RI 8921

Bureau of Mines Report of Investigations/1985

Compaction Criteria for Metal and Nonmetal Tailings

By C. M. K. Boldt

UNITED STATES DEPARTMENT OF THE INTERIOR

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Library of Congress Cataloging in Publication Data:

Boldt, C. M. K. (Christine M. K.)

Compaction criteria for metal and nonmetal tailings.

(Bureau of Mines report of investigations ; 8921)

Bibliography: p. 27.

Supt. of Docs. no.: I 28.23:8921.

1. Tailings (Metallurgy). 2. Spoil banks. 3. Embankments—Safety measures. I. Title. II. Series: Report of investigations (United States. Bureau of Mines) ; 8921.

TN23.U43 [TN535] 622s [622'.7] 84-600203.

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm/s	centimeter per second	in/s	inch per second
c/min	cycle per minute	lb	pound
deg	degree	m	meter
ft	foot	mi	mile
ft•lb/ft^2	foot pound per square foot	min	minute
ft/min	foot per minute	mm	millimeter
ft/yr	foot per year	mph	mile per hour
g	gravity	pcf	pound per cubic foot
gal	gallon	pct	percent
h	hour	psi	pound per square inch
h/yr	hour per year	yd^3	cubic yard
in	inch	yd^3/h	cubic yard per hour
in^2	square inch	yr	year

COMPACTION CRITERIA FOR METAL AND NONMETAL TAILINGS

By C. M. K. Boldt [1]

ABSTRACT

The Bureau of Mines studied the compaction characteristics of metal and nonmetal tailings. Densities of the tailings and zone of compaction influence, compactive effort, and cost of equipment are related to changes in the factor of safety for specific grain-sized tailings and embankment configurations.

Field testing was accomplished in two distinct phases. The first phase investigated the effectiveness of using a nuclear gauge on metal and nonmetal tailings to produce rapid, instantaneous measurements of moisture content, wet density, and dry density. The results of the nuclear gauge testing are presented in chapter 1.

Chapter 2 presents a comparison of the compactive effectiveness of three different pieces of construction equipment on a coarse-grained metal tailings pond. The three pieces of equipment chosen for study were a D8H track-mounted dozer, a D500 rubber-tired dozer, and a SP848 vibratory smooth-drum compactor.

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CHAPTER 1.--NUCLEAR GAUGE APPLICABILITY ON MINE WASTES

INTRODUCTION

Since 1963, the Bureau of Mines has conducted field density tests on tailings and wastes using the rubber-balloon method, in accordance with ASTM D2167-66, and the sand-cone method, ASTM D1556-64. Although these tests have been adequate in obtaining in-place densities, the bulkiness of the test apparatus and the labor and time-intensive mode of securing results are drawbacks.

Surface nuclear source instruments capable of measuring moisture content and density are not new. Advances in technology, however, have resulted in improved reliability of the instrument and ease of operation. At present, nuclear gauges are used extensively by the construction industry to monitor soil compaction properties and conformance to specifications.

Although the use and reliability of the nuclear gauge in natural, compacted soil are generally accepted, a question remained as to its performance on processed mill tailings and waste piles. Side-by-side density tests were conducted on metal mine tailings ponds in Arizona, California, and Washington, and a coal preparation plant's compacted waste pile in West Virginia. In the case of the metal tailings tests, nuclear gauge results were compared with results from the Washington Balloon Dens-o-meter.[2] As part of another Bureau project (1),[3] the preparation plant coal waste pile was tested using the nuclear gauge and the sand-cone method.

Specifically, the present investigation compares the results of in-place density readings obtained by the balloon densimeter and the Troxler model 3411 nuclear gauge on the metal tailings. The procedures used and the test results obtained are discussed in detail in the following sections.

[2]Reference to specific products does not imply endorsement by the Bureau of Mines.

[3]Underlined numbers in parentheses refer to items in the list of references at the end of this report.

TEST METHODS

Rubber-Balloon Test

The ASTM-approved method of conducting the rubber-balloon in-place density test involves placing a template on the ground, mounting the densimeter on the template, and securing a zero reading. A test hole is then dug, which has a minimum required volume dependent on the maximum particle size of the material to be tested, thickness of the compacted layer, and capacity of the equipment (ASTM standard test D2167-66). The test hole is measured for volume by replacing the densimeter on the template and filling the void with the membrane-enclosed fluid. All material from the hole is kept in an airtight container and is weighed, dried, and weighed again to determine the water content and dry density.

