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Cap Stabilization for Reclaimed Uranium Sites

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Introduction

The decommissioning of uranium mills and long-term reclamation of uranium mill tailings impoundments must include engineering designs to protect against disruption of the tailings and the potential release of radioactive materials. The goals for such engineering designs should be to provide overall site stability for long-term periods with no need for planned on-going maintenance and to provide a repository for waste materials that will not burden future generations. The U.S. Environmental Protection Agency (EPA) established technical criteria governing the design and construction of reclaimed uranium tailings and decommissioned mill sites. Designs shall be effective for 200 to 1000 years. Also, reasonable assurance shall be provided that radon releases from residual radioactive material to the atmosphere will not exceed an average release rate of 20 picocuries per square meter per second or increase the annual average concentration of radon outside the disposal site by more than one-half picocurie per liter.

The purpose of this paper is to present some of recently developed, state-of-the-art engineering techniques and methodologies used to evaluate uranium tailings reclamation plans designed to provide

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long-term stability against potential failure modes. In some cases, evaluative techniques have been developed for long-term stabilization where methodologies have not previously existed.

Failure Modes

The initial step in effectively designing reclaimed impoundments for the long-term is to recognize and assess the potential failure mechanisms that may result in the release of radioactive materials. A comprehensive investigation was reported by Nelson and Shepherd (1978) which identified and evaluated the potential modes of failure that should be considered in the analysis of long-term stability of tailings management plans. Nelson and Shepherd categorized the failure modes as Elemental and Natural Processes.

The Elemental failure modes identify mechanisms that must be addressed when designing engineered components of the reclaimed impoundment. These components include the cap, the liner(s), the embankment and diversion structures. The Natural failure modes encompass earthquakes, floods, windstorms, tornadoes and glaciation. It was emphasized that since the monitoring of natural failure modes cover a relatively short time period, an element of conservatism should be integrated into the design process.

Nelson and Shepherd provided the foundation from which the present comprehensive design and review process for evaluating long-term stabilization of uranium tailings impoundments is derived. Minimally, each failure mode must be specifically analyzed in order to provide a reasonable assurance of stability prescribed by EPA.

Design Flood Selection

Nelson et al. (1983) provided a rational for selecting a design flood in accordance with criteria presented in evaluating failure modes (Nelson et al., 1978). Nelson et al. stipulated that the selection of a design flood event must take into consideration the level of risk associated with that event. Level of risk should be distinguished from the probability of occurrence of an event, since it depends upon the ability of the reclamation plan to withstand the particular flood and the consequences of the impact that could result from that event. Level of risk is difficult to quantify and is very site-specific.

Generally, the selection of the design event and its associated probability of occurrence is made on the basis of the acceptability or unacceptability of the level of risk. Implicit in this choice is the acceptance of the level of risk posed by any event of a larger magnitude and lower probability of occurrence than the design event.

The design periods being considered herein for long-term stability without planned maintenance are 200 to 1000-year periods. The design flood to be used in designing protective measures with a resonable assurance of stability over these periods should have a probability of occurrence that is fairly small and in accordance with normal engineering practice. For reclaimed uranium tailings impoundments, public health and safety, not just property damage, is an important concern. Therefore, greater safety should be required than for situations where only property damage is concerned. Thus, the probability of occurrence on which the designs are based should be a value lower than that used where only property damage is concerned, i.e., 0.01.

It can be seen that even for 200-year periods, the recurrence interval corresponding to a probability of failure of 0.01 is about 20,000 years. For even a probability of failure of 0.05, which is the probability associated with 95 percent confidence levels commonly used in general experimentation where public health and safety is not involved, the corresponding design flood recurrence interval for a 200-year stability period would be about 4000 years. The prediction of floods having recurrence intervals of thousands of years from limited data bases that extend over periods of only 50 to 100 years is very unreliable. Considerable inaccuracy is likely to result from attempting to predict floods having such long recurrence intervals.

