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MATERIAL CONSIDERATIONS IN THE DESIGN OF DOWNSTREAM EMBANKMENTS FOR TAILINGS IMPOUNDMENTS

Jack A. Caldwell and Adrian Smith

Steffen, Robertson and Kirsten, Denver, CO (U.S.A.)

(Received January 1985; accepted March 1985)

ABSTRACT

Downstream embankments are constructed to impound tailings when the tailings are fine-grained or toxic, or the environment is wet, seismic, or sensitive. This paper discusses the geotechnical and hydrogeochemical elements of downstream embankments to impound tailings, and illustrates points made by describing two case histories: the embankments for the Cannon Mine Project (Washington) and the Greens Creek Project (Alaska).

The major geotechnical elements described are: the core, the filters, the drains, the shell, the foundations, the reservoir, and the decant facilities. While many of these are common to embankments to impound water, the need to impound tailings imposes different design and construction constraints, such as the need for staged construction, the use of other mine wastes in construction, less permeability (due to the sealing action of the tailings) and consideration of the response of construction materials to the chemicals in water seeping from the impoundment.

Hydrogeochemical considerations such as chemical attack and chemical precipitation are described and their influence on design considered.

INTRODUCTION

Downstream embankments, while the most expensive way to impound tailings or residue, are the best solution when fine-grained, amorphous or toxic wastes are deposited in wet, seismic, or environmentally sensitive areas. This paper discusses the reasons why a downstream embankment should be built, of coarser tailings or borrowed or quarried soil and rock, in preference to an upstream or centerline embankment. The basic elements of an embankment to impound tailings and the hydrogeochemical factors relevant to design are discussed. Case histories of embankments to impound tailings are described.

CHOICE OF DOWNSTREAM METHOD

Embankments to impound tailings or waste residues may be constructed by the upstream, centerline or downstream method. If the downstream embankment is constructed primarily of the coarser tailings the cost is less than that of embankments built of borrowed soil or quarried rock. As shown in Fig. 1, the cost of a downstream embankment compared to that of an upstream embankment may be nine to sixteen times as much, depending on whether tailings or imported soil and rock are used. A downstream embankment may cost three to nine times as much as a centerline embankment.

In spite of the greater cost, downstream embankments are often built to impound tailings or mine and industrial residues. The main reasons for selecting a downstream embankment if the coarser tailings themselves can be used in the construction of the embankment are:

- sensitivity of uncompacted tailings to liquefaction;
- seepage control to preclude piping is required;
- rate of rise is too high for adequate consolidation of the total tailings to occur;
- seepage control requires an impermeable core.

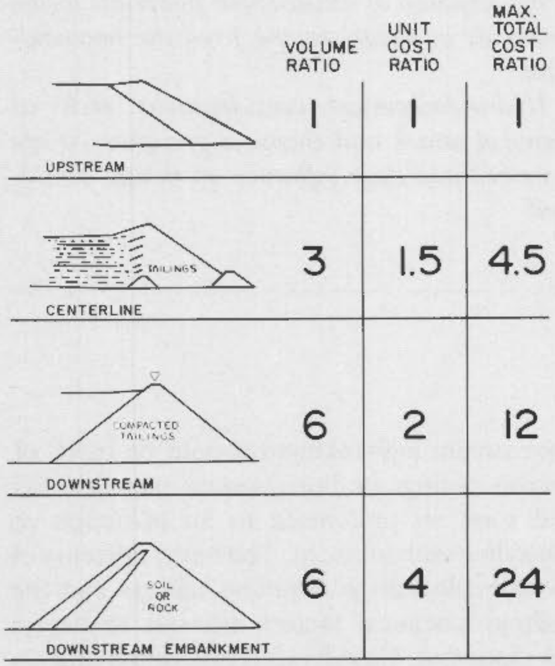

Fig. 1. Embankment comparison.

The coarser tailings may not be suitable for embankment construction and a downstream embankment may be required for these reasons:

- tailings too fine to be incorporated in an embankment;
- tailings considered unsuitable to incorporate in embankment (e.g., uranium tailings);
- seismic risk too great to use compacted sandy tailings, if saturated;
- the impoundment will store large volumes of water in addition to the tailings;
- logistics required an embankment built before deposition begins (say of waste rock from open pit stripping).

From the above reasons, it follows that the disadvantages of downstream embankments are the need to borrow soil or quarry rock, the need for cyclone tailings and the need to build what are often complex embankment cross-sections. The major disadvantage that results is higher costs.

Conversely, the advantages of downstream embankments are that a well-supervised embankment may be built which controls seepage, is stable under adverse loading (such as those caused by earthquakes, i.e., seismic disturbance), can impound water and fine toxic tailings or residues and which can be built at once or subsequently according to the availability of material, plant and money.

ELEMENTS OF THE EMBANKMENT

Civil engineering has a long history of designing and building embankments or dams to impound water. Those principles and practice, developed from experience and theory, are applicable to the design and layout of downstream embankments to impound tailings. They are not repeated in this paper, the reader is referred to the standard works.

There are, however, important differences between embankments to impound water and embankments to impound tailings. These differences are discussed in this paper by way of a brief description of the essential elements of a downstream embankment intended to impound tailings or residues.

RATE OF CONSTRUCTION OF THE EMBANKMENT

A completely different philosophical approach dictates the rate at which embankments to impound water and tailings are constructed. A water-impounding embankment is usually built in one construction phase to the ultimate crest elevation, and at that elevation a spillway is constructed. The purpose of the embankment is to impound as much water as possible, and cash flow is best if the dam is full.

Conversely, an embankment to impound tailings is required only to contain the tailings already produced by the mine. The best cash flow is achieved if no more of the embankment is constructed at any time than is required to contain current tailings volumes. As described in the second case history, it is economic to build a number of spillways at the crest of successive stages of the embankment.