The Washington Balloon Dens-o-meter (fig. 1) meets the ASTM requirements and is used frequently by the Bureau for in-place density tests on tailings ponds. Some of the disadvantages of using the rubber-balloon method are

1. The weight and size of the densimeter and necessary equipment make it difficult for one person to carry.

2. The rubber membrane is susceptible to breaking or leaking.

3. For each test conducted, the soil from the excavated hole must be scrupulously preserved and weighed in a laboratory setting to determine the water content and subsequent dry density.[4]

[4]To avoid handling large samples, the excavated material can be weighed in the field and only a representative sample of soil analyzed for water content.

FIGURE 1. - Balloon densimeter.

4. The time required to obtain the dry density averages 16 h. This reflects only the ASTM-recommended drying time and does not take into account the elapsed time of transporting the sample to the laboratory. Field drying can be accomplished in 20 min; however, final results should be based on laboratory ovendrying.

5. Since the volume is obtained by pressurizing the fluid-filled membrane, the material being tested should not deform easily nor should the test hole have too rough a surface.

Sand-Cone Test

The sand-cone method is similar to the rubber-balloon test in that a hand-dug hole is filled with a calibrated medium in order to measure the volume--in this case, clean, dry, calibrated sand. Figure 2 illustrates the sand-cone apparatus and test procedure. After the excavated material is weighed and the water content determined, the dry density can be calculated.

The disadvantages of using the sand-cone method are

1. The sand-cone apparatus and necessary equipment for conducting this test are bulky and difficult to transport for repetitive testing.

2. For each test conducted, the soil from the excavated hole must be scrupulously preserved and weighed to determine the water content and subsequent dry density.

3. The time required to calculate the dry density averages 16 h. If there was a mobile laboratory at the site, the time to complete the test would still be 20 min; however, the convenience of on-site determination of moisture content, wet density, and dry density would be available.

4. A supply of clean, dry, calibrated sand must be maintained.

5. In material with large particles, it is difficult to excavate the hole smoothly and fill all the voids.

Nuclear Gauge Test

For the particular gauge studied, the nuclear source emits cesium-137 gamma photons from a submerged source to sensors located on the instrument. As the density of the material increases, more photons are scattered by the test material's electrons. This phenomenon is internally calibrated, enabling the direct readout of wet density. Figure 3 illustrates the typical direct transmission mode of density readings. For moisture readings, americium-241:beryllium

FIGURE 2. - Sand-cone apparatus.

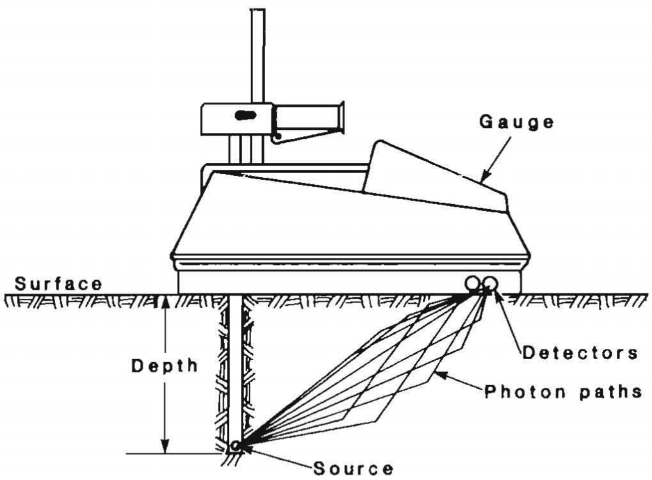

FIGURE 3. - Nuclear gauge.

neutrons are emitted from a source in the middle of the bottom plate with the detectors immediately adjacent. The moisture content reading is based on hydrogen's slowing the emitted neutrons. If more hydrogen is present (water form is assumed by the gauge), increased water content is read.

Direct readings are computed and displayed for percent Marshall, percent Proctor, wet density, dry density, and percent moisture when the corresponding buttons on the gauge keyboard are pressed.

The nuclear source densimeters have the following disadvantages, inherent in the theory behind the photon-neutron principle:

1. In elements higher than atomic No. 30, fluorescence occurs. This photoelectric interference happens when an electron falls back into a normal orbit from the excited state after being hit by the photon. In construction soils, this would not be a major problem; however, mineral wastes or ore bodies can contain significant concentrations of the elements above atomic No. 30 (i.e., lead, uranium, mercury, molybdenum, silver, gold, and arsenic), which can affect the direct wet density readings.