The Probable Maximum Flood (PMF) is based on limitations imposed by site-specific physical capacities of the meteorological system. The PMF represents a limiting value and removes uncertainties associated with extrapolation of a limited data base to extremely long time periods. Thus, in view of the uncertainties associated with extrapolation of a limited data base and the accepted use of the PMF concept, it is reasonable and prudent to use the PMF as the design flood where the stability time period of concern is 200, 500, or 1000 years.

Nelson et al. (1986) presents a summary of PMF determination procedures and input parameters. Input parameters commonly used in a PMF determination include, but are not limited to, the watershed area, average slope, elevation differences, length of watercourse, soil type and runoff potential, type and amount of cover, antecedent moisture conditions, soil infiltration rates and soil compaction. The flood hazard should also be determined. It is recommended that a high hazard analysis, as discussed in Design of Small Dams (USBR, 1977), be used for evaluating the long-term stability for the reclamation of uranium mill tailing impoundments due to the radioactive nature of the tailings and EPA regulations which quantify the time period of stability.

Fluvial Geomorphology Influences

Although a tailings site may be located some distance from a river, if the site is on the flood plain or on a low terrace, there is potential for river shift which will lead to direct river attack on the pile and to increased flood damage. Hence, it is necessary to take into consideration the potential for river channel change. There are a number of reports that describe the morphologic and dynamic responses of rivers to include Nelson et al. (1983), Nelson et al. (1986), Shen and Schumm (1981) and Schumm et al. (1987).

The behavior of the river depends not only on the stability of that particular river reach, but also on the behavior of the fluvial system of which it is a part. Rivers are complex landforms; therefore, a simple and straightforward approach to the identification of river hazards is not always possible. Although detailed studies may indicate that a particular site is stable, upstream and downstream changes may affect the future stability of the site.

Rapid and otherwise unexpected river changes may occur in response to natural or man-made disturbances of the fluvial system, and it is important to be able to predict changes in channel morphology, location, and behavior. To a large extent the relative stability of a channel is revealed by its patterns. A major problem in predicting river behavior is that natural disturbances, such as floods, drought, earthquakes, landslides, forest fires, and hurricanes, may result in a large change in sediment load and major channel change. It is difficult to anticipate channel changes due to these disturbances because these are short-term episodic disturbances that cannot be accurately predicted.

Man-made changes in the drainage basin and the stream channel may also cause significant channel response. Alteration of vegetation, surface materials, and landforms changes water yield, snow accumulation and melt, water table configuration, timing and magnitude of flood peaks, sediment yield, and channel geometry. Alteration of stream courses by channelization; straightening; and construction of streamside structures, such as diversions, and culverts, significantly modifies the channel at the site of this activity and, in addition, can be expected to impact on the channels both downstream and upstream. Land use can be expected to have potentially profound downstream effects on stream channels.

A quantitative method for assessing fluvial stability can be developed on the basis of equations and charts presented by Schumm (1977). Factors influencing river morphology include bed-material load, mean water discharge, median sediment size, channel slope, and other external geomorphological controls on the overall river system. Rivers can be classified into three types of channels: straight, meandering, and braided channels. Factors influencing the type of channel include slope, mean annual discharge, amount of sediment load, and whether the channel sediment is characterized as bed load, mixed load, or suspended load.

In assessing the potential for the river channel to intrude upon the tailings impoundment, it is necessary to consider factors affecting both horizontal and vertical channel stability. Table 1 summarizes the changes that can occur in or along river channels, including changes in channel type.

Horizontal stability refers to the potential for a river to change from one type to another with accompanying change in location. At low slopes the river is just capable of carrying the sediment load. if the slope were to decrease due to development of a meander, the flow rate (velocity) would decrease and the meander channel would begin to fill with sediment. As a result, the stream would probably return to the original straight channel. As the slope of the channel increases, the river is capable of transporting more sediment and meanders can develop, thus increasing the sinuosity. However, if the sinuosity increases to a point that is too great, the river may become unstable again. As the slope increases, the stream can become braided and depending upon flow conditions and sediment load changes, the river can fluctuate between braided and meandering.

Vertical stability relates to the potential for the slope to change which can result in down cutting. Down cutting can lead to erosion at the impoundment site or cause a channel to change from one type to another.

