Chapter 22

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HYDRAULIC TAILINGS

1. INTRODUCTION

Tailings, defined as sand-, silt-, or clay-sized solid wastes from mineral-processing operations that were originally produced, handled, and deposited in slurry form, represent a special case of slope stability in that they are artificially constructed deposits of manufactured soil. Tailings are distinct from other types of coarse mining wastes or smelter slag that are dumped or piled under dry conditions. Tailings deposits share many geotechnical characteristics of such other hydraulic fills as offshore drilling islands, hydraulic-fill water dams, dredged material deposits, and certain other industrial wastes (e.g., fly ash and papermill sludge). These related materials are not discussed here, but pertinent information can be found in two publications from the American Society of Civil Engineers: *Geotechnical Practice for Disposal of Solid Waste Materials* (ASCE 1977) and *Hydraulic Fill Structures* (Van Zyl and Vick 1988).

Tailings are often identified by their association with mining and milling operations. Where encountered along transportation routes, tailings deposits may affect the stability or safety of these facilities by (*a*) causing instability of excavated cuts, (*b*) creating potential landslide hazards from adjacent deposits, (*c*) increasing subgrade compressibility and settlement, and (*d*) possessing adverse environmental characteristics (high erodibility, heavy-metal pollution, and acid drainage).

2. CHARACTERIZATION AND PROPERTIES

For most metalliferous ores, tailings represent the end product of crushing and grinding operations after extraction of the valuable mineral particles. For other ores, such as phosphates, coal, or construction aggregates, tailings are produced by simple washing and screening operations. In either case, the maximum particle size typically varies from 0.1 to 1.0 mm, with the relative proportions of sand- and silt-sized particles governed by the type of processing required for optimum mineral extraction efficiency. Mechanical grinding produces particles that are highly angular; clay is contained in the tailings only if present in the parent ore, and clay content is usually significant only for tailings produced by washing operations. Specific gravity of tailings solids varies from as low as 1.5 for coal to almost 4.0 for tailings derived from sulfide-type orebodies where pyrite is rejected during processing. Vick (1990) summarized gradation and index properties for tailings from a variety of ore types.

2.1 Construction of Tailings Impoundments

During operation of a milling facility, the tailings slurry is usually pumped to a tailings impoundment at a pulp density of 15 to 50 percent solids by weight. Within the impoundment the solids settle

from suspension, and the supernatant water collects in a *decant pond* from which it is discharged or recycled to the mill process. Central to geotechnical characterization of any tailings deposit is the manner in which discharge and deposition of the tailings slurry have been conducted, and conventional exploration and sampling techniques alone cannot substitute for an understanding of these operations.

Usually the tailings slurry is discharged from the embankment perimeter, typically as shown in Figure 22-1. To the extent that a sand fraction may be present in the slurry, these particles tend to settle nearest the point of discharge, with finer particles carried farther in the slurry stream. This sedimentation pattern gives rise to an above-water beach of *sand tailings* (defined as those with less than 50 percent passing the No. 200 sieve) and a zone of *slimes* (more than 50 percent passing the No. 200 sieve) extending from the more distant regions or the above-water beach to beneath the decant pond, as shown in an idealized manner in Figure 22-2. The degree of particle-size segregation on the beach, and therefore the extent to which the sand tailings and slimes are differentiated, depends on such factors as gradation of the original slurry and its solids content (Abadjiev 1985). The

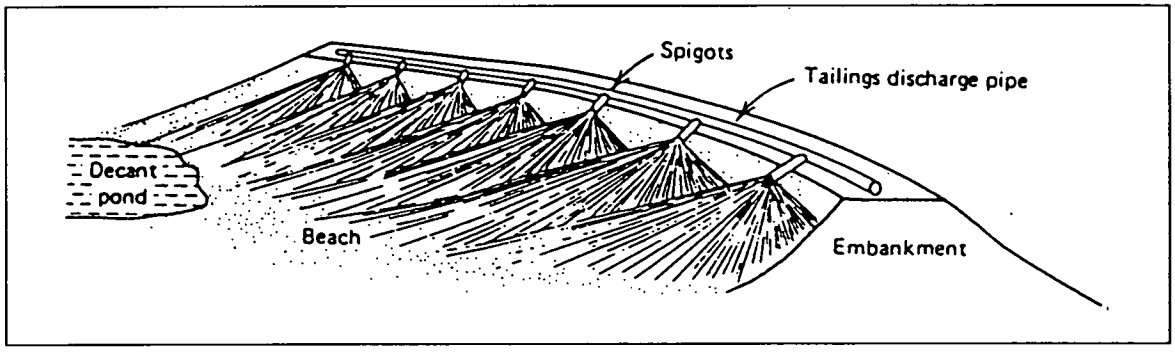

FIGURE 22-1 Tailings slurry discharge and beach deposition (modified from Vick 1990).

