THE DISPOSAL OF MINE TAILINGS MATERIAL

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ABSTRACT

The mining industry is an important component of the Canadian economy. The principal waste material from this industry is tailings. Numerous failures of tailings dams have caused loss of life and serious pollution problems.

This thesis relates to the broad scale investigation and development of improved methods for tailings disposal.

A systematic morphology has been developed which provides an effective approach to the overall problem for long-term planning and design.

Improved design and construction techniques are advanced for the hydraulic construction of tailings dams with mobile hydrocyclones. The new design incorporates a sealed structure to improve the structural quality and safety of the dam by reducing and maintaining the porewater pressure at zero or negative values over the long-term period.

Significant economic benefits are also attainable with the new design techniques.

Economic advantages and structural considerations are presented for the system to decant effluent from the tailings basin.

Special instrumentation has been designed, developed, and tested which will facilitate the evaluation of the material shear strength for this specific type of tailings dam.

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CHAPTER 1

INTRODUCTION

1.1 Reason for the Research Program

This research was undertaken in order to achieve a solution to a problem in the mining industry, i.e., the disposal of waste mine tailings. This process has created a problem which has resulted in serious effects on other natural resources and has created safety hazards in all mining countries throughout the world.

The mining industry constitutes an important component of the Canadian economy. Revenue from this industry is increasing rapidly and in 1970 reached the substantial figure of 5.8 billion dollars [1]; this figure represents an increase of over one billion dollars from 1969 and more than double the revenue in 1962. On the other hand, numerous marginal mining operations have been abandoned during the past ten years. It is important, therefore, to find acceptable solutions to the problems associated with mine tailings which can offer adequate protection for valuable natural resources and eliminate the hazards without seriously restricting the development of mining resources.

1.2 Mine Tailings Material

This section outlines the pertinent data associated with mine tailings.

1.2.1 Tailings Definition

Tailings may be defined as the waste material from a mining operation after the process of concentration during which valuable minerals are extracted for commercial use.

1.2.2 Tailings Volumes

The volume of tailings from a mining operation is frequently greater than the volume of crude ore because of the "bulking factor" and the small quantity of valuable mineral recovered during the process of concentration. The bulking results from the blasting, crushing and grinding of the crude ore. The average weight recovery of one of the most common industrial minerals, copper, is in the order of ½ to 1%, and the average weight recovery in a gold mining operation is only a fraction of an ounce per ton of crude ore.

It is estimated that the quantity of tailings produced by the Canadian Mining Industry during 1970 exceeded 400,000,000 tons.

An ore may be defined as a mineral that can be extracted at a profit. In North America a number of known large low-grade mineral deposits have only recently become ore bodies owing to advances in modern equipment and technology. Over the past 25 years there have been phenomenal advancements in the production capacity and efficiency of mining equipment. Off-highway haulage trucks have increased from 15 to 200 ton payload capacity. The largest operating shovel, which was placed in service in March 1969, has a 160 cubic yard bucket, a 45,000 horsepower power-plant, and its capital cost was $27,000,000.

The advances in equipment and methods have shifted the emphasis from small production underground operations to large scale low-grade open pit mining operations. A capacity of 2,000 to 3,000 tons per day is considered a medium sized underground mining operation. Some of the largest open pit mining operations exceed 230,000 tons per day.

The "stripping ratio" for open pit mining operations is generally much greater than the "development ratio" for underground mining operations. These waste ratios may be defined as follows: The "stripping ratio" is the ratio of waste material removed to crude ore recovered from an open pit. The "development ratio" is the ratio of development waste removed to crude ore mined from underground.

Some existing tailings disposal areas contain over 200,000,000 tons of tailings from a single mining operation. The majority of the existing tailings dams are less than 100 feet in height with a few dams exceeding 300 feet in height. An open pit mining operation in New Mexico had a waste dump with a height of 1728 feet in January 1971 [2]. In the mining industry the term "waste" refers to waste rock, whereas, tailings or waste tailings is the waste product after the process of concentration.

The above details not only indicate the tremendous volumes of tailings being produced within the mining industry at this time, but the trend indicates a rapid increase in the future volumes of mine tailings material.

1.2.3 Tailings Disposal

Following the metallurgical process of concentrating, the tailings is usually in the form of a slurry. Therefore, essentially all mine tailings disposal systems use hydraulic procedures for convenience and economy. The tailings material is commonly disposed of in designated tailings basins adjacent to the mining operations in order to prevent pollution of other natural resources. If suitable disposal areas are available close to the mining operations, it also facilitates the reclaiming of the tailings at a future date if the tailings are to be reprocessed to recover additional valuable minerals as a result of advances in technology or price changes.

Tailings dams are used to restrict the tailings material to the designated areas. In the process of selecting a site for a tailings basin, it is desirable to achieve the maximum possible "returns ratio" which is defined as "tons of tailings stored per cubic yard of dam-building material". In some cases only flat land is available for tailings disposal and this condition dictates the building of a complete perimeter dam. The necessity of a perimeter dam results in a low returns ratio causing high disposal costs. Actual returns ratios, for tailings disposal areas, vary from 2:1 to over 100:1, depending on the nature of the available disposal area.

If suitable tailings basins are not available close to the mining operation, it may be necessary to pump the tailings a considerable distance. In the United States one mining company has 23 miles of tailings pipeline. In Japan a mining company is pumping 1 3/4 million tons of tailings a year over a distance of 44 miles [3]. This tailings disposal system was placed in service in 1968. The route of the tailings line follows a river course and bridges the river in 42 places. The capital expenditure for the disposal system was $6,350,000.

1.2.4 Uses for Tailings Material

The principal use for tailings material is the construction of tailings dams to retain the tailings slimes in a designated tailings basin.

In underground mining operations, when it becomes necessary for structural reasons to backfill the mined out sections, many companies use the coarse fraction of classified tailings for backfilling the stopes. In these instances the particular operations usually have an inadequate supply of coarse tailings to meet their backfill demands. The removal of the coarse fraction of the tailings for backfill usually precludes the use of the remaining tailings for the construction of tailings dams.

A few other commercial uses have been found for mine tailings. In Germany a kyanite mining operation has used the clean silica sand recovered from tailings to construct a complete ski resort, swimming pool, and bathing beach. In Canada a limited quantity of high grade silica sand recovered from tailings has been used as a component in the manufacture of transite pipe [4].

In general, few commercial uses have been found for tailings other than dam building and mine backfill.

1.3 Typical Problems Associated with the Disposal of Tailings

1.3.1 Introduction

To reinforce the information contained in a literature survey and to gain a direct assessment of the current field conditions and environment relating to mine tailings disposal systems, several field trips were made to mining operations. These trips included visits to thirty seven mines during which time over eighty tailings dams were inspected. The inspections included: the disposal system, tailings dam, decant facilities, and tailings basin.

To substantiate further the existence of tailings problems within the industry, extensive discussions were held with technical personnel directly associated with the industry [5].

Twenty years of participation in the mining industry has led to an appraisal of:

1. the general environment relating to the disposal of tailings within the industry
2. the attitude of the mining officials toward the disposal of tailings and
3. the attitude of government officials toward the disposal of tailings.

These factors have had an important influence on the present aspect of the disposal of tailings in Canada.

1.3.2 History

The history of mining has been plagued with failures of tailings dams and pollution from tailings disposal systems.

In 1968 the Federal Government initiated a study on the stability of waste embankments [6]. The questionnaires returned from mining companies across Canada indicated that only 33% of the companies had experienced stability problems with tailings dams. The problems reported are primarily in the category of serious failures.

Investigations and discussions with technical personnel on numerous mining operations indicate that over 90% of the larger mining operations have had tailings dam failures of some kind. These failures vary from minor slip failures with little resulting damage to catastrophic failures. In a particular instance [7] one of the larger mining companies experienced seventeen failures over a period of seven years at a single mining property.

Major failures have occurred in Canada, United States, Chile, Australia, New Zealand, South Africa, England and throughout the mining countries in Europe.

A dam failure occurred in Ontario which released 450,000 tons of tailings instantaneously into a popular sporting stream. The flow of solids covered a provincial highway to a depth of 14 feet. In the U.S.A. a tailings dam failure released several million tons of stored tailings and inundated a large valley. In 1972 the failure of a tailings dam in U.S.A. killed 118 persons [8]. In South Africa a tailings dam failure of a large gold mining operation released 42 years of stored tailings and completely engulfed a train [9]. In another instance, a large crystal clear lake, 350 feet deep with over 20 square miles of surface area was polluted with acid from a mining operation resulting in an extremely low pH of 3.9 for the average lake water. In Chile, there have been numerous tailings dam failures, two of which resulted in extensive loss of life. One failure occurred in 1928 and 54 people were killed and another occurred in 1965 and 203 people were killed [10].

Historically, rigorous criteria have been established for the design and construction of earth dams for water storage. This is not the case for tailings dams. When a water storage dam fails it can result in property damage and possible loss of life. A failure of a tailings dam can be more serious because it includes the above possibilities plus several types of pollution. The breakaway of a tailings dam can, and usually does, result in the liquefaction of the saturated tailings slimes stored behind the dam. Considering the case of a uranium mining operation where sulphuric acid is used for leaching, the following pollution possibilities exist when the failure of a dam occurs:

1. pollution by large quantities of finely ground solids,
2. pollution by acids and
3. pollution by radioactivity.

One of the waste products contained in uranium tailings is radium and this material has a half-life of 1,620 years. In general, however, the principal sources of pollution resulting from tailings disposal systems are derived from the quality of the decant water and from the quality of the seepage water which emits from the downstream toe of the dam. It is not intended that the scope of this thesis cover the specific items relating to pollution.

The above cases are extreme; however, they are only a few of the numerous problems resulting from mine tailings. These cases are presented to indicate the potential seriousness of a failure of a tailings dam.

It should be appreciated that the majority of the details relating to the failure of tailings dams are withheld by mining officials to protect their interests and to reduce the embarrassment of the companies.

For this reason, there are extremely few details published which relate to the failure of tailings dams.

1.4 Attitude of the Mining Industry Towards the Disposal of Tailings

Until recently, the mining industry throughout North America and in most mining countries throughout the world looked upon tailings material as a waste product which should be disposed of in the most economical manner possible. There have been cases, particularly in remote areas, where disposal by the cheapest possible method meant dumping the tailings into the closest river, stream or water course. There are still a few areas today (1972) in North America, as well as in other countries, where mine tailings are dumped into local rivers.

As a general rule waste tailings material is contained in a restricted area by tailings dams, however, as outlined in Section 1.3 numerous breakaway failures have occurred which released the saturated tailings from behind the dams. When a breakaway occurred, a new dam was built and in many instances no penalties were imposed on the mining organization. There are few specific cases on record where the mining companies were financially penalized by the government for pollution of water resources by mine tailings. There are, however, cases where judgements were awarded for damage to private property or loss of life.

The directors of mining companies represent the interest of the shareholders. Profit is the fundamental goal and tailings disposal has a low priority unless it has a significant effect on profit.

Although some tailings dams are among the largest man-made structures in the world, they are non-profitable entities and are treated as such by the industry. Frequently the planning and engineering for the mine production facilities are complete before consideration is extended to the selection of a tailings basin. The tailings basin is often located in a swampy area which causes structural problems for the foundation of the tailings dam. Unlike water storage dams, tailings dams do not produce power, irrigation water, or recreation facilities but merely contain a waste product.

Mining companies spend vast sums of money on field exploration. They also spend millions of dollars annually on process research but have been extremely reluctant to spend money on research for waste disposal or pollution control until subjected to public, political, and financial pressures. When there are no financial penalties the industry prefers to have the public believe that in order for a remote community to be prosperous, the inconvenience of water pollution must be accepted. In the author's opinion competent tailings dams and adequate pollution control can be provided at small cost in relation to the benefits derived from extraction of the non-renewable natural resources.

1.5 Attitude of the Responsible Government Authorities Towards the Disposal of Tailings

In Canada the jurisdiction and authority for the approval, regulation and inspection of details relating to tailings disposal, overlap or are divided between several independent bodies. In the Province of Ontario the following departments are involved:

1. The Department of Mines and Northern Affairs
2. The Department of Health
3. The Department of the Environment and
4. The Department of Lands and Forests.

The three levels of government - Federal, Provincial and Municipal - are also involved with the disposal of mine tailings.

Recently, as a result of strong public opinion and the recognition of the value of the natural resources, the Federal Government has decreed specific penalties for polluters. Substantial daily fines (up to $5,000 per day) can be imposed for violation of pollution regulations as outlined in the recent "Canada Water Act" [11]. The Government also controls the mining rights in most areas in Canada (some of the older patented deeds contain surface, mining and timber rights).

Several Provincial Governments have created legislation requiring mining companies to submit complete details of the tailings disposal system for approval, before commencement of production operations. Approval is also required for modifications to existing disposal systems.

Authorities have separated the disposal systems into two distinct categories:

1. new disposal systems and
2. existing disposal systems.

The problem and solution to problems associated with new disposal systems are appreciably easier to control and regulate than those relating to existing systems. The rehabilitation of abandoned disposal systems present difficult problems which in some instances have become a liability of the Government.

Authorities have abstracted guidelines for tailings dams which were originally intended for water reservoir dams. This situation has created numerous problems. Tailings dams are subject to unique operating conditions and therefore require different analysis.

Some authorities prefer to draft "objectives" or make "recommendations" to the mining companies rather than establish rigid regulations or laws governing tailings. One reason why the provinces have adopted this practice is that objectives are easier to change where a specific situation requires special consideration.

1.6 Scope of the Research

The major problems in developing safe tailings disposal systems are classified as follows:

1. adequate methodology is required whereby the planning of a tailings disposal system is logically incorporated as an integral component of the planning for the mine production facilities and
2. criteria for dams unique to the containment of tailings are not adequately developed.

Therefore this thesis is developed to meet the following principal objectives:

1. to develop a morphology for planning and designing mine tailings disposal systems
2. to investigate the adequacy of criteria for the design and construction of dams currently used for the containment of mine tailings

3. to select and develop a promising construction technique and
4. to carry out an analysis of the potential of this technique.

The scope of the research includes:

1. a systems engineering analysis of tailings disposal in relation to mine planning
2. field investigation of
    a) tailings disposal systems
    b) tailings dams
    c) tailings basins, and
    d) tailings decant systems
3. field testing of tailings material with mobile hydrocyclones to improve dam construction techniques
4. laboratory testing of tailings material
5. a geotechnical and economic analysis of the construction of hydrocycloned tailings dams and
6. development of instrumentation for hydrocycloned tailings dams.

1.7 Summary by Chapters

Chapter 2 introduces the existing conditions and outlines a number of problems associated with the planning procedure for the disposal of mine tailings. The methodology of systems engineering is used to develop a planning and design morphology for the disposal of tailings.

Chapter 3 reviews the well-defined design criteria for conventional earth dams in order to provide a background for tailings dams. The specific conditions and problems relating to tailings embankments and decant systems are discussed and subsequently a method of hydraulic construction for tailings dams is selected for further investigation.

The potential of new design and construction criteria for tailings dams using mobile hydrocyclones is investigated in Chapter 4 and this method is compared with the predominant method of hydraulic construction with spigots.

The development of special instrumentation to be used in conjunction with hydrocycloned tailings dams is described in Chapter 5.

Chapter 6 summarizes the major conclusions of the thesis.

CHAPTER 2

THE DEVELOPMENT OF A MORPHOLOGY FOR PLANNING AND DESIGNING A MINE TAILINGS DISPOSAL SYSTEM

2.1 The Relative Importance of Tailings Disposal Within the Realm of the Mining Industry

The general conditions relating mining to the Canadian economy have been outlined in the introduction; at this stage it is considered appropriate to outline the relative importance of tailings disposal within the realm of the mining industry.

The prime motivation of industry is profit. The public in general and recent government regulations have made strong demands that the mining industry, which derives benefits from a non-renewable natural resource, broaden its perspective beyond the profit objective to provide careful consideration of the environment and the protection of other natural resources. During the past five years, in Canada and the United States, organized environment oriented groups have gained sufficient support from the government authorities to prohibit mining within specific areas. These actions have been prompted by the undesirable experience of a disregard for the environment by the mining industry. The situation has developed where society places a high priority on anti-pollution measures because of the value of the natural environment.

In general, industrial management give top priority to operating costs because these factors have the greatest direct effect on operating profit. The cost of tailings disposal as a component of mine operating cost is extremely small and is usually in the order of a few cents per ton of crude ore mined. It is desirable for management to evaluate carefully all of the elements within the system and the system environment during the planning stage. With regard to the allocation of the "surface space resource" on a mining operation, the disposal of tailings dictates top priority as a space-volume requirement. Tailings disposal also commands considerable respect with regard to the potential effects that the disposal system has on the environment. If an acceptable solution for the disposal of tailings cannot be provided, the production operation will not be approved by the authorities regardless of the profitability of the mining operation.

2.2 Problems or Shortcomings with the Existing Planning Procedures for Tailings Disposal Systems

1. The disposal of tailings has been treated as a separate entity with low priority rather than a component of the production facilities during the planning and design stage.
2. The planning of tailings disposal is frequently done on a short-term or year-to-year basis and this procedure can add substantially to the long-term costs.
3. A rigorous basis for planning in accordance with a hierarchial procedure is seldom used.
4. Alternative solutions are investigated in a random manner.
5. Alternative solutions are frequently omitted.
6. It is difficult to visualize the nature and extent of the inter-dependencies of the various elements within the system without a graphic perspective of the total planning process.

7. Preliminary studies for the purpose of eliminating unnecessary details, expenditures, and lost time, are frequently omitted.
8. Hydrologic studies are frequently omitted for proposed tailings basins.
9. Foundation investigations are frequently omitted for proposed tailings dams.

The following examples outline some recent histories relating to the above points.

1. A national survey in 1969 [12] indicated that foundation investigations for tailings dams are omitted on more than 80% of the projects.
2. In 1966 one of the largest mining companies experienced a breakaway failure of a dam retaining saturated tailings. The resulting flow of tailings covered several farms and approximately one mile of state highway. The day following the failure, one of the senior mining officials commented as follows: "The dam didn't fail, the soil beneath the dam failed".
3. In 1970 a mining company, with proven long-term ore reserves, considered the expansion of the tailings disposal area. The previous planning had been made on a short-term basis. A recent study indicated that an initial long-term planning procedure could have eliminated the necessity of constructing four of the existing tailings dams.

4. In 1969 a mining company proposed to increase the height of an existing tailings dam in order to provide additional tailings storage capacity for one year's production. The returns ratio had not been carefully investigated. A subsequent investigation indicated that a tailings dam could be built at a new location to provide 10 years storage capacity with a volume of fill closely approximating the volume required for the proposed increase of the existing dam.
5. In 1969 a mine that had been in production for 10 years, considered reusing tailings water for plant process water. The study indicated that this procedure would not only reduce the demand for process water from the natural resources but would also provide a significant saving in operating cost.
6. In 1971 a company produced detailed engineering drawings for a tailings dam prior to a feasibility study to determine the most advantageous method for tailings disposal.
7. In 1971 the structural details were determined for a decant system prior to determining the construction procedure for the dam or the principal point of discharge for the tailings.

The deficiencies of the existing practices justify the development of an effective procedure for solving the problems of tailings disposal.

2.3 Problem Solving Methodology

In order to be effective in the planning and design stage of any important project, a rational planning procedure must be developed. The advances in technology and world competition have rendered the older method of decision making solely by intuition, inadequate to compete with modern systematic approaches to planning and problem solving methods.

2.3.1 Systems Engineering

Over the past ten to fifteen years a number of technical developments have evolved to improve the efficiency of planning and problem solving. One such method that has been successfully applied to industrial projects is "systems engineering".

In general terms, systems engineering is an attempt to consider the total environment surrounding the system in addition to the elements within the system in order to achieve more effectively certain goals from the output of the system.

"System", "Environment" and the common terms relating to "systems engineering" have been defined in slightly different terms by many authors. For the purpose of this thesis the terminology outlined by Hutchinson [13] has been adopted.

"A system may be defined as a set of elements that is organized in such a way as to direct the behaviour of the system toward specific goals or objectives".

"An environment may be defined as the set of all elements outside a system which both influences the behaviour of a system and in turn is influenced by the behaviour of the system".

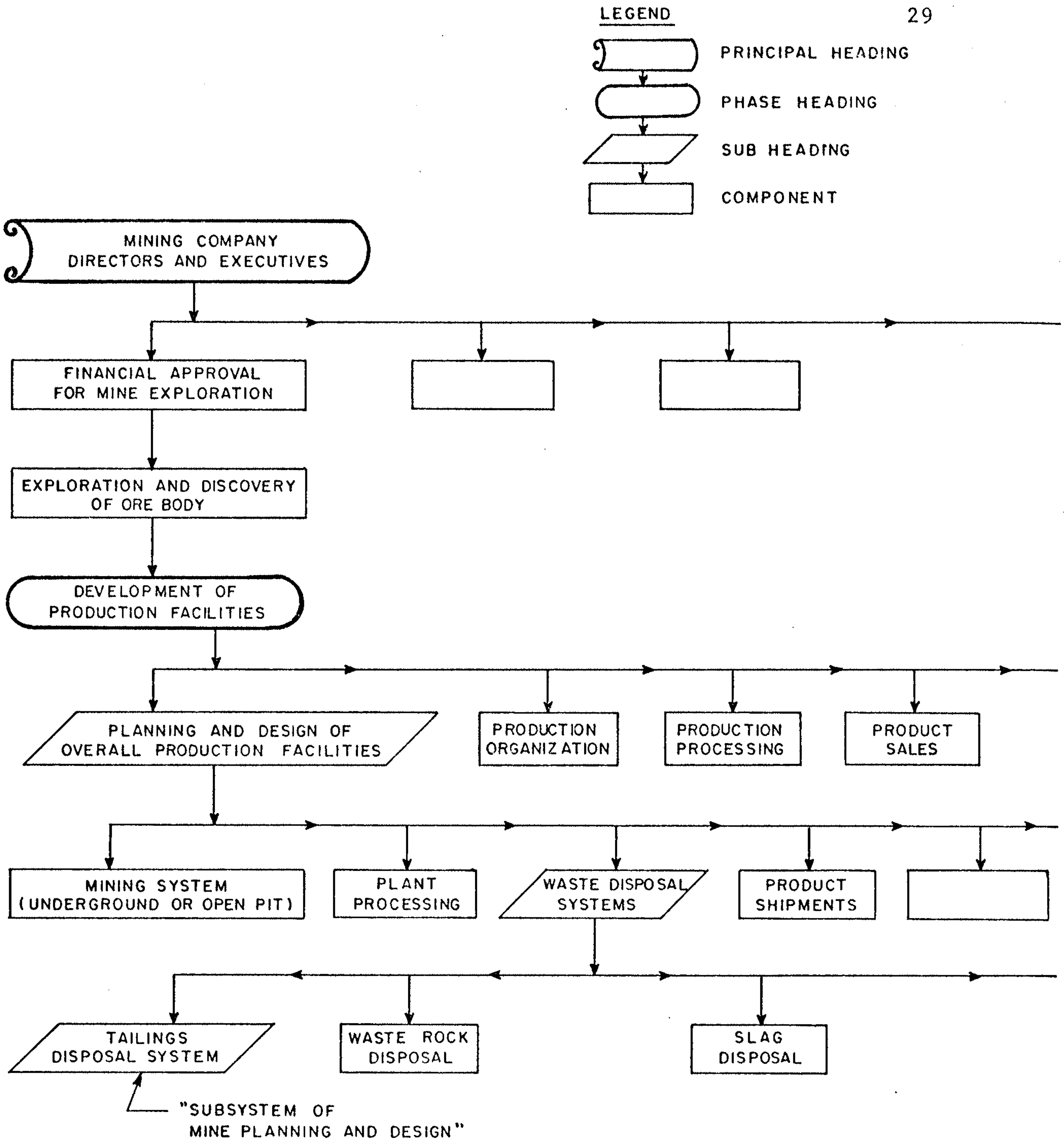
In systems engineering we are dealing with systems engineered by man, the majority of which can be classified as subsystems or divisions of a larger system. The graphic perspective of the hierarchial location of a system for mine tailings disposal, within a mining complex, is shown in Figure 2.1.

The problem solving process as outlined by systems engineering divides the procedure into a series of steps:

1. General problem definition or principal goal and refinements of the problem definition in terms of
    a. objectives
    b. inputs
    c. constraints
    d. outputs
    e. value functions, and
    f. decision criteria
2. solution generation
3. evaluation of alternative solutions
4. selection of the best solution
5. project implementation, and
6. observations of the project performance or effectiveness.

Stated another way it can be said that systems engineering asks a series of appropriate questions in a rational sequential manner with a view to improving the problem solving process. These questions are:

1. What is the problem?
2. What are the possible solutions?



GRAPHIC PERSPECTIVE OF THE HIERARCHIAL LOCATION OF A SYSTEM FOR MINE TAILINGS DISPOSAL WITHIN A MINING COMPLEX

Fig. 2.1

3. What are the relative values of these solutions?

4. What is the best solution?

5. How do we implement the solution generated?

6. How effective is the solution?

2.4 Systems Engineering Applied to Tailings Disposal

This section deals with the organization of tasks and the interdependencies between various components of the system.

The undesirable conditions with respect to tailings disposal throughout the mining industry indicates a serious requirement for a sequential planning and design morphology to achieve a general solution to the problems associated with tailings disposal.

Over the past thirty years the improvements in the field of tailings disposal have involved improvements to existing practices or improvements to isolated details for various components.

As a prerequisite for developing the schematic model it is necessary to have acquired a firm grasp of the details associated with tailings disposal and its environment, with particular reference to the function of each element and the interdependencies between components of the system.

2.4.1 Problem Definition for a Mine Tailings Disposal System

The principal goal is to provide a safe tailings disposal system with the lowest cost per ton of tailings stored over the long-term period, consistent with the rules or regulations of government authorities.

Systems engineering is used to define the problem in detail in the subsections to follow:

2.4.1.1 Objectives

"The system objectives may be defined as a set of operational definitions that identifies the needs that a system must attempt to satisfy". The common objectives for a tailings disposal system are:

1. To contain the tailings material within a designated area by construction of a competent tailings dam.
2. To meet the criteria as outlined in Section 2.4.1.6.
3. To consider the future possibility of reprocessing the tailings material when selecting the tailings basin.
4. To provide disposal facilities to meet the initial tailings production schedule.
5. To provide storage capacity to meet the long-term requirements for tailings.
6. To minimize the lost production of the plant by including an alternative short tailings dumpline and standby pump facilities.
7. To minimize the volume of makeup water obtained from the natural resources.
8. To divert any significant quantities of streamflow in order to by-pass the tailings basin.
9. To route stream diversion projects in a manner that minimizes the changes to the existing environment.

10. To make provision for the removal of:

    a) the clear process water after the solid particles have settled, and

    b) the excess runoff water from the tailings basin.

11. To provide a tailings line with the minimum operating maintenance.

12. To provide instrumentation in the tailings pumphouse for determining the quality and quantity of the tailings material.

13. To make provision for the collection of the seepage water, which emits from the downstream toe of the dam, permitting neutralization treatment where necessary.

14. To provide a convenient arrangement to facilitate the determination of quality and quantity of water discharged from the tailings basin into any natural watercourse, and

15. To comply with the environmental constraints imposed by government authorities.

2.4.1.2 Inputs

"The inputs to the system are those characteristics of the environment which a system must transform into outputs in the light of the system objectives".

The principal inputs to a tailings disposal system are:

1. tailings material (the significant factors are: total volume, production schedule and physical characteristics).

2. process water from the natural resources
3. stream flow and runoff into the proposed storage area (The significant factor is the maximum probable storm)
4. alternative areas for storage of tailings material and auxiliary areas for short term and emergency tailings storage. (The significant factors relating to the storage areas are: distance from the concentrator, elevation with respect to the concentrator and maximum ground height between the concentrator and the storage area, storage volume, potential returns ratio, accessibility to the storage area and the foundation conditions for the proposed dam and decant system).
5. labour, materials and equipment for construction and operation of the tailings dam and ancilliary system facilities, and
6. chemicals for neutralization of tailings material.

2.4.1.3 Constraints

"System constraints are those characteristics of the environment that limit the extent of the feasible solutions".

The constraints associated with tailings disposal systems are social, physical and economic and are as follows:

1. approval of the general arrangement of the tailings disposal system by the governing authorities with particular emphasis regarding:
   a) the effects of the tailings disposal system on the local environment

b) the proposed tailings storage area

c) complete control of the property encompassing the ultimate tailings disposal area by the mining company

d) the proposed diversion of natural water courses

e) the process water requirements from the natural resources

f) the proposed rehabilitation of the tailings basin after the cessation of tailings disposal

2. approval of the design details by the governing authorities with particular emphasis regarding:

   a) the requirement of a foundation investigation for the tailings dam and decant system

   b) the stability of the tailings dam and decant system

   c) the provision for facilities to permit monitoring the operating conditions of the system, by both the mining company and government representatives and maintenance of suitable records relating to these details by the mining company

3. the quality of the tailings discharged from the plant must be continuously controlled in accordance with the government regulations

4. the quality and quantity of seepage water which emits from the tailings dam must be controlled in accordance with the government regulations

5. the quality and quantity of water discharged from the decant system into any natural water course must be controlled in accordance with the government regulations
6. restrictive measures must be exercised to minimize the dust pollution from the tailings disposal area
7. the physical interdependencies between various components of the disposal system
8. the long-term storage requirements and schedule of storage requirements for the disposal of tailings material
9. the location and characteristics of available tailings basins
10. the quantity and quality of natural materials and waste process materials available for construction of the tailings dam
11. the construction procedures and the climatic conditions affecting the construction schedule
12. the economic interdependencies between scarce resources which are common requirements for the tailings disposal system and other components of the mining operation, and
13. the limiting economic constraint on the overall mining operation to satisfy the individual policy relating to return on capital investment.

2.4.1.4 Outputs

"The outputs of a system are those functional properties of a system which influence the environment and which derive from the system inputs and the system properties".

The outputs from a tailings disposal system are:

1. a tailings dam and decant facilities
2. waste tailings material contained within a designated area
3. the discharge water from the decant system
4. permanent records of the quality and quantity of materials associated with the decant system, and
5. a financial injection, into the local economy, which is directly influenced by an acceptable solution to the disposal of tailings material.

2.4.1.5 Value Functions

"A value function maps an output variable into the system objectives".

The value of a tailings disposal system falls within two general categories:

1. tangible values which can be appraised in terms of economic factors including wages and materials. The tailings disposal system is not a profit producing entity of the mining operation but can be classified as an operating expense which detracts from the operating profit. Therefore, the tangible value of the tailings disposal system to the company is a direct function of the effect it has on the profit from the mining operation.

   It has previously been stated that if an acceptable solution for the disposal of tailings cannot be provided, the operation will not be approved. The value of the outputs from the mining operation are the economic benefits to the company and to the local community. These tangible benefits are indirect benefits resulting from the existence of a tailings disposal system.

2. intangible values in terms of social, physical and psychological effects.

   The intangible values are primarily disbenefits derived from the detrimental effects on the quality of the water, air, general environment and appearance of the landscape.

2.4.1.6 Decision Criterion

"Decision criterion may be defined as a rule which instructs the systems planner how the individual measures of value associated with each objective should be manipulated in order to arrive at a single index of value for the system".

The prime decisions are made by the company representative and from a company standpoint the index of value can be represented in dollar units. The value will be the long-term cost of tailings disposal measured in terms of present value. The criterion by which alternatives are selected is to minimize the cost of tailings disposal. The cost of tailings disposal is one component for determining the viability of the overall mining project. The directors of mining companies usually initiate policies which limit the minimum return on investment for the project to be considered economically feasible.

Auxiliary decisions are made by government representatives by way of approval of the general arrangement and details of the tailings disposal system. These decisions are intended to safeguard the interests of society and are primarily associated with intangible values which also reflect in tangible expenditures by the mining company.

2.4.2 The Morphology

The morphology should be amenable to the problems of tailings disposal; however, the desirable characteristics for the model are different from the objectives for the tailings disposal system. The morphology should have the following characteristics: it should

1. provide an efficient sequential procedure for planning and designing a mine tailings disposal system
2. provide a total perspective in the form of a schematic model of all important components of the system to remove the possibility of overlooking significant elements during the planning and design stages
3. provide a perspective of the planning and design interdependencies between the components of the system
4. incorporate or inject the long-term planning aspect (It has been frequently argued that it is difficult to use long-term planning in the mining industry because some operations have an expected life of only one or two years. In instances where the proven ore reserves indicate a short production life, the long-term is coincident with the life of the operation).
5. outline the alternatives to be considered for the principal components

6. identify the major components or milestones in a sequential manner
7. provide an isolated initial phase in order to minimize unnecessary expenditures and investigations by means of a preliminary analysis of the possible alternatives and the project feasibility
8. provide an estimated evaluation of the contribution from tailings disposal to the long-term mine operating costs, and
9. provide a pictorial reference which will be expedient for training personnel in the required disciplines during the planning and design stages.

In developing the morphology, the following factors were considered:

1. the general environment relating to mining operations and tailings disposal systems
2. the shortcomings of the existing planning and design practices applied to tailings disposal systems
3. the availability of soil mechanics technology which can be applied to tailings dams
4. the availability of flood routing technology which can be applied to tailings basins
5. the observations of existing field problems associated with tailings disposal systems, and
6. the detailed problem definition for "a mine tailings disposal system" as defined by systems engineering in the previous section.

The detailed problem definition for a mine tailings disposal system combined with the desirable characteristics and considerations as previously outlined provide a basis for developing the morphology.

Before commencing with the schematic model, benefits can be derived from a complementary flow sheet to the model which outlines the potential sources of dam building material in the form of a "flow chart for tailings dam materials" as shown in Figure 2.2. The flow chart and the schematic model are intended to cover the broad aspects relating to the planning and design of a tailings disposal system.

The morphology is separated into five distinct functional phases. These phases are organized in a sequential arrangement in which each phase is directly dependent upon the output from the phase immediately preceding it.

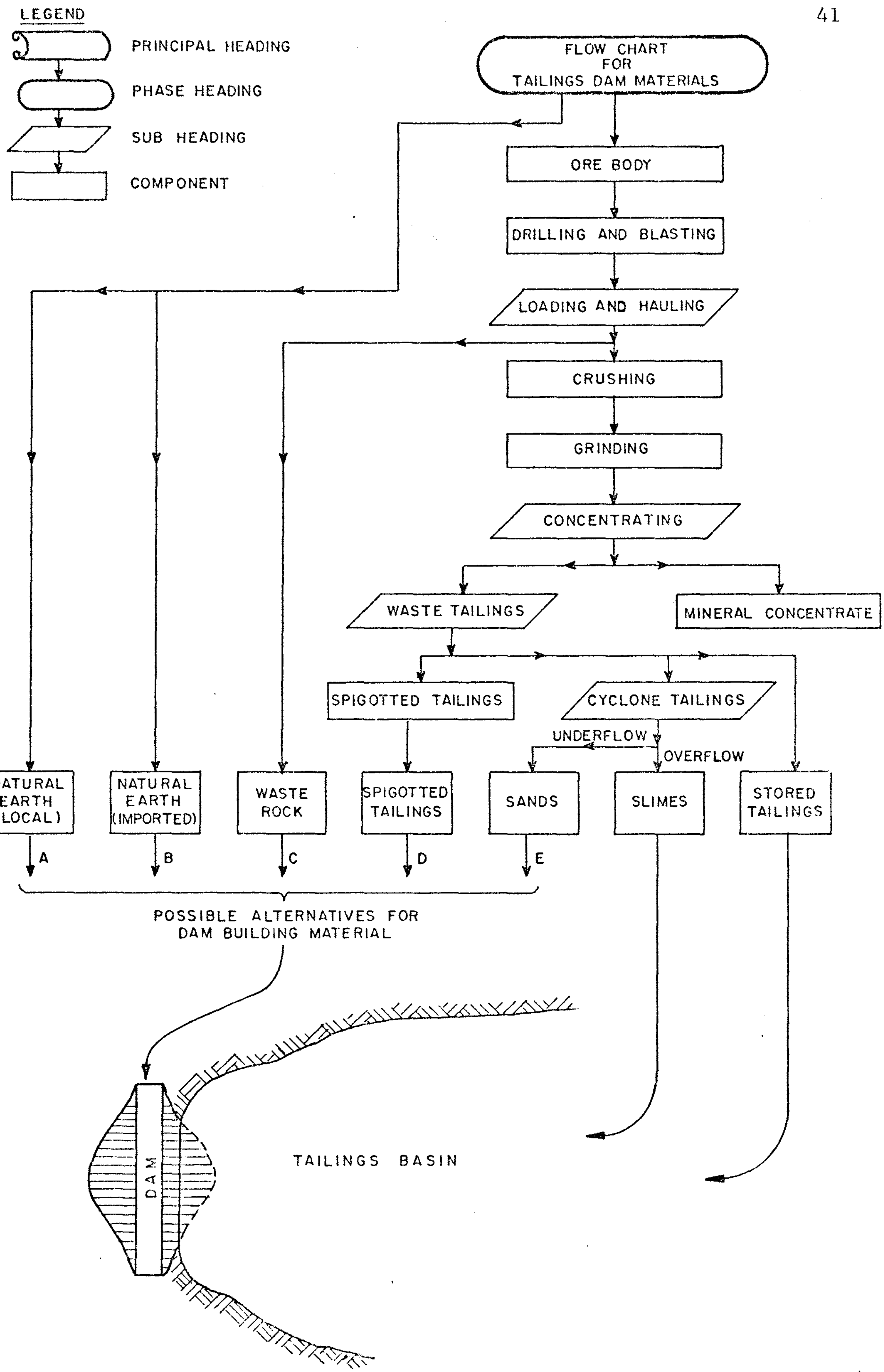
Phase one presents the tasks necessary for a preliminary feasibility study intended to minimize unnecessary expenditures prior to selecting the final site for the tailings disposal basin.

Phase two presents a comprehensive perspective of the design components and interdependencies between components to facilitate a rational organization of the planning and design procedure.

Phase three is an outline of the cost components to provide an economic evaluation of the proposed system, prior to obtaining approval of the design details and before commencement of the project implementation.

Phase four outlines the principal components for planning and scheduling in the implementation phase.

Finally, an epilogue is presented in phase five as a reminder of the post construction details, which are frequently overlooked or neglected



FLOW CHART FOR TAILINGS DAM MATERIALS

Fig. 2.2

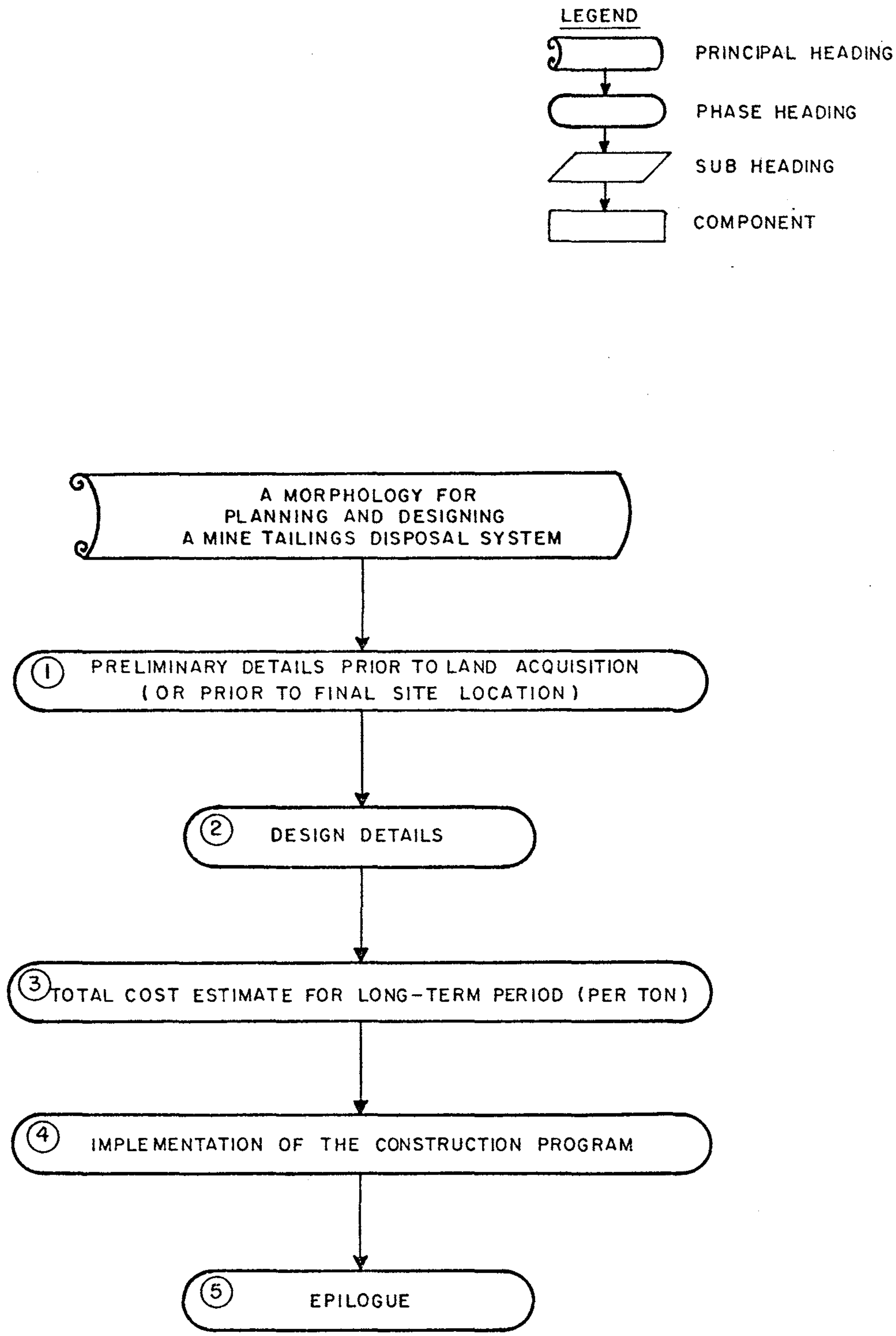
on mining operations owing to the attention demanded by the physical components of the profit producing production facilities.