THE CORE

A core may or may not be required in a downstream embankment for tailings impoundments. If the tailings or residues are toxic or the impoundment is to hold water in addition to the tailings or residues, a core is required. The core may be of natural or synthetic material, but must have a low enough permeability to preclude the passage of significant quantities of water. No core is ever entirely impermeable; some seepage will always occur. The core should be designed to limit seepage to a value where flow quantities may be controlled in seepage dams, returned to the impoundment, or treated for release.

If the tailings are toxic, the specifications for the core may be more stringent than for a water dam. For the average dam, loss of water through the core is satisfactory provided such seepage is controlled to prevent distress to the embankment and provided the quantities lost do not impair the storage potential of the dam. This may be different for a tailings impoundment. Cores are built not so much to prevent excessive loss from the reservoir (as for a dam), as to preclude escape of potentially contaminated fluid to the environment. There are cases where the seepage from the impoundment, through both the embankment and the liner, of potentially contaminated seepage are small. In those cases, it may be possible to show that the impact on the groundwater downstream of the impoundment is small due to attenuation by the foundation soils and rocks.

A well-designed impoundment usually provides for deposition of the tailings in a way that they augment the core (Fig. 2): thus, even though the geometry may be the same, the seepage gradient through the core of the tailings embankment will be less than that through the core of an embankment impounding water. Fine tailings are usually of low permeability: if placed correctly upstream of

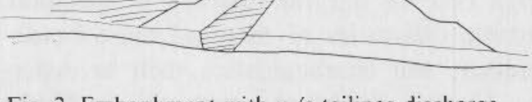

Fig. 2. Embankment with u/s tailings discharge.

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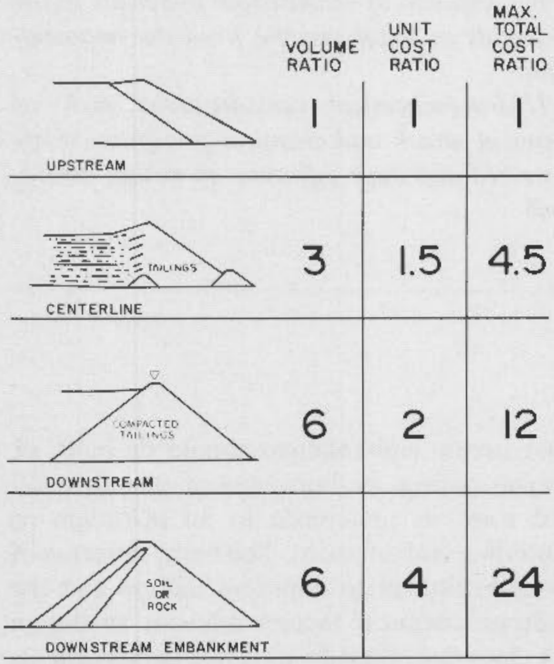

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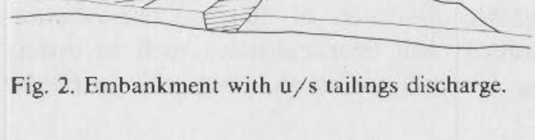

Fig. 2. Embankment with u/s tailings discharge.

the embankment or core they may act as a backup, or secondary lower-permeability element to the embankment proper. This is particularly so if the pool can be kept some way back from the embankment.

With time the tailings in the impoundment will consolidate and drain, and at closure or some time thereafter the seepage gradients may be less than during the operation of the impoundment. Thus, the requirement for long-term integrity or performance of the core may be less than in the case of a water dam, which, theoretically at least, has an unlimited service life.

In Example 2 discussed later, two alternative cross-sections for the embankment are described. One incorporates an HPDE liner as the core; the other incorporates a core of compacted glacial till. Cost and availability of suitable material affect the final choice of core. Because the tailings may be used to augment the core and thus reduce pressures and gradients and because the service period of the core may be limited, synthetic liners may be used in some downstream embankments. Data on liner properties are obtainable from manufacturers; the designer must seek to understand the product with which he deals and provide features to deal with the following problems that could occur when liners are used (note possible solutions as given in brackets):

— a tear or puncture of the liner (incorporate liner within low permeability zones, and provide adequate drains);
— inadequate connection to foundations and abutments (provide substantial anchor trenches);
— difficulty of connecting new section to old sections as the embankment is raised (reduce number of stages of construction or provide for substantial overlaps).

If a core of natural material is specified, available quantities of material must be determined; soil characteristics such as Atterberg Limits, gradation, strength, hydraulic conductivity and compaction characteristics must be determined. From the hydraulic conductivity the designer may determine the thickness of the core that is required to limit seepage to acceptable amounts. From the strength he may examine the effect of different core orientations on the stability of the embankment. From compaction characteristics the designer may specify the water content of the soil and the amount of compaction required to achieve the desired strength and hydraulic conductivity.

The core may slope downstream or it may be vertical as shown in Fig. 3. Downstream sloping cores are preferable if the embankment is to be constructed in a number of stages. As shown in Fig. 3, the size of the first-stage embankment required for a vertical core, which must be close to the line through the ultimate crest of the embankment, is greater than the size of the first stage for an embankment with a downstream sloping core.

A downstream sloping core may, if the material of the core is weak, give rise to potential stability problems in the upstream portion of the dam. Preferential failure paths may develop along the core. This problem may be avoided by:

— using a vertical core
— flattening the upstream slope of the embankment

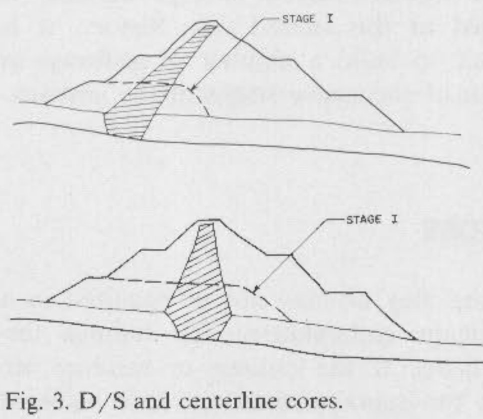

Fig. 3. D/S and centerline cores.