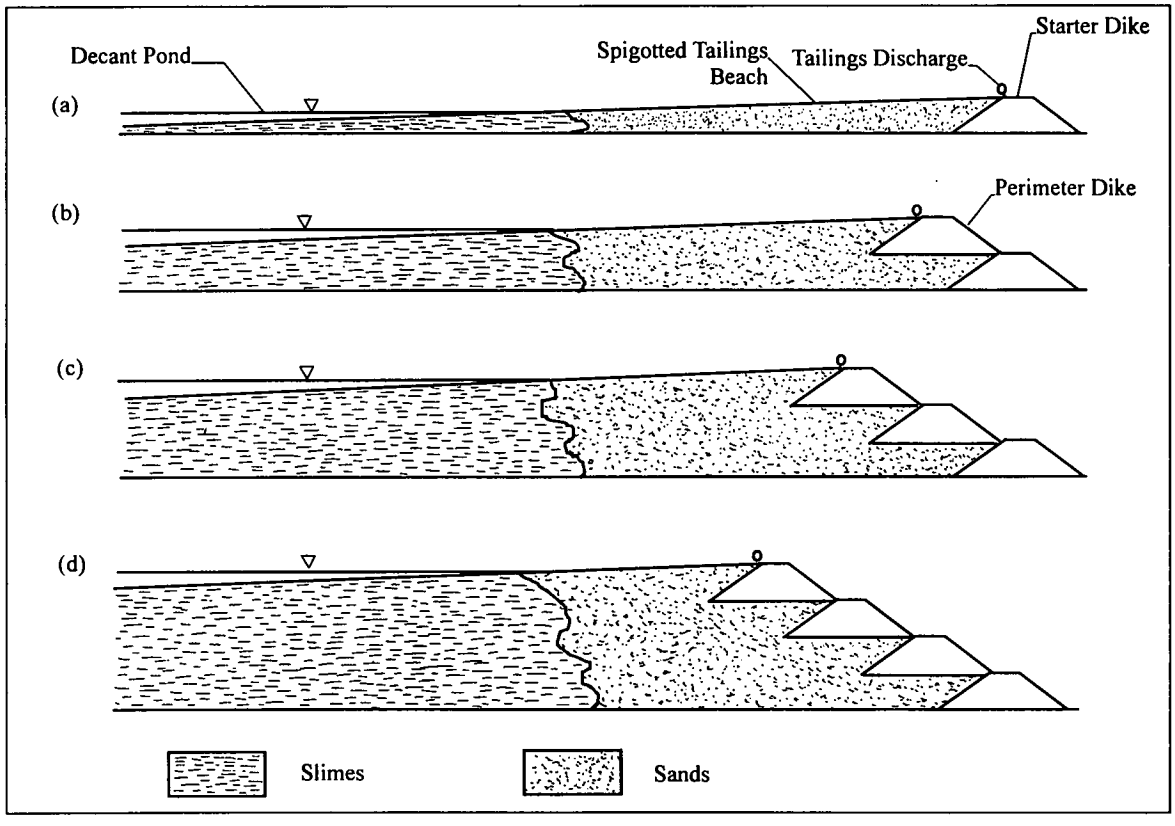

FIGURE 22-2 Sequential tailings dam raising and tailings deposition showing idealized sand and slimes regions (modified from Vick 1990).

transition between zones of sand tailings and slimes in a tailings deposit is gradual, interlayered, and indistinct and is governed by the various techniques and locations of tailings slurry discharge adopted during operation of the impoundment. Nevertheless, characterization of a tailings deposit into regions of predominantly sand and slimes is fundamental to establishing broad ranges of physical, index, and engineering properties and to targeting subsurface exploration in key areas.

2.2 Sand Tailings Characteristics

Sand tailings derived from beach deposition are usually loose, with relative densities ranging from 30 to 50 percent. Upon initial deposition, they typically exhibit corrected standard penetration test (SPT) blowcounts, expressed as $(N_1)_{60}$, of 3 to 5. There is evidence to support some increase in $(N_1)_{60}$ values with time due to "aging" effects (Troncoso 1990).