2. The moisture readings will be affected and must be adjusted if the material contains a significant amount of hydrogen not in water form. This is true for organics, either as a mineral processing additive or in the material itself, such as coal.

3. Since the gauge is based on molecular interaction, readings may be misleading in materials containing a significant amount of voids. Accuracy of the gauge increases with increasing density; therefore, in tailings or waste rock, which have been loosely deposited, irregular readings may be generated. It is important that the gauge operator be familiar with the material's properties to recognize this condition.

4. Because the gauge uses radioactive material, the storage, transport, disposal, and use of the gauge are closely regulated, with correspondingly strict recordkeeping and operating procedures.

5. The operator may lose a "feel" for the soil, since tests are quick and totally instrumented.

TEST PROCEDURE

At each site, tests were conducted along a line at designated intervals, starting at the periphery and running inward toward the pond area.

At each sample station, the ground was prepared by leveling the area with as little disturbance as possible. The test using the nuclear source method was usually conducted first, since it involved less area disruption. Next to the nuclear test site, not more than 3 ft away, but far enough to miss the direct transmission probe hole, the balloon or sand-cone control test was conducted. All nuclear source tests used the direct transmission geometry (the radiation source positioned from the bottom of the gauge by inserting a probe down a prepunched hole) with the source set at 4 in below the surface. This was done to more closely parallel the balloon testing procedure, which involved digging an average 6-in-deep test hole below the balloon densimeter plate.

Soil samples obtained from the balloon tests were brought back to the Bureau for weighing and drying.

TEST SITES

Test sites were chosen for their diversity in mined mineral content. Wastes from coal, zinc, copper, and iron were tested. At each site, multiple tests were conducted and the results tabulated for comparative purposes.

Test site A is located in West Virginia. The nuclear gauge method was compared with the sand-cone method in a previous Bureau project entitled "Compaction Criteria for Coal Waste Embankments" (1). The waste studied was from a coal preparation plant and consisted of a variety of materials, including mudstones, shales, stiff clays, and weakly cemented sandstones. The wastes were used to construct an impoundment for fly ash and fine refuse.

The test site was built in controlled layers, and various construction equipment was studied for compactive effectiveness. Therefore, the test results indicate varying degrees of densities. The important consideration, however, is still valid, namely, the performance of a nuclear gauge on mining wastes.

Test site B is located in Washington State. This zinc operation has not been active for over 10 yr. The tailings embankment was constructed by the upstream-spigoting method and consists primarily of limestone and quartz.

Test sites C and D are in Arizona. These are primarily copper mines with secondary mineralization of silver, gold, selenium, and molybdenum. Both tailings ponds use the upstream-spigoting method of deposition, with the wastes consisting of schist, quartz, magnetite, and pyrite.

Test site E is an iron ore mine located in California. The tailings material consists of quartzite, andesite, and limestone.

TEST RESULTS

Of the five sites, three sites (A, B, and C) produced direct nuclear wet density readings having between a 3.2- and 4.2-pcf average discrepancy with the control test readings. The average discrepancy was calculated as the average of the whole number difference between the nuclear and control readings. This discrepancy is within the 3- to 5-pcf range of acceptance as specified by ASTM D2922-78, standard test method for density of soil and soil-aggregate in-place by nuclear methods (shallow depths).

Site D contained extremely wet, silty tailings, averaging 20 pct moisture. As the tests were conducted, the nuclear gauge visibly settled into the material, and the side walls of the excavated hole probably deformed during the volume calibration of the balloon densometer.

At site E, all of the direct readings from the nuclear gauge were higher than those from the rubber-balloon control test.

Tables 1 through 5 summarize the comparative readings at each test site and include the average discrepancies between the nuclear gauge readings and the control test readings.