— constructing the embankment in stages so that successively placed tailings buttress subsequent lifts of the embankment.

A downstream sloping core may be less susceptible to earthquake-induced cracking; as the embankment settles, the core moves down and is generally placed under compression. A vertical clay core may also be dragged down as the adjacent shell settles. If the compression potential of the core is greater than that of the shell, however, the core may crack as it seeks to settle more than the adjacent shell. This is avoided with a downstream sloping core.

As, in general, the vertical core is closer to the downstream toe of the embankment, it may result in shorter drains and hence a cost saving as compared to a downstream sloping core. Also, if low permeability materials are used in the upstream shell, the central, vertical core may be thinner than a downstream sloping core. The low-permeability upstream shell reduces the head on the core; some of the total head in the reservoir is taken up in flowing through the shell.

FILTERS

Filters are required both upstream and downstream of the core in order to prevent particles from the core from washing out and to secure controlled collection of seepage. The design of filters is discussed in many standard references. Because the life of an impoundment is generally short in comparison with a water dam, geotextiles may, in appropriate circumstances, be used to form the filters. The geotextile should be chosen to last for the service life of the impoundment and perform satisfactory with regard to clogging, tearing, deforming, and filtering. If natural materials are economically available, they are preferable, as in the long term they will be a natural part of what is, after all, a new topographic form in the environment. If the core is of clay and cracking of the core is possible, the filter should be designed to trap the fine flocs and aggregates that may pipe through such a crack.

DRAINS AND TRANSITION ZONES

Drains serve to remove water from the embankment and hence to control the phreatic line within the embankment. A continuous drain is usually required downstream of the filters. The orientation is thus similar to that of the core.

The topography of the area beneath the embankment controls the layout of the drains on the ground. Blanket, strip, or finger drains may be used. In steep valleys it may be possible to place a drain only down the center of the valley. In broad, flat valleys, drains may be installed at suitable spacings up the sides of the valleys. On flat ground, for long embankments, drains are placed at spacings determined by the capacity of the drain and the seepage quantities.

The design of drains is discussed in many references and is not covered here. Generally, however, if at all possible, rounded stones and gravels should be used. Pipes within the drains should be avoided in seismic areas. They may break or clog and cannot in the long term be relied on to function as an harmonious part of the reclaimed impoundment. In non-seismic areas, if pipes are used, they should be so designed that they can be cleaned with a roto-rooter or equivalent. They must be corrosion resistant.

THE SHELL

The shell of an embankment may be constructed of coarser, usually cycloned tailings, of waste rock from the mine, or of borrowed soil or quarried rock.

The first criterion in selecting the shell material is that adequate quantities are economically available. Next, the material should be of adequate strength to ensure that reasonable side slopes to the embankment can be used. If the site is seismically active, the material should not liquefy under the design earthquake; most sands can be suitably compacted to prevent liquefaction at moderate cost.

Compaction of the shell material may or may not be required; the extent of compaction may differ depending on the zone of the embankment within which the material is placed. The designer specifies compaction requirements from a knowledge of the material properties, the function of the zone within the embankment and the effect or consequence of movement as a result of a given degree of compaction.

Generally, the more free-draining materials should be placed on the downstream side of the embankment; less free-draining materials should be placed on the upstream side of the embankment. Less free-draining materials tend to reduce the seepage gradient through the core. The free-draining materials on the downstream side promote stability in that water pressures do not build up within the embankment.

The upstream shell of the embankment will be buttressed by the rising tailings. Rapid drawdown conditions will not occur in a tailings impoundment under normal operating conditions. For these reasons it may be possible to construct the upstream shell steeper than is conventional for water impounding embankments.

The coarsest, least-erodible materials should be placed on the outer faces of the embankment. This will be required on the upstream face, where tailings are discharged, or water may lap against the face. If water will stand against the face of the embankment, the upstream material should be designed as a riprap.

If environmental or reclamation considerations dictate, the downstream face of the embankment may have to be dressed with soil in which vegetation may be established. Care should be taken to specify slopes at which such soil will remain on the embankment and will not slide down. This angle will depend on the soil type and strength in the downstream slope. The authors' preference is that the situation shown in Fig. 4 be used: flat berms on which vegetation may be established. The interberm slopes should be dressed with coarse non-erodible rock placed at its natural angle of repose.

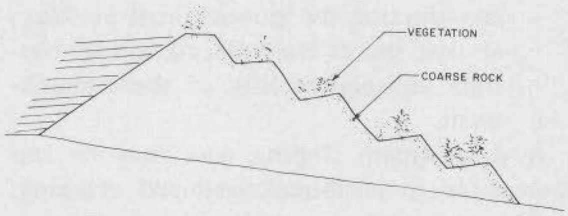

Fig. 4. Downstream face reclamation.

FOUNDATIONS

The foundations for a downstream embankment should be excavated to bedrock if the soils are shallow. If this is not possible, then the embankment slope must be chosen to provide for stability on the actual foundation soil. Cognizance should be taken of the fact that the chemistry of the seepage liquid may change the geotechnical properties of the foundation material; this is discussed later.

The core of the embankment should be keyed into the foundation. If necessary, the foundation should be grouted beneath the core, in order to provide positive control of seepage.

The settlement of the foundation, due to the load from the embankment, must be established, and provision made in the design of the embankment for any settlements that may occur.

RESERVOIR

Tailings or residues deposited behind a downstream embankment may be placed wet, dry or semi-dry.

Generally, the tailings will be fine-grained and will be placed wet. If at all possible, the tailings should be spigotted from the upstream crest of the embankment. In this way, they form an extension to the embankment which serves both to buttress the embankment and to reduce seepage through the embankment. Discharge from the embankment enables the pool to be kept away from the embankment. This further reduces the potential for seepage loss.

