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UNIVERSITY OF ALBERTA

CHARACTERISTICS OF A HYDRAULIC FILL BEACH

BY

PETER KWESI EGYIR

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH IN
PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF
MASTER OF SCIENCE

IN
GEOTECHNICAL ENGINEERING
DEPARTMENT OF CIVIL ENGINEERING

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Dr. K. Barron

March 1, 1994

DEDICATION

This thesis is dedicated to the greater glory and honor of the Lord, the Almighty God for blessing me with the greatest gift that comes from Him; the gift of Life, life in the birth of my triplets- Anita, Andrew and Anthonette and in Rebecca, their lovely sister.

ABSTRACT

Hydraulic fills are utilized in the mining industry for the construction of tailings embankment and the backfilling of underground mine openings. The greater proportion of the hydraulic fill material is derived from mechanically separating the coarse and the fine grained fractions of the mine tailings and using the coarse fraction for the construction. The fines (slime) together with the water are disposed of and stored permanently behind the tailings embankment.

This thesis is part of the ongoing studies on the characteristics of mine tailings deposited hydraulically. It studies the characteristics of the depositional environment of the Brenda Mines' emergency tailings beach. Conventional laboratory testing program was conducted using disturbed and undisturbed samples retrieved from the abandoned emergency depositional area. The index properties of the in-place total tailings were determined. Consolidated undrained monotonic triaxial compression tests were performed on the undisturbed samples to evaluate the undrained response of the deposited tailings.

The results of the laboratory tests indicate a relatively slight reduction in the mean grain size over a distance of about 1km from the point of discharge thereafter decreasing significantly near the pond. The variation in density across the beach is not well defined, the loosest material being deposited near the point of discharge and close to the pond respectively. The relative density ranges from 27.7 to 72.8% with large portion of the central part of the beach attaining relative densities greater the 60 per cent. The q-p' effective stress paths from the triaxial tests show a consistent dilative behavior of all the tailings samples along the approximately 1.5 km length of the hydraulically deposited emergency beach.

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I wish to register my heartfelt gratitude to Dr. D.C. Sego for his incalculable help, guidance and advice which he generously dispensed during all levels of the research. His comments and directions were valuable and inevitably helped me to successfully complete this thesis. I am also indebted to the renowned professors of the Geotechnical Group for their excellent teaching which has better my understanding of Soil Mechanics and Foundation Engineering.

I would like to thank the management of the Brenda Mines Limited for providing access to the mine site and especially to Mr. Ron Brown for giving detailed tour of the site including the tailings facility and willingly furnishing the necessary data.

My sincere thanks goes to Gerry Cyre and Steve Gamble who provided the necessary technical assistance for the field sampling and the laboratory testing programs. Gerry's expertise led me to obtain quality samples for this study. Steve's assistance in the laboratory works was essential to completing the tests. I acknowledge their help.

I wish to express my gratitude to my wife, Josephine, and my family for supporting me throughout the period of my studentship. I thank my in-laws, Dr John C. Hagan and his family who encouraged and supported me to pursue this program.

I recognize in a special way my dear departed Mother for her unique love and respect she had for me. Though you have left this world, I am always conscious of your presence for I constantly draw on the many good values you taught me.

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PRINCIPAL NOTATIONS

A	Cross-sectional area of discharge pipe
B	Skempton's pore pressure parameter
CH	Chainage, i.e. distance from the point of tailings discharge
C_i	Inside clearance ratio of a sample tube
c/L	Center-line
C_u	Coefficient of uniformity (D_{60}/D_{10})
C_w	Slurry concentration based on weight
D_e	Inside diameter of the cutting edge of a sample tube
D_s	Inside diameter of a sample tube
D_n	Diameter at which n percent of grains are finer
D_r (R.D.)	Relative density
e	Void ratio
e_f	Void ratio at failure
e_{max}	maximum void ratio
e_{min}	minimum void ratio
G_s	Specific gravity of soil solids
g	Acceleration due to gravity
H	Maximum beach elevation
H_i	Elevation of beach at location i
h	height between discharge pipe and the maximum beach elevation
i_{av}	Average beach slope
I.D.	Inside diameter of core barrel
i_{ov}	Overall slope
L.H.S.	Left hand side of center-line

n	A parameter of the normalized beach profile
P'	Dimensionless slope parameter
p	Mean normal stress
Q	Total flow rate
q'	Effective mean shear stress
R.H.S.	Right hand side of center-line
u_c	Pore water pressure at the end of consolidation
u_f	Sample pore water pressure at failure
w	water content
ε_a	Axial strain
ϕ'	Effective frictional angle
γ	Unit weight
γ_d	dry unit weight
σ'_c	Effective cell pressure
σ'_v	Effective vertical overburden pressure
σ'_1	Maximum effective principal stress
σ'_2	Minimum effective principal stress

CHAPTER I

INTRODUCTION

Hydraulic fills originate from many natural sources: namely, river beds and flood plains, beaches, the bottom of the ocean, alluvial fans and along the path of debris flows. The disposal of processed wet waste streams, including waste generated from mineral extraction, results in man-made fills. Such disposal often involves hydraulically transporting the waste and depositing the material in a fill.

The disposal of the waste stream may be subareal or subaqueous. Most of the subareal waste deposits can be classified as side-hill, cross-valley, or stockpile deposits (Smith, 1969). Subaqueous deposition is carried out below water as in oceans, rivers and lakes. Both subareal and subaqueous depositions result in the formation of a beach structure. The material in hydraulic fills is usually an unaged sediment.

The construction of hydraulic fills have various engineering applications. Some are used for earth structures, land reclamation and backfill of underground mines. Küpper (1991) points out that the lack of a rational design approach hampers the increasing use of hydraulic fills in engineering projects.

Tailings, a by-product of the mining and milling processes, is disposed of economically by hydraulic means and is usually retained by a dam which form a retaining pond. The cost of the tailings disposal facility can be a significant portion of the total capital outlay of a mining operation (Mittal, 1974). At the Brenda Mines in British Columbia, 8.2 percent of the initial capital outlay of 62.3 million dollars was allocated to the tailings system (Tetu and Pells, 1971). However, the mine tailings are also a source material for the construction of the tailings dams which is used to impound the remaining fluid and solid wastes.

To ensure safe performance of tailings dams, only the coarse fraction of the wastes are utilized during the hydraulic fill construction. Coarse tailings provide a more suitable fill for the retaining dikes than the fine tailings. Jigins (1957) describes the construction of the Barahona dam (Braden Copper Co.) where the tailings were separated using sand-settlement boxes and then utilized the coarse sands for construction of the dam. The fine tailings (slimes) deposited and stored behind the dam are generally soft, loose, relatively impervious and usually saturated except for a thin layer at the surface which dries by evaporation. The consistency of these fine tailings may range between a solid and a semi-fluid depending on their grain size, age and location of the water table within the facility. The lower layers generally are unconsolidated with excess pore pressures which can create artesian conditions within the fine stratified impervious layers in the mass of tailings. In the event of dam failure, the stored material usually liquefies to a high unit weight fluid which flows.

In the mining industry, large volume of wastes are generated. At most sites, the volume of tailings produced is greater than the volume of ore mined. Hoare *et al*, (1970) estimate that over 305 million tonnes of tailings are produced annually in Canada. An estimateu 178 to 203 million tonnes of tailings were produced at the Brenda Mines (Mittal, 1974). Other mining companies are expected to produce even larger quantities of tailings. The Highland Valley Copper Mine in British Columbia is estimated to preduce nearly 1.8 billion tonnes of tailings (Scott and Lo, 1992). At completion, the Mildred Lake Pond will contain approximately 475 million cubic meters of sand, 400 million cubic meters of sludge (fine tailings) and 50 million cubic meters of fresh water from the production of synthetic crude oil at the Syncrude Canada Ltd (Yano and Handford, 1990).

With the increasing need to mine lower - grade ores, the host rock must be ground more finely to produce the mineral. Consequently, the ratio of recoverable minerals to total tailings waste generated is decreasing. Thus, increasingly larger volumes are required for waste storage. The waste storage area required for a given mined tonnage is usually difficult to estimate. Given (1959) gives as a rule of thumb a minimum waste storage area of 4.4 ha per 1000 tonne rock mined.

Occasionally, insufficient quantity of coarse waste may be available for use in the hydraulic fill construction of the embankment. This is especially so in the early stages of the operation of the mine or when the coarse fraction is used as backfill in the underground operation. It may be necessary to import material to supplement that available for construction of the tailings dam during the early mine operation. The added cost associated with this fill to the operation maybe high. The method of depositing the tailings may also affect the quantity of coarse material available for the hydraulic fill construction.

Some of the common methods of hydraulic deposition for the fill construction include spigotting, cycloning with direct deposition of its underflow, and cell construction. These deposition techniques are employed in the upstream, downstream or the centerline methods of constructing tailings dams (Figure 1.1).

The need to maintain a continuous mining operation requires that an area be set aside where the total tailings can be discharged during any shutdown periods associated with the ongoing deposition methods during and after the dam construction is completed. The wastes deposited in such an emergency depositional area generally will not undergo any mechanical separation processes such as is associated with the other depositional approaches used to construct the hydraulic fill. At the Brenda Mines, gravity discharge was used to deposit tailings to form a 1.5 km long emergency depositional beach in the tailings impoundment area.

Tailings disposal at all mining extraction operations presents a major potential threat to the environment. This threat stems from the increasingly large volumes of tailings stored and the possible pollution of surrounding sources of water including streams and groundwater systems which may occur by interaction between leakage from the tailings impoundment and the natural water. It maybe worthwhile to optimize the use of the tailings to the exclusion of any imported material for the construction of the tailings dam in an effort to reduce the tailings volume to be stored. Pollution has presently become a major public issue which has affected the design, construction and operation of tailings dams (Klohn, 1972). In the Province of British Columbia, prior to issue of a permit, the Department of Lands, Forests and Water Resources, Pollution Control Branch require mining operators to satisfy the Pollution Control Branch that no serious escape of pollutants will occur. Alkaline mine drainage in contrast to acid mine drainage is at present a major ongoing concern at the Brenda Mines (Brown, 1992).

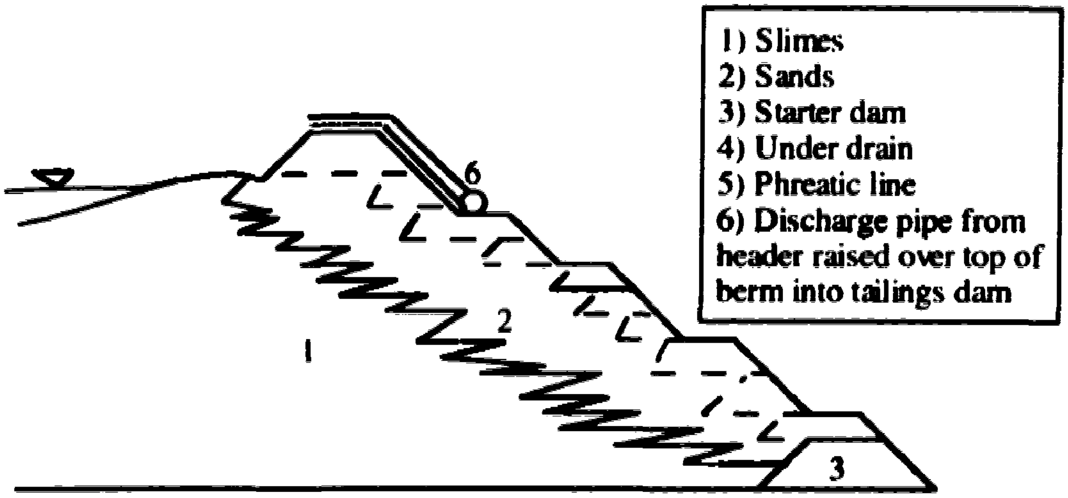
The design of the tailings disposal system depends on the available space, the characteristics of the tailings and site characteristics. The growing public awareness for the need to protect the environment and the stringent legislation governing tailings containment, demand that operators of mines move towards not only safe engineered disposal of tailings but also disposal which minimizes ongoing and future environmental pollution.

In utilizing hydraulic transport and fill construction for waste disposal, there is the option of separating the waste for placement in diverse areas using different placement methods. The proportion of fluid to solids to be stored can therefore be controlled or altered during the disposal. A reduction in the amount of fluids can result in maximizing the embankment slope and minimizing the potential environmental impact of polluting fluids and/or need to store soft materials (Robinski, 1979). On the other hand, increasing the fluid content can result in higher density in the material being placed (Küpper 1991).

Economic considerations require that the selected disposal methods be as inexpensive as possible. In situations where the material is utilized for hydraulic fill construction, workability requirement must also be considered. Küpper (opt cit) suggests that the placement methods be designed with the additional objective of enhancing the properties of the constructed fill for each project.

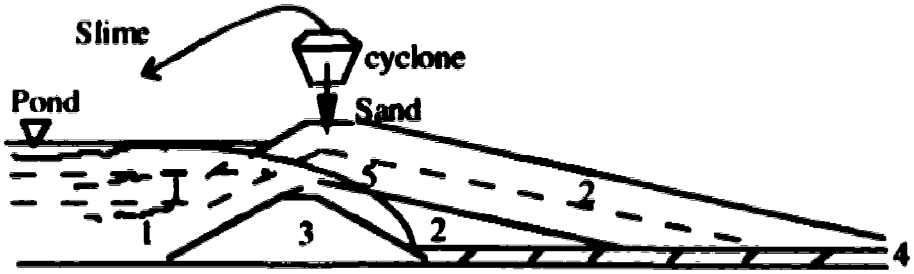
The objective of this thesis is to study the geotechnical properties of the as-placed tailings in the emergency depositional beach of the Brenda Mines. To achieve this a systematic laboratory testing program was carried out using both disturbed and undisturbed samples retrieved from the emergency beach to determine the properties of the in-place total tailings. An understanding of the characteristics of this fill for which no special engineering consideration was made will provide a better understanding of what controls the basic properties of hydraulically placed material. The measured laboratory and field data are then compared with predicted characteristics obtained from existing design concepts (Küpper, 1991). It is hoped that the research results from this thesis may be utilized to enhance the understanding and use of hydraulically placed tailings.

Chapter II briefly describes the geology of the Brenda Mines site, the mining and milling processes and the subsequent waste generation. Chapter III reviews briefly previous works on the study of hydraulic fills by presenting published laboratory flume tests and field depositional tests carried out to study hydraulic fills. It also describes some of the common deposition methods for large scale fill construction, their applications and the resulting material properties. The hydraulic fill properties outlined in the chapter are then compared with the data obtained from this research in a later chapter. Chapter IV describes the field program at the mine's site and outlines the field sampling. The laboratory tests conducted are presented in Chapter V and the results discussed in Chapter VI. Chapter VII presents a summary of conclusions arrived at in this study and outlines some suggestions for future research.



Upstream method of tailings dam construction using spigotting

Downstream method of tailings construction



Centreline method construction using cycloned sand

Figure 1.1- Tailings dams construction methods

CHAPTER II

MINING OPERATION AT THE BRENDA MINE

2.1 Introduction

Brenda Mines Limited is a copper - molybdenum concession located (49° 52'N, 119° 58'W) about 225 km east northeast of Vancouver and 40 km northwest of the City of Kelowna in south central British Columbia, within the western boundary of the Okanagan Lake drainage basin (Figure 2.1). Physiographically, the area is situated in the Thompson Plateau of the Interior system of the Canadian Cordillera and is separated from the west coast by the ranges and high plateaus of the Coast Range system of mountains. The annual precipitation is less than 375 mm, the bulk of it being winter snowfalls. In spite of the semi-arid nature of the region, the Okanagan valley is a fruit growing area as well as a tourist and resort center in which irrigation is used extensively.

During deglaciation, major outlets for the ice were blocked including outlets along the lower Similkameen Valley and through gaps at the head of the Ashnola, Pasayten and Similkameen rivers (Bostock, 1948). The blocking of the outlets and the slow melting of stagnant ice in the valleys resulted in the formation of a network of spillways. These, together with the ice-dammed Fraser Canyon to the west, created many major lakes (Fulton, 1969). Present day year-round supply of domestic and irrigation water is derived from run-off from a regular winter snow cover which is stored in the glacial lakes and streams. High level pollution control measures are therefore exercised in the region to minimize potential contamination of these storage facilities.

2.2 Geology

The Thompson Plateau is a late Tertiary erosion surface with gently rolling uplands of low relief. The uplands are separated from each other by deep cut valleys. In the Okanagan region, the plateau rises generally to between 1500 and 1830 m. Near the Brenda mine, the upland has been dissected by the Okanagan lake system and its tributary system. Figure 2.2 shows the relative locations of the mine, the Okanagan Lake and its tributaries. The mine site is located at an elevation of about 1463 m which is approximately 1100 m above the Okanagan Lake.

The Canadian Cordillera is seen as an assemblage of terrains separated by major faults traces, ophiolite exposures and oceanic marginal basin stratigraphy. However, no known faults are shown on Geologic Survey of Canada Maps near the Brenda Mine site. Instead, implied faults are mapped within the Okanagan Valley. These faults have been inferred to exist near the valley walls. The mine is located approximately 18 km west of these valley walls.

Reports from Klohn Leonoff Consulting Engineers (1984) indicate that examination of Earth Resources Technology Satellite (ERTS) images shows lineations approximately 10 km west of the Brenda the site. It states that these lineations are less marked and that examination of topographic maps of the region indicate they are not fault traces but rather the boundary between ancient highlands in which the Brenda Mine is situated and the relatively flat plateau area to its west.

Many minor faults are known to pass close to and through the mine site. The majority and possibly all of the surface faults are believed to be related to ancient tectonic activities and are presently inactive. Carr (1969) also shows that a zone of intense fracturing, about 2 km wide, trends northeast and extends through the mine site.

2.3 Seismicity

Seismic design criteria are an important consideration in the siting of a tailings disposal facility. The Brenda mine is located in a low to moderate seismic zone. No earthquakes have been recorded within the ancient highlands where the mine is situated nor along the lineations about 10 km west of the mine. However, two seismic events have been recorded near Peachland, B.C. which most likely are related to the implied Okanagan Valley fault system. The largest recorded earthquake linked with the Okanagan Valley fault system was the Grande Coulee (U.S.A.) earthquake of Magnitude 5.0.

No induced seismic events of significant Magnitudes (greater than 5.0) from human activities such as fluid injection in oil fields, impounding of water in large reservoirs and mining have been reported in the area (Milne and Berry, 1976). Nevertheless, an induced earthquake which was triggered by a slide within part of the mined open-pit was recorded at the Brenda mine site (Brown, 1992).

Maximum credible earthquakes from the implied Okanagan Valley fault system and from a source near the tailings dam site were assessed for the Brenda tailings dam seismic analysis (Klohn, 1984). A conservative maximum credible earthquake of Magnitude 6.5 was chosen for the Okanagan Valley with epicentral distance of 18 km to the dam site. A maximum credible earthquake of Magnitude 5.5 was assigned to an assumed source close to the dam site.

The geology of the dam site, the seismic history and the potential future seismic activity were considered in the design of the tailings dam to ensure that it performs adequately under any possible static and dynamic loading conditions. To ensure the stability and integrity of the Brenda tailings facility required the mechanical separation of the tailing into its fine and coarse fractions and use of only the more competent coarse size fraction for the dam construction. It was judged that the finer fraction if included in the constructed dam might produce a structure which could potentially liquefy during an earthquake.

2.4 Mining and milling processes

The Canadian Geological Survey memoir of 1947 contains the first written report of deposits of low-grade copper and molybdenum ore in the Brenda Mine area. Efforts to develop the concession began in the 1930's and 1940's (Tetu and Pells 1971). The Brenda Mines had its first mill run in 1969 and production at the design rate was achieved in 1970.

Brenda Mines is an open-pit copper-molybdenum operation. The ore body occurs in a relatively homogenous quartz diorite rockmass of Jurassic age referred to as the Brenda Stock (Soregalori, 1974). The mill was designed to process about 22,000 tonnes of low-grade ore per day to produce two concentrates, namely, copper and molybdenum. It was estimated to have a production life of 20 years. With later modifications, the daily mill throughput was increased to about 27,000 tonnes. Table 2.1 shows the monthly mill throughput for the period January 1988 to May 1990. An average high of 32,000 tonnes of ore per day was processed between January 1988 and December 1989.

Processing of the ore consisted of crushing, grinding and extraction using flotation. Fresh water for the milling process was provided by diverting spring flows from the Brenda, MacDonald, Peachland and Crescent creeks and storing it in the Peachland Lake. Reclaimed water was recycled through the plant from a separate storage.

The tailings generated from the milling process was hydraulically transported by pipes to the area designated for their storage. About 24,000 tons of tailings per day was stored in the disposal area.

2.5 Tailings facilities

Tetu and Pells (1971) report that twenty-four thousand tons of low grade ore produces virtually 24,000 tons of tailings. At the initial design capacity of the mill, Mittal (1974) estimates nearly 175 million tons of tailings would require disposal. The siting of the tailings disposal facility was greatly influenced by the location of mill relative to the mine and the surrounding topography.

The tailings disposal facility of the Brenda mine is located in an adjacent creek valley. Due to the steep longitudinal and lateral gradients of the valley, a large dam had to be constructed to provide sufficient storage volume for the tailings in the valley. Various methods were used throughout the mine operation to construct the tailings dam.

Initially, tailings were transported by gravity flow from the mill through nearly 3 km of wood-stave pipeline to a battery of cyclones located on the hillside above the present damsite. The tailings were then separated into two streams, a coarse free-draining sand underflow and fine grained slime overflow. The sand underflow was used for construction of the main tailings dams while the fines were placed behind the dam as it was being constructed.

Later, double cycloning of the tailings was introduced to ensure a sufficiently clean sand to meet the design requirement for the dam construction. Even then, the double cycloning could not provide an adequate volume of clean sand to raise the dam at the gentle slopes which resulted from the hydraulic deposition of the underflow. Cell construction was therefore introduced to allow steeper slopes to be constructed from the lower density dilute slurry.

Sand was deposited in cell containment dykes which were constructed using bulldozers to heights between 1.2 and 1.8 m. Details of the construction of the Brenda

Mines tailings dam are presented in Lighthall *et al*, (1989) and Tetu and Pells (opt cit). The main dam was ultimately constructed to a final height of 138 m in 1986.

The remaining tailings from the mine operation were discharged into the tailing pond by spigotting from along the crest of the dam in an upstream direction. After completion of the dam, subsequent tailings were stored in the reservoir which also included the emergency depositional area. Figure 2.3 is an airphotograph showing the layout of the tailings disposal facilities at the Brenda Mines (June 1990).

As mentioned earlier, the emergency beach was created to ensure continuous mining operation. The emergency beach was formed by sporadically discharging tailings slurry from the crest of the adjacent mountain into a steep walled narrow valley at an estimated flow rate of 0.63 m^3/s (Brown, 1992). The slurry was transported via a 600 mm diameter pipe and discharged through a height of about 10 m. Figure 2.3 shows that flow after the discharge point was concentrated and perhaps prevented from spreading by the narrow width of the upstream section. Sheet flow began to occur only as the width of the emergency beach increased. The depositional conditions at the emergency beach are thus seen as differing from that which prevail during conventional tailings beach deposition from a single point or spigot operation.

In forming a tailings beach, tailings are discharged from the crest of the dam either by single point discharge, spigotting or overflow from cycloning operation into the reservior created behind the dam. The tailings are discharged continuously and regularly from low heights usually not exceeding five meters. The depositional process is associated therefore with low energy and low flow rate.

The difference in the mode of forming the emergency beach may account for the variation in the properties of the material deposited as well as the profile of the emergency as presented in Chapter VI

2.6 Conclusion

Tailings management at the Brenda Mines had many facets and underwent continuous evolution dictated by the changing geometry and operating requirements of the mine. The ultimate objective of designing, constructing, operating and subsequent decommissioning of the tailings facility is to operate an efficient and cost effective system which meets ongoing requirement for tailings storage and provides long-term protection of the environment. Incorporating planning and geotechnical consideration in the tailings management scheme can result in increased flexibility and efficiency during the design and planning process.

Open-pit mines located in mountainous areas have the added disadvantage that large volumes of tailings must be stored behind high dams, situated in valleys which maybe upstream of inhabited areas. The stability and successful performance of the tailings storage structure are therefore of eminent importance. At the Brenda mine, a comprehensive site investigation provided data necessary to develop a safe and economical design for the tailings system. Modifications in the construction process and occasional review of the main tailings structure resulted in the successful operation of the tailings disposal system for twenty years (1970-1990).

Table 2.1- Monthly throughput of the Brenda Mines Ltd

Month	Tonnes milled		
	1988	1989	1990
January	910,555	999,268	898,431
February	851,874	843,903	839,478
March	942,812	971,905	994,225
April	963,050	954,181	784,303
May	991,095	1,007,357	705,027
June	928,077	991,781	60,406
July	924,814	963,736	-
August	915,704	965,978	-
September	954,912	981,226	-
October	984,520	988,201	-
November	915,758	942,168	-
December	1,033,975	942,922	-
Average (tonnes/month)	940,512	962,719	713,645

(Source: Brenda Mines Ltd. Monthly Tailings Pond Report)

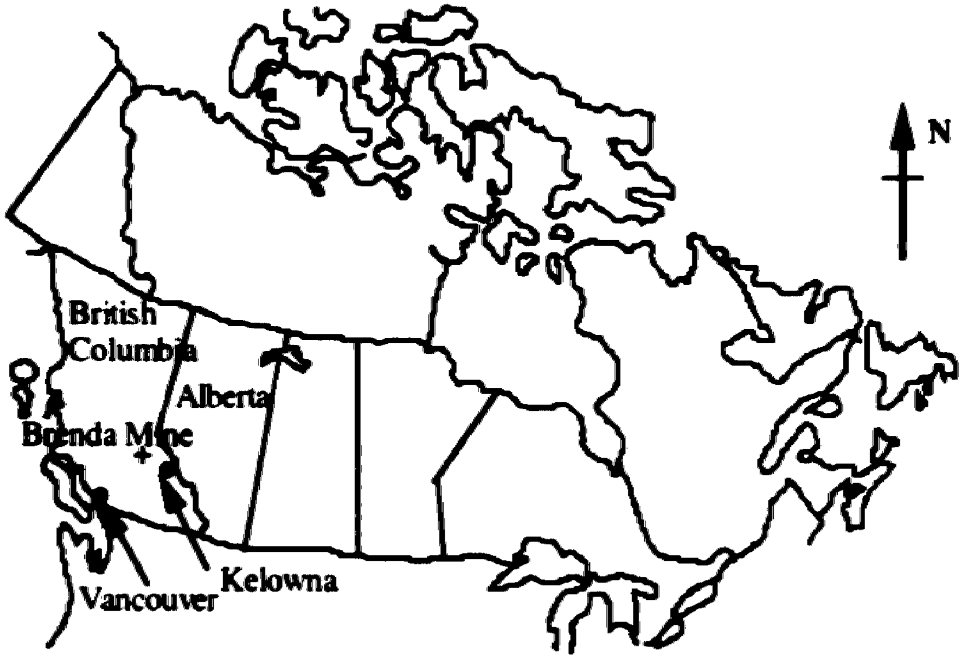


Figure 2.1- Map Showing the Location of the Brenda Mine Ltd.