Rivers may be categorized as bedrock-controlled channels or alluvial channels depending upon their freedom to adjust their shape and gradient. Bedrock-controlled channels are those where the slope of the river is controlled by nickpoints and bedrock outcrops. The vertical stability of a bedrock-controlled channel is dependent primarily upon the erosion resistance of the bedrock forming the nickpoints. Generally, bedrock-controlled channels are vertically stable.

Those parameters which define the stability of a fluvial system have been outlined by Schumm (1977). However, the interpretation of the data and application of the methodology will require considerable engineering and geological judgement. The concepts presented above are based upon threshold considerations and judgement. It must also be recognized that meandering streams may experience radical shifts in channel location without transition to straight or braided courses. Channel shifting is likely to be gradual during normal flow but may be catastrophic during extreme flood flows.

The influence of geologic structure upon stream channels should be considered. Mill tailings impoundments located away from channel controlling geologic features are less susceptible to flood intrusion and are unlikely to be affected by either a temporary or a permanent channel shift under non-flood conditions.

Stable Slope Prediction

In the event that the tailings and/or milling site is to be reclaimed with an earthen cover, it is important to design the impoundment with a stable slope. Schumm (1977), Nelson et al. (1986) and others have recognized the need to quantify the erosional geomorphic threshold at which gullies are initiated. Based upon site specific soil, climatic and hydrologic conditions, it is possible to estimate a slope at which gullying or extensive erosion will be minimized.

Nelson et al. (1983) present a series of site evaluation criteria for preventing gully hazards. Site evaluation criteria include:

Table 1. Types of Changes Occurring Along River Channels

Erosion

1. Degradation and scour
2. Nickpoint migration

Deposition

3. Aggradation and fill
4. Down filling and back filling

Pattern-change

5. Meander growth and shift
6. Channel bars and islands
7. Cutoffs
8. Avulsion

River-metamorphosis

9. Straight to meandering
10. Straight to braided
11. Braided to meandering
12. Braided to straight
13. Meandering to straight
14. Meandering to braided

Source: Nelson et al., 1983 and Shen and Schumm, 1981.

1. Flat slope--a relatively flat slope will minimize the erosive forces acting, and the probability of gully development is greatly reduced.
2. Low relief--a flat slope may be subject to gullying if it lies above adjacent drainage channels.
3. A plane or convex surface--a surface that prevents concentration of surface runoff, is more stable than a concave surface that concentrates runoff.
4. A regular surface without abrupt changes of slope or depressions that can channelize runoff is relatively more stable than an irregular surface, although a rough surface will impede runoff.
5. Absence of nearby active channels can threaten a site by headward extension, by lateral shift, or by avulsion.
6. Resistant rock--a site on resistant rock is unlikely to be affected by gullies, whereas alluvium, shale, and other weak sedimentary rocks are highly erodible. If the site is on weak rock but a supply of resistant cobbles or boulders is nearby, this material can be used to stabilize the site.
7. Low potential for surface change--a relatively stable surface can be greatly affected by change of vegetation cover, surface disturbance and land use.

Clearly, a site will be stable if it is located on a low relief, flat or slightly convex, smooth surface isolated from channel change by resistant bedrock.

Nelson et al. (1986) presented a procedure for predicting the stable slope of a steep earthen gradient (slope > 10%) with drainage length of 1000 ft or less and comprised of a noncohesive or low cohesive material. It was determined that the tributary drainage area (A), the number of annual precipitation events causing runoff (P) and the median particle size (D_{50}) of the material used to reclaim the impoundment can be correlated to a stable slope (S_s) where

$$S_s = \frac{41.2\ (1 + D_{50})}{(A)\ (P)} \tag{1}$$

Equation 1 predicts a conservative gradient where severe erosion ceases. The estimated stable slopes generally agree with the slope-drainage area relationships derived by Schumm (1977). The estimation of stable slopes on soil covers presents one of the greatest research and development potentials in reclamation design.