Figures 2.3 through 2.9 outline the morphology as developed with reference to the foregoing sections contained within this chapter.

2.4.3 Comments Relating to Phase Two, "Design Details", of the Morphology

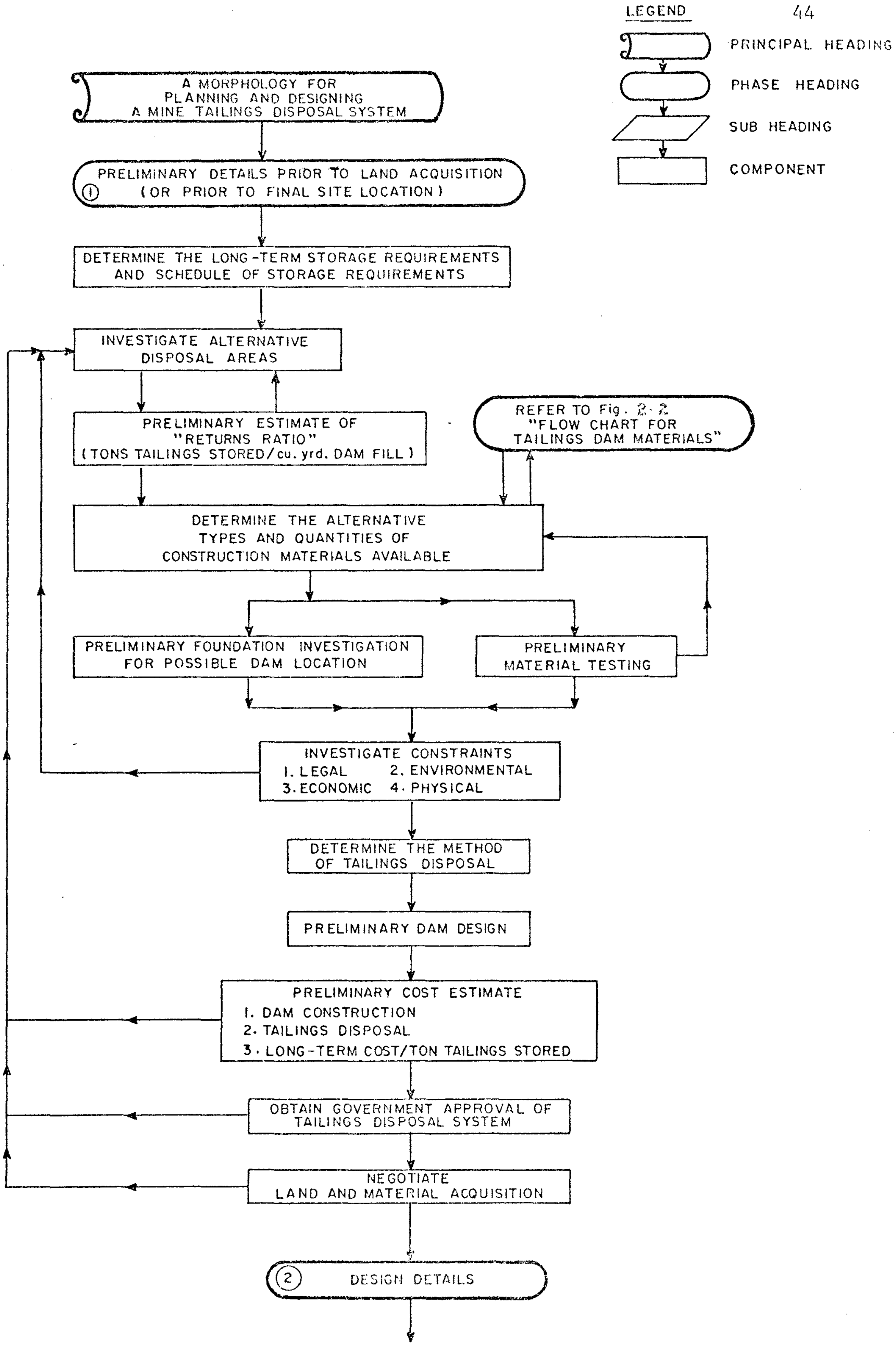
Three of the most critical interdependencies have been accentuated with heavy interconnecting lines on Figures 2.5 and 2.6. If these interdependencies are not fully recognized or adequately evaluated in the early stages of planning and design, it can lead to costly and unnecessary expenditures.

1. It is not practical to detail a decant system prior to determining the sectional details for the embankment. If the embankment contains a structural seal, this feature reflects favourable changes in both economy and engineering for the decant system.
2. When a spigotted procedure is selected to recover tailings material for dam building, it is not possible to provide a competent seal within the embankment. Consequently, the settling pool must be kept at a sufficient distance from the embankment to restrict seepage. (Further details are provided in Chapter 3).
3. It is necessary to discharge the tailings at a remote distance from the dam to maximize the returns ratio for a specific tailings basin. When the tailings is discharged at



OUTLINE OF MORPHOLOGY PHASE DIVISIONS

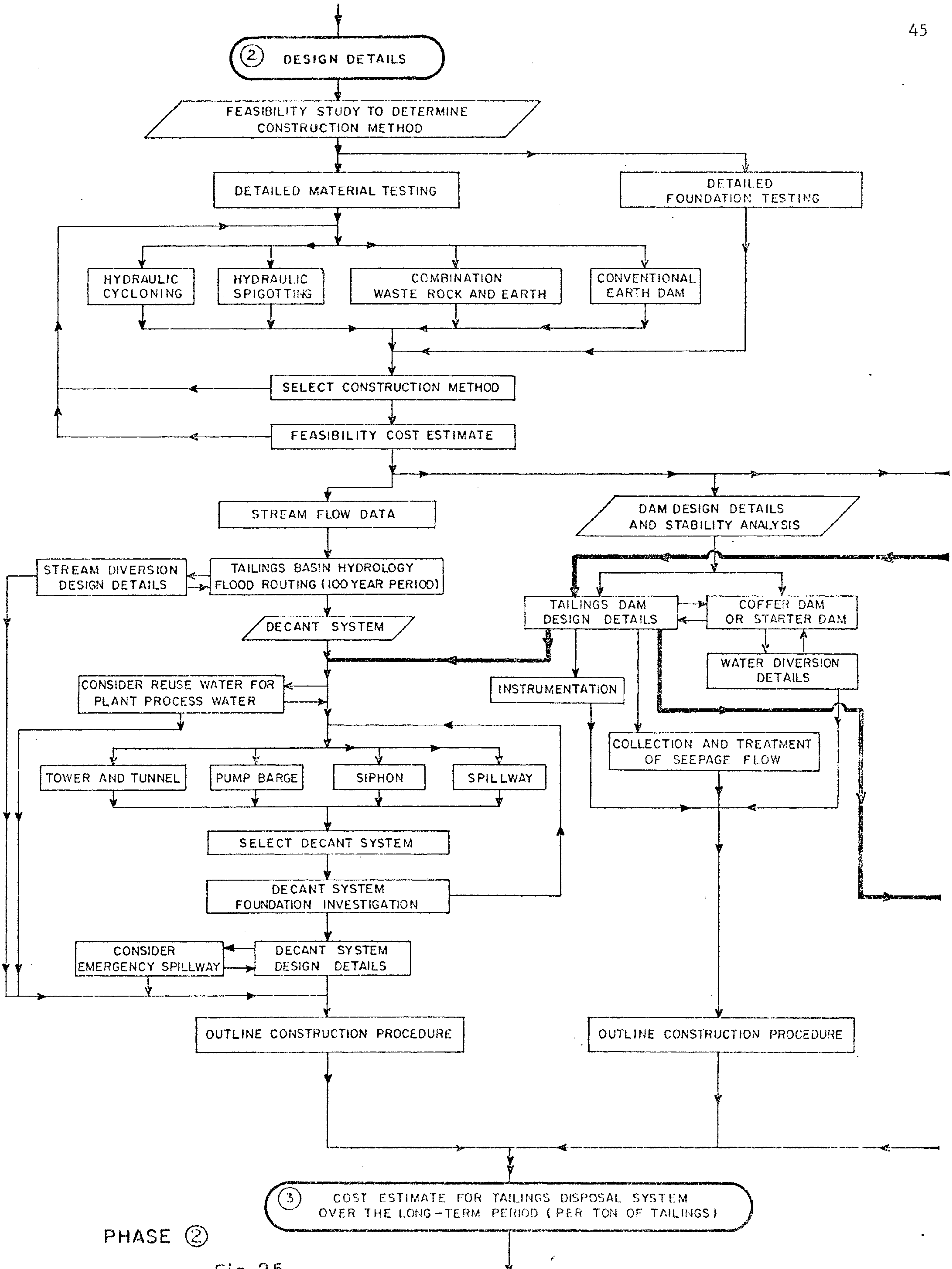
Fig. 2.3



PHASE ①

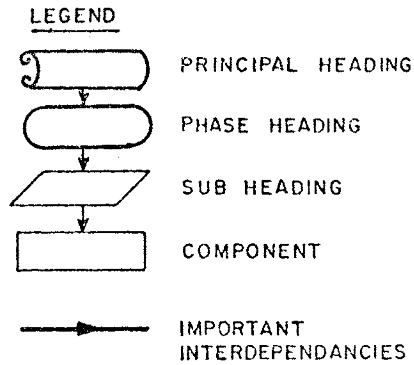
Fig. 2.4

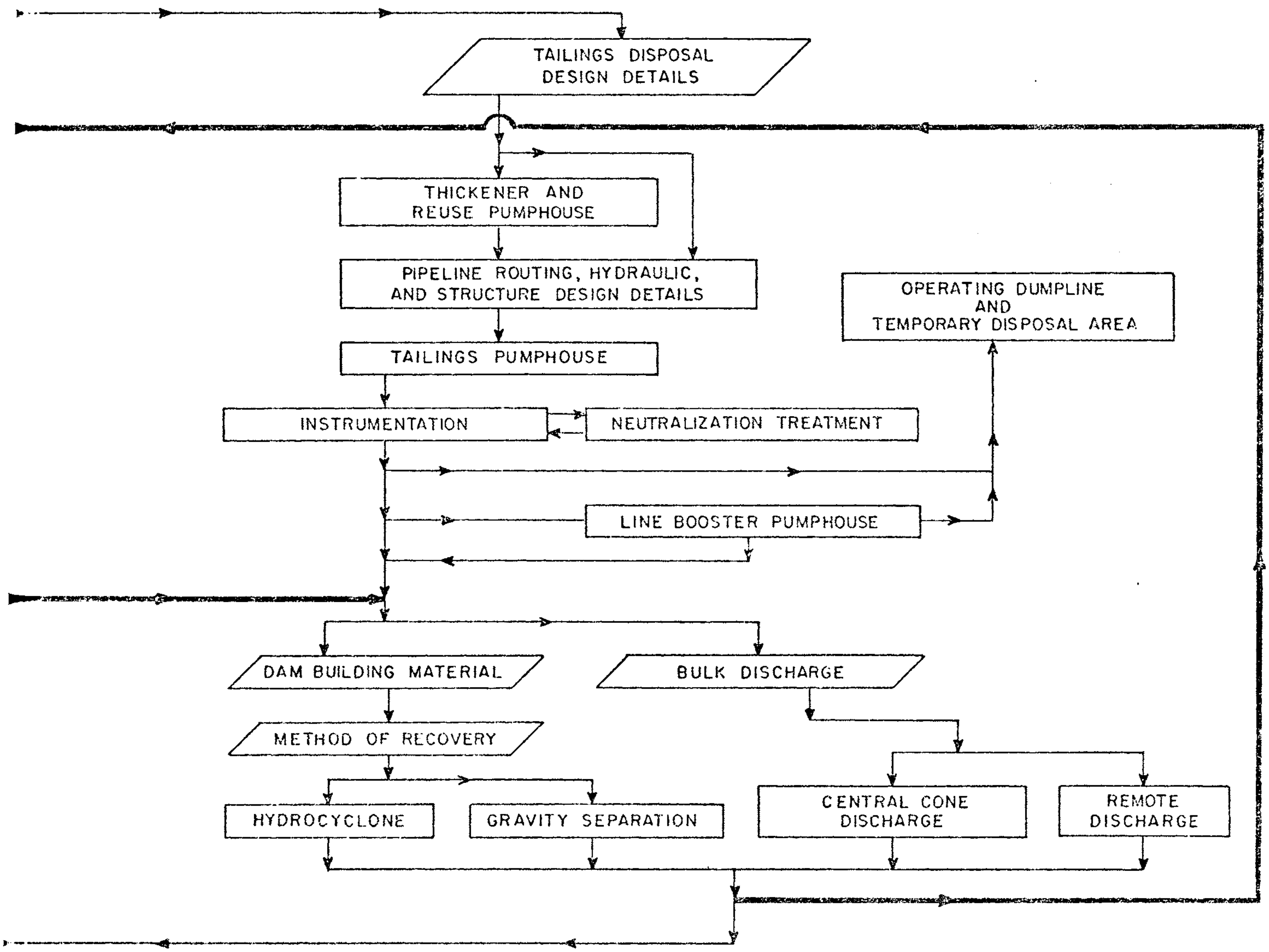
CONTINUE PHASE ②



PHASE 2

Fig. 2.5

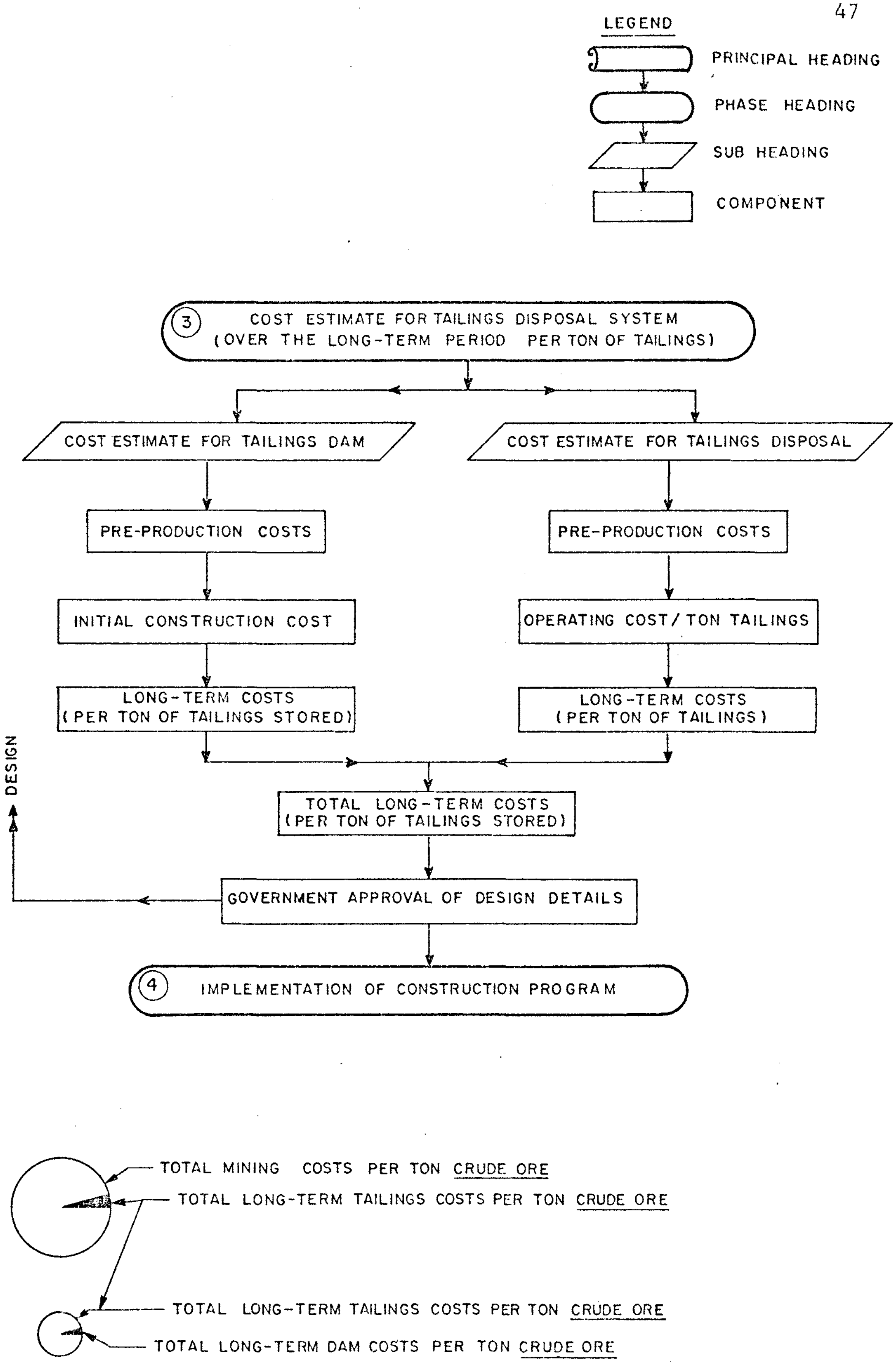




PHASE 2

Fig. 2.6

CONTINUE PHASE 3



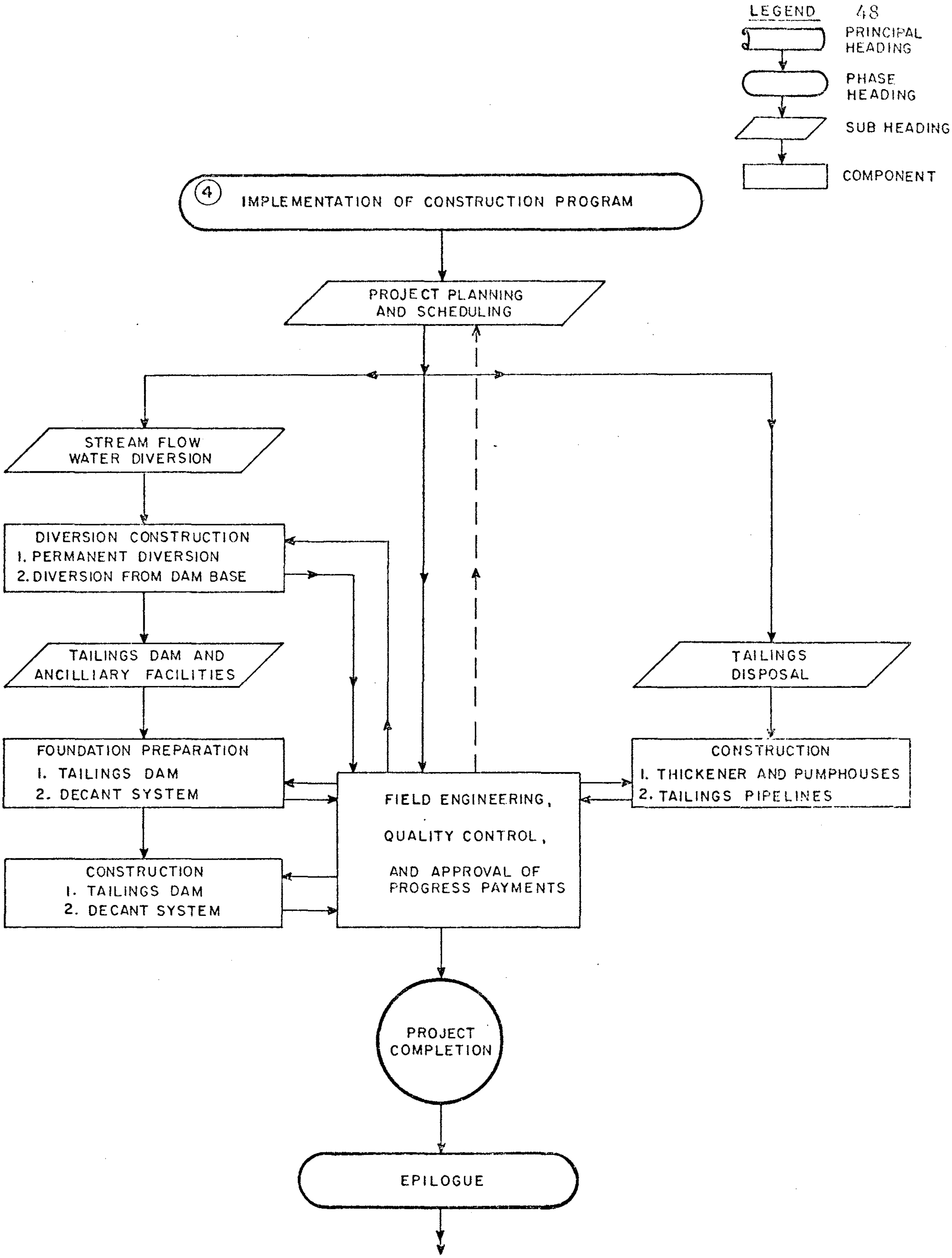
LONG TERM COST ESTIMATE

(PER TON CRUDE ORE)

PHASE 3

Fig. 2.7

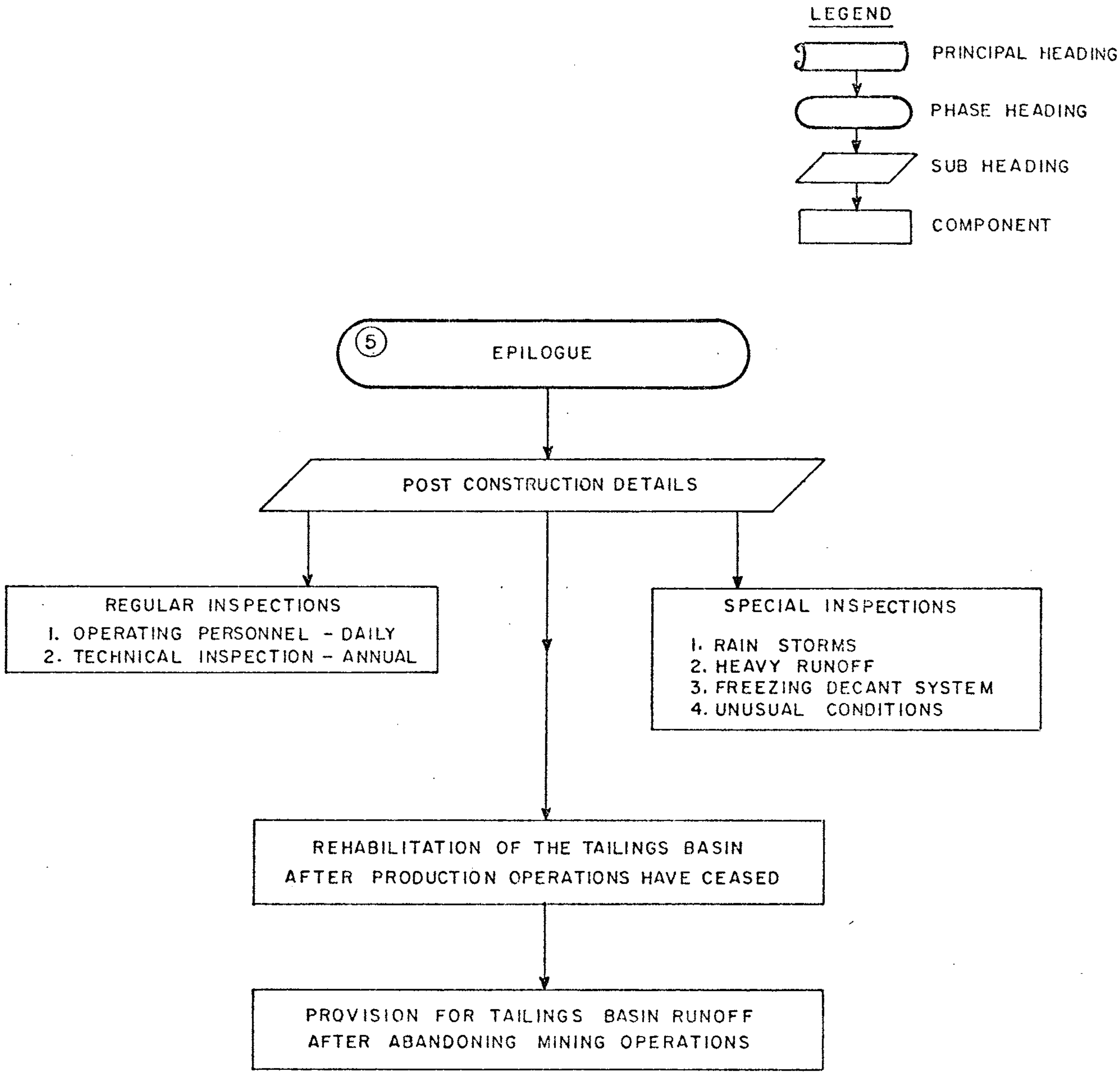
CONTINUE PHASE 4



PHASE 4

Fig. 2·8

CONTINUE PHASE 5



PHASE 5

Fig. 2.9

either a central cone or upstream from the dam, the settling pool will be in contact with the upstream face of the embankment and a seal must be provided. A suitable detail will permit the designer to take advantage of the benefits by considering the point of discharge for the tailings.

The model as developed offers simplicity in visualizing: the total components comprising the system, the alternatives for solutions to the problems and the interdependencies between components of the system. The value of the morphology will be determined by its effectiveness in planning and design.

The design phase of the system is dominated by the tailings dam which is presented in detail in Chapter 3.

CHAPTER 3

TAILINGS DAMS

3.1 Introduction

Included in this chapter are the following details: a brief discussion of the features of a conventional earth dam, special conditions inherent to tailings dams, structural deficiencies in existing tailings dams and decant systems, and the selection of a hydraulic construction method for further development.

This chapter begins with the fundamentals of earth dams to provide a background for comparison with tailings dams.

Two types of hydraulic tailings dams are also compared. In this context it is intended to stress the details relating to tailings dams constructed for the purpose of retaining tailings in a designated area and using tailings as the primary construction material. The vast majority of existing tailings dams are constructed with tailings material; however, some tailings dams are constructed with natural soils. Recent developments of large mining operations, with extensive requirements for storage of tailings, have a tendency to use natural materials and conventional construction procedures when high tailings dams are required.

3.2 Features of Conventional Earth Dams

The history relating to the construction of earth dams dates back several centuries. The remains of the Sadd el Kafara dam, an earth-rock structure, is located twenty miles south of Cairo, Egypt. This dam was constructed between 2950 and 2750 B.C. [14].

The fundamental requirements for an earth dam are: to obstruct the flow of water and to provide a competent structure with an adequate factor of safety during the life of the dam. The intended meaning of adequate factor of safety is discussed in Section 4.5.

The two principal classifications of earth dams are homogeneous and zone-filled dams. The term homogeneous as related to earth dams, is intended to mean a dam constructed primarily of one material even though an internal drainage system may be included within the structure.

Developments in the field of soil mechanics, over the past twenty five years, have advanced dam building technology to the stage where several structural features and design procedures have proven to be essential components for competent earth dams.

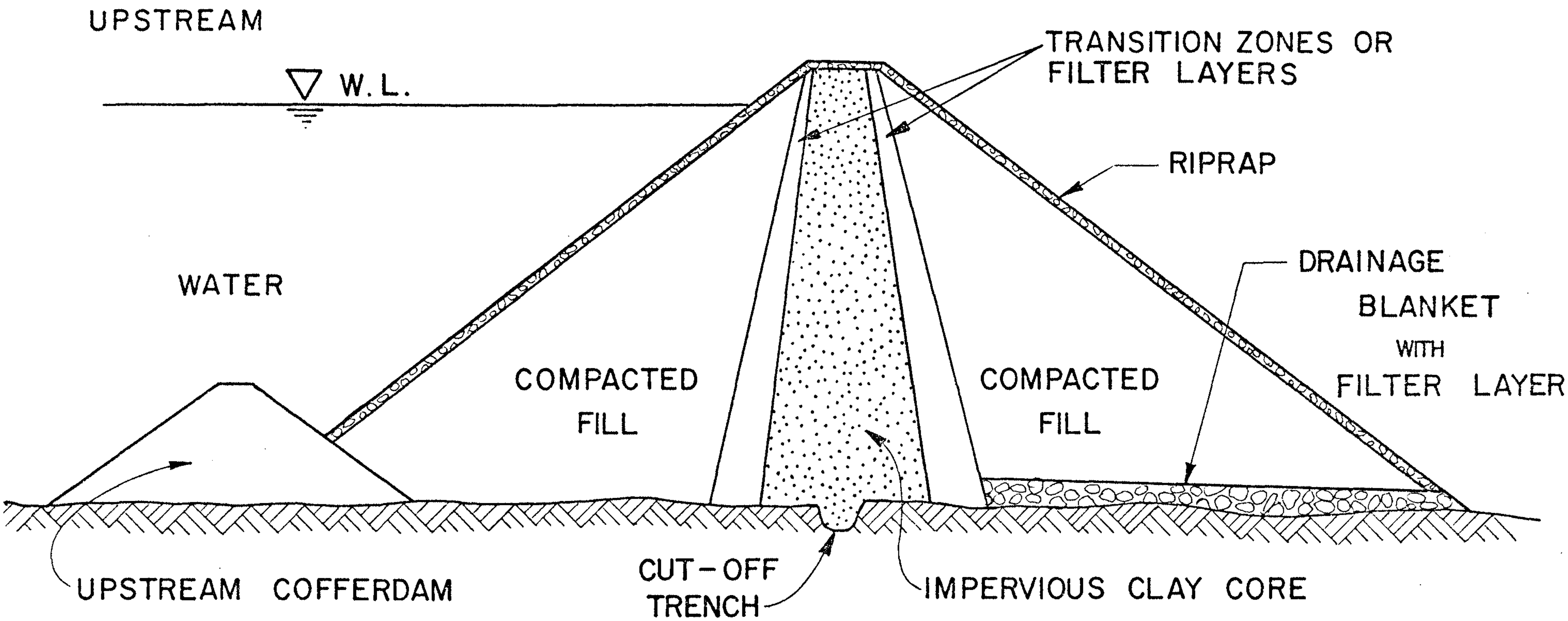
The features of a conventional zone-filled earth dam are shown on Figure 3.1 and are discussed in this section.

1. Cofferdam

   Following the areal survey, site selection and foundation exploration, the dam is located and the foundation is prepared to accommodate the dam. In most instances it is necessary to provide a cofferdam to facilitate the preparation of the foundation.

2. Principal Zones

   The three principal zones of a conventional earth dam are: an upstream zone, an impervious core zone and a downstream zone.



TYPICAL FEATURES OF ZONE-FILLED EARTH DAM

Fig. 3·1

3. Transition Zones and Filters

Whenever a differential head of water exists across an earth dam, there is a flow of seepage water through the dam. Because of the flow of seepage water a transition zone or "filter" is placed between the fine impervious core and the downstream zone. Filters are used in earth dams to restrict the movement of fine soil particles without disrupting the flow of seepage water which escapes through the zone of fine material. If the seepage water causes the fine soil particles to flow, internal erosion of the structure will occur by "piping". If the water in the reservoir is subject to rapid decreases in the surface elevation, as in the case of some reservoirs associated with power projects, a second filter will be required between the impervious core and the upstream zone. The design criteria for filters are well defined in several textbooks [15,16].

4. Protection from Surface Erosion

Both the upstream and downstream slopes of the embankment are susceptible to surface erosion. The upstream slope is subject to wave action and the downstream slope is subject to rainfall, runoff and wind action. Therefore, to protect the embankment from surface erosion, riprap or some other form of surface protection is required.

5. Internal Drainage

The stability of the embankment slope is directly dependent upon the shear strength of the material which in turn is dependent upon the porewater pressure in the embankment. An increase in porewater pressure produces a decrease in the shear strength. In the zones downstream from the impervious zone in an earth dam, it is desirable to lower the phreatic surface or reduce the saturated zone in order to improve the strength of the structure and increase the factor of safety. This improvement can be achieved by including a coarse granular drain within the dam. It is important to prevent the drain from becoming clogged with fine material and the properties of the adjacent materials may indicate a filter is required.

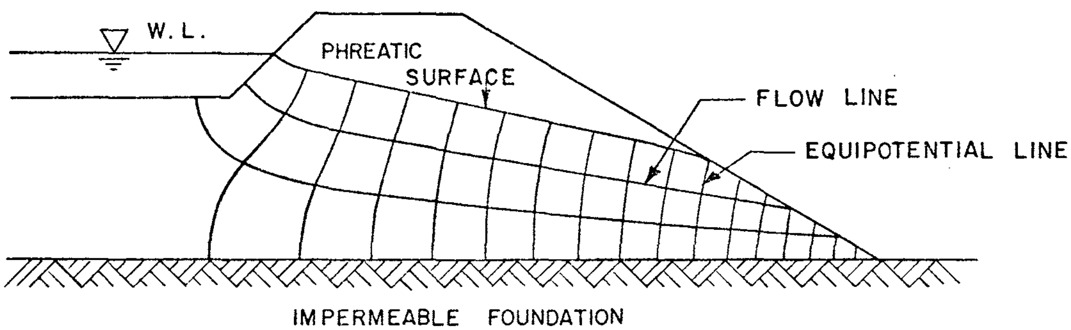
The flow of seepage water through a tailings dam may be represented graphically by a flow net (Figure 3.2). The section at the bottom of the page illustrates the desirable effect of one type of internal drain used to improve the stability of the downstream zone of a dam.

6. Cutoff Trench

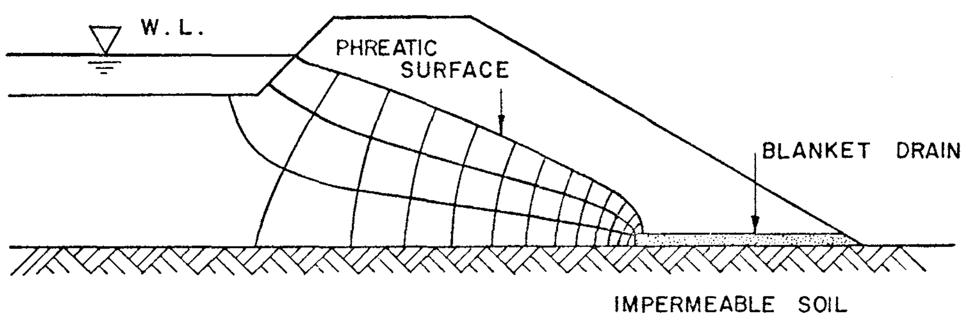
When a dam is constructed on a hard impervious stratum, the interface forms an ideal path for a flow of seepage water through the dam creating a potential source of internal erosion. An impervious cutoff trench is used to obstruct the seepage water at the interface. Cutoff trenches are also used to obstruct the flow of water under a dam when a pervious stratum exists in the foundation.

7. Embankment Slopes

The slopes of earth dams are usually expressed in terms of a horizontal to vertical slope ratio. To provide a specific factor of safety for a dam maintaining a water reservoir, it is



FLOW NET FOR A TAILINGS DAM WITH AN IMPERMEABLE FOUNDATION



FLOW NET FOR A TAILINGS DAM WITH A BLANKET DRAIN

(HOMOGENEOUS SECTIONS)

Figure 3.2

frequently necessary to specify a flatter slope upstream than downstream. This detail is provided to counteract the porewater pressure following a rapid drawdown of the water surface in the reservoir.

8. Conditions Requiring Stability Analysis

Three critical conditions require a slope stability analysis during the design of a conventional earth dam:

a) Construction Condition

During construction of a dam, the porewater pressure reduces the stability of both the upstream and downstream slopes of the embankment. This condition is of particular significance when the embankment or foundation contain relatively impervious soil.

b) Steady Seepage Condition

When a reservoir has been full of water for an extended period, the dam attains a maximum zone of saturation from the seepage water. This state called the "steady seepage condition" may produce the lowest factor of safety for the downstream slope.

c) Drawdown Condition

If a rapid drawdown of the water level in the reservoir occurs after the steady seepage condition is attained, the factor of safety for the upstream slope of the dam reaches a minimum value immediately following the drawdown of the reservoir.

3.3 Conditions Inherent to Tailings Dams

Many of the conditions associated with tailings dams are not associated with dams for water reservoirs. This section is intended to enumerate these conditions, thereby providing a background for the design of tailings dams.

3.3.1 Construction Materials for Tailings Dams

Figure 2.2 outlines the potential sources of materials for constructing tailings dams. Two of these materials, tailings and waste rock, are byproducts of mining which are discarded from the production operation. Frequently, mines are located in rocky terrain where the rock outcrops on surface and there is limited overburden material which is suitable for dam building. On the other hand, an over-abundance of hydraulic tailings material is available and in most cases this material is suitable for dam building if properly classified and dewatered.

Waste rock is generally available from the development operations of the mine ore body and can be obtained for the price of overhaul between the waste dump and the tailings dam. Of particular significance is the waste rock from preproduction development which is available as a construction material prior to the requirement for storage of tailings.

3.3.2 Upstream Operating Conditions

The design of a tailings dam is directly dependent on the following upstream operating conditions:

1. Depth of the Settling Pool

   The tailings material, discharged as a slurry upstream from the centerline of the dam, flows toward a pool of water intended to settle the solid particles. The depth of water in the pool is maintained at, or slightly above, the minimum depth necessary to provide an effluent free of solids in suspension. Three to eight feet of water is usually an adequate depth to settle the solid particles.

2. Location of the Settling Pool

The distance of the water pool from the centerline of the dam is primarily dependent on the point of discharge for the tailings. When the tailings is discharged by spigots along the crest of the dam, the pool can be several hundred feet from the centerline of the dam. Discharging the tailings upstream from the dam will cause the pool of water to rest against the upstream slope of the dam.

3. Natural Classification of the Tailings After Discharge

The coarse fraction of the tailings settles above the elevation of the surface of the pool. The fine fraction or "slimes" settles in the pool where the flow velocity is low permitting time for settlement.

4. Accessibility of the Tailings Basin

The stored tailings behind the dam is saturated except for a limited depth at the surface which is desiccated by evaporation rendering it accessible for light surface loads during the dry season. In Canada the surface of the tailings basin freezes during the cold winter months and following the spring thaw, the settled tailings has extremely low strength making it impassible. During this period the meandering, in the basin, of a tailings stream from a point discharge is uncontrollable and the decant tower is frequently inaccessible for servicing.

5. Liquefaction of Tailings Slimes

The saturated tailings slimes behind the dam is very susceptible to liquefaction* when a breakaway occurs.

6. Density of the Settled Tailings

The density of the settled tailings against the upstream face of the dam will approximate 100 pcf on a dry basis or 125 pcf saturated.

7. Pollution from Seepage Water

Tailings material frequently contains minerals and chemicals. in the liquid phase of the settled tailings. Therefore seepage water which infiltrates the dam is a potential source of stream pollution.

8. Removal of Effluent from the Tailings Basin

The following methods are used for the removal of liquid effluent from the tailings basin

a) decant towers and tunnels

b) spillways and sluices

c) floating pumphouses, and

d) syphons.

3.3.3 Items Relating to Tailings Embankments

Mine tailings embankments constructed with tailings material by hydraulic methods provide conditions which warrant specific consideration

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* defined in Section 3.4.1-9.

during the design and construction phases. The following items are of particular interest:

1. Stage Construction

The common practice of using stage construction for tailings dams has been influenced by the following operating conditions:

a) the requirement for capacity to store tailings increases continuously with the length of time the mine is in production

b) the quantity of construction material available for dam building from the mining operation also increases with the length of time the mine is in production

c) mine management is held responsible for the operating costs as reflected in annual reports which provide an important assessment of the efficiency of the senior operating staff, and

d) major demands for initial capital expenditures are necessary to place a mining property in production.

The propensity to use stage construction for tailings dams is not without justification.

2. Expected Particle Size for Tailings Material

The average tailings is a fine grained material of silt size containing fifty to eighty percent minus 200 mesh. The specific analysis for any operation depends on the desirable fineness to liberate the valuable mineral during plant processing. The effective size of tailings material for a particular operation is consistent from year to year unless a major change is made in the process.

The typical range in the size of tailings from mining operations varies from 20% minus 200 mesh to 95% minus 325 mesh. Coarse tailings is a suitable material for dam building; however, it is necessary to supplement this material with a fine impervious material to provide a desirable seal. It is impractical to build a tailings dam by hydraulic methods with extremely fine tailings because of the high costs of recovering the limited quantity of suitable coarse material. A typical material in this category is the sieve analysis for tailings material #2 in the Appendix (Table A-1).

3. Homogeneous Embankments

Existing tailings dams, constructed with tailings material, are predominantly homogeneous structures without the inclusion of a separate internal drainage system.

4. Decant Tunnel

When a decant system is employed, the discharge tunnel is usually buried in the lower section of the embankment on a line perpendicular to the longitudinal axis of the dam.

5. Hydraulic Construction

It has previously been stated that essentially all tailings material leaves the concentrator as a slurry and hydraulic disposal procedures are used for convenience and economy. Therefore, hydraulic construction methods are used universally when constructing tailings dams with tailings materials. The fine slurry is piped to the construction site as a suspension of tailings particles in water. To facilitate the removal of water from the embankment, it is desirable to eliminate the finer tailings particles. Four methods of classification are used:

a) gravity separation by a series of pipeline spigots along the crest of the dam

b) centrifugal separation using hydrocyclones

c) gravity separation around the crest perimeter of the tailings dam; between two relatively low hand-built dykes similar to that shown in Figure 3.5, and

d) in a limited number of cases mechanical classifiers (rake or spiral) are used to separate the sand fraction from the tailings slimes.

A review of the national survey on tailings dams indicates that 95% of the hydraulic tailings dams in Canada are constructed by spigotted methods.