TABLE 1. - Site A, coal waste

Sample	Wet density, pcf		Dry density, pcf		Moisture content, pct		Wet density difference,[1] pcf	Dry density difference,[1] pcf	Moisture difference,[1] pct
	Sand	Nuclear	Sand	Nuclear	Sand	Nuclear			
1...	120.0	123.2	112.1	104.4	5.7	18.8	+3.2	-7.7	+13.1
2...	123.4	123.9	115.3	107.2	7.0	15.5	+.5	-8.5	+8.5
3...	121.1	125.3	114.2	110.7	6.1	13.3	+4.2	-3.5	+7.2
4...	122.6	119.4	115.1	104.0	6.4	14.6	-3.2	-11.1	+8.2
5...	124.3	123.8	116.7	108.6	6.5	14.1	-.5	-8.1	+7.6
6...	130.1	129.1	120.8	109.9	7.7	17.5	-1.0	-10.1	+9.8
7...	122.4	119.4	117.5	107.4	4.1	11.2	-3.0	-10.1	+7.1
8...	120.6	123.6	113.1	105.8	6.7	16.9	+3.0	-7.3	+10.2
9...	134.1	132.0	124.2	113.7	8.0	16.0	-2.1	-10.5	+8.0
10..	140.8	129.7	130.3	113.6	8.1	14.2	-11.1	-16.7	+6.1
11..	137.3	131.2	128.3	115.4	7.0	13.6	-6.1	-12.9	+6.6
12..	135.8	128.1	128.3	112.2	5.9	14.2	-7.7	-16.1	+8.3
13..	126.4	121.7	118.0	100.6	7.1	20.2	-4.7	-17.4	+13.1
14..	134.8	128.5	125.2	110.8	7.7	16.0	-6.3	-14.4	+8.3
15..	133.4	136.8	126.0	124.5	5.9	10.7	+3.4	-1.5	+4.8
16..	145.0	135.2	135.5	120.4	7.0	12.3	-9.8	-15.1	+5.3
17..	138.5	138.6	129.7	123.5	6.7	12.2	+.1	-6.2	+5.5

[1]Difference = nuclear test result - control test result.

TABLE 2. - Site B, zinc tailings

Sample	Wet density, pcf		Dry density, pcf		Moisture content, pct		Wet density difference,[1] pcf	Dry density difference,[1] pcf	Moisture difference,[1] pct
	Balloon	Nuclear	Balloon	Nuclear	Balloon	Nuclear			
1...	116.8	113.6	105.1	99.4	11.1	14.3	+3.2	-5.7	+3.2
2...	111.8	109.8	101.2	98.8	10.5	11.2	-2.0	-2.4	+.7
3...	113.1	110.0	106.4	102.4	6.3	7.5	-3.1	-4.0	+1.2
4...	[2]138.9	109.9	124.7	96.4	11.4	14.1	-29.0	-28.0	+2.7
5...	114.9	113.3	101.7	98.7	13.0	15.7	-1.6	-3.0	+2.7
6...	97.6	108.6	92.9	97.7	5.1	11.1	+11.0	+4.8	+6.0
7...	119.5	115.3	110.4	103.3	8.2	11.7	-14.2	-7.1	+3.5
8...	117.7	115.2	104.3	98.3	12.8	17.2	+2.5	-6.0	+4.4
9...	109.8	109.1	103.6	99.1	6.0	10.1	-.7	-4.5	+4.1
10..	108.6	109.6	103.9	101.3	4.5	8.2	+1.0	-2.6	+3.7
11..	110.5	110.9	101.4	98.8	9.0	12.3	+.4	-2.6	+3.3
12..	111.5	109.5	102.7	97.2	8.6	12.6	-2.0	-5.5	+4.0
13..	107.0	107.2	100.3	97.6	6.7	9.9	+2.0	-2.7	+3.2

[1]Difference = nuclear test result - control test result.
[2]Balloon membrane disengaged.

TABLE 3. - Site C, copper tailings

Sample	Wet density, pcf		Dry density, pcf		Moisture content, pct		Wet density difference,[1] pcf	Dry density difference,[1] pcf	Moisture difference,[1] pct
	Balloon	Nuclear	Balloon	Nuclear	Balloon	Nuclear			
1...	97.4	98.6	90.0	93.6	7.8	5.3	+1.2	+3.6	-2.5
2...	95.2	99.7	80.5	86.6	19.1	15.2	+4.5	+6.1	-3.9
3...	95.3	98.0	84.5	90.8	12.8	7.9	+2.7	+6.3	-4.9
4...	100.8	105.5	92.0	93.9	9.6	12.3	+4.7	+1.9	+2.7
5...	101.9	104.1	87.0	89.6	17.2	16.3	+2.2	+2.6	-1.1

[1]Difference = nuclear test result - control test result.