2.3 Slimes Characteristics

Slimes, on the other hand, qualify as low-plasticity to nonplastic silts for tailings derived from grinding of metalliferous ores. Other ores and processes, most notably Florida phosphatic ores, exhibit less favorable plasticity, sedimentation, and consolidation characteristics in their clay slimes (Bromwell and Raden 1979; Schiffman et al. 1988). A void ratio of 0.8 to 1.3 is typical of many slimes deposits, with $(N_1)_{60}$ values often ranging from 1 to 3. Of particular significance to slope engineering issues is the high specific retention of void water exhibited by slimes. Once sedimentation and consolidation processes are complete, further gravity drainage seldom results in appreciable reduction in water content or gain in strength except in the zone affected by surface desiccation, which seldom extends below depths of 1 to 2 m. Thus, slimes deposits, even in dry climates, have remained soft and virtually fully saturated for up to 60 years after deposition has ceased and surface water has been removed. This feature, along with the associated low undrained shear strength, makes slimes the most troublesome tailings material from the point of view of slope engineering or embankment construction. Slimes deposits also exhibit high compressibility, although rates of consolidation are usually relatively rapid.

2.4 Typical Strength Characteristics

Strength characteristics governing slope stability vary according to sand or slimes characterization. For most types of sand tailings, the drained (effective-stress) friction angles typically range from 33 to 38 degrees. These relatively high values for loose materials are attributable to particle angularity. Sand tailings display virtually no effective cohesion intercept (c') except in special cases involving chemical cementation, such as gypsum tailings or tailings affected by oxidation of sulfide minerals (usually pyrite). Vick (1990) extensively summarized drained strengths for various tailings types.

Provided that the nature, origin, and depositional characteristics of sand tailings deposits are fully understood, estimates of drained strength based on published values for similar tailings types are often sufficient for effective-stress analyses. Slope stability is seldom sufficiently sensitive to ordinary variations in drained strength to justify extensive laboratory testing.

For slimes tailings, either drained or undrained strength may be pertinent to slope stability, depending on such factors as the degree of desiccation-induced overconsolidation that the slimes may have experienced during deposition. For slimes derived from metalliferous ores, drained (effective-stress) angles of internal friction are generally in the range of 28 to 37 degrees (Vick 1990). Slimes exhibit little or no effective cohesion.

The undrained strength (s_u) of slimes is, however, sensitive to details of the original deposition process. For slimes deposited within and beneath the decant pond, normally consolidated conditions prevail after dissipation of deposition-induced excess pore pressures, and the variation of undrained strength with depth can be characterized by stress-normalized ratios (s_u/σ_c') ranging from about 0.20 to 0.27 (Vick 1990; Ladd 1991). In contrast, slimes deposited above water or on intermittently saturated portions of the beach or otherwise influenced by local desiccation during deposition may exhibit far more irregular undrained strength patterns, which may be difficult to assess (MacIver 1961). Although recovery of undisturbed samples of saturated slimes for laboratory testing is possible using fixed-piston samplers, vibration during sample transport or sample extrusion frequently causes gross disturbance and densification. Draining of sample tubes in the field

before transport and freezing of recovered samples have both been used successfully to reduce these effects. Alternatively, Wahler and Associates (1974) and MacIver (1961) provided examples of undrained strength assessment for slimes by field vane-shear testing. However, thin sand seams are often present, especially in beach transition zones, and these may make drainage conditions during vane-shear testing difficult to ascertain. In conjunction with conventional sampling, the cone penetrometer test (CPT) is very useful for identifying interlayering and other stratigraphic details of tailings deposits.

3. SLOPE STABILITY AND ENVIRONMENTAL ISSUES

Slope stability problems related to tailings deposits most commonly arise in connection with dams that contain the deposited slurry, and a rich literature on tailings-dam stability exists, including work by Morgenstern (1985), Kealy and Soderberg (1969), Soderberg and Busch (1977), Klohn (1972), Vick (1990), and Corp et al. (1975). Brawner (1979) described several failures and repair case histories. Seismic stability of tailings dams is of considerable importance because of the liquefaction susceptibility of tailings deposits; examples of current practice in dynamic analysis were provided by Finn et al. (1990), Troncoso (1988), Lo et al. (1988), and Vick et al. (1993).