DECANT FACILITIES

Barges are the best way of decanting water from a pool behind a downstream embankment. This precludes the need for decant pipes passing through the embankment, or for spillways which may have to be re-established as the embankment is raised in successive stages. At reclamation, a spillway may be established to pass water from the surface of the reclaimed impoundment. If possible, the spillway should pass over a natural saddle. If this is not possible, the spillway should be cut into the rock of the surrounding hillside. Only as a last resort should a spillway over the embankment be considered.

HYDROGEOCHEMICAL ASPECTS OF EMBANKMENT DESIGN

Four major areas where the hydrogeochemistry of impounded tailings or waste material may affect embankment design are:

- seepage of contaminants or toxic liquids from the impoundment;
- chemical attack and modification of the geotechnical properties of the materials used to construct the embankment;
- chemical precipitation in and hence reduction of the capacity of the drains;
- chemical attack of concrete structures in the facility.

As previously noted, the core is used to control seepage from the impoundment. Solute transport modeling enables the engineer to assess the potential for and the nature of the impact of seepage from the impoundment through the core. A comprehensive analysis and a proper understanding of the nature and extent of seepage, obtained from hydrogeochemical modeling, may enable the engineer to avoid unnecessary complex or costly seepage control measures.

Before construction, extensive and detailed testing of the materials is done to establish their geotechnical properties. These properties can be adversely affected by chemical reactions with the tailings, the waste, or their interstitial liquids. Tailings and wastes that have been shown to cause problems include:

- acidic wastes, such as phosphogypsum, which have an inherently low pH;
- acid-generating materials, such as sulfide-bearing tailings and calcine;
- alkaline wastes, such as high alkali fly ash at pH 11–12;
- sulfate-bearing wastes or those that generate sulfates;
- highly-saline wastes, such as brines and bitterns.

There are several types of reactions that occur when natural materials are in contact with aggressive tailings solutions:

- solution reactions, for example dissolution of iron by an acid;
- compound formations, such as the change of calcite to gypsum in contact with sulfuric acid;
- redox reactions, e.g., reduction of ferric iron which increases the solubility of the iron;
- pH reactions: neutralization of an acid solution by carbonate minerals in the rock or soil.

Such reactions can lead to a loss of the mineral phase of the soil or rock to the tailings liquid, or a change of state of the minerals in the material. The material's geotechnical properties—for example permeability or bearing capacity—may be altered and the embankment may not perform as it was originally designed for.

Another part of the embankment which is vulnerable to chemical reactions is the drainage system, including the filters and the drains. Precipitation or ex-solution of dissolved species due to a change in temperature or exposure to air can impair drain operation, particularly when flow velocities and quantities are small. A blocked drain can detrimentally affect embankment stability.

The most common drain blocking process is precipitation of iron species. Iron, in solution in its ferrous state, is oxidized to its less soluble trivalent ferric state when interstitial liquids come in contact with free oxygen in the drain. The precipitates can and often do block the drains.

Species whose solubility is controlled by temperature may precipitate in the drains in cold or high-altitude environments. The tailings and the associated liquids in the impoundment tend to retain heat, having been discharged above the current ambient temperature. Their temperature is higher than that in the drains, particularly close to the drain exit on the downstream side of the embankment. If the hydrochemical system is saturated with respect to that species at the waste temperature, a drop in temperature in the drain results in a decrease in the solubility product of that species, causing precipitation. An example of this process is the precipitation of silica (quartz), a common constituent of most mine tailings, whose solubility is controlled by temperature.

The possibility of chemical attack on concrete structures, such as spillways and decant towers, in the tailings impoundment embankment, has been widely examined. Concrete is susceptible to attack by high-sulfate solutions, brines, low pH wastes such as tars and creosote sludges, and high-alkali wastes, such as sodium hydroxide stripping sludges. Preventative measures can be employed to minimize the adverse effects of these solutions on the concrete, providing the problems are anticipated.

RECLAMATION

The objectives of reclamation of a tailings impoundment are primarily to create a new topographic form which responds to the forces of the environment sculpturing the landscape in a way that reduces, to the maximum extent possible, the rate of release of contaminants to the environment. The rate of release of tailings and the rate of erosion should be no more than can be accommodated by natural processes.

The water dam can be breached at the end of its useful life; but this is not possible with a tailings pile. Recontouring, covering with rip-rap, permanent diversion of streams, and establishment of vegetation are the way open to the designer to create from the tailings pile a new topographic form that does not detrimentally impact the environment.

EXAMPLE 1: CANNON MINE TAILINGS IMPOUNDMENT

The Cannon Mine is just southwest of Wenatchee, WA. A tailings impoundment to contain between five and ten million tons of tailings deposited over ten to fifteen years is required. The site chosen after a detailed site selection is up Dry Gulch to the west of the mine.

Dry Gulch is part of the valley and ridge system that rises from the flatter alluvial terrace on which the mine and the town are situated. The elevation of the gulch rises from

300 m at the alluvial terrace to about 480 m at the impoundment site to about 1500 m at the catchment boundary. The climate of the area is relatively mild and dry. Winters are characterized by light precipitation and cool temperatures while summers are hot and dry. The mean annual precipitation is 230 mm and the annual evaporation is 760 mm.

The principal geologic feature of the area is the Chiwaukum graben. The oldest rocks are the Swakane Biotite Gneiss. The Swauk consists of fluvial and lacustrine rocks deposited on the Gneiss. As the graben developed, fluvial and lacustrine sediments of the Chumstick Formation accumulated. Igneous activity occurred during this period. The Wenatchee Formation which underlies the area of the embankment of the impoundment was deposited on top of the eroded surface of the Chumstick Formation. Sometime after deposition, the Wenatchee and older formations were extensively folded and faulted. After the faulting the Columbia River Basalt Group was deposited, probably covering the entire area.

The Ancestral Columbia River, and its tributaries, breached the basalt as the entire area was raised as part of the uplift of the Cascade Mountains.

Figure 5 shows the general geology of the site of the impoundment, and Fig. 6 shows a cross section down the valley. This layout was defined from an understanding of the regional geology and a site investigation which involved drilling eight boreholes, profiling twenty test pits, and running eight refraction seismic lines. Borehole drilling was done with a conventional wireline core rig. NX-size core was obtained. Packer testing was done in order to measure the hydraulic conductivity of each stratigraphic section. Figure 7 is a typical borehole log.