TABLE 4. - Site D, copper tailings

Sample	Wet density, pcf		Dry density, pcf		Moisture content, pct		Wet density difference,[1] pcf	Dry density difference,[1] pcf	Moisture difference,[1] pct
	Balloon	Nuclear	Balloon	Nuclear	Balloon	Nuclear			
1..	106.7	115.8	87.4	92.9	22.0	24.7	+9.1	+5.5	+2.7
2..	88.0	120.7	67.8	92.4	29.8	30.7	+32.7	+24.6	+.9
3..	86.4	117.1	71.1	92.3	21.6	26.8	+30.7	+21.2	+5.2
4..	97.5	120.7	79.5	96.7	22.6	24.8	+23.2	+17.2	+2.2
5..	110.2	115.7	91.8	95.5	20.1	21.4	+5.5	+3.7	-1.3
6..	103.7	121.2	85.8	96.5	20.9	25.6	+17.5	+10.7	+4.7
7..	113.5	121.7	94.0	96.9	20.7	25.5	+8.2	+2.9	+4.8
8..	105.2	117.7	83.2	92.0	23.5	28.0	+12.5	+8.8	+4.5
9..	103.5	119.9	87.1	96.5	18.8	24.3	+16.4	+5.5	+5.5
10..	105.6	114.7	89.6	96.6	17.8	18.8	+1.0	+1.0	+1.0

[1]Difference = nuclear test result - control test result.

TABLE 5. - Site E, iron tailings

Sample	Wet density, pcf		Dry density, pcf		Moisture content, pct		Wet density difference,[1] pcf	Dry density difference,[1] pcf	Moisture difference,[1] pct
	Balloon	Nuclear	Balloon	Nuclear	Balloon	Nuclear			
1..	102.2	114.7	87.4	101.1	5.7	13.6	+12.5	+13.7	+7.9
2..	106.9	110.4	92.5	98.2	5.0	12.4	+3.5	+5.7	+7.4
3..	99.1	108.9	87.5	99.1	5.7	9.9	+9.8	+11.6	+4.2
4..	90.6	106.2	78.4	95.1	5.2	11.6	+15.6	+16.7	+6.4
5..	98.8	108.2	85.3	96.5	6.4	12.1	+9.4	+11.2	+5.7
6..	96.9	118.0	83.6	106.0	5.9	11.3	+21.0	+22.4	+5.4
7..	113.5	118.8	98.4	107.0	5.3	11.0	+5.3	+8.6	+5.7
8..	98.2	112.1	87.6	99.7	5.7	12.4	+13.9	+12.1	+6.7
9..	91.7	97.4	79.9	88.4	6.2	10.2	+5.7	+8.5	+4.0
10..	101.3	108.2	90.1	97.7	12.4	10.7	+6.9	+7.6	+1.7

[1]Difference = nuclear test result - control test result.

Study of the data shows that moisture readings from both the nuclear gauge and the control test on all sites tended to parallel each other from one sample station to another. The following example is taken in part from table 1:

	Moisture content, pct: Nuclear	Moisture content, pct: Control		Moisture difference between sample stations, pct
Sample 1....	18.8	5.7		
Sample 2....	15.5	7.0		
Difference..	3.3	- 1.3	=	2.0
Sample 2....	15.5	7.0		
Sample 3....	13.3	6.1		
Difference..	2.2	- 0.9	=	1.3

At site A, 7 of the 17 nuclear-versus-control moisture content readings varied more than 2.0 pct between sample stations. Sites B through E recorded only two or three readings varying more than 2.0 pct between sample stations.

The hydrogen content of the coal waste explains the more varied moisture data at site A, while at the remaining sites the majority of readings were consistently parallel. It is deduced that once the nuclear gauge is calibrated for moisture at each site, the readings would be within tolerances for direct dry density readings.

In comparing the wet density readings from the nuclear gauge with the control test readings, the average discrepancies at sites A, B, and C were within the ASTM tolerances of 3 to 5 pcf. This was anticipated since no overriding reason for discrepancies existed prior to testing. Adequate control tests could not be obtained at site D because of excessively wet material. However, site D's nuclear wet density readings could be assumed correct since calculating the volume of the hole is not necessary, unlike in the control test. Also, the nuclear source determination of wet density does not depend on a physical "volume of a hole" variable. Site E's nuclear and control wet density readings were neither within ASTM tolerances nor significantly alike. This could be attributed to the visible amount of magnetically attracted material in the samples, indicating a considerable amount of iron. Because the nuclear moisture content readings are not affected by heavy metals, they remained within the paralleling trend of the remainder of the test sites.