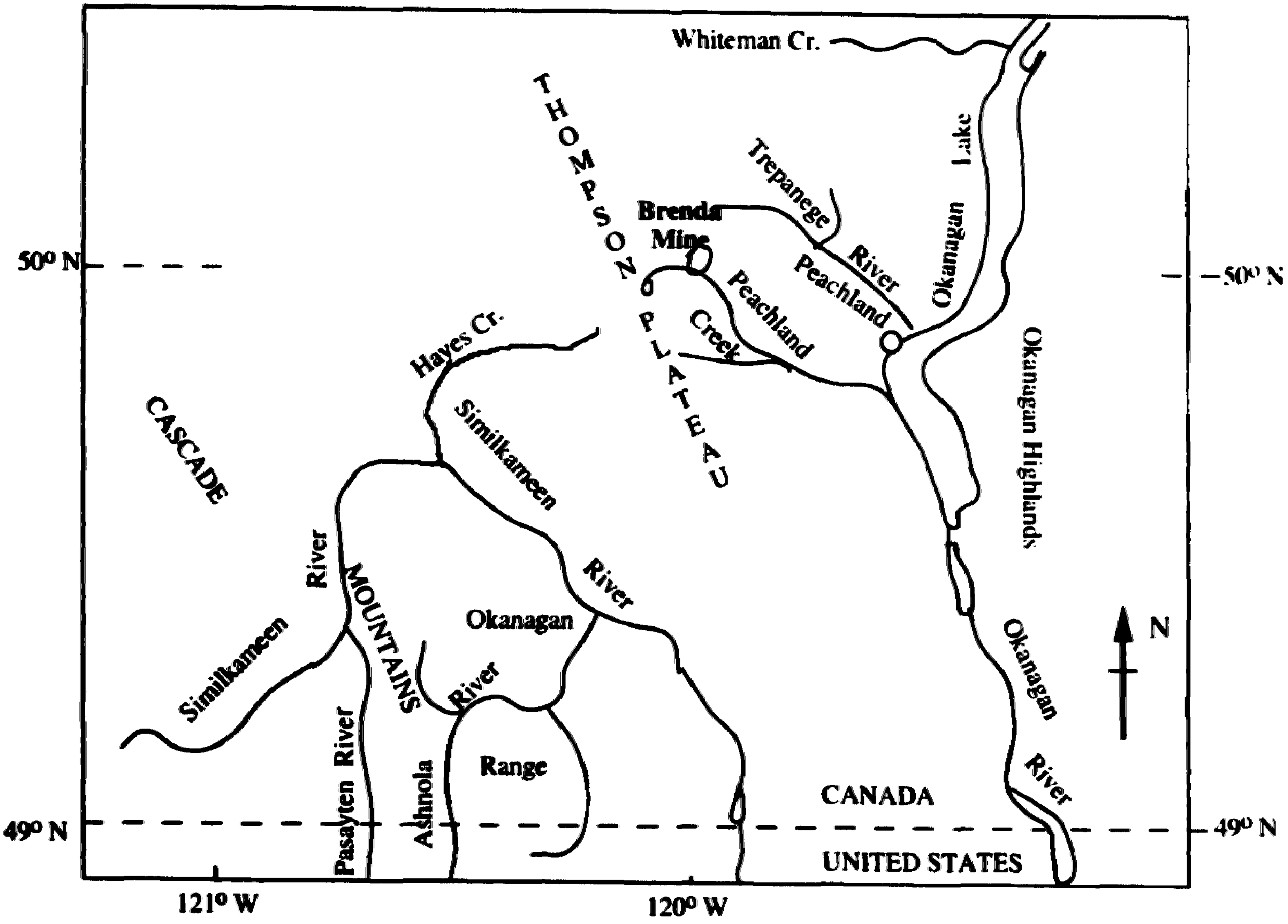


Figure 2.2- Brenda Mine and the Okanagan drainage basin (Map drawn not to scale)

Figure 2.3- Aerial view of Brenda Mines site

CHAPTER III

STUDY OF HYDRAULIC FILLS

3.1 Introduction

Hydraulic fill is an economical construction technique which is often considered to be more cost-effective than many other construction methods. It has been used to construct breakwaters, harbor extensions, artificial islands and closure dams in seas, estuaries, rivers and lakes in addition to tailings dams. The use of hydraulic fills in shallow waters has more advantages than steel or concrete structures in terms of cost, maintenance, durability, material, labor and the rate of construction. However, difficulties may arise with its use as the depth of water increases (Mitchell, 1984).

Hydraulic fill is utilized in the mining industry for the construction of tailings dams and the backfilling of underground mine openings. In both cases, the majority of the fill is derived from mechanical separation of mine tailings into different size fractions and subsequently dewatering or from naturally occurring sand or waste rock from an open-pit operation. Zahary (1973) reports that 76 per cent of mine fill is separated from tailings and 84 per cent of the backfill is placed hydraulically.

Hydraulic fill has the disadvantage that the gentle slopes produced from its use necessitates the use of large quantities of the material over relatively large areas. Traditionally, the hydraulic fill consists of material placed at low relative density and with low shear resistance which can introduce the potential risk of liquefaction or flow slides (Sasitharan, 1993).

The performance of a hydraulic fill depends on many factors among which is the method of placement. Morgenstern and Küpper (1988) suggest that since hydraulic fill technology is an interdisciplinary activity, the geotechnical engineer needs to collaborate with the hydraulic and the marine construction engineer to take full advantage of the economies offered by properly constructed hydraulic fill structures.

3.2 Depositional methods for hydraulic fill construction of tailings structures

Different tailings disposal techniques have emerged as a result of variations in site conditions, mineral ore bodies and extraction processes. Mill superintendents also incorporate special handling facilities to provide the most economical disposal methods consistent with accepted safety standards.

Two main hydraulic fills are formed from the surface disposal of mine tailings, namely, tailings dams and tailings beaches. Several methods of construction of these structures have been developed to optimize the use of the tailings in the process. The methods selected often depend on the scale of the project. Some of the common methods of deposition for hydraulic fill construction of tailings structures are spigotting, cycloning with direct deposition of underflows and cell construction (Lighthall *et al*, 1989).

3.2.1 Spigotting

Spigotting involves the discharging of tailings from a number of points along a tailings header line to achieve a nearly uniform flow of tailings onto the dam surface. Compared to discharging from a single point, discharging from several points results in considerable steeper slopes in the fill formed. Spigotting is used to construct tailings beaches for all types of tailings dams. However, for tailings dams construction, it is most commonly used in the conventional upstream method to obtain gravity separation of the tailings along the beach which forms.

The spigots are small diameter pipes taken off a main tailings line at regular intervals. The intervals are usually close enough to prevent the fines within the tailings from collecting between the spigot points. Spigots are often positioned at or below the center point of the header line. During upstream construction the spigot points are usually raised either by spigotting down or spigotting up (figure 3.1). The spigotted beach which forms constitutes the dam. When spigotting is used in the centreline and downstream construction, the spigotted beach provides support for the main structural section of the dam and/or reduces seepage by creating a long seepage path from the pond into and through the dam.

3.2.2 Properties of spigotted tailings

Spigotting generally results in segregation of the tailings along the beach. The coarse particles settle closest to the point of discharge and the fines are transported the longest distance towards the pond. The segregation process depends on the original gradation of the tailings and its solid concentration. Blight (1988) postulates that where an overall reduction in grain size from the spigot point results, the permeability of the tailings decreases along the beach from the spigot point. This results in a phreatic surface which is depressed from the isotropic permeability case reducing the exposed wetted surface of the downstream slope of the constructed tailings dam.

The density of the deposited tailings depends on the gradation and solids concentration of the tailings during deposition and the seepage conditions on the beach at the time of deposition. Tailings deposited on the upper part of a beach where there is a downward seepage gradient have a higher density than tailings deposited near the pond where little downward seepage occurs. Tailings deposited near the pond usually have the lowest density.

Table 3.1 presents typical properties measured on the beach surface from some spigotting operations in British Columbia (Lighthall *et al*, 1989). More detailed data is required from different spigotting operations in Canada for a more reliable understanding of the properties which can be produced during ongoing operations.

3.2.3 Cycloning

Cyclones provide a simple mechanical means of separating and dewatering tailings into a high density coarse underflow and a low density fine overflow. The coarse fraction may be hydraulically deposited directly onto the embankment or placed mechanically and then compacted. When cycloned sand is utilized for the construction of embankments a good under drain system needs to be provided to handle the construction water used to deposit the sand and to control the phreatic surface within the sand fill being produced. Two types of cycloning systems commonly used for hydraulic fill construction are;

a) on-dam cyclones and

b) remote central plant cyclones.

In the on-dam cyclone system, the mill tailings feed is transported directly to a number of on-dam cyclones ranging from a number of small, light units mounted on wooden scaffolds to large skid-mounted or truck mounted towers. The number of units depends upon their size and the mill throughput which must be handled.

Central cyclones may be located in clusters on the dam abutments at an elevation higher than the projected dam crest or within a central plant. This system is normally used when double cycloning is required to produce tailings with the desired material properties.

Double cycloning is necessary for very fine mill ground material or for material containing a high percentage of clay minerals. Again, the number of cyclones housed in the central stations depends on their size and the tailings throughput from the mill.

Cyclones are normally designed to produce an underflow containing less than 10 to 20% passing the No. 200 sieve with a a solids content of between 60 and 75%. The fine grained overflow is transported by pipeline and discharged directly into the impoundment generally at some distance upstream of the embankment being constructed. The underflow is often diluted to a lower solids content with water for transport in a pipeline to a secondary cyclone units situated on the dam crest. The secondary cyclone units then removes more water along with additional fines from the primary cyclone underflow to produce a final underflow containing less than 10% passing the No. 200 sieve.

Double cycloning was employed at the Brenda mine to provide adequate clean sand for the construction of the tailings embankment. This material handling procedure was later changed to cell construction as the volume of the sand produced proved insufficient for the required needs for dam construction.

3.2.4 Properties of cycloned sand

The density of the underflow sand from a cyclone operation can be related to the quantity of fines in the sand. Thicker underflows produce fills with steeper slopes and thus result in dams with steeper slopes. Direct deposition of cycloned sand onto an embankment from a well controlled cycloning operation can form slopes of between 3 to 4 horizontal to 1 vertical.

The cyclone underflow when placed directly onto the beach generally behaves as a non-segregating mixture (Küpper, 1991). The gradation of the sand placed directly from cyclones does not vary with distance from the discharge point. As mentioned previously, the gradation of the cyclone underflow depends upon the gradation of the tailings feed which comes from the mill. Table 3.2 presents gradation data from different cyclone operations (Lighthall *et al*, 1989). In 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 in the underflow and they will contain about 10 to 15% passing the No. 200 sieve. A second-stage cyclone would reduce the solids recovery to approximately 35% and the fines would drop to between 5 and 10%.

The in-situ relative density of cycloned sand placed directly on the embankment may range between 30 and 68% with average relative densities between 45 and 50%. Since the fill placement is essentially uncontrolled, relative densities below 30% can result. Generally it is desirable to have fills with relative densities greater than 60% especially to ensure resistance against liquefaction (Mittal, 1974). A summary of various data from cycloned sands presented by Lighthall *et al*, (opt cit) is presented in Table 3 .3.

3.2.5 Cell construction

Cell construction is a refined form of a gravity separation method (Klohn, 1972). The tailings are discharged into one end of a long, gently sloping channel or cell which has been constructed on top of the dam. The solids are allowed to settle along the base of the cell while the fines remain in suspension. The excess liquid containing the fines are decanted at the lower end of the cell generally opposite from the tailings discharge into the retention cell. Wide-track bulldozers are used to form and maintain the containment dykes around the perimeter of the cell and to compact the sand deposited on the cell base.

Cell construction is effective for very coarse tailings or for removing excess amounts of fines from a sand that has been obtained by single stage cycloning. The method also allows good control over placement location and thus dam construction. The selected materials can be placed and compacted to high density thus guarding against the potential for liquefaction. In cell construction the slopes of the dam can be controlled to any desired slope angle. The cost of construction is moderate. Cell construction is however, not suitable for fine mill ground tailings since the flow velocities in the cells required to remove the fines (slimes) will also remove a large portion of the finely ground sand size tailings and generally leave behind insufficient quantity to construct the dam at the required rate (Klohn, 1972).

Cell construction was used to provide a high quality material for the construction of the Brenda mine's tailings dams. It was introduced to permit steeper slopes to be constructed from a lower solids content tailings stream (Lighthall *et al*, opt cit).

3.2.6 Properties of fill material deposited by cell construction

Table 3.3 presents typical properties measured from some cell construction operations in Canada. No trend can be drawn from the limited data. However, it can be seen that the material deposited in cells have higher in-place relative densities. At the Highland Valley Copper Ltd, the mean density achieved was equivalent to approximately 102 per cent of the Standard Proctor density (Lighthall *et al*, opt cit). The data from the other mines are however, not compared to the Standard Proctor density.

3.3 Laboratory flume tests to study tailings structure

Laboratory flume tests have been conducted by various researchers to investigate the effects of hydraulic deposition techniques on the physical properties of the resulting fill structures. The procedure involves depositing the tailings in a flume and measuring the physical properties of the hydraulically deposited material along the length of the beach.

Laboratory flume tests are also used to study the profile of hydraulic fill beaches. The prediction of the profile of a tailings beach is an important aspect of the tailings management scheme for any mine. The prediction of the beach profile permits the design of the size of the storage pool and allows for a more accurate assessment of the storage capacity within the reservoir being created behind the embankment dam.

The beach development in a tailings disposal is similar to the aggradation along a reach of a river due to bed overloading, an area of study which is extensively dealt with in hydraulic engineering (Küpper, 1991). Laboratory test to study the beach building processes in tailings structures utilizes the concepts of hydraulic modeling.

Hydraulic models can be either undisturbed or disturbed (French, 1987). In the former, the model is geometrically similar to the prototype. The horizontal and vertical scales are the same. Disturbed models have different horizontal and vertical scale. They are usually used when inadequate laboratory space is available or when satisfactory model performance is expected. Models are also classified as Froude's (French, opt cit) and Reynold's models. In Froude's models, gravity is the dominant force and the surface of flow is exposed to the atmosphere. Examples include models of rivers, spillways and harbors. Viscous forces dominate in Reynold's models relative to other forces. These models are appropriate to study flows through pipes, pumps and turbines.

The choice of a model scale is dictated by factors which include availability of space, equipment, the need for correct representation of prototype flow conditions in the model and economic considerations. Scaling down hydraulic phenomena involving sediments poses difficulties. The sediment size can only be scaled down to a certain minimum beyond which the model becomes invalid as cohesive interparticle forces are introduced (Küpper, opt cit).

The Reynold's and Froude's models can be used to model successfully the transport of loose sediment by steady unidirectional flows. However, due to the practical limits associated with the standard scale modeling techniques for the various flow parameters, it is suggested that flume tests be considered as fundamental tests, small systems in their own right instead of a scaled version of a prototype beach (Küpper, 1991).

Flume tests are used in hydraulic fill studies to determine the equilibrium slope for a given set of deposition conditions and/or to study the physico-mechanical properties of the deposited material. A general description and operation of flumes have been given in the earlier section of this chapter. Southard and Middleton (1984) note that flume experiments have the disadvantage that the channel cross section is rectangular, sidewalls are straight and unerodible, width-to-depth ratio is usually small, the channel reach is much too short and the greatest flow depths attainable are near the lower end of natural flow depths. However, they acknowledge that flume tests provide valuable information on various aspects of bed configurations, flow resistance, transport rates and geometry as a wide range of bed configurations over a wide range of conditions of flow and sediment can be produced and studied easily.

Laboratory flume tests are used to investigate the beach profile during hydraulic deposition of tailings and the characteristics of the deposited material. Fan and Masliyah (1990), describe one such experiments to study the transient beach profiles and to establish the effects of sediment concentration and total slurry discharge on the beach profile.

In their test, tap water was first fed at a preset rate through a stainless steel box into a plexiglass flume measuring 4.87 m in length, 0.31 m in width and 0.46 m in depth. The box was located in the upstream end of the flume, sluicing out the water uniformly across the width of the flume. Dry sand was fed steadily at a specified rate by a mechanically operated feeder onto a specially designed sand distributor. The sand spread evenly to form a uniform slurry with the flowing water.

Two types of experiments were conducted to model the beach profiles: one for different solids concentrations at a fixed water flow rate, and the other for different total slurry flow rate at a fixed solids concentration. Fan and Masliyah, (opt cit), observed that the slope and the growth rate of the beach profiles were strongly dependent on the solids concentration. The total slurry flow rate had some influence on the growth rate of the beach profile, however, it did not significantly influence the beach slope.

Blight *et al*, (1985) present the results of model tests used for the prediction of the beach profile of a gold tailings dam. The laboratory flume consisted of a Perspex-sided tank or a short flume. Tailings slurry was charged into the tank at one end and the water decanted and collected at the other end. Test material for the model tests was obtained from the dam to represent the total tailings, the fine material taken from close to the pool and coarse material retrieved from near the point of deposition.

The slurry discharged into the tank formed a plunge pool which overflowed to form a 1500 mm beach. Model beaches were formed from each of the three materials at three different solids contents (50, 60 and 70 %) corresponding to water contents on a dry basis of 100, 67, and 43 per cent and slurry densities of 1.47, 1.62, and 1.81 Mg/m^3 respectively. Dimensionless profiles were obtained for the model beaches and compared with the dimensionless profiles of the prototype beach.

Blight *et al*, (opt cit) deduced that the field profile was in excellent agreement with the laboratory profile for the total tailings deposited at 50 per cent solids which corresponded to the field deposition conditions. As the solids content increased, the beach profile became steeper near the point of discharge and flatter as the distance increased from the discharge point. The model beach profile for the fine tailings at 50 per cent also showed good agreement with the field profile while that of the coarse material was flatter than the profile for the prototype beach.

It was concluded from the study that excellent simulation of the prototype beach profiles could be obtained using model studies provided the same material is used and deposited at the same solids content. The laboratory flume tests also showed that as the solids content increased, the beach profile became steeper close to the point of deposition. The same trend resulted if the coarseness of the material was increased while maintaining the same solids content.

Boldt (1988) conducted laboratory tests to determine the resultant physical properties of the materials deposited along the length of a beach. The tests involved discharging tailings slurry into a 0.6 m wide by 12.2 m long wooden flume. The tailings materials consisting of a fine, copper-silver mill waste and silver-lead-zinc mill waste containing coarser particles obtained from two different mine sites with different particle size distribution.

The tailings were diluted with water to a specific slurry density, mixed in a large 6340 liter tank. The slurry density of each tailings sample was altered by changing the amounts of solids. The slurry was then pumped at controlled flow rates through a 3.15 cm pipe opening and discharged into the flume. Once the deposited tailings were sufficiently dewatered, Shelby tube samples were taken at designated locations along the length of the deposited tailings for analysis.

It was pointed out that the confined dimensions of the trough influenced the depositional trials. Attempts to correlate the tailings deposition conditions to the prototype beach characteristics were obscured by eddies along the sides of the flume and the short distance between the ponded water at the toe and the point of discharge.

Küpper (1991) performed a series of flume tests to study the influence of the total flow rate, slurry concentration and grain size distribution of sand on the beach geometry, particle size distribution and density variation along the deposited fill. A clear Plexiglass wall flume measuring 6.1 m long by 0.60 m wide with a feeding and drainage systems was used. Removable Plexiglass walls was employed to vary the width of the flume.

The slurry used was formed by feeding dry sand to a controlled water stream coming from a constant head reservoir. The slurry was discharged onto a smooth bed of pre-deposited sand by a spreader designed to create a one dimensional flow and to minimize the effects of the walls by having the flow parallel to a hydraulically smooth wall. The flow rate and the slurry concentration were varied independently to study their effects on the characteristics of the deposited fill.

Undisturbed samples were retrieved along the flume and used for density determination, triaxial tests and fabric study. Remolded samples were also taken to study the variation in grain size distribution. Three different sands were used in the tests to evaluate the influence of the mean grain size on the characteristics of the fill.

In all the tests concave slopes were obtained which were steeper for higher slurry concentration, smaller flow rates and larger mean grain diameter (Küpper opt cit). The average fill density tended to decrease as slurry concentration increased and as the flow rate decreased.

A comprehensive review of the laboratory tests used to study hydraulic fills is presented by Küpper (opt cit). The results of many of the flume tests confirmed generalized predictions of the depositional environment of hydraulic fills. However, the need to conduct full-scale field tests to verify the conclusions drawn from laboratory tests was recognized by most researchers.

3.4 Field tests to study hydraulic fills

The inherent difficulties associated with laboratory modeling of hydraulic events necessitate that full-scale field deposition tests be embarked upon to validate results obtained from laboratory flume tests. In a full-scale field tests, auxiliary pipelines may be installed to control the flow rates of the tailings deposition process. The appropriate header lines and spigots are installed and the tailings stream discharged under controlled conditions to form a beach which is monitored throughout the experiment. The beach formed by each controlled deposition can be analyzed and its physical properties measured. Field pilot tests may be embarked upon using standard techniques to serve as preliminary tests to assist in designing the subsequent field tests (Küpper, 1991).

Prior to the commencement of the tests, elevation surveys are run to obtain the initial beach geometry. During the tests, the beach profile is regularly surveyed. Samples of both the slurry and the deposited tailings are retrieved and analyzed. Samples may also be taken from the mine's ongoing deposition for comparison

Field deposition tests performed at an on-going large scale mine are limited to what can be deposited using the available equipment. They have the advantage of working under actual operational conditions and occasionally receive assistance from the mine facilities including labor and equipment to set up and monitor the tests. Boldt (1988) and Küpper (1991) present detail procedures and results of full-scale field tests conducted at large scale active mines. The former field deposition tests were carried out at two different mines designated as Mines A and B respectively and the latter conducted at the Syncrude Canada Ltd, Fort McMurray.

The results of the laboratory and field tests briefly reviewed in this chapter are compared with the results of the current study in chapter VI.

3.5 Conclusion

A review of some of the common methods of depositing hydraulic fills utilized in the disposal of tailings and/or construction of tailings structure has been presented in this chapter. The properties of the deposited material are also discussed. It should be observed that for a given method of deposition, the properties of the resultant fill depends on the physical composition of the tailings feed.

Fills constructed using spigots placement of the total tailings stream have the least in-situ density and are potentially the most susceptible to liquefaction (Lighthall *et al*, 1989). Cycloning produces clean sand provided the tailings feed does not contain more than 60 per cent passing the No. 200 sieve. When cycloning is used for the construction of tailings embankments in seismic areas adequate drainage facilities must be provided to control the phreatic surface (Lighthall *et al* , opt cit). Cell construction provides the greatest flexibility in exercising control over the in-situ density produced and the embankment slopes of a tailings structure.

The chapter also discusses a few of the laboratory flume and full-scale field deposition tests for the study of hydraulic fills as presented in the literature. The results of these experiments show a generally consistent trend in the properties of hydraulic fills. In segregating slurries, the depositional process results in flatter and denser beaches. The mean grain size of the beach material decreases with distance from the point of discharge. Non-segregating slurries do not undergo hydraulic sorting. The beach formed from a non-segregating slurry has a steeper profile and consist of material with approximately constant granulometric characteristics and low relative density.

Table 3.1- Characteristics of same spigotted beaches (after Lighthall, *et al*, 1989)

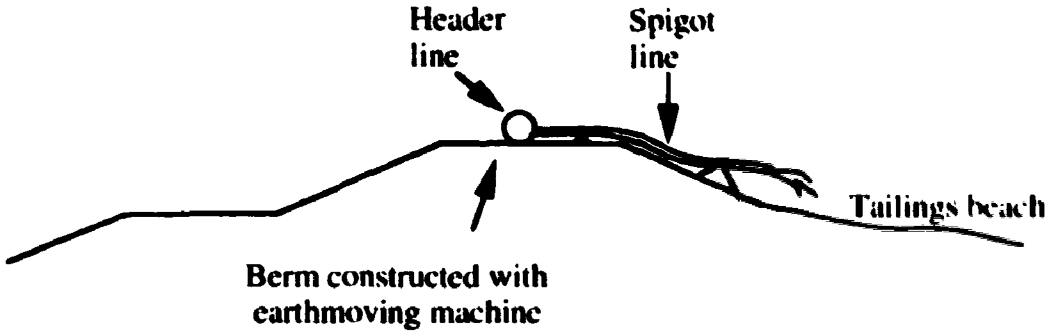
Material property	Highmont		Trojan		Equity	
	Range	Mean	Range	Mean	Range	Mean
Tailings feed (% passing No. 200)	-	50	-	10	-	80
Beach tailings (% passing No. 200)	9 - 20	20	2.8 - 10.6	5.4	-	47
In-situ density (t / m^3)	1.36 - 1.55	1.45	1.46 - 1.65	1.53	-	1.49
Relative density (%)	20 - 65	41	26 - 84	49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

Table 3.2- Gradation of cycloned sand (after Lighthall, *et al*, opt cit)

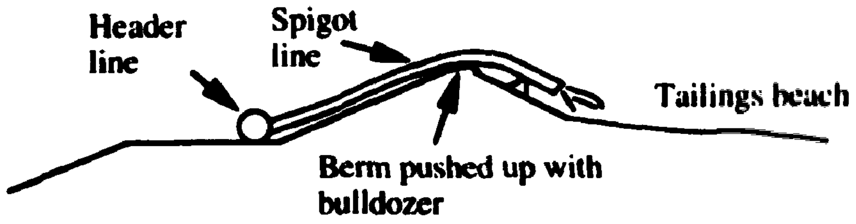
Mine	% pssing No. 200		Remarks
	Feed	Underflow	
Highland Valley	45	5 - 10	Single-stage located in mill
Gibralter	45 - 50	10	Single-stage, on-dam cycloning
Brenda	45	< 5	Double-stage cycloning

Table 3.3- Material properties from some cell construction operations

Mine	Fines	In-situ density (t / m^3)		Rel. density (%)		Remarks
	(%)	Range	Mean	Range	Mean	
Brenda	-	1.41 - 1.53	1.46	23 - 57	38	Uncompacted
Brenda	-	1.47 - 1.55	1.52	41 - 63	54	Compacted
Highland	8	-	1.62	-	-	
Syncrude	5	-	1.62	-	77	compacted



SPIGOTTING "DOWN'



SPIGOTTING 'UP'

Figure 3.1 - Spigotting configurations (After Lighthall *et al*, 1989)

CHAPTER IV

FIELD SURVEY AND SAMPLING

4.1 Introduction

A preliminary visit to the Brenda Mines site was conducted in June 1992. The visit was aimed at examining the ongoing reclamation process and the subsequent decommissioning plan, appreciating the successful performance of the tailings embankment and identifying any potential geoenvironmental hazards. The Project Manager of the mine provided a detailed tour of the entire facilities.

The tailings disposal site revealed some interesting features which led to the conclusion that a research project to evaluate the geotechnical properties of the tailings material discharged onto the emergency beach be carried out as part of the ongoing studies on the characteristics of mine tailings deposited hydraulically.

Permission was therefore obtained from the Project Manager to carry out the research project. The mine provided access to its tailings site and the use of a rented equipment for the field sampling. It also furnished data on the pumping rate, the slurry concentration and other pertinent information including topographical maps and aerial photographs of the tailings disposal site and the surrounding areas. Geotechnical reports on the tailings system were acquired from the mine's consulting engineers with the permission of the Project Manager.

Field research work was begun on July 14, 1992 and completed on July 17, 1992. The works consisted primarily of site inspection, elevation and transit surveying of the emergency depositional area and sampling of the total tailings at various locations to characterize the depositional environment. The details of the field work are described in the subsequent sections of this chapter.

4.2 Site Inspection

The emergency beach is located to the north, northwest of the longitudinal axis of the saddle dam and the northeast of the longitudinal axis of the main dam. It is fan-shaped, narrow at the upstream section and widens toward the pond (Figure 4.1).

Prior to the commencement of the field work, a detailed study of available topographical maps and orthophoto maps of the site was carried out. From the topographic maps, a point on the saddle dam was selected as a temporary bench mark. The orthophoto maps reveal that the flow on the emergency beach started as a single channel from the point of discharge and then divided into multiple channels as it flowed towards the pond (figure 4.1).

Inspection of the site showed that fresh water from the mine is currently being discharged onto the beach where it divides into two main flows at the upstream section of the beach. The flows are concentrated at the right and left boundaries of the emergency depositional area respectively. However, at a distance of about 600 m from the discharge point, the former flow disappears by seeping into the tailings thereafter all the surface flow to the pond takes place near the left boundary.

Two channels were observed along the right and left boundaries of the beach. The channels are deeper at the upstream section, becoming shallower at the downstream. With the mining and milling operations stopped, these channels are mechanically desilted occasionally to allow for the flow of fresh water into the pond. An excavator was seen desilting the right side channel at the time of the field work. Two other channels presently exist on the beach. They are located at the upstream and downstream sections of the emergency area respectively.

The upstream channel cuts across the beach from left to right taking part of the current flow with it. The channel cross sectional dimensions were measured. The top and bottom widths measured approximately 1.5 m and 0.8 m respectively. The depth was nearly 2.5 m. The exposed faces show a uniform coarse sand deposit with no visible structure in the deposited sand.

The downstream channel is about 200 m long and located approximately at the mid-center and close to the left side boundary. There is presently no flow in this channel. The exposed faces indicate a layered deposit. The layered profile may have resulted from the intermittent mode of depositing tailings onto the beach.