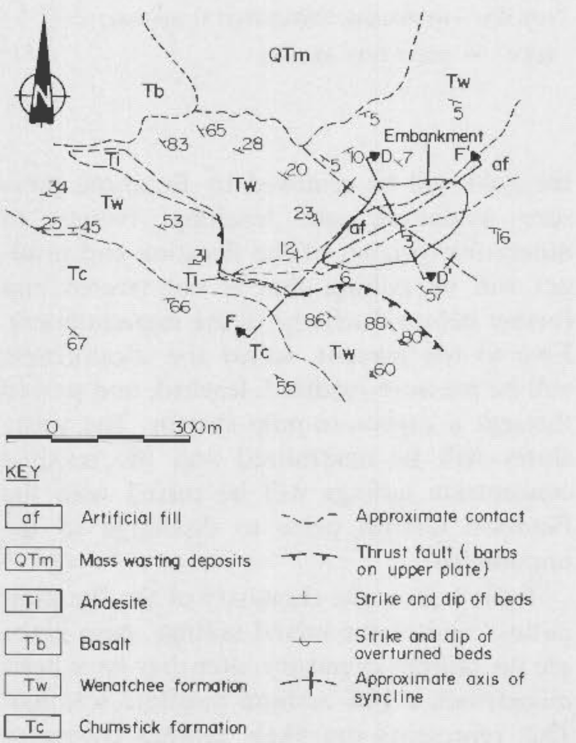

Fig. 5. Site Geology.

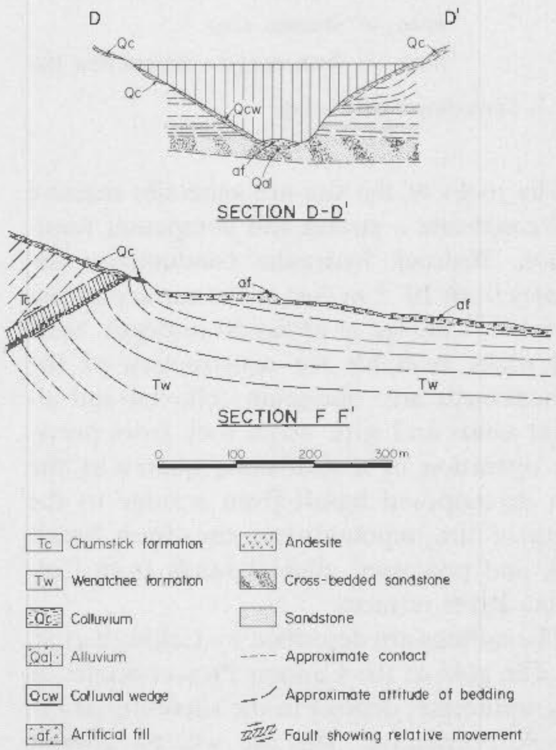

Fig. 6. Geologic sections.

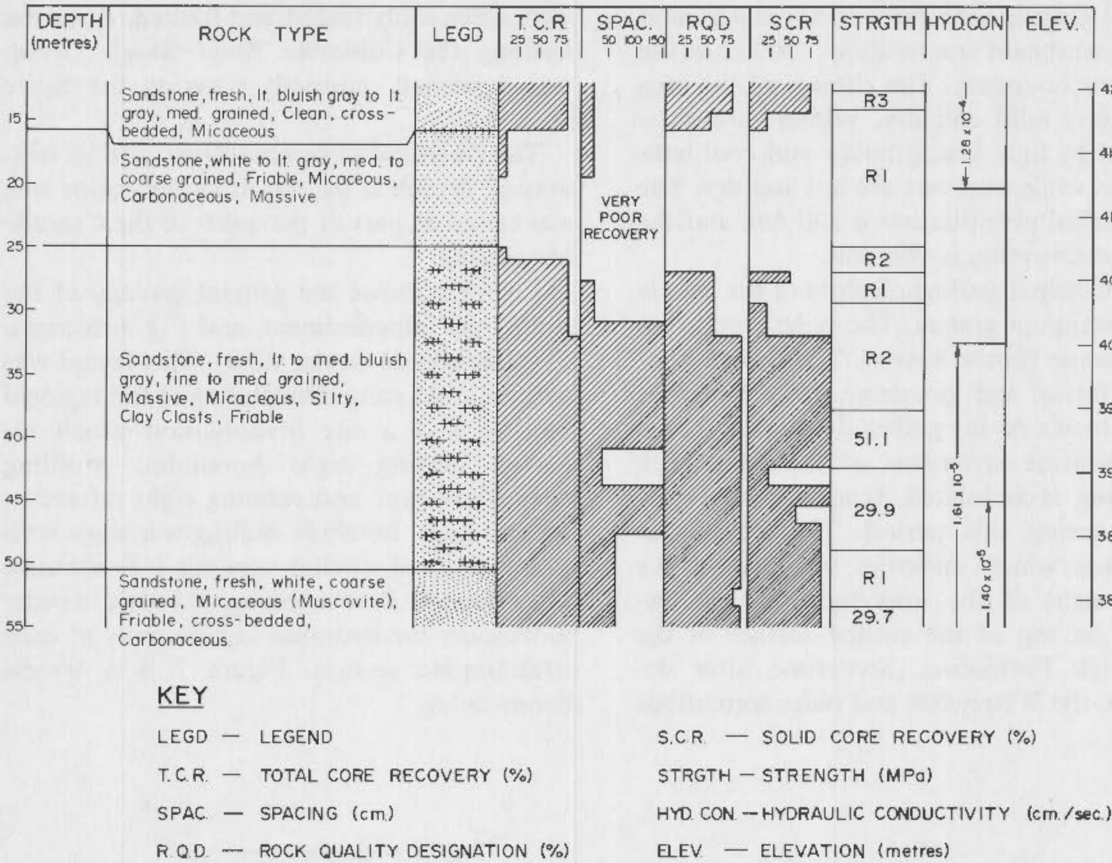

Fig. 7. Centerline borehole log.