CONCLUSIONS

Sites A through C, representing coal, zinc, and copper wastes, were read directly for wet density without correction of the nuclear gauge, and the discrepancies fell within ASTM-approved tolerances. Site D's nuclear wet density readings could be assumed correct, but adequate control tests could not be obtained.

Site E, representing iron tailings, produced wet density readings outside ASTM tolerances. This could be caused by the high level of iron residue left in the tails after mill processing.

The nuclear gauge should have been calibrated for moisture correction on all of the tailings studied. Since this was not done during the field testing, the dry density readings were also nontolerant.

The conclusions of this investigation cannot, at present, be used to generalize that all coal, zinc, and copper wastes can be directly read for density and moisture with the nuclear gauge, or that direct density or moisture readings cannot be taken on any iron tailings. Even on the same site, direct nuclear readings cannot be automatically assumed to be accurate merely because past correlations have shown them to be, since the mineral composition of tailings and wastes can be changed by a change in the ore body or milling process.

After the instrument has been calibrated for the site, the rapid and simple procedures involved in obtaining readings make the nuclear gauge a valuable tool. However, because of the instrument's strict operative and maintenance guidelines and calibration requirements, it would have limited usefulness unless a considerable number of moisture and density tests are needed or immediate tests results are necessary.

In the area of research, numerous mine sites are tested in the course of a study. The advantage of quick and immediate test results at each site is countered by the necessity of conducting calibration control tests by either the balloon or sand method. This would entail transporting two sets of instruments to each site, plus the equipment to conduct weighing and drying of the soil samples in the field. This cumbersome disadvantage may be avoided if tailings are shipped to the home laboratory prior to tests at the study sites. The nuclear gauge can then be precalibrated by conducting the control and nuclear tests on the tailings, which should be placed at optimum moisture and contained in a box roughly 18 by 18 in and 4 in deeper than the depth of measurement.

CHAPTER 2.--COMPACTION OF METAL TAILINGS

INTRODUCTION

The objective of this phase was to obtain scientific data concerning compaction efforts and corresponding densities in metal and nonmetal tailings ponds. Both advantageous and detrimental effects are anticipated when tailings are compacted. As an example, compaction of an embankment could increase the factor of safety by increasing the shear strength of the material. This would allow the mine operators to consider increasing the total height or steepening the embankment to increase the disposal capacity of the site. However, when the density of the impoundment and the height of the pond increase, the pond level and phreatic surface could rise because of horizontal slime layer buildup from segregation during compaction or less seepage capacity of the tailings. This rise could offset the stability gained by densifying the tailings. Also, mechanical manipulation of the tailings need not necessarily mean the tailings are being compacted. If sands are not completely saturated or ovendry while being worked, bulking may occur.

Three pieces of construction equipment were studied on various grain-sized tailings, to derive a relationship linking work effort and costs to factor of safety. The three pieces of equipment chosen for study were the 1965 Caterpillar D8H track-mounted dozer, a 1965 Hough D500 rubber-tired dozer, and a 1974 Rexnord SP848 17,000-lb vibratory smooth-drum compactor. The characterizations of each type of equipment are listed separately in the "Equipment Specifications" section in this chapter.

Increases in density were correlated to increasing shear angles and decreasing permeabilities. The U.S. Army Corps of Engineers two-dimensional, finite-element seepage program was used to determine the phreatic surface location and flow changes at the embankment exit face (2). A program using both Bishop's and Fellenius' method of slices was used to calculate factor of safety associated with increasing density (3).

TAILINGS CHARACTERISTICS AND COMPACTION

Previous studies have shown that cohesionless sands with a relative density (D_r) of 50 to 60 pct will not liquify under seismic motion less than 0.1 g (4). However, hydraulically placed tailings tend to achieve no greater than 50 pct relative density (5). Although slurry densities can be increased to increase the density of the deposited tailings, an optimum limit exists after which any increases in slurry density will not produce any higher deposited density (6-7).

The frequency, amplitude, and total weight of a vibrating unit necessary to achieve compaction were studied by Forssblad and Hall in 1965 and 1968 (8-9). The U.S. Army Corps of Engineers found that cohesionless material with little fines could be compacted by vibration (10), and Townsend, in 1972, quantified it to soils with less than 12 pct fines (11). In all of the studies, greater densities could be achieved by vibratory methods when the cohesionless material was compacted in a saturated state.