Slope Stabilization with Riprap

Rock riprap is one of the most economical materials that is commonly used to provide for cover and slope protection. Factors to consider when designing rock riprap are: (1) rock durability, density, size, shape, angularity, and angle of repose; (2) water velocity, depth, shear stress, and flow direction near the riprap; and (3) the slope of the embankment or cover to be protected. Through the proper sizing and placement of riprap on any impoundment cover, rill and gully erosion can be minimized to ensure long-term stabilization.

The primary failure mechanism of concern is the removal of material from the impoundment due to shear forces developed by water flowing parallel and/or adjacent to the cover as described by Nelson et al. (1983). One purpose of the cover is to expedite the removal of precipitation and tributary waters away from the cover to minimize seepage and percolation. When surface waters are not properly managed, extreme erosion may result and endanger the impoundment stability. For example, slopes are often designed and constructed to develop and maintain sheet flow conditions.

The design requirements for placing rock riprap on a cover vary depending upon cover location. It is suggested that four areas exist on the cover in which different failure mechanisms can result from tributary drainage. The four areas or zones of concern are:

1. Zone I: This zone is considered the toe-of-the-slope of the reclaimed impoundment. The riprap protecting the slope toe must be sized to stabilize the slope due to flooding in the major watersheds and dissipate energy as the flow transitions from the impoundment slope into the natural terrain. Zone I is considered a zone of frequent saturation.
2. Zone II: This is the area along the side slope which remains in the major watershed flood plain. The rock protection must resist not only the flow off the cover, but also floods. The riprap must serve as embankment protection similar to river and canal banks. Zone II is considered a zone of occasional saturation.
3. Zone III: Riprap should be designed to protect steep slopes and embankments from potential high overtopping velocities and excessive erosion. Flows in Zone III are derived from tributary drainage and direct runoff from the reclaimed site cap. Zone III is considered an occasionally saturated zone.
4. Zone IV: Rock protection for Zone IV is generally designed for flows from mild slopes. Zone IV will usually be characterized by sheet flow with low flow velocities. Zone IV is considered a zone of occasional saturation.

Abt et al. (1987) conducted a series of flume studies evaluating the U.S. Army Corps of Engineers Method (USAE, 1970), the Safety Factors Method (Richardson et al., 1975), the U.S. Bureau of Reclamation Method (USBR, 1978), and the Stephenson Method (1979) for sizing riprap in overtopping flows. Each procedure was compared in sizing riprap for overtopping flows on slopes ranging from 1-20 percent with median riprap sizes of 1-6 inches in diameter. The objective of the comparison was to determine which procedure provided an adequate rock size to stabilize the slope without an excessive degree of conservatism.

The comparison of riprap design procedures indicated that for slopes of 10 percent or greater, the Stephenson Method yielded adequate slope protection with the least over-conservatism. Also, the Stephenson method for riprap sizing was specifically developed for overtopping flow conditions. The Safety Factors Method was considered to provide adequate protection for slopes less than 10 percent with the least over-conservatism.

Abt et al. (1987, Phase II) reported several design relationships for sizing riprap subjected to overtopping flow. For example, a relation was presented to estimate the interstitial velocity, v_i, within the stone layer expressed as

$$v_i = 19.29 \left[C_u^{-0.074} S^{0.46} n_p^{4.14}\right]^{1.064} \left[g D_{50}\right]^{0.5} \qquad (2)$$

where D_{50} is the median stone size, n_p is the stone layer porosity, S is the gradient, g is the acceleration of gravity and C_u is the coefficient of uniformity.

A relationship was derived to predict the unit discharge for angular rock at which the riprap layer would fail when subjected to overtopping flow as shown in Figure 1. The median stone size was correlated to the embankment gradient and unit discharge at failure where

$$D_{50} = 5.23\ S^{0.43}\ q_f^{0.56} \tag{3}$$

Equation 3 indicates a failure criteria and requires adjustment to compensate for layer thickness and gradation and resist stone movement.

