of the downstream slope. Where there is not a uniform variation in permeability, the seepage regime in the tailings may be characterized by a series of perched water tables.

The density of deposited tailings is highly variable. It depends on tailings gradation, solids concentration and the seepage conditions on the beach at the time of deposition. Tailings deposited on the upper part of the beach where there is a downward seepage gradient will have a higher density than tailings deposited near the pond where there is little downward seepage flow. Tailings deposited in the pond generally have the lowest density in the impoundment. As an example tailings deposited on the beach (referred to as beach above water) at the Syncrude Mildred Lake tailings impoundment have a mean relative density of 55% while the tailings deposited in the pond (referred to as beach below water) have mean relative densities of 30%.

Table 2 summarizes typical data from a few spigotting operations in British Columbia. These operations are the Highmont Copper Mine, the Highland Valley Copper, Trojan Copper and the Equity Silver Mine.

Table 2: Some Typical Spigotted Beach Characteristics

Property	Highmont		Trojan		Equity	
	Range	Mean	Range	Mean	Range	Mean
Tailings Feed % passing No.200	-	±50%	-	±10%	-	±80%
Beach Tailings % passing No.200	9-50	20	2.8-10.6	5.4		47
In situ Density (t/m^3)	1.36-1.55	1.45	1.46-1.65	1.53		1.49
Relative Density (%)	20-65	41	26-84	49%		-

In all three cases given in Table 2 the properties were measured on the beach surface. A consistent change in density or grain size was not measured with the distance from the spigot point. We consider that much more detailed data is required from spigotting operations in Canada to establish reliable trends in properties.

CYCLONING WITH DIRECT DEPOSITION

THE USE OF CYCLONES

Cyclones offer a simple mechanical method of separating the tailings into coarse and fine fractions and are normally used to manufacture clean sand for dam or containment dyke construction. The sand is either deposited directly into the embankment or placed mechanically and compacted. This section deals with cycloned sand placed directly into the embankment.

The main advantage of cyclones is the ability to produce a relatively inexpensive construction material from tailings under controlled conditions and at the same time reduce the volume of material to be stored in the impoundment. The economics of cycloning as a viable option depends upon:

1. Tailings gradation which determines the amount and quality of material that can be recovered. It is generally considered that sand of acceptable quality can be produced from most mill tailings with less than 60% passing the No. 200 sieve. However, depending upon the desired properties, a two stage cycloning operation may be necessary; and

2. The ratio of the volume of sand required for dam construction to the volume of storage created must be satisfactory. Enough sand of the required quality must be produced fast enough to raise the crest of the dam ahead of the tailings stored in the impoundment. Dam construction with cycloned sand is usually not possible in winter, so that cycloning is normally limited to about eight months per year.

Dams designed to be constructed of cycloned sand deposited directly into the embankment rely on a good underdrainage system to handle construction water deposited with the sand and to control the phreatic surface within the sand fill.

CYCLONE SYSTEMS AND THEIR OPERATION

There are essentially two types of cycloning systems in common use for tailings dam construction. These are:

1. Central cyclone stations situated at strategic locations, usually on one of the abutments of the dam at a higher elevation than the projected dam crest. This type of system is often used when double cycloning is necessary to produce the desired material quality. These central stations are normally permanent or semi-permanent and house a number of cyclones. The number of cyclones depends upon the cyclone size and the tailings throughput rate. A guide to the throughput capacity of various sized cyclones at typical pulp densities are presented in Table 3. Cyclones are usually controlled by the tailings operator to produce a product (underflow) containing less than 10% to 20% passing the No. 200 sieve with a pulp density of between 60% and 75% solids. The overflow or fine fraction is transported by pipeline and discharged into the impoundment some distance upstream of the embankment. The underflow is often diluted with water and transported in a pipeline to secondary cyclone units situated on the dam crest.

