Strategies for Reclamation of Tailings Impoundments

STRATEGIES FOR RECLAMATION OF TAILINGS IMPOUNDMENTS

L.F. Sawatsky [1], D.L. Cooper [2], E. McRoberts[3], H. Ferguson[4]

ABSTRACT

There are several hydrologic, geotechnical and environmental issues which govern the long term sustainability of reclaimed tailings disposal sites. One issue is the possibility of catastrophic dewatering. This can normally be avoided by dewatering tailings impoundments and breaching tailings dams. Where tailings are stored in abandoned mine pits, ponding may be acceptable if the scheme is not vulnerable to breaching, accelerated erosion , or rapid flow releases.

Often neglected, surface erosion of the reclamation cover is a governing issue where the underlying tailings material is highly erodible. Reclaimed tailings storage areas with long uniform side slopes may not be sustainable over the long term. Uniform slopes may appear to perform well during the short term under controlled conditions of high maintenance but such topography is normally not sustainable over the long term unless the contributing drainage area is small. Irregular topography, with well defined swales as found in the natural environment, is required to minimize erosion.

Long-term geotechnical safety criteria differ from short-term safety criteria used for design of operating tailings dams. Geotechnical design for long-term sustainability must consider slope failures due to erosion and steepening of embankments, extreme seismic events and unexpected water table and seepage conditions. Concepts such as the "safety factor", "design recurrence interval" and "life of a civil engineering project" need to be replaced with concepts such as robust systems, self-healing capability and natural analogues which replicate natural systems in a similar environment.

[1] L. F. Sawatsky, M.Sc., P.Eng., AGRA Earth & Environmental Limited
[2] D.L. Cooper, P.Eng. AGRA Earth & Environmental Limited
[3] E. McRoberts, Ph.D., P.Eng., AGRA Earth & Environmental Limited
[4] H. Ferguson, B.Sc., M.E.Des., P.Biol. AGRA Earth & Environmental Limited

Introduction

Attempts by mankind to build permanent structures ultimately fail. Even the pyramids in Egypt, which have survived several thousands of years, are deteriorating slowly and will ultimately become unrecognizable due to the slow but certain effects of weathering. Most other attempts by mankind to leave such a legacy in other more dynamic environments are much less successful. It is not unreasonable to conclude that modern reclamation of mine disturbed lands cannot be expected to remain unchanged indefinitely.

At best, man-made landscape might be expected to evolve slowly, like natural landscape which appears to be static only because the rates of change are slow. In fact, natural landscape is dynamic and subject to significant change. Change is particularly significant where landforms are subject to water erosion. The forces of change are particularly evident at rivers where river banks move rapidly due to erosion; where channel bed topography changes in elevation and bedform; where islands move slowly downstream; and where the channel itself relocates from time to time due to meander development, meander cutoffs, shortcuts across floodplains and aggradation at deltas. Although rivers are subject to obvious change, other landforms are also dynamic and yield much of the sediment load in the rivers.

Wind can move large quantities of soil at locations of minimal vegetation cover. However, wind erosion is responsible for minor quantities of erosion if the surface is covered by dense vegetation.

The forces of erosion control the rate of change in the natural environment. Immature landforms at seismically active areas and recent glaciated areas are subject to rapid erosion. However, mature geomorphic landforms are subject to relatively low rates of change. Reclaimed landscape at disturbed minelands are subject to the same forces of erosion; however, the rates of erosion may be far greater if the landforms resemble geomorphically immature landscape. Consequently, reclaimed mineland which is built of continuous uniform slopes which resemble immature landscape, is often subject to relatively rapid change as the forces of change attempt to develop more stable landforms.

Therefore mine planners, reclamation designers, and government regulators need to adopt criteria and strategies which take account of the inevitable changes in landforms caused by water and wind erosion. Rigid design criteria governing erosion for design events up to a specific recurrence interval, can be counter productive. Exceedance of the design event may lead to failure and accelerated erosion. More commonly, rigid erosion protection systems such as a layer of armouring or provision of a flow control structure will fail due to other unexpected causes such as debris, ice forces, frost action, sediment deposition, slope failure, settlement from consolidation of underlying material, vegetation, animal activity such as beaver dams, and human interference.