Abt et al. (1988, Phase II) investigated the difference in stability between rounded and angular shaped stones. Figure 1 presents the relationships of the median stone size versus the slope and unit discharge at failure parameter for rounded as well as angular shaped stones. It is observed that the rounded stones fail at unit discharges of approximately 40 percent lower than the angular rock. In other words, an angular stone 4-inches in diameter would require a rounded stone of 5.5-inches in diameter to maintain a similar level of stability.

Some of Abt et al. (1987, 1988) other findings included:

1. There exists a unique procedure for estimating the resistance to flow for angular riprap expressed as a Manning's n.
2. Flow channelization occurred along riprap protected slopes. Channelization concentrated the flows as high as three times greater than uniform flow conditions.
3. Riprap gradation was determined to significantly influence riprap stability. A coefficient of uniformity of 2.3 or less was recommended.

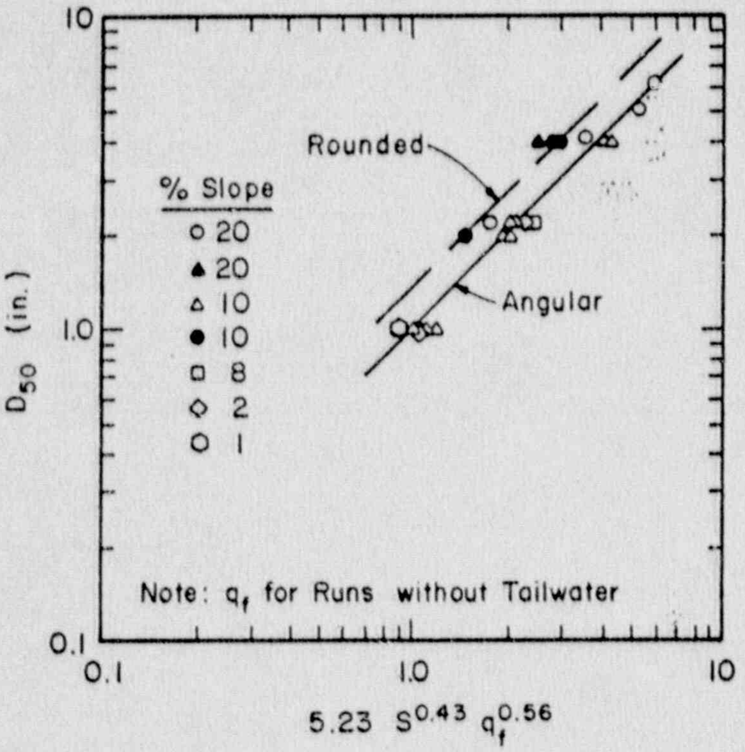

Figure 1. Riprap failure relationships from overtopping flow for angular and rounded rock. (From Abt, et al., 1987).

4. It was determined that riprap layer thicknesses of 1.5 D_{50} or greater is adequate for median stone sizes of 6-inches or greater. However, a layer thickness of 1.5 D_{50} may not be adequate for median stone sizes less than 6-inches.

5. A riprap-soil matrix without soil cover increases the riprap barrier stability over riprap alone.

Riprap Selection, Quality and Durability

The use of riprap to protect a reclaimed impoundment requires that an extensive investigation be conducted in the selection and evaluation of riprap materials to meet the long-term performance objectives. Nelson et al. (1986) delineated a riprap selection methodology to provide reasonable assurance of stone durability. It was determined that suitable riprap sources will be governed by the size and design requirements of the site specific conditions.

Rock sources must satisfy two main requirements: (a) the rock fragments must be produced in suitable sizes for the required usage and the (b) rock fragments should be hard, dense, and durable enough to withstand procurement and placement, and the processes involved in weathering. If material of required quality is available in sufficient quantity in the immediate vicinity of the project, it will be unnecessary to investigate more distant sources. If, however, there is a deficiency of suitable rock in the immediate area, it will be necessary to explore further. In this case, prospecting for rock should extend radially outward from the site until a deposit of rock is located which is suitable in quality and sufficient in quantity to fulfill the anticipated requirements.