Although tailings-dam design and analysis methods apply in principle to transportation-related slope engineering situations involving tailings, important differences exist. Chief among these are the following:

1. Route alignments on or through tailings deposits most often involve excavated cuts,
2. Tailings may be considered as a borrow source for embankment fill, and
3. Tailings deposits are inactive and abandoned rather than actively operated in conjunction with ongoing mining operations.

3.1 Stability of Excavated Cuts

Stability of excavated cuts in inactive tailings deposits is ordinarily controlled by the cohesionless nature of the sand and the undrained strength behavior of the slimes. Conventional limit-equilibrium procedures of slope stability analysis apply to tailings deposits, but more important than the computational procedure is the adoption of appropriate strength parameters. Ladd (1991) provided a thorough discussion of effective stress analyses versus undrained strength analyses in actively operating tailings impoundments and demonstrated that pore pressures due to undrained shearing must be addressed in assessing slope stability. These findings apply to excavated slopes in tailings slimes as well and emphasize the previously discussed importance of stress history and undrained strength resulting from the original circumstances of slimes deposition.

Equal in importance to calculating stability of cuts in tailings deposits is evaluating the feasibility of excavating them. The typically dry and even dusty surface of abandoned tailings deposits may produce a misleading impression. Although sand tailings eventually dewater by gravity drainage given sufficient time and foundation permeability, even perched water remaining in sand layers can produce "running" conditions on excavated faces. The same is true for slimes, which may remain fully saturated only a few feet below the desiccated surface crust long after the impoundment has been abandoned. Both saturation and low undrained shear strength of slimes seriously impede the mobility of wheeled construction equipment during excavation, and costly and time-consuming dragline or backhoe excavation techniques must often be used. These problems have been avoided during large-scale remining of tailings by hydraulic excavation (McWaters 1990), but this requires that a new impoundment be constructed to retain the excavated tailings slurry.

3.2 Use of Tailings as Fill

Tailings from abandoned deposits have been considered for use as highway fill. Dry sand tailings have been found to have suitable compaction characteristics and engineering properties. Pettibone and Kealy (1971) presented typical engineering properties for compacted tailings fill and described the use of tailings borrow for construction of a 6-km section of Interstate-90 near Kellogg, Idaho.

However, in the construction of highway fills using tailings, their highly erosive nature must be considered (see Section 3.4). A roadway fill constructed from tailings at Silverton, Colorado, was rapidly eroded when a culvert designed to carry the flow of a small stream became blocked with debris

FIGURE 22-3
Erosion of highway fill constructed from tailings, Colorado State Highway 110, Silverton, Colorado, May 1985. Road embankment was destroyed in a few hours when culvert designed to carry flow of Boulder Creek became blocked with debris during a period of high spring runoff. Fill acted as temporary dam but was quickly eroded once flowing water overtopped it. Reconstruction of roadway with new culvert took several weeks.
COURTESY OF *THE SILVERTON STANDARD AND THE MINER*

FIGURE 22-4
View across eroded section of highway fill constructed from tailings, Colorado State Highway 110, Silverton, Colorado, May 1985. Light-colored slope (*background*) is part of active tailings disposal, which has been constructed with relatively steep slope. Remains of wooden supports for former tailings discharge pipes are visible on slopes. Mill is situated behind tailings, and access to it was disrupted by this failure.
COURTESY OF *THE SILVERTON STANDARD AND THE MINER*

during a spring storm (Figures 22-3 and 22-4). The blockage was not detected during the night and the stream overflowed the fill and rapidly eroded it. Once started, the erosion occurred so rapidly that nothing could be done to prevent it. Reconstruction took several weeks. This road was not a major highway but did provide the only access between an active gold mine and its mill as well as the only feasible access to recreation sites in a mountain valley. The erosion of the road fill thus caused some measurable economic hardship.

3.3 Toxicity of Tailings

Use of tailings as highway fill or disposal of excavated tailings may present environmental issues related to toxic liability. Potential toxicity of tailings depends on the geochemistry of the orebody and the nature of the metallurgical processing and cannot be generalized even for ores of the same basic type. Although probably the majority of tailings deposits are chemically innocuous, some tailings may contain high levels of such constituents as arsenic, lead, cadmium, fluoride, or molybdenum, which can be harmful if ingested by humans, grazing animals, or certain plants. Such exposure can be enhanced when disturbed tailings are dispersed by wind. The solubility, mobility, and potential for transport of many heavy metals within groundwater or surface-water environments are greatly enhanced by the low pH levels generated by sulfide oxidation of some abandoned deposits, especially those rich in pyrite, pyrrhotite, or marcasite minerals. Exposure of such tailings surfaces to the atmosphere accelerates oxidation and acidification through complex chemical and biological reactions. Gadsby et al. (1990) provided an overview of recent research and practice in this area.