The alternative to rigid systems designed for specific extreme events is a dynamic system capable of accommodating evolutionary change without accelerated erosion or unacceptable environmental impacts. Such dynamic facilities must be robust systems with several lines of defense and self-healing capability. Self-heal capability can be built into a reclamation system; however, it is usually by design and seldom by default.

Avoiding Dam Breach and Runout

Since the rate and character of landscape evolution cannot be predicted accurately, containment of tailings pond fluids by tailings dams is not sustainable in the long term. Reclamation planners need to accept that dam breach and runout of tailings pond fluids are inevitable over the long term. Therefore, large water bodies and fluid tailings slimes should not be included in a reclamatic scheme, if the containment structure is a dam or similar narrow land mass which can be eroded rapidly in the event of a breach and runout of ponded fluids. Equally, containment structures which are required to maintain saturated conditions for preventing acid rock drainage may not be sustainable over the long term.

The rejection of dams from reclamation schemes is not a departure from common practice. Most jurisdictions presently require dewatering of water of tailings fluid impoundments prior to abandonment. Many regulating agencies would accept permanent bodies of water or tailings fluid if they were included in mined-out pits in bedrock. The acceptability of such impoundments in man-made lakes or mined-out pits in erodible sand, silt or clay is less certain.

The strategy of adopting reclamation design criteria based on dynamic end-state conditions offers a criterion by which reclamation planners and regulators can determine the acceptability of a body of water or tailings slimes in the final landscape. The concept of permanent water bodies and tailings ponds need not be abandoned. It is only necessary to prove that catastrophic runout and accelerated erosion would not occur under any realistic scenario of landscape evolution. A 5 to 10 thousand year term could be used to define "realistic scenario" to avoid consideration of force majeure events such as ice age glaciers, meteorites and volcanoes.

Landscape evolution by erosion can be simulated by computer model to provide a better understanding of the process, the time frame, flow rates and impacts of the evolutionary process. Such a model is especially valuable for assessing the sensitivity of governing parameters which cannot be estimated accurately. A gully erosion model was developed by AGRA Earth & Environmental Limited to estimate the rate of degradation and the associated releases from an end-pit lake. The pit was excavated in erodible soils. An outlet channel was planned along a route with gentle slope, thereby minimizing the tendency for erosion. Although the lake would be built with ample freeboard, it was postulated that a deep gully might form which could divert outflow to an adjacent river valley resulting in releases to a steep erodible channel.

The rate of erosion, degradation of channel bed and associated increases in lake outflow were modelled. The resulting flood hydrograph was used to assess the acceptability of this worst case scenario. Remedial measures were then established to minimize the chance of this occurrence. Computer simulation proved to be a useful tool in assessing the acceptability of end-pit lakes in a mineland reclamation scenario.

Vegetative Cover

Vegetative cover is one of the most important factors governing the sustainability of reclaimed disturbed areas [1]. The vegetative canopy and surface litter plays an important role in absorbing the impact of raindrops. Even more important is the density of the fine root mass at the soil surface, which holds the soil together and minimizes soil erosion.

Like landscape evolution, the mix of vegetation may change in time. Planned vegetative cover required by reclamation permits may bear little resemblance to the ultimate vegetation mix after several hundreds of years of change. There is a characteristic "natural" vegetation mix (or set of mixes, relating to the cycle of growth) which depends on the local climate, soil type, aspect and drainage conditions as well as biotic factors. Water availability for evapotranspiration and groundwater conditions are governing factors in determining the characteristic vegetation mix. Water balance, in particular, integrates the effects of climate, soil moisture holding capacity, aspect (exposure to the drying potential of the sun), and drainage conditions.

Vegetative cover changes in time because of several factors. Some types of vegetation may survive for a period of time and then may be eliminated by a drought condition which is natural to the climate regime of the region. Initial (planted) types of vegetation may gradually be replaced by other varieties which are better suited to the local conditions of water balance, soil fertility, disease, drought and drainage conditions. Forest fires can eliminate certain types of vegetation. Fire may stimulate a new cycle of vegetative growth, maturing of a forest and replacement of plant species. Resistance to soil erosion will change with the growth cycle of the vegetative cover and evolution of vegetation mix.

Mine planners and reclamation planners have some control on vegetative cover, not only by the initial planned vegetation mix but by the type of soil cover, exposure to the sun and the effectiveness of the drainage system. The objective should be to develop a dense root mass at the soil surface with enough vegetation to intercept and absorb the energy of high impact raindrops. Achieving this objective may require some trial and error iterations and comparison with natural analogues present in the nearby natural environment.