Table 3: Typical Cyclone Capacities
from Lighthall et al. (1989)

Cyclone Diameter (inches)	Input Rate (USgpm)		Equivalent Throughput (tons/day)	
	@ 10 psi	@ 15 psi	@10 psi	@ 15 psi
4	30	40	95	125
6	90	110	285	350
10	200	250	635	790
15	350	450	1,110	2,500
20	800	1,000	2,500	3,150
26	1,600	2,000	5,100	6,350
30	2,500	3,000	7,900	9,500

The secondary cyclone units remove more water and fines from the primary cyclone underflow producing an underflow containing less than 10% passing the No. 200 sieve. Similco Mines Ltd. at Princeton, British Columbia uses such a system. A variation on this system has been used successfully at the Trojan Tailings Dam, serving the Bethlehem mill at Highland Valley Copper in British Columbia. At Trojan Dam the underflow from cyclones in the final scavenging circuits in the mill is mixed with enough cyclone overflow to make it pumpable and it is pumped to mobile secondary cyclones located on the dam crest. In this particular case the mill cyclones are closely controlled by the mill personnel and the underflow contains less than 10% passing the No. 200 sieve. The main purpose of the on-dam cyclones is to dewater or thicken the underflow. The cyclone overflow is discharged some distance upstream of the critical embankment zone; and

2. On-dam cyclones. In this system, the mill tailings feed is transported directly to a number of on-dam cyclone units. A typical configuration of on-dam cycloning is shown in Figure 2. The number of units depends upon the cyclone size and the mill throughput. On-dam cyclones range from a number of small, light units mounted on wooden scaffolds, which are labour intensive to operate, to large skid-mounted or truck-mounted towers. Gibraltar Mines, British Columbia operated by Placer Dome Inc., utilizes skid-mounted towers each supporting a single 30-inch cyclone. At the Bethlehem Trojan Dam, cyclones are mounted on trucks.

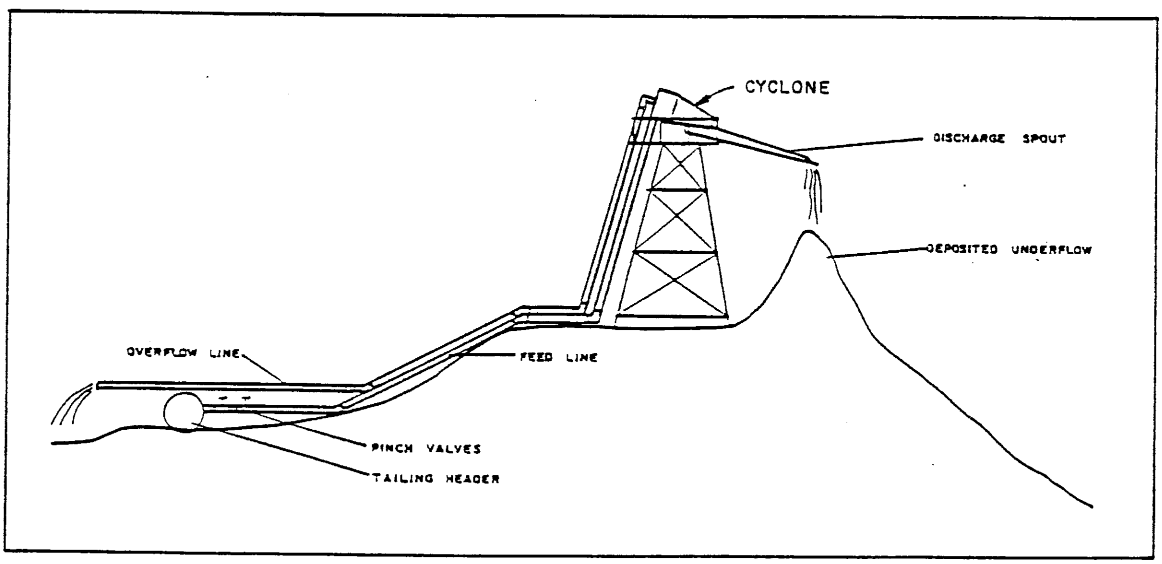

Figure 2: Typical On-Dam Cyclone Arrangement
(after Lighthall et al., 1989)

Quality control of cycloned sand is monitored by tailings operators who regularly measure underflow and overflow pulp densities and observe cyclone inlet pressures. The underflow pulp density can normally be related to the quantity of fines in the sand product. Routine adjustments of cyclones are required to meet pulp density and grain size objectives.

The thicker the underflow the steeper the side slopes of the cone and hence the steeper the slopes of the dam. Conversely, the thicker the underflow the more frequently the cyclones must be moved because the sand cones build up faster. This occasionally causes conflicts with operating personnel who sometimes reduce the pulp density of the underflow and wash out the cone rather than move the cyclones too frequently.