Selection investigations occur in three stages: (1) reconnaissance, (2) feasibility, and (3) verification. The initial or preliminary exploration involves field surface reconnaissance using topographic, geologic, and agricultural soil maps and aerial photographs with supplemental information provided by records of known developed sources of material. A study of maps and aerial photographs may reveal possible sources of material. Contours are often an indication of the type of material: sharp breaks usually indicate hard rock and slopes below cliffs often have talus deposits. During field reconnaissance, the countryside should be examined for exposed rock outcrops or cliffs. Data obtained should define the major advantages or disadvantages of potential materials sources within reasonable (economic) haul distance to the project site.

Information accumulated during the feasibility stage is needed to prepare preliminary designs and cost estimates. A complete survey of possible material sources located within economical haul range of the project site is made at this time. The potential material sources are examined to determine size and character, and particularly to observe joint and fracture spacing, resistance to weathering, and variability of the rock. The spacing of joints, fractures, and bedding planes will control the size of rock fragments obtainable from the deposit. Observation of weathering resistance of rock in situ along with resistance to fracturing will provide good indication of its durability. Particular attention should be given to location and distribution of weak seams or strata which must be avoided or wasted during quarrying operations. Representative samples of riprap material from the most promising potential sources are required for quality evaluation tests.

The purpose of verification is to document a rock source's durability and its suitability for use as riprap on tailings embankments and covers or on outfall areas of diversion channels. Core drilling may be required to verify the volume and uniformity of source material available.

Johnson (1988) assembled the efforts of Nelson et al. (1986), Staub (1982), Depuy and Ensign (1965), Depuy (1965) and the U.S. Bureau of Reclamation (1986) to identify a rock scoring criteria for the rating and oversizing of rock for long-term survivability for armoring covers. Johnson recommends that a battery of rock quality tests be conducted on each prospective rock sample. The quality tests include petrographic analysis, specific gravity, absorption, sodium sulfate, L/A abrasion, Schmidt Hammer and Tensile strength. Weighting factors are assigned to each test depending upon rock type. An example of the proposed weighting factors and minimum scores for good and fair ratings are presented in Table 2. Scores reflected in Table 2 are subject to adjustment and do not reflect intermediate values.

Based upon the results of the rock quality tests, rocks obtaining a composite score of 80 or greater do not require oversizing. Rocks with composite score of 50-80 may be used for erosion protection but require oversizing. Rocks with composite scores under 50 are not acceptable for cover protection. These results are applicable to areas of occasional saturation. Frequently saturated areas require higher composite scores than those cited.

Oversizing of rock is applicable for rock with composite scores of 50-80 for occasionally saturated areas. Rock diameters are increased by multiplying the design rock size by one plus the difference of 80 and the composite score. Although the procedure for estimating rock

Table 2. Proposed Scoring Criteria*

	Weighting Factor			Score	
Test	Limestone	Sandstone	Igneors	8 (good)	5 (fair)
Specific Gravity	12	5	9	2.65	2.50
Absorption %	13	6	2	0.5	1.0
Sodium Sulfate %	4	3	11	5	10
L/A Abrasion (100) %	1	8	1	5	10
Schmidt Hammer	11	13	3	60	40
Tensile Strength psi	5	4	10	1000	500

*Rock is not considered if not rated at least "fair" in petrographic examination.

quality and durability remains in a developmental stage, a successive step toward quantifying and rating riprap to assure long-term performance has been taken.

Summary

The long-term stabilization of decommissioned uranium mill sites and of reclaimed uranium mill tailings sites encompass a broad spectrum of design capabilities. This paper has presented a few of the quantitative methodologies recently developed or refined to evaluate physical factors (i.e. precipitation, fluvial geomorphology, stable slope, slope stabilization with riprap and riprap selection) that influence long-term stabilization of uranium mill and mill tailings sites. It is acknowledged that the degree of refinement of these methodologies are in their infancy and that extensive research and development are warranted to increase the level of assurance. However, these methodologies provide an initial guideline for evaluating long-term stabilization that has not previously existed.

APPENDIX I.--REFERENCES

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APPENDIX II.--ACKNOWLEDGMENTS

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