The hydrology of reclaimed tailings areas normally differs dramatically from natural conditions because of increased infiltration into pervious cover materials, reduced water holding capacity of the tailings, and steeper topography. This will affect the type of vegetation which can be supported in the long term. Without an adequate depth of fine grained soils with high moisture holding capacity, it may be difficult to support anything more than grasses, low bushes and sparse tree cover.

Some research on vegetation varieties is conducted jointly by the Land and Forest Service and the various mining companies. The Land and Forest Service has been working with mining companies to research different techniques and evaluate successes of reclamation species. There is a trend toward reclamation using native species rather than cultivars, but usage depends on seed availability and cost. Some historical reclamation species are no longer recommended in reclamation, and some are even considered weeds (e.g., crested wheatgrass). A 1984 reclamation book "Resources Handbook on Operational Guidelines for Industry" is somewhat dated, but still contains many of the reclamation principles that can be used today (pers. comm. Adolf Bruneski, Oct. 6, 1995). After a minesite has been closed, remediation techniques using local materials and available stock should be used wherever possible to reclaim a site.

In Alberta, the Alberta Environmental Centre in Vegreville has propagated 3 wheatgrasses, 1 bluegrass, and 15 legumes for use in coal mine reclamation along the eastern slopes of the Rocky Mountains. These "ecocultivars" have been sent to Prairie Seeds for propagation and availability to the public (pers. comm. Michelle Pahl, Reclamation Specialist, Alberta Environmental Centre, Vegreville, Oct. 13, 1995). Species include:

Scientific Name	Common Name
Elymus trachycaulum	slender wheatgrass (AEC Highlander)
Elymus trachycaulum	awned (bearded) wheatgrass (AEC Hillcrest)
Elymus trachycaulum	violet (broadglume) wheatgrass (AEC Mountaineer)
Poa alpina	alpine bluegrass (AEC Blue Ridge & AEC Glacier)
Astragulus alpinus	milk vetch
Astragulus americanus	American milk vetch
Asragulus vexillislexus	few-flowered milk vetch
Hedysarum	American hedysarum
Hedysarum boreale	northern hedysarum
Hedysarum sulphurenscens	yellow hedysarum
Lupinus nootkatensis	nootka lupin
Lupinus sericeus	flexile lupin
Oxytropis cuskii	alpine loco weed
Oxytropis deflexa	reflexed loco weed
Oxytropis monticola	late yellow loco weed
Oxytropis sericea	early yellow loco weed
Oxytropis splendens	showy loco weed
Oxytropis viscida	viscid loco weed

The Alberta Environment Centre is presently working on the following 3 native grass species:

Trisetum spciatum	spike trisetum
Festuca saximontana	Rocky Mountain fescue
Koeleria macrantha	June grass

Mature Topography

Large tailings storage areas with long slope lengths should be subdivided into numerous small catchment areas. This is necessary to prevent concentration of large quantities of surface runoff and minimize the potential for erosion and gullying.

Some designers mistakenly believe that large tailings waste storage areas with uniform slopes and large catchment areas are sustainable over the long term. This approach may be valid for the short term under controlled conditions of high maintenance but is normally not sustainable over the long term, unless the contributing drainage areas are small. Such a configuration represents immature landscape which is ripe for rapid evolution by erosion. Surface water will concentrate readily, even on uniform topography, to form incised channels which may penetrate the mantle of overburden material and lead to accelerated erosion of underlying materials. Consequently, uniform topography at tailings storage areas is often not compatible with the goal of long-term sustainability. It is preferable to reconfigure the mine closure landscape to replicate mature topography. This strategy acknowledges the evolutionary process of landscape development.

Mature topography, in contrast, has already been subjected to the rapid erosion of its immature state, and has developed to a state of relatively slow change [2]. Mature topography is characterized by relatively short slope lengths with slopes becoming gentler as flow concentrates in the downslope direction. Flow paths are well defined in swales which are deep enough to handle any extreme flood without chance of flow being diverted into another swale or sub-basin. Instead of uniform slopes, mature topography has variable slopes with hills and valleys which serve to blend in the reclaimed topography with the natural environment, provide protective habitat for wildlife and avoid large surface flow rates on steep slopes.