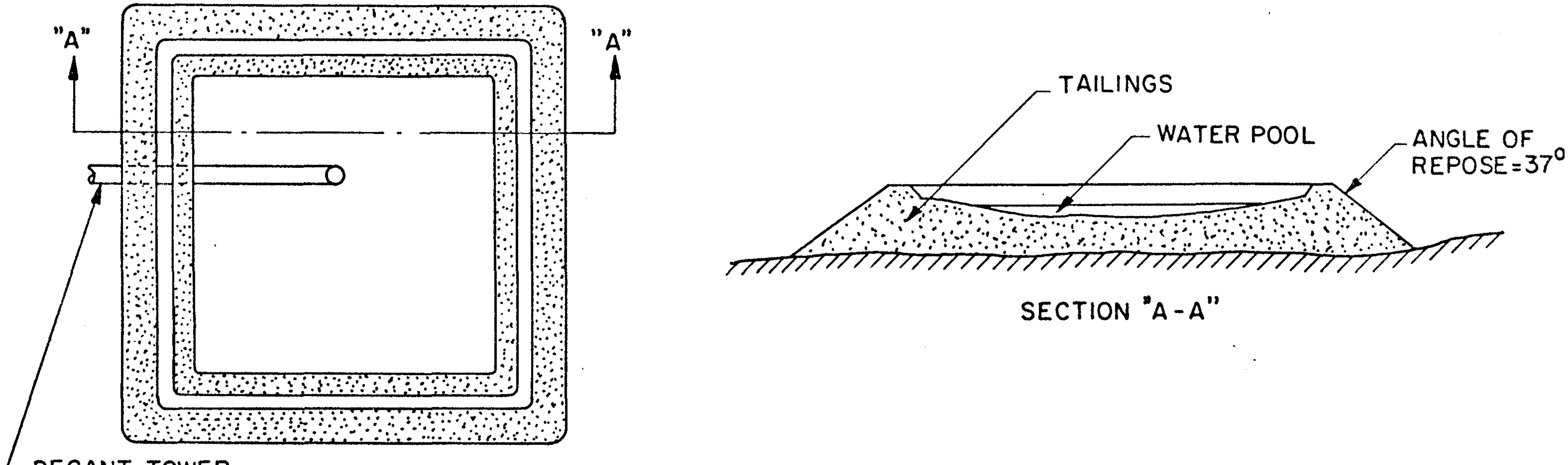
6. Common Types of Tailings Dams*

The successive stages of a tailings dam can be built with an upstream, downstream, or fixed centerline procedure. When spigots or gravity separation are used, the upstream procedure is adopted. All three procedures are applicable with hydrocyclones. The common types of tailings dams are shown in Figures 3.3 through 3.6. These sketches show typical existing structures and are not intended as recommended details.

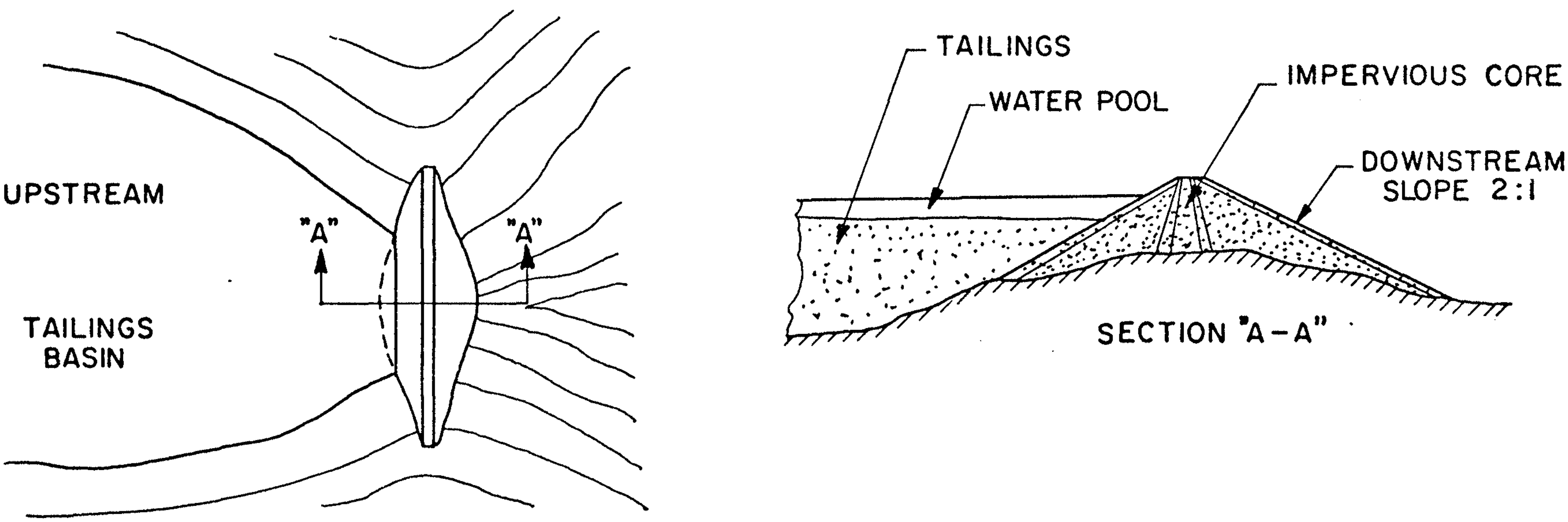
7. Negative Porewater Pressure

Tailings embankments containing fine grained tailings material can develop high negative porewater pressure or suction during a dry season.

*Figures 3.7 and 3.8 show mobile hydrocyclones and spigots for hydraulic dambuilding.

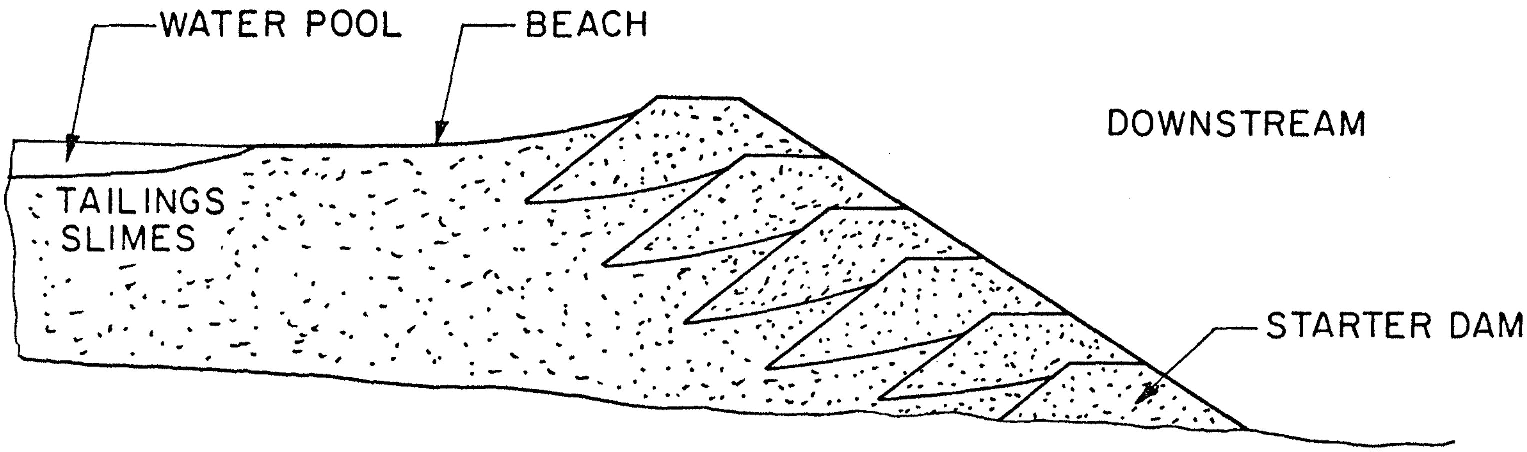


PERIMETER TAILINGS DAM

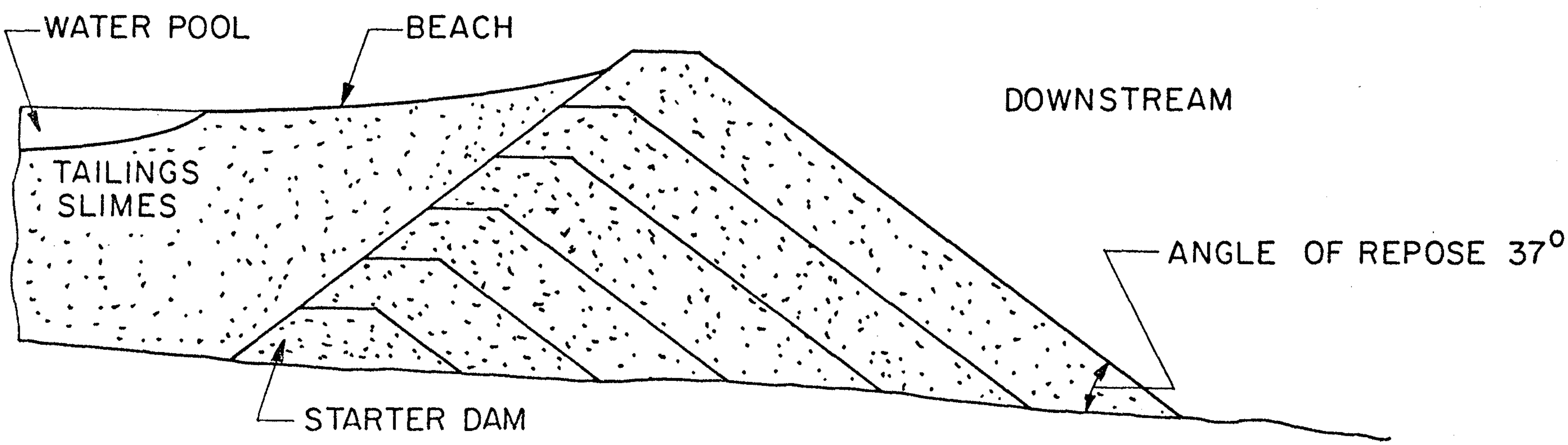


VALLEY TAILINGS DAM (ZONE-FILLED EARTH DAM WITH SEAL)

Fig. 3·3

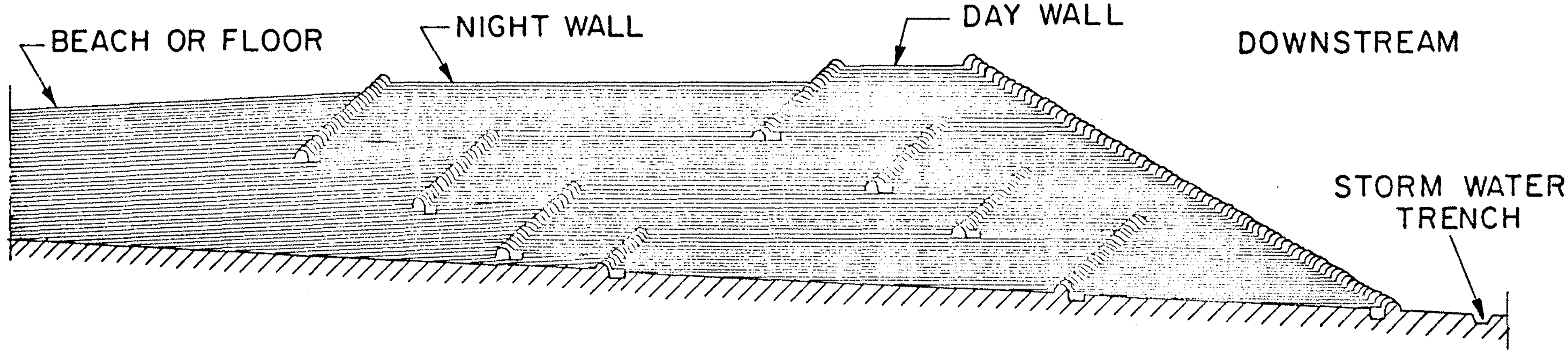


TAILINGS DAM - UPSTREAM METHOD OF STAGE CONSTRUCTION
(SPIGOTS PLUS DRAGLINE - DOZER BUILDUP)

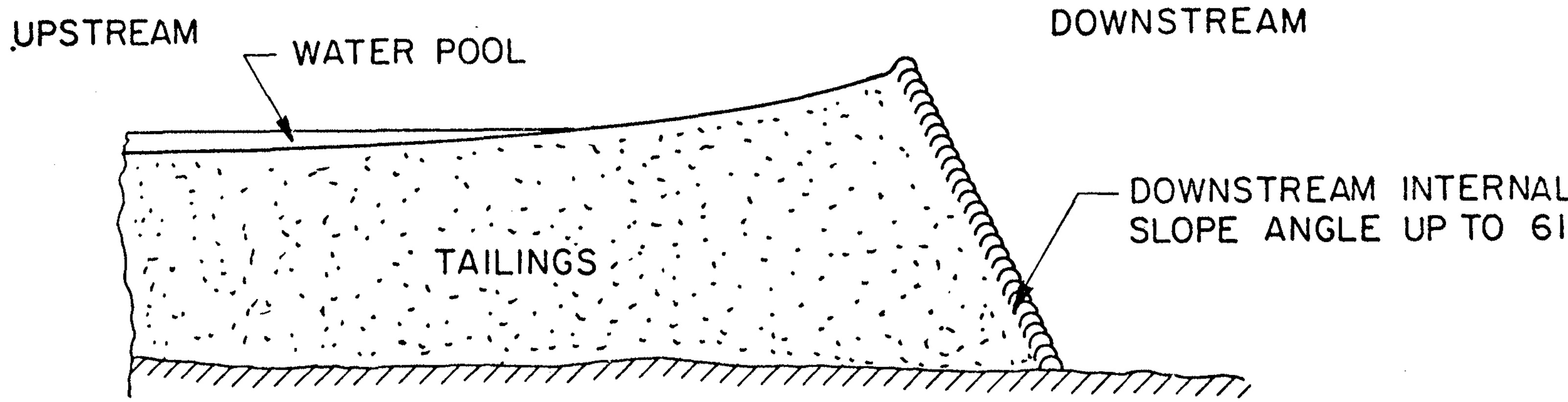


TAILINGS DAM - DOWNSTREAM METHOD OF STAGE CONSTRUCTION

Fig. 3.4

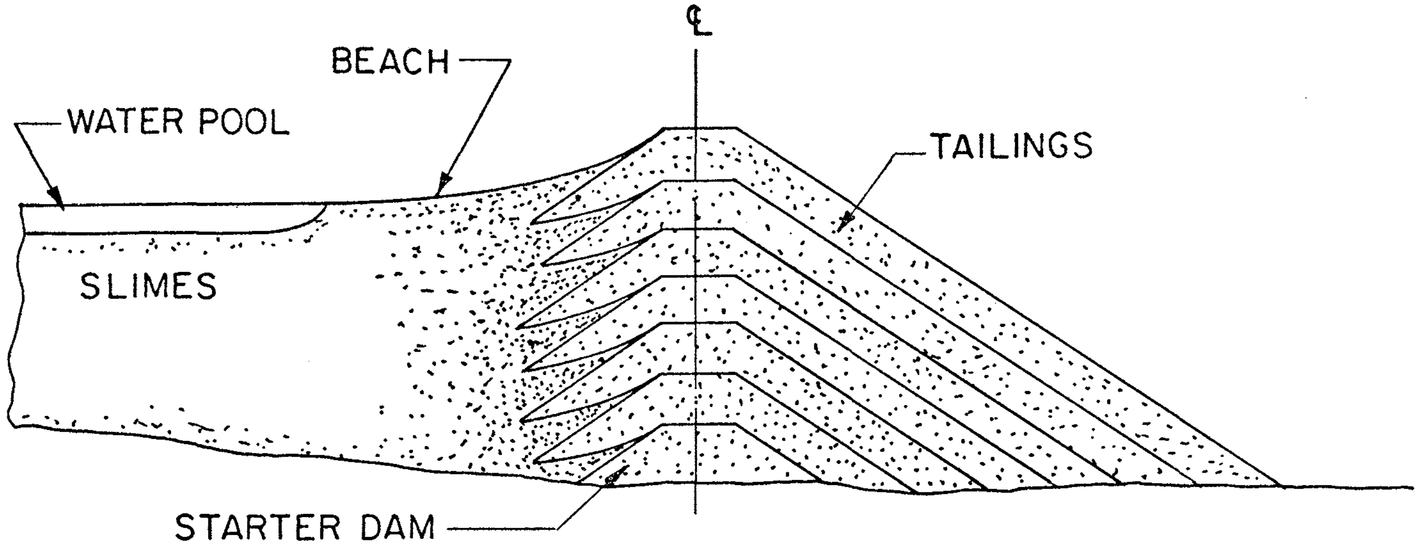


TAILINGS DAM—GRAVITY FLOW WITH MECHANICAL BUILDUP BY HAND
COMMON PRACTICE IN SOUTH AFRICA REF(9)

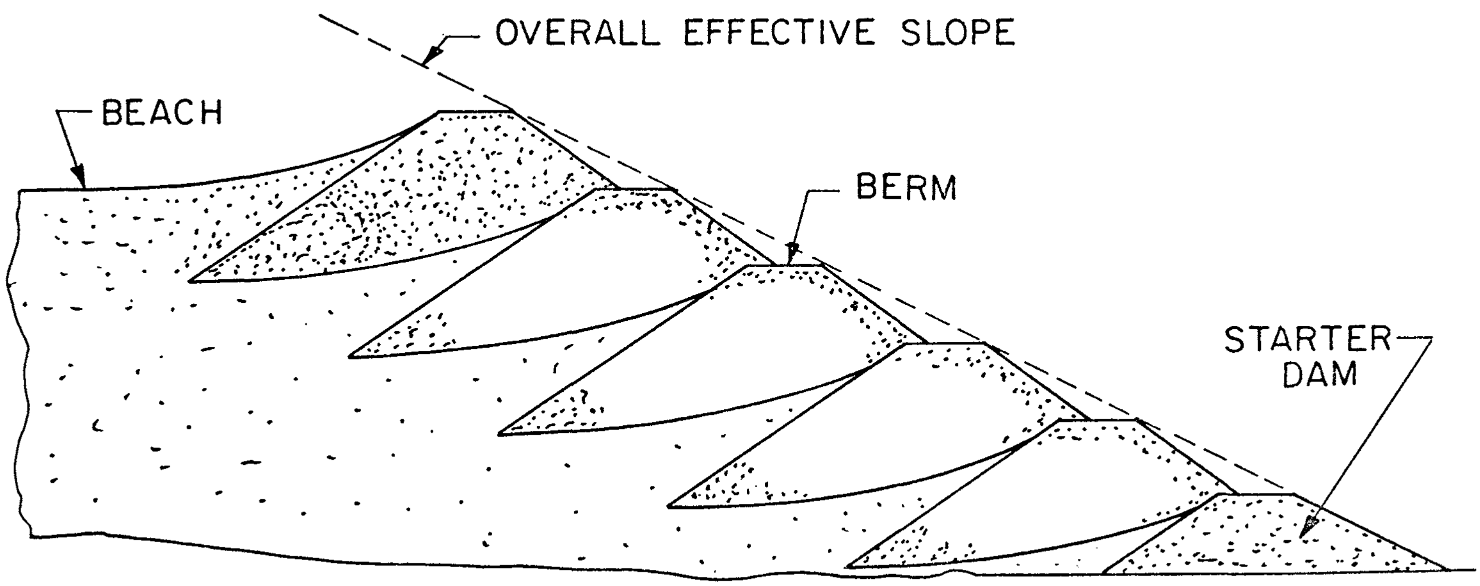


TAILINGS DAM - GRAVITY SEPARATION WITH MECHANICAL BUILDUP BY HAND
NEGATIVE POREWATER PRESSURE IN ARID OR SEMI-ARID AREA

Fig. 3.5



(FIXED CENTERLINE METHOD)
TAILINGS DAM

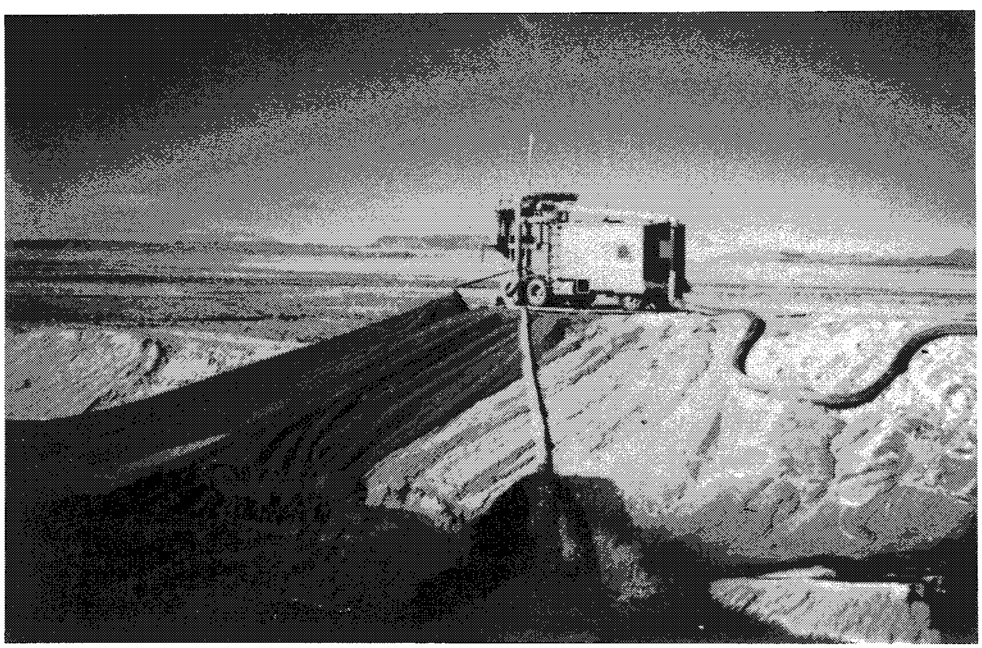


UPSTREAM METHOD WITH BERMS TO FLATTEN THE SLOPE
(SPIGOTS PLUS DRAGLINE - DOZER BUILDUP)

Fig. 3.6

General Arrangement of Spigotted Tailings
from Main Tailings Header (24)

Fig. 3.7



Mobile Hydrocyclones for Dam Building

Fig. 3.8

The soil suction will dissipate immediately if the material becomes saturated. In arid and semi-arid areas embankment slopes much steeper than the natural angle of repose for dry material have existed for many years without experiencing slope stability problems. Figure 3. 9 shows a tailings dam with an exceptionally steep slope. This dam, which was constructed by sluicing and manual labour, attained an ultimate height exceeding 300 feet.

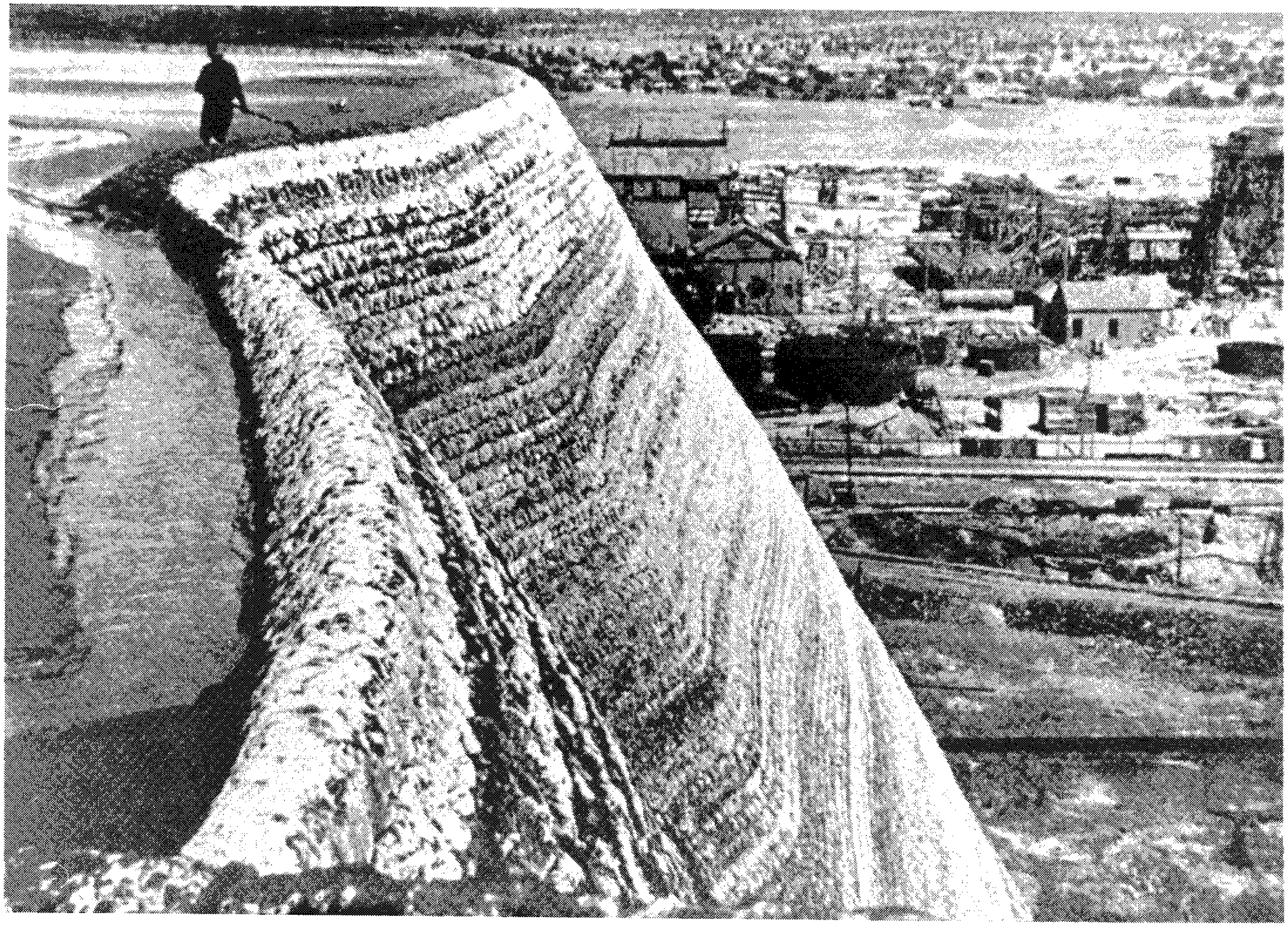
3.4 Structural Deficiencies and Problems with Existing Tailings Dams

A variety of deficiencies create problems and failures in tailings dams. This section is divided into three subsections covering the embankments, decant tunnels and decant towers.

3.4.1 Embankments

The principal factors contributing to embankment problems and failures are:

1. stability of embankments
2. starter dam
3. embankment seal
4. crest width and freeboard
5. overtopping of the dam
6. water content during construction
7. frost conditions in the embankment
8. erosion, and
9. sensitivity of tailings embankments to liquefaction.



Growth of Tailings Dam in Arid Region (17)

Fig. 3.9

1. Stability of Embankments

The factor of safety for an embankment is defined as the ratio of the resisting forces to the forces tending to cause failure. Therefore, a slope cannot exist with a factor of safety less than unity.

The factor of safety for the downstream slope of many existing tailings dams is inadequate and dangerously close to unity. Slight changes in conditions, such as an increase in porewater pressure, surface erosion, or minor seismic vibrations initiate slip failures.

Many of the downstream slopes for existing tailings dams are too steep to provide an adequate factor of safety. Field observations of nineteen dams at eight different mining operations indicate the downstream slopes are between 35 and 37 degrees. These embankments were constructed by hydraulic procedures and the records show several failures.

The majority of hydraulic tailings dams have an average downstream slope of 36 degrees. In arid and semi-arid climates some slopes are considerably steeper.

The United States Atomic Energy Commission, and other governmental authorities [18] have published recommended embankment slopes for tailings dams which include upstream slopes as flat as 4:1 (horizontal to vertical). In all cases the recommended upstream slopes are flatter than the downstream slopes. These recommendations were originally intended for water dams and are not realistic for tailings dams. A factor of safety slightly above unity is acceptable for the upstream slope of a tailings dam which is subject to "normal" operating conditions. The normal operating conditions for a tailings dam are considered to mean a system operating with the minimum depth of water upstream to provide a clear effluent. The slopes are not necessarily representative of the stability of an embankment. This statement is particularly applicable in the case of a weak foundation where it is necessary to provide a relatively flat slope in order to attain the desirable overall stability. It would be more realistic if the authorities would establish recommended factors of safety for various conditions relating to tailings dams, rather than the use of recommended slopes.

The upstream method of construction is inferior to the downstream method for two reasons:

a) a portion of the embankment is supported on fine tailings stratifications as indicated in Figure 3.4, and

b) it is difficult to provide an adequate seal and an internal drainage system.

The most significant detail that warrants attention is the factor of safety for the downstream slope of existing tailings dams.

In general, the factor of safety for tailings dams is not given the serious consideration that is given to other types of dams.

2. Starter Dam

The starter dams in the majority of the existing tailings dams, which have been constructed by spigotting procedures, are located in an undesirable position within the ultimate dam section. This condition has resulted from the practice of using the upstream method of stage construction and placing the starter dam coincident with the downstream toe of the ultimate dam section.

A starter dam may be considered as a small cofferdam which becomes an integral component of the ultimate tailings dam. The starter dam acts as a self-contained dam to obstruct the flow of water or tailings during the initial stage of the project. The location of the starter dam within the ultimate section is an important structural feature because it could create porewater pressures within the dam.

When upstream construction methods are used, some starter dams are built as pervious structures to overcome future porewater problems. This condition permits undesirable seepage water from the tailings basin to enter the local watercourse.

3. Embankment Seal

The absence of an efficient seal in a hydraulic tailings dam is always a source of troublesome seepage when the spigot procedure is used for construction. The coarse fraction of the tailings settles close to the point of discharge on the embankment and the extremely fine particles are carried in suspension until the velocity approaches zero on entering the water pool where these particles are permitted time to settle. The natural classification process leaves an inadequate seal in the embankment. The fine particles form an impervious mat on the bottom of the pool at a considerable distance from the dam. Therefore it is essential to keep the water pool as far as possible from the embankment in order to reduce the volume of seepage.

In addition, a spigot procedure presents a second problem; it is very difficult to maintain the depth of water necessary to provide a clear effluent unless the surface area of the pool is relatively large. When the elevation of the outlet is raised, excess seepage occurs because the water inundates the coarse beach sand. Even when supplemental mechanical equipment is employed, it is difficult to construct a competent seal for spigotted tailings dams.

When hydrocyclones are used for construction, the homogeneous embankment is composed of the coarse fraction of the tailings which produces a steep upstream slope with pervious qualities. Because of the steepness of the embankment, the water pool is close to the centerline of the dam. It is impossible to produce an efficient seal with the coarse underflow from hydrocyclones. It is also extremely difficult to provide a seal with the fine overflow from hydrocyclones because the overflow product has a high water content and the majority of fine solid particles settle below the surface of the water pool. This is one of the factors contributing to the reluctance to use hydrocyclones for the construction of tailings dams.

The products of spiral and rake classifiers are similar to hydrocyclone products but have the disadvantages of being expensive and power driven. At most mining operations three phase electrical power is not available in the vicinity of the tailings dams.

The product from gravity separation in launders is similar to the product from the spigot process. The disadvantage of this process is that it requires extensive manual labour or mechanical equipment for placing the construction material.

4. Crest Width and Freeboard

The crest width and freeboard of a tailings dam are restricted to undesirable dimensions (only a few inches) when the construction is limited to gravity separation.

5. Overtopping of the Dam

When water from a reservoir passes over the top of an earth dam, the result is usually a complete failure of the dam. The failure of a tailings dam from overtopping is a rapid process on account of the fine material in the embankment. The factors contributing to overtopping of a tailings dam are:

a) limited freeboard is created by the construction and operating procedures

b) hydrological studies are often omitted entirely and the hydraulic design for the decant system is inadequate to provide for the combined capacity of the tailings disposal system and the peak runoff volumes

c) floating debris such as ice or wood restricts the capacity of the decant system, and

d) operational failure of the decant system which removes the effluent from the tailings basin.

6. Water Content During Construction

All hydraulic processes contain high water contents with the solid tailings particles in suspension at the instant of discharge from the pipeline. There are fundamental differences in the water content and water distribution between the spigot process and the hydrocyclone process.

a) Spigot Water

The discharge from spigots contain the total water content from the tailings line. This volume of water is discharged continuously along an extended length of the crest of the dam. After a limited period with only a few inches of build-up, spigots are opened along a different section of the crestline. The opening of alternate sections of spigots is repeated continuously at short time intervals. The water content of the embankment is changing continuously and the excess water creates local zones of saturation because the drainage is restricted by horizontal stratifications of fine tailings. The stability of the embankment varies with changes in porewater pressure.

b) Hydrocyclone Water

The construction material which is obtained from the underflow of hydrocyclones contains only a limited portion of the total water volume from the tailings pipeline. The bulk of the tailings water is discharged to the slimes pond in the overflow from the hydrocyclones. There are several construction procedures using hydrocyclones. The most desirable method is to advance a group of mobile hydrocyclones along the crest of the dam to produce a single lift per stage of any desirable height. The construction water is then concentrated at one point which is the extreme point of advance along the longitudinal crest. The construction product is a homogeneous free-draining material with consistent qualities and potential for controlling the permeability at a desirable level, dependent on the material supplied and the economic weight recovery. If the returns ratio for the system is high, as is the case for a valley dam, it may be several years (2-7 years) before additional hydraulic construction water is added to the embankment.

7. Frost Conditions in the Embankment

In Canada the exposed surface of the downstream slope freezes during the colder winter months. A combination of the frozen impervious shell downstream, inadequate drainage below the frost-line and excessive seepage which infiltrates an inefficient upstream seal creates a serious build-up of porewater pressure against the downstream slope. This condition causes embankment slip failures during the spring thaw.

8. Erosion

Tailings embankments are susceptible to surface erosion and internal erosion by piping because of the fine particle sizes and low relative density.

Attempts to restrict the surface erosion by planting grass or some other form of vegetation have achieved limited success for short durations. Tailings embankments frequently contain pyrite or other chemicals which are conducive to the generation of an acidic condition in the water component of the three-phase material (solid, liquid, gas). In addition to the undesirable source of downstream pollution from seepage water, the acidic condition is very detrimental to the growth of most forms of surface vegetation. Even in cases where top soil has been added to cover the surface of the tailings, the acidic condition eventually penetrates the topsoil as the soil moisture moves upwards from the tailings into the top soils with seasonal variations.

9. Sensitivity of Tailings Embankments to Liquefaction

When a saturated soil in a loose state (above critical void ratio) is subjected to a rapid shock or seismic vibration, the void ratio is decreased and intergranular pressure is temporarily transferred to porewater pressure. If the intergranular pressure approaches zero and the soil is in an embankment, it is likely to flow like a viscous fluid; a phenomenon known as liquefaction.

The material in all tailings embankments constructed by hydraulic methods is in a loose state. The majority of the existing tailings embankments also contain a saturated zone within the loose tailings material and are therefore sensitive to liquefaction. This problem is compounded by the fact that the saturated slimes behind tailings dams are particularly sensitive to liquefaction.

3.4.2 Decant Tunnels

The decant system is the predominant method in use for removing liquid effluent from tailings basins. Deficiencies in design and installation of the two principal components (vertical tower and horizontal tunnel) create numerous problems with tailings disposal systems. One of the sources of trouble is attributed to the fact that many of the decant systems are installed to accommodate initial conditions, disregarding future or ultimate operating conditions to which the system may be subjected.

The common problems associated with decant tunnels are discussed under the headings to follow:

1. Wire Wound Wood Stave Pipe

   Wire wound wood stave pipe is commonly used for tailings pipe lines. Because of the economy of the material and its availability at the mine site, small production operations often use wood stave pipe for decant tunnels. This material is unsatisfactory for decant tunnels. The pipe is designed to withstand high internal pressures only. The tunnel operates partially full under gravity flow conditions. It is subjected to high external soil pressures from the embankment and the settled tailings upstream in the basin. The intermittent acidic conditions of the tailings water destroys the strength of the wood through time. The pipe will usually withstand the low initial stresses, however, the loads increase with time and the strength of the material decreases causing the pipes to collapse and plug the tunnel beneath the embankment. A more serious situation occurs when the break permits the slimes to flow through the pipe into a downstream watercourse. A break beneath the embankment may permit the decant water to increase the porewater pressure in the structure and initiate internal erosion. A failure of a decant tunnel is a difficult and expensive problem to correct. At least twice (to the author's knowledge) within the past year, engineering representatives from a pipe company have recommended wood stave pipe for decant tunnels in tailings dams.

2. Seepage Diaphragms

Very few decant tunnels are installed with seepage diaphragms to restrict excessive seepage water along the outside of the tunnel. This condition has created internal erosion problems causing complete breakaways.

3. Acidic Conditions

The intermittent acidic conditions from tailings effluents have disintegrated

a) reinforced concrete tunnels with 12" concrete walls, and

b) tunnels constructed of steel pipe with ½" wall thickness.

4. Floating Tunnels

Large concrete tunnels (60" I.D.), with a limited amount of fill covering the upstream portion of the tunnel have floated when the water level in the settling pool was increased to decant the effluent.

5. Rigid Concrete Tunnels

Rigid concrete decant tunnels frequently fail as a result of differential settlement when the structures are placed on fill or a combination of fill and bedrock.

The conditions creating vulnerability to differential settlement of decant tunnels may be listed as follows:

a) the exceptionally long tunnel necessary with spigotted tailings dams

b) variation in tunnel bedding conditions

c) variation in foundation conditions

d) varying depth of settled tailings covering the tunnel

e) varying depth of embankment covering the tunnel

f) variation in density of the overburden loads which cause tunnel settlement such as: unsaturated embankment materials, submerged embankment materials and submerged tailings slimes.

3.4.3 Decant Towers

Some of the problems affecting decant towers are similar to the problems affecting decant tunnels with specific reference to wood, acid and settlement.

1. Timber Framing

Timber framing is frequently used for decant towers on smaller mining operations. The operating stresses increase with the accumulation of settled tailings and the deterioration of the timber with time is accelerated by acidic conditions. Tailings dams and decant systems are intended to be permanent structures and this factor must be considered during the design phase.

2. Timber Weirs

Timber has also been used to raise the weir elevations in concrete towers. Some mining companies reinforce the timber weir with concrete in stages, other companies leave the timber exposed to the elements and continually increasing loads.

3. Unprotected Concrete

As stated previously the strength of unprotected concrete can be adversely affected by tailings effluent.

4. Tower Reinforcing Steel

The inspection of several concrete decant towers indicates the absence of reinforcing steel in many towers. All mining operations have an abundance of scrap steel which can be incorporated in a design to reinforce the concrete towers with essentially no increase in the material costs. Not only are the towers subject to lateral loads from tailings, in the colder climates they are also subject to heavy lateral thrusts near the top of the tower by icing conditions unless the ice is broken during regular inspections.

5. Inconvenience of Tower Extension

Pouring concrete to extend decant towers, which are located near the center of a settling pond, is an inconvenient operation.

6. Tower Settlement

When a decant tower is located on fill, settlement will occur with the increase in loads. The loads tending to affect settlement of the tower are different from the loads affecting settlement of the tunnel connected to the base of the tower. When a differential settlement occurs between the tower and the connecting tunnel, a problem of major proportion results.

The principal loads tending to affect settlement of the tower are:

a) dead load of the tower (increases)

b) tailings load on the spread footing or base of the tower

c) impact of the effluent at the base of the tower

d) negative skin friction acting on the external surface of the tower with the accumulation and consolidation of the tailings, and

e) uplift at the base of the tower.

The conditions and problems associated with tailings dams as outlined in this chapter provide a basis for investigation to generate solutions to the problems.

3.5 The Selection of a Hydraulic Construction Method for Further Development.

The most important factors are the stability of the structure over the long-term and the long-term costs.

To be assured of the stability, the design, construction and operating procedures must provide consistent and reliable conditions. The characteristics of the spigotted process will not assure consistent conditions with regard to permeability, seal, drainage or porewater pressure. Alternatively the hydrocycloned process will provide excellent drainage with relatively consistent permability at a controllable value and offers the potential for providing a competent seal with desirable porewater pressures within the embankment.

The ancillary decant facilities are much easier to provide when associated with a hydrocycloned tailings dam as compared with a spigotted dam.

The hydrocycloned dam also affords the maximum returns ratio which yields an economic advantage under many circumstances.

For the reasons outlined above the hydrocycloned dam is selected for further investigation with regard to potential improvements in the design and construction of tailings dams.

CHAPTER 4

AN INVESTIGATION OF THE DESIGN AND CONSTRUCTION POTENTIAL FOR A SPECIFIC TYPE OF HYDRAULIC DAM USING TAILINGS MATERIAL AND MOBILE HYDROCYCLONES

4.1 Introduction

The fundamental questions to be answered are whether or not it is possible and practical to build a competent tailings dam which is constructed primarily of waste tailings material by mobile hydrocyclones and if so, under what general conditions is it economically viable?

To be a competent structure the problems outlined in Section 3.4 must be overcome and to satisfy the second requirement, a practical solution must be generated which is economically competitive with other hydraulic procedures.

The following subjects relating to the investigation are presented in this section:

1. a brief description of hydrocyclones and the field testing of hydrocyclones with large volumes of tailings material
2. porewater pressure in tailings dams
3. an economic evaluation of tailings dams constructed with hydrocyclones
4. an investigation of the sensitivity of tailings embankments to soil suction
5. preliminary estimates of potential soil suctions in tailings materials

6. considerations for hydrocyclone tailings dams
7. considerations relating to decant systems, and
8. advantages of hydrocycloned tailings dams over spigotted tailings dams.