PROPERTIES OF CYCLONED SAND

Cycloned sand deposited directly onto the embankment from a well controlled cycloning operation will normally form slopes of between 3 and 4 horizontal to 1 vertical. Experience at Gibraltar Mines has indicated that the slope tends to steepen as the dam gets higher as a result of the rate of drainage of construction water from the deposited cycloned sand. Generally, the cyclone underflow behaves as a non-segregating mixture and the gradation of sand placed directly by cyclone does not vary with distance from the discharge point.

GRADATION

The gradation of the cyclone underflow depends upon the gradation of the tailings feed. In the case of a feed containing 60% passing the No. 200 sieve a well controlled single-stage cycloning operation will recover approximately 15% to 35% of the solids but with approximately 30% passing the No. 200 sieve. A second-stage cyclone would reduce the fines to approximately 10% but with a corresponding drop in the recovery to 10% to 15% of the solids.

By comparison, with a tailings feed containing 40% to 60% passing the No. 200 sieve a well controlled single-stage cyclone can recover approximately 50% of the solids with between 10% and 15% passing the No. 200 sieve. A second-stage cyclone would reduce the recovery to approximately 35% and the fines to between 5% and 10%.

Data from some typical cyclone operations are summarized on Table 4.

Table 4: Gradation of Cycloned Sand

Mine	% Passing No. 200		Remarks
	Feed	Underflow	
Highland Valley Copper Trojan Dam	45	5-10	Single-stage cyclones located in mill
Gibraltar	45 - 50	10	Single-stage, on-dam cycloning
Brenda	45	less than 5%	Double-stage cycloning central cyclone house

The in situ density of cycloned sand placed directly in the embankment generally ranges between approximately 30% and 68%. Average relative densities between 45% and 50% can normally be achieved. However, because the fill placement is essentially uncontrolled relative densities below 30% are not uncommon. Some erosion due to wind action occurs and sand can be carried and deposited in processes characteristic of sand dunes. A summary of various test data is presented in Table 5 below.

Table 5: In Situ Densities of Cycloned Sand Placed by Direct Deposition

Dam	In situ Density (t/m^3)		Max Density (t/m^3)	Min Density (t/m^3)	Relative Density %		Reference
	Range	Mean			Range	Mean	
Gibraltar	1.43-1.51	1.46	1.76	1.30	35-53	44	Klohn and Maartman (1973)
Trojan	1.41-1.59	1.47	1.71	1.39	7-67	28	Klohn Leonoff project files
Bethlehem No. 1 Dam	-	-	-	-	45-68	55	Mittal and Morgenstern (1977)

CELL CONSTRUCTION

Deposition in cells is the most sophisticated method of hydraulic fill construction. Cell construction offers a number of advantages:

- it allows good control over placement location;
- materials can be placed to high density so they will be essentially non-liquefiable;
- slopes can be controlled to any desired angle;
- costs are moderate.

Cell construction is the method whereby slurry flows are discharged to a hydraulic fill cell. The solids are allowed to settle and surplus water and fines are decanted from the end of the cell opposite the point of discharge. Wide-track bulldozers are used to maintain containment dykes around the perimeter of the cell and to compact the sand in the base of the cell.

Cell construction has been utilized to provide high quality fill zones in three major tailings structures: Brenda Mines tailings dam, Highland Valley Copper L-L tailings dam and Syncrude Canada Ltd. Mildred Lake tailings pond dykes. The applications of cell construction at these three operations are described in the following sections.

BRENDA TAILINGS DAM

Brenda Mines' copper-molybdenum mine located near Peachland, British Columbia has operated since 1969. The main tailings structure is a centreline-constructed sand fill embankment completed in 1986 to a height of 138 m. The dam was initially constructed using direct deposition from on-dam cyclones, depositing tailings between an earth and rockfill starter dam on centreline and a rockfill toe dam. Finger drains were installed to provide underdrainage. Double cycloning of the tailings was found to be necessary to provide sufficiently clean sand, with a primary cyclone station constructed on the left abutment and secondary cyclones on the dam crest. Because the double cycloning resulted in a low yield of clean sand, sufficient volume could not be produced to raise the dams at the flatter slopes resulting from direct deposition of underflow. In 1971 the second-stage cyclones were moved to the cyclone station and the second-stage cyclone underflow was mixed with water for transportation to the dam. Cell construction was introduced to allow steeper slopes to be formed with the lower density, diluted slurry.