It is probable that the downstream section of the beach close to the pond was previously below water. A sudden change in the slope of the beach was observed at this location. Pond water is currently being pumped into the open pit created by the mining operation for storage. Thus, the pond level is dropping and exposing the toe of the previous beach deposited below water.

Boulders and rock fragments transported with the tailings were found deposited between the point of discharge and the beginning of the predominantly sandy beach. They had been sorted and deposited to give the impression that the arrangement was manually placed to prevent erosion of the steep valley slope. However, it was confirmed that the arrangements of the boulders and rock fragments were the result of being placed hydraulically and had not been altered by any mechanical action (Brown, 1992).

The surface of the emergency beach has been reworked. Tracks of construction machinery can be seen on the surface of the beach. It was disclosed that an access road was constructed across the beach and used for hauling overburden material across the site. However, the reworking may not have been thorough due to the presence of scattered soft spots on the surface of the tailings structure. These soft spots potentially can be dangerous for any equipment working on the surface.

As part of the ongoing reclamation program, a bituminous substance is being sprayed on the exposed sandy beach to bind the surface material in an effort to reduce wind and water erosion. The beach is then planted with grass to re-establish vegetation which will become the long term protection against erosion. The action of rodents and other animals loosens the surface deposit which subsequently allows for erosion by the wind.

The field observations made shall also be incorporated into later sections on the interpretation of the field and laboratory results.

4.3 SURVEY OF EMERGENCY DEPOSITIONAL BEACH

A chain survey was carried out to determine the length of the beach and to locate where samples of the beach tailings were taken. An approximate center line of the beach profile was located. Wooden stakes were driven into the beach along the center line at defined interval and at specific distances measured to the left and right of the assumed center line. Due to the irregular and fan-shaped nature of the beach profile, the left and right distances were not maintained constant along the beach profile.

Levels were run with readings taken near the wooden stakes. The elevation of the TBM was deduced from a topographic map of the tailings pond area furnished by the mine. The relative elevations of the sample locations (staked points) on the beach were subsequently obtained from which transverse and longitudinal cross sections of the beach were later produced. The survey was not carried to the point of discharge where the tailings left the pipe because of the steepness and ruggedness of the terrain. In addition to the elevation survey, transit survey was conducted to obtain the general layout of the beach and the points where samples were retrieved (Figure 4.2).

The measured profile of the emergency beach is discussed in Chapter VI.

4.4 Sampling procedure

Samples were retrieved at locations where the wooden stakes had been driven. Prior to sampling, a small backhoe machine was employed to remove the top 150 mm of wind blown material. At each sample point, disturbed samples were obtained from various depths to establish the spatial variation in particle grain size along the beach. The depths varied from 0 to 120 cm with samples taken at 30 cm intervals.

Bulk disturbed samples were taken at the surface (depth 0) and kept in 15 liters bucket. At the other depths, two grab samples each were taken in plastic bags. The grab samples were kept in rubber containers and covered.

To obtain the undisturbed samples, the next 100 mm thick layer suspected of having been disturbed by the backhoe was gently excavated by hand. Then a 100 mm diameter by 200 mm high sample tube was gradually pushed in the undisturbed deposit. The outside friction along the samplers was relieved by excavating around the tube as it was pushed into the deposit. When a sample tube was pushed to the required depth, the tube was surrounded with carbon dioxide pellets (dry ice) and covered with plastic bags to control the amount of dry ice consumed. The tailings sample in the tube was then allowed adequate time to freeze completely from the bottom upward. The tailings beneath some of the tubes to a shallow depth were also frozen. It therefore became necessary to strike the samplers to retrieve it together with the frozen sample.

The tubes containing the frozen samples were then retrieved and wrapped in plastic bags. To prevent the samples from subliming, the air in the bag was evacuated by forcing it out by hand before sealing the bag. They were then temporally stored in the refrigerator containing dry ice for subsequent transportation to the laboratory at the University of Alberta, Edmonton.

Thin-walled, rigid metal and PVC samplers having inside clearance ratio of zero (i.e. $C_i = 0$) were used. The inside clearance ratio, C_i, is defined by Hvorslev (1949) as $(D_s - D_e)/D_e$ where, D_s, D_e are the inside diameter of the sample tube and cutting edge of the sampling device respectively. The rigid walls of the sampling tubes provided adequate confinement needed to obtain relatively undisturbed samples.

To minimize sample disturbance from thawing during transportation, maximum care was exercised in arranging the undisturbed samples to ensure that they did not slide or roll. The temperature was maintained constant by the use of the carbon dioxide pellets. On arrival at the University of Alberta, the samples were taken out of the freezer and permanently stored in a frozen state in a temperature-controlled cold room until they were required for testing.

4.5 Discussion of sampling procedure

Sampling procedures for disturbed and undisturbed samples depend upon the type of soil and the specific aim of an investigation. The quality of soil sample needed for a given site investigation is determined by the requirements of the specific case. Studies indicate that if confining pressure is maintained and drainage is not impeded, insitu and laboratory freezing of sand samples result in insignificant volume change and the static and dynamic soil strengths are not altered upon thawing (Yoshimi *et al*, 1978). Marcuson and Franklin (1979) conclude that the freezing technique offers the best method for obtaining higher quality undisturbed samples. Freezing is used extensively as a method for obtaining undisturbed samples by the Geotechnical group at the University of Alberta (Küpper, 1991; Sasitharan, 1993).

The quality of the samples obtained for this study can be inferred from the results of the soil properties such as the grain size distribution, moisture content, density and the shear strength measured during the laboratory testing program (Idel *et al*, 1969; Brooms, 1980). These results which are discussed in Chapter VI compare with others conducted and presented on the same tailings material and on similar deposits.

4.7 Conclusion

Detailed field works were conducted at the Brenda Mines emergency depositional area to obtain good quality disturbed and undisturbed samples for laboratory testing to study the geotechnical characteristics of the total tailings. Samples were retrieved on a grid pattern. In the longitudinal direction, the samples were taken at 200 m intervals starting from a location about 400 m from the point of discharge to 1400 m near the pond except at station 600 (i.e. CH 0 + 600 c/L) where water ingress from depth to the surface prevented any undisturbed sample to be retrieved. Two containers of disturbed sample were also taken from the beach beneath the pond.

No samples were obtained between the point of the tailings discharge and CH 0+400 because of the inaccessibility of this section of the emergency beach. The upstream channel that cuts across the beach mentioned in section 4.2 is located within this area. The data from the tailings samples from this section of the beach may have been used to confirm the presence of the fanhead entrenched channel referred to in section 6.5.1.

Levels were run to establish the profile of the beach. The slope of this profile shall be compared with the slope estimated by using the empirical relationship proposed by Küpper (1991) and using data furnished by the mine. Transit survey was run to locate the positions of test-pits and the general layout of the beach.

The presence of a deep channel upstream of the beach, the obvious loosely deposited sand in a relatively steep slope at this section of the beach are consistent with the phenomenon of deep channeling discussed by Küpper (opt cit).

Reworking of the beach may have altered some of the characteristics of the depositional environment. However, the presence of soft spots possibly prevented any thorough use of construction machinery on the beach. Thus, the tailings deposit can be said to be practically unaltered from a characterization point of view.

The samples obtained from the field were transported to the University of Alberta, Edmonton where they were stored under standard conditions until required for laboratory testing. Chapter V presents the elaborate and systematic laboratory tests conducted to obtain the geotechnical properties of the as-placed total tailings.

Figure 4.1- Detail of the emergency depositional area
(Source: Orthophoto Map of Brenda Mines, June 1990)

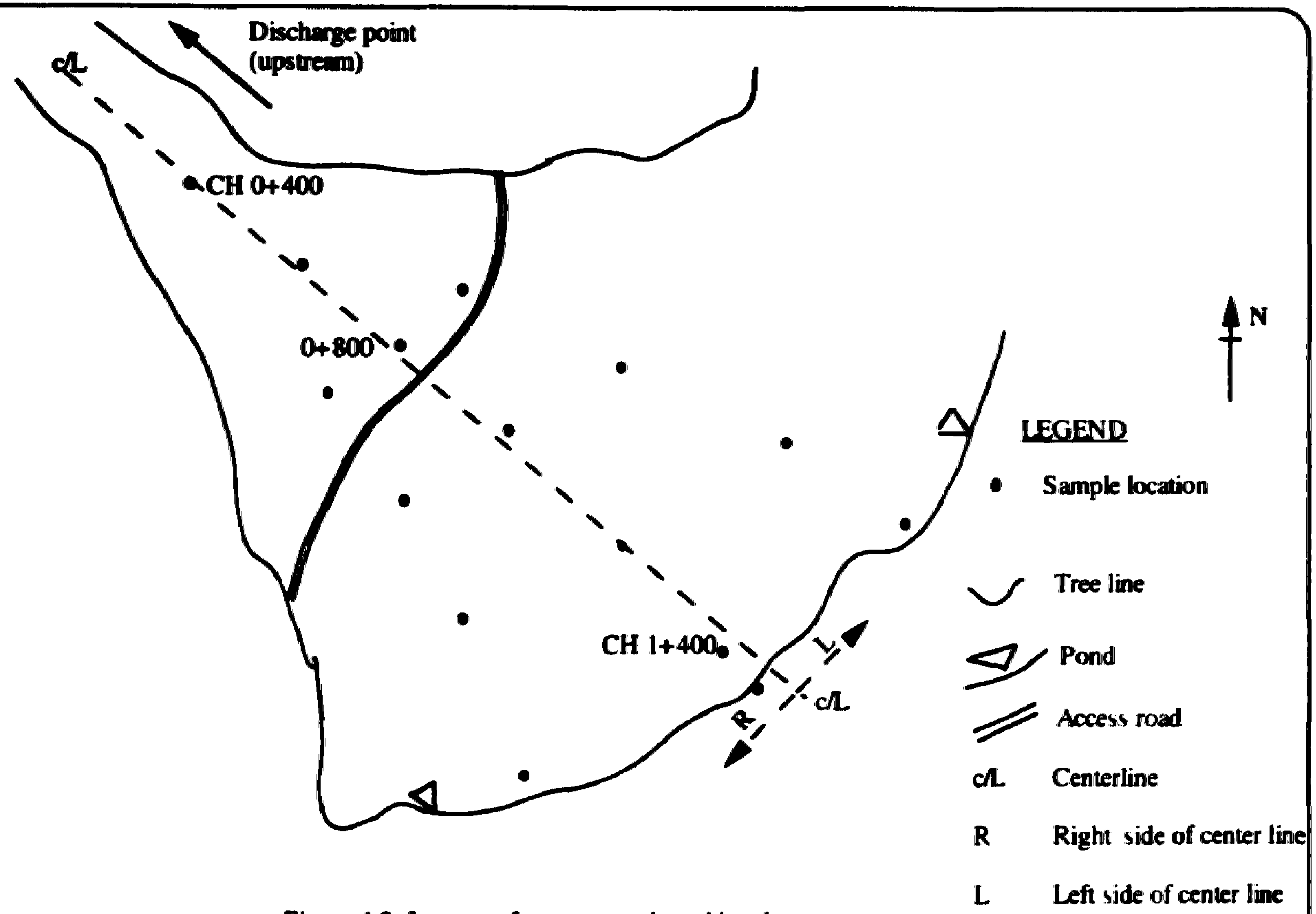


Figure 4.2- Layout of emergency depositional area
(Drawn not to scale)

CHAPTER V

DETERMINATION OF MATERIAL PROPERTIES OF AS-PLACED TAILINGS

5.1 Introduction

An elaborate and systematic laboratory testing program was undertaken to evaluate the geotechnical properties of samples obtained from the tailings deposit. The material tested were limited to the Brenda tailings samples retrieved from the emergency beach.

The tests were performed from August 1992 to May 1993. Conventional geotechnical tests were conducted using both reconstituted samples and specimen trimmed from undisturbed frozen samples. The tests were performed using standard ASTM procedures. The investigations were undertaken as part of an ongoing research to study the characteristics of mine wastes deposited by hydraulic depositional methods.

The results of the experiments are compared with that obtained from recent studies as well as trends in material properties observed from tests on similar deposits. Details of the various tests procedures are discussed herein and the results presented in Chapter VI.

5.2 Storage of samples

The disturbed samples contained in the 15 liter tightly covered rubber buckets did not require any elaborate storage facility. They were stacked and kept in the laboratory under ordinary room conditions. Appropriate quantities were taken when needed for specific tests.

The frozen samples were however, stored in a specially equipped temperature-controlled cold room at a constant temperature of -25°C. Precautions were taken to ensure that the frozen samples did not undergo any sublimation and thermal disturbance. On arrival from the mine site, the samples were rewrapped and placed in plastic bags. To prevent sublimation, efforts were made to evacuate all the air from the bag, forcing it by hand, before sealing. The frozen samples were extruded from the sample tubes only when they were required for the preparation of test specimens.

5.3 Method of extruding the frozen sample

Tap water was used to extrude the frozen samples from the sample tubes. The water was run on the outside cylindrical surface of the tubes. The tubes were rotated constantly with care taken to ensure water did not come into contact with the frozen samples. However, this was not always achieved as the water occasionally made contact with the bottom of the samples.

After a short run of the water, the adhesion between the frozen samples and the inside wall of the tubes was destroyed. This was recognized by a creaking sound. The frozen samples were then removed by gently pressing on the top surface. The extruded samples were wrapped in plastic bags and stored for a brief period to allow them to reestablish temperature equilibrium before being used for specimen preparation.

5.4 Preparation of specimens

Attempt was made to employ a milling machine mounted in the cold storage room and fitted with a 38 mm I.D. (40 mm O.D.) rotating bit to core a 38 mm diameter specimen. The rotating bit was cooled by compressed gas which was passed through carbon dioxide pellets. By passing the gas through the dry ice, it was expected that the temperature at the core bit would be substantially lowered to prevent any thawing of the frozen specimen.

Two difficulties were encountered with the use of the milling machine. First, the core barrel wobbled during the coring resulting in reduced cross sectional area of the specimen. Secondly, when the barrel penetrated deep into the sample, the cuttings could not be cleared readily. The cuttings thawed and became smeared on the surface of the specimen and the tip of the core bit, blocking the holes and subsequently preventing the compressed air from exiting. This prevented the cooling of the bit and sample as well as prevented removal of the cuttings. For the samples with high fines content, the blocking of the holes led to the freezing of the core barrel into the sample. The use of the milling machine was therefore abandoned.

Machining using a lathe was embarked upon to prepare the specimen from the frozen samples retrieved from the field. The samples were initially sawn into two, top and bottom sections. Each section was again sawn into halves along its length. The halves were then trimmed at the edges to fit into a circular fitting to be gripped by a lathe machine. The trimmings were used for the water content determination. Both the saw and the lathe are housed in the temperature controlled cold room.

The lathe was successfully employed to prepare the specimen required for the triaxial testing. However, due to pronounced depositional layering in some of the samples, a number of specimens were lost during the machining process. These specimens separated along the layers while the samples were being machined. The pieces were used for water content determination to verify the data obtained from the use of the trimmings for moisture content determination.

5.5 Determination of grain size distribution

The grain-size analysis attempts to determine the relative proportions of the different grain sizes constituting a given mass of the beach material. This is accomplished by obtaining the quantity of material passing through a given sieve opening but retained on a sieve of smaller sized openings and relating the retained quantity to the total sample. To achieve a significant result, it is required that the sample be statistically representative of the tailings deposit (Bowles, 1978).

Different soil classification systems are used in different countries. However, all the various systems use the No. 200 sieve as a dividing point resulting in two major classifications defined in terms of the amount retained or passing the No. 200 sieve. The two main classes are referred to as coarse grained soils and fine grained soils respectively. Each class can be further subdivided.

The Brenda tailings material is angular coarse to very fine grained, grayish green in color when wet and light gray colored when dry. It is derived from the mechanical processing of unweathered granodiorite rock containing copper and molybdenum ore. The grain size of the material in the tailings deposit were determined in this study to evaluate its spatial variation along the tailings beach.

5.5.1 Tests procedure

Tests were performed on thirty eight samples taken from the stored material. The weights of the samples used in the tests varied from 200 to 400 g depending on the quantity of material in the bulk sample. ASTM standard procedures (D 421-58) were followed to conduct the tests.

Weighed quantities of samples were obtained from the bucket of stored material by random spooning of the tailings. The samples were oven-dried, weighed and washed through No. 200 sieves. The material passing the No. 200 (-No 200) was discarded. The residues were carefully poured, using backwashing, into weighed containers. The suspensions were set for short periods until the top became clear. As much top clear water as possible was poured and the container and the remaining soil-water suspension kept in the oven to dry.

The oven-dried residues were weighed and run through stacks of U.S. standard #10, #20, #40, #60, #100, and #200 sieves. The stacks of sieves were placed in a mechanical shaker and sieved for ten minutes. After the shaking, the weight of material remaining on each sieve was obtained and the per cent passing computed. Where more than 12 per cent of the material passed the No 200 sieve (- No 200), hydrometer analysis was performed in addition to obtain an estimate of the grain size distribution from the No. 200 (0.075 mm) sieve to about 0.001 mm.

Semilogarithmic plots of grain size versus per cent finer were prepared. The spatial variation in grain size distribution of the Brenda tailings tested are presented and discussed in Chapter VI.

5.6 Determination of the specific gravity

The specific gravity of a soil, G_S, is required for the determination of the void ratio and useful for predicting the unit weight of the soil. It is also used in the hydrometer analysis. For a given soil mass, the specific gravity is taken as the average value for the soil grains and defined as the ratio of unit weight of the material to the unit weight of distilled water at 4 °C.

$$G_S = \gamma_{material} / \gamma_{water\ at\ 4^{\circ}C}. \qquad (5.1)$$

The specific gravity of the material in the Brenda tailings was determined and employed in computations where required. Twelve samples taken from different locations and depths were used and the average value calculated for use in further analysis.

5.6.1 Tests procedure

In each test, about 120 g of oven-dried samples was mixed in an evaporating dish to form a creamy paste. The paste was transferred to a malt mixer container and water added to make about 200 ml of soil-water mixture. The mixture was agitated for between 5 and 10 minutes.

After the mechanical mixing, the mixture was transferred with backwashing of all the soil, into to a volumetric flask. A sufficient volume of temperature-stabilized water was added to fill the flask to two-thirds to three-quarters full. The volumetric flask was initially weighed dry, carefully filled with deaired water to a volume mark and reweighed. The temperature of the water in the flask was taken.

To remove entrapped air from the mixture, the soil-water mixture was heated and allowed to boil for about 30 minutes. Deaired and temperature-stabilized water was added until the bottom of the meniscus was exactly at the volume mark. The neck above the calibration mark was carefully dried with a rolled paper towel. The temperature of the soil-water mixture was brought to within 1°C of the temperature of the water in the flask before weighing.

The flask and its contents were weighed to the nearest 0.01 g. The contents in the flask were emptied into deep evaporating dish and oven-dried. The oven-dried sand was weighed and the weight of the sand grains obtained. G_S was computed using equation 5.1.

Average values of G_S were calculated to the nearest 0.01 and taken as the G_S for the tailings at the given location. A normal distribution of the specific gravity results shows that the overall average G_s is within the fiftieth percentile of the test data obtained (figure 6.4a). Results of the specific gravity at different locations on the emergency beach are presented and discussed in Chapter VI.

5.7 Atterberg limits

The liquid and plastic limits are used primarily for identification and classification of soil. They are a measure of the shear strength of a given soil at a particular water content (Bowles, 1978). The liquid and the plastic limits are the moisture contents below which the soil behaves as a plastic and non plastic materials respectively. The plastic limit tends to increase in numerical value with decreasing grain size. For given grain sizes, the plastic limit tends to increase for soils with larger amounts of clay (Bowles, 1978).

The liquid and plastic limits were determined for the Brenda tailings deposit and are used in explaining the results obtained from consolidated undrained triaxial testing.

5.7.1 Test procedure

Liquid and plastic limits determinations were performed on four samples obtained at different locations along the center line of the beach. The samples were air-dried for seven days. Standard ASTM (D 4318 - 84) procedures were followed in performing the tests. The data from the tests are presented in Chapter VI.

5.8 Relative density determinations.

Relative density is often used as a criterion for controlling the quality of compaction in earthworks and embankments construction. Compressibility, shear strength and permeability are the engineering properties of a compacted fill which are of particular importance to a designer. When predominantly granular soils are employed as material for fill construction the relative density is frequently specified as the basis for compaction control (Lacroix *et al*, 1972).

ASTM Definitions of Terms and Symbols Relating to Soil and Rock Mechanics (D 4253 - 83) defines relative density as

$$R.D\ (\%) = (e_{max} - e_0) \times 100 / (e_{max} - e_{min.})$$

where $e_{max.}$ is maximum void ratio i.e. the reference void of a soil at the minimum density.

$e_{min.}$ is minimum void ratio i.e. the reference void ratio of a soil at the maximum density, and

e_0 is a given void ratio i.e., the insitu or stated void ratio of a soil deposit.

Tests were conducted to obtain all three densities required for the determination of the relative density of the Brenda tailings discharged onto the emergency area.

5.8.1 Tests procedure

Maximum and minimum density tests were performed in accordance with the procedures described in ASTM Standard Tests Methods for Maximum Index Density of Soils Using a vibratory Table (D 4253 - 83) and Minimum Index Density of Soils and Calculation of Relative Density (D 4254 - 83) respectively using oven-dried specimen.

The minimum density was determined by filling the standard ASTM mold to the brim using a scoop. The tailings sample was loosely placed by holding the scoop above the surface of the specimen. Precautions were taken to ensure the tailings sand slid gently onto the previously placed sand. A metal steel straightedge was used to level the surface of the sand with the top of the mold.

Tests to obtain the insitu density of the tailings were performed using cylindrical specimens prepared from the frozen samples. For each specimen, three linear measurements of length equally spaced around the cylindrical surface were made with vernier calipers and the average taken. Two measurements of diameter were taken at the two ends and the mid-length which gave six values. The average value was similarly obtained and taken as the diameter of a specimen.

With the mean values of each dimension, the volume of the specimen was computed. The specimen was then weighed to obtain its mass. The bulk density was then calculated by dividing the mass by the volume. The void ratios corresponding to each density were calculated for use in determining the relative density.

A vibratory table with a mold assembly attached to it was used for the determination of the maximum density. The mold was filled with the sample, striking the sides of the mold a few times in the process to settle the tailings sample. A surcharge base plate was placed on the surface of the sample and twisted slightly to ensure it was firmly and uniformly in contact with the surface of the sample. The mold assembly containing the sample was then vibrated for 8 minutes on the vibratory table.

The results of the densities and the void ratios together with other results related to tailings deposits reported by various writers are discussed in the Chapter VI.

5.9 Water content determination

Tests to determine the water content were performed using trimmings obtained during the specimens preparation. For a given sample, the cuttings were divided into either 4.5 or 5 cm layers from the top surface to bottom depending on the height of the sample.

The water content determined was considered as that for depths varying from 0 to 15 cm in order to obtain a sense of the changes in the water content across a given sample. For a sample, the water content was calculated as an average of four measurements. The test data from the water content determination are presented in Chapter VI.

5.10 Triaxial testing

To study the undrained behavior of the Brenda Mines tailings deposit, a series of consolidated undrained monotonic triaxial compression tests were performed using undisturbed samples obtained by insitu freezing. The frozen samples were cut and machined into 76 to 90 mm length and approximately 38 mm diameter specimens. The test specimens were set up in a triaxial cell following the standard procedure.

However, to prevent the specimens from thawing and collapsing prior to any application of load, the setting up was carried out in a cold room where a -10°C temperature was maintained. The triaxial apparatus and the rubber membranes were allowed time to cool before the specimens were mounted in the cell. Water to which a small quantity of antifreeze had been added was used as the cell fluid. The water was kept in a container fitted with a tap at the bottom. The container was placed in the cold room to allow the water to cool to the room temperature.

On setting up the sample, the triaxial apparatus was transferred to the laboratory maintained with room tempearture where under no drainage conditions, an all round confining pressure of 50 kPa was applied and the specimen allowed adequate time to thaw. Deaired water under gravity was percolated through the thawed specimen from the bottom end and drained at the top end to evacuate entrapped air out of the specimen.

After virtually all the air had been forced out of the specimen, the specimen was back pressure saturated. The all around cell confining pressure was initially increased to 60 kPa and a back pressure of 40 kPa was applied to the sample. Both the all around confining pressure and the back pressure were increased in steps of 60 kPa up to the maximum values that depended on the total confining pressure at which the specimen was to be sheared to failure. However, a constant effective confining stress of 20 kPa was maintain for all the specimen during the saturation stage. Adequate time was allowed for the sample pore pressure to stabilize after each total stress increment before recording the sample pore pressure.

The pore pressure parameter B was evaluated for every increment to establish the degree of saturation achieved. The specimen was considered to be fully saturated when the B parameter was obtained to be not less than 0.98. Summary of the results of evaluating the B parameter is presented in Table 6.5.

Maintaining the condition of no drainage, the specimens were isotropically consolidated by increasing first the cell pressure and then the back pressure to give the required effective stresses. The zero readings of the volume change device and the pore pressure at time zero were recorded. The valve which connected the specimens to the volume change apparatus was then opened to allow drainage to occur. The samples were generally consolidated to effective stresses greater than the estimated insitu effective stress for the depth at which they were obtained. The specimen void ratios at failure presented in Table 6.5 show that the specimens were consolidated to a medium to dense state except for the specimen retrieved from CH 1 + 400 c/L. After the consolidation, the drainage valves were closed.

The specimens were sheared under no drainage condition by applying axial load at constant vertical strain rate using a Wykeham-Farrace loading press triaxial apparatus. Figure 5.1 shows schematically the triaxial cell assembly. Shearing was continued until at least 20 % vertical strain was achieved. An electronic data acquisition system consisting of a microcomputer and a datalogger board was used to read and record the load cell, volume change and the various pressure transducers. The sample data, test conditions and summary of the results of six consolidated undrained triaxial tests are presented and discussed in chapter VI.

5.11 Summary and Conclusion

Standard ASTM tests procedures were used to obtain the index and strength properties of the Brenda Mines Ltd total tailings as discharged onto the emergency depositional beach of the mine. The tests performed have been described in this chapter. Presentation and discussion of the tests data and results shall be given in Chapter VI.

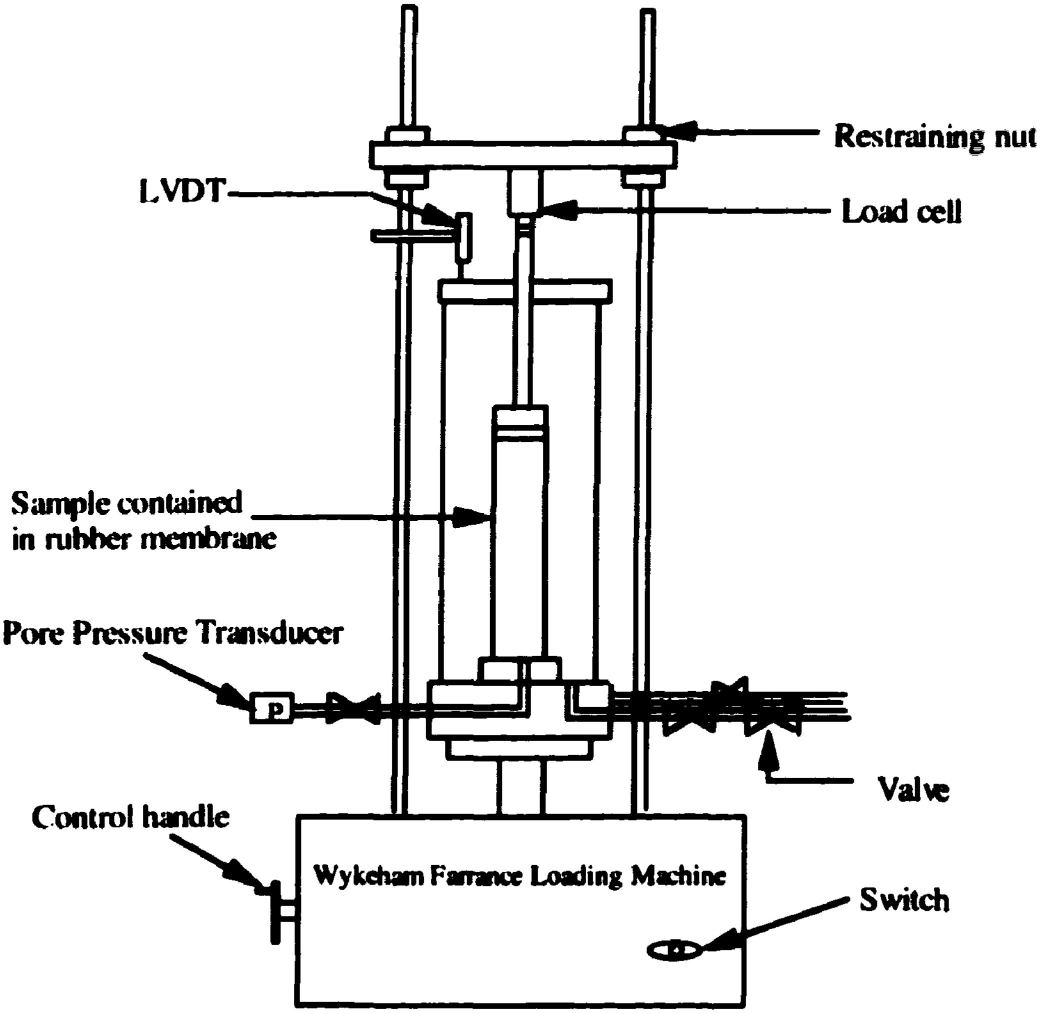


Fig. 5.1- Schematic of triaxial apparatus.