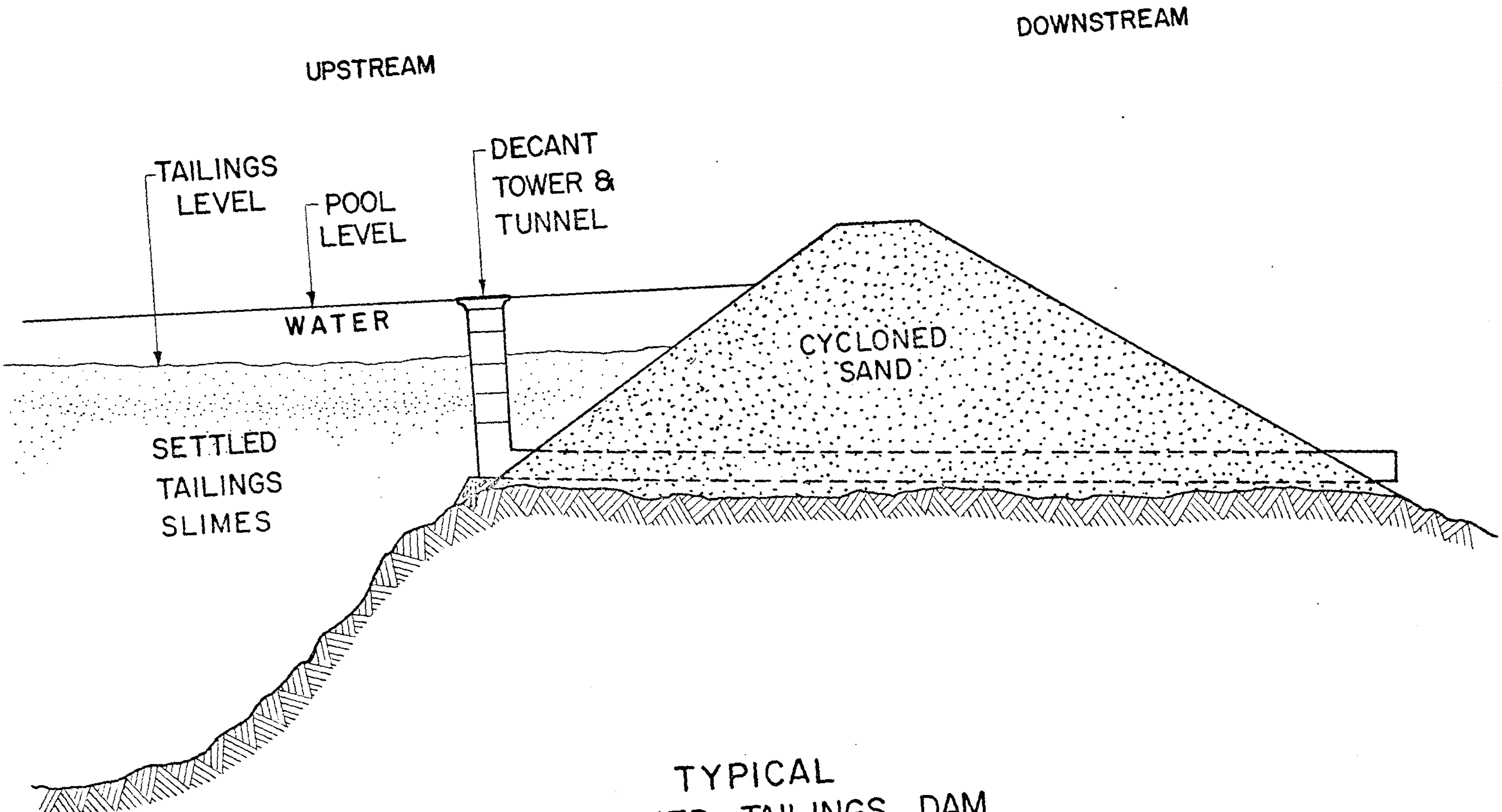
4.2 Hydrocyclones

It is not within the scope of this thesis to discuss the design details for hydrocyclones; however, it is considered appropriate to provide a brief description of the operation including sketches of the assembly and flow patterns of the tailings slurry through the hydrocyclone (Figures 4.2 and 4.3). Bradley has made an extensive study on the design details of hydrocyclones [19].

Hydrocyclones have been used for many years but it was not until the late 1940's that their industrial use became prominent. A number of international symposiums were held between 1950 and 1970 and during the past thirty years more than fifty patents relating to hydrocyclones have been registered.

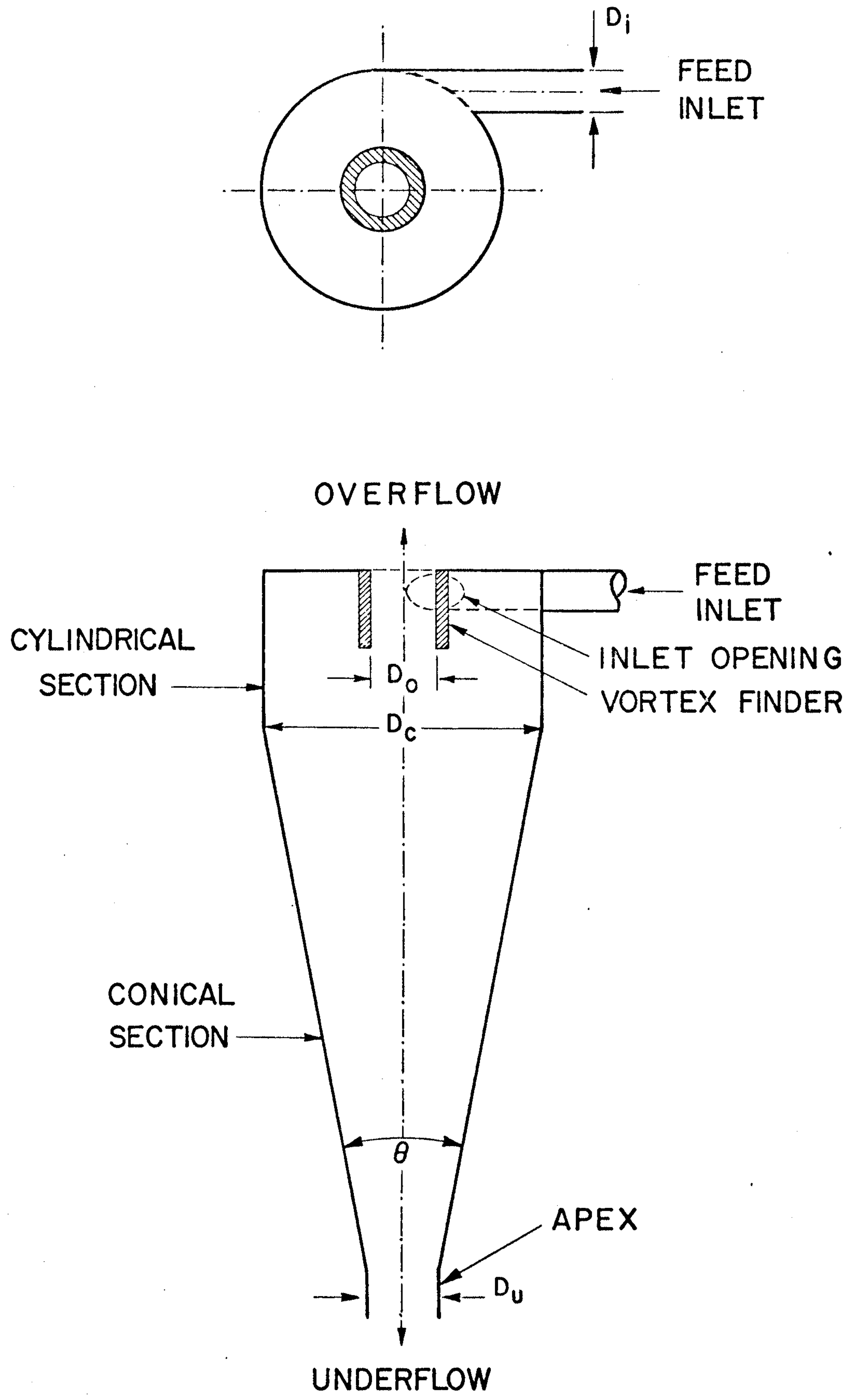
Figure 4.1 shows the general arrangement of a typical hydrocycloned tailings dam with decant tower and tunnel.

Hydrocyclones are frequently used in mining operations as thickeners or classifiers. When they are employed for constructing tailings dams, the apex is restricted to provide a particular underflow product combining dewatering and desliming at a desirable point of separation. The result is a relatively free-draining material which produces a steep embankment slope.



TYPICAL
CYCLONED TAILINGS DAM
(BULK TAILINGS DISCHARGED UPSTREAM)

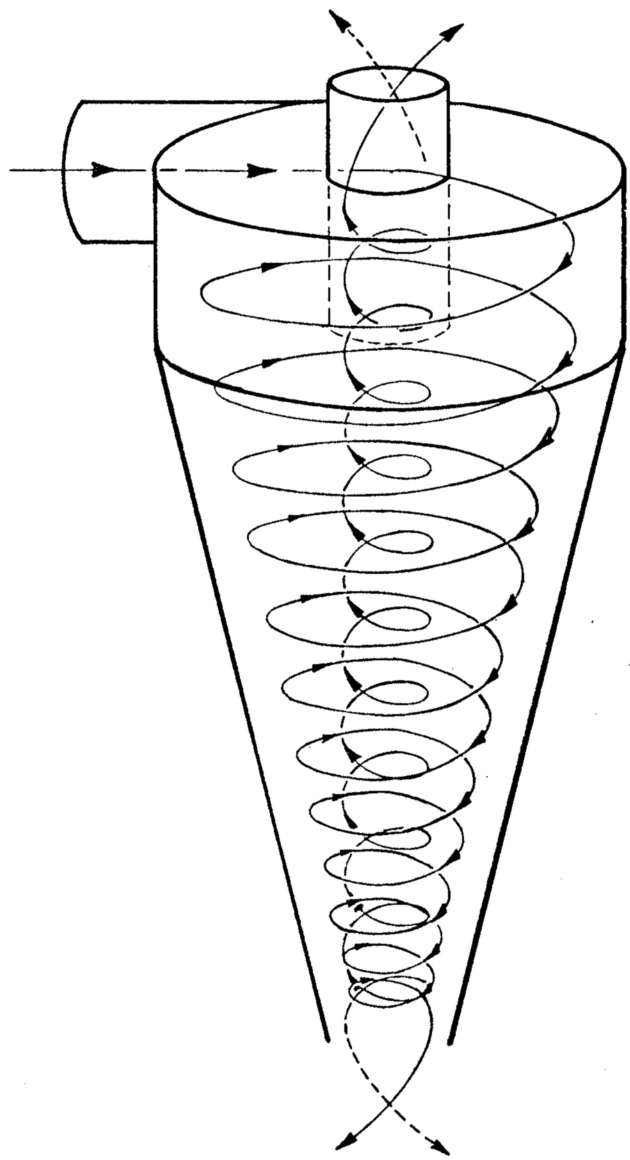
Fig. 4·1



PRINCIPAL FEATURES OF A HYDROCYCLONE (19)

FIG. 4·2

HYDROCYCLONE



SCHEMATIC REPRESENTATION OF THE SPIRAL FLOW (19)

FIG. 4·3

"The hydrocyclone is a piece of equipment which utilizes fluid pressure energy to create rotational fluid motion. This rotational fluid motion causes relative movement of the materials suspended in the fluid thus permitting separation of the materials, one from the other or from the fluid" [20].

The tailings, in a slurry form, enters the hydrocyclone tangentially under pressure and is discharged at two points; the underflow containing the coarse solid particles and the overflow containing the fine solid particles. The separation within a hydrocyclone is not by gravity. There are two opposing forces acting on a particle in suspension, centrifugal force acting in an outward radial direction and fluid drag acting in an inward radial direction. By altering the design and operating parameters, almost any desirable separation of the solid particles can be achieved.

In order to construct a tailings dam with hydrocyclones, the underflow product must be a rope type discharge with relatively low water content. Considerable performance data are available for hydrocyclones operating with vortex discharge but rope discharge is seldom used and very few performance details are available for this operating condition. It is of interest to note that only one of the 547 articles listed in Bradley's bibliography [21] features the building of tailings dams with hydrocyclones.

4.2.1 Hydrocyclone Field Tests

The testing of hydrocyclones to obtain research data for building tailing dams is restricted. Some of the more significant reasons are as follows:

1. The testing procedures usually contribute to a loss in plant production resulting from experimental changeover, varying operating parameters or shutdown periods for modifications.
2. Small-scale hydrocyclone models for testing tailings material are not practical. It is possible to provide small-scale hydrocyclones; however, it is extremely difficult to scale the size of the tailings particles or to correlate the results of scale models when slurries are involved.
3. The testing of full size hydrocyclones with a fraction of the production volume also presents a number of difficulties. There is significant segregation of the particle sizes and percentage of solids within the cross-section of a tailings pipeline. These conditions make it difficult to obtain a fractional flow volume which is representative of the tailings analysis. A vertical tailings line including a mixing chamber, multiple splitter and additional pumping facilities provide one method of obtaining a representative fractional flow.
4. Each changeover for experimental test purposes requires a tailings line desanding* period at the modified operating conditions before steady state flow conditions are achieved.

---

* Unless the tailings pipeline is flushed with clear water when the flow of tailings is discontinued, the line sands up with settled solids. With the resumption of tailings flow it usually requires a period of steady pumping to remove the sand waves and attain steady state conditions.

Therefore, to attain a steady state flow condition in the shortest possible time with a minimum effect on plant production, the test facilities should be situated close to the concentrator. The disadvantage of this arrangement is that large volumes of underflow and overflow material from the hydrocyclone have to be disposed of in the tailings basin which may be a considerable distance from the concentrator.

5. Complete by-pass facilities and standby equipment are required to minimize the production losses.
6. To obtain simultaneous samples, the testing procedures usually require personnel and direct communications at a number of remote locations during the test period.
7. It is desirable to use a method of automatic sampling which traverses the cross-section of the tailings stream to procure representative samples.
8. It is estimated that an expenditure of $150,000 is required to obtain the research data which is necessary for an extensive evaluation of hydrocyclones operating with rope discharge from tailings slurries. An expenditure of this category requires approval of the company Board of Directors.

Because the University's facilities could not accommodate the large volumes of material that are processed through a hydrocyclone with steady flow conditions, hydrocyclone tests were conducted in the field at an operating mining plant.

In June 1970 field tests were performed with a bank of mobile hydrocyclones during which period approximately 30,000 tons of tailings were processed. More than 75 samples were collected for determining:

a) the mechanical analysis

b) the permeability, and

c) the potential weight recovery for dam building.

The weight recovery is defined as the weight of solid tailings recovered in the hydrocyclone underflow product. The underflow product contains the coarse fraction of the tailings and this product is used for dam building.

Careful consideration was given to the possibility of using a fraction of the normal tailings production for test purposes. From a practical standpoint it was considered to be less costly and more convenient to process the total plant production through the test equipment.

4.2.2 Equipment for Hydrocyclone Field Tests

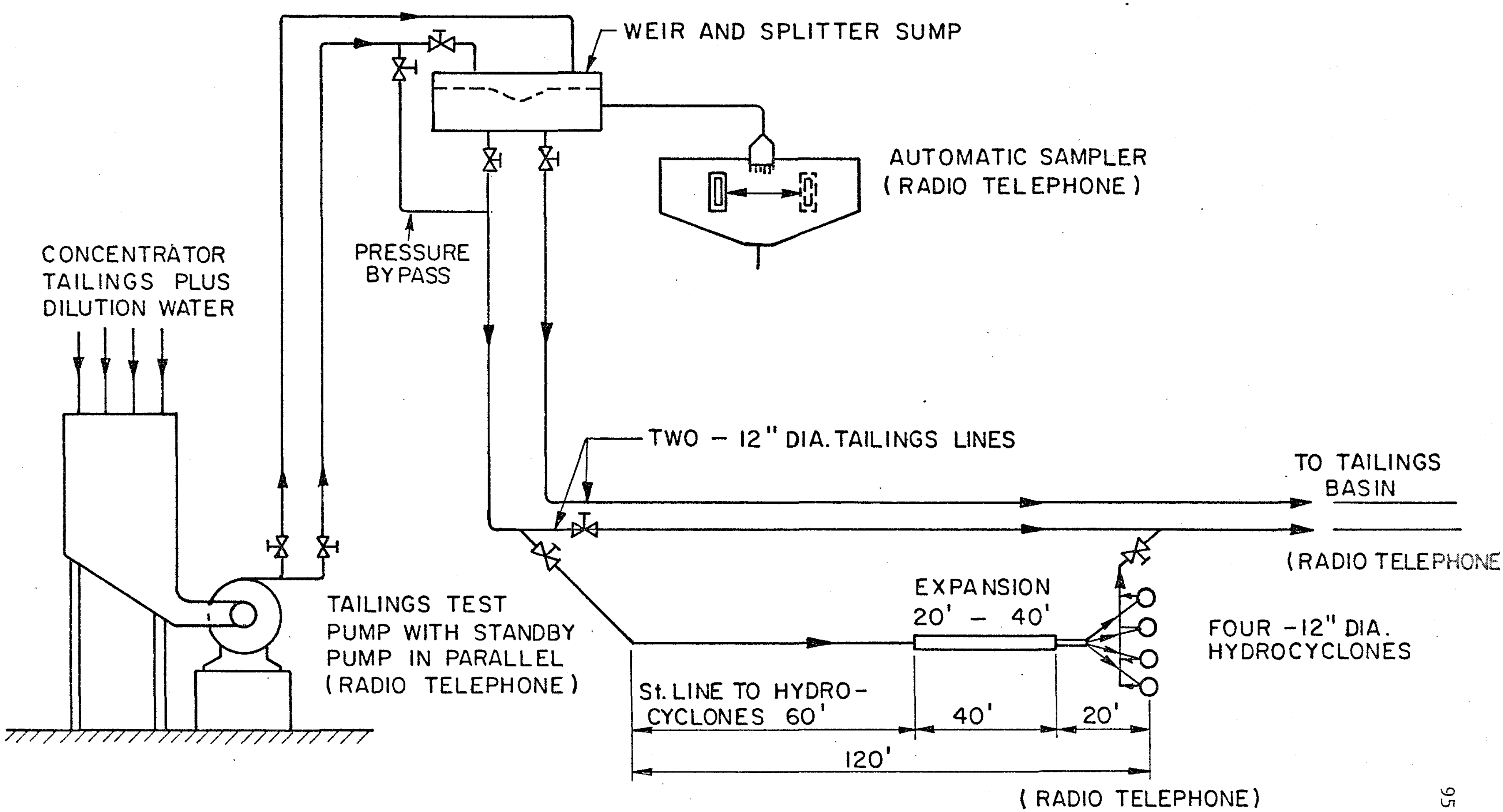
The field tests included provision for the following facilities:

1. an expandable mobile hydrocyclone unit with provision for four 12" hydrocyclones (expandable from 20 to 40 ft. - see Figure 4.4).
2. a minimum of 60 ft. of straight pipe immediately preceding the mobile hydrocyclone unit
3. automatic power driven sampling equipment on the feedline to the hydrocyclones
4. radio telephones at four locations:

    a) concentrator tailings pump feed sump

    b) automatic sampler

    c) mobile hydrocyclones, and



GENERAL ARRANGEMENT OF HYDROCYCLONE FIELD TESTING FACILITIES

Fig. 4·4

d) the discharge point of the tailings line

5. standby pump facilities, and

6. by-pass piping and valving at three locations.

The general arrangement of the test facilities is shown in Figure 4.4.

4.2.2.1 Results of Hydrocyclone Field Tests

1. Material Size Analysis

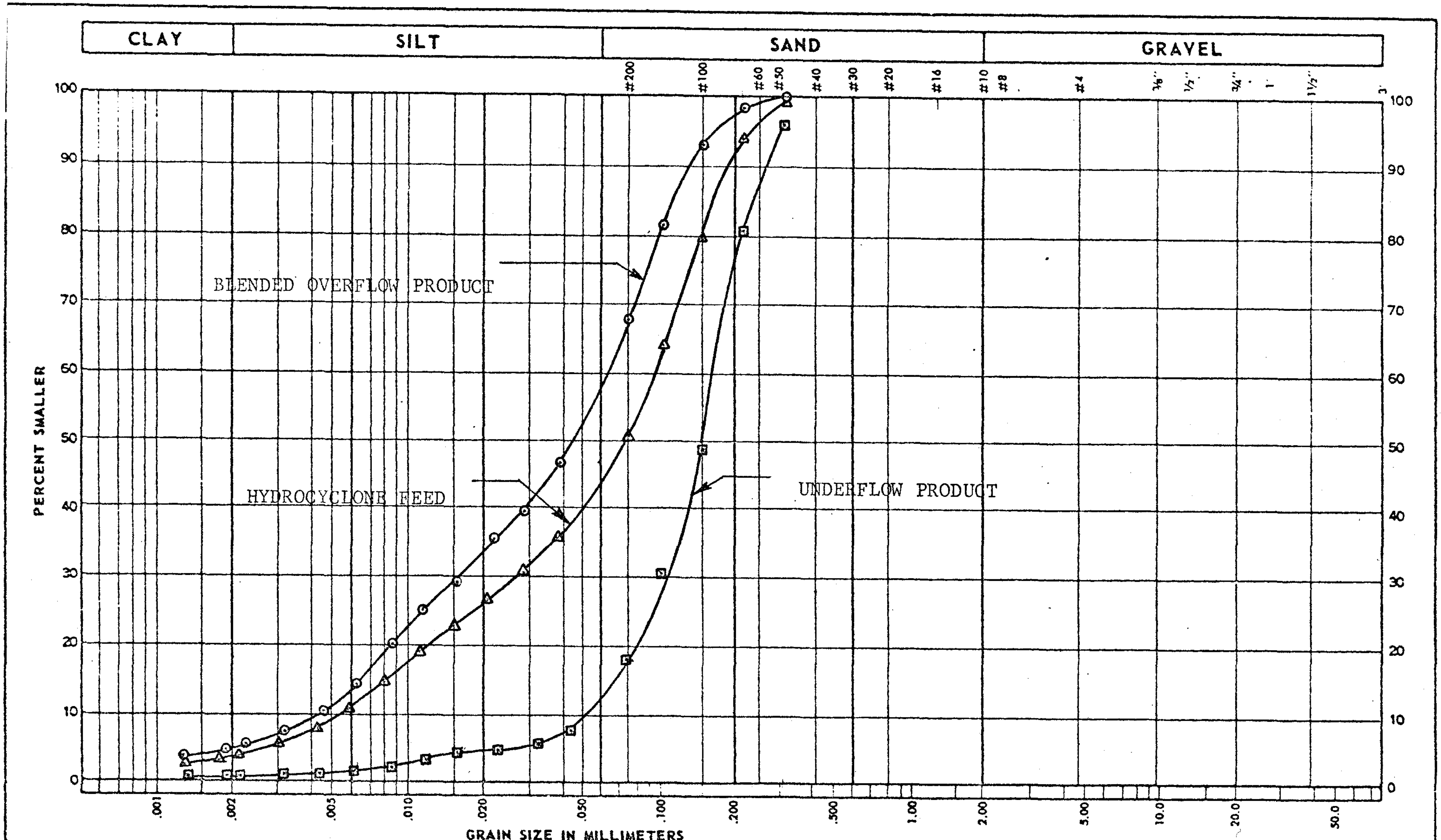
A typical tailings analysis for the feed size and the hydrocyclone underflow product from test run number eleven are shown in Table 4.1 and on the graph in Figure 4.4.1.

Mine Tailings

Hydrocyclone Test Number Eleven (Mine Tailings)

Grain Size Analysis					
Hydrocyclone Feed Sample # T-11-1 Total Weight 200.7 grams			Hydrocyclone Underflow Product Sample # T-11-2 Total Weight 201.1 grams		
Mesh Size	Passing Weight	Passing Percent	Mesh Size	Passing Weight	Passing Percent
48	198.7	99.0	48	193.1	96.1
65	189.1	94.4	65	162.0	80.6
100	161.2	80.4	100	99.4	49.5
150	131.6	65.5	150	63.2	31.5
200	105.8	52.7	200	38.8	19.3
MM		Passing Percent	MM		Passing Percent
0.0375		37.1	0.0451		7.9
0.0278		31.5	0.0325		5.8
0.0202		27.9	0.0232		5.2
0.0147		23.3	0.0165		4.3
0.0110		19.5	0.0121		3.4
0.0080		15.1	0.0087		2.3
0.0058		11.0	0.0062		1.9
0.0042		8.1	0.0044		1.4
0.0030		5.8	0.0031		1.1
0.0021		3.9	0.0022		.9
0.0017		3.4	0.0018		.8
0.0013		2.4	0.0013		.4

Table 4.1



REMARKS:

MINE TAILINGS MATERIAL

12" ϕ HYDROCYCLONE PERFORMANCE

TEST RUN #11 JUNE 9, 1970

FIGURE 4.4.1

UNIVERSITY OF WATERLOO

DEPARTMENT OF CIVIL ENGINEERING

2. Permeability

The permeability of the various hydrocyclone underflow products were in the range of 2.7×10^{-3} cm./sec. to 1.71×10^{-4} cm./sec. as shown in Table 4.2. A sample test data sheet for test run number eleven follows the permeability table.

Mine Tailings Material

Permeability Tests For
Hydrocyclone Underflow Product

Test Run Number	Permeability cm./sec.
9	2.21×10^{-3}
11	2.70×10^{-3}
12	1.79×10^{-3}
13	1.50×10^{-3}
13	1.56×10^{-3}
16	6.16×10^{-3}
16	4.68×10^{-3}
22	1.71×10^{-4}
22	1.96×10^{-4}

Table 4.2

The permeability of the fine tailings slimes was found to be 2.88×10^{-7} cm./sec.

Name: BERT HOARE

Date: November 27, 1970

UNIVERSITY OF WATERLOO

DEPARTMENT OF CIVIL ENGINEERING

SOIL MECHANICS LABORATORY

DIRECT PERMEABILITY TESTS
DATA SHEET

T-11-2

Description of Sample: MINE TAILINGS Test Run # 11
Hydrocyclone Underflow

Specific Gravity of Soil Solids: 2.80

Initial Dry Weight of Container + Sample: 797.85 gm.
Final Dry Weight of Container + Sample: 357.32 gm.
Dry Weight of Solids in Sample: 440.53 gm.
Volume of Solid Material $= V_s = W_s/s =$ 157.33 cc.

Diam. of Sample Cylinder: 4.6 cm.
Area of Sample Cylinder: 16.6 cm^2.

Length of Sample: 18.0 cm.
Volume of Sample: 298.80 cm^3.

Void Ratio of Sample $= e = \frac{V - V_s}{V_s} =$ .90 = =

Manom. = 14.0 cm. = 5.52 in.

CONSTANT HEAD PERMEABILITY TEST DATA

Time	Elapsed Time Sec.	Quantity Q cc.	Head h in.	Hydraulic Gradient $i = h/L$	Temp. of Water	k_T $\times 10^{-3}$ cm/sec	k_{20} $\times 10^{-3}$ cm/sec	Remarks
	67	25	41.5	7.52	23.5	3.0×10^{-3}	2.75×10^{-3}	
	68	25	41.5	7.52	23.5	2.95	2.71	
	65	25	43.0	7.80	23.2	2.97	2.75	
	66	25	43.0	7.80	23.2	2.92	2.71	
	305	15	5.8	1.05	22.9	2.82	2.62	
	137	25	21.0	3.81	23.6	2.89	2.65	

$$k_T = \frac{Q}{i\ A\ t} = \frac{Q\ L}{h\ A\ t}, \quad k_{20} = K_T \frac{r_t}{r_{20}}, \quad k_{20_{ave.}} = 2.70 \times 10^{-3} \text{ cm./sec.}$$

FALLING HEAD PERMEABILITY TEST DATA

Time	Elapsed Time Sec.	Quantity Q cc.	Area of Burette a cm^2.	h_1	h_2	$\log h_1/h_2$	k_T cm/sec	k_{20} cm/sec

Remarks

$$k_T = \frac{a\ L}{A\ t}\ 2.3 \log h_1/h_2 = \frac{\qquad}{t} \log h_1/h_2$$

Note any changes in sample during tests:

3. Weight Recovery

The weight recovery, of tailings material from the hydrocyclone underflow for dam building, has been calculated to be 34% from test run number twenty.

Data:

a) plant capacity = 3100 tons/day of dry tailings

b) specific gravity of the solids = 2.8 or 175 pcf

c) hydrocyclone underflow volume = 109.4 I.G.P.M.

d) underflow pulp density = 1.86 or 116 pcf.

Calculate percent solids by volume

$$175x + 62.4(1 - x) = 116 \text{ pcf}$$

$$x = .476 \text{ or } 47.6\% \text{ by volume.}$$

Check

	by weight
weight of solids = .476 x 175 = 83.3 pcf	= 71.8%
weight of water = .524 x 62.4 = 32.7 pcf	= 28.2%
∴ weight of slurry = 1.0 x 116 = 116 pcf	

$$\text{Weight recovery} = 109.4 \times (10 \times 1.86) \times \frac{60 \times 24}{2{,}000} \times .718 = 1053 \text{ tons/day}$$

$$\text{Percent weight recovery} = \frac{1053}{3100} \times 100 = \underline{\underline{34\%}} \text{ weight recovery.}$$

HYDROCYCLONE FIELD TESTS
FOR MINE TAILINGS MATERIAL

DATE June 12, 1970

Test No. 20

	AUTO S.	LCUF.	CCUF.	RCUF.	OVERFLOW COMBINED
1 Sample No.	T-20-1	T-20-2		T-20-4	T-20-5
2 Time	3.50	3.50		3.50	3.50
3 Line Press.		30		30	
4 Cyclone Press.		35		35	
5 O.F. Press.		10		10	
6 Diam. Spigot		$1\frac{1}{4}$"b		$1\frac{1}{4}$"b	
7 Diam. Vortex Fdr.		5"		5"	
8 Lgth.Vortex Fdr.		8"+1		8"+1	
9 Sp.Gr. Slurry	1.240	1.872		1.859	1.125
10 Pump Power	40	40		40	40
11 Pump R.P.M.	740	740		740	740
Grain Size Analysis					
Mesh	GRAMS				
+48	2.3	4.5		5.0	0.3
+65	10.0	19.0		18.7	1.05
+100	27.4	53.65		48.35	4.8
+150	26.6	45.0		44.2	9.25
+200	24.75	33.0		37.3	17.1
sub-total	91.05 45.4%	155.15 77.4%		153.55 76.7%	32.5 18.2%
-200 Pan	13.75	11.6		16.5	14.0
-200 Wash	95.75	33.6		30.15	133.0
-200 Filter	0.2	0.2		0.1	0.3
sub-total	109.2 54.4%	45.4 22.6%		46.75 23.3%	147.3 81.8%
TOTAL	200.75 100%	200.55 100%		200.3 100%	179.8 100%

Notes

1) Plant Production 3100 t/d
2) Good rope product
3) Density reading for "A" taken at 3:45
4) Slope 15:48 = $17\frac{1}{2}^o$ or 3.2:1) after shutdown
   $16\frac{1}{2}$:48 = $18\frac{1}{2}^o$ or 2.91:1)
5) Volume LCUF = 42.8 IGPM
   RCUF = 66.6 IGPM
   109.4 IGPM

Legend

Auto S — Automatic Sampler in Concentrator
LCUF — Left Cyclone Underflow
CCUF — Center Cyclone Underflow
RCUF — Right Cyclone Underflow

4. Hydrocyclone Performance

The degree of variation in the operating parameters for the hydrocyclones was restricted within narrow limits for economical and physical reasons.

These tests produced useful information with regard to the feasibility of dam building; however, it should be appreciated that serious economic constraints were associated with the field tests. It is estimated that a value slightly greater than $33,000 per day can be attached to the lost production during experimental changeover or modification and adjustment necessary to change the operating parameters.

In general, the production within the concentrator was maintained at a constant level. The reduction of the flow of tailings to the field hydrocyclones for test purposes caused the tailings to overflow the sump in the concentrator and these large volumes of overflow material had to be returned to the process circuit for disposal.

In addition to the details relating to weight recovery and the characteristics of the underflow products, some performance trends for the hydrocyclones with rope type discharge were observed which could be useful for future research:

a) An increase in the size of the apex will increase the weight recovery as long as the underflow remains as a rope type discharge.

With similar operating conditions the following observations were made:

Apex bushing diameter	3/4"	1"	1½"
Underflow slurry volume per cyclone (GPM)	8.6	28.1	47.3

b) An increase in the diameter of the vortex finder decreases the amount of fine material in the underflow product.

Diameter of vortex finder	3"	4"	5"
Minus 200 mesh in underflow product	23.9%	21.1%	15.6%

c) A decrease in the length of the vortex finder causes a decrease in the amount of fine material in the underflow product.

Length of vortex finder	8"	4"
Minus 200 mesh in underflow product	23.9%	19.5%

d) It is difficult to obtain a rope product with an overloaded hydrocyclone.

Tests were made with the total tailings capacity going to a single hydrocyclone with a 3/4" apex. The underflow was a straight stream with no spiral motion. A portion of the tailings flow was permitted to by-pass the hydrocyclone and the underflow product appeared as a rope type discharge.

e) A vortex type discharge can easily be converted to a rope type discharge by placing a bushing in the apex (unless the hydrocyclone is operating in an overloaded condition).

On several occasions during the field tests smaller apex bushings were inserted to convert the "vortex type of discharge" to a "rope type discharge." A vortex discharge is a wild spray with a hollow cone, through which the air core passes.

f) An increase in the hydrocyclone feed pressure increases the recovery.

Hydrocyclone feed pressure (PSI)	19	32
Underflow slurry volume (GPM)	27.7	32.9

5. Specific Gravity

The average specific gravity of the tailings tested was determined to be 2.8.

4.3 Porewater Pressure in Tailings Dams

It was postulated that the downstream zone of a tailings dam would remain unsaturated with an impervious upstream seal and adequate internal drainage. It was also considered that these conditions might be attained in a tailings dam constructed with tailings material.

There is a major difference in permeability between cycloned tailings and tailings slimes. The ratio of permeabilities usually exceeds 1,000:1. If tailings slimes are suitably located to form an impervious upstream seal, pervious cyclined tailings will provide adequate drainage to accommodate the limited seapage from upstream.

An unsaturated downstream zone in a dam provides a significant increase in the stability of the structure.

A drilling program was carried out in two relatively high tailings dams (95 ft. and 220 ft.) and six piezometers were installed in each tailings dam to determine the porewater pressures within the embankments.

The upstream embankment slopes were 1½:1 and 2:1 for the respective dams listed above. A layer of fine tailings slimes covered the upstream slope of both tailings dams. Underlying the slimes was a zone of coarse pervious tailings in the embankment which was placed independently and prior to the accumulation of tailings slimes. At the time that the piezometers were installed in 1969 and 1970, free water had been in contact with the upstream slope of the slimes for a considerable time. Piezometer readings were taken during two successive years and it is of considerable interest to note that the downstream zone and the major portion of the upstream zone in both embankments were unsaturated. The tailings slimes which settled underwater had formed an effective upstream seal for the embankments.

The grain size analyses of the tailings material from the concentrator and the cycloned tailings material were as follows for the 95 ft. dam. Details for the 210 ft. dam were similar to those of the 95 ft. dam.

Mine Tailings

Grain Size Analysis

Concentrator Tailings	
Mesh Size	Percent Passing
48	98.4
65	93.3
100	81.3
150	69.3
200	58.1
M.M.	
0.0389	37.8
.0286	32.8
.0208	28.2
.0151	23.8
.0113	20.4
.0082	13.0
.0059	11.4
.0043	8.1
.0030	5.8
.0013	1.9

Cycloned Tailings	
Mesh Size	Percent Passing
48	97.2
65	89.6
100	52.4
150	30.0
200	14.0

Table 4.3

PIEZOMETER DATA (REF. FIG. 4.4.1)

Summary (Datum Elevation 100')

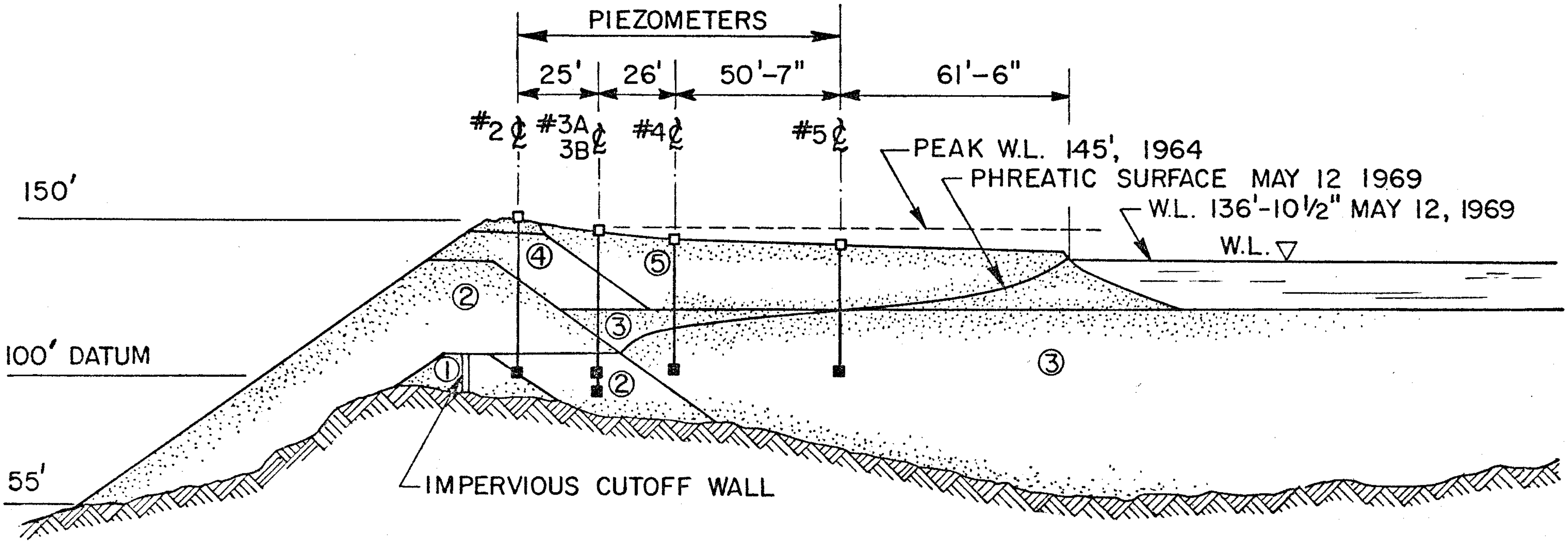
Borehole	#2	#3	#4	#5
Top of Tubing	150'	144'-6"	145'-11"	145'-2"
Stickup	3'-8"	0	4'-1"	4'-8"
Surface El.	146'-8"	144'-6"	141'-10"	140'-6"
Piezometer El.	100'	3A, 100' 3B, 105'	100'-11"	100'-5"
Piezometric Reading (Below Top)	43'-3"	3A, 35'-9" 3B, 35'-8"	33'-6"	23'-6"
Water Level (Stabilized)	106'-9"	108'-9"	112'-5"	121'-8"

Table 4.4

NOTE:

Borehole #1 was located 1150 ft. north of #2 along the crest of the dam. This borehole was found to be unsaturated at the base of the dam; 26'-5" below the crest of the dam.

The details of the cross-section of the embankment, location of the piezometers and the phreatic surface (May 12, 1969) are shown in Figure 4.4.2. for the 95 ft. dam.



LEGEND (MATERIALS)

① STARTER DAM WITH IMPERVIOUS CUTOFF WALL

② CYCLONED TAILINGS

③ TAILINGS SLIMES

④ CYCLONED TAILINGS

⑤ SPIGOTTED TAILINGS

95 FT. TAILINGS DAM

SHOWING

a) EMBANKMENT MATERIALS

b) LOCATION OF PIEZOMETERS and

c) PHREATIC SURFACE

FIGURE 4·4·2

4.4 Cost Estimates for Construction of Tailings Dams

The initial cost estimate is based on a proposed tailings dam in the Province of Ontario. The tailings material as processed during the field testing of hydrocyclones was slightly coarser than the average mine tailings but not uncommon to mining operations. In Canada it is common practice to use valleys or low lying areas for the disposal of hydraulic tailings and valley applications were used in these calculations together with 1971 unit costs for Ontario. Following the initial calculations, examples are presented in which the data are modified to include the costs associated with different dam volumes.

4.4.1 General Data

1.	proven ore reserves	60,000,000 tons
2.	design capacity of the mining plant	6,000 tons/day
3.	weight recovery from tailings material for dam building (This data was obtained from hydrocyclone field tests)	34%
4.	length of tailings basin	6,200 feet
5.	average slope of surface of the tailings basin (Data obtained by field survey in adjacent tailings basin)	1%
6.	cyclone labour	\$5/hr.
7.	12" wood stave tailings pipe including couplings	\$8.50/ft.
8.	asphalt membrane (Hand spray at 50 g.p.m., two coats at 1/8" each to total 1/4"; proposal obtained 1971)	.34/sq. yd.

9. density of tailings in an embankment — 95 pcf

10. expected long-term life at design capacity of 6,000 tons/day — 27 years

11. volume of tailings material for dam building at 95 pcf and 34% weight recovery — 1,600 cu.yds/day

12. tailings basin storage capacity (Figure 4.5) The capacity of the tailings basin was calculated with a computer program; the input was derived from a topographical map.

13. dam height required to store 60,000,000 tons of tailings

    a) Hydrocyclone dam — 70 ft.*
    b) Spigotted dam — 124 ft.*

    * above the base of the dam or lake outlet elevation.