The rocks at the site are generally massive and constitute a strong and competent foundation. Bedrock hydraulic conductivity decreases from 10^{-6} m/sec at the surface to less than 10^{-10} m/sec at about 50 m depth. Soils and rocks available for construction of the embankment are: fine-grain colluvial and alluvial sands and silts, waste rock from previous operation of a sandstone quarry at the site, decomposed basalt from a ridge to the north of the impoundment site, fresh basalt rock and processed alluvial sands from Columbia River terraces.

The tailings are described by Caldwell et al. [1]. The gold at the Cannon Project occurs as a hydrothermal deposit in the siltstones of the Swauk Formation. The ore will be ground and crushed to 90% less than 200 mesh and the gold will be removed by flotation, pressure oxidation, and leaching. Ninety to ninety-five percent of the flotation end product will be tailings that is not treated any further before discharge to the impoundment. Five to ten percent, called the concentrate, will be pressure-oxidized, leached, and passed through a carbon-in-pulp system. The waste slurry will be neutralized and the residual concentrate tailings will be mixed with the flotation tailings prior to discharge to the impounded.

Table 1 gives the chemistry of the flotation tailings and of the mixed tailings. Also given are the tailings chemistry after they have been mixed with a 10% sodium bisulfate solution. This represents the likely tailings chemistry after hydrogeochemical reduction of the tail-

TABLE 1

Chemistry of "mixed" tailings, flotation tailings liquids, and reaction products chemistry of "mixed" tailings

Parameter *	Mixed tailings supernatant	Floatation tailings supernatant	Mixed tailings reduced with $Na_2S_2O_3$	Mixed tailings leached with rainwater
pH value (units)	7.17	7.30	5.17	4.80
Total dissolved solids	4320	440	N/A	2750
Sulfate	1660	170	N/A	1587
Chloride	1040	15.5	3750	202
Total cyanide	284	< 0.05	< 0.05	57
Free cyanide	0.35	< 0.05	< 0.05	2.58
Sodium	480	90	N/A	87
Iron	10	< 0.05	1100	18
Arsenic	0.07	0.01	< 0.01	0.08
Cadmium	< 0.01	< 0.01	< 0.01	< 0.01
Cobalt	0.33	< 0.01	0.55	0.08
Copper	0.03	< 0.01	< 0.01	< 0.01
Lead	< 0.01	< 0.01	< 0.01	< 0.01
Mercury	0.0024	< 0.0003	0.0062	0.0011
Nickel	< 0.05	< 0.05	5.4	< 0.05
Selenium	< 0.01	< 0.01	< 0.01	< 0.01
Silver	< 0.01	< 0.01	< 0.01	< 0.01

* All values in mg/l, except pH.

ings supernatant in the impoundment. In order to assess the potential modification of the tailings liquid chemistry that might occur on the top of the tailings and in the pool, mixed tailings were equilibrated with simulated rainwater (distilled water mixed with hydrochloric acid to a pH of 5). The results of this are given in Table 1.

As shown in Table 1 the bulk of the residual cyanide is chemically complexed, hence chemically unreactive and non-toxic. Dilution with rainwater increases the level of free cyanide and iron slightly, but the overall chemistry of the liquid is better than that of the initial tailings slurry. Hydrogeochemical reduction increases the soluble iron, and decreases both total and free cyanide and copper to below analytical detection limits.

Figure 8 shows a cross section of the embankment intended for the site. The embankment incorporates the following zones:

— a low-permeability core which slopes upstream in order to provide for stage construction, and facilitate proper contact with bedrock;
— a filter to preclude movement of particles from the core due to seepage of water from the reservoir;
— drains which remove water from the embankment and control the position of the phreatic line within the embankment;
— shells of free-draining, compacted soils

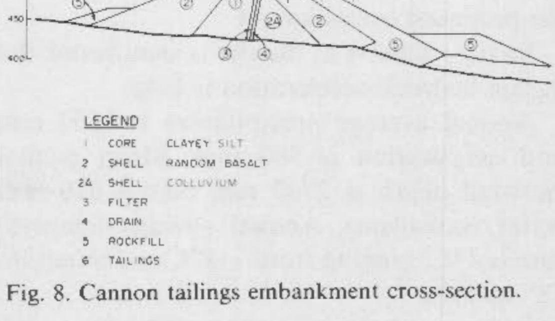

Fig. 8. Cannon tailings embankment cross-section.

and rock to provide the required stability;

- an upstream blanket, which is an extension of the core; this is installed in order to control seepage and maintain low hydraulic gradients at the core to foundation contact;
- a grout curtain which is intended to preclude seepage through significant joints or other geological discontinuities.

The embankment will be constructed in stages to accommodate the rising tailings.

EXAMPLE 2: GREENS CREEK EMBANKMENTS

The Greens Creek Impoundment is on Admiralty Island in southeast Alaska. The impoundment is designed to receive up to four million tons of tailings at about six hundred tons per day for a design life of ten to seventeen years.

The site chosen is a flat muskeq-covered valley bounded on the north by a low saddle; on the east is a steep ridge rising to a series of mountains; on the west is a series of low, nearly parallel, discontinuous ridges between which are sediment-filled gaps. The site is drained by a small creek which flows south.

During glaciation, the layered metasediments were scoured to form a series of deep U-shaped valleys. The valleys were filled with sequences of sand, silt and clay as the glaciers retreated. Figure 9 shows the layout of the site and the embankment, and Fig. 10 shows the bedrock and soils along the centerline of the proposed embankment.

Seismic activity at the site is significant: the design bedrock acceleration is 0.3g.

Annual average precipitation is 1500 mm and evaporation is 500 mm. Mean annual snowfall depth is 2700 mm (about 410 mm water equivalent). Annual average temperature is 4°C, ranging from −1°C in January to 18° in July.