The cell construction method employed at Brenda is shown schematically in Figure 3 (Klohn Leonoff, January 1984). Low containment dykes were bulldozed up using previously deposited sand. Cells were developed parallel to centreline with lengths of 150 m to in excess of 1000 m with widths of 30 m to 90 m.

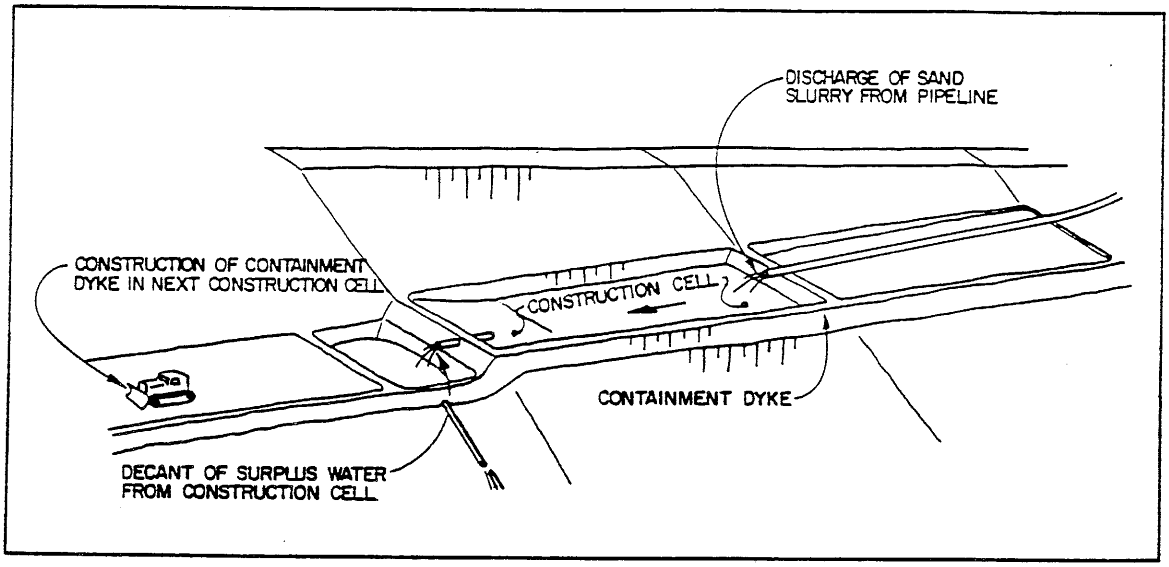

Figure 3: Cell Construction by Sluicing

Typical depths of sand deposited in the cells at Brenda were 1.2 to 1.8 m. Bulldozers were utilized only for containment dyke construction and no attempt was made to alter or move sand after deposition. The net effect of the bulldozers was that the top of each lift, down to a maximum depth of about 0.6 m, was compacted by tracking of the bulldozers. Table 6 below indicates that the mean relative density was improved from D_R = 38% to D_R = 54% as a result of the bulldozer compaction.

Table 6: Effect of Bulldozer Compaction in Hydraulic Fill Cells, Brenda Tailings Dam

Material	In situ Density (t/m^3)		Relative Density (%)	
	Range	Mean	Range	Mean
Sand not affected by bulldozer	1.41-1.53	1.46	23% - 57%	38%
Sand affected by bulldozer	1.47-1.55	1.52	41% - 63%	54%

HIGHLAND VALLEY COPPER L-L DAM

The Highland Valley Copper L-L tailings dam was started in 1976 and will be constructed to an ultimate height of 169 m and a crest length of 3.2 km. Highland Valley Copper, south of Kamloops, British Columbia, is the world's third largest copper mine in terms of daily mill throughput, which will reach

135 000 tonnes/day in 1989. The L-L dam will form one end of an impoundment with an ultimate volume of about 1.4 billion m^3 (about 2 billion tonnes) one of the largest in the world. The dam is raised by centreline construction, with a vertical impervious core supported by tailings sand shells upstream and downstream.