The tailings basin has the capacity to store 60,000,000 tons of tailings to a depth of 105 feet or 85 feet above the elevation of the lake outlet; however, the required dam height will differ appreciably from this elevation.

The height of the required tailings dam is directly dependent on the construction process and the location of the point of discharge for bulk tailings material.

In the particular tailings basin under consideration, the sides of the valley are approximately parallel except for a relatively short section near the low point which will become common tailings storage over the long-term period regardless of the construction method. Considering an average slope of 1% for the surface of the stored tailings over the 6,200 ft. tailings basin, the difference in elevation between the ends is approximately 62 feet. Using a design freeboard of 8 ft. in each case and a

TAILINGS BASIN CAPACITY

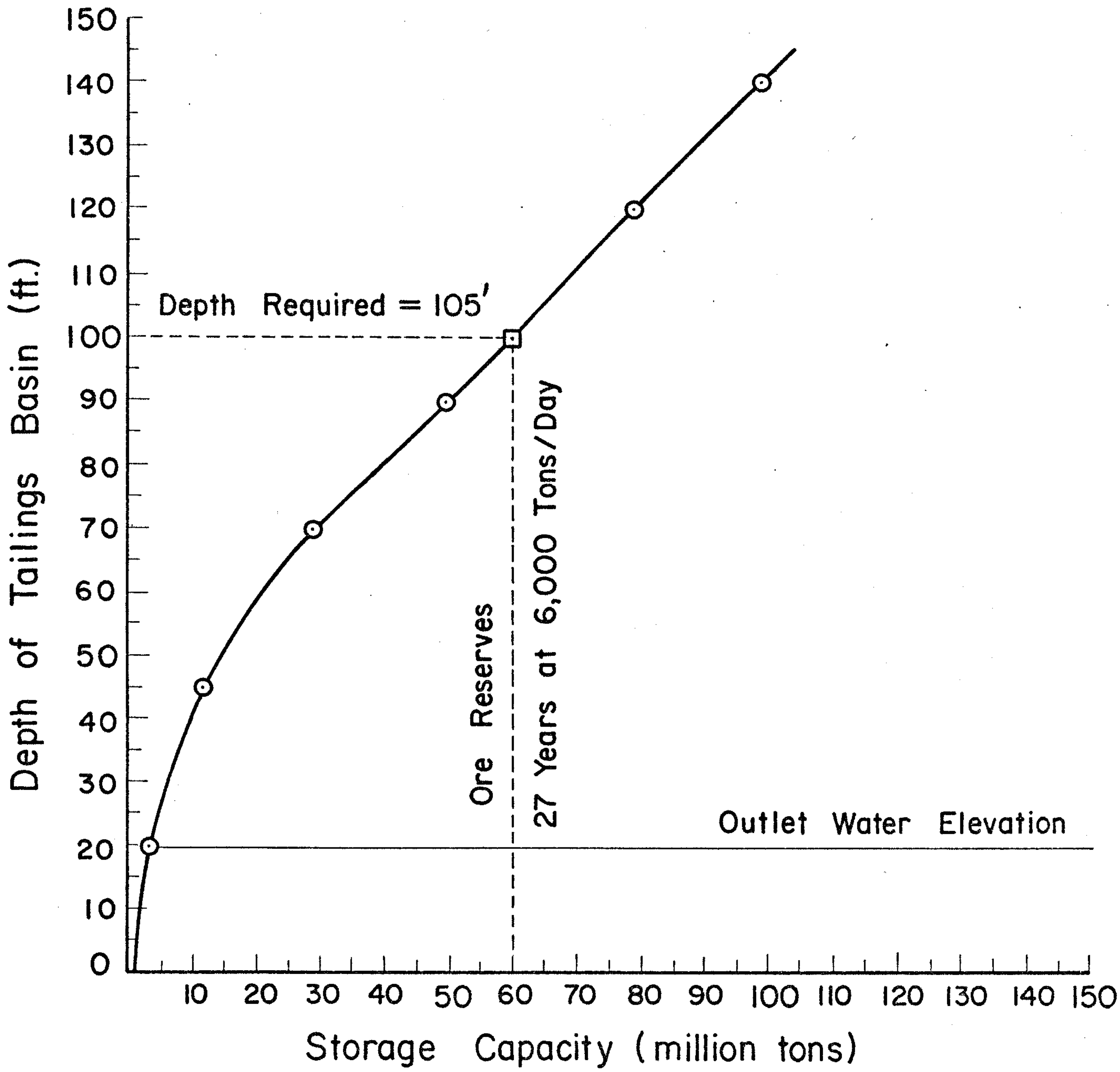


Fig. 4·5

pool depth of 7 ft. for the hydrocyclone dam where the water is against the upstream embankment face, the required heights for a hydrocyclone dam and a spigotted dam become 70 ft. and 124 ft. respectively.

14. volume of fill above the base of the dam

    a) Hydrocyclone dam (70' Dam, 1.4:1 slopes) 291,910 cu. yds.

    b) Spigotted dam (124' Dam, 2:1 slopes) 1,570,000 cu. yds.

    (volume calculations were obtained from twelve cross-sections at 200 ft. spacing)

15. construction time for hydrocyclone dam 182 days

    This figure refers to a 70 ft. dam,

    6,000 tons/day of tailings yielding 1,600 cu. yds./day of dam building material.

    A desirable construction schedule is: one summer to construct the decant system, foundation preparation and dam base; and two summers for stage construction to 70 ft. during the 27 year expected life of the mining operation.

4.4.2 Cost Data

In order to permit an evaluation of the principal embankment material, the embankment costs are separated from the other components of the dam.

The embankment includes the embankment fill and seal above the elevation of the base of the dam; which in this case is considered to be the elevation of the lake outlet.

The costs associated with the base of the dam, decant system,

Tailings Dams
Sectional Areas (sq.ft.)

70'Dam	Embankment	Base	115' Dam	Embankment	Base	124' Dam	Embankment	Base
A1	----	----	A1	----	----	A1	----	----
A2	----	----	A2	2,500	----	A2	5,000	----
A3	2,100	----	A3	10,400	----	A3	14,800	----
A4	6,000	----	A4	17,000	----	A4	22,800	----
A5	8,000	3,800	A5	20,700	3,800	A5	25,400	6,600
A6	8,000	10,500	A6	20,700	11,800	A6	27,500	13,700
A7	8,000	14,000	A7	20,700	15,700	A7	26,500	15,500
A8	4,800	700	A8	16,900	2,000	A8	22,600	1,800
A9	2,000	----	A9	12,000	800	A9	18,000	1,600
A10	1,900	----	A10	5,000	----	A10	8,300	----
A11	----	----	A11	1,000	----	A11	1,200	----
A12	----	----	A12	----	----	A12	----	----

Notes:

1) Planimeter areas obtained from plot.
2) 20 Ft. crest width.
3) Dam heights are above base at lake outlet elevation.
4) Sections are 200 ft. apart.
5) For preliminary purposes all slopes are considered to be 1.4:1 except the downstream slope of the 124' dam which is 2:1.

Table 4.5

Tailing Dams
Sectional Volumes (cu.yds.)

70' Dam	Embankment	Base	115' Dam	Embankment	Base	124' Dam	Embankment	Base
V1-2	----	----	V1-2	6,180	----	V1-2	12,350	----
V2-3	5,170	----	V2-3	44,400	----	V2-3	70,000	----
V3-4	28,600	----	V3-4	101,000	----	V3-4	138,000	----
V4-5	51,600	9,380	V4-5	139,000	9,380	V4-5	178,600	16,300
V5-6	59,300	50,800	V5-6	142,000	55,000	V5-6	196,000	73,600
V6-7	59,300	90,300	V6-7	142,000	103,000	V6-7	200,000	108,000
V7-8	44,400	60,800	V7-8	139,000	57,500	V7-8	181,600	55,700
V8-9	24,400	1,730	V8-9	106,400	10,000	V8-9	150,600	12,600
V9-10	14,450	----	V9-10	61,000	1,970	V9-10	95,200	3,950
V10-11	4,690	----	V10-11	20,300	----	V10-11	31,300	----
V11-12	----	----	V11-12	2,470	----	V11-12	2,960	----
	291,910	213,010		903,750	236,850		1,256,010	270,150
Total	504,920			1,140,600			1,526,160	

Notes

1) 20 Ft. Crest Width.
2) Dam heights are above the base at lake outlet elevation.
3) Sections are 200 ft. width.
4) For preliminary purposes all slopes are considered to be 1.4:1 except the downstream slope of the 124' dam which is 2:1.

Table 4.6

and engineering are included as components of the complete tailings dam.

Seven cases have been evaluated as follows:

Case # 1

70 ft. hydrocyclone tailings dam with the upstream and downstream slope 1.4:1 (horizontal to vertical) including a rain seal on the crest and downstream slope.

Case # 2

70 ft. conventional rolled earth dam with an upstream slope of 1.4:1 and downstream slope 2:1.

Case # 3

124 ft. spigotted tailings dam, effective downstream slope 2:1 with berms every 10 ft. in height.

Case # 4

70 ft. hydrocyclone dam, case # 1 modified with 2:1 downstream slope without rain seal.

Case # 5

115 ft. hydrocyclone dam, slopes 1.4:1/1.4:1.

Case # 6

115 ft. rolled earth dam, slopes 1.4:1/2:1

Case # 7

115 ft. hydrocyclone dam, case # 5 modified with 2:1 downstream slope without rain seal.

Case # 1 Cost Estimate of Tailings Dam Embankment

(70 ft. hydrocyclone dam, slope = 1.4:1/1.4:1)

1. Cost of fill			
a) hydrocyclone operation labour, 98 days at $120.		11,760	
b) additional labour for material delivery 8 hrs./week at $5/hr.		560	
c) fuel and lighting		97	
d) extra tailings pipe at $8.50/ft. including couplings		23,000	
e) additional pump power (5½ H.P.)		73	
f) cyclone repairs, 3½ months at $100/month		350	
g) mobile hydrocyclones			
4 - 12" hydrocyclones	2,000		
used truck	1,000		
pipe	2,000		
	$5,000	5,000	
(The truck will travel less than five miles a year)			
		40,840	40,840
2. Cost of Seal			
a) upstream asphalt membrane; 10,350 sq.yds. at .34		3,510	
b) impervious soil, 10,350 cu. yds. at $1		10,350	
c) crest and downstream rain seal; 12,800 sq. yds. at .34		4,352	
		18,212	18,212
3. Top soil and seed, 2.65 acres @ $900 =		2,380	2,380
Total cost of embankment above lake level			$61,432

Unit cost of embankment $\dfrac{61{,}432}{291{,}910 \text{ cu. yds.}}$ = 21 cents/cu. yd.

Case # 1 Cost of Tailings Dam Complete

(70 ft. Hydrocyclone dam, slope = 1.4:1/1.4:1)

1.	Cost of embankment		61,432
2.	Cost of decant system (226' tunnel)		
	Rock excavation 130 cu. yds at $9	1,500	
	Concrete cradle) 48 cu. yds at Concrete tower base) $60	2,900	
	Concrete tunnel) Concrete elbow) Concrete tower)	15,475	
	Acid Protection	1,000	
		20,875	20,875
3.	Cost of dam base and blanket drain		
	Base 213,010 cu. yds. at .60	128,000	
	Drain 15,000 cu. yds. at $2	30,000	
		158,000	158,000
4.	Engineering at 5%		12,000
5.	Contingency at 10%		24,000
	Cost of tailings dam complete 276,307 say		$276,000

Long term cost of construction

$$\frac{276,000}{60,000,000} = \$.0046\text{/ton tailings stored}$$

Returns ratio $\frac{60,000,000}{539,270} = \underline{\underline{111.3}}$.

A summary of the construction cost estimates for seven cases is shown in Table 4.7.

The first four cases apply to dams which are intended to store 60,000,000 tons of tailings. The last three cases, numbers 5, 6 and 7 are

Tailing Dams
Cost Summary

	Tailings Storage Volume	Type of Dam Construction	Embankment (Fill and Seal above base)					Tailings Dam Complete (Embankment, Foundation, Decant, Eng.)			
			Height	Embank. Slope	Embank. Volume	Cost	Cost/cu.yd.	Dam Volume	Total Cost	long term Cost	Returns Ratio
	Tons	----	Ft.	Horiz/vert. Ups./Dns.	Cu.yds.	$	¢/cu.yd.	cu.yds.	$	$/ton tailings Stored	----
Case #1	$60x10^6$	Hydrocyclone and rain seal	70	1.4:1/1.4:1	291,910	61,432	21	539,270	276,000	.0046	111.3
Case #2	$60x10^6$	Conventional rolled earth	70	1.4:1/2:1	344,000	292,500	85	613,000	583,495	.0097	99:1
Case #3	$60x10^6$	Spigotted + Dozer-dragline	124	Berms 2:1/2:1*	1,570,000	686,880	43.7	1,850,000	1,126,000	.0188	32.4:1
Case #4	$60x10^6$	Hydrocyclone + Dozer	70	1.4:1/2:1	344,000	81,200	21 & 45 23.5	613,000	339,940	.0057	98:1
Case #5	----	Hydrocyclone and rain seal	115	1.4:1/1.4:1	903,750	167,965	18.5	----	----	----	----
Case #6	----	Conventional rolled earth	115	1.4:1/2:1	1,075,000	914,550	85	----	----	----	----
Case #7	----	Hydrocyclone + Dozer	115	1.4:1/2:1	1,075,000	223,985	18.5 -43.5 22.2	----	----	----	----

* The upstream slope of the spigotted tailings dam is considered to be 2:1 for volume calculations

Table 4.7

similar to cases 1, 2 and 4 respectively, except that the dam height has been increased to 115 ft. from 70 ft. to provide an indication of the change in the cost of the embankment with an increase in volume. Cases 5, 6 and 7 are limited to the cost of the embankment only as defined in Section 4.4.2.

The cost shown in Table 4.7 for the spigotted dam (case number 3) is based on the unit cost for a long-term mining program from 1926 to 1969 during which period over 56,000,000 tons of tailings were spigotted. The labour figures were adjusted to the current rate (1972) at $5 per hour including overhead. A second method was also used to estimate this construction cost and essentially the same result was obtained.

The long-term costs shown in Table 4.7 provide significant details which can be used to make economic decisions with regard to the most desirable type of tailings dam and method of tailings disposal for the conditions outlined in the preceding cases.

The sealed hydrocycloned tailings dam is the most desirable economic selection. It is not practical from an economic standpoint to use the spigotted tailings dam. The long-term cost of the spigotted tailings dam is slightly more than 400% of the cost of the sealed hydrocycloned tailings dam. The two principal factors contributing to the lower cost of construction with hydrocyclones are:

1. the more efficient use and placement of the tailings material in the embankment, and
2. the method of disposing of the tailings at a remote distance from the embankment.

The long-term cost of the conventional rolled earth dam is double the cost of the sealed hydrocycloned dam and one-half the cost of the spigotted tailings dam. This comment is based on the assumption that there is an adequate supply of natural soil in the vicinity of the proposed dam. In some mining communities the unit cost of fill for dam building has been as high as $2.40/cu. yd.

Assuming that future field tests confirm the predictions in this thesis relating to sealed hydrocycloned tailings dams, a 33% saving on the cost of the embankment can be affected by using a sealed hydrocycloned tailings dam compared with a hydrocycloned tailings dam without the special seal arrangement.

An increase in the volume of the embankment by approximately 300% produces a small reduction in the unit cost of the material.

4.5 Negative Porewater Pressures in Tailings Material

The existence of negative porewater pressure in tailings material is supported by the work of researchers and by field observations of embankment slopes. Donaldson [22] and other soil specialists [23] have measured effective soil suctions, in tailings material, up to 100 psi. The material under study contained 60% minus 200 mesh which places the material in a common range of fineness for mine tailings. In general the research by Bugatsch [41] supports the existence of negative porewater pressure in tailings; however, the boundary conditions will be more favourable. Figure 3.9 shows a tailings embankment with a slope angle approximating 62° from the horizontal and the natural angle of repose is only $35\frac{1}{2}^{\circ}$. The U.S. Bureau of Mines [24] have observed apparent cohesion in mine tailings resulting from effective soil suction approximating 5 psi. Blight [25] has conducted research experiments with natural soils relating to soil water suction in earth embankments.

With regard to soil suctions, it is appreciated that the actual field conditions will have to be verified by an extended field program of suction measurements to provide a historical record of the suctions within a sealed tailings embankment. To obtain preliminary estimates of the effective soil suction for cycloned tailings material, attempts to simulate potential field conditions were made in the laboratory as part of this study.

4.5.1 Shear Tests

1. Dry Tailings Material

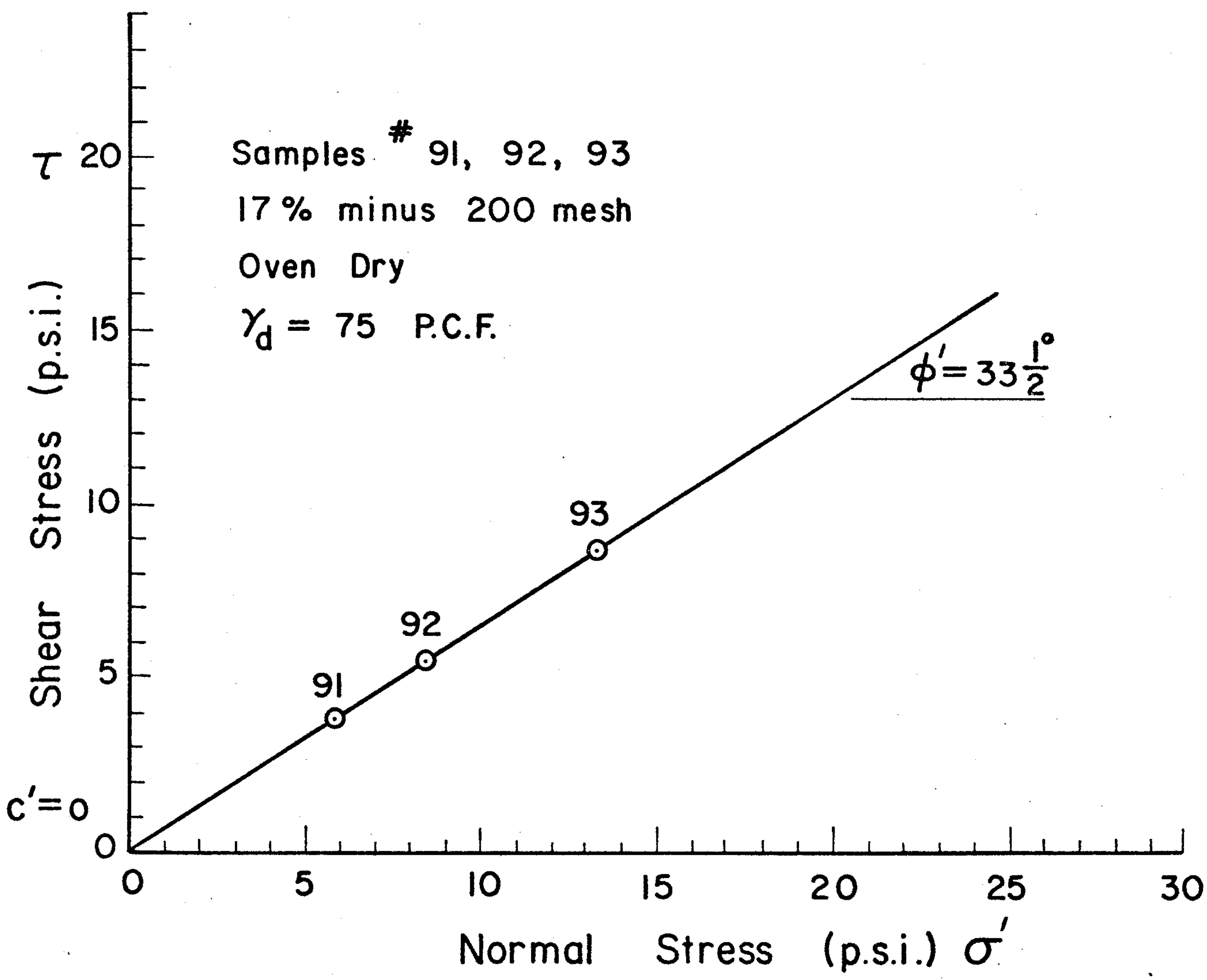
Initially direct shear tests were made on oven dry material to determine the shear strength parameters. These tests indicated that with extremely loose tailings having a density of 75 pcf (dense tailings will approximate 120 pcf) and a relative density of zero, the apparent cohesion was zero and the apparent angle of shearing resistance was $33\frac{1}{2}^{o}$ as shown in Figure 4.6.

2. Partially Saturated Sample

A sample of dry cycloned tailings was placed in a shear box complete with porous stones and water was added to attain a high degree of saturation. The assembled unit was dried to produce a partially saturated specimen. The sample was then sheared after which the average moisture content of the sample was determined (Table 4.8 sample 109).

3. Tailings Slurry Sample

To provide a closer approximation of the field conditions a quantity of tailings was mixed with water to form a slurry. The slurry was placed in a shear box and dried to provide a partially saturated specimen. After shearing the sample the moisture content was determined (Figure 4.7).



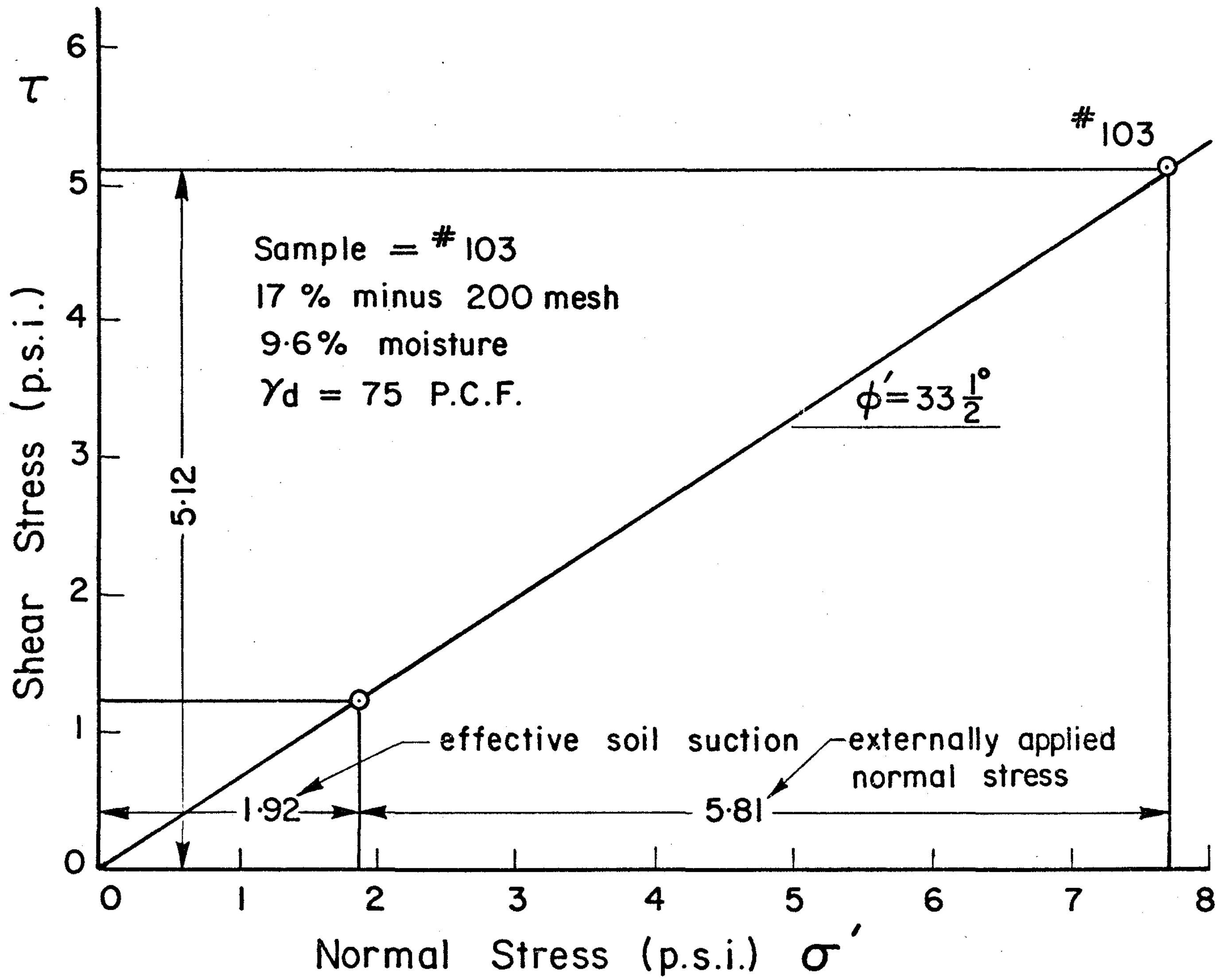
DIRECT SHEAR TEST, MINE TAILINGS
(effective stress plot)

Fig. 4·6

MINE TAILINGS
(SUMMARY OF SHEAR TESTS)

Sample Number	Minus 200 Mesh	Water Content	External Normal Load	c'	ϕ'	Shear Strength	Effective Soil Suction	S_r	χ	Soil Water Suction
#	%	%	psi	psi	degrees	psi	psi	Ratio	Parameter	psi
91	17	Dry	5.81			3.84	0.0	0.0	0.0	0.0
92	17	Dry	8.31	0.0	33½	5.51	0.0	0.0	0.0	0.0
93	17	Dry	13.31			8.82	0.0	0.0	0.0	0.0
103	17	9.60	5.81	0.0	33½	5.11	1.92	.201	.38	5.1
109	17	.64	0.00	0.0	33½	2.18	3.29	.013	.23	14.3
110	17	3.34	0.00	0.0	33½	1.31	1.98	.070	.27	7.2
111	52.4	.13	0.00	0.0	33½	20.00	30.20	.003	.22	136.0

TABLE 4.8



DIRECT SHEAR TEST, MINE TAILINGS

(effective stress plot)

Fig. 4·7

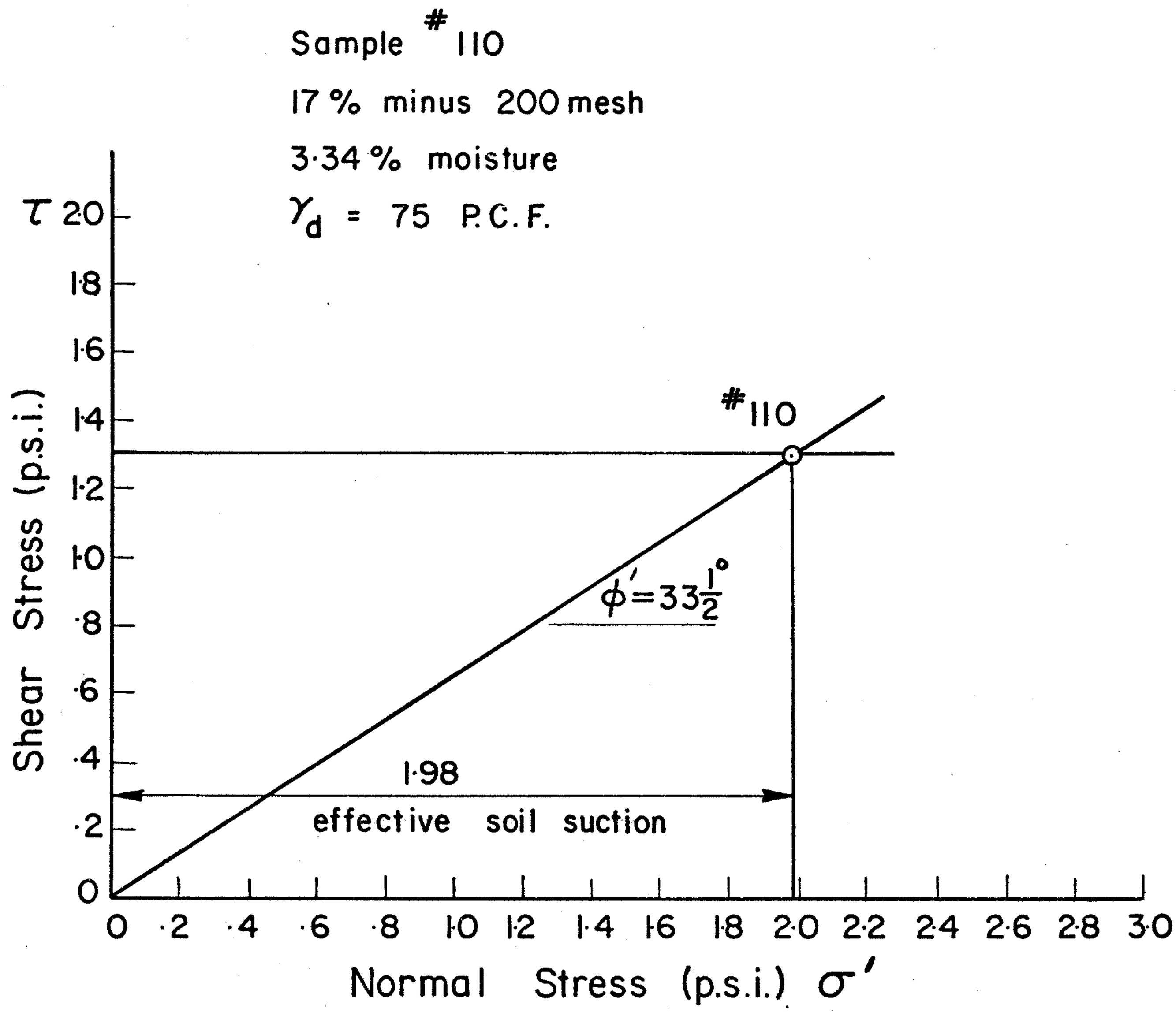
4. Shear Without External Normal Load

The previous shear tests were conducted with external normal loads applied prior to shearing. The component of shear strength derived from suction in partially saturated soil is independent of the component of shear strength derived from external normal load. In the case of a slurry sample reduced to an unsaturated condition, it was considered that a minor amount of friction between the loading block and shear box would produce distorted results by limiting the extent of the normal load transferred to the sample. To eliminate the possibility of this discrepancy, partially saturated samples were sheared without the application of external normal loads (Figures 4.8 and 4.9).

5. Fine Material Increased in Tailings from 17% to 52.4% Minus 200 mesh

Finally an additional shear test was made in which the percentage of minus 200 mesh tailings was increased from 17% to 52.4% in the tailings slurry. The sample was reduced to partial saturation and sheared without an external normal load (Figure 4.9).

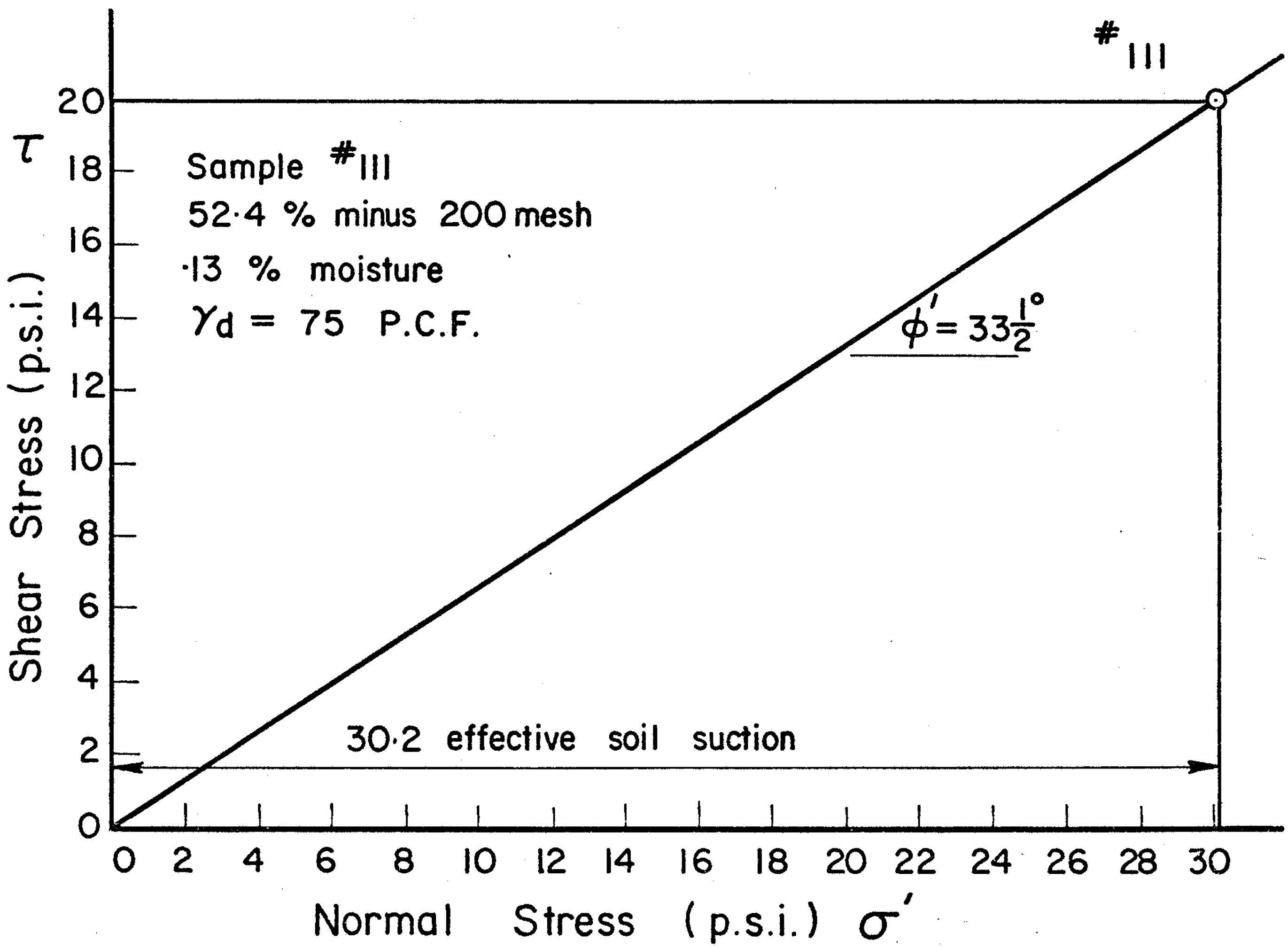
It is extremely difficult to dry multiple slurry samples to the same moisture content; however, a reasonable approximation of the stress co-ordinates were plotted from a single shear test. The shear strength is measured during the test and the effective angle of shearing resistance is assumed to be equal to the effective angle of shearing resistance ($33\frac{1}{2}^{\circ}$) for tailings material at a similar density. The intersection of these two lines provide the stress co-ordinates at the peak point as shown on Figure 4.8.



DIRECT SHEAR TEST, MINE TAILINGS

(effective stress plot)

Fig. 4·8



DIRECT SHEAR TEST, MINE TAILINGS
(effective stress plot)

Fig. 4·9

The results of the shear tests are summarized in Table 4.8 and Figures 4.6 through 4.9.

4.6 Stability of Tailings Embankments with Negative Porewater Pressure

The stability of a tailings embankment is dependent on the shear strength of the tailings material in the embankment.

Tailings material from any particular concentrator is very consistent in size because of the practice of closed-circuit classification during the process of mineral extraction. The size of this particulate material is predominantly silt.

When fine grained materials are partially saturated they possess negative porewater pressure or "suction" in the water phase at the points of contact between the solid particles. The suction increases the intergranular pressure and shear strength of the material.

Terzaghi's [26] effective stress equation was extended by Bishop [27] to accommodate partially saturated soils. This equation is expressed as:

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w)$$

where σ' = effective normal stress

σ = total normal stress

u_a = poreair pressure

u_w = porewater pressure

χ = is a variable which, for incompressible cohesionless soils (cycloned tailings), may be expressed in terms of the saturation ratio; $\chi = .22 + .78\ Sr$; Aitchison [28].

Experimental results by Lee and Donald [29] show evidence that this expression is reasonably correct for silts or sands but is not applicable for clays where hysteresis effects from wetting and drying are prominent. The cycloned tailings screen analysis as shown in Figure 4.1 indicates that this material is a silty-sand and therefore "χ" can be evaluated from the above expression.

Instrumentation was developed (refer to Chapter 5) as part of this research to facilitate evaluation of the effective normal stress for partially saturated tailings material. In the effective stress equation

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w),$$

where $(\sigma - u)$ is the "stress difference",

$(u_a - u_w)$ is the "soil water suction", and

$\chi(u_a - u_w)$ is designated as the "effective soil suction" in the thesis and is defined as the average suction per unit area.

The "stress difference" and "soil water suction" can be evaluated with the instrumentation developed specifically for this purpose.

The suction in the water phase of partially saturated fine grained soils can attain large values at low water content. The soil water suction only acts over a portion of the cross-sectional area of the soil and the effective soil suction in tailings material may represent a relatively small value compared with the value of the soil water suction. To become a useful engineering unit, in slope stability analysis, the soil water suction must be converted to effective soil suction.

In order to determine the sensitivity of the embankment with respect to effective soil suction, several stability analysis were made with the aid of a computer program. This program originally developed at the Massachusetts

Institute of Technology based on Bishop's simplified stability analysis (1954) was debugged and modified to make it amenable to the WATFIV compiler at the University of Waterloo. The equation used to determine the factor of safety in the computer program is:

$$F = \frac{\Sigma \left[c'b + (W - \mu b) \tan \Phi' \right] \dfrac{\sec \alpha}{1 + \dfrac{\tan \Phi' \tan \alpha}{F}}}{\Sigma W \sin \alpha}$$

This equation and the associated computer program are applicable for partially saturated hydrocycloned tailings material by making a minor modification to the input data. In hydrocycloned tailings, the cohesion is zero and the effective soil suction in the partially saturated zone is an individual component of shear strength. The effective soil suction $[\chi(\mu_a - \mu_w) = \mu]$ may be evaluated as apparent cohesion $(-\mu \tan \Phi' = c')$ and substituted as a cohesion value in the input data. The soil parameters in all other zones of the embankment are used in the normal procedure.

The output of the modified program was checked against an embankment with a known factor of safety and a sample computer output is included in the Appendix. Recently the program was checked with a program purchased by the Civil Engineering Department of the University of Waterloo (Lease I, a subsystem of "ICES" - Integrated Civil Engineering System). In both cases the output from the modified program proved satisfactory with close agreement in the factor of safety.

Stability analysis were made for different embankment heights with effective soil suction varying from zero to 10 psi. The other soil properties used for the tailings material were:

a) total unit weight (γ) = 110 pcf

b) effective cohesion (c') = zero

c) effective angle of shearing resistance (Φ') = 35.5°.(Field conditions)

The results of these tests are plotted in Figures 4.10 through 4.13. Factors of safety between 1 and 1.5 represent the range of principal interest and graphs were constructed accordingly. Figure 4.12 is similar to Figure 4.10 except that the curves are plotted with multiples of "30 foot dam heights" to provide a better perspective of the variation in factor of safety with suction and dam height.