CHAPTER VI

GEOTECHNICAL PROPERTIES OF A TAILINGS DEPOSIT

6.1 Introduction

The susceptibility of the coarse tailings fraction to liquefaction and the permeability of tailings are two of the major geotechnical issues associated with the use of tailings as an embankment construction material. As mentioned in Chapter II, the need to store large volumes of tailings produced during the life of a mining operation is also an important consideration during development of a tailings management system.

Knowledge of the material properties of a given mine tailings is thus essential to the successful performance of a tailings impoundment structure and thus the mining industry. The construction of a tailings embankment in a seismic environment requires that the material be placed at a minimum relative density of 60 percent (Mittal, 1974). Being able to predict the profile of a tailings beach permits the assessment of the position of the pool and the tailings storage capacity (Blight *et al*, 1985). Keshian and Roger (1988) point out that the future reclamation of tailings deposits also requires the in-situ characterization of their material properties.

The index and strength properties of tailings which were hydraulically placed in the emergency depositional area of the Brenda Mines Limited have been studied. Elevation survey of the beach has been conducted to obtain the beach profile. The results of these laboratory and field studies are discussed in this chapter. While conducting the studies the samples were identified by the distance from the discharge point on the emergency depositional area at which they were retrieved.

The investigations were carried out with the aim of obtaining typical data in relation to the ongoing studies of hydraulic fills. It is hereby emphasized that the research project is not detailed enough, and was not intended to assess the performance of the tailings facilities referred to in this study. However, it is hoped that the research results from this thesis may be utilized to enhance the understanding and use of hydraulically placed tailings for future embankment design and construction.

6.2 Grain size distribution

Figures 6.1 and 6.2 present the areal and vertical distributions of the particle grain size along the emergency beach tailings. The surface deposits indicate that the emergency beach material varied within a relatively narrow range. However, the material close to the pond varied significantly in grain sizes (figure 6.1a). Electric cone friction ratio of the sandfill in the main tailings dam obtained from static cone penetration tests indicates that the sandfill consists of uniform sand with negligible amounts of silt and slime materials (Klohn Report, 1984). Figure 6.1b shows the range of the grain sizes of the main dam tailings. At a given location on the emergency beach, the grouping of the vertical distribution of the grain sizes is relatively close (figure 6.2) except at CH. 1 + 200 (figure 6.2c), where a greater amount of silt was deposited at a depth 120 cm.

Table 6.1 contains a summary of the various grain size parameters determined along the Brenda mine emergency tailings beach. The variation of these parameters for samples taken at the beach surface along the centerline are presented in figure 6.3.

Figure 6.3 shows that there is a slight overall reduction in the D_{10} (effective size), D_{50} (mean grain size) and D_{90} from the point of discharge towards the pond. However, the trend of the variations of the D_{50} and D_{10} sizes does not apply to the D_{90}. The D_{90} shows greater variation within the majority of the emergency beach deposit and greater decrease near the pond. Close to the pond, a sudden reduction in the three parameters is observed which reflects the deposition of the tailings below water.

The variation in the uniformity coefficients ($C_u = D_{60} / D_{10}$) and D_{90} / D_{10} are presented in figure 6.3b while figure 6.3c shows the fines content. The results indicate that the tailings deposit has a fairly uniform C_u. The quantity of fines does not vary significantly at the upstream section. A sudden increase in the fines content is however, observed in the material deposited close to the pond (Figure 6.3c).

6.2.1 Discussion of result

The particle grain size distribution curves show that the tailings slurry discharged onto the emergency beach behaved as a segregating mixture depositing predominantly medium to fine sand at the upstream portion of the beach (figure 6.1). The fine grained sandy silt tailings were transported and deposited further downstream close to the pond. The fines may have been initially deposited below the pond level but is presently exposed due to the subsequent lowering of the pond water level by pumping the stored water into the mined out pit. The grain size curves of the sand fraction are comparable to that of the sandfill in the main tailings dam.

The slight reduction in D_{10}, D_{50} and D_{90} with distance along the beach (figure 6.3) are consistent with the effect of hydraulic sorting in a segregating slurry which is placed by hydraulic deposition (Küpper, 1991). The values of D_{60}/D_{10} and D_{90}/D_{10} presented in figure 6.3b exceeded 2.5 and 5 respectively, and suggest that hydraulic sorting is occurring (Küpper, opt cit).

Küpper, (opt cit) referring to Yufin (1965) and Melent'ev *et al*, (1973) points out that higher flow rates, lower slurry concentrations and small flow velocity along a beach tend to promote hydraulic sorting. Hydraulic sorting in the Brenda tailings may have resulted from the relatively high flow rate of 0.65 m^3/s when discharged to the emergency beach and the lower slurry concentration deposited (30 % solids by weight; Brown, 1992). No data is available on the flow velocity along the beach but predictions from the configuration of the valley containing the emergency beach suggest it is probable that flow of tailings began at a high velocity in the narrow upstream section and decreased significantly as the beach width increased allowing the flowing sand to spread laterally and for the flow velocity to decrease significantly. Thus, the specific flow rate decreased with increasing distance along the beach, a condition which enhances the segregation of the flowing slurry as previously discussed.

6.3 Atterberg limits

Tests to determine the liquid and the plastic limits were abandoned when the tailings sample containing the highest percentage of fines showed non plastic behavior. It was inferred that the remaining tailings samples would similarly be non plastic.

6.4 Specific gravity

The results of the specific gravity tests are presented in Table 6.2. The values of the specific gravity range from 2.72 to 2.80. An average value of the specific gravity is calculated for a given sample location and the variation of the specific gravity with distance from the point of discharge plotted as shown in figure 6.4a. An overall mean value of the specific gravity is determined to be 2.74 which lies within the fiftieth percentile of the test data (figure 6.4b). This value was used in all the computations requiring the specific gravity.

6.4.1 Discussion of results

The specific gravity of the Brenda beach tailings material is found to be fairly constant. The value of the specific gravity is higher than for most sands due to the presence of heavy minerals in the tailings. The high specific gravity of the downstream deposits may be attributed to high percentage of heavy minerals such as magnetite in the finer grained material which would be carried along the beach (Kuerbis, 1989).

The measured value of the specific gravity compares well with those obtained and reported in other investigations (Klohn, 1984; Kuerbis, 1989) and included in Table 6.2.

6.5 Densities and void ratio of beach material

Table 6.3 shows the summary results of the in-situ water content, densities and void ratios determined for the tailings material. The in-situ and laboratory moisture content ~ density relationship is plotted in figures 6.5a and 6.5b, respectively. The variations of densities, void ratio and the relative density along the emergency beach are presented in figures 6.6 to 6.8.

Figure 6.5 shows that in-situ dry density of about 100% standard Proctor was attained at some portions of the emergency beach. However, compaction from construction traffic may account for the high density of the samples obtained from CH 0+800 c/L.

The variations in the densities of the tailings specimens along the beach show irregular patterns. The bulk density initially increases with distance from the point of discharge, then decreases to a minimum value and increases near the pond (figure 6.6a). The maximum dry density increases slightly along the beach and remains nearly constant, then slightly decreases and increases again toward the pond. The minimum dry density shows an initial decrease, becomes constant, then decreases again and increases near the pond. The in-situ dry density initially increases with distance from the point of discharge to a maximum value and then decreases steadily towards the pond. It ranges from 1.328 to 1.618 Mg/m^3. The maximum bulk density and the highest insitu dry density occur at CH 0 + 800 c/L which is located about mid length of the emergency beach. The insitu bulk density range from 1.507 to 1.920 Mg/m^3.

Measurements from undisturbed samples retrieved at the surface of the tailings dam indicate that the initial in-situ dry density of the hydraulically-placed cycloned sand ranged from 1.413 to 1.530 Mg/m^3 with an average of 1.456 Mg/m^3 (Table 6.4). The introduction of cell construction methods altered the surface densities. The upper 0.6 m of sandfill in a construction layer within a cell was compacted to densities varying from 1.472 to 1.547 Mg/m^3 with an average of 1.519 Mg/m^3 (Klohn Report, 1984).

The bulk and dry densities of undisturbed samples obtained at varying depths in the main dam indicates that the densities increase with depth (Klohn Report, opt cit). The density increase with depth is most pronounced near the surface and becomes gradual at depth. In-situ densities obtained by continuous logging of nuclear probes (figure 6.6b) confirm that the densities determined using undisturbed samples retrieved at discrete locations do represent a continuous density profile of the dam tailings.

Table 6.3 indicates that the void ratio of the emergency beach tailings deposit is a minimum at the water content corresponding to the highest in-situ dry density. The in-situ voids varied between 0.693 and 1.064. The insitu void ratio initially decreased with distance from the discharge point and then increased steadily towards the pond (figure 6.7). Both the insitu dry density and void ratio show similar consistent variations in trend. It is interesting to note the relatively high void ratio of the material deposited at CH. 0 + 400 c/L which is close to the point of discharge.

Figure 6.8 presents a plot of relative density versus distance from the discharge point. It can be observed that there is no defined pattern in the variation of the relative density along the beach. The loosest materials are deposited near the pond and close to the point of deposition of the tailings respectively. The densest material is obtained at approximately the mid length of the beach. The relative density ranged from 28 to 73% with an overall average value of 52%.

Results from static CPT carried out on the main dam and contained in Klohn's Report (1984) indicate that the relative density of the sandfill ranged from 40 to 80% (figure 6.8 b). These relative densities were obtained using Schmertmann's (figure 6.8c) and Baldi *et al* correlations between the electric cone bearing values and relative densities for normally consolidated, saturated, uncemented fine sands. The bearing values were found to increase with increasing depth.

However, cone bearing values of the beach tailings were found to be considerably lower than those of the dam fill at corresponding elevation and decreased with increasing distance from the center-line at any given elevation. It therefore suggests that finer tailings material was deposited in the pond becoming less consolidated with increasing distance from the dam. The relative densities of the main dam tailings were also estimated from SPT data using Gibbs and Holtz and Bazaraa correlations as ranging from 50 to 70% and 40 to 60% respectively.

6.5.1 Discussion of results

The in-situ water content - density relationship of the Brenda tailings shows that the hydraulic deposition process resulted in material attaining densities comparable with the optimum dry density from laboratory standard compaction test (figure 6.5). The mean density of the emergency beach deposit is slightly higher than the mean density of the uncompacted hydraulically placed cycloned sand in the main tailings dam (Table 6.4). However, greater variation in the measured density occurred within the emergency beach deposit compared to the cycloned sand in the main dam.

The density of a granular material is affected by factors such as grain size distribution, shape of grains, roughness of the grain surface and the level of energy associated with the depositional environment. In hydraulic fills, high flow rates and low slurry concentrations are known to cause an increase in beach density by creating a high energy environment associated with a low rate of deposition, but it may also cause a decrease in density by accentuating hydraulic sorting and depositing a uniform material (Küpper, 1991).

Figure 6.8a shows that the variation of the relative density along the beach is irregular. The relatively loose sand close to the point of discharge may have resulted from material being deposited downslope of a fanhead entrenched channel. As mentioned in section 4.2, this location is near the end of a channelized zone which formed during the deposition and building of the emergency beach.

In the study of alluvial fans temporary or permament entrenchment of channels near the apex of the fan is a common and hydraulically important characteristics (French, 1987). The apex is the highest elevation on an alluvial fan and occurs where the stream responsible for the formation of the fan emerges from a mountain. Channel entrenchment occurs when erosion rather than deposition takes place at the apex.

French (opt cit) reviews some of the explanations suggested for the formation of fanhead entrenchment of flow channels. In one of the explanations it is noted that rare flow events such as large-scale flooding which has a greater sediment transporting capacity may cause temporary channel entrenchment. It is suggested that frequent flow events result in aggradation of the channels. However, a series of moderate flow events with low sediment loads can also cause degradation and channel entrenchment.

The material eroded at the point of channel entrenchment is redeposited further down the fan. Fanhead trenches act therefore as conduits for the material entering the fan from the apex. The effect is that coarse and loose material is deposited downslope of the fanhead entrenched channel (French, opt cit).

At the Brenda Mines the configuration of the valley containing the emergency beach and the mode of slurry discharge to the beach as discussed in section 2.5 suggest that the formation of fanhead entrenchment was possible. The high energy flow of the tailings likely promoted flow dynamics of the chute-and-pool conditions (Küpper, opt cit) in which the previously deposited material was eroded and transported by the high energy flow of the chute and thrown into suspension by a hydraulic jump at the end of the chute. A subcritical flow in the pool immediately after the hydraulic jump could cause the material in suspension to be rained down to form a loose deposit. Such flow characteristics would easily occur in a fanhead entrenched channel and may account for the presence of the loose sand deposited upstream of the emergency beach.

The low relative density of the material near the pond suggests that the tailings were initially deposited below water. Here, lowering of the pond water level also may have led to an artificial oversteepening of the previously underwater slope and disturbing the already loose deposit (Küpper, 1991).

Relative density is widely used to define and control the quality of compaction within granular fills. In the construction of tailings embankments, compaction control is often used to reduce the danger of any potential liquefaction failure. This is controlled by specifying a minimum relative density for the compacted material. In-situ relative density of 60% or greater are required to ensure a reasonable safety against failure by liquefaction (Mittal, 1974). Specifications for rolled sand fill usually require compaction to 70 per cent relative density or greater. Poulos and Hed (1972), however cite the case where relative density of 50 per cent or less was achieved during hydraulic filling yet the fill was still considered satisfactory.

Hydraulic fills usually consist of clean sands compared to rolled fills which generally contain more fine grained materials. Rolled fills are more likely to have non uniform density because they are normally placed at water contents that encourage bulking while being compacted.

The emergency beach tailings have an average relative density of 52%. The high relative density of 72.7% of the sample retrieved from CH 0 + 800 c/L maybe due to compaction provided by construction traffic using the access road that passed close to this location. However, samples which were taken from two other locations far from the access road attained relative densities greater than 60 per cent.

Table 6.4 compares the densities of the Brenda tailings as reported by various investigators. The results of the densities of the tailings deposit presented in this chapter show that relatively high densities were achieved within the unengineered hydraulic fill deposition. It is thus probable that if the method of direct hydraulic placement were optimized the overall density of the fill could have been substantially improved without the use of additional compaction effort or use of methods to preferentially remove the fines fraction prior to placement of the fill.

6.6 Shear strength

The stress ~ strain curves, stress paths and pore pressure change for each of the consolidated undrained triaxial test are presented in figures 6.9 to 6.14. The triaxial tests results were not corrected for membrane penetration as the maximum mean grain size was smaller than the thickness of the membrane used. The stress ~ strain and the pore pressure curves are plotted respectively in the form of deviatoric stress and pore pressure change versus axial strain. The effective stress paths are illustrated in terms of the mean shear stress against the mean normal stress plane (q ~ p').

The stress - strain curves presented in figures 6.9a to 6.14a indicate that the Brenda tailings exhibit post peak strain hardening characteristics. The specimens continued to gain in strength with increase shearing until the steady state line was reached thereafter the samples began to fail. Strain localization resulting in nonhomogenous deformation occurred in the samples after they steady state line was reached. failure strengths were only reached at strains ranging from 9 to 23 %. The pore pressure response (figures 6.9b to 6.14b) and the effective stress paths (figures 6.9c to 6.14c) indicate a consistent dilative behavior of the tailings specimens.

6.6.1 Discussion of results

Pitman (1993) summarizes the stress - strain behaviors that can be observed from undrained monotonic triaxial testing on a sand and groups them into three response types (figure 6.15a). According to this grouping, Types 1 and 2 exhibit strain softening responses which may lead to liquefaction failure or partial or limited liquefaction respectively. A sand which behaves in either mode is referred to as having a contractive behavior during undrained loading.

In Type 1 response, the strain softening behavior is highly pronounced. The peak strength is attained at a relatively small strain. The sand exhibits a remarkable loss in resistance with continuous shearing after the peak strength is reached. Type 2 response represents a transition stage in which the strength of the specimen decreases to a residual value and then increases again. Type 3 soils, referred to as dilative, exhibit a strain hardening behavior in which the postpeak strength increases with continuous shearing.

Figure 6.15b presents the corresponding effective stress paths associated with the three response types.

The dilative behavior of the specimens obtained from this study consisting of consolidated undrained tests are consistent with the dense state at which the tailings were deposited (figures 6.10, 6.11, 6.13). However, the behaviour of the tailings which were deposited loose and are shown in figures 6.9, 6.12 and 6.14 were expected to exhibit a contractive response similar to either Type 1 or Type 2, whereas, they showed a dilative response until failure was reached. These specimens had relative densities of approximately 30% but contained significantly different amount of fines. The data shown in figure 6.9 and 6.14 were for specimens prepared from the same undisturbed sample containing 6% fines but tested at different effective confining stresses while figure 6.12 shows the behavior of a sample containig 69.9% fines.

More detailed tests data is required from consolidated undrained triaxial tests on similar tailings specimens before one can establish firm conclusion about the behavior shown in figures 6.9 and 6.14. However, the failure void ratios, e_f of these specimens shown in Table 6.5 indicate that the specimens were consolidated to dense and medium dense states prior to shearing. Results reported by Klohn Leonoff Ltd (1984) show a similar dilative response in a fine, predominantly non stratified cycloned sand containing about eight per cent non-plastic fines (Figure 6.16).

Figure 6.17 is a plot of the steady state/critical void ratio line for the Brenda cycloned sand obtained by substituting values for the state boundary constants Γ and λ into equation 6.1 (Sasitharan, 1993).

$$e = \Gamma - \lambda \ln p' \qquad (6.1).$$

The in-situ void ratios of the samples and the void ratios of the specimens at the end of consolidation are also plotted in figure 6.17. The results show that with the exception of the specimen retrieved from CH 1+ 400 c/L, all the specimens tested were consolidated to states which were dense of the steady state line obtained for the cycloned material.

The results presented in figure 6.12 were obtained from the tailings specimen taken from CH 1 + 400 c/L. The particle grain size distribution curve for the sample (figure 6.1) shows that the sample is predominantly silt with approximately 69.9% of non plastic fines. Kuerbis *et al.* (1989) reporting on the Brenda tailings sand established that the dilative behavior of the tailings sand under undrained monotonic triaxial compression is enhanced when the test samples have increased silt content. This trend was also observed by Pitman (1993). The effective stress response obtained in this study (figure 6.12c) is therefore consistent with these two observations.

Consolidated undrained triaxial results from tests conducted on the Brenda tailings sand and reported by others indicate that the behavior of the tailings sand ranges from contractive to moderately and highly dilative (Klohn Leonoff, 1984; Kuerbis *et al*, 1989). Whereas the material tested in this study was obtained from insitu sampling of the total tailings, the materials in the other two studies were obtained from the main dam which was constructed by first cycloning the tailings sands to remove much of the fines. The samples tested were then reconstituted from the undisturbed material obtained from the dam. Pitman (1993) argues that sands which have sufficiently high plastic or non plastic fines contents will exhibit purely dilative behavior and that purely contractive behavior which will result in collapse liquefaction flow failures will only occur in clean sand containing little or no fines.

Loose, saturated sands have a great tendency to contract. Such sands are unstable and the application of shear stress causes the inter particle structure of the sand to decrease in volume or contract. If no drainage is allowed during shear, rather than a volume decrease a large build up in pore pressures occurs allowing the shear resistance of the sand to decrease from the peak strength to a lower value known as the steady state strength.

Liquefaction occurs when the saturated sand loses a large percentage of its shear resistance and can flow in a manner resembling a liquid until the internal shear stresses acting on the mass reduce to the steady state strength. For liquefaction to occur a triggering mechanism consisting of monotonic or cyclic load application to overcome the peak strength must be made available.

The results of the consolidated undrained triaxial tests on specimens of the Brenda tailings deposited in the emergency beach presented herein suggest that relatively stable deposits were formed from the hydraulic fill deposition process. The tailings samples are found to exhibit post peak strain hardening at low to relatively high confining pressures. The samples, however, required substantial deformation before they reached their ultimate resistance after which nonuniform deformation began to occur.

A modified Mohr plot presented in figure 6.18 shows the effective friction angle, ϕ', of the tailings material ranges from 35° to 39°. Figure 6.18 is obtained by plotting the mean shear stress, q at failure against the corresponding mean normal stress, p', for all the tests. The high ϕ' results from the high degree of particle angularity which are characteristics of mineral processing tailings.

Figure 6.19a shows a typical specimen set up in the triaxial apparatus prior to shearing. Few of the specimens failed by bulging (figure 6.19b) while others failed by shearing along a relatively defined plane inclined at approximately 30° to the plane of the deviator load (figure 6.19c). Table 6.5 presents a summary of the sample data, tests conditions, and summary of the results for six consolidated undrained monotonic triaxial compression tests.

It can be observed from Table 6.5 that specimens consolidated to the same effective confining stresses exhibited different failure conditions. The variations in the peak stress conditions may be attributed to the different total confining stresses on the specimens (Figures 6.9a-6.14a) and the void ratios, e_c at the end of consolidation.

Specimens consolidated to higher total confining stresses sustained higher peak effective normal stresses and generated corresponding higher pore water pressures. Table 6.5 shows that the specimens obtained from CHs 1 + 200 and 1 + 400 which were consolidated to the same total and effective confining stresses but different void ratios showed different peak values of σ'_1 and u_f. The two specimens which were of different heights, however, failed in a similar mode. The variation in the peak values of σ'_1 and u_f observed may therefore be due to the difference in the consolidation void ratios of the specimens. The more dense specimen sustained higher effective normal stress and generated lower pore pressure. Table 6.5 also shows variations in minimum effective stresses and the axial strains at failure. However, no defined trend in the variations was observed.

6.7 Beach profile

Figure 6.20 presents the slightly concave longitudinal profile measured along the assumed centreline of the Brenda Mine's emergency tailings beach. The slope of the emergency beach is calculated using two points - one at the upstream section (CH 0 + 400 c/L) and the other at the downstream (CH 1 + 200 c/L) respectively. The measured slope is compared with the overall slope provided by the mine. The slope of the emergency beach is also estimated using the empirical relationship proposed by Küpper (1991). Utilizing data provided in the literature, the empirical relationship is used to determine the slopes of two other tailings beach reported by Boldt (1988).

The results of the measured beach slopes are compared with the calculated for all the beaches (Table 6.7). Section 6.7.1 summarizes and discusses the results of the estimated and measured beach slopes in relation with the mechanisms of fill formation.

6.7.1 Discussion of results

The importance of an accurate estimation of the slope of a tailings beach has been stressed by various writers. Melent'ev *et al*, (1973) show that the slope formed by hydraulically placed granular materials can be represented by a dimensionless "master profile" as;

$$\frac{h}{y}=\left(1-\frac{H}{x}\right)^{n}, \tag{6.2}$$

where the parameters are defined in figure 6.21. n is a material property that can be determined in laboratory.

The master profile is a normalization of the slope profile of the beach. It is considered to apply to all slopes constructed of a similar material regardless of the beach length or the elevation difference between the slurry discharge point and the pond. The formation of a master profile suggests that the depositional characteristics, modes of sediment transport and profile formation are consistent for any slope (Conlin, 1989).

The concept of the master profile has been discussed by Blight (1987), Wates *et al*, (1987), Blight and Bentel (1983) and Küpper (1991). Küpper (1991) also reviews other relationships proposed by many investigators, then discusses the limitations associated with the use of the available empirical equations to predict the overall slope of a tailings beach and suggests a dimensionless parameter, P' to estimate the overall slope of a hydraulic fill beach as

$$i_{av}=5\sqrt{P'},$$

where

$$P'=\frac{AC_w\sqrt{g(G-1)D_{50}}}{Q} \tag{6.3}$$

and $$G = \rho_s / \rho_w.$$

The various parameters which affect the overall slope of the tailings beach and used in equation 6.3 are defined as

C_W	is the slurry concentration in terms of weight
D_{50}	the mean grain size [L]
g	the acceleration of gravity [LT^{-2}]
ρ_s, ρ_w	the specific weights of the grains and water respectively [FL^{-3}]
Q	the total flow rate at the discharge point [L^3T^{-1}]
A	the area of the discharge pipe [L^2]

The dimensionless parameter P' represents the ratio between gravitational forces and inertial forces and allows tests performed at different scales such as laboratory flume and field tests to be normalized according to Küpper (opt cit).

To utilize equation 6.3 a record of reclaim and fresh water discharged into the tailings pond at the Brenda mine from the period January 1988 to December 1990 was obtained as shown in Table 6.6. The total tailings discharged into the pond, Q is estimated as water from mill to reclaim pond with tailings = reclaim water + two-thirds of fresh water (Brown, 1992), which gave a value of Q to be used in equation 6.3 of 0.65 m^3/s. The following quantities were also obtained for use in equation 6.2, $C_w = 30$ %, $D_{50} = 0.275$ mm, $G = 2.74$, $d = 0.61$ m and $g = 9.81$ m/s^2. Substituting these values into equation 6.3 gives the overall slope, i_{av}, of the emergency beach as

$$i_{av} = 4.8 \%.$$

The average slope of the beach computed from the plot of the levels taken at the emergency depositional area was 1.48 %. In measuring the slope of the emergency beach the upstream point was taken about 400m from the start of the beach. Thus, about one-third the length of the beach was not considered. However, calculation of the beach slope from the topographic map of the tailings facility gave a maximum slope of the emergency beach as 1.7%. The slope of the beach was also furnished by the mine authority as varying from about 2 % at the upstream section to 1 % at the downstream section (Brown, 1992) which gave an average slope of 1.5 %.

It can be seen therefore that the slope of the beach profile measured from the levels taken during the field sampling approximately represent the slope of the profile of the emergency beach. The overall slope calculated using the P' parameter is, however, about three times the actual measured values for the beach.

As mentioned in section 4.2, at the time of the fieldwork the emergency beach had been manually reworked. It is most probable that the beach slope was slightly altered in the process. The leveling of the beach to facilitate the revegetation program might have involved moving some of the in-placed material from the upstream section and depositing it downstream, thus, reducing and increasing the upstream and downstream slopes respectively. The result is that the overall slope of the beach is likely to have been made less steep than that of the as-placed condition. It is however, unlikely that the slope was altered to such an extend as to explain the difference between the predicted and actual slopes of the emergency beach.

The difference in the measured and predicted slopes of the beach profile maybe attributed to the method by which the emergency beach was formed as explained in 2.5. A possible high energy flow of the tailings at the narrow upstream section probably eroded previously deposited material and redeposited further downstream. Thus, the profile of the beach was made flatter reducing the overall slope. In conventional tailings beach, slopes of 4.5% from spigotted discharge have been reported (Yano and Handford, 1990).

Table 6.7 presents the discharge characteristics and the measured beach slopes of tailings deposited in two field studies and reported by Boldt (1988). Using the data presented, the beach slopes are calculated using the P' parameter for each run and compared with the measured slope. It is found that the calculated slopes are always greater than the measured slopes. However, the trend is similar to that observed in the case of the Brenda mine tailings.

The P' parameter can be said to give an estimate of the initial undisturbed slope of a beach profile formed under normal flow conditions. In this study the slope of the hydraulic fill emergency tailings beach could not be predicted using the P' parameter.