Sand for construction of the L-L dam is produced by cycloning of the tailings stream in a central cyclone station on the dam abutment, consisting of fifteen 508 mm (20 inch) cyclones with adjustable apexes. Transportation water is added to the primary cyclone underflow and the sand is transported by a slurry line to secondary cyclone units, each consisting of four 508 mm (20 inch) cyclones, operated on the dam crest. The clean sand underflow from each secondary cyclone unit is collected in a launder and conducted by gravity in one of two 356 mm (14 inch) delivery lines down the downstream slope of the dam for hydraulic placement. Hydraulic cells consist of long panels, 450 m long x 9 m to 24 m wide. A low dyke, approximately 1 m high, is maintained on the outside edge of the cell and the sand deposited in the cell is compacted by tracking of D7 and D8 bulldozers. The retention dyke fill is relatively loose as placed and is recompacted with the new dam fill in the following year. At the lower end of each panel, decant water is collected in a temporary settling pond and conveyed by a drainage pipe to decant ponds beyond the dam toe. The L-L dam cell construction is illustrated schematically on Figure 4.

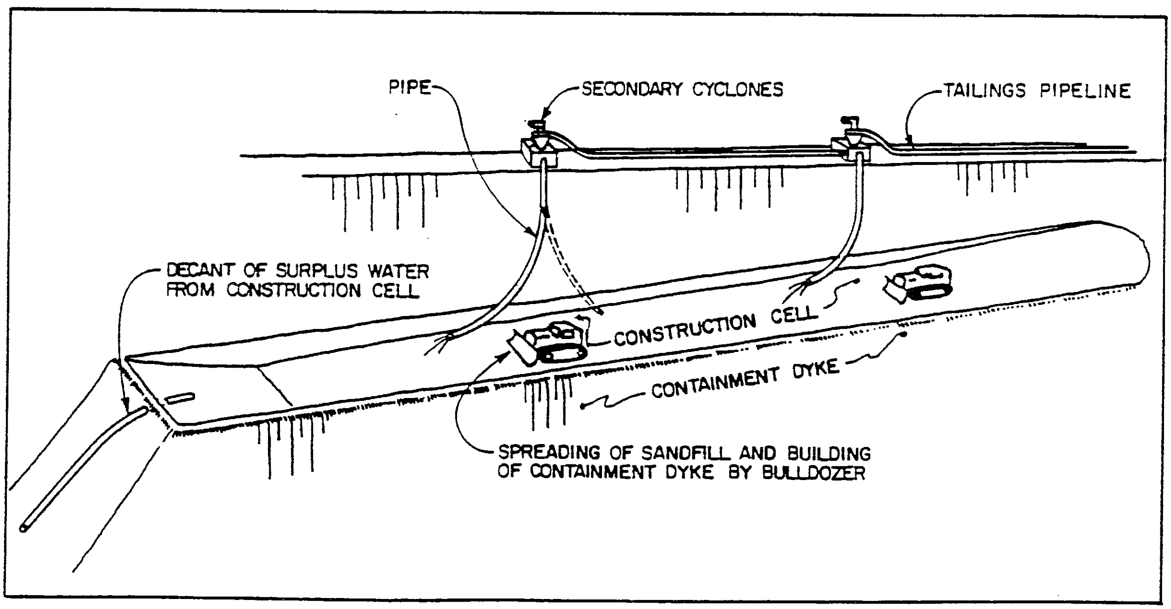

Figure 4: Cell Construction by Bulldozer Spreading

Construction control of the quality and density of the sand fill is maintained by a resident geotechnical engineer and field inspectors. Cycloned sand as structural fill is specified to have less than 20% passing the No. 200 sieve and to have a minimum density of 97% standard Proctor. Quality control test data from Klohn Leonoff (1988) indicates a range of fines content of 3% to 18% and a mean fines content of about 8% passing the No. 200 sieve and a mean density of 16.2 kN/m^3 (103.1 lb/ft^3), equivalent to approximately 102% standard Proctor, as determined by about 2,250 density tests.

SYNCRUDE CANADA LTD. MILDRED LAKE TAILINGS DYKES

Syncrude utilises cell construction in a modified centreline technique for construction of its Mildred Lake tailings impoundment. Syncrude, located north of Fort McMurray, Alberta, extracts 120,000 barrels per day of crude oil from 300 000 tonnes/day of oilsand feed. After removal of the bitumen, approximately 240 000 tonnes/day of tailings require disposal. The tailings pond is formed by dykes with a total perimeter length of 18 km. Dyke construction is described in detail by Yano and Fair (1988).