MINE TAILINGS

Effect of Soil Suction on Embankment Stability

(Embankment Slope = 1·4:1 ; H/V)

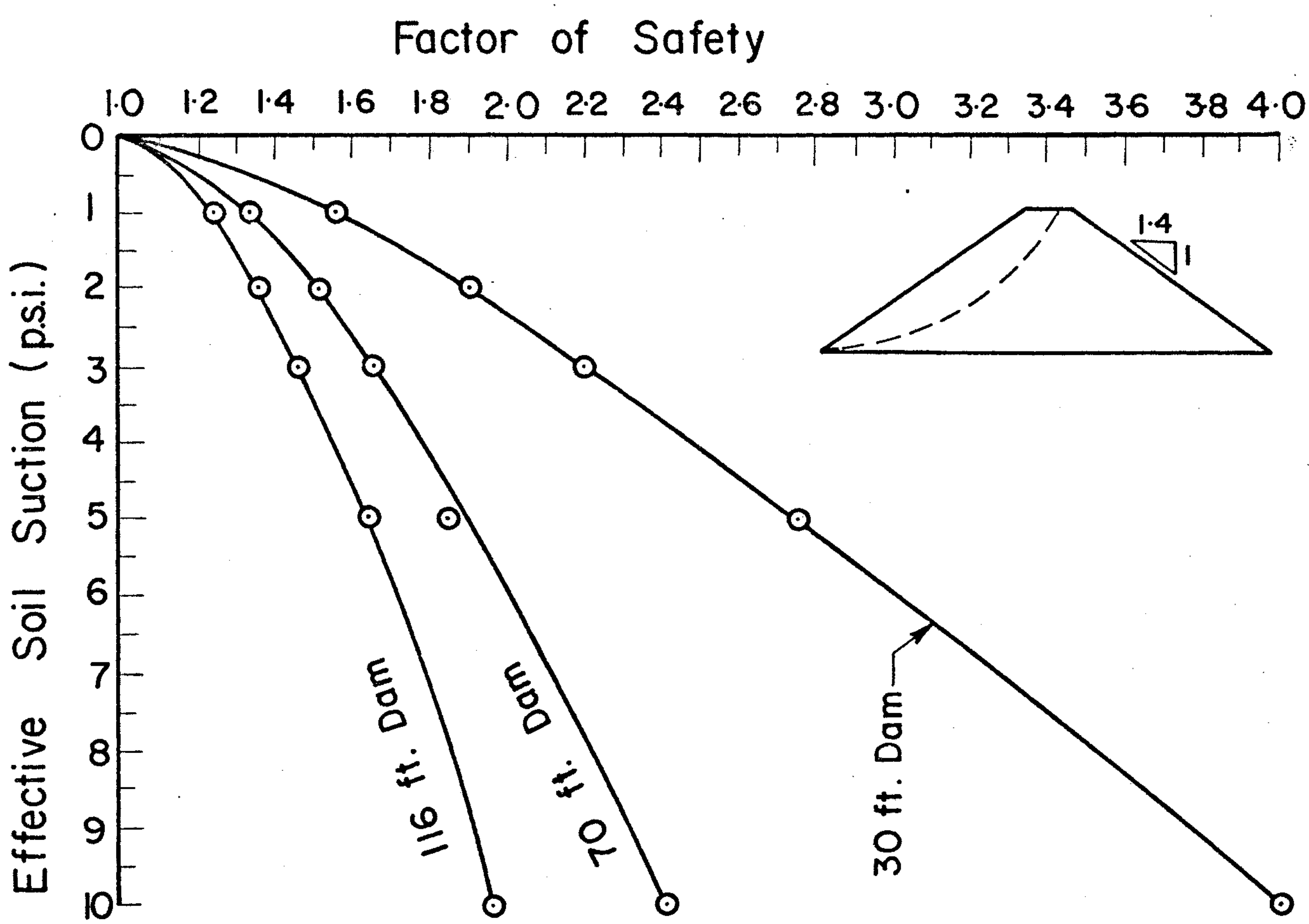


Fig. 4·10

MINE TAILINGS

Relation Between Dam Height and Factor of Safety

(Embankment Slope = 1·4 : 1 ; H/V)

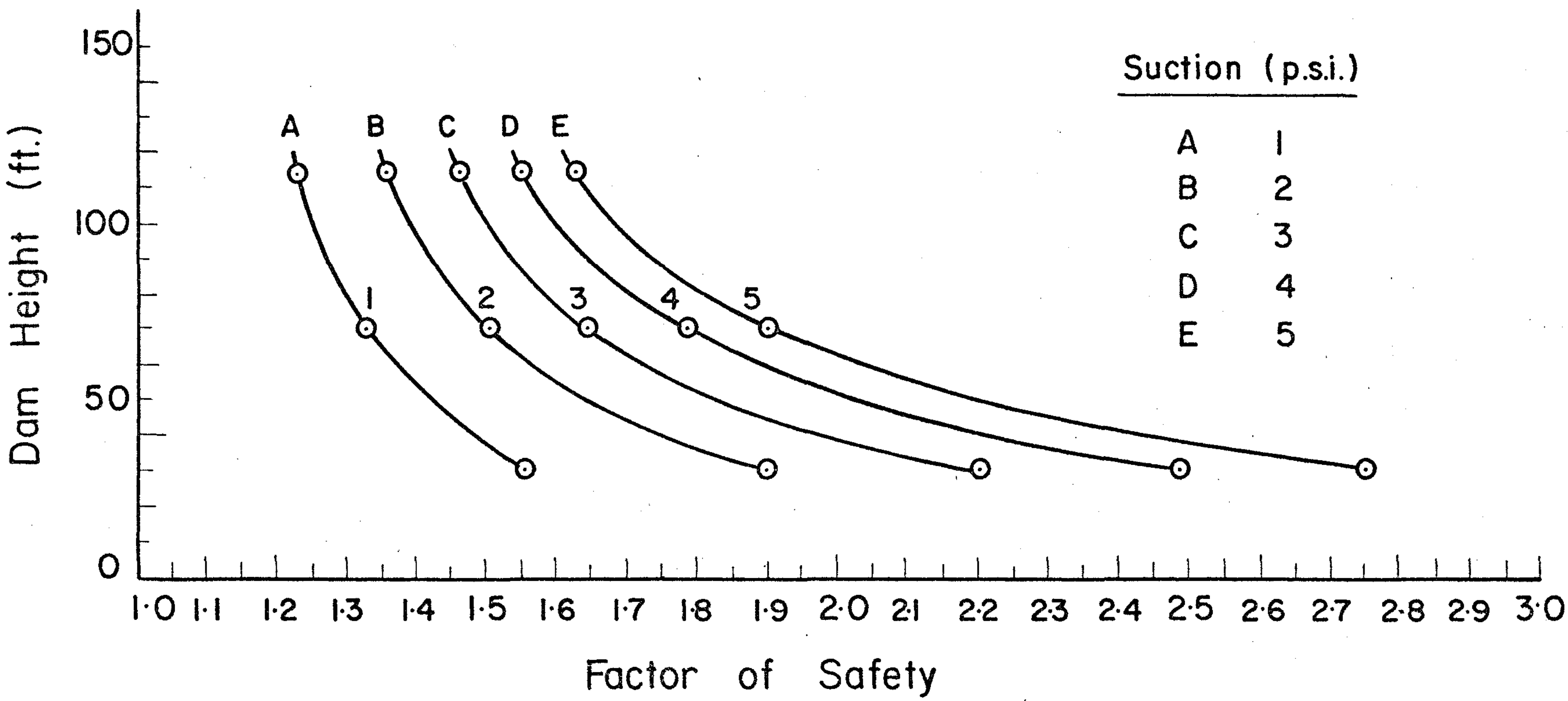


Fig. 4·11

MINE TAILINGS

Effect of Soil Suction on Embankment Stability

(Embankment Slope = 1·4 : 1 ; H/V)

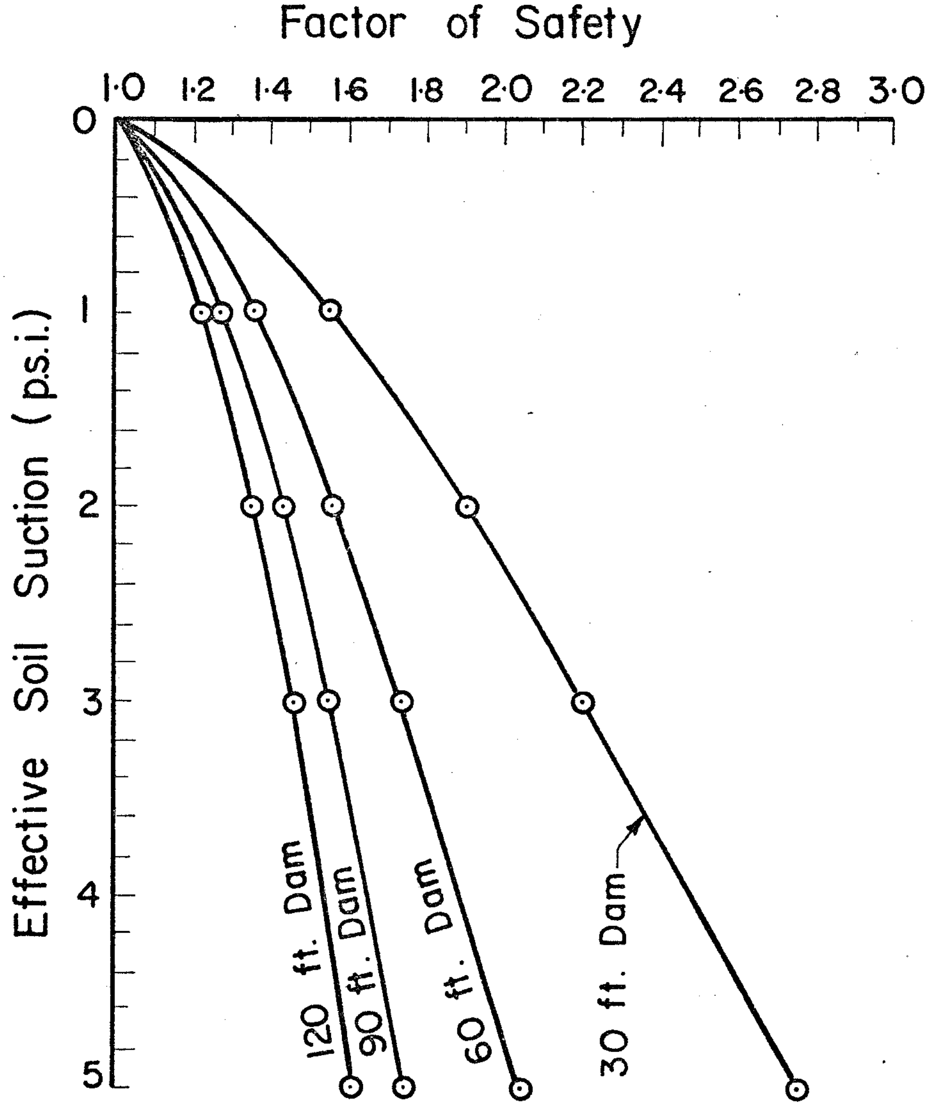


Fig. 4·12

MINE TAILINGS

Relation Between Dam Height and Soil Suction

(Embankment Slope = 1·4:1 ; H/V)

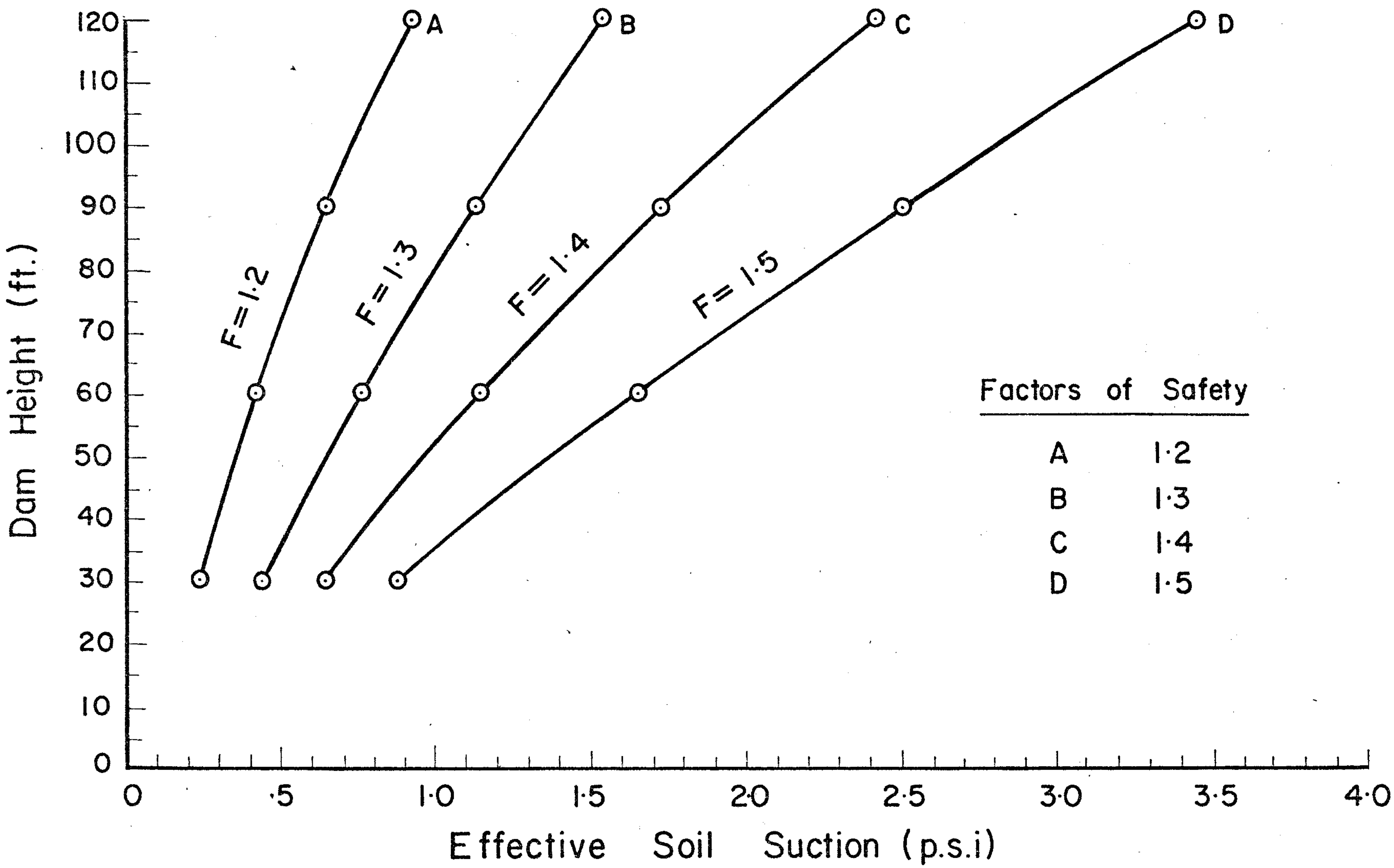


Fig. 4·13

4.7 Considerations for Hydraulic Tailings Dams

4.7.1 The Critical Parameter

In hydraulic tailings dams the critical parameter, of the material shear strength, is the porewater pressure. This parameter has:

1. the widest range in variation
2. a significant effect on safety and stability, and
3. a significant potential for reducing the cost of the dam.

The porewater pressure may vary from the undesirable condition of positive pressure in a saturated zone to the desirable condition of negative porewater pressure in an unsaturated zone. There are many tailings dams or sections of tailings dams that exist solely because of the negative porewater pressure. The slopes of these sections are steeper than the natural angle of repose (for dry material) in a cohesionless tailings material.

Dam design is based on the most severe operating conditions that are likely to occur. Therefore, the conditions contributing to the variations in porewater pressure and the solutions for restricting the variation in porewater pressure warrants consideration.

4.7.2 Conditions Contributing to Variable Porewater Pressure

The principal conditions contributing to variable porewater pressure are:

1. the combined effect of continually increasing the elevation of the pool surface and an inefficient upstream seal

2. the rainfall and runoff infiltrating the embankment, and
3. the construction water from hydraulic procedures infiltrating the embankment (this condition is particularly applicable to continuous spigotting along alternate sections of crestline of the dam).

4.7.3 Solutions for Restricting the Variations in Porewater Pressure

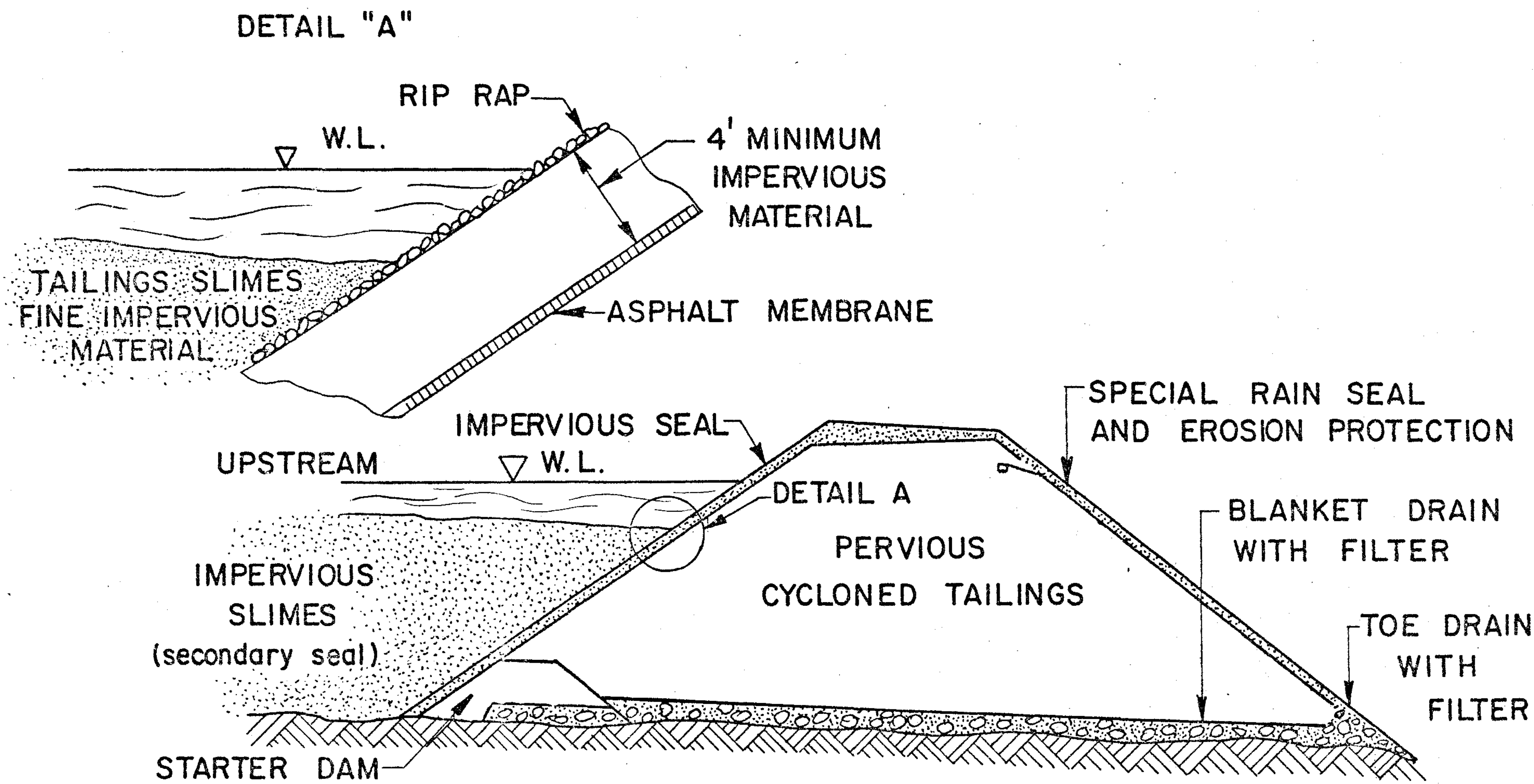
The variation in porewater pressure is reduced substantially by constructing a hydrocyclone dam in accordance with the design as shown on Figure 4.14. This design is constructed with hydrocyclones and includes a specific upstream seal, blanket drain and rain seal which are described as follows:

1. Upstream Seal

   The upstream seal is composed of a primary and secondary seal.

   The primary upstream seal is intended to provide an immediate and temporary seal to permit time for the accumulation of slimes to settle and form the permanent secondary seal. It is essential to provide a primary seal because there is a small depth of clear water in contact with the upstream slope. The selection of a hydrocyclone method of construction conveniently facilitates the superior method of downstream construction and provides a steep upstream slope which permits the application of a primary upstream seal.

   The starter dam is ideally located with the upstream toe of



CYCLONED TAILINGS DAM (unsaturated)
(Bulk tailings discharged upstream)

(DECANT SYSTEM NOT SHOWN)

Fig. 4·14

the starter dam coincident with the upstream toe of the ultimate dam when the downstream method of construction is used.

After completing the starter dam (and if necessary the first stage of the primary seal), bulk tailings is discharged at a remote distance upstream from the dam. The coarse tailings particles settle close to the discharge point and the fine micron size slimes settle against the upstream face of the dam forming an impervious secondary seal. Slimes also settle in the bottom of the reservoir, immediately upstream from the dam, providing an upstream basin seal to restrict the seepage under the dam.

The width and thickness of the secondary seal are essentially unlimited. Therefore, it is extremely difficult to destroy.

The ratio of permeabilities between the tailings slimes upstream and the cycloned tailings in the embankment is usually greater than 1,000:1. The permeability of tailings slimes may vary from less than 10^{-7} to 10^{-4} cm./sec. [30], depending on the density of the material. The permeability of hydrocycloned tailings will approximate 2×10^{-3} cm./sec. This large differential in permeabilities provides a cutoff for the flow of seepage water from the slimes into the downstream zone of the embankment. The embankment remains unsaturated because the limited volume of seepage water is collected in the blanket drain.

2. Blanket Drain

The blanket drain is included at the base of the dam to insure that the embankment will remain unsaturated at all times after the initial state of saturation during hydraulic construction.

3. Rain Seal

An asphalt membrane is used to restrict the rainfall and runoff water from entering the embankment. Top soil is placed over the membrane to facilitate the growth of vegetation which prevents surface erosion and airborne dust. The rain seal provides a second important function by way of restricting the development of an acidic condition in the top soil.

4. Construction Porewater With Mobile Hydrocyclones

It has previously been stated in Section 3.4.1-6 that mobile hydrocyclones have a major advantage with regard to the construction porewater pressure.

The combined features of the hydrocycloned dam as outlined above provide an unsaturated embankment containing negative porewater pressures.

4.7.4 Desirable Factors of Safety for Tailings Dams

An appropriate factor of safety is determined by the conditions associated with the tailings dams. These conditions are:

1. the downstream conditions affecting the seriousness and extent of damage that could result from a major breakaway
2. the length of time that the factor of safety is applicable
3. which slope of the embankment is being considered
4. the range of variation in shear strength parameters during normal operating conditions, and
5. seismic activity.

4.7.4.1 Downstream Conditions

Where the immediate downstream area is populated and a breakaway could result in serious loss of life the minimum factor of safety should be 1.5.

4.7.4.2 Time Applicable

a) For the long-term steady seepage condition, it is recommended that the factor of safety be in the range of 1.2 to 1.5 for the downstream slope. Earth dam designers have used a factor of safety of 1.5 for a number of years [31]. Since 1940 there have been practically no earth dam failures where the dams have been engineered and construction supervised by qualified personnel [32]. Failures have occurred in small poorly constructed dams or where soft foundations were encountered. With the excellent record of earth dams, increase in technology and instrumentation, the 1.5 factor of safety is conservative. A factor of safety of 1.3 is considered acceptable for the downstream slope of a "normal" tailings dams where the parameters are well defined.

b) A factor of safety of less than 1.2 is acceptable in some instances. A small cofferdam constructed to permit the preparation of a dam foundation with a useful life of only a few days may have a factor of safety of 1.1. During the construction of a hydraulic tailings dam, immediately after the particles are arrested on the slope, the factor of safety is just slightly above unity; however, there is no material stored against the stage under construction and the stability will increase as the porewater pressure decreases within the embankment.

4.7.4.3 Upstream Slope

a) A factor of safety slightly above unity is acceptable for the upstream slope of a tailings dam which is subject to "normal" operating conditions. The upstream slope of a tailings dam is not subject to rapid drawdown conditions and the settled tailings reinforces the stability of the upstream slope. The water pool is maintained at a minimum and approximately constant depth throughout the life of the operation. As the depth of the settled tailings increases, the surface elevation of the pool is increased to maintain a clear effluent. The upstream slope of a normal tailings dam can be as steep as the natural angle of repose for the construction material without creating a serious stability hazard. To the author's knowledge there is no known or published data to indicate that an upstream slip failure for a tailings dam has ever resulted in a breakaway.

b) There are circumstances where it may be desirable to retain a considerable depth of water behind the initial stage of a tailings dam. Under these special circumstances, the upstream slope should be designed with specifications for a water dam.

4.7.4.4 Variation in Porewater Pressure

If the porewater parameter is likely to vary over a wide range with seasonal climatic conditions or with the construction process water, the designer is justified in using a higher factor of safety. When the design and construction details assure a relatively consistent porewater pressure over the long-term period, a factor of safety of 1.3 is recommended for the downstream slope unless external conditions justify higher values.

4.7.4.5 Seismic Activity

In earthquake areas it has been common practice [33] in slope stability analysis to make allowance for seismic activity by adding a horizontal acceleration force to the stresses tending to cause failure. This procedure is not realistic from a theoretical standpoint because the forces rapidly reverse direction. Recently it has been acknowledged that a qualitative approach to protection against seismic activity has more merit than the quantitative approach by the application of an arbitrary static horizontal force [34]. Based on Stone and Smith [34] the proposed recommendations for tailings dams are:

1. reduce the zone of saturation in the dam with a better seal and improved internal drainage
2. thicken the seal
3. increase the width of the crest with a self-sealing granular material in the event of cracking or movement
4. increase the freeboard
5. increase the densities of material by compaction, and
6. flatten the downstream slope.

In addition to the qualitative approach a minimum factor of safety of 1.5 is recommended in areas subject to frequent or intensive seismic activity.

4.7.5 Mechanical Improvements for Hydraulic Dams

Four methods are used to improve the stability of the hydraulic embankments by supplementing the hydraulic procedures with mechanical methods:

1. the slope ratios are increased by a redistribution of the tailings with mechanical equipment
2. a toe berm of pervious material is added to the downstream toe for a relatively low embankment
3. the overall effective downstream slope is flattened by including berms at stage elevations (Figure 3.6), and
4. the density of the material is increased by compaction with mechanical equipment.

4.8 Considerations for the Decant System

The decant system is likely to remain the preeminent method of removing effluent from tailings basins due to the operating advantages of this system. Some pertinent comments relating to the decant system are:

1. During the site investigation for the decant system it is of paramount importance to locate the base of the tower on a competent foundation. Whenever possible the base of the tower and the thrust block should be supported by bedrock.
2. Reinforced concrete is a suitable construction material, however, all exposed surfaces (both inside and outside) should be provided with an acid resisting protective coating.
3. The decant tunnel should not be designed as a rigid structure. Flexible sealed joints should be incorporated to compensate for possible differential settlement and temperature variations.

4. The buried conduit must be capable of withstanding the ultimate overburden loads of the tailings embankment. Both the bedding conditions and the method of installation have significant effects on the allowable height of the overburden.

Data have been published [35] for the classification of bedding and for the installation methods affecting the load factors of precast concrete pipe. Load factors have been established for four classes of bedding:

A) concrete cradle or concrete arch

B) shaped subgrade with granular foundation (50% of diameter)

C) shaped subgrade or granular foundation (1/6 of diameter)

D) flat bottom trench, and

four methods of installation:

a) trench conduit

b) positive projecting conduit

c) negative projecting conduit, and

d) induced trench conduit.

A precast, embedded-cylinder, prestressed concrete pipe is available in Canada which will withstand more than 165 feet of overburden depending on the conditions. The allowable height of overburden can be increased if class "A" bedding and an induced trench method of construction are used. For exceptionally high dams, a multiple stage decant system can be used to accommodate the height of overburden.

5. Seepage diaphragms should be included along the tunnel in the upstream zone of the embankment.
6. The inconvenience of pouring concrete to extend the height of the decant tower, which is usually located near the middle of the settling pool, can be eliminated by floating precast concrete extension sections into place and welding the joints with high strength epoxy resins. In this manner the tower can be extended in fifteen minutes following the preparation for rigging.
7. The capacity of the decant system should be designed to accommodate the production flow plus the flood runoff with a recurrence interval similar to those used for water reservoirs. It is of interest to note that the production flow represents less than 10% of the peak runoff in many tailings basins. The actual capacity of the decant system can be reduced appreciably if emergency spillways or additional freeboard are provided to handle the surge capacity from runoff. A removable antivortex device is recommended for all drop inlets [36].
8. In severe climates where icing conditions restrict the flow volumes entering the decant tower, submerged discharge arrangements can be provided.

9. It is desirable to provide a flow calibration chart to indicate the volume of discharge with respect to the pond surface elevation, and

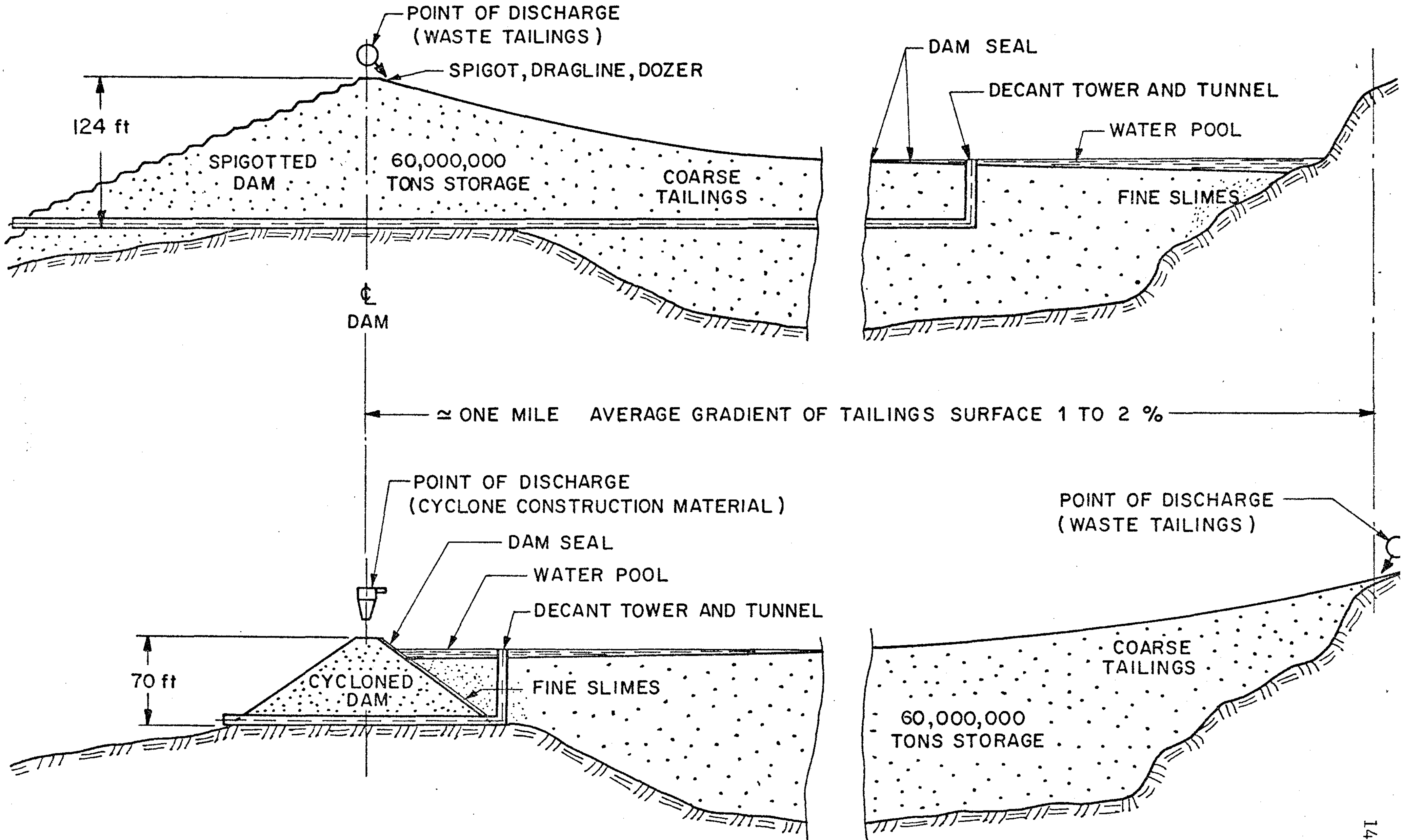
10. The design details should include convenient access to the discharge of the decant system for purposes of quality sampling or chemical treatment where necessary.

4.9 Advantages of Hydrocycloned Tailings Dams Over Spigotted Tailings Dams

Figure 4.15 is a sketch outlining a comparison of spigotted vs. hydrocycloned tailings dams for a valley application. The storage volumes and dimensions are realistic figures which have been calculated for a specific tailings disposal system.

Some of the advantages of a hydrocycloned tailings dam are as follows:

1. The hydrocycloned dam permits the construction of a much lower dam for the same storage volume.
2. The required volume of dam building material is less for a dam of the same height and comparable factor of safety.
3. The hydrocycloned tailings dam as outlined in Figure 4.14 provides an unsaturated embankment which is less susceptible to liquefaction or to frost damage and can be built to greater heights with safety.
4. It is convenient to use the superior method of downstream stage construction with hydrocyclones.



COMPARISON OF SPIGOTTED vs CYCLONED TAILINGS DAM

Figure 4·15

5. The factor of safety remains relatively constant on account of the consistency of the internal conditions. On the other hand a spigotted dam has zones which are intermittently saturated producing positive porewater pressures and allowance must be made in the design to accommodate the most severe operating conditions.
6. It is almost impossible to destroy the secondary upstream seal because of the extensive width of the slimes.
7. The amount of slimes or minus 200 mesh material in the hydrocyclone underflow product is controllable by adjusting the operating conditions. These fine particles have an acute effect on the permeability of the embankment.
8. A safe upstream slope is provided at the steepest possible angle.
9. The construction labour is limited to one hydrocyclone operator. It is not necessary to frequently elevate the tailings line as is normally the case for construction operations with spigots.
10. Large expensive construction machinery such as draglines and bulldozers are not required.
11. Mobile hydrocyclones can conveniently build their own road, on the crest of the dam, which may be over rugged terrain such as steep rock faces.
12. The impervious slimes immediately upstream from the embankment provide an excellent seal in the tailings basin to obstruct the flow of seepage water under the dam.

13. The base of a hydrocycloned dam is more suitable where the width of the competent foundation is limited.
14. Shrinkage cracks are seldom in existence in hydrocycloned tailings dams.
15. The seeding of tailings embankments with grass is a desirable and acceptable method of preventing surface erosion. To overcome the extreme difficulty of having continuous surface vegetation where the tailings materials generate acidic soil conditions, the seal on the hydrocyclone dam offers an excellent base which restricts acidity in the layer of soil above the seal.
16. A much shorter decant tunnel is required with less complicated stress problems and lower construction costs.
17. The decant tower may be located on a more suitable foundation with less expense.
18. The decant tower is more readily accessible for servicing.
19. The decant flow volume can be calibrated with a reference gauge close to the crest of the dam, and
20. It is more economical to construct a hydrocyclone tailings dam.

Hydrocyclones are an effective means of classifying tailings material for the construction of tailings dams. The effectiveness of the method may be enhanced if negative porewater pressure, as shown in Figures 4.10 and 4.13, could be used in design. The development of instrumentation is required in order to evaluate the negative porewater pressures and effective soil suction in tailings. Chapter 5 deals with instrumentation to facilitate this evaluation.

4.10 Prediction for Future Tailings Dams

It is predicted that there will be a significant reduction in the number of future tailings dams which are constructed by the upstream spigotted method. The adoption of more stringent regulations for the safety of tailings dams will make it difficult to comply with the legislation using the spigotted method. The predominant method of using spigots will be replaced with dam designs incorporating a competent seal to provide lower porewater pressures over the long-term period.

CHAPTER 5

INSTRUMENTATION

5.1 Introduction

It is essential to develop instrumentation and elucidate the long-term in situ soil conditions, in sealed tailings embankments, in order to permit the application of negative porewater pressure in the design of tailings dams. A number of successful methods for measuring negative porewater pressure are presently in use; however, the majority of these methods have been developed for laboratory tests and are unsuitable or inconvenient for long-term in situ readings in embankments.

The initial concept was to develop a small triplex meter to evaluate the effective stress in partially saturated tailings embankments in accordance with Bishop's modified effective stress equation. The three components of the meter were:

1. a stress difference pressure cell
2. a porewater pressure cell, and
3. a psychrometric module.

During the development process it became apparent that the sensitivity and fidelity of the stress difference cell could be improved by separating it from the pore pressure components.

The output data from these instruments facilitate the evaluation of the effective stress and shear strength necessary for a stability analysis of the embankment. The instruments were specifically developed to evaluate the effective stress in partially saturated cycloned tailings material. They can also be used to obtain the stress difference (σ - u), porewater pressure (u_w) and soil water suction (u_a - u_w) in any soil. In addition, a minor modification to the stress difference cell will provide an earth pressure cell.

5.2 Stress Difference Pressure Cell

A review of previous research on earth pressure cells of the diaphragm type [37], indicates that very sensitive instrumentation is required to overcome the limitation of allowable deflection of the diaphragm. Pressure diaphragms embedded in a particulate material may register either higher or lower pressures than those existing in the surrounding soil; depending on the bridging effect on the diaphragm or the stiffness of the overall cell. Both the U.S. Corps of Engineers [38] and Trollope [39] recommend a stiff diaphragm to limit the maximum deflection at the center of the diaphragm to 1/2,000th of the diaphragm diameter. This suggested design constraint places a severe demand on the sensitivity of the sensing mechanism and readout equipment.

Miniature foil type strain gauges have been applied successfully as transducers to measure strains on many types of structural members. It was considered appropriate to combine the mechanisms of a diaphragm and a cantilever beam in order to enhance the sensitivity of a pressure cell. The first beam amplified diaphragm was designed during the summer of 1969. This design was followed by modifications to include: a double diaphragm, a short cantilever beam (5/16" long) mounted directly on the active portion of one diaphragm, and filters to permit pore pressure to enter the cell as shown in Figures 5.1, 5.2 and 5.3. Both the upper and lower surfaces of each diaphragm are exposed to pore pressures (neutral stresses) to permit the unit to act as a stress difference pressure cell.

5.2.1 Calibration

A bridge type, Budd P-350 portable strain indicator, complete with accompanying switch and balance unit were used as readout equipment for all pressure cell calibrations.

1. Beam Calibration

   An initial test was made to investigate the linearity of the output signal from the cantilever beam which was fitted with four transducers in a full bridge circuit. The beam was loaded with weights in stages to provide a deflection well beyond the normal operating range. Linear characteristics were observed throughout the range of loading for the test (Figure 5.4). The output was stable with no change in deflection over a three day period during which time the beam was subjected to a static load.

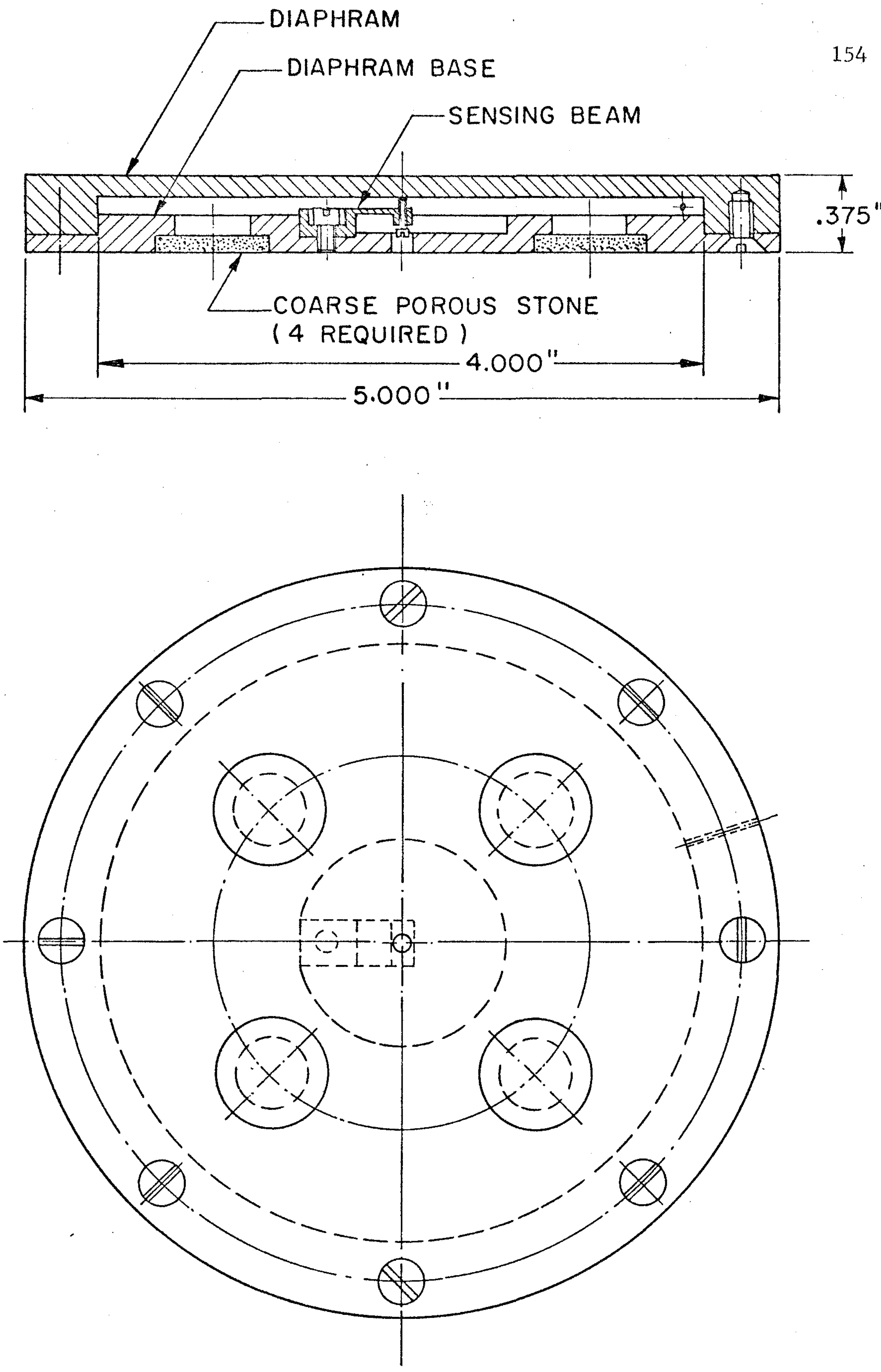
2. Commercial Transducer Calibration (DYNISCO PT 25-30 # 48077)

   Prior to calibrating the stress difference pressure cell a fluid calibration was made for the commercial transducer which was used as a pressure reference instrument. This instrument was zeroed in air and then calibrated against a column of mercury. The characteristics were observed to be linear (Figure 5.5).