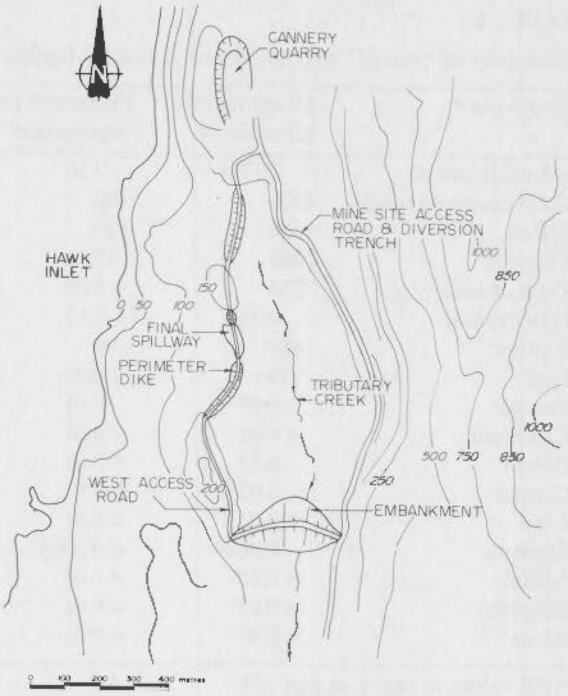

Fig. 9. Greens Creek embankment layout.

Figures 11 and 12 show alternative cross-sections proposed for the embankments. The outer dimensions and side slopes of the embankment are the same for both alternatives. The first, incorporating the till core, is the

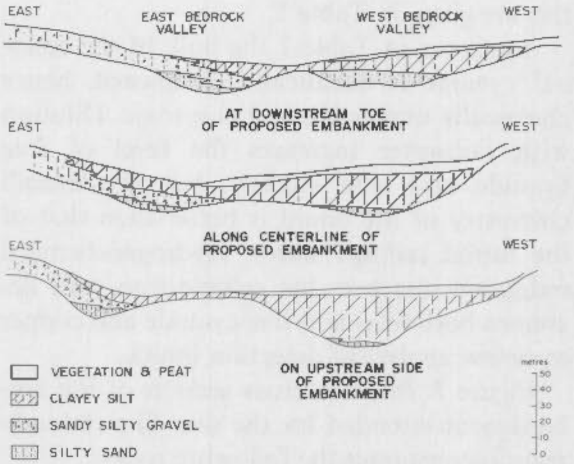

Fig. 10. Tailings impoundment site geological cross-sections.

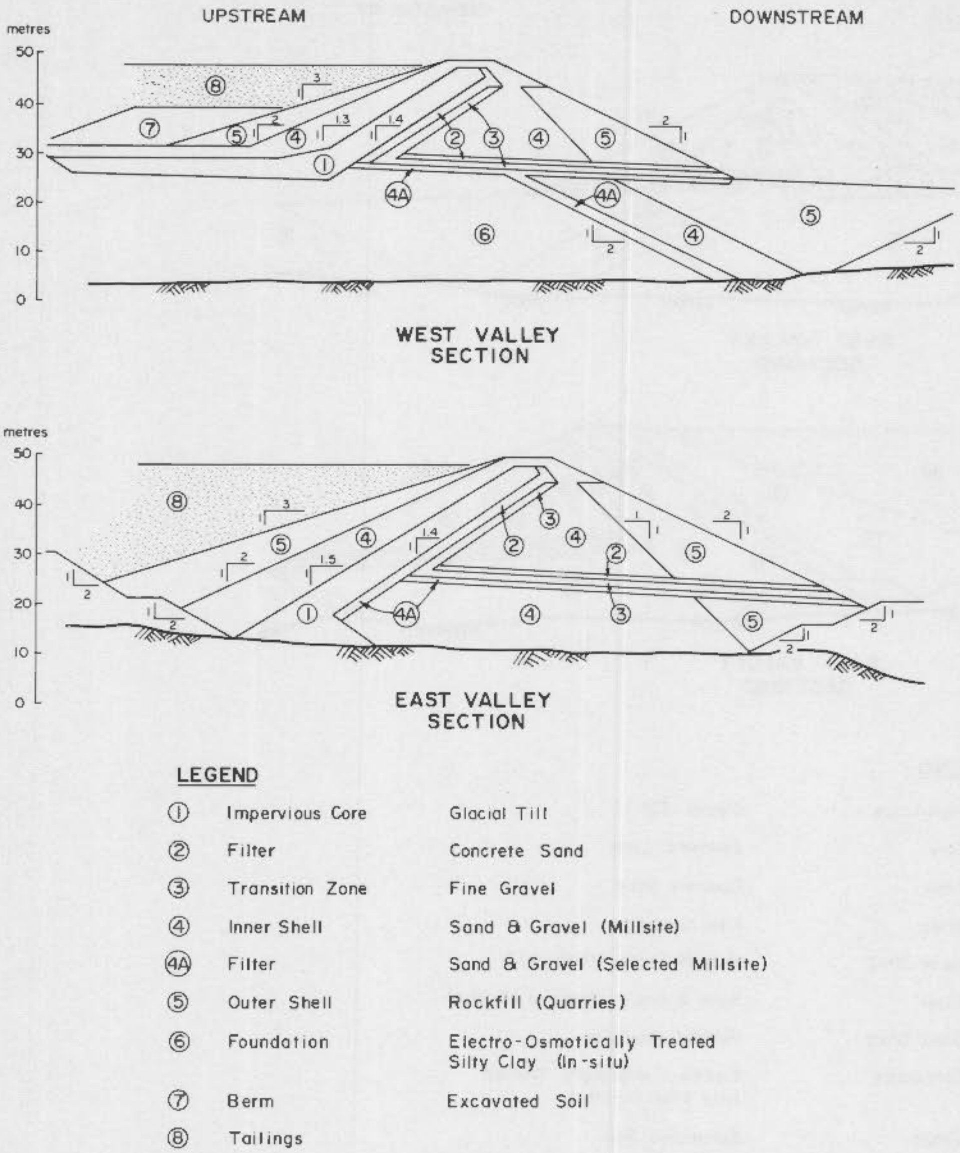

Fig. 11. Embankment cross sections alternative 1—till core.

more conventional. There is, however, some concern that sufficient quantities of suitable till are available. Also, difficulties may be encountered in placing a till core in the wet climate at the site. Accordingly, the second alternative incorporates a synthetic (high-density polyethylene) liner. The liner is flexible and can strain in tension eight times its original length before breaking. These properties make it well suited for use where settlement of the foundations and earthquake-induced deformations could occur.