Steep slopes are acceptable as long as the contributing drainage areas are small, preventing surface erosion associated with large flow rates on steep slopes. The allowable slope length and steepness are a function of the density of vegetation and root mass, soil erodibility, and infiltration capacity of the soil. Some areas such as the sand dunes near Lake Athabasca have steep slopes and minimal vegetative cover but are not subject to surface erosion by water. The reason for this is that the sand dunes are composed of coarse sand which allows high infiltration, greater than rainfall intensities. As a result, surface runoff and surface erosion by water is minimal.

Slopes covered by dense grasses which develop a thick root mass are resistant to erosion. Allowable slopes at such areas may be steeper and longer than areas with a sparse vegetation cover or forest without significant underbrush. Cohesive soils are less erodible than sandy soils and therefore can support steeper slopes with larger catchment areas.

Climate represents strong control over the allowable slope length and steepness of grade. Whereas a wet climate may cause higher rates of overland flow, the higher moisture, if present throughout the year, provides for dense vegetation which more than compensates for the larger quantities of surface runoff associated with a wet climate. The worst condition is a dry climate with occasional high intensity rainstorms which results in large rates of erosion.

The allowable slope length can be described in terms of drainage density which is the total length of drainage channels per unit area [3]. Drainage density can be qualitatively related to dependent parameters as indicated in Figure 1.

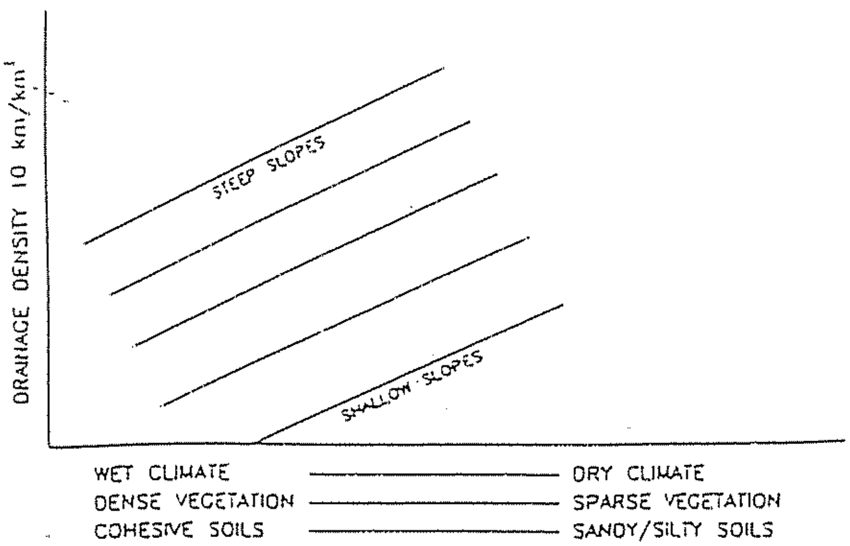

Figure 1. Qualitative Relationship of Drainage Density to Dependent Parameters

- growth of in-channel vegetation which could slow the flow velocities and raise the design flow levels;
- reduction in the width of channel due to sedimentation on one side of a wide channel that was built wider than the regime width;
- erosion of the channel bed resulting in degradation (overall lowering of the channel bed);
- bank erosion;
- rerouting of the channel due to beaver dams or sedimentation;
- bank failure due to slope instability or slumping; and
- erosion or riprap failure due to ice conditions.

By anticipating these potential changes, the reclamation planner is able to achieve sustainability by building in a dynamic character which can be controlled more easily than rigid systems.

Instead of providing channel armouring, the reclamation planner should design regime channels. These types of channels are designed to replicate the dynamic character of natural channels. Channel geometry and pattern are selected based on extensive available data and research by fluvial geomorphologists. There is a large body of literature available for the planner to select appropriate channel parameters to suit the required overall valley gradient and bed/bank materials [4]. The parameters include channel depth, slope, width, sinuosity, meander wave length, and width to depth ratio. The resulting regime channels, which are patterned after natural channel characteristics, will exhibit equilibrium conditions, thereby avoiding progressive channel degradation or aggradation.

Regime channels are capable of handling extreme events. Erosion control is not necessary because the channels are designed to accommodate erosion. Flow capacity can be achieved by building drainage channels in well defined swales or small valleys, just like natural drainage systems.