3. Pressure Cell Calibration

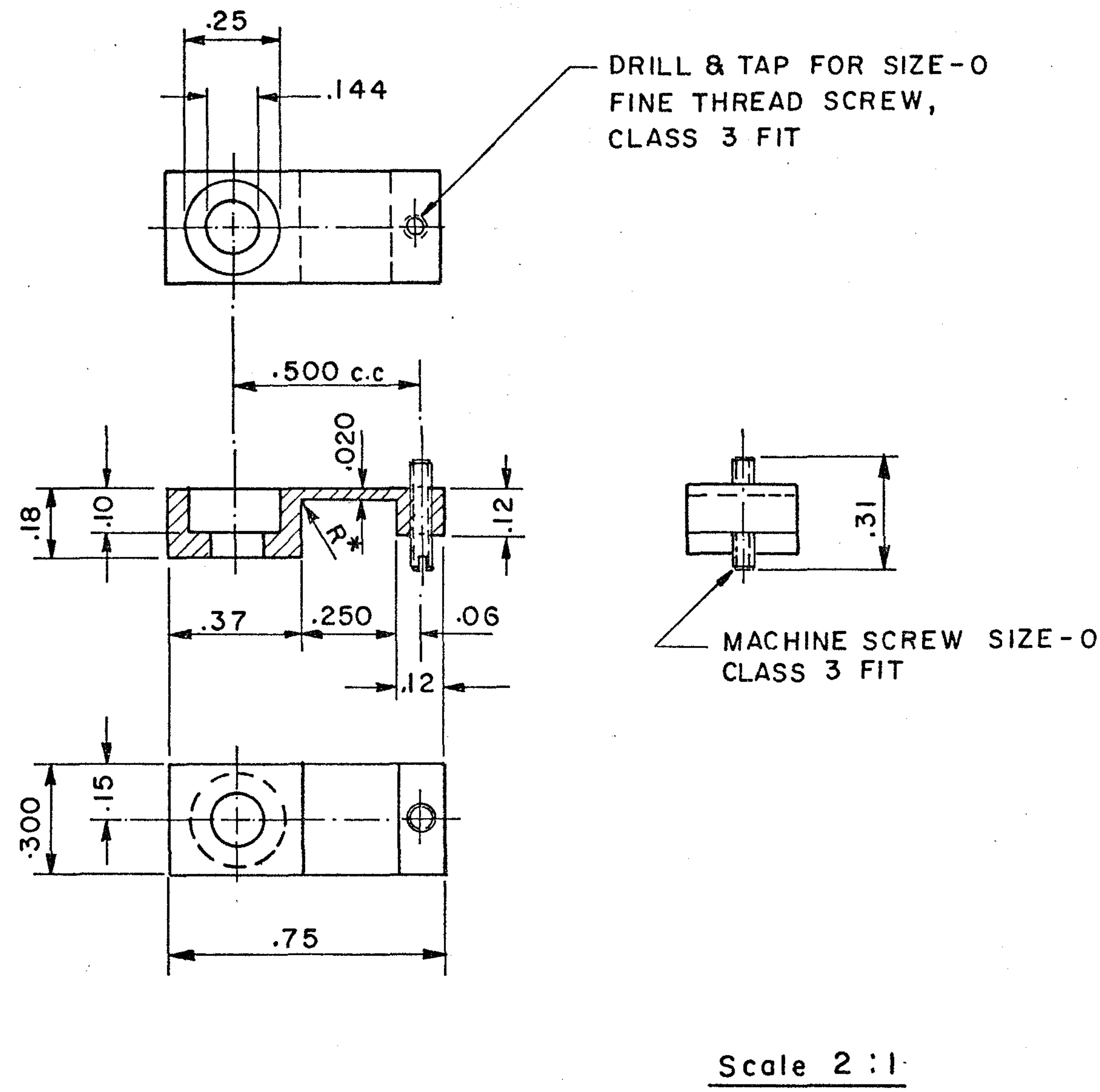
   a) Fluid Calibration

      The pressure cell assembly was zeroed in air and calibrated



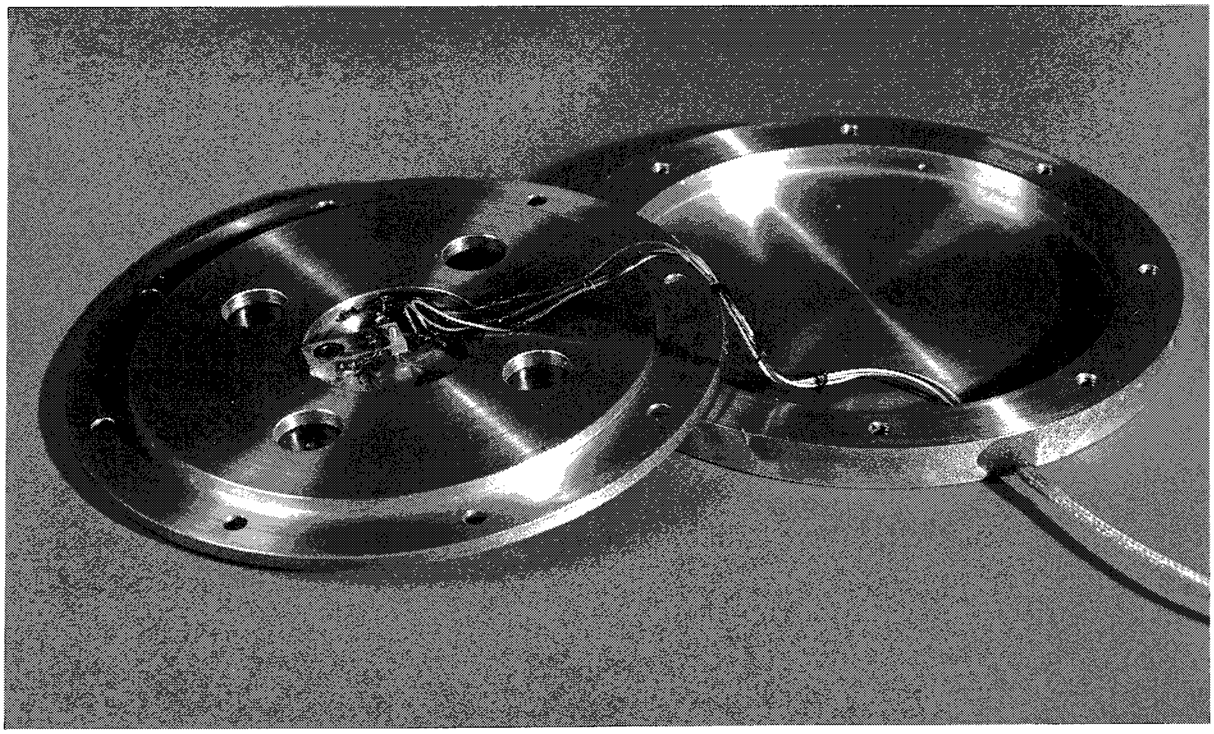
STRESS DIFFERENCE PRESSURE CELL

Figure 5.1

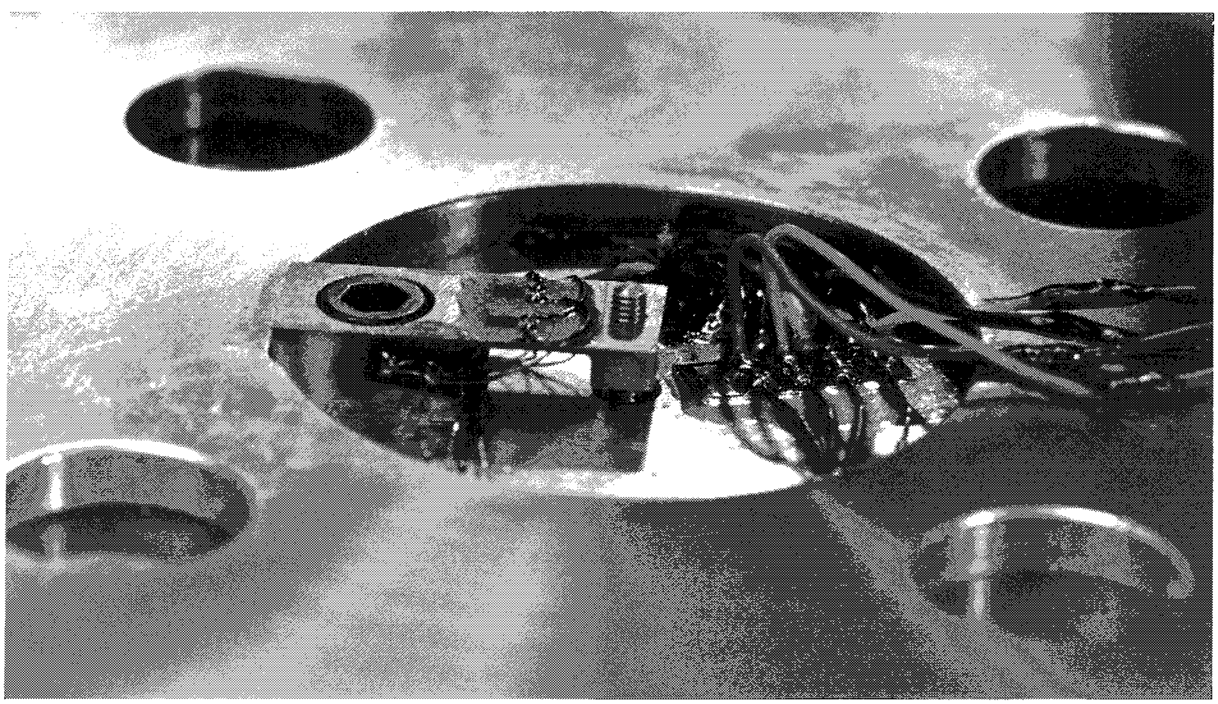


SENSING BEAM

Figure 52



Stress Difference Pressure Cell



Close-up Cantilever Beam

Fig. 5.3

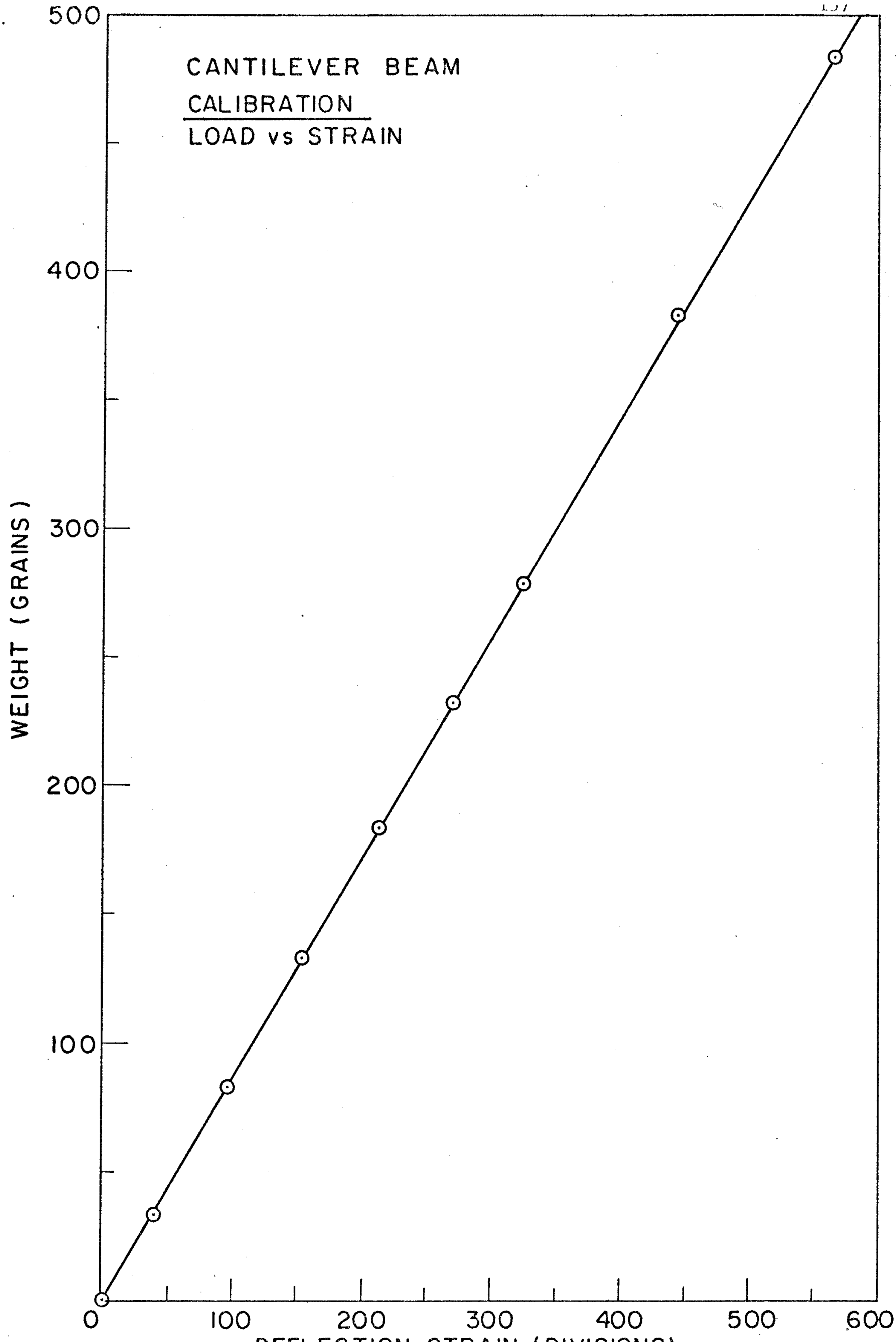

CANTILEVER BEAM
CALIBRATION
LOAD vs STRAIN
WEIGHT (GRAINS)
DEFLECTION STRAIN (DIVISIONS)
0
100
200
300
400
500
600

Figure 5.4

with fluid pressure (water) referring to the Dynisco transducer.

b) Sand Calibration

Following the fluid calibrations of the pressure cell it was calibrated in sand. The general arrangement of the test equipment is shown in Figure 5.6.

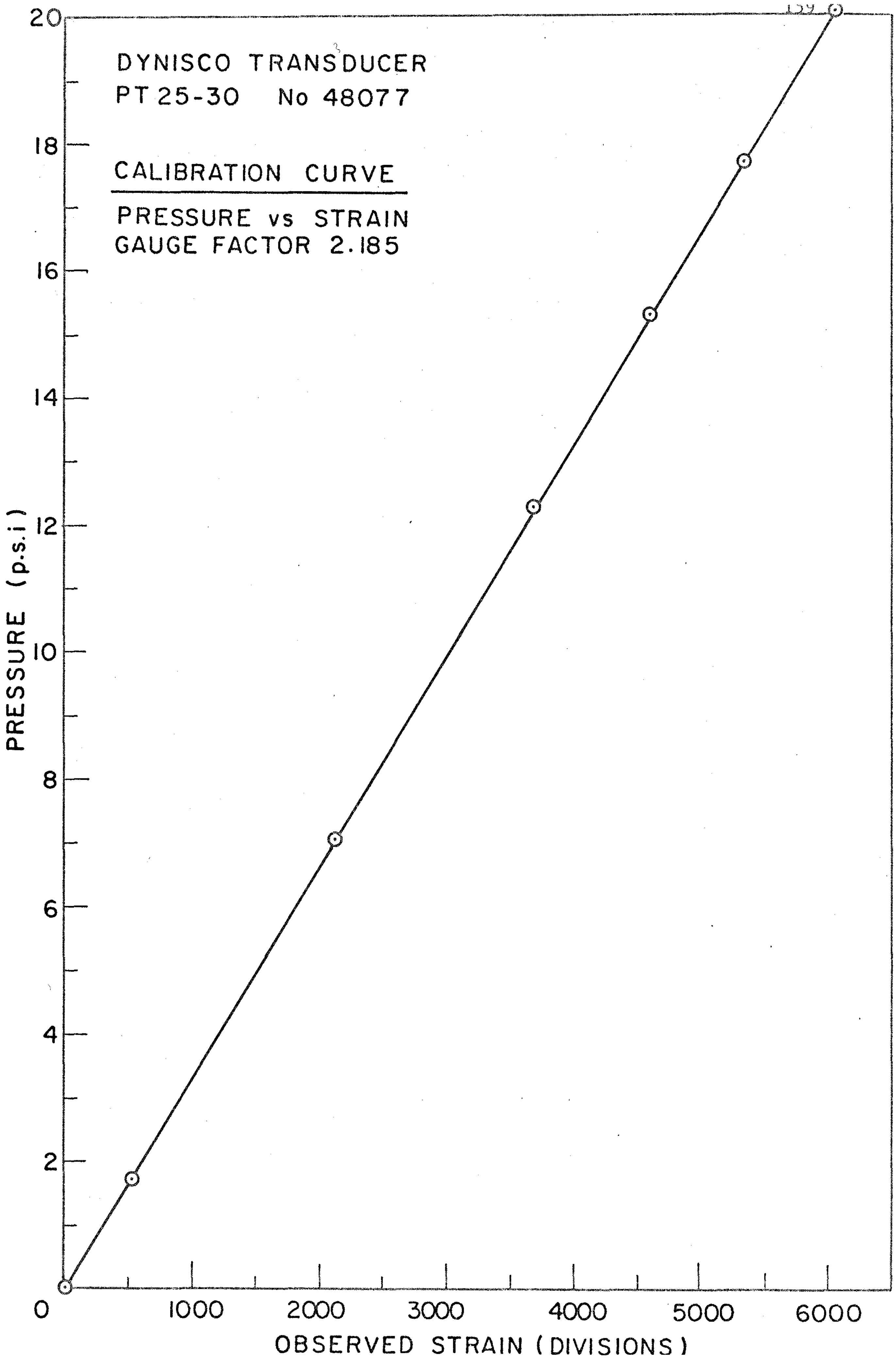
The calibration chamber is a steel tank fitted with a flanged cover and rubber diaphragm at the top of the tank. Water pressure is transmitted through the diaphragm to the contents of the chamber.

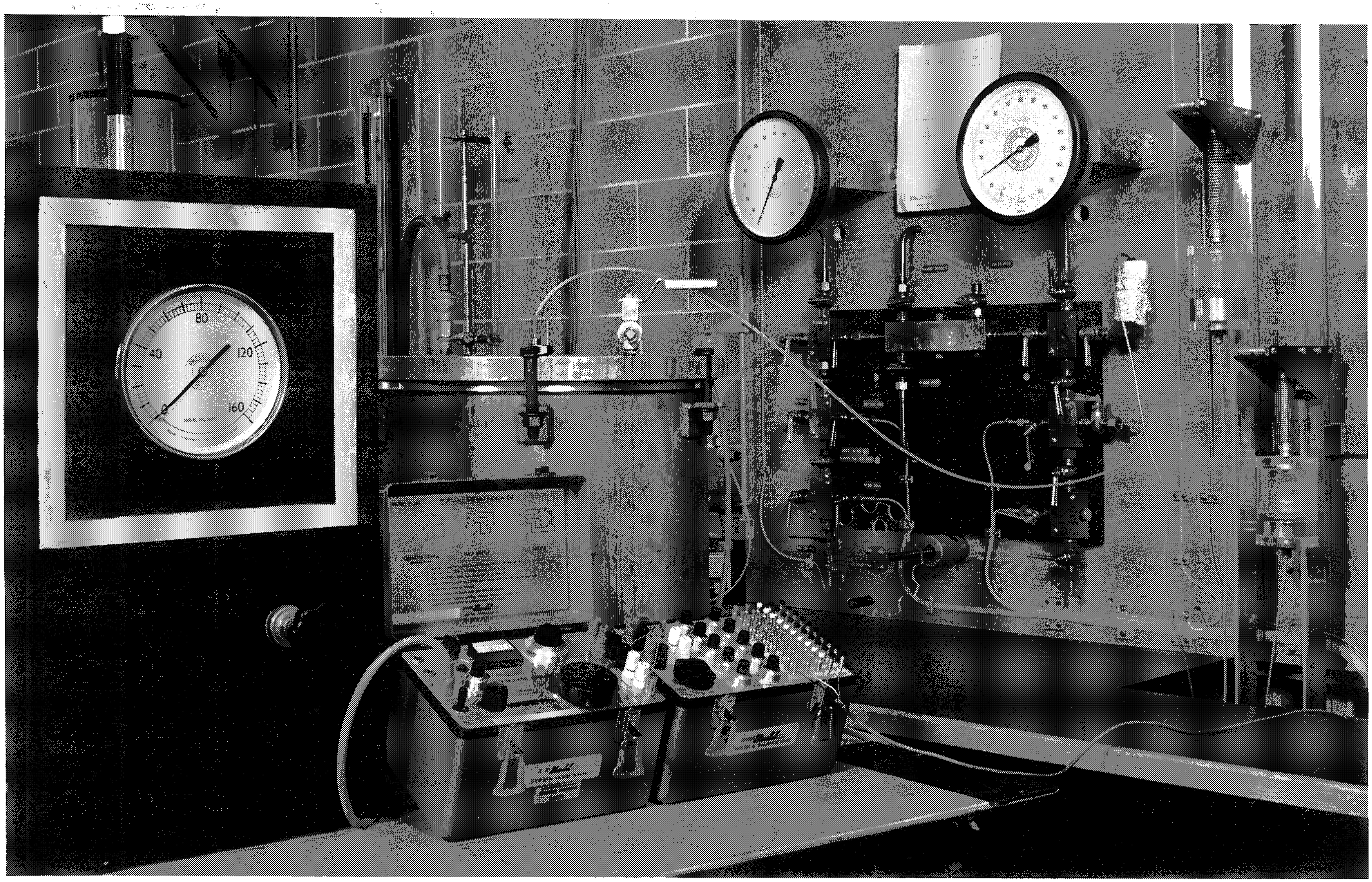
The pressure cell was embedded in dry sand in the center of the calibration chamber with 6" of sand covering the cell. The fine uniform Ottawa sand was placed in a loose state with a density approximating the field density for tailings embankments.

The fluid calibration curve (Figure 5.7) depicts linear characteristics. The sand calibration closely approximates the fluid curve; however, a close observation indicates that it is slightly concaved to the vertical pressure axis. Calibration readings were taken with gauge factors of 1.0, 1.95 and 2.185. The last gauge factor was selected at a convenient setting where the Dynisco transducer approximated 300 divisions per psi providing a quick reference for pressure increments.

5.2.2 Sensitivity

The sensitivities of the stress difference pressure cell, as developed during the research, in association with a P-350 strain gauge having a gauge factor of 1.0 are as follows:


DYNISCO TRANSDUCER
PT 25-30 No 48077
CALIBRATION CURVE
PRESSURE vs STRAIN
GAUGE FACTOR 2.185
PRESSURE (p.s.i)
OBSERVED STRAIN (DIVISIONS)
0
1000
2000
3000
4000
5000
6000
2
4
6
8
10
12
14
16
18
20



General Arrangement of Calibration Equipment

Fig. 5.6

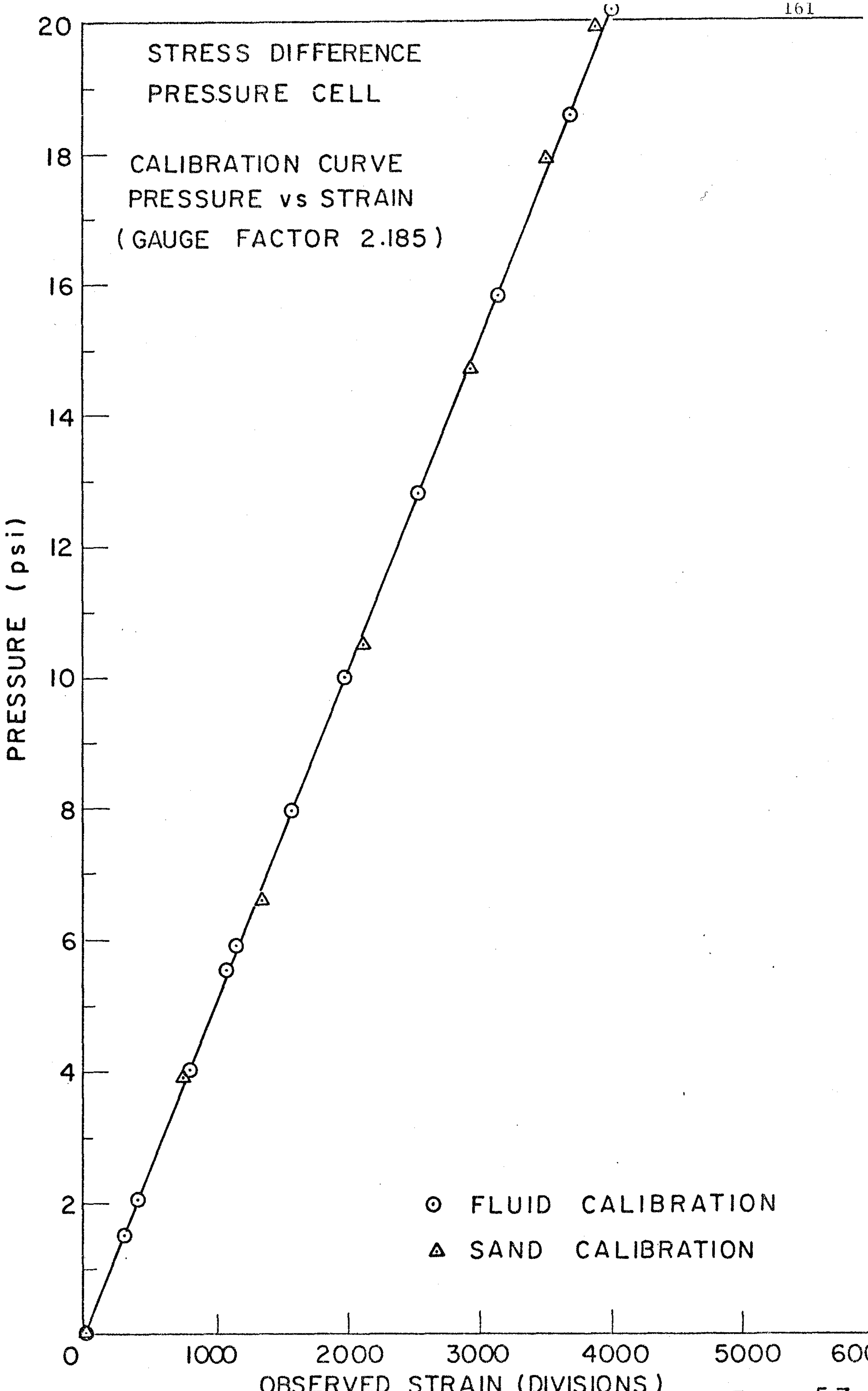

STRESS DIFFERENCE
PRESSURE CELL
CALIBRATION CURVE
PRESSURE vs STRAIN
(GAUGE FACTOR 2.185)
PRESSURE (psi)
OBSERVED STRAIN (DIVISIONS)
FLUID CALIBRATION
SAND CALIBRATION
0
2
4
6
8
10
12
14
16
18
20
1000
2000
3000
4000
5000

Figure 5.7

a) Readout sensitivity = $\frac{8425 \text{ Divs.}}{19.2 \text{ psi}}$ = 439 Divs./psi

b) Diaphragm deflection sensitivity

$$= \frac{.00193''}{19.8 \text{ psi}} \times \frac{1 \text{ psi}}{439 \text{ Divs.}} = 0.000,\ 000,\ 222''/\text{Div.}$$

(at the center of the diaphragm) which is believed to be one of the most sensitive earth cells at the present time.

5.2.3 Investigation of the Stress Difference Theory

An investigation of the stress difference pressure cell was made to confirm the theory of the stress difference instrument (σ - u).

A P-350 strain gauge was used as readout equipment for the test. The gauge factor setting was 2.185 providing a readout of 201 divisions per psi applied to the stress difference pressure cell.

The cell was embedded in dry sand with 8 inches of sand covering the cell and producing a readout of 98 divisions.

Therefore the calculated dry density was

$$\frac{98}{201} \times 144 \times \frac{12}{8} = 105 \text{ pcf.}$$

After determining the dry density, water was added slowly through a filter paper placed on top of the sand. The addition of water was continued until the sand was submerged and assumed to be saturated. The water level was then increased to approximately 1" above the top of the sand.

The following conditions were expected with the addition of water to the top of the dry sand:

a) The readout would gradually increase with the added weight of water until the buoyant force became effective.

b) The readout would then decrease to a final value which is proportional to the submerged density of the sand, and

c) The increase in water level above the top of the sand would not affect the readout because the water acts as a neutral stress on the stress difference pressure cell.

Observations

The observations were in accordance with the expected conditions listed above having a peak readout of 116 divisions and a final readout of 61.5 divisions. The increase in water level above the top of the sand did not change the readout.

Check Calculation

The volume of solids with a specific gravity of 2.65 is

$$\frac{105 \times 100}{2.65 \times 62.4} = 63.6\%$$

Therefore the submerged density = 105 - .636 x 62.4 = 65.3 pcf

$$\text{The final expected readout} = 98 \times \frac{65.3}{105} = 61 \text{ divisions.}$$

This test indicated that the instrument is performing satisfactorily as a stress difference pressure cell.

5.3 Porewater Pressure Cell

The porewater pressure cell utilizes a beam amplified diaphragm. A cantilever beam connected directly to the rigid rim of the diaphragm is fitted with four transducers in a full bridge circuit (Figures 5.8 and 5.9). Extreme sensitivity is not required for this application because the diaphragm is subject to fluid conditions which permit relatively large deflections without appreciable discrepancies in the observed strains. The porewater pressure cell and the psychrometric module are contained in a common housing with filters to exclude the granular material and permit pore pressure to activate the internal components.

5.3.1 Calibration

Before commencing the calibration of the pressure cell, the linear characteristics of the cantilever beam were investigated.

A small fluid calibration chamber was specifically designed to accommodate the porewater pressure cell. The pressures applied during the test were referred to a Dynisco transducer which had been calibrated against a mercury column prior to the calibration of the porewater pressure cell.

Calibration tests were made with gauge factors of 1.0 and 1.95. The cell characteristics were found to be linear as indicated in Figure 5.10.

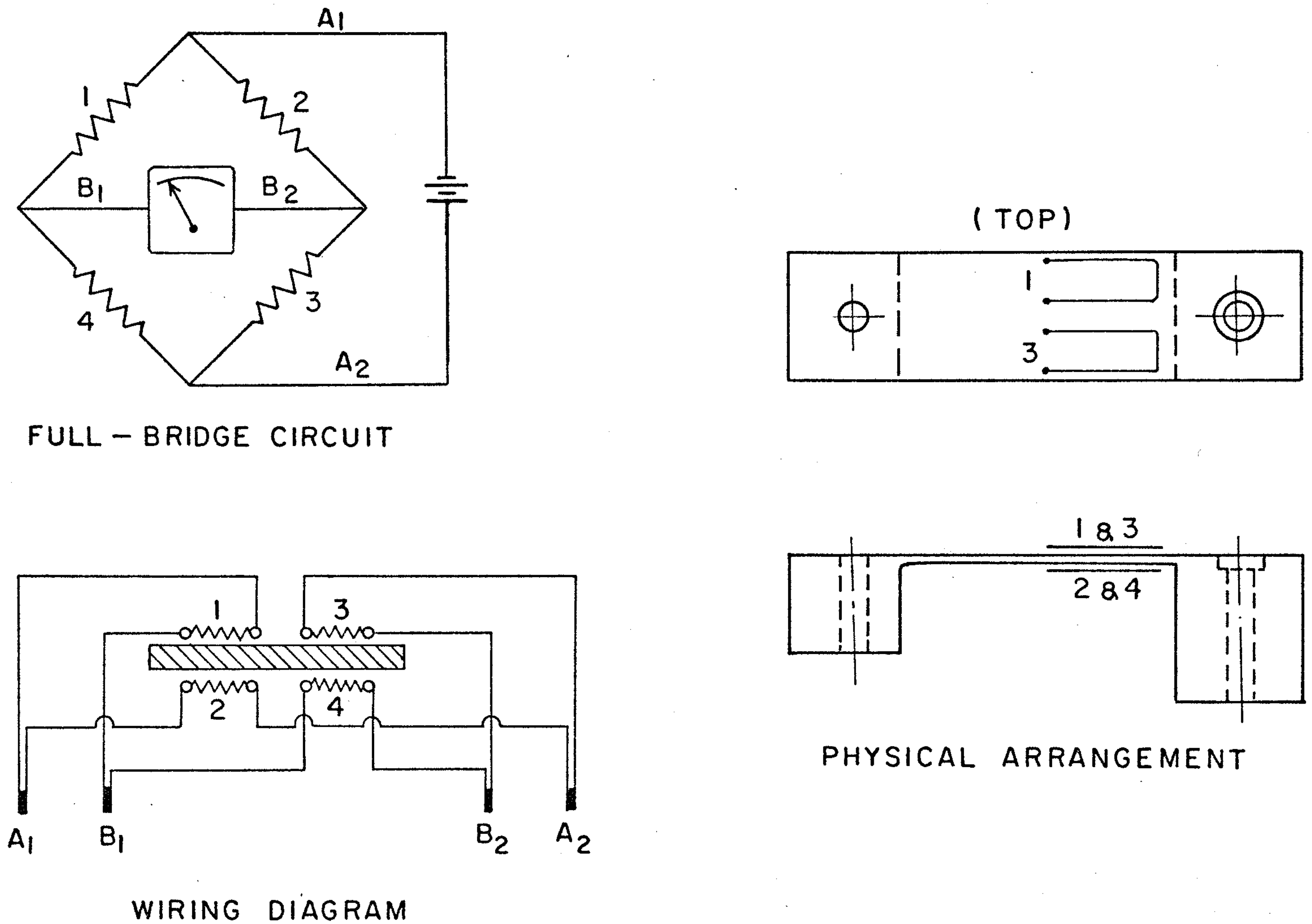
5.3.2 Sensitivity

The sensitivities of the porewater pressure cell, with a guage factor of 1.0 for the readout equipment, were found to be:

a) Readout sensitivity = 35.2 Divisions/psi, and

b) Diaphragm deflection sensitivity =

0.00, 007,7"/Division (at the center of the diaphragm).



CANTILEVER BEAM
STRAIN GAUGE DISPOSITION

Figure 5.8

Porewater Pressure Cell

Fig. 5.9

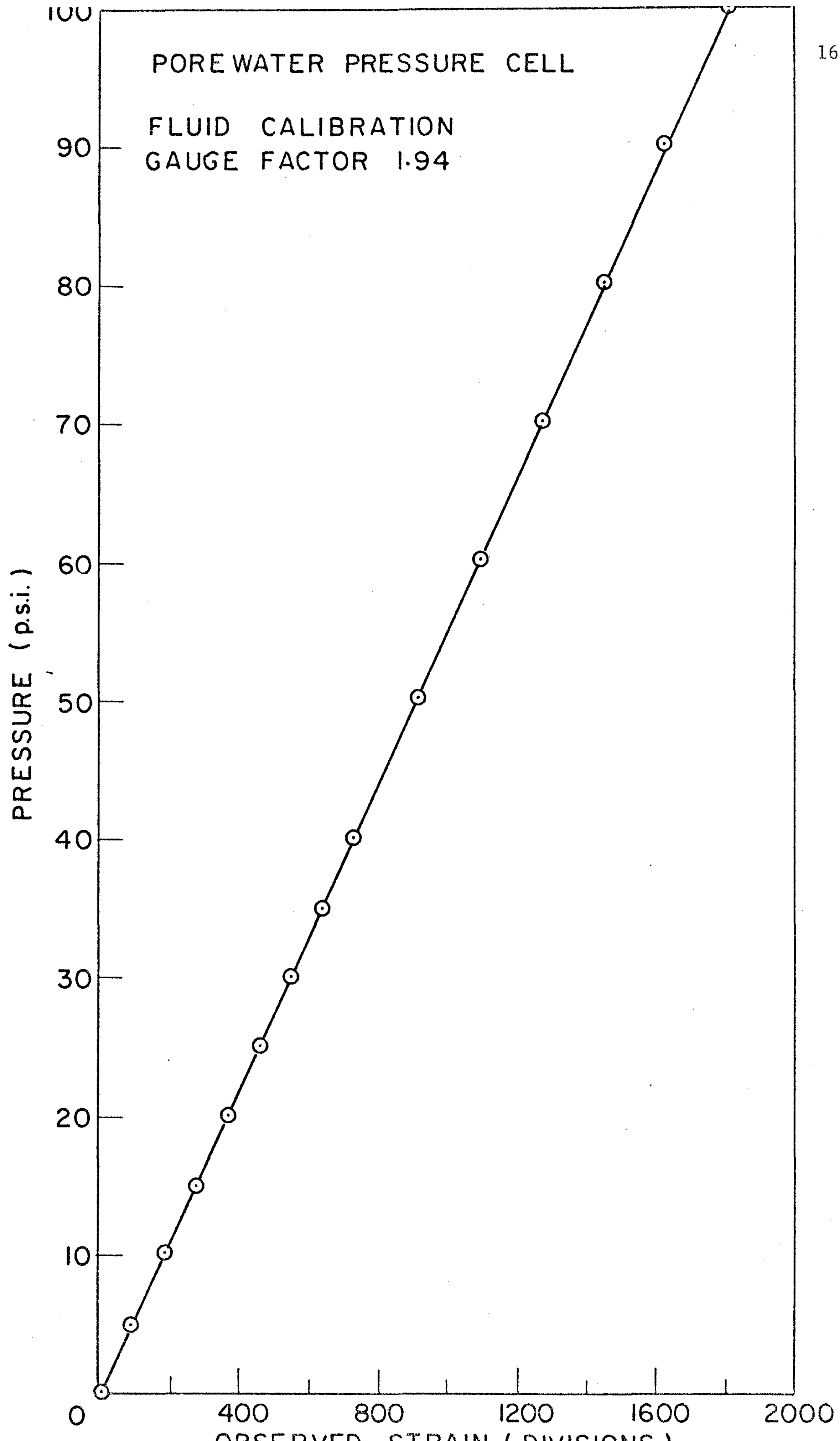

PORE WATER PRESSURE CELL
FLUID CALIBRATION
GAUGE FACTOR 1·94
PRESSURE (p.s.i.)
100
90
80
70
60
50
40
30
20
10
0
400
800
1200
1600
2000
OBSERVED STRAIN (DIVISIONS)

Figure 5.10

5.4 Psychrometric Module

The psychrometric module was designed to obtain in situ soil data to facilitate the determination of soil water suction in partially saturated soils. This unit is an expansion of the method used by Richards to evaluate suction in soil samples.

The module incorporates a wet bulb thermistor and a dry bulb thermistor connected in an electrical circuit (Figure 5.11) to measure the relative humidity of the soil atmosphere of partially saturated soils. (A thermistor is a semi-conductor with a relatively large change in resistance for a small change in temperature). After obtaining the relative humidity, the soil water suction can be determined from the thermodynamic relationship between the soil mosture suction and relative humidity of the soil atmosphere [40] expressed as:

$$h = \frac{RT}{gM} \log_e R.H.$$

where h = total suction in cm. water

R = $8.314 \times 10^7/^\circ C/\text{mol.}$

T = Absolute Temp., $^\circ C$

g = 981 cm./sec.^{2}

M = molecular weight of water = 18.02

R.H. = relative humidity

Because of the large suctions that can be developed in the water phase of partially saturated fine grained soils, Schofield has suggested a convenient scale to represent these large values in which $pF = \text{Log}_{10} h$

$$pF = 6.502 + \log_{10}(2 - \log_{10} R.H.) \text{ at } 20^\circ C.$$

Although the psychrometric principle has been used successfully to evaluate suctions in soil samples, difficulties have been experienced in attempts to obtain in situ readings. The chief problem has been to provide a simple effective means of saturating the wet bulb by remote control at long-term intervals. Once the unit is buried in the base of a dam, it is impractical to service or recover the instrument.

Thermistors have the advantages of being robust and sensitive. They also have linear calibration characteristics in the psychrometric module. The relationship between output voltage and soil water suction is a straight line.

Numerous methods were investigated for saturating the wet bulb thermistor by remote control, before developing the method shown in the prototype (Figures 5.12 and 5.13). This method incorporates a horizontal shaft with a vertical hole drilled through the polarized shaft. This portion of the shaft is submerged in a sealed reservoir of distilled water which fills the hole. A horizontal movement of the shaft along its longitudinal axis carries the slug of water out of the reservoir into the thermistor chamber. In this position, the wet bulb thermistor can be saturated by activating the interlocking solenoid and dipping the thermistor into the vertical slug of water. The shaft is then returned to its normal position within the reservoir. A four component seal prevents leakage from the reservoir. The operation requires less than one second to saturate the surface of the thermistor.

The prototype was encased in a plastic housing to permit visual observation of the mechanism for saturating the wet bulb thermistor.

A minor modification is desirable, for a commercial prototype, which entails the replacement of the solenoids with small hydraulic cylinders having a 3/8" stroke. This modification eliminates the residual temperature generated during the short period of the operation of the solenoid.

5.5 Effective Stress

The effective stress $[\sigma' = (\sigma - u_a) + \chi(u_a - u_w)]$ is determined from a direct reading of the stress difference $(\sigma - u_a)$ plus the effective soil suction $[\chi(u_a - u_w)]$.

The soil water suction $(u_a - u_w)$ is determined by the psychrometric module.