6.8 Summary and conclusion

The results of the laboratory tests on specimens of the Brenda total tailings presented in this chapter give the geotechnical characteristics of the depositional environment. Index and strength properties obtained show that the hydraulic method of depositing the tailings slurry yielded beach material with satisfactory engineering properties comparable to the properties of the sandfill in the main dam. It is interesting to note that no engineering consideration was given to the deposition at the emergency area (Brown, 1992).

The particle grain size distribution curves of the samples taken from different points on the beach show that the solid fraction of the tailings slurry has relatively uniform grain size. However, the depositional process resulted in hydraulic sorting along the beach.

The in-situ densities of the emergency beach deposits are comparable with densities of the same tailings material derived from cycloned sand and hydraulic cell construction method and used in the construction of the main tailings dam. The relative densities obtained in this study suggest that the hydraulic discharging of the slurry at the emergency beach yielded nonliquefiable tailings deposit in the large central portion of the beach. It is seen that phenomena such as fanhead channel entrenchment and deep channelling which contribute to the deposition of loose and/or coarse material in alluvial fan delta have similar effects in hydraulic deposition of the tailings as outlined by Küpper (1991).

The stress-strain response from consolidated undrained monotonic triaxial compression tests on the tailings specimens indicate that the tailings behave in a dilative mode at low and high confining stresses. The dilative response of the specimens increases with increasing silt contents.

Level survey shows that the emergency beach has slightly concave longitudinal profile. The measured slope of the beach profile is found to be about three times less than that estimated using an empirical relation proposed by Küpper, (opt cit). A high rate and energy of deposition from sporadic discharge of tailings slurry onto the emergency beach caused a much smaller beach angle.

Though the single point gravity discharge of tailings slurry at the Brenda mine emergency area was not designed as an engineering structure, most of the resulting characteristics of the deposited tailings suggests that the material formed a stable fill.

Table 6.1- Grain size parameters of tailings deposit

Sample	Dist. (m)	Depth (cm)	D_{10} (mm)	D_{50} (mm)	D_{60} (mm)	D_{90} (mm)	$C_u = D_{60}/D_{10}$	% < #200	D_{90}/D_{10}
0 +400 c/l	400	0	0.12	0.50	0.35	0.60	2.92	6.00	5.00
0 + 600 c/l	600	0	0.14	0.32	0.35	0.68	2.50	5.47	4.86
0 + 800 c/l	800	0	0.13	0.29	0.32	0.60	2.46	5.93	4.61
0 + 800 c/l	800	30	0.13	0.33	0.37	0.60	2.82	6.10	4.61
0 + 800 c/l	800	60	0.15	0.37	0.40	0.64	2.68	5.62	4.29
0 + 800 c/l	800	90	0.15	0.37	0.40	0.66	2.68	5.50	4.40
0 + 800 c/l	800	120	0.14	0.33	0.36	0.66	2.58	6.31	4.71
0 + 800 R	800	0	0.12	0.32	0.36	0.60	2.91	5.90	4.88
0 + 800 R	800	30	0.14	0.27	0.33	0.55	2.38	4.78	3.93
0 + 800 R	800	60	0.13	0.32	0.37	0.60	2.82	7.79	4.61
0 + 800R	800	90	0.11	0.30	0.36	0.63	3.26	6.80	5.73
0 + 800 R	800	120	0.10	0.30	0.34	0.65	2.17	2.48	6.50
0 + 800 L	800	0	0.11	0.29	0.32	0.58	2.82	7.06	5.27
1 +000 c/l	1000	0	0.09	0.25	0.29	0.60	3.07	8.00	6.38
1 +000 c/l	1000	30	0.16	0.34	0.40	0.72	2.50	5.50	4.50
1 +000 c/l	1000	60	0,09	0.28	0.31	0.60	3.44	8.30	6.67
1 +000 c/l	1000	90	-	0.32	0.38	0.70	-	21.77	
1 +000 c/l	1000	120	-	0.35	0.60	8.76	-	26.28	
1 +000 R	1000	0	0.09	0.15	0.28	0.42	3.11	7.60	4.67
1 +000 R	1000	30	0.10	0.25	0.29	0.42	2.90	7.36	4.20
1 +000 R	1000	60	0.10	0.25	0.26	0.42	2.59	7.36	4.20
1 +000 R	1000	90	-	0.24	0.25	0.40	-	11.61	
1 +000 R	1000	120	0.12	0.28	0.32	0.56	2.67	6.21	4.67
1 +200 c/L	1200	0	0.09	0.26	0.29	0.42	2.89	64.23	4.67
1 + 200 R	1200	0	-	0.20	0.24	0.38	-	11.60	
1 +200 R	1200	30	-	0.19	0.21	0.35	-	12.70	
1 +200 R	1200	60	0.10	0.25	0.29	0.40	3.02	5.86	4.17
1 +200 R	1200	90	0.07	0.25	0.30	0.60	3.33	9.84	8.00
1 +200 R	1200	120	0.07	0.25	0.27	0.42	3.86	9.57	6.00
1 + 200 L	1200	0	0.03	0.16	0.20	0.30	5.88	13.08	8.82
1 + 200 L	1200	30	0.03	0.17	0.20	0.20	6.67	11.88	9.00
1 + 200 L	1200	60	-	0.12	0.14	0.20	-	31.31	
1 + 200 L	1200	90	-	0.10	0.13	0.25	-	42.43	
1 + 200 L	1200	120	-	0.03	0.04	0.10	-	84.65	
1 + 400 c/L	1400	0	0.02	0.06	0.06	0.15	3.10	69.90	7.50
1 + 400 c/L	1400	30	-	0.07	0.08	0.18	-	50.02	
1 + 400 c/L	1400	60	-	0.07	0.12	0.13	-	35.79	
1 + 400 c/L	1400	90	-	0.07	0.14	0.02	-	33.43	4.40
1 + 400 c/L	1400	120	0.08	0.11	0.17	0.23	2.25	7.45	2.88
1 + 400 R	1400	0	0.13	0.22	0.24	0.39	1.80	1.20	3.00
1 +400 L	1400	0	0.02	0.07	0.08	0.21	4.00	35.61	10.50
Underwater	1410	0	0.02	0.04	0.06	0.14	3.00	74.74	7.00

Table 6.2 Specific gravity of tailings material

Sample	Dist.(m)	Depth (cm)	Specific gravity
0 + 400 c/L	400	0	2.72
0 + 800 c/l	800	0	2.80
0 + 800 R	800	0	2.73
1 + 000 c/L	1000	90	2.74
1 +000 c/L	1000	120	2.74
1 + 200 c/L	1200	0	2.72
1 + 200 L	1200	0	2.73
1 + 200 L	1200	30	2.72
1 + 200 L	1200	60	2.76
1 + 200 L	1200	90	2.74
1 + 200 L	1200	120	2.79
1 + 400 c/L	1400	30	2.77
1 + 400 c/L	1400	60	2.75
1 + 400 c/L	1400	90	2.76
1 + 400 L	1400	0	2.73
Underwater	1410	0	2.73
Klohn (1984)			2.70
Kuerbis (1989)			2.72

Table 6.3- Index properties of tailings samples.

Sample	w (%)	γ_w (Mg/m^3)	γ_d (Mg/m^3)			e			D_r (%)
			in-situ	min.	max.	in-situ	min	max.	
0 + 400 c/L	11.60	1.626	1.457	1.356	1.741	0.881	0.574	1.021	31.34
0 + 800 c/L	18.63	1.920	1.618	1.326	1.764	0.693	0.553	1.066	72.78
1 + 000 c/L	14.61	1.792	1.564	1.327	1.761	0.752	0.556	1.065	61.39
1 + 200 c/L	7.39	1.507	1.403	1.183	1.562	0.953	0.754	1.316	64.70
1 + 400 c/L	35.29	1.796	1.328	1.229	1.679	1.064	0.632	1.229	27.72

Table 6.4 - Densities of Brenda tailings deposits

Location of tailings	Dry density (Mg/m^3)		Reference
	range	mean	
Initial cycloned sand (hydraulic cell)	1.414 - 1.529	1.455	Klohn Report (1984) Lighthall, *et al, (1989)*
Dozer compacted sand	1.470 - 1.550	1.520	
Sand unaffected by dozer	1.410 - 1.530	1.460	Lighthall *et al*, (1989)
Emergency beach	1.328 - 1.618	1.470	Current study

Table 6.5- Consolidated undrained triaxial tests results

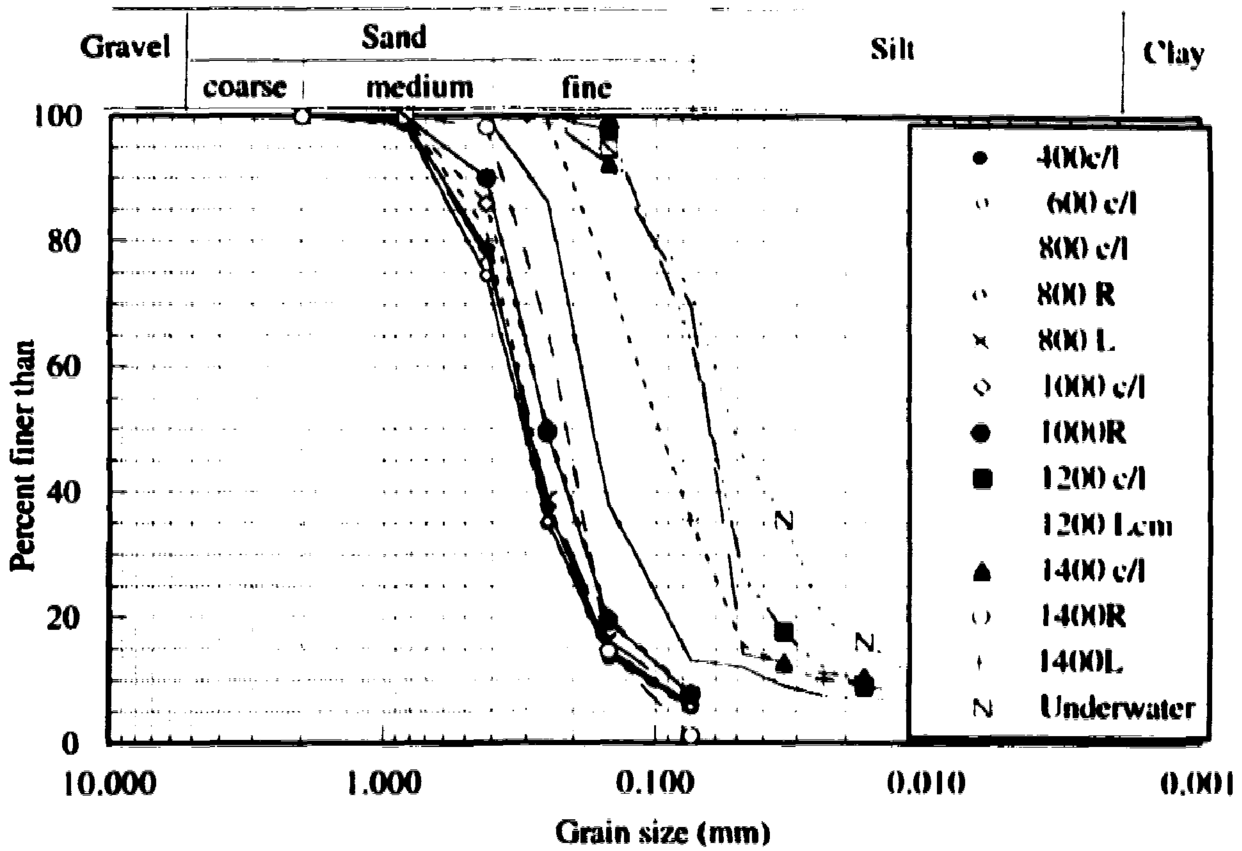
Sample		Dimensions		In-situ		Consolidation conditions				Peak stress conditions (kPa)						ε_a (%)	Mode of failure
location	No	Diam. (mm)	Hgt. (mm)	γ_d (Mg/m^3)	e_o	B-value	σ'_c	u_c	e_c	σ'_1	σ'_3	u_f	q	p'	e_f		
0+400	2	38.2	81.3	1.457	0.881	1.00	200	178.9	0.695	849.9	240.4	159.6	304.8	545.5	0.693	11.2	
0+400	3	36.1	87.6	1.471	0.881	0.98	50	1030	0.736	1566	392.2	707.8	587.0	979.2	0.736	18.9	
0+800	1	38.2	84.4	1.618	0.693	0.99	50	287.5	0.520	1265	292.4	57.6	486.3	778.7	0.520	9.4	
1+000	1	36.5	82.2	1.564	0.752	1.00	20	76.0	0.742	181.6	51.3	48.7	65.2	116.5	0.742	10.7	
1+200	2	37.3	59.4	1.403	0.953	1.00	50	299.3	0.552	962.1	210.8	139.2	375.6	586.4	0.552	18.1	
1+400	2	38.7	77.7	1.328	1.064	0.99	50	400.0	0.97	885.7	227.7	222.3	329.0	556.7	0.970	22.5	

Table 6.6 Record of reclaim and fresh water discharge (Brenda Mines)

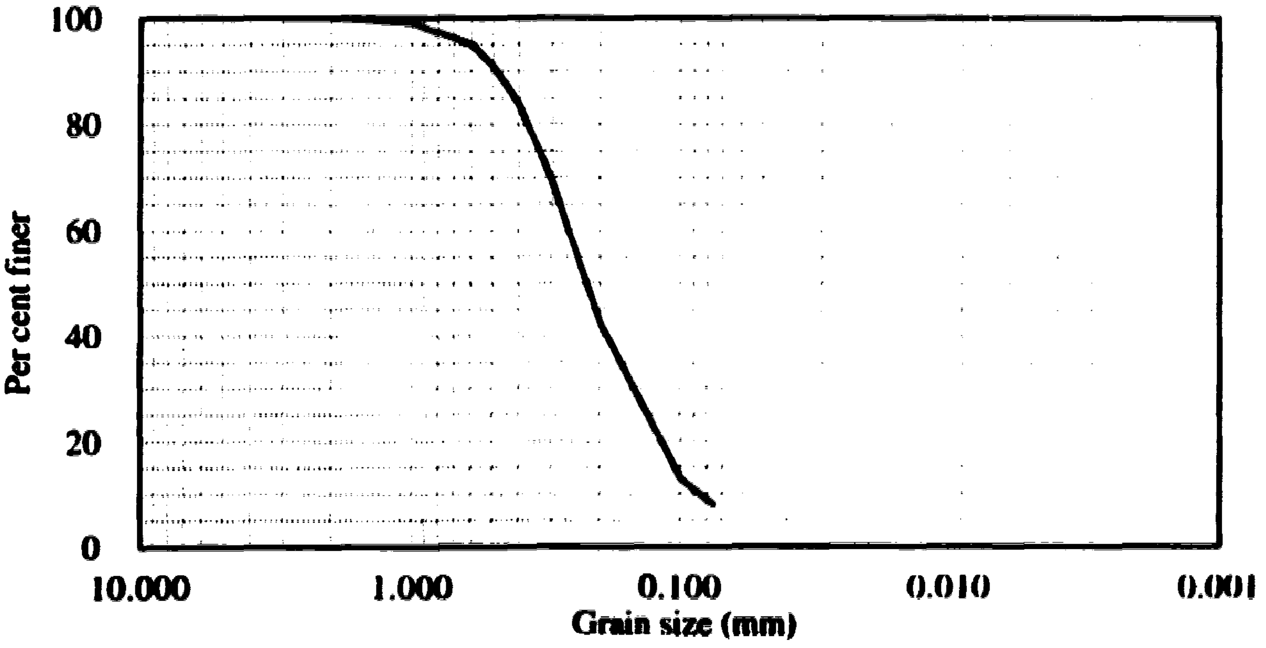
Month	Water discharged (USGPM)					
	1988		1989		1990	
	reclaim	fresh	reclaim	fresh	reclaim	fresh
January	9980	557	10021	583	10513	637
February	10016	540	9824	537	10665	717
March	10086	541	9753	576	10918	669
April	10237	402	9717	596	10080	510
May	10346	413	9984	427	9454	403
June	9898	495	10141	390	-	206*
July	10166	528	10534	421	-	184*
August	10152	530	10755	446	-	134*
September	9888	497	10800	454	-	135*
October	9954	591	10749	469	-	130*
November	9830	737	11060	523	-	130*
December	10298	587	10659	593	-	130*
Average values (except data with*)						
USGPM	10071	534.8	10333	501.3	10326	587.2
m^3/s	0.635	0.034	0.652	0.032	0.651	0.037

Table 6.7 Physical properties of deposited tailings (modified after Boldt, 1988)

Run	Slurry density (% solids)	Exit velocity (V)		G_s	D_{50} (mm)	P'	Av.beach slope (%)		$\frac{\text{calc.}}{\text{meas}}$
		(ft / s)	(m / s)				Calc.	meas.	
A_1	45.0	4.0	1.220	2.68	0.09	1.389	5.89	3.24	1.82
A_2	43.0	9.0	2.743	2.68	0.10	0.646	4.02	2.32	1.73
A_3	57.0	4.0	1.220	2.68	0.07	1.565	6.25	3.60	1.74
A_4	55.0	9.0	2.743	2.68	0.09	0.768	4.38	2.80	1.56
A_5	26.0	4.0	1.220	2.68	0.09	0.835	4.57	2.60	1.76
A_6	27.0	7.0	2.134	2.68	0.07	0.442	3.32	1.74	1.91
B_1	30.0	5.0	1.520	2.84	0.12	0.930	4.82	2.74	2.77
B_2	29.0	9.0	2.743	2.84	0.14	0.524	3.62	1.21	2.99
B_3	50.0	8.0	2.438	2.84	0.12	0.974	4.93	2.26	2.19
B_4	50.0	5.0	1.524	2.84	0.11	1.448	6.02	2.86	2.10
B_5	22.0	8.0	2.438	2.84	0.11	0.395	3.14	2.08	1.51
B_6	20.0	5.0	1.524	2.84	0.10	0.571	3.77	2.38	1.58

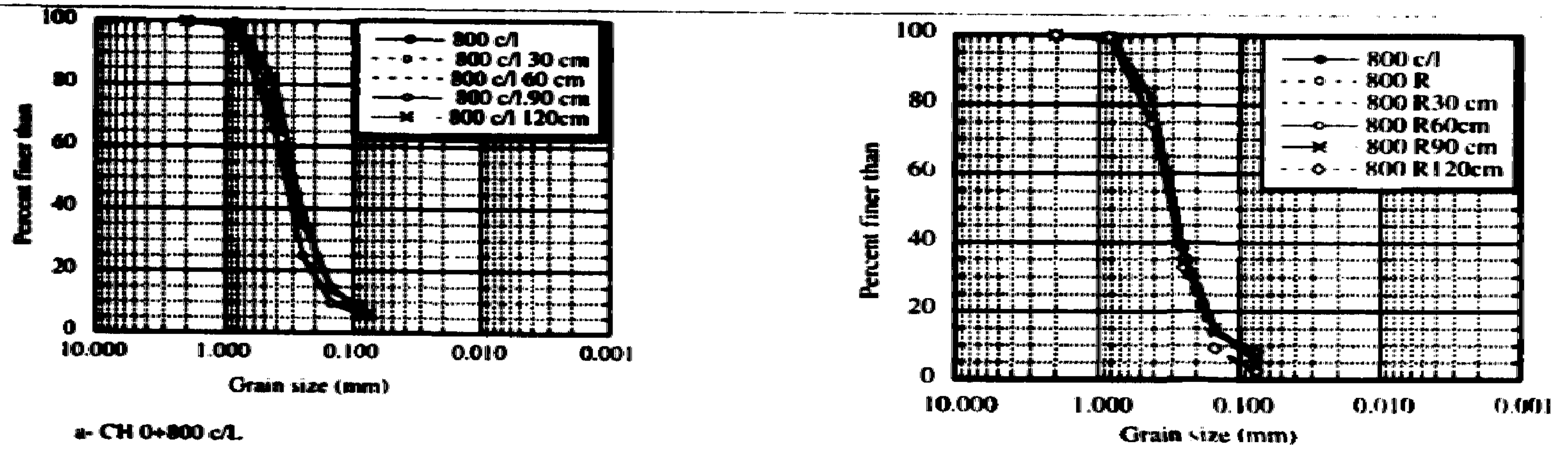


a- Emergency beach



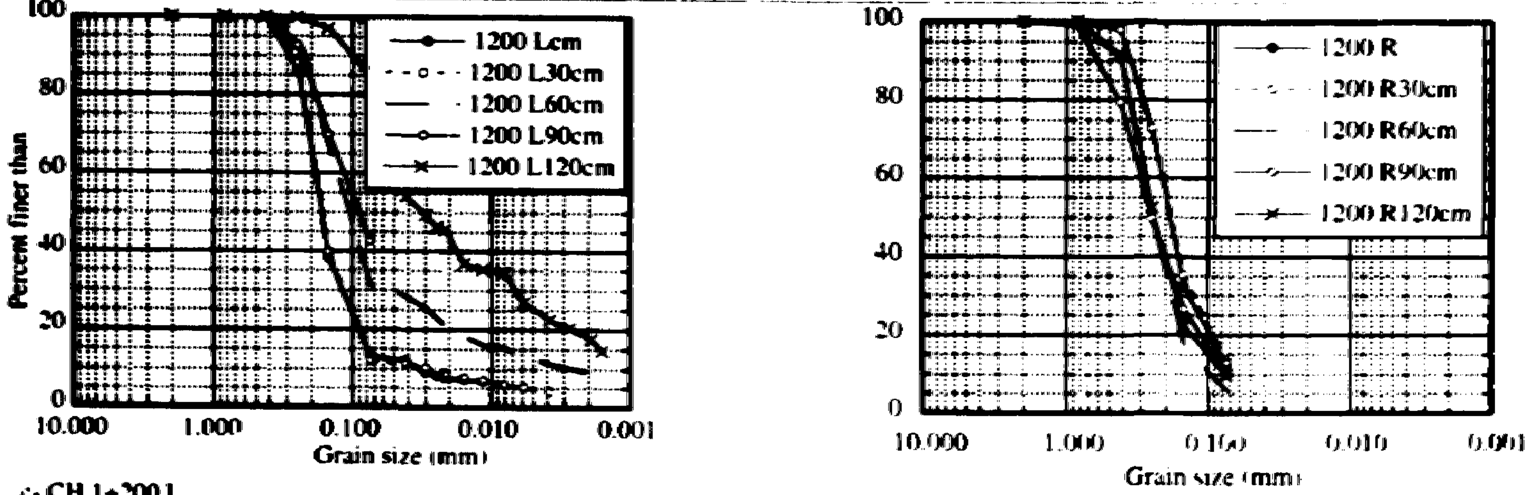
b- Tailings dam sandfill (Source: Klohn Report, 1984)

Figure 6.1- Grain Size Distribution Curves for Brenda Tailings



a- CH 0+800 c/L

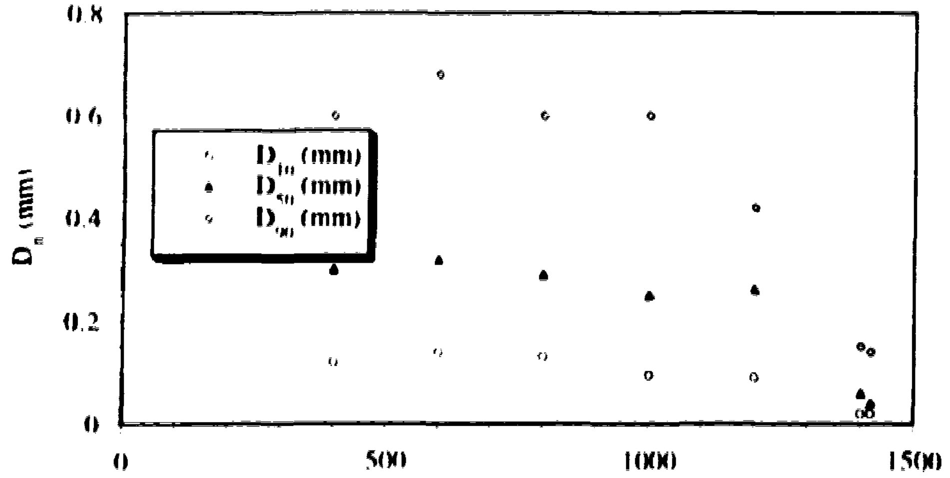
b- CH 0+800



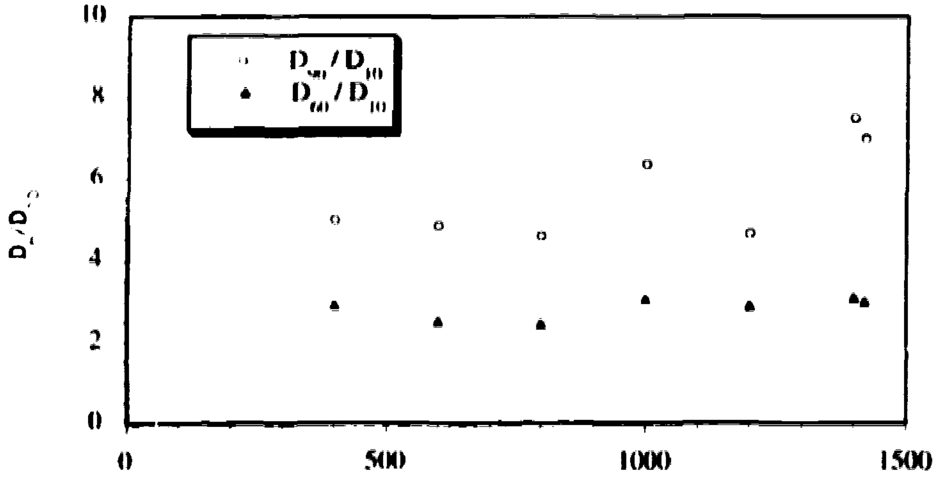
c- CH 1+200 L

d- CH 1 + 200 R

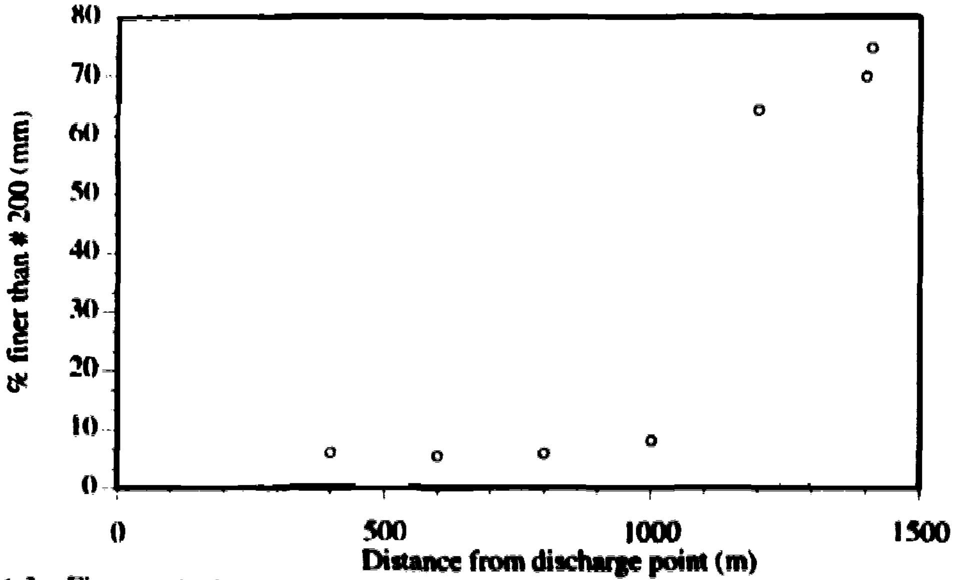
Figure 6.2- Vertical distribution of grain sizes