3.4 Erosion Susceptibility of Tailings

Environmental issues also derive from the highly erosive nature of tailings slopes, and special measures may be necessary to reduce and control sediment transport. Because of their relatively fine and uniform grain size, tailings are erodible by water and wind. Slopes as flat as 3H:1V are frequently considered necessary for erosion control and establishment of vegetation. Erosion considerations rather than mass stability may ultimately be found to govern slope design for tailings.

Slope erosion notwithstanding, eroded material from adjacent flat tailings surfaces can affect transportation facilities. Tailings eroded by water can quickly plug ditches and culverts, and wind erosion has been known to cause visibility-related safety hazards in dry climates. The rapid erosion of a highway fill constructed from tailings near Silverton, Colorado, was mentioned in Section 3.2. This rapid erosive failure resulted from a blocked culvert, which dammed a small stream and caused it to overtop the highway fill. The adjacent active tailings disposal site is shown in Figure 22-4. This site was constructed with comparatively steep slopes. Wind erosion on these slopes produced large dust clouds under relatively low wind velocities. The steepness of the slopes hampered revegetation efforts. With the recent final closure of the mine and mill, these slopes are being regraded to lower angles and revegetation is beginning to help stabilize these tailings. Such revegetation of exposed tailings surfaces can be complicated by the absence of nutrients, poor textural characteristics, and sometimes by the high residual metal concentrations in the tailings, which may be toxic to plants. Successful revegetation of large areas of tailings often requires specialized studies, including field test plots. Smaller areas can be quickly revegetated by covering tailings surfaces with topsoil, although this may be quite expensive.

4. FAILURE OF TAILINGS IMPOUNDMENTS

Slope failure and breaching of actively operating tailings dams are frequently accompanied by flowing of the saturated tailings deposit. These flows have produced extensive damage and loss of life in the past, but damage to adjacent transportation facilities has historically been limited to temporary closure of railroads and highways. Perhaps the greatest potential hazard may be posed by certain types of actively operating tailings dams where flows triggered by seismic failure may affect lifeline transportation facilities such as highways or pipelines and impede postearthquake disaster response and recovery efforts. Vick (1991) presented methods of estimating flow runout distances in the event of tailings embankment failure. These procedures have been used to address the impacts of potential tailings flows on adjacent highways for existing and proposed tailings dams in Utah and Montana (Vick, unpublished study).

The potential for flow failures from abandoned tailings deposits is less clear but is the topic of current research (Troncoso 1990). Dobry and Alvarez (1967) studied many tailings deposits subjected to strong earthquake ground motion in Chile and documented a number of liquefaction failures and flows from actively operating tailings impoundments. However, with inactive deposits, slope effects were limited to deformation and cracking. No flow failures are known to have occurred for abandoned tailings deposits that did not retain impounded water, under earthquake loadings or otherwise (USCOLD 1994).

Nevertheless, in one recent case involving two abandoned tailings deposits in Missouri that were constructed using unusual tailings deposition procedures and that retained surface water, dynamic analyses and flow-failure runout assessments were performed to evaluate the potential for inundation of a downstream community resulting from tailings-dam failure triggered by a seismic event (Vick et al. 1993). It was found that a proposed highway embankment downstream from the dams could be designed to retain a possible flow and thus substantially reduce the hazard to downstream residents. Thus, if potential failure hazards from tailings dams are evaluated and recognized in advance, judicious planning and layout of transportation facilities can mitigate their effects.

5. MITIGATION MEASURES

Construction of cuts and fills on or through tailings deposits requires addressing stability, subgrade compressibility, construction feasibility, and environmental factors. The characteristics of tailings deposits can be less favorable than those of natural soils in most of these respects. Various soil improvement methods have been considered for tailings deposits, many of which were summarized by Mitchell (1981, 1988). However, the applicability of virtually all such techniques is limited to specific characteristics of soil, saturation, or both. No single technique has been found universally feasible for both sand and slimes tailings under all conditions. Avoidance of tailings deposits during route selection, with due consideration for the risks that adjacent impoundments may pose, therefore remains a primary mitigation strategy.

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ABBREVIATIONS

ASCE American Society of Civil Engineers
USCOLD U.S. Committee on Large Dams

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