Soils in the east bedrock valley are sands and silts. They could liquefy in the event of the design earthquake, and seepage may occur through them. Because the depth to bedrock beneath the embankment in the east bedrock valley is limited, an excavation to bedrock

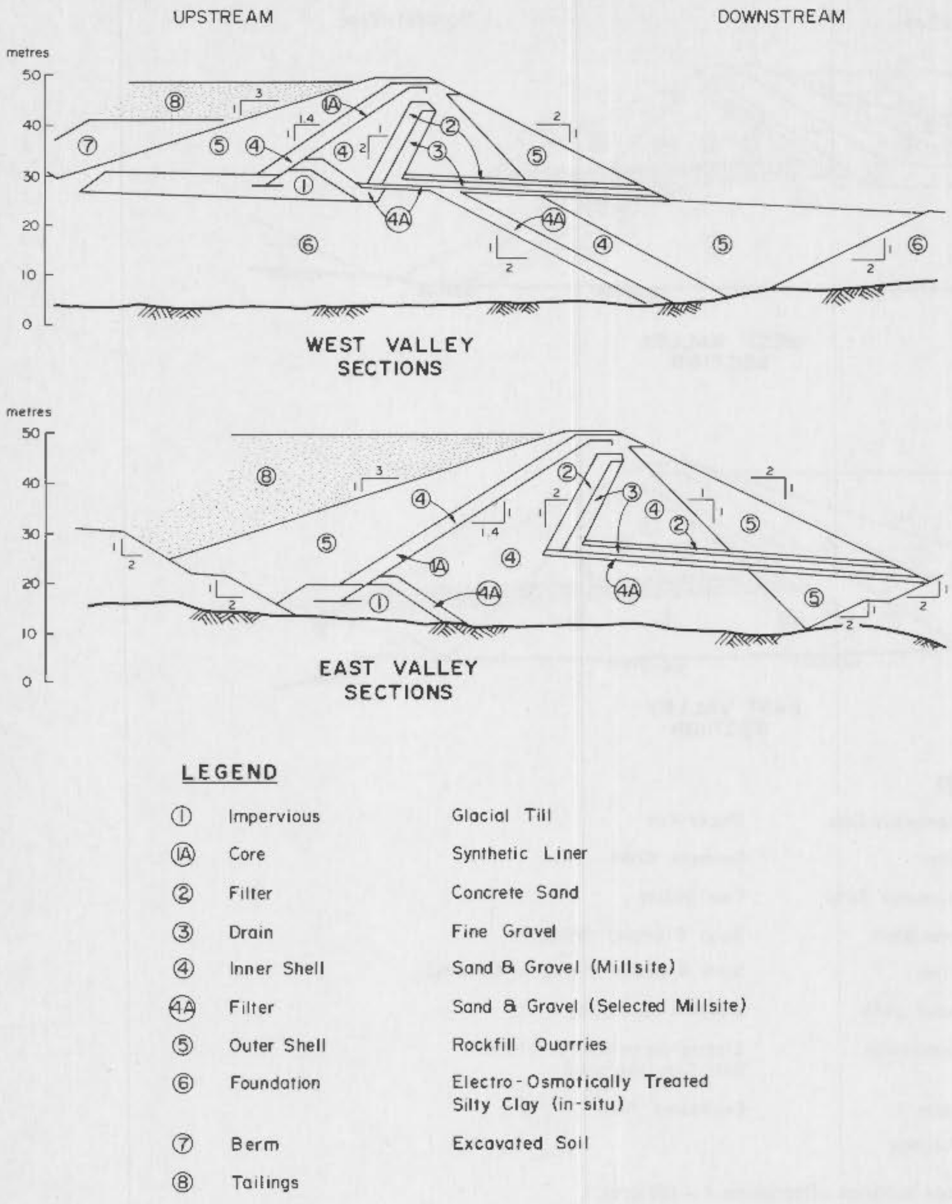

Fig. 12. Embankment cross sections alternative 2—synthetic liner.

will be formed under most of the embankment.

The silty clays in the west bedrock valley are a glacially-derived rock flour of low plasticity. The upper 6 m are medium stiff and over-consolidated. Below that, they are soft and sensitive. When remolded to a reasonable degree in the hand, they become rather sticky, flowing materials. Depth to bedrock and problems of disposing of material preclude complete excavation to bedrock. Accordingly, where the silty clays are left in place as a foundation for the tailings embankment, they will be stabilized by electro-osmosis.

A layer of sand beneath the silty clay, and the limited bedrock depth lead to a decision to excavate beneath the downstream part of the embankment in the west bedrock valley.

CONCLUSIONS

This paper has described why a downstream embankment may be chosen in preference to a centerline or upstream embankment. The advantages and disadvantages of the downstream embankment have been considered; while a downstream embankment is the most costly way to impound tailings or residues, it provides the best method of containing fine-grained or toxic tailings in seismic, wet or sensitive areas.

The various components of embankment built by the downstream method have been described in order to highlight the differences between embankments built to impound tailings or residues and embankments built to sotre water.

The two case histories described have illustrated the basic features of downstream embankments, and have displayed the extent to which the downstream embankment is suitable for use in a wide diversity of areas, to contain a wide variety of waste products.

REFERENCES

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2 Caldwell and DeDycker, "Site Selection of a Tailings Impoundment using Utility Functions". Submitted for publication.