6.3a- Grain sizes of tailings



6.3b- Variation of D_{60} / D_{10} and D_{90} / D_{10}



6.3c- Fines content

Figure 6.3- Grain size parameters of emergency beach tailings

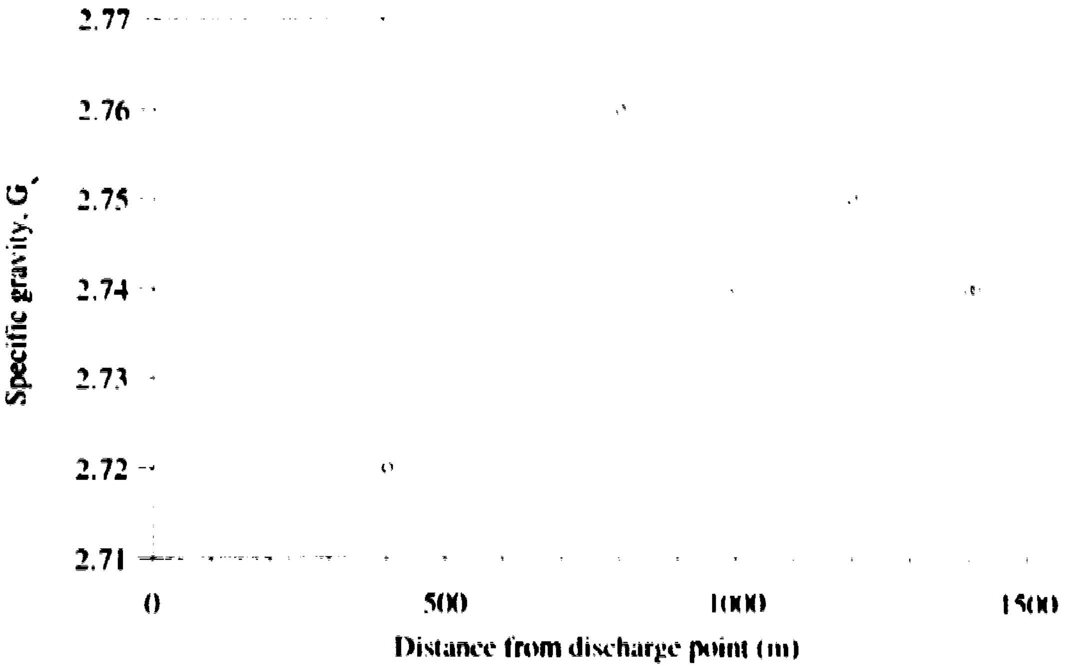


Figure 6.4a- Average specific gravity along tailings beach

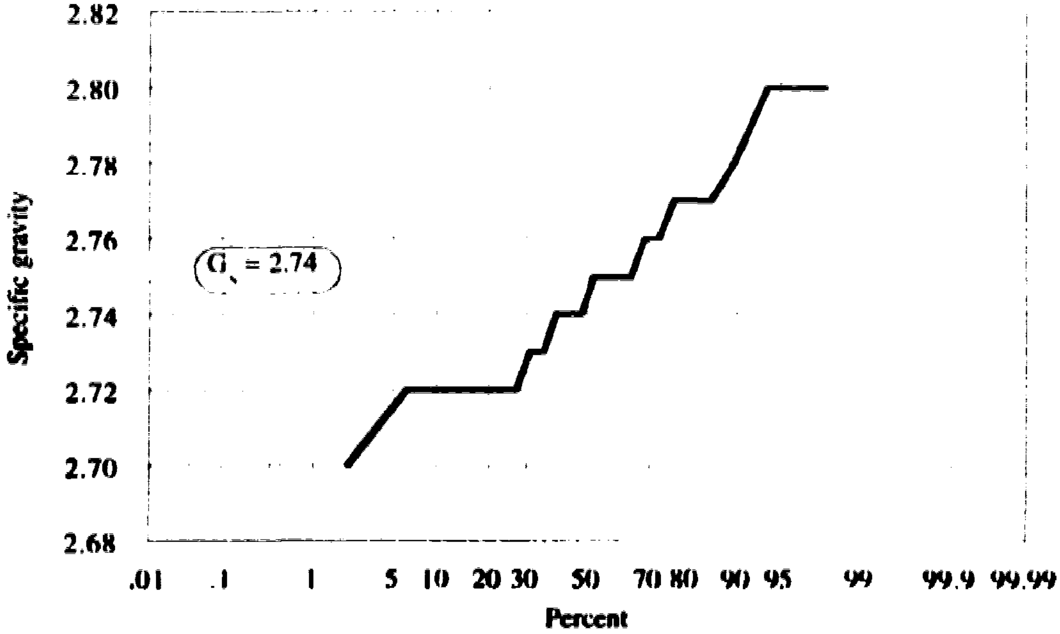
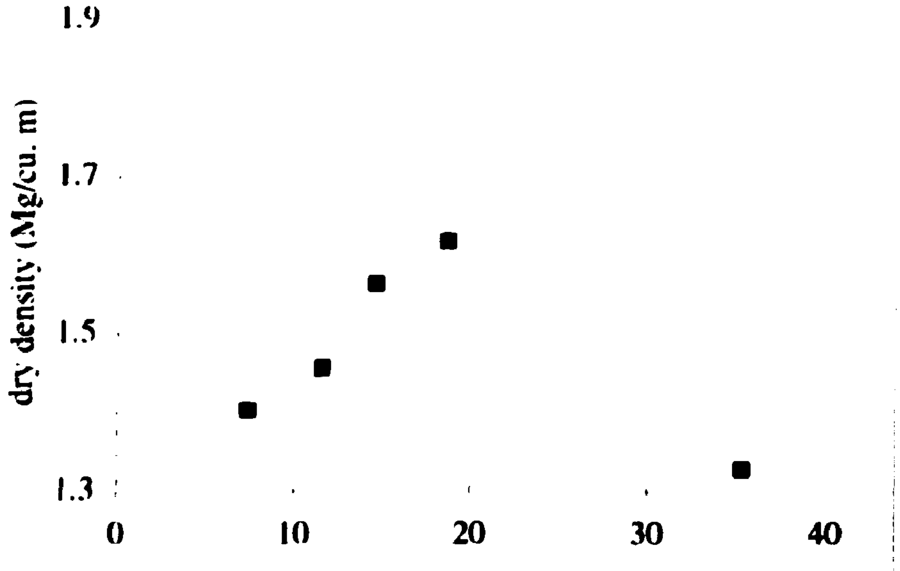
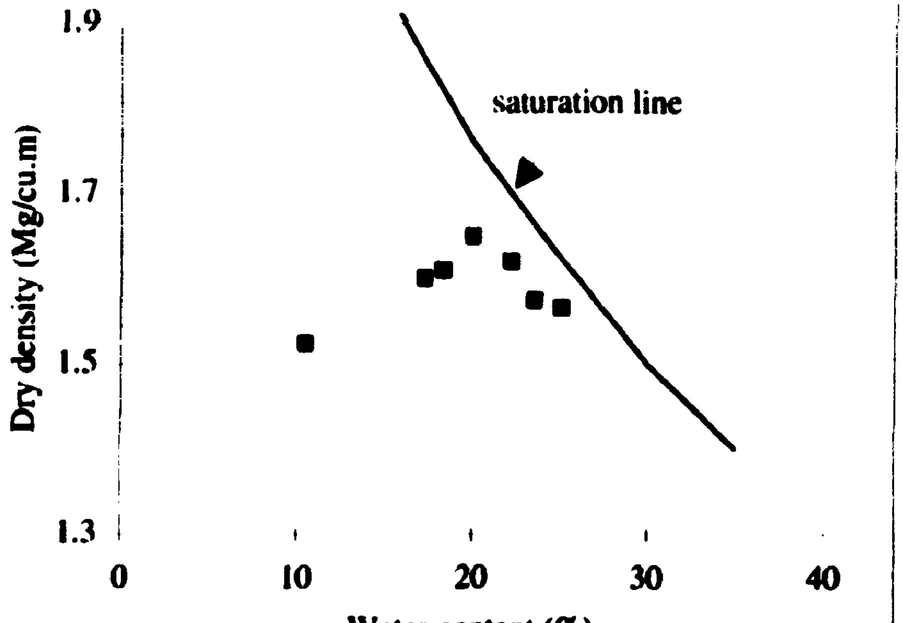


Figure 6.4b - Normal Distribution of specific gravity data

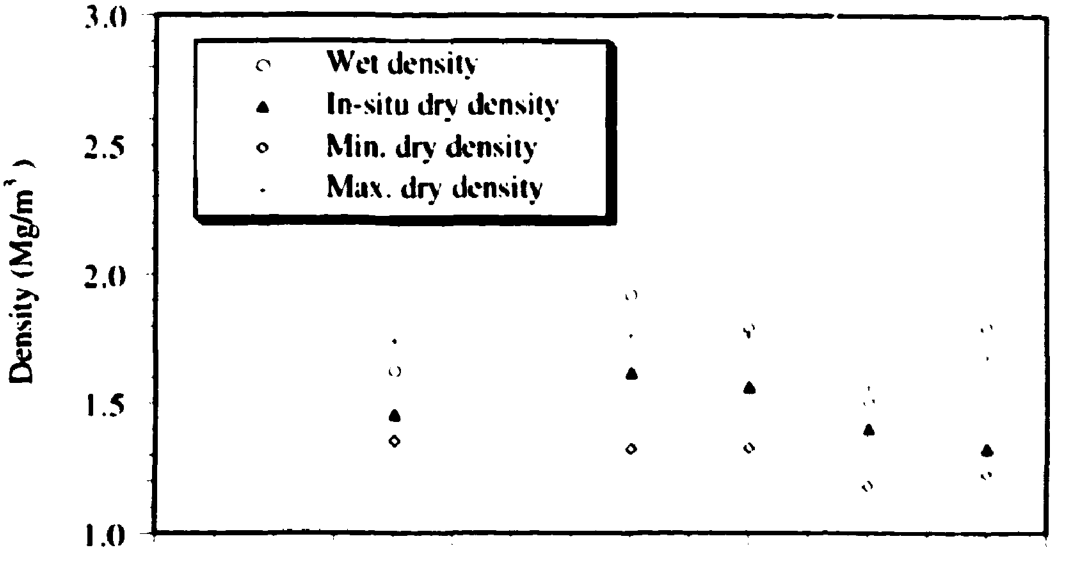


6.5a- Insitu water content~density relationship

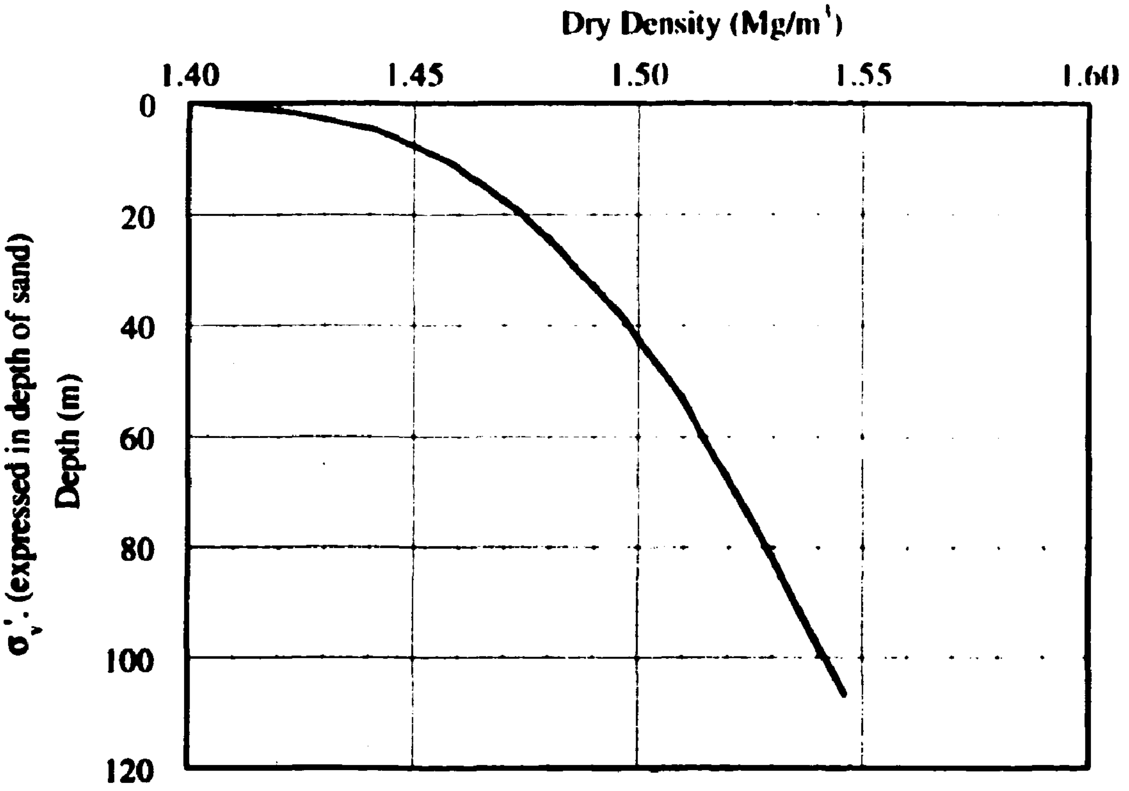


6.5b- Laboratory standard compaction test

Figure 6.5- Water content~density relationship for tailings samples



6.6a- Emergency beach



b. Dry density of cycloned sand

Figure 6.6- Densities of Brenda Tailings

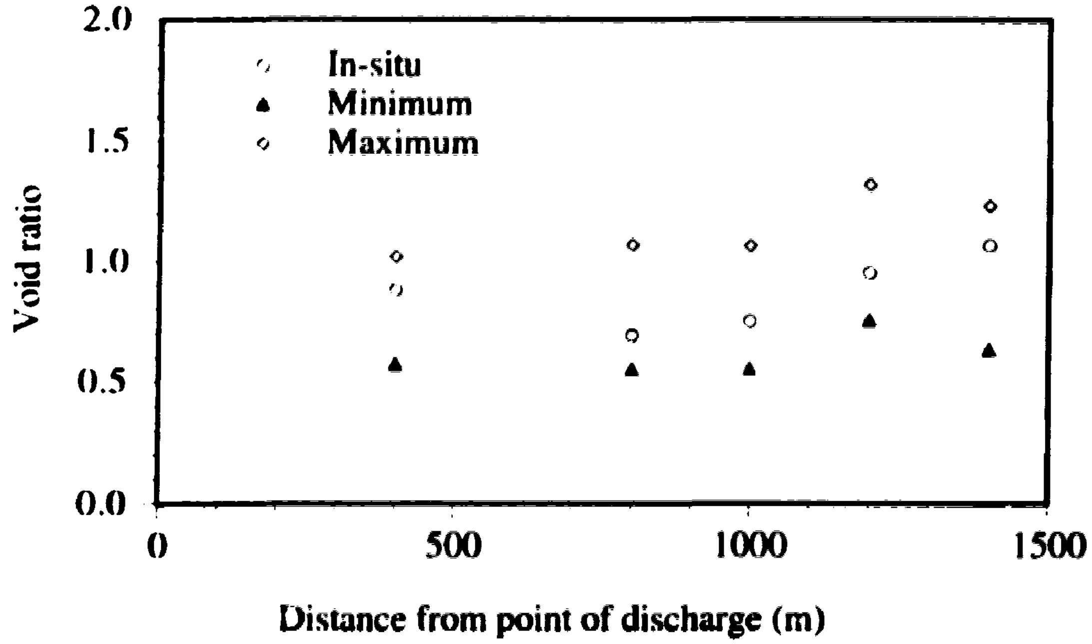


Figure 6.7- Void ratios of tailings deposit

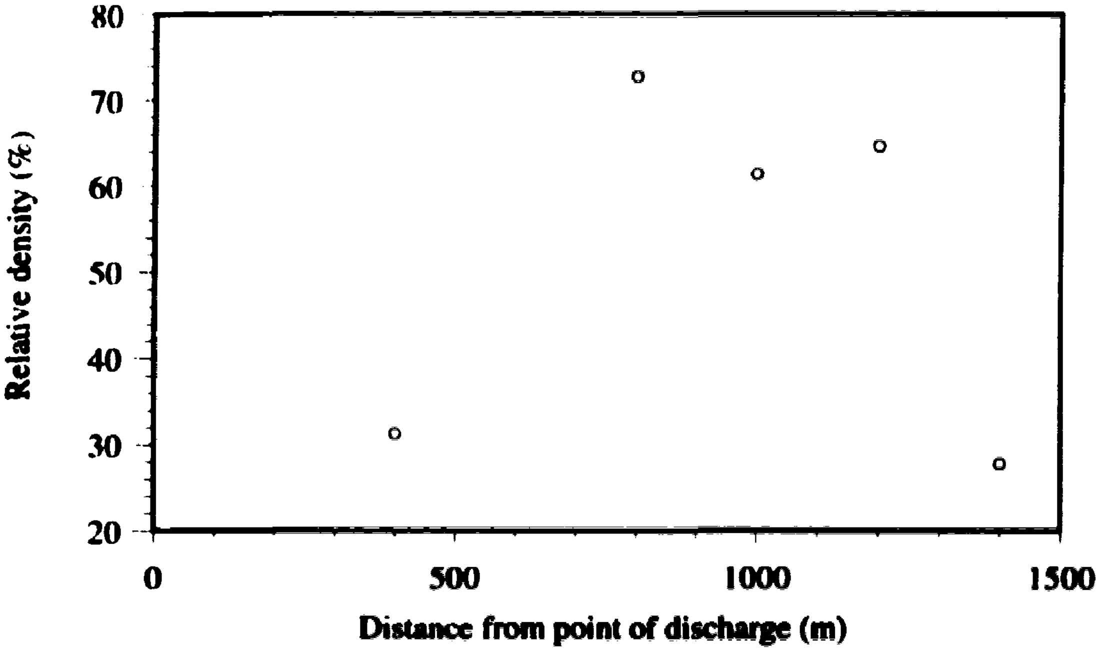


Figure 6.8a- Relative density of Brenda tailings

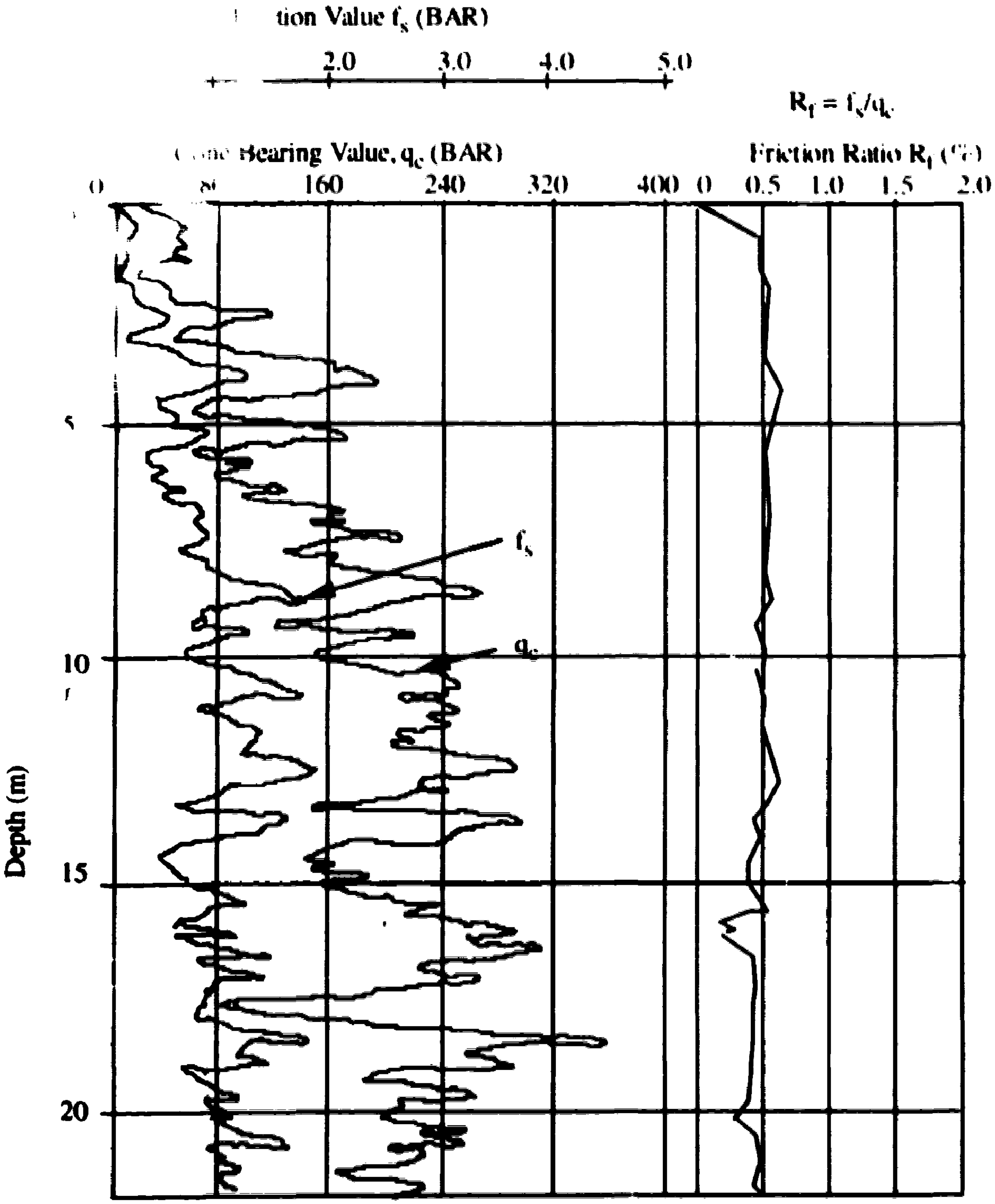


Figure 6.8b- Static Cone Penetration Hole C-201
(Modified after Klohn Report, 1984

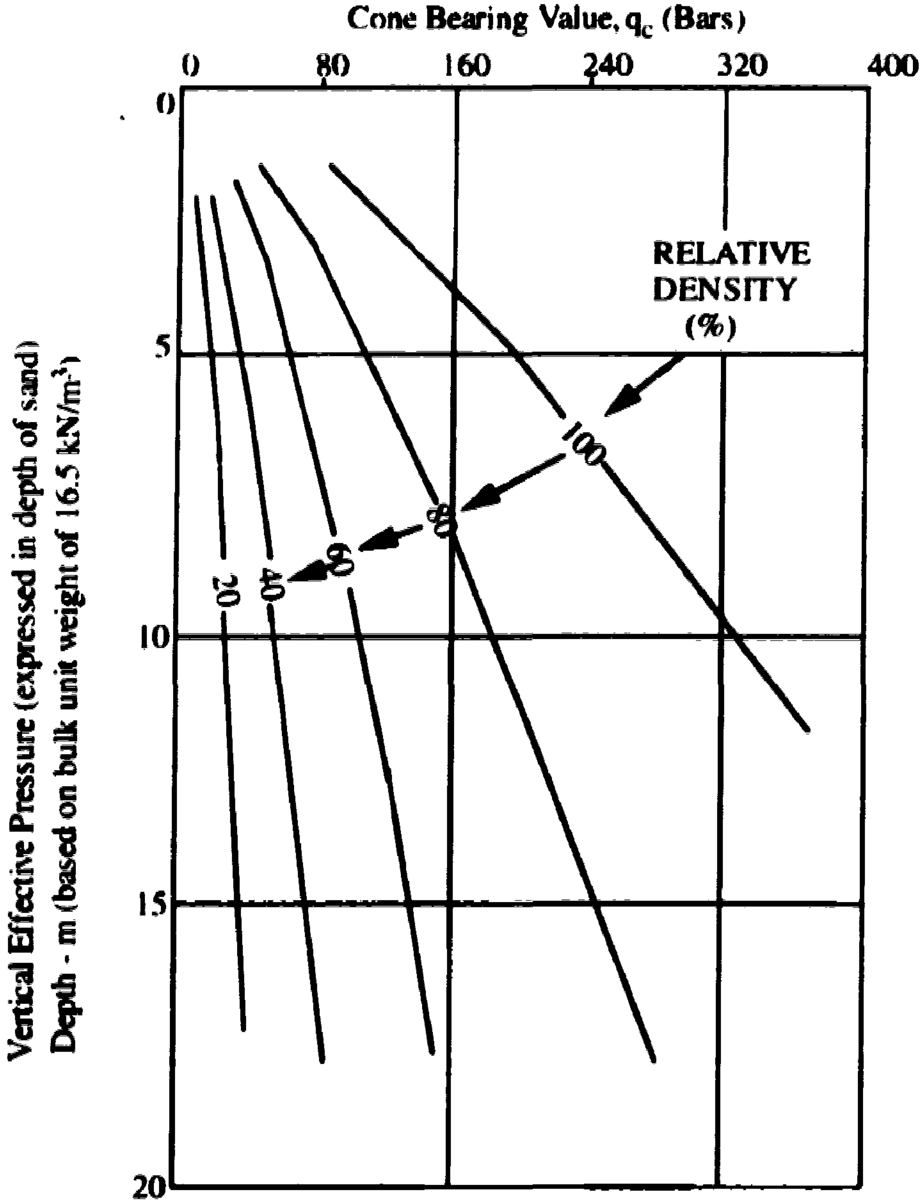
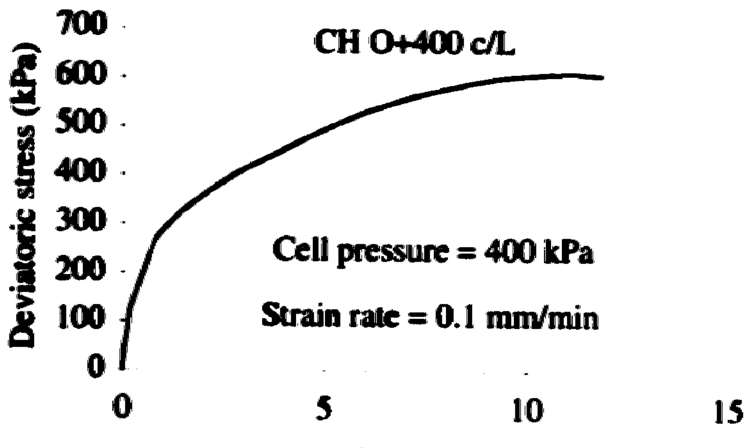
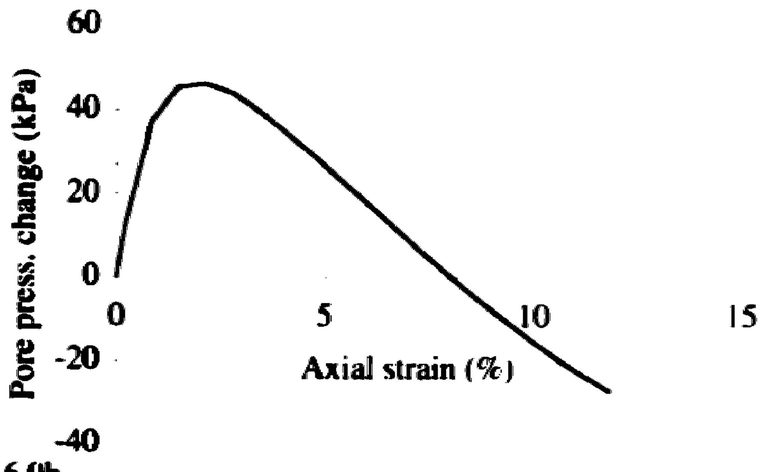


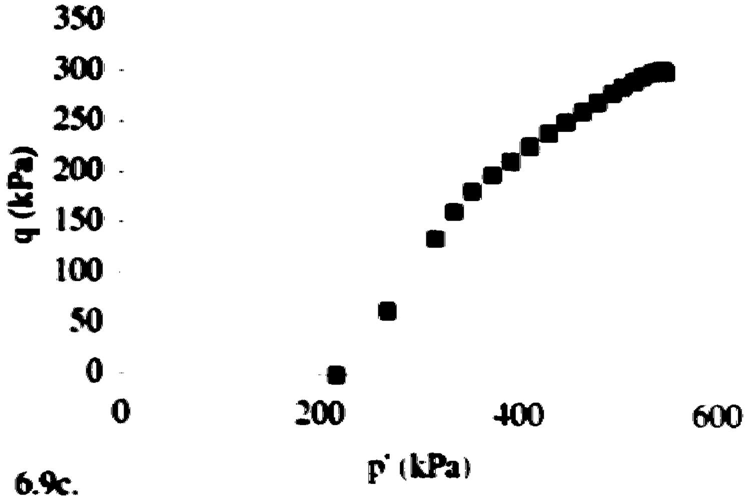
Figure 6.8c- Static Cone Correlation Curves- Schmertmann



6.9a.



6.9b.



6.9c.