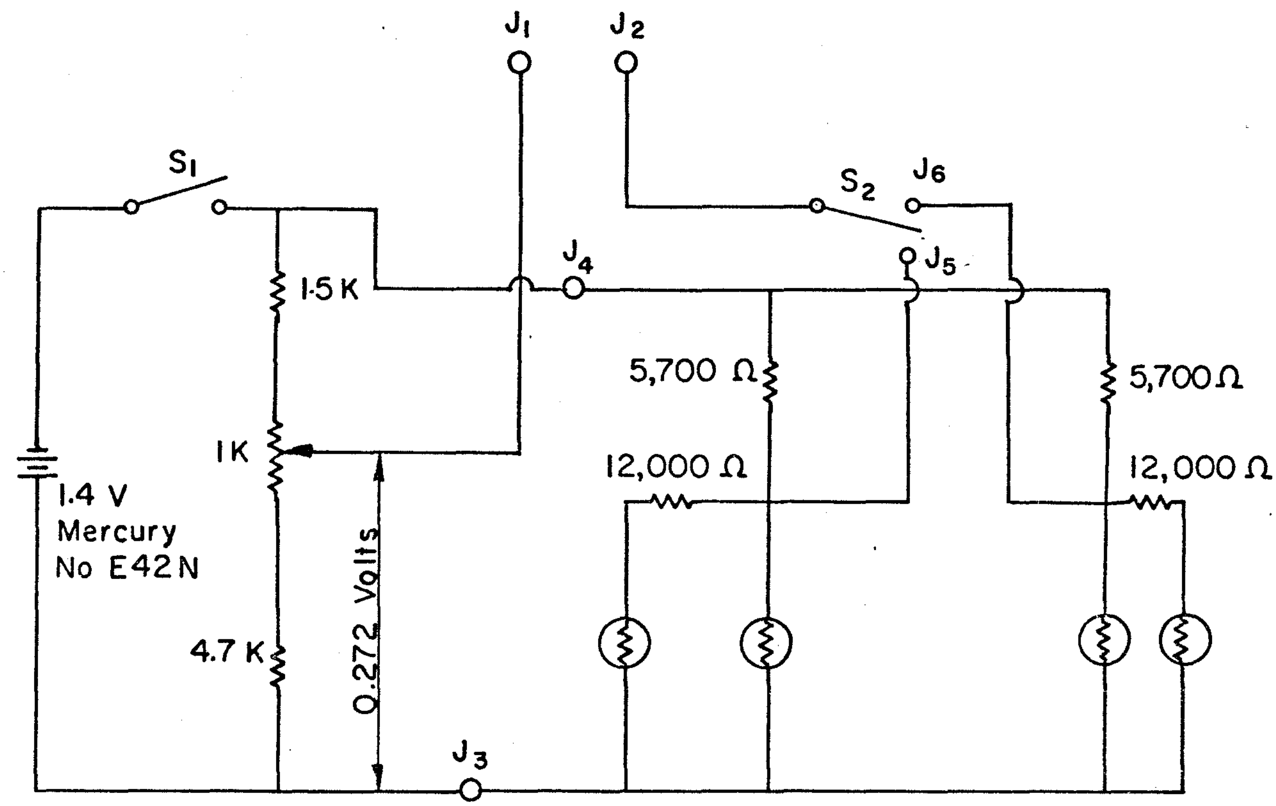
The parameter χ, $(\chi = .22 + .78Sr)$, for cycloned tailings material is closely approximated by supplementing the data obtained from the instruments with the moisture content from a conventional soil sample. The moisture content and total density will determine the saturation ratio (Sr). χ can then be evaluated as a function of the saturation ratio for the special case of hydrocycloned tailings.

5.6 Conclusions of Instrumentation

Instrumentation has been developed which is capable of measuring in situ data for stress difference, overburden pressure, porewater pressure, poreair pressure and negative porewater pressure.

This information facilitates the evaluation of effective soil suction in tailings dams; a parameter which is used in the stability analysis for the embankment.

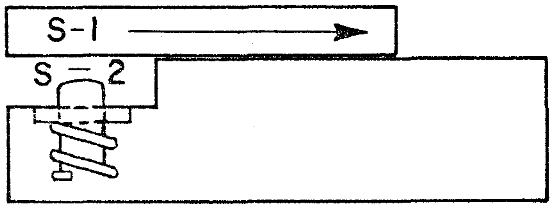
The use of such instrumentation combined with the morphology and dam design as outlined in this context, is expected to produce details for a safe and economical structure.



NOTE:
SOLENOID CIRCUIT NOT SHOWN

PSYCHROMETRIC MODEL
SCHEMATIC WIRING DIAGRAM

Figure 5.11



PSYCHROMETRIC MODULE

(FOR EARTH DAM INSTRUMENTATION)

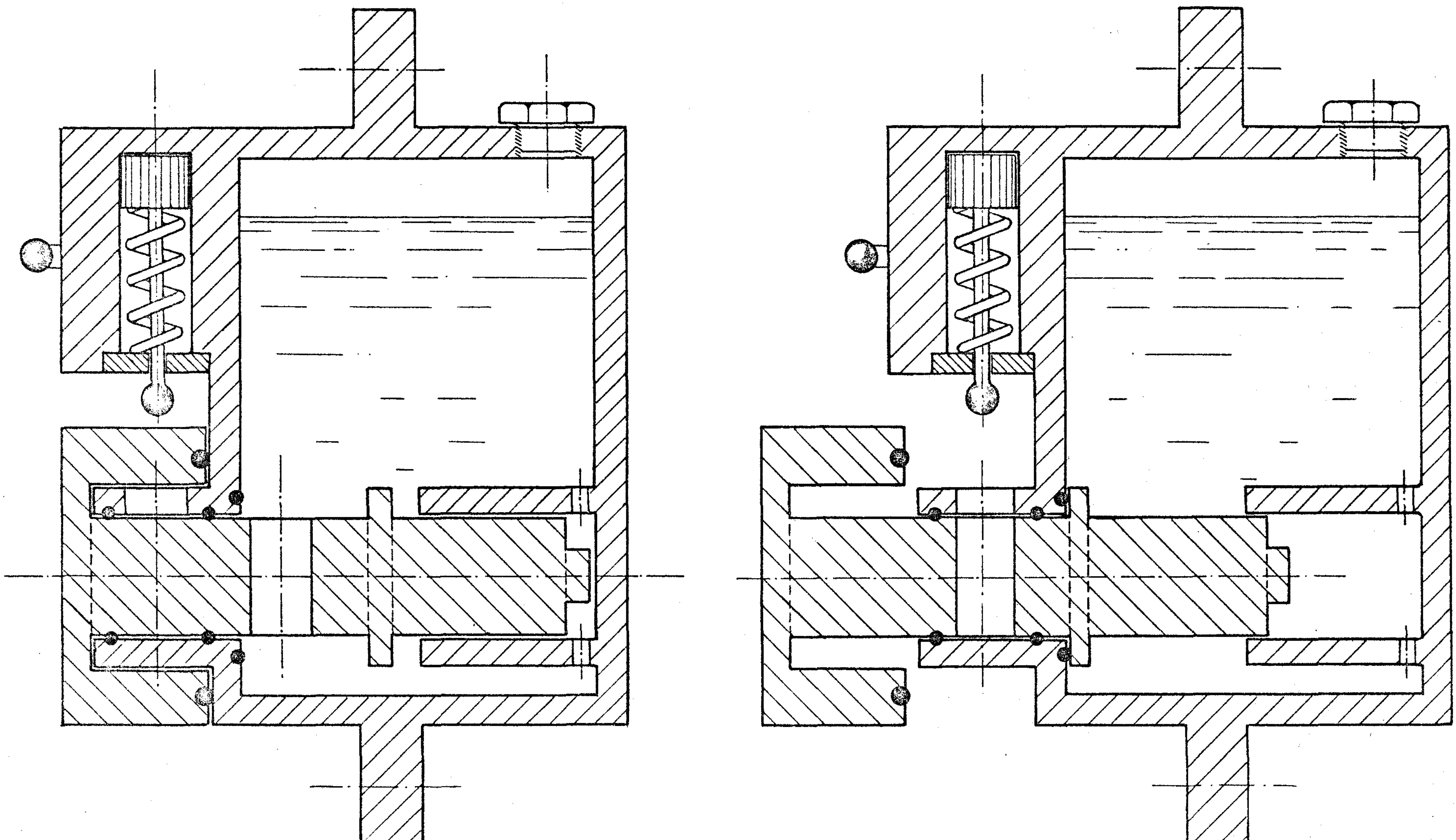
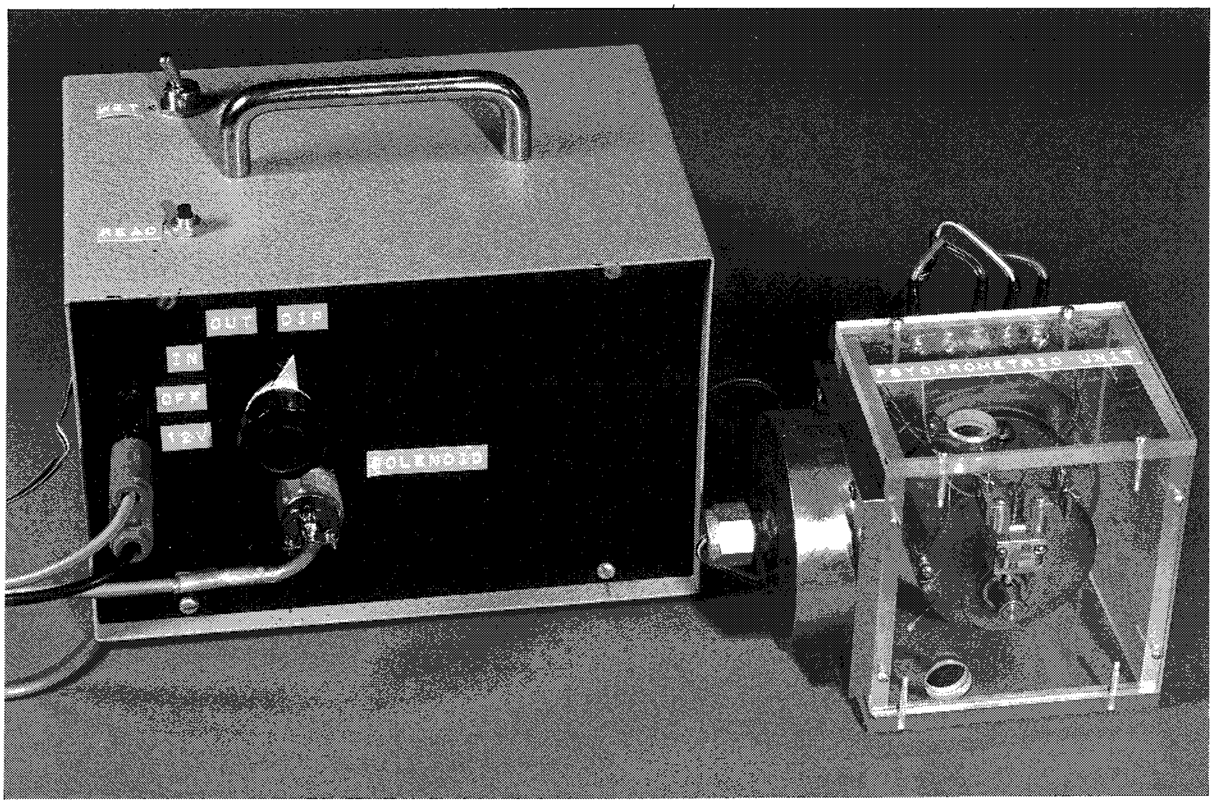
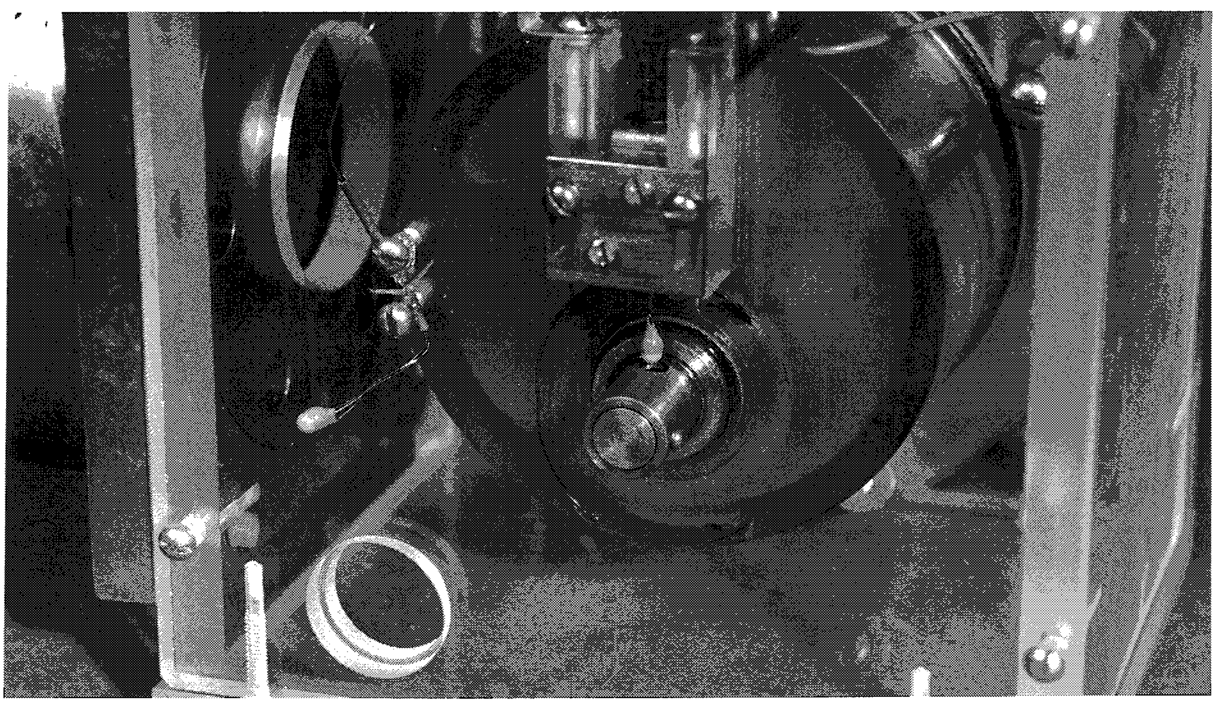


Figure 5.12

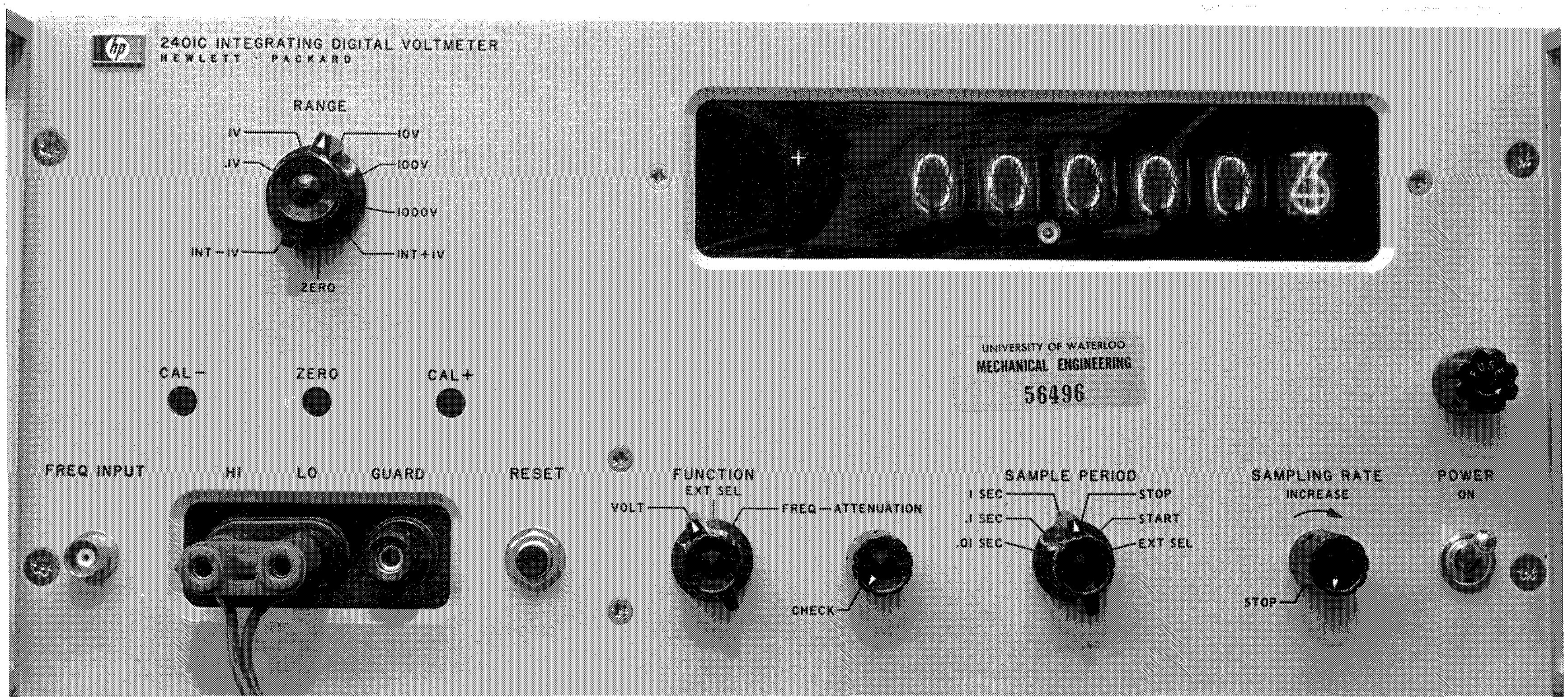


Psychrometric Module and Porewater Pressure Cell



Close-up of Wet Bulb Thermistor

Fig. 5.13



Digital Voltmeter

Fig. 5.14

CHAPTER 6

SUMMARY OF MAJOR CONCLUSIONS

The macrocosm of mine tailings disposal in this thesis, relates to a broad scale investigation of the disposal systems with particular emphasis on long-term planning and on tailings dams. The major conclusions of this research are summarized below:

6.1 History

The history of mining indicates numerous failures of tailings dams and pollution of watercourses from tailings disposal. Many mining operations stress the economic factors which tend to minimize the immediate costs of tailings disposal and give only secondary consideration to the safety aspects for the ultimate operating conditions or to the effects on other natural resources.

6.2 Planning

During the initial stage of a mine development the production facilities are the principal concern and in general a lack of systematic or long-term planning has been given to the tailings disposal system. This situation has created very undesirable effects on the local environment and on the long-term costs associated with tailings disposal.

The morphology as presented in this thesis provides an effective approach to the problem of planning and design. A systematic long-term procedure similar to that shown in Section 2.4.2 should be used for all mine tailings disposal systems to safeguard the environment and maximize the benefits to be gained from the natural resources.

6.3 Economic Benefits of Tailings Material

In most instances economic benefits are derived by using tailings as a principal material for the construction of tailings dams as compared with the use of natural soils.

6.4 Safety

The author's analysis shows that failures of tailings dams are common and the consequences of failure may be more serious than the failure of water dams. There is an urgent need to rectify this situation in order to eliminate the safety and pollution hazards. Section 4.7.4 outlines recommended factors of safety for various conditions relating to tailings dams.

Regulations are relatively easy to apply to new structures, but there are situations existing which involve enormous volumes of tailings accumulated over many years where it would be difficult to apply rigid regulations. In some cases the factors of safety are grossly inadequate to meet desirable engineering requirements and the costs involved to correct these situations are prohibitive to the mining companies. It may require years to achieve a mutually acceptable economic solution to problems which originated in the past.

With regard to future tailings dams, it is possible to use tailings material and provide an adequate factor of safety for the embankment. The following items warrant consideration during the design stage;

(assuming competent foundations).

a) The upstream slope of a tailings dam, which is operated as a normal tailings dam, does not present a serious stability problem and a saving in cost is achieved with a steep embankment slope.

b) If a tailings embankment is likely to become saturated as a result of a poor upstream seal, a very flat downstream slope should be provided. A 70 ft. tailings embankment which is saturated requires a downstream slope approximating 6:1 to provide an adequate factor of safety.

c) If a competent upstream seal is incorporated, the downstream slope can be increased to 2:1.

d) If a competent upstream seal and rain seal are provided, and the effective soil suction for the sealed structure exceeds 1 psi, a downstream slope approximating 1.4:1 provides a satisfactory factor of safety. Relatively large soil water suctions are known to exist in tailings materials, but the degree of effective soil suction in sealed tailings dams must be confirmed with long-term in situ observations.

e) In all mining districts which are subject to frequent or intensive seismic activity, the material in tailings dams should be compacted. This recommendation is of particular importance in instances where the embankment is likely to contain saturated zones making it susceptible to liquefaction. In addition to the high density, the qualitative factors listed in Section 4.7.4.5 should be considered.

6.5 Advantages of Hydrocycloned Tailings Dams

A hydrocycloned tailings dam has a number of structural advantages over the commonly used spigotted tailings dams. Some of the more significant ones are given below:

a) it is convenient to use the superior method of downstream stage construction

b) the starter dam can be easily located in the ideal location within the future structure

c) this construction method affords an opportunity to provide a competent upstream seal

d) the dam can be designed to provide an unsaturated structure with relatively consistent internal conditions

e) construction of the decant system is simplified, and

f) the construction cost for a valley application is significantly less.

6.6 Decant System

The recommendations for decant towers and tunnels provide a guideline for minimizing the problems with decant systems.

6.7 Instrumentation

Instrumentation developed during the course of the research facilitates the determination of effective soil suction in hydrocycloned tailings dams. It behooves the engineer to use this parameter in the design of tailings dams, however, long-term in situ readings are required to confirm the applicable values for various operating conditions.

These instruments are also capable of measuring in situ data for other granular materials.

6.8 Future Trends

Concomitant with the application of more stringent government regulations it is predicted that the percentage of future spigotted tailings dams will be reduced appreciably and that this type of dam will be replaced with a dam design incorporating a specific seal with more consistent porewater conditions.

6.9 Suggested Areas for Continuing Research

The objectives of the research, as outlined in Section 1.6, have been fulfilled and it is hoped that the findings as presented will form a basis for future research associated with tailings disposal not included in the present study. Items of particular interest are:

1. in situ readings of negative porewater pressure in sealed tailings dams
2. further testing of hydrocyclones on tailings material with facilities for greater variation in the operating parameters
3. there is an urgent need for a technical evaluation of existing tailings dams leading to a policy for upgrading the safety of these dams, and
4. research to develop commercial uses for the enormous volumes of waste tailings material.

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APPENDIX

Appendix A

Appendix B

Mine Tailings Material

Grain Size Analysis for Various Mining Operations

Percent Passing

	Type of Operation	Tyler Mesh Sieve Size 35	48	65	100	150	200	325
1.	Copper			95	81	67	54	42
2.	Copper						99	89
3.	Copper		98.0	90.4	76.8	65.8	56.6	
4.	Gold	99.9	99.3	93.7	85.5	75.3	67.1	
5.	Nickel	99.6	97.0	89.2	74.7	63.2	51.6	
6.	Nickel		94.1	77.4	67.2	56.4	47.9	
7.	Uranium		98.4	93.3	81.3	69.3	58.1	
8.	Uranium		99.0	94.4	80.4	65.5	52.7	

Table A-1

HYDROCYCLONE FIELD TESTS
FOR MINE TAILINGS MATERIAL

DATE June 9, 1970

Test No. 11

	AUTO S	LCUF	CCUF	RCUF	OVERFLOW COMBINED
1 Sample No.	T-11-1	T-11-2	T-11-3	T-11-4	T-11-5
2 Time	2:00	1:55	1:55	1:55	2:05
3 Line Press.		28	28	28	
4 Cyclone Press.		33	33	33	
5 O.F. Press.		9	9	9	
6 Diam. Spigot		1"b	1"b	1½"b	
7 Diam. Vortex Fdr.		4"WR	4"WR	4"WR	
8 Lgth. Vortex Fdr.		8"+1	8"+1	8"+1	
9 Sp.Gr. Slurry	1.300	1.878	2.005	2.03	1.215
10 Pump Power	48	48	48	48	48
11 Pump R.P.M.	750	750	750	750	750
Grain Size Analysis					
Mesh	GRAMS				
+48	2.0	8.0	3.6	4.1	0.4
+65	9.6	31.1	22.6	21.7	1.8
+100	27.9	62.6	62.8	62.85	11.0
+150	29.6	36.2	42.15	42.9	22.4
+200	25.8	24.4	26.6	26.0	25.4
sub-total	94.9	162.3	157.75	157.55	61.0
	47.3%	80.7%	78.7%	78.3%	30.4%
-200 Pan	13.8	8.6	11.4	8.7	14.5
-200 Wash	91.6	29.5	31.2	34.3	124.8
-200 Filter	0.4	0.7	0.2	0.7	0.3
sub-total	105.8	38.8	42.8	43.7	139.6
	52.7%	19.3%	21.3%	21.7%	69.6%
TOTAL	200.7	201.1	200.55	201.25	200.6
	100%	100%	100%	100%	100%

Notes

1) Plant Production 3115 T/D
2) Good rope all cyclones
3) Slope LCUF 9":24 = β = 20.5°
   8":24 = β = 18.4°
4) Shutdown for pump speed reduction
5) Volume; Drum = 45 gal., one third full = 15 gals.

			IGPM
Time	(LCUF = 32 secs.	=	28.1
	(CCUF = 33 secs.	=	27.3
	(RCUF = 19 secs.	=	47.3
			102.7 IGPM

Legend

AUTO S Automatic Sampler in Concentrator
LCUF Left Cyclone Underflow
CCUF Center Cyclone Underflow
RCUF Right Cyclone Underflow

HYDROCYCLONE FIELD TESTS FOR MINE TAILINGS MATERIAL

DATE June 11, 1970

Test No. 14

	AUTO S	LCUF	CCUF	RCUF	OVERFLOW COMBINED
1 Sample No.	T-14-1	T-14-2			T-14-5
2 Time	11:10	11:00			11:05
3 Line Press.		28			
4 Cyclone Press.		50			
5 O.F. Press		8			
6 Diam. Spigot		3/4"b			
7 Diam. Vortex Fdr.		4"WR			
8 Lgth. Vortex Fdr.		8"+1			
9 Sp.Gr.Slurry	1.780	1.981			1.504
10 Pump Power	35	35			35
11 Pump R.P.M.	700	700			700
Grain Size Analysis					
Mesh	GRAMS				
+48	4.2	16.3			2.9
+65	12.1	27.5			11.1
+100	28.1	42.0			27.6
+150	27.3	31.45			26.7
+200	23.8	24.4			24.0
sub-total	95.5	141.65			92.3
	47.6%	70.6%			45.9%
-200 Pan	12.2	10.6			22.4
-200 Wash	92.2	47.6			85.5
-200 Filter	0.5	0.9			1.0
sub-total	104.9	59.1			108.9
	52.5%	29.4%			54.1%
TOTAL	200.4	200.75			201.2
	100%	100%			100%

Notes

1) Plant Production 3129 T/D
2) Overflow pressure gauge may be plugged
3) No dilution
4) Sump full
5) Difficulty obtaining rope underflow with overloaded cyclone
6) Volume 30 gals./1 min. 9 secs. = 26.1 IGPM

Legend

AUTO S Automatic Sampler in Concentrator
LCUF Left Cyclone Underflow
CCUF Center Cyclone Underflow
RCUF Right Cyclone Underflow

SLOPE STABILITY ANALYSIS
SIMPLIFIED BISHOP METHOD

***** SABILITY ANALYSIS OF TAILINGS DAM (TEST)

POINT DATA--USE 100 POINTS MAXIMUM

POINT NO.	X-COORD	Y-COORD
1	10.00	50.00
2	300.00	50.00
3	398.00	120.00
4	418.00	120.00
5	425.00	50.00
6	429.00	112.00
7	700.00	112.00
8	439.00	105.00
9	700.00	106.00
10	516.00	50.00
11	700.00	50.00

LINE DATA---USE 100 LINES MAXIMUM

	POINT	POINT	SOIL
1	1	2	1
2	2	3	2
3	3	4	2
4	4	6	2
5	6	7	4
6	2	5	1
7	5	6	3
8	6	8	3
9	8	9	5
10	8	10	3
11	5	10	1
12	10	11	1

SAMPLE OF COMPUTER OUTPUT

Notes (Stability Analysis)
1) Tailings cohesion = zero
2) Consider 1 p.s.i. effective soil suction.
Then the apparent cohesion from suction
$= p' \tan \phi' = 1 \times 144 \times \tan 35\frac{1}{2}^{\circ} = 103$ p.c.f.

SOIL PROPERTIES:

SOIL NO.	DENSITY PCF	COH. PSF	PHI DEG	PP RATIO	PP RATIO CAPLRY
1	130.	0.0	37.00000	1.1	0.0
2	95.	103.0	35.50000	1.1	0.0
3	110.	0.0	35.50000	1.1	0.0
4	62.	5.0	0.00000	1.1	0.0
5	110.	200.0	20.00000	1.1	0.0

PHREATIC SURFACE POINTS--USE 10 POINTS MAXIMUM

	X-COORD	Y-COORD
1	10.000	50.000
2	425.000	50.000
3	429.000	112.000
4	700.000	112.000

THE FOLLOWING IS A PRINTOUT OF THE LINE ARRAY. THE INITIAL 5 LINES MUST BE THE SURFACE OF THE SLOPE GOING FROM LEFT TO RIGHT. THERE MUST BE NO VERTICAL LINES AFTER NO. 5 .

NO.	X-LEFT	Y-LEFT	X-RGHT	Y-RGHT	SLOPE	SOIL
1	10.00	50.00	300.00	50.00	0.0000	1
2	300.00	50.00	398.00	120.00	0.7143	2
3	398.00	120.00	418.00	120.00	0.0000	2
4	418.00	120.00	429.00	112.00	-0.7273	2

5	429.00	112.00	700.00	112.00	0.0000	2
6	300.00	50.00	425.00	50.00	0.0000	1
7	425.00	50.00	429.00	112.00	15.5000	3
8	429.00	112.00	439.00	105.00	-0.7000	3
9	439.00	105.00	700.00	106.00	0.0038	5
10	439.00	105.00	516.00	50.00	-0.7143	3
11	425.00	50.00	516.00	50.00	0.0000	1
12	516.00	50.00	700.00	50.00	0.0000	1

NUMBER OF SLICES--100 OR LESS

100.

THE LOWEST ELEVATION THAT SHOULD OCCUR ALONG
ANY TRIAL FAILURE SURFACE (YMIN.)
50.00

THE MINIMUM VALUE FOR THE GREATEST
DEPTH OF THE SLIDING MASS (DMIN).
0.00

1 COMPUTE USING AUTOMATIC SEARCH ROUTINE
2 COMPUTE USING PRESCRIBED CONTROL GRID

1

1 PRINT ALL TRIAL CIRCLE DETAILS
2 PRINT LOWEST FS AND X Y R FOR EACH CENTER

1

X AND Y COORDINATES OF THE CENTER OF
THE INITIAL TRIAL FAILURE SURFACE.

X = 300.00 Y = 200.00

INCREMENTS OF X AND Y USED IN THE COARSE GRID
IN SEARCHING FOR THE MINIMUM FACTOR OF SAFETY.
THE FINAL GRID IS 4 TIMES FINER.

X = 10.000 Y = 10.000

X-COORD	Y-COORD	RADIUS	NO.SLICES	F.S
300.00	200.00	150.00	18	1.511
300.00	200.00	149.77	17	1.524
300.00	200.00	147.45	17	1.503
300.00	200.00	145.13	16	1.475
300.00	200.00	142.81	16	1.453
300.00	200.00	140.49	14	1.435
300.00	200.00	138.17	14	1.416
300.00	200.00	135.85	12	1.411
300.00	200.00	133.53	12	1.403
300.00	200.00	131.22	10	1.435
300.00	200.00	135.27	12	1.407
300.00	200.00	134.69	12	1.404
300.00	200.00	134.11	12	1.403
300.00	200.00	132.96	11	1.405
300.00	200.00	132.38	11	1.410
300.00	200.00	131.80	10	1.433
300.00	200.00	128.90	9	1.478
300.00	200.00	126.58	8	1.667

300.00	200.00	124.26	6	2.280

THE LOWEST SAFETY FACTOR FOUND WAS 1.403 AT R= 134.11 .

310.00	200.00	150.00	19	1.672
310.00	200.00	149.72	19	1.666
310.00	200.00	146.92	18	1.646
310.00	200.00	144.12	17	1.604
310.00	200.00	141.32	16	1.580
310.00	200.00	138.51	15	1.536
310.00	200.00	135.71	15	1.504
310.00	200.00	132.91	13	1.484
310.00	200.00	130.11	12	1.462
310.00	200.00	127.31	10	1.459
310.00	200.00	124.51	10	1.478
310.00	200.00	129.41	11	1.475
310.00	200.00	128.71	11	1.468
310.00	200.00	128.01	11	1.462
310.00	200.00	126.61	10	1.458
310.00	200.00	125.91	10	1.460
310.00	200.00	125.21	10	1.466
310.00	200.00	121.71	8	1.577
310.00	200.00	118.90	5	2.035

THE LOWEST SAFETY FACTOR FOUND WAS 1.458 AT R= 126.61 .

290.00	200.00	150.00	16	1.410
290.00	200.00	149.82	16	1.408
290.00	200.00	147.98	16	1.398
290.00	200.00	146.14	16	1.385
290.00	200.00	144.31	14	1.380
290.00	200.00	142.47	14	1.367
290.00	200.00	140.63	13	1.366
290.00	200.00	138.80	12	1.383
290.00	200.00	142.01	13	1.366
290.00	200.00	141.55	13	1.365
290.00	200.00	141.09	13	1.365
290.00	200.00	140.17	13	1.368
290.00	200.00	139.72	12	1.384
290.00	200.00	139.26	12	1.383
290.00	200.00	136.96	11	1.398
290.00	200.00	135.12	10	1.454
290.00	200.00	133.29	9	1.557
290.00	200.00	131.45	7	1.782
290.00	200.00	129.61	5	2.489

THE LOWEST SAFETY FACTOR FOUND WAS 1.365 AT R= 141.09 .

280.00	200.00	150.00	15	1.341
280.00	200.00	149.86	15	1.340
280.00	200.00	148.51	15	1.339
280.00	200.00	147.16	13	1.348
280.00	200.00	149.53	15	1.340
280.00	200.00	149.19	15	1.339
280.00	200.00	148.85	15	1.339
280.00	200.00	148.17	14	1.352
280.00	200.00	147.83	14	1.351
280.00	200.00	147.49	13	1.349
280.00	200.00	145.80	13	1.349
280.00	200.00	144.45	13	1.359
280.00	200.00	143.09	12	1.385
280.00	200.00	141.74	11	1.422
280.00	200.00	140.39	10	1.474

280.00	200.00	139.03	9	1.560
280.00	200.00	137.68	8	1.723
280.00	200.00	136.32	6	2.026
280.00	200.00	134.97	4	2.990

THE LOWEST SAFETY FACTOR FOUND WAS 1.339 AT R= 148.85 .

270.00	200.00	150.00	13	1.362
270.00	200.00	149.91	13	1.363
270.00	200.00	149.04	12	1.377
270.00	200.00	148.17	12	1.399
270.00	200.00	147.30	11	1.428
270.00	200.00	146.43	10	1.459
270.00	200.00	145.55	10	1.511
270.00	200.00	144.68	9	1.572
270.00	200.00	143.81	8	1.665
270.00	200.00	142.94	8	1.837
270.00	200.00	142.07	6	2.047
270.00	200.00	141.20	5	2.525
270.00	200.00	140.32	4	4.136

THE LOWEST SAFETY FACTOR FOUND WAS 1.362 AT R= 150.00 .

280.00	210.00	160.00	16	1.365
280.00	210.00	159.85	16	1.364
280.00	210.00	158.34	15	1.362
280.00	210.00	156.83	14	1.353
280.00	210.00	155.32	14	1.350
280.00	210.00	153.81	12	1.369
280.00	210.00	156.45	14	1.351
280.00	210.00	156.08	14	1.351
280.00	210.00	155.70	14	1.350
280.00	210.00	154.95	14	1.351
280.00	210.00	154.57	14	1.352
280.00	210.00	154.19	14	1.354
280.00	210.00	152.31	12	1.372
280.00	210.00	150.80	11	1.390
280.00	210.00	149.29	11	1.437
280.00	210.00	147.78	9	1.513
280.00	210.00	146.27	9	1.656
280.00	210.00	144.76	7	1.932
280.00	210.00	143.25	5	2.818

THE LOWEST SAFETY FACTOR FOUND WAS 1.350 AT R= 155.70 .

280.00	190.00	140.00	14	1.337
280.00	190.00	139.88	14	1.337
280.00	190.00	138.68	14	1.341
280.00	190.00	137.48	13	1.353
280.00	190.00	136.28	12	1.372
280.00	190.00	135.08	12	1.387
280.00	190.00	133.88	11	1.420
280.00	190.00	132.68	10	1.459
280.00	190.00	131.48	9	1.525
280.00	190.00	130.28	8	1.619
280.00	190.00	129.08	7	1.809
280.00	190.00	127.88	6	2.145
280.00	190.00	126.68	4	3.218

THE LOWEST SAFETY FACTOR FOUND WAS 1.337 AT R= 140.00 .

280.00	180.00	130.00	13	1.355
280.00	180.00	129.90	13	1.355

280.00	180.00	128.85	13	1.365
280.00	180.00	127.81	11	1.386
280.00	180.00	126.76	11	1.398
280.00	180.00	125.72	11	1.424
280.00	180.00	124.67	9	1.464
280.00	180.00	123.63	9	1.509
280.00	180.00	122.58	9	1.594
280.00	180.00	121.54	7	1.697
280.00	180.00	120.49	7	1.919
280.00	180.00	119.45	5	2.296
280.00	180.00	118.40	3	3.531

THE LOWEST SAFETY FACTOR FOUND WAS 1.355 AT R= 130.00 .

290.00	190.00	140.00	15	1.382
290.00	190.00	139.83	15	1.380
290.00	190.00	138.15	15	1.372
290.00	190.00	136.47	15	1.360
290.00	190.00	134.79	14	1.355
290.00	190.00	133.10	13	1.363
290.00	190.00	136.05	14	1.358
290.00	190.00	135.63	14	1.356
290.00	190.00	135.21	14	1.355
290.00	190.00	134.37	13	1.370
290.00	190.00	133.94	13	1.367
290.00	190.00	133.52	13	1.365
290.00	190.00	131.42	12	1.363
290.00	190.00	129.74	12	1.383
290.00	190.00	128.06	10	1.428
290.00	190.00	126.38	10	1.486
290.00	190.00	124.69	8	1.600
290.00	190.00	123.01	6	1.848
290.00	190.00	121.33	4	2.625

THE LOWEST SAFETY FACTOR FOUND WAS 1.355 AT R= 134.79 .

270.00	190.00	140.00	11	1.404
270.00	190.00	139.93	11	1.406
270.00	190.00	139.21	11	1.432
270.00	190.00	138.49	10	1.457
270.00	190.00	137.78	10	1.489
270.00	190.00	137.06	9	1.538
270.00	190.00	136.34	9	1.613
270.00	190.00	135.63	8	1.672
270.00	190.00	134.91	7	1.797
270.00	190.00	134.19	6	1.957
270.00	190.00	133.47	6	2.257
270.00	190.00	132.76	4	2.836
270.00	190.00	132.04	3	4.691

THE LOWEST SAFETY FACTOR FOUND WAS 1.404 AT R= 140.00 .

282.50	190.00	140.00	14	1.349
282.50	190.00	139.87	14	1.348
282.50	190.00	138.55	14	1.342
282.50	190.00	137.23	13	1.344
282.50	190.00	139.54	14	1.346
282.50	190.00	139.21	14	1.344
282.50	190.00	138.88	14	1.343
282.50	190.00	138.22	14	1.342
282.50	190.00	137.89	14	1.342
282.50	190.00	137.56	14	1.342
282.50	190.00	135.91	13	1.354

282.50	190.00	134.59	12	1.380
282.50	190.00	133.27	11	1.396
282.50	190.00	131.95	11	1.435
282.50	190.00	130.63	9	1.488
282.50	190.00	129.31	9	1.584
282.50	190.00	127.99	7	1.729
282.50	190.00	126.67	6	2.046
282.50	190.00	125.35	5	3.197

THE LOWEST SAFETY FACTOR FOUND WAS 1.342 AT R= 138.22 .

277.50	190.00	140.00	14	1.341
277.50	190.00	139.89	14	1.342
277.50	190.00	138.81	13	1.360
277.50	190.00	137.73	12	1.367
277.50	190.00	136.66	12	1.383
277.50	190.00	135.58	12	1.415
277.50	190.00	134.50	10	1.443
277.50	190.00	133.42	10	1.496
277.50	190.00	132.34	8	1.564
277.50	190.00	131.26	8	1.681
277.50	190.00	130.18	6	1.865
277.50	190.00	129.10	6	2.304
277.50	190.00	128.02	4	3.503

THE LOWEST SAFETY FACTOR FOUND WAS 1.341 AT R= 140.00 .

280.00	192.50	142.50	14	1.340
280.00	192.50	142.38	14	1.340
280.00	192.50	141.14	14	1.339
280.00	192.50	139.90	13	1.345
280.00	192.50	142.07	14	1.339
280.00	192.50	141.76	14	1.338
280.00	192.50	141.45	14	1.338
280.00	192.50	140.83	14	1.340
280.00	192.50	140.52	14	1.341
280.00	192.50	140.21	14	1.343
280.00	192.50	138.66	13	1.363
280.00	192.50	137.42	12	1.383
280.00	192.50	136.19	11	1.407
280.00	192.50	134.95	11	1.457
280.00	192.50	133.71	9	1.508
280.00	192.50	132.47	9	1.622
280.00	192.50	131.23	7	1.772
280.00	192.50	129.99	6	2.106
280.00	192.50	128.76	4	3.159

THE LOWEST SAFETY FACTOR FOUND WAS 1.338 AT R= 141.45 .

280.00	187.50	137.50	14	1.338
280.00	187.50	137.38	14	1.338
280.00	187.50	136.22	14	1.348
280.00	187.50	135.06	12	1.364
280.00	187.50	133.90	12	1.374
280.00	187.50	132.74	12	1.397
280.00	187.50	131.58	10	1.429
280.00	187.50	130.42	10	1.470
280.00	187.50	129.26	9	1.552
280.00	187.50	128.10	8	1.638
280.00	187.50	126.94	6	1.815
280.00	187.50	125.77	6	2.200
280.00	187.50	124.61	4	3.309

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THE LOWEST SAFETY FACTOR FOUND WAS  1.338 AT R=  137.50 .

**MINIMUM FACTOR OF SAFETY=  1.337 FOR X=  280.00 AND Y=  190.00
                                   AND RADIUS=  140.00.
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CORE USAGE        OBJECT CODE=   50872 BYTES,ARRAY AREA=   44368 BYTES,TOTAL AREA AVAILABLE=  159840  BYTES

DIAGNOSTICS        NUMBER OF ERRORS=       0, NUMBER OF WARNINGS=       0, NUMBER OF EXTENSIONS=       0

COMPILE TIME=     3.78 SEC,EXECUTION TIME=    36.40 SEC,  WATFIV - VERSION 1 LEVEL 3   APRIL  1971    DATE=  72/272
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