To reduce flow velocities, the planner may follow the example of natural systems where streams are flanked by floodplains. The floodplains provide extra flow capacity and storage to attenuate the peak flood flow.

Where *insitu* material size gradations and required channel gradients prevent the use of regime channels, the planner should selectively place coarser mine waste material in the vicinity of the planned drainage course. The coarse bed material (ie., boldery ground or soil with some coarse fractions) will provide for a much steeper regime channel gradient which has built-in capability for armouring and re-armouring. Erosion of channel armour during extreme events is readily replaced by coarse sediments from tributary streams or by degradation of the stream to expose coarse fractions.

Stability of End-Pit Lake Shores

End-pit lakes situated in erodible soils are subject to erosion, depending on wind conditions, fetch, water depth and exposure. Like landforms and stream channels, lake shorelines will change over time. The rate and nature of change can be estimated and mitigative measures can be provided to minimize unacceptable environmental impacts.

There are numerous common misunderstandings regarding erosion control. One is that terraces prevent erosion. Whereas terraces intercept surface runoff during low intensity storms, erosion can only be controlled if the accumulation of surface water does not exceed the storage capacity on the terrace or if the spillage is properly controlled by a spillway structure. Whereas terraces can prevent erosion in the short term during normal hydrologic events, they cause accelerated erosion during extreme events when their storage capacity is exceeded. The erosion damage caused by such uncontrolled spills can be very severe as illustrated by many such failures in tropical rice production areas. Terraces can cause accelerated erosion even during normal hydrologic events if they are improperly maintained. Terracing represents immature topography and is not represented in nature as an erosion control mechanism.

Mature topography is very well represented in nature, especially in areas not subject to seismic activity, or recent glacial activity. Reclamation planners will find many examples in the natural environment to serve as natural analogues for specific reclamation scenarios. This will involve non-uniform topography with a built-in characteristic drainage network which replicates the natural regime for similar conditions of soils, vegetation, climate, slopes and drainage density.

The natural environment segregates the erosion resistance of surfacial soils and vegetative cover. Upper reaches of a basin often have steeper slopes. Erosion in these areas is minimized by coarse surfacial material and by minimum surface runoff flow rates from relatively small catchment areas.

Erosion is minimized at the downslope reaches of large basins by conveyance of flows at the base of valleys where the gradient is relatively small, resulting in reduced flow velocities. Flows are also conveyed in channels which are armoured with coarse sediment on the channel bed and banks.

Sustainable Drainage Channels

Despite the fact that natural rivers and streams are commonly known to be dynamic, some reclamation planners and regulators are more comfortable with rigid reclamation drainage systems equipped with channels which are designed to resist erosion (immobile boundaries) during events up to a design recurrence interval such as the 100 or 1000 year recurrence interval, or even the Probable Maximum Flood (PMF).

A principle reclamation strategy is that reclaimed landforms such as drainage channels will change over time and that no attempt should be made to resist such change. Instead, every attempt should be made to anticipate such change so that the system can be designed to accommodate the change. Anticipation of changes enables the reclamation planner to build robust systems with second and third lines of defense.

The types of post-reclamation changes to drainage channels might include the following:

- deposition of sediment which could raise the channel bed and reduce the design freeboard;

If the end-pit lakes are small or shallow (ie., less than 2 metres), it may be possible to protect the shoreline by littoral zone vegetation, following the pattern of similar conditions in the natural environment. If the end-pit lakes are large and deep, then it will be necessary to provide a large source of coarse materials at the shoreline and inland from the shoreline. This will enable a degree of shoreline erosion and development. The alternative, to provide a relatively thin layer of riprap shore protection, may not be sustainable because such rigid shore protection measures are subject to failure by ice, design event exceedances, subsidence, lake level fluctuations and undermining.

Conclusions

Structural methods of erosion control which require rigid systems designed for specific extreme events are not considered to be sustainable over the long term. Such systems no longer satisfy the criterion of best available demonstrated technology.

A superior strategy is to design geomorphically mature reclamation landforms and drainage systems which can accommodate changes caused by erosion. The objective is to develop robust systems with self-healing capabilities equal to similar systems in the natural environment. The resulting reclamation works are superior to rigid structural systems, are sustainable over the long term, and may be more economical.

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