Cell construction is used both at Syncrude and at the neighboring Suncor oil sand mine to form the structural shell of the tailings dykes.

Hydraulic cells are constructed parallel to the dyke centreline with lengths of 500 m to 700 m. The system is shown schematically in Figure 5. Cells are constructed to the full width of the crest surface, except in some cases where wide cells have been subdivided into 50 m wide subcells. Dykes 3 m high are dozed up to form the cells. The tailings is sluiced into the cell where coarse sand settles out and is spread and compacted by wide track dozers. The excess transport water and sludge are decanted at the discharge end of the cell through a moveable spillbox structure, which consists of an adjustable rectangular weir with drainage pipes connected to its base.

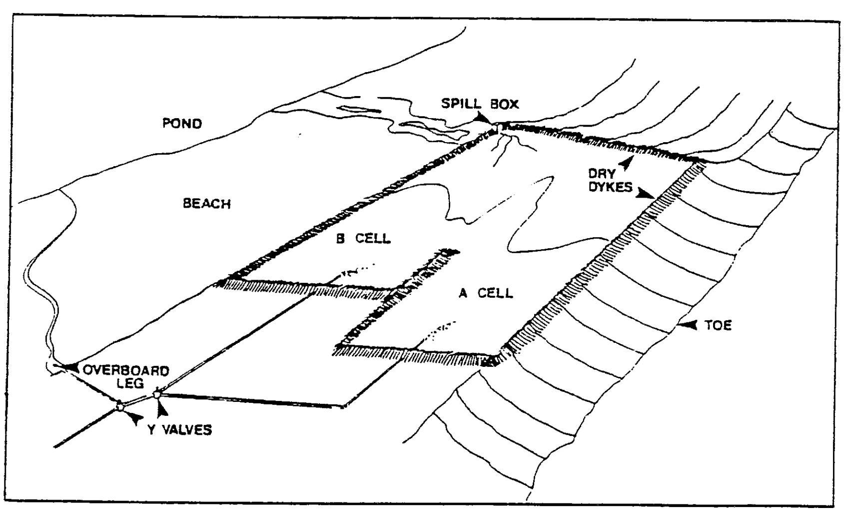

Figure 5: Hydraulic Cell Construction at Syncrude
(after Yano and Fair, 1988)

Cell filling is carried out by building to the 3 m height of the retaining dykes and advancing the pipelines and raising the weir height within the spillbox. Once the lift has advanced to within 50 m of the spillbox, the end dyke is breached and placement is shifted to another cell.

Cell construction at Syncrude produces an in situ dry density of 1.60 t/m^3 (100 pcf) with a relative density of 77%. The fines fraction, defined at Syncrude as the portion of the solids less than 22 microns, is reduced from 10% to about 5% in the cell construction process.

SUMMARY AND CONCLUSIONS

This paper has reviewed three general deposition methods for construction of hydraulic fill tailings dams. Some of the main conclusions are summarized below:

1. Spigotting Spigot construction is the simplest technique and is commonly applied to upstream tailings dam construction. The method can be used to construct stable upstream tailings dams in non-seismic areas. Better control over fill gradation and density are achieved by spigot construction than by point discharge to a beach. However, the density of spigotted fills is generally too low for adequate resistance to liquefaction. Spigotting can be successfully utilized for upstream construction in seismic areas only if the fill has adequate permeability so that effective drainage measures can be implemented and if the embankment slopes are designed sufficiently flat. Spigotting has a special application in maintaining wet beaches where dust control is a concern.

2. Cycloning with Direct Deposition Cycloning can produce clean sand which can be used to construct free draining embankments by direct hydraulic deposition. Clean sand can generally be produced by cycloning if the tailings feed contains no more than 60% finer than the No. 200 sieve. Either one or two stages of cycloning may be required. Densities produced by cycloning are generally in the range considered liquefiable under earthquake loading, hence suitable drainage measures must be implemented for tailings embankments in seismic zones.

3. Cell Construction Cell construction can be applied to fills requiring a high level of control over in situ density and embankment slopes. Fill can be compacted in cells to densities which will absolutely preclude the potential for earthquake liquefaction. The cell construction method has been applied at several large, sophisticated tailings disposal operations.

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