Sample: CH 0 + 400 c/L #2

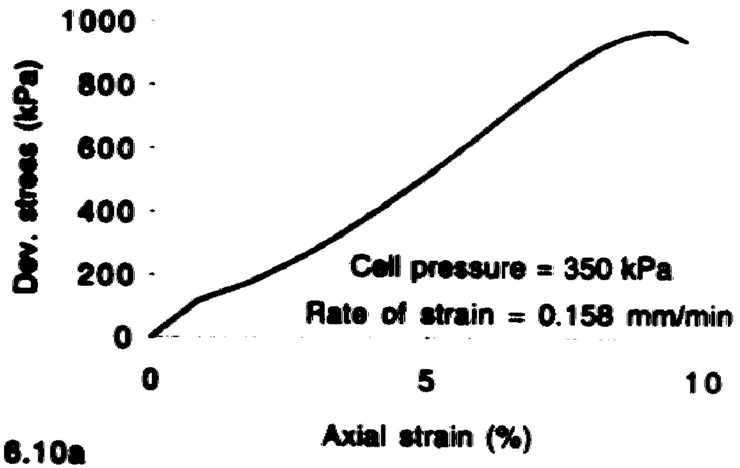
Description: Greyish green medium to fine sand.

Specimen dimensions: height~81.28 mm; Diam.~38.16 mm

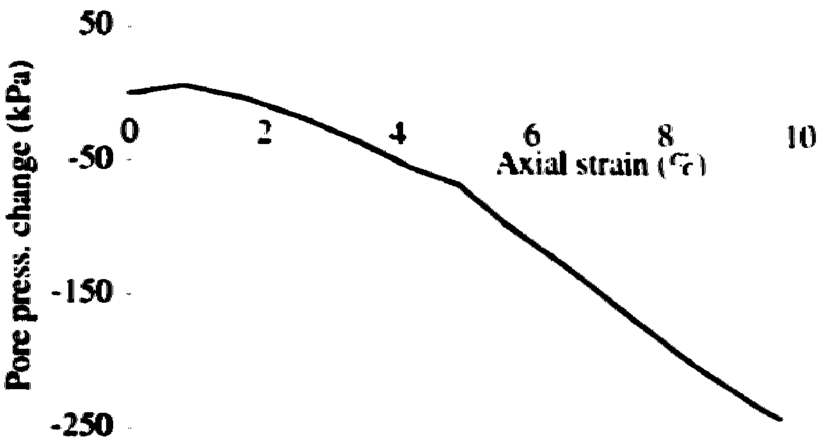
Cu	D50 (mm)	% fine	dry density (Mg/cu. m)		
			in-situ	min.	max.
2.92	0.30	6.00	1.457	1.356	1.741

Void ratio				Rel. density
in-situ	min.	max.	Cons.	(%)
0.881	0.573	1.021	0.693	31.34

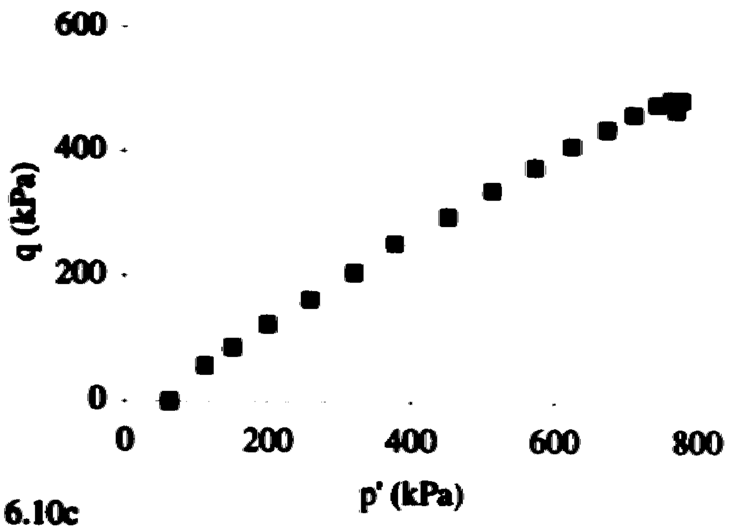
Figure 6.9- Results from CU Triaxial Test



6.10a



6.10c



6.10c

Sample: CH 0 + 800 c/L #1

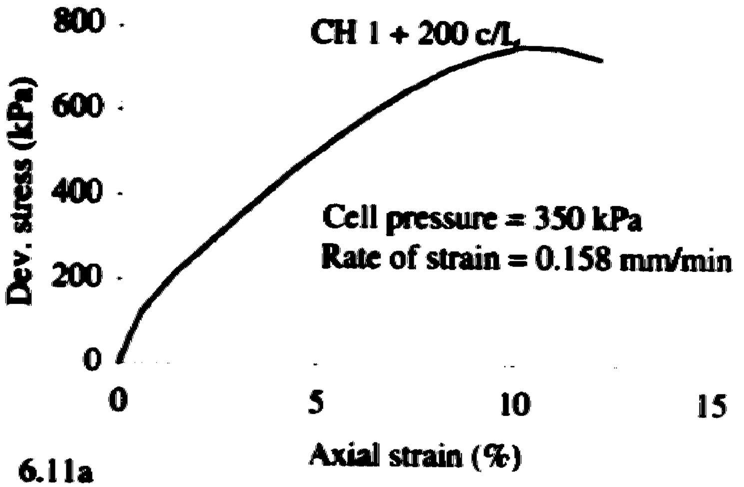
Description: Greyish green medium to fine sand.

Specimen dimensions (mm): height 84.4 ; Diam.~38.2

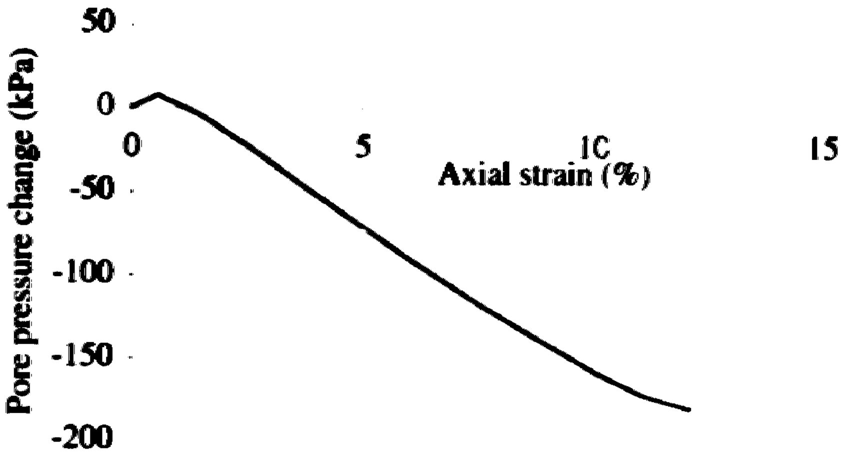
Cu	D50 (mm)	% fine	Wet density (Mg/cu. m)	dry density (Mg/cu. m)		
				in-situ	min.	max.
2.46	0.29	5.93	1.92	1.618	1.326	1.764

Void ratio			Rel. density
in-situ	min.	max.	(%)
0.693	0.553	1.065	72.78

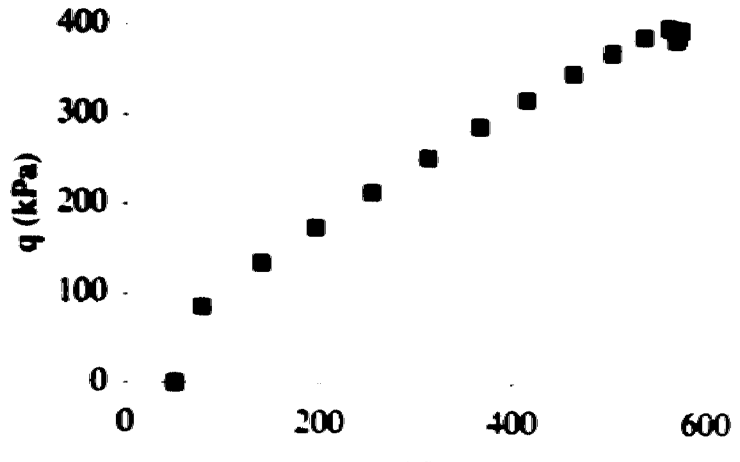
Figure 6.10- Results from CU Triaxial Test



6.11a



6.11b



6.11c

Sample: CH 1 + 200 c/L #2

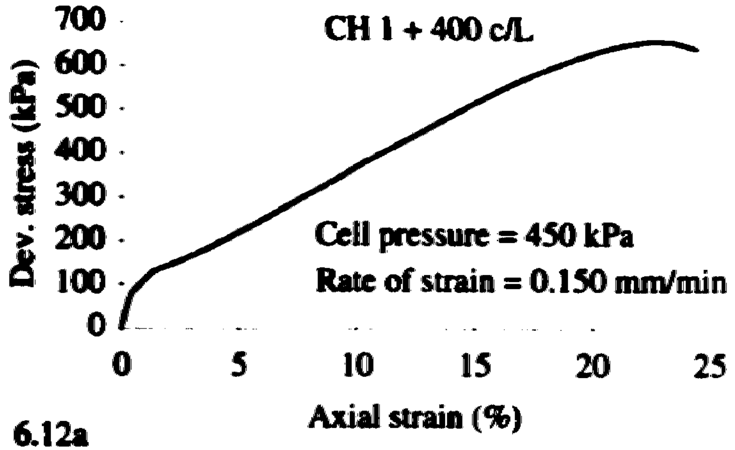
Description: Greyish green sandy silt.

Specimen dimensions: height~59.4 mm; Diam.~37.3 mm

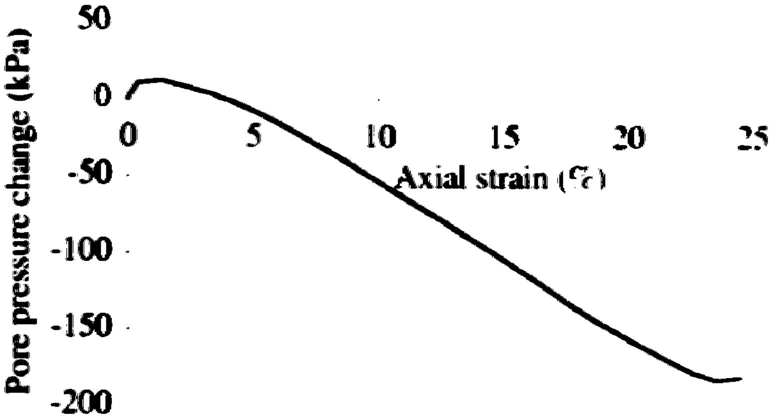
Cu	D50 (mm)	% fine	wet density (Mg/cu. m)	dry density (Mg/cu. m)		
				in-situ	min.	max.
2.89	0.26	64.2	1.507	1.403	1.183	1.562

Void ratio			Rel. density
in-situ	min.	max.	(%)
0.953	0.754	1.316	64.7

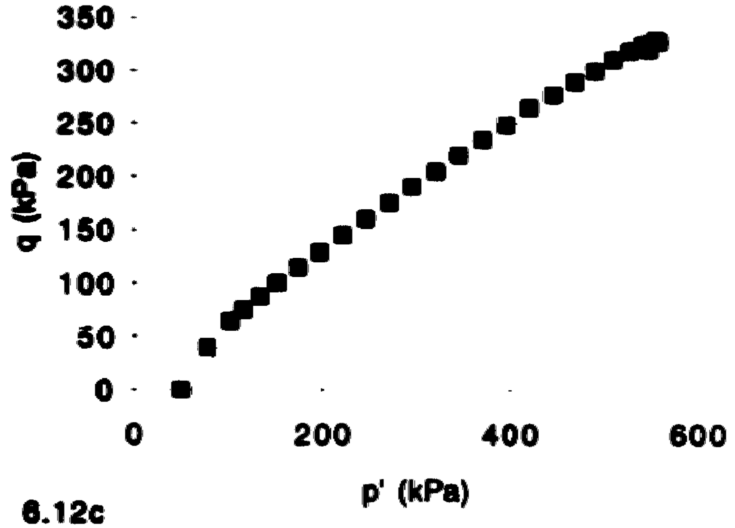
Figure 6.11- Results from CU Triaxial Test



6.12a



6.12b



6.12c

Sample: CH 1 + 400 c/L #2

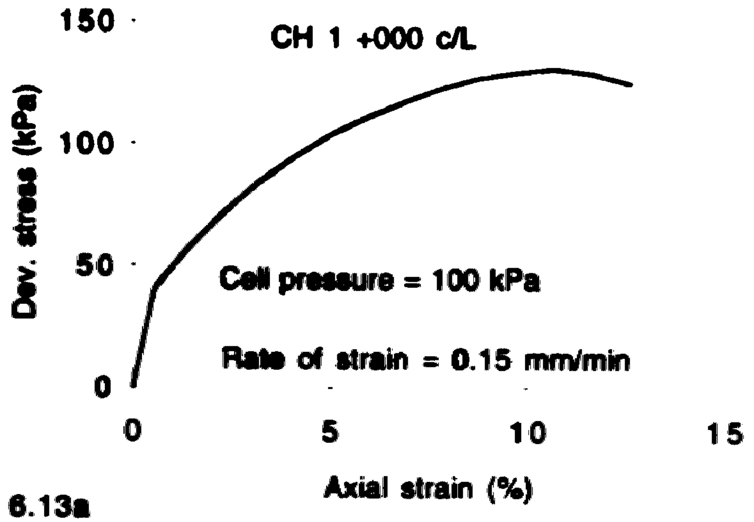
Description: Greyish green silty clay.

Specimen dimensions: height~84.43 mm; Diam.~38.18 mm

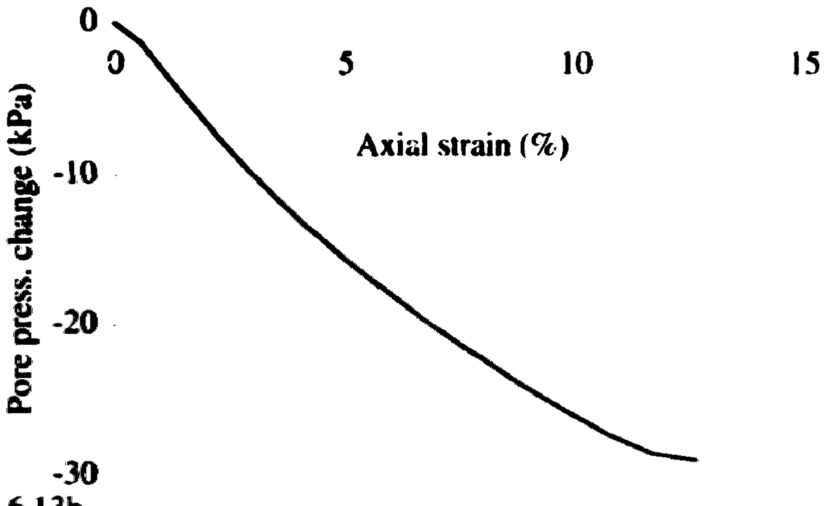
Cu	D50 (mm)	% fine	Wet density (Mg/cu. m)	dry density (Mg/cu. m)		
				in-situ	min.	max.
3.1	0.06	69.9	1.796	1.328	1.229	1.679

Void ratio			Rel. density
in-situ	min.	max.	(%)
1.064	0.632	1.229	27.72

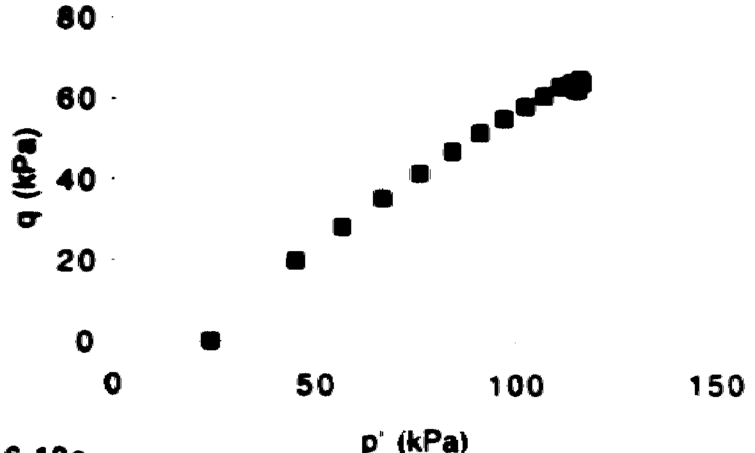
Figure 6.12- Results from CU Triaxial Test



6.13a



6.13b



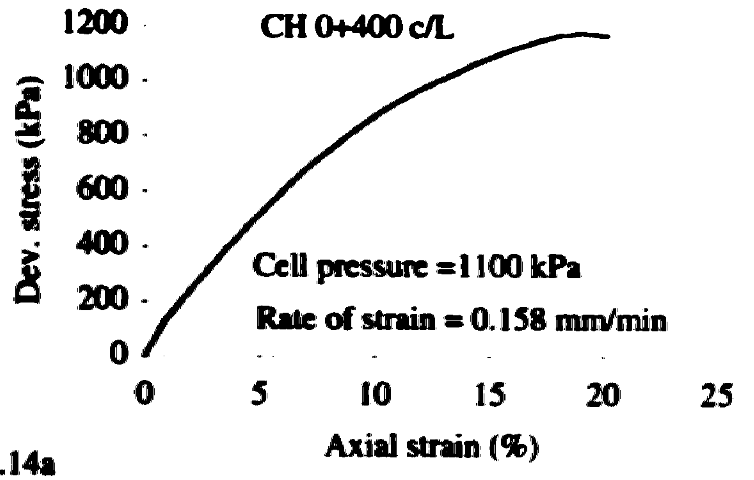
6.13c

Sample : CH 1+ 000 c/L
Greyish green medium to fine sand
Specimen dimensions: height ~ 82.2 mm; Diam. ~ 36.5 mm

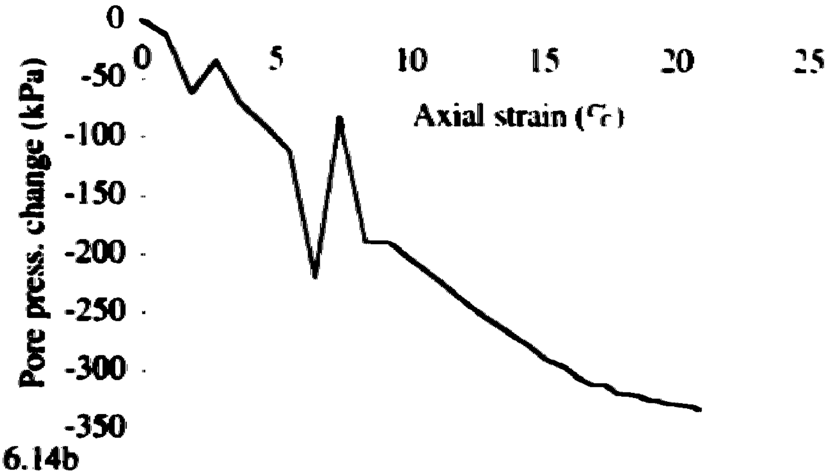
Cu	D50 (mm)	% fine	Wet density (Mg/cu. m)	dry density (Mg/cu. m)		
				in-situ	min.	max
3.07	0.25	8.00	1.792	1.564	1.327	1.761

Void ratio			Rel density
in-situ	min.	max.	(%)
0.752	0.556	1.066	61.39

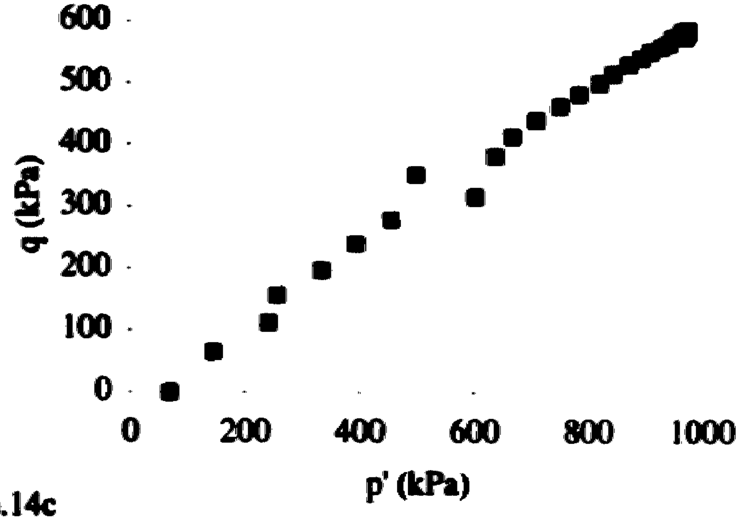
Figure 6.13- Results from CU Triaxial Test



6.14a



6.14b



6.14c

Sample : CH 0 + 400 c/L
Greyish green medium to fine sand
Specimen dimensions (mm): height ~ 87.6; Diam.~ 36.1

Cu	D50	% fine	Wet density	Dry density (Mg/cu. m)		
	(mm)		(Mg/cu. m)	in-situ	min.	max
2.92	0.3	6.00	1.626	1.457	1.356	1.741

Void ratio			Rel density
in-situ	min.	max.	(%)
0.881	0.573	1.021	31.34

Figure 6.14- Results of CU Triaxial Test

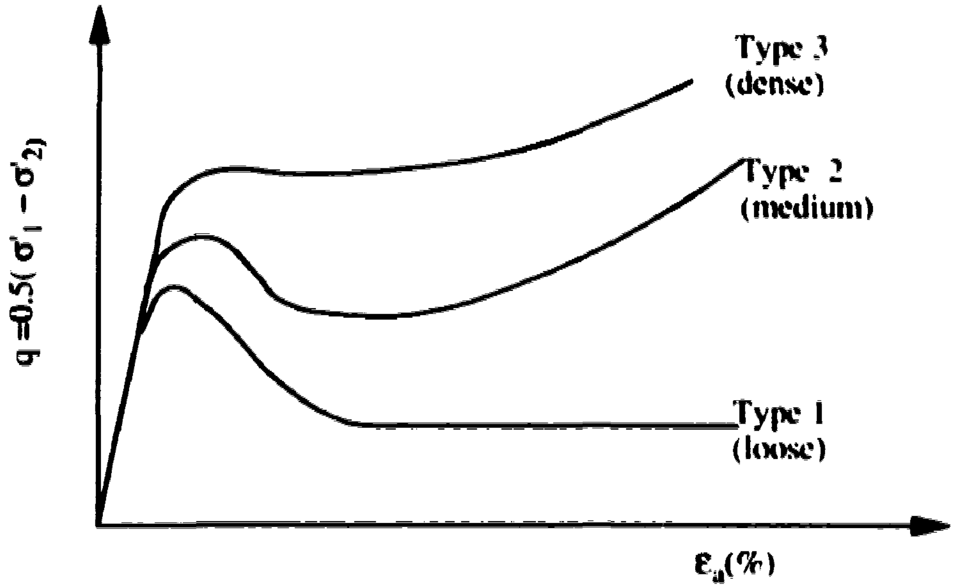


Figure 6.15a- Typical stress - strain curves from CU triaxial tests (modified after Pitman, 1993)

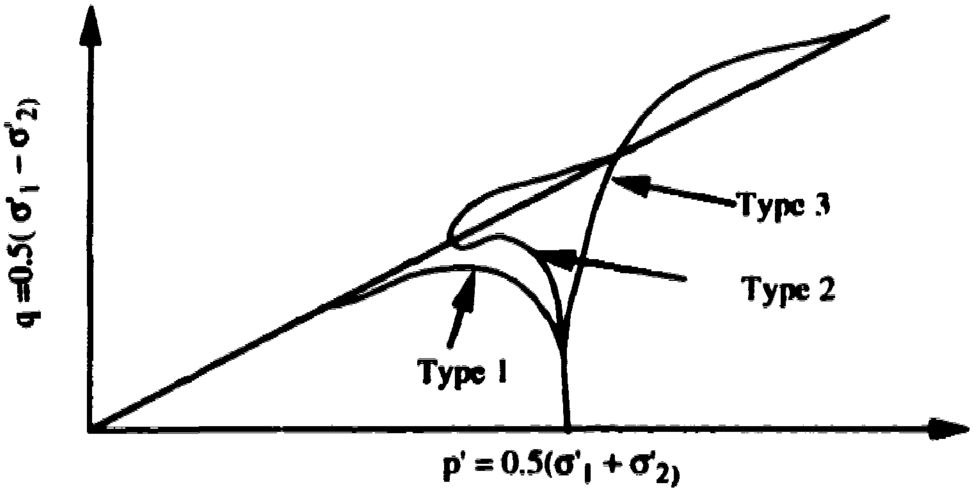
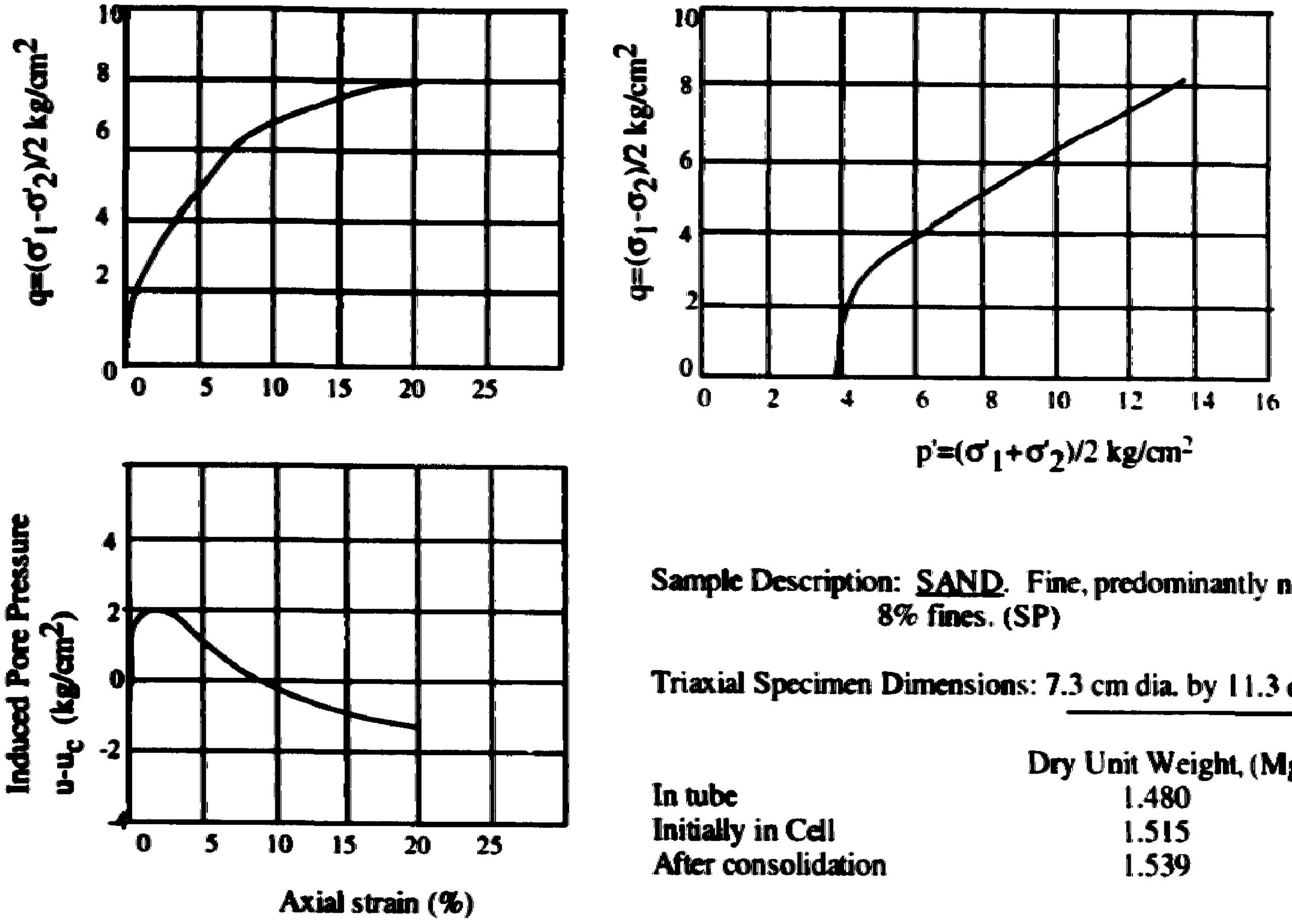


Figure 6.15b- Effective stress paths for undrained triaxial tests (modified after Pitman, 1993)



Sample Description: SAND. Fine, predominantly non-stratified, 8% fines. (SP)

Triaxial Specimen Dimensions: 7.3 cm dia. by 11.3 cm high

	Dry Unit Weight, (Mg/m^3)
In tube	1.480
Initially in Cell	1.515
After consolidation	1.539

Figure 6.16- Results of consolidated undrained monotonic triaxial compression test (after Klohn Report, 1984).

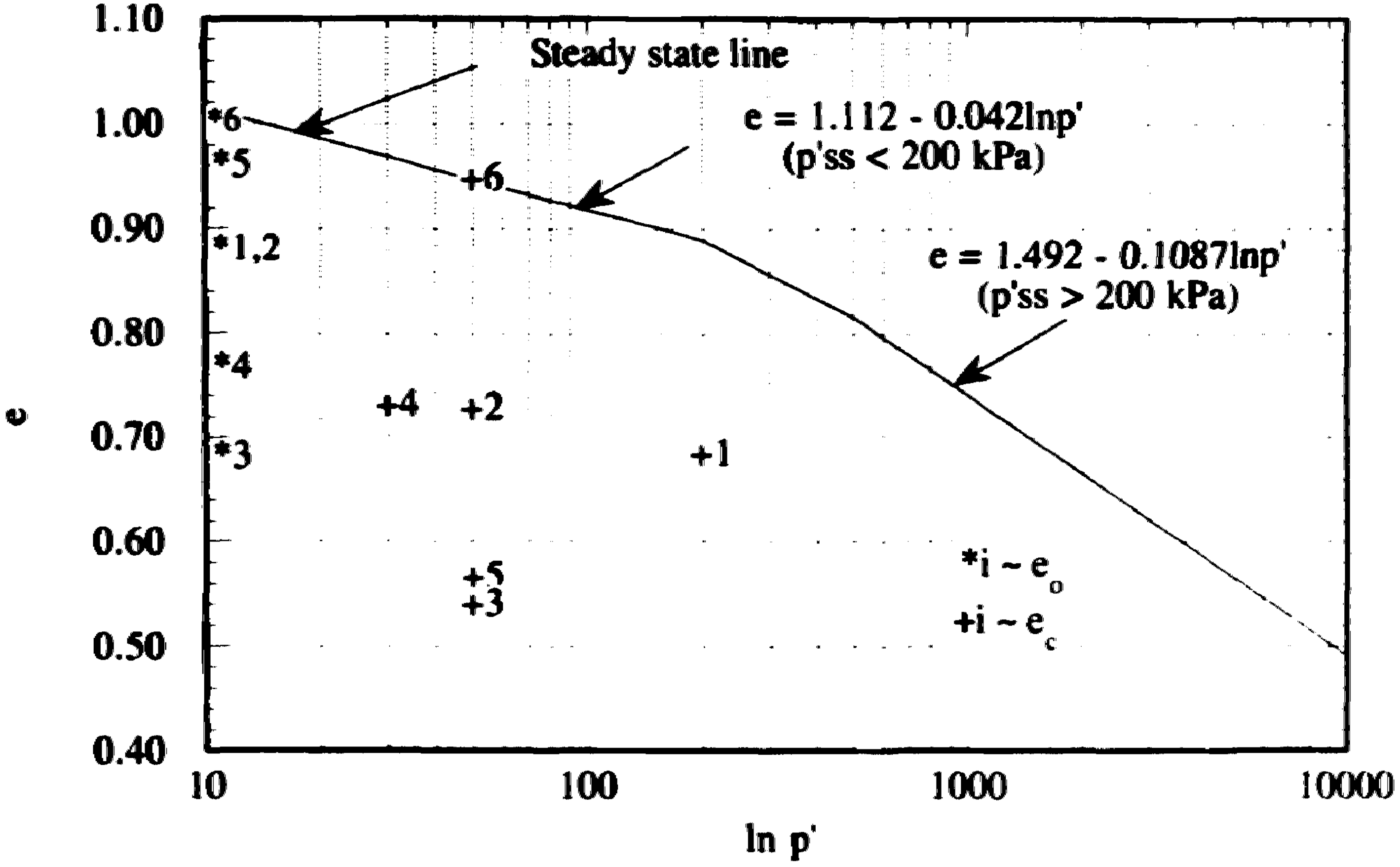
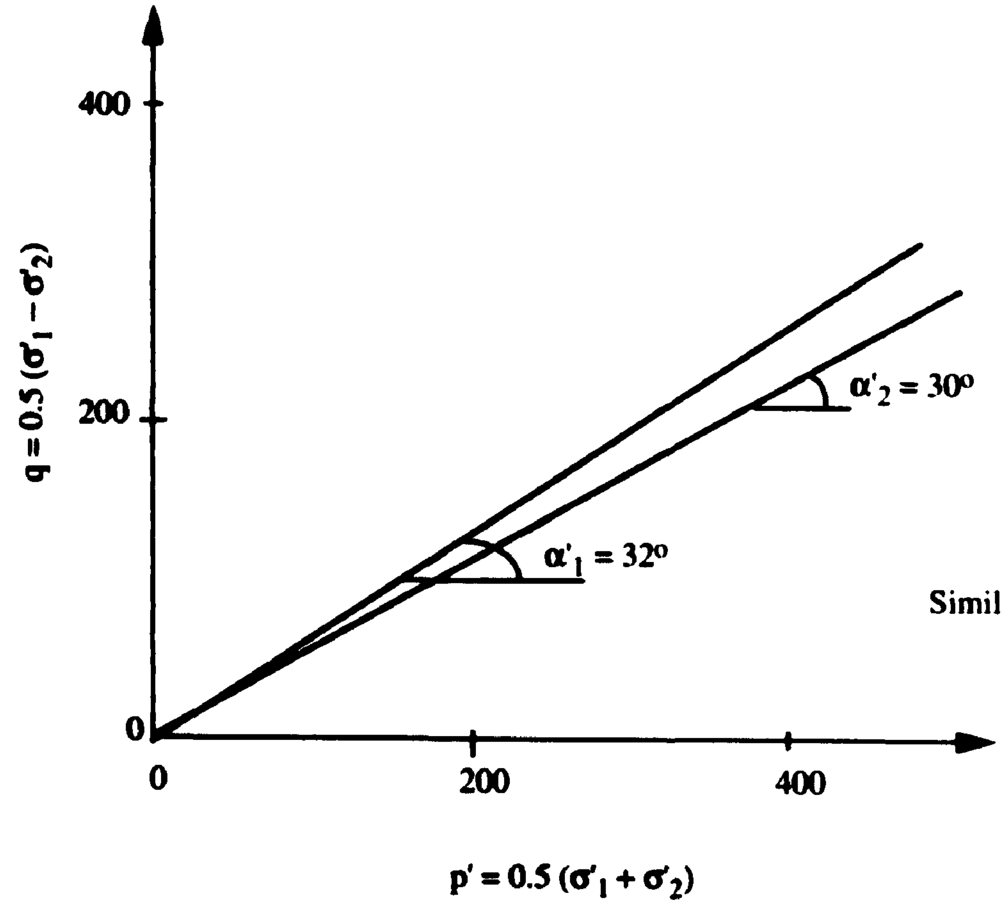


Figure 6.17- Steady state/critical void ratio line for the Brenda cycloned sand in relation to void ratio of the emergency beach specimens



$\phi'_1 = \sin^{-1} (\tan^{-1} 32^\circ)$
$= 38.7^\circ$

Similarly,

$\phi'_2 = 35.3^\circ$

Figure 6.18- Modified Mohr plot from CU triaxial compression tests

Figure 6.19a- Photograph showing a sample in a laboratory triaxial set-up.

Figure 6.19b- Photograph illustrating one of the two modes of failure of the Brenda tailings sample.

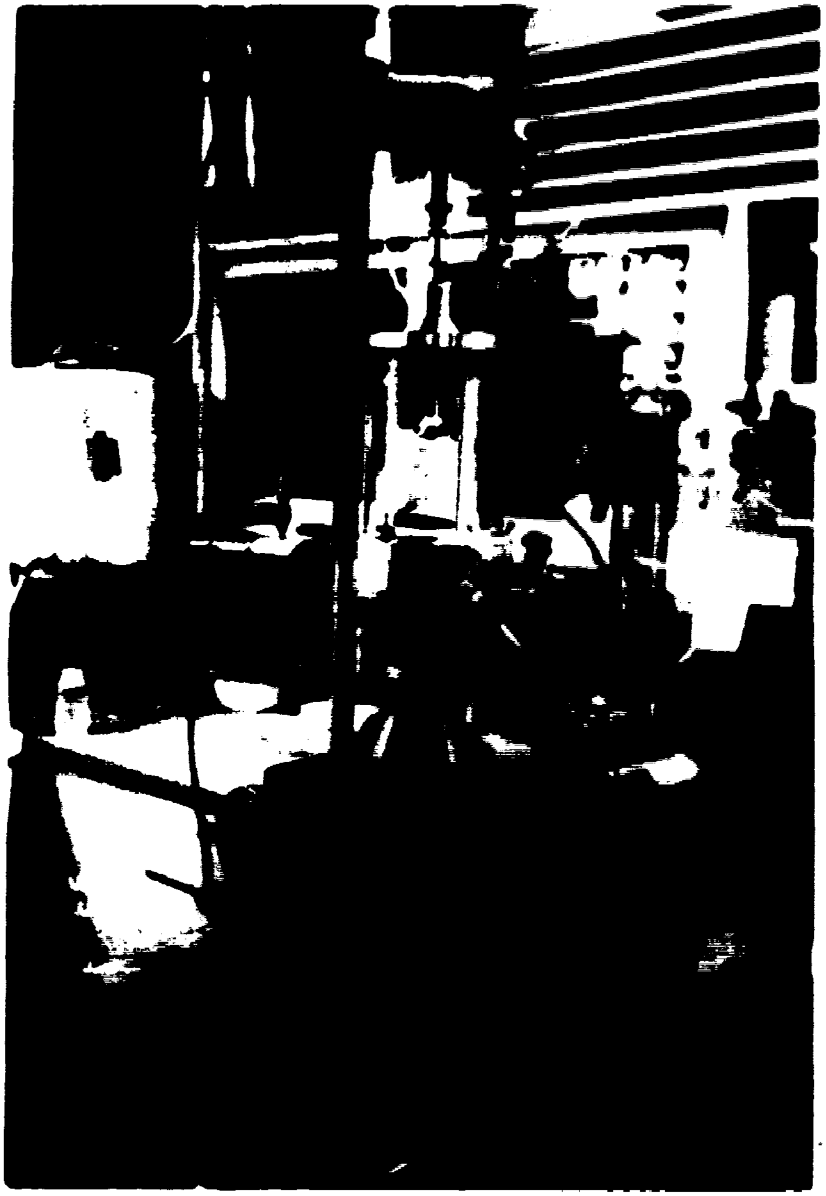


Figure 6.18c - Photograph showing the predominant mode of failure of Brenda tailings sample in a CU monotonic triaxial compression test.

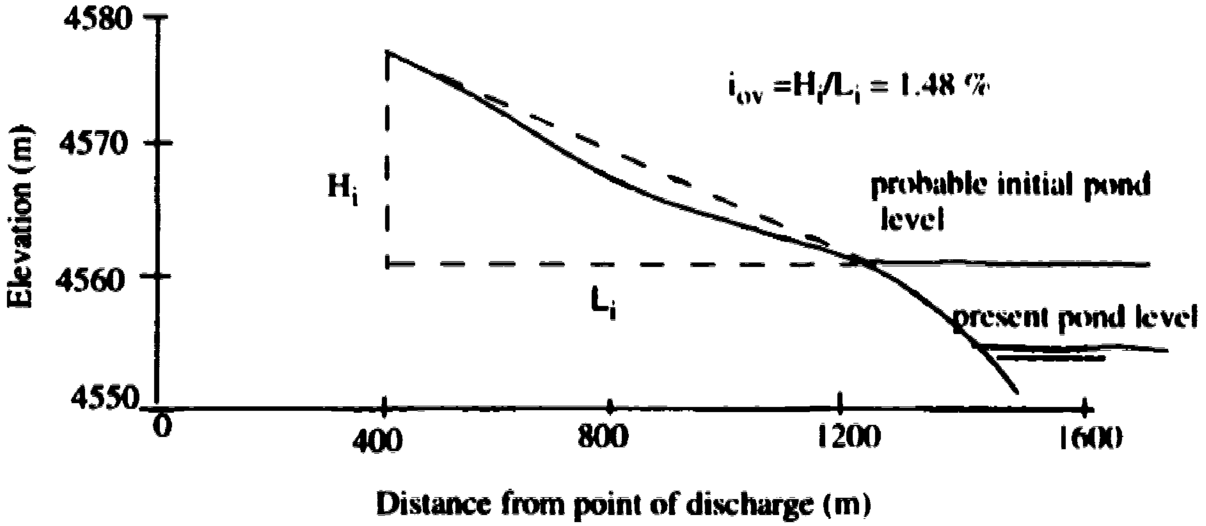


Figure 6.20- Longitudinal profile of tailings beach
(Brenda Mines emergency beach)

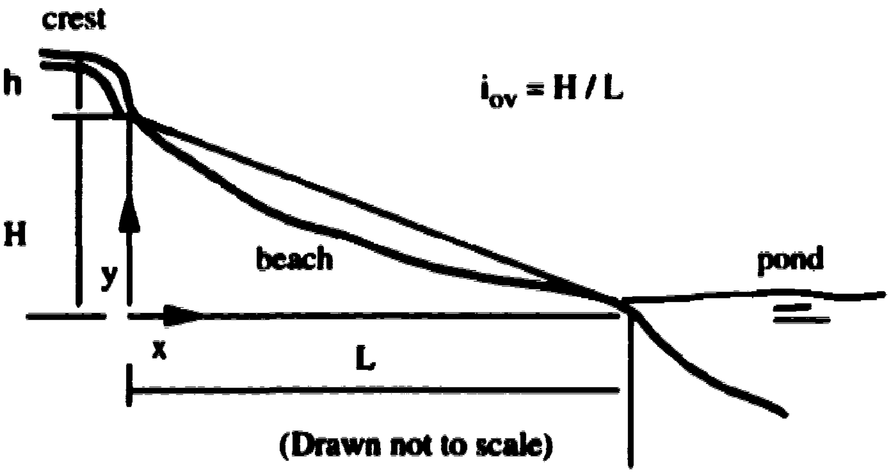


Figure 6.21- Sketch of a typical profile of a hydraulic beach
(After Kupper, 1991)

CHAPTER VII

CONCLUSION

Hydraulic fills are utilized as a method of construction and/or as a construction material in the disposal of mine tailings and in the construction of tailings embankments. Flexibility and efficiency in the design and planning of tailings facilities may be achieved by incorporating geotechnical considerations in the management of the tailings scheme.

The necessity to reduce environmental pollution by decreasing the areas available for wastes disposal require that engineered solutions be found to minimize the cost of disposing of mine tailings and at the same time minimizing their effect on the environment. The engineered solution demands understanding of the mechanical behavior of the tailings slurry and require the insitu characterization of the material properties of the deposited tailings.

Hydraulic fill has been used extensively in the mining industry because they are economical and easy to construct. To enhance its use, different investigations have been conducted to study the properties of the deposited fill. One of these studies was recently carried out to investigate the deposition process, the characteristics of the hydraulic fill and the relationship between the mechanisms of fill formation and the resulting properties (Küpper, 1991). The study established that for it to perform adequately under the conditions required by a project, the hydraulic fill needs to be designed as an engineering material. Küpper, (opt cit) points out that the properties of the hydraulic fill depends on the composition of the tailings and the method of placement.

The current research was carried out as an ancillary study to Küpper's work. This study was conducted at a time when the mine herein referred to was no longer active and the tailings discharged to the emergency beach had ceased. It was not possible therefore to observe most of the characteristics of the slurry flow on the beach and has limited the interpretation of some of the results.

To achieve the objective of the research, a systematic conventional geotechnical testing program was embarked upon to study the characteristics of the total tailings which were discharged onto the emergency disposal area of the Brenda Mines. The tests were conducted using disturbed and undisturbed frozen samples retrieved from the emergency beach to obtain the variation of the grain size distribution, density and the strength characteristics of the beach material. The geometry of the beach profile was also studied.

The particle grain size distribution along a tailings beach is influenced by the type and behavior of the tailings slurry. The grain size curves obtained from this study varied within a relatively narrow range suggesting that the solid fraction in the tailings slurry had a nearly uniform grain sizes. However, hydraulic sorting along the beach was observed. The results showed a slight reduction in the grain size with distance from the point of discharge. The coarse materials were deposited at the upstream section. At the downstream end of the beach a sudden and significant reduction in grain size was observed. It may be inferred that much more fines were discharged into the pond.

The densities of the deposited tailings were found to be comparable with that obtained in other investigations. Average relative densities ranging from 27 to 73% were obtained. The loosest materials were found at both the upstream and downstream portions of the beach respectively. The upstream loose sand was deposited downstream of a probable fanhead entrenched channel. The downstream material was located close to the pond and probably was deposited under water. The deposition process yielded some material with relative density greater that 60% indicating that some of the deposited sand would likely not liquefy.

The results of the consolidated undrained triaxial compression tests showed a consistent dilative response of the beach deposits at low and moderately high confining pressures. The positions of the void ratios of the emergency beach tailings specimens at the end of consolidation (and the in-situ void ratio) on a plot of a steady state/critical void ratio line for the Brenda cycloned sand indicate that the tailings in the former were deposited in a dense state. The triaxial tests were not carried out at very high effective confining stresses and no extension tests were performed. The behavior of the total tailings specimens under these conditions was therefore not studied.

The dilative or contractive response of sand under undrained loading is an important consideration in assessing the liquefaction potential of the sand. Loose, saturated sands are known to be susceptible to liquefaction. For sands to liquefy, a triggering mechanism consisting of monotonic or cyclic loading to reduce the peak strength of the material is required. Monotonic loading may arise from static loads from the embankment self weight and any imposed loads. Cyclic loading may be due to dynamic load such as from earthquake or impact loading.

In utilizing tailings in embankment constructions, various methods of improving and placing the appropriate material are embarked upon to ensure that only coarse, nonliquefiable solid fractions of the tailings are used. Compaction control is usually used to minimize the potential danger of a liquefaction failure. A minimum relative density is specified for the compacted material.

Küpper, (1991) demonstrated that a properly designed hydraulic fill could be deposited such that the initial density will be below the steady-state line and remain non-liquefiable up to significant stress levels. The current research has shown that relatively dense non-liquefiable deposits resulted from the single point gravity discharge of tailings slurry. The results suggest that the total tailings discharged to the emergency beach was suitable for the construction of the tailings embankment. It is anticipated that if adequate engineering considerations had been given to the method of discharging the tailings slurry the physical properties of the material in the emergency beach could have improved significantly. It was observed that the sporadic discharge of the tailings and the high flow and energy of deposition affected the properties of the material deposited on the emergency beach.

Single or double stage cycloning and hydraulic cell construction are frequently employed to obtain suitable material for constructing tailings embankment. The results of this study show that the physical properties of the total tailings in the emergency beach are comparable to those obtained for use in the construction of the main tailings dam. It is therefore recommended that further research to study the material behavior of total tailings deposited under field conditions be carried out. Stress-strain response under different loading conditions should be studied using specimens obtained from undisturbed samples of the actual deposit.

The observational method may be utilized to study the performance of a test embankment constructed using total tailings. Measurements of the insitu density and other pertinent parameters can be used to monitor the suitability of the material deposited in the test embankments.

The prediction of tailings beach profile enables the estimation of the position of the pond and tailings storage capacity. Many empirical relationships to estimate the slope have been proposed. The P' parameter proposed by Küpper, (1991) was used to predict the slope of the emergency beach profile. It was found that predicted beach slope was about three times greater than the measured slope.

References

ASTM, 1988. Annual Book of ASTM Standards, Section 4, Construction, Soil and Rock Building Stones, Geotextiles, Volume 04. 08.

Blight, G.E., Thomson, R.R. and Vorster, K. 1985. Profiles of hydraulic-fill tailings beaches, and seepage through hydraulically sorted tailings. Journal of South African Institute of Mining and Metallurgy, 85(5): 157-161.

Blight, G.E. and Bentel, G.M. 1983. The behavior of mine tailings during hydraulic deposition. Journal of South African Institute of Mining and Metallurgy, April, pp. 73-86.

Boldt, C.M.K. 1988. Beach characteristics of mine waste tailings. Bureau of Mines Report of Investigation. United States Department of Interior, RI 9171, 24 pp.

Bowles, J.E. 1978. **Engineering properties of soils and their measurements.** McGraw-Hill Inc. New York, pp. 35-77.

Brooms, B.B. 1980. Soil sampling in Europe: State-of-the-art. Journal of the Geotechnical Engineering Division. Proceedings of the American Society of Civil Engineers, 106(GT 1): 65 - 97.

Brown, R. 1992. Personal communication

Burmister, D.M. 1962. Field testing of soils, ASTM STP 322, American Society for Testing Materials, pp 67 - 97.

Carr, J.M. 1968. Geology of the Brenda Lake area, B.C., Ministry of Mines and Petroleum Resources, Annual Report, 1967, pp. 183 - 210.

Chu, J., Lo, S.C.R. and Lee, I.K. 1992. Strain-softening behaviour of granular soil in strain-path testing. Journal of Geotechnical Engineering, 118(2); 191- 208.

Conlin, B.H. 1989. Tailings beach slopes. Geotechnical Aspects of Tailings Disposal and Acid Mine Drainage. The Vancouver Geotechnical Society.

Fan, X. and Masliyah, J. 1990. Laboratory investigation of beach profiles in tailings disposal. Journal of Hydraulic Engineering, 116(11): 1357-1371.

French, R.H. 1987. Hydraulic processes on alluvial fans. Developments in Water Science 31, pp. 62-65.

Fulton, R.J. 1969. Glacial Lake History, southern Interior Plateau. Geological Survey, Canada, Paper 69-37.

Given, E.V. 1959. Designing for tailings disposal in the Southwest. Mining Engineering, July, pp. 691-693.

Hoare, B. and Hill, H.M. 1970. The hydraulic construction of mine tailings dams. Canadian Mining Journal, June, pp. 51-58.

Hunt, R.E. 1984. **Geotechnical Engineering Investigation Manual.** McGraw-Hill, pp. 15-17.

Hvorslev, M.J. 1949. Subsurface exploration and sampling of soils for civil engineering purposes, U.S. Army Engineers Waterways Experiment Station, Vicksburg, Massachusetts.

Idel, K.H., Muhs, H. and Soos, P. von. 1969. Proposal for 'quality-classes' in soil sampling in relation to boring methods and sampling equipment. 7th International Conference on Soil Mechanics and Foundation Engineering, Proceedings of the Specialty Session No. 1, Mexico, pp. 11 - 14.

Jigins, R.W. 1957. Tailings Disposal at Braden Copper Co. (Chile). Mining Engineering, October, pp. 1135-1140.

Keshian, B. Jr. and Rager, R.E. 1988. Geotechnical properties of hydraulically placed uranium tailings. Geotechnical Special Publication (21) Edited by D.J.A. Van Zyl and S.G. Vick, pp 227-253.

Klohn, E.J. 1972. Design and construction of tailings dams. The Canadian Institution of Mining and Metallurgy Bulletin, April, pp. 28-44.

Klohn Leonoff Consulting Engineers 1984. Seismic investigation for Brenda main dam. Summary Report, I: 3 - 6.

Kuerbis, R.H. 1989. The effect of gradation and fines content on the undrained loading response of sand. M.Sc. Thesis. Department of Civil Engineering, University of British Columbia, Vancouver, B.C.

Kuerbis, R.H., Negussey and Vaid, Y.P. 1988. Effect of gradation and fines content on the undrained response of sand. Geotechnical Special Publication (21) Edited by D.J.A. Van Zyl and S.G. Vick, pp 330 - 345.

Küpper, A. M. A.G. 1991. Design of hydraulic fill. Ph.D. Thesis, Department of Civil Engineering, University of Alberta, Edmonton, Alberta. pp. 50-157.

Lighthall, P.C., Watts, B.D. and Rice, S. 1989. Deposition methods for construction of hydraulic fill tailings dams. Geotechnical Aspects of Tailings Disposal and Acid Mine Drainage. The Vancouver Geotechnical Society.

Lacroix, Y and Horn, H.M. 1972. Direct determination and indirect evaluation of relative density and its use on earthwork construction projects. Evaluation of Relative Density and Its Role in Geotechnical Projects Involving Cohesionless Soils, ASTM Standard Technical Publication 523, edited by Selid/Ladd, pp. 251-280.

Marcuson W.F. and Franklin, A.G. 1979. State of the art of undisturbed sampling of cohesionless soils. Proceedings of the International Symposium of Soil Sampling. The Sub-Committee on Soil Sampling, International Society for Soil Mechanics and Foundation Engineering, pp. 57 - 71.

Marsland, A., McGown, A. and Derbyshire, E. 1980. Soil profile mapping in relation to site evaluation for foundations and earthworks. International Association of Engineering Geology. Bulletin No. 21, pp. 139 - 155.

Milne, W.G. and Berry, M.J. 1976. Induced seismicity in Canada. Engineering Geology, 10, No. 2-4, December, pp. 219-253.

Mittal, H.K. 1974. Design and performance of Tailings dams. Ph.D. Thesis, Department of Civil Engineering, University of Alberta, Edmonton, Alberta, pp. 109-113.

Morgenstern, N.R. and Küpper, A.A.G. 1988. Hydraulic fill structures - A perspective. Hydraulic Fill Structures. Geotechnical Special Publication (21) Edited by D.J.A. Van Zyl and S.G. Vick, pp. 1 - 27.

Pitman, T.D. 1993. Effects of fines and gradation on the collapse surface of a loose saturated soil. M. Sc. Thesis, Department of Civil Engineering, University of Alberta, Edmonton.

Poulos, S.J. and Hed, A. 1972. Density measurements in a hydraulic fill.

Evaluation of Relative Density and Its Role in Geotechnical Projects Involving Cohesionless Soils, ASTM Standard Technical Publication 523, edited by Selid/Ladd, pp. 402-424.

Robinsky, E. 1979. Tailings disposal by the thickened discharge method for improved economy and environmental control. Proceedings of 2nd International Tailings Symposium, Miller Freeman, San Francisco, pp. 75-95

Sasitharan, S. 1993. Collapse behavior of very loose sand. Ph.D. Thesis, Department of Civil Engineering, University of Alberta, Edmonton, Alberta.

Scott, M.D. and Lo, R.C. 1992. Optimal tailings management at the Highland Valley Copper. The Canadian Institution of Mining and Metallurgy (CIM) Bulletin July/August, pp. 85-88.

Sharp, J.J. 1981. **Hydraulic Modelling**, Butterworth, London.

Smith, E.S. 1969. Tailings disposal and liquefaction. Transaction. Society of Mining Engineers, AIME, 244: 179 - 187.

Soregaroli, A.E. 1974. Geology of the Brenda copper-molybdenum deposit in British Columbia. The Canadian Institution of Mining and Metallurgy Bulletin, October, pp. 76-83.

Southard, J.B. and Middleton, G.V. 1984. Mechanics of sediment movement. Society of Economic Paleontologists and Mineralogists' Short Course Number 3, March, pp. 241-252.

Tetu, H. and Pells, F. 1971. Design, construction and initial operation of the tailings system at Brenda Mines Ltd. The Canadian Institution of Mining and Metallurgy (CIM) Bulletin, August, pp. 101-107.

Yano, L.T. and Handford, G.T. 1990. Tailings engineering at Syncrude. The Canadian Institution of Mining and Metallurgy (CIM) Bulletin, July, pp. 89-91.

Yano, L.T. and Fair, A.E. 1988. Overview of hydraulic construction techniques utilized at the Syncrude Canada Limited tailings pond. Hydraulic Fill Structures. American Society of Civil Engineers Geotechnical Special Publication No. 21 Edited by D.J.A. Van Zyl and S.G. Vick, pp. 971-986.

Yoshimi, Y., Hatanaka, M. and Oh-Oka, H. 1978. Undisturbed sampling of saturated sands by freezing. Soils and Foundations, 18(3): 57 - 73.

Zahary, G. 1973. First progress report - subcommittee on fill, Internal Report 7 3/40, Mining Research Centre, Mines Branch, Department of Energy Mines and Resources, Ottawa, Canada.