Specific equipment was developed to achieve maximum density with a minimum of work. Vibratory rollers, sheepsfoot rollers, vibratory sheepsfoot rollers, and vibratory probes were used. Even conventional earthmoving machinery was adapted to compact soils. Sowers, in 1970, studied the influence zone of the treads of a crawler tractor (12) and found that the soils did not densify to any great degree 3 or 4 in below the treads. Table 6, taken from CANMET's Pit Slope Manual (13), lists some conventional construction equipment and their compactive zones of influence, with the number of passes necessary to obtain maximum density.

TABLE 6. - Comparative influence[1] of various equipment (13)

Equipment type and applicability	Compacted lift thickness, in	Coverages	Remarks
Sheepsfoot rollers: For fine-grained soils or dirty coarse-grained soils with more than 20 pct passing No. 200 mesh; not suitable for clean coarse-grained soils. Particularly appropriate for compacting impervious zone for earth dam or linings where bonding of lifts is important.	6	[2]4-6 [3]6-8	Foot contact--5- to 12-in^2 area and 250- to 500-psi pressure for fine-grained soil (Pl>30); 7- to 14-in^2 area and 200- to 400-psi pressure for fine-grained soil (Pl<30); 10- to 14-in^2 area and 150- to 250 psi pressure for coarse-grained soil. Efficient compacting of wet soils requires less contact pressure than for the same soils at lower moisture contents.
Rubber-tired rollers:			
For clean coarse-grained soils with 4 to 8 pct passing No. 200 mesh.	10	3-5	Tire inflation pressures 60 to 80 psi for clean granular material or base course and subgrade compaction; wheel load 18,000 to 25,000 lb; tire inflation pressures in excess of 65 psi for fine-grained soils of high plasticity; for uniform clean sands or silty fine sands, use large-size tires with pressure of 40 to 50 psi.
For fine-grained soils or well-graded, dirty coarse-grained soils with more than 8 pct passing No. 200 mesh.	6- 8	4-6	
Smooth-wheel rollers:			
Appropriate for subgrade or base course compaction of well-graded sand-gravel mixtures.	8-12	4	Tandem-type rollers for base course compaction, 10- to 15-ton weight, 300 to 500 lb per lineal inch of width of rear roller.
May be used for fine-grained soils other than in earth dams; not suitable for clean, well-graded sands or silty uniform sands.	6- 8	6	3-wheel roller for compaction of fine-grained soil; weights from 5 to 6 tons for materials of low plasticity to 10 tons for materials of high plasticity.
Vibrating baseplate compactors: For coarse-grained soils with less than about 12 pct passing No. 200 mesh; best suited for materials with 4 to 8 pct passing No. 200 mesh, placed thoroughly wet.	8-10	3	Single pads or plates should weigh no less than 200 lb; may be used in tandem where working space is available; for clean coarse-grained soil, vibration frequency should be less than 1,600 c/min.
Crawler tractor: Best suited for coarse-grained soils with less than 4 to 8 pct passing No. 200 mesh, placed thoroughly wet.	10-12	3-4	No smaller than D8 tractor with blade, 34,500-lb weight for high compaction.
Power tamper or rammer: For difficult access, trench backfill; suitable for all inorganic soils.	[4]4- 6 [5]6	2	30-lb minimum weight; considerable range is tolerable, depending on materials and conditions.

[1]Requirements for compaction of 95 to 100 pct Standard Proctor maximum density.
[2]Passes for fine-grained soil.
[3]Passes for coarse-grained soil.
[4]For silt or clay.
[5]For coarse-grained soils.

The use of construction equipment to provide vibratory-type compaction on mine tailings was documented by Mittal in 1977 and 1981 (14-15). On material slurried at 40 to 45 pct solids and 30 pct passing 200 mesh, he found that compaction by wide-track dozers, as soon as the tailings were deposited, helped enable the mine to increase the embankment height from 40 ft, using overburden waste, to 300 ft, using tailings.

EQUIPMENT SPECIFICATIONS

Three different pieces of equipment were studied for their effects on metal and nonmetal tailings. The individual equipment specifications are shown in figures 4, 5, and 6. No in-house modifications were made. Selected specifications for the equipment are given in tables 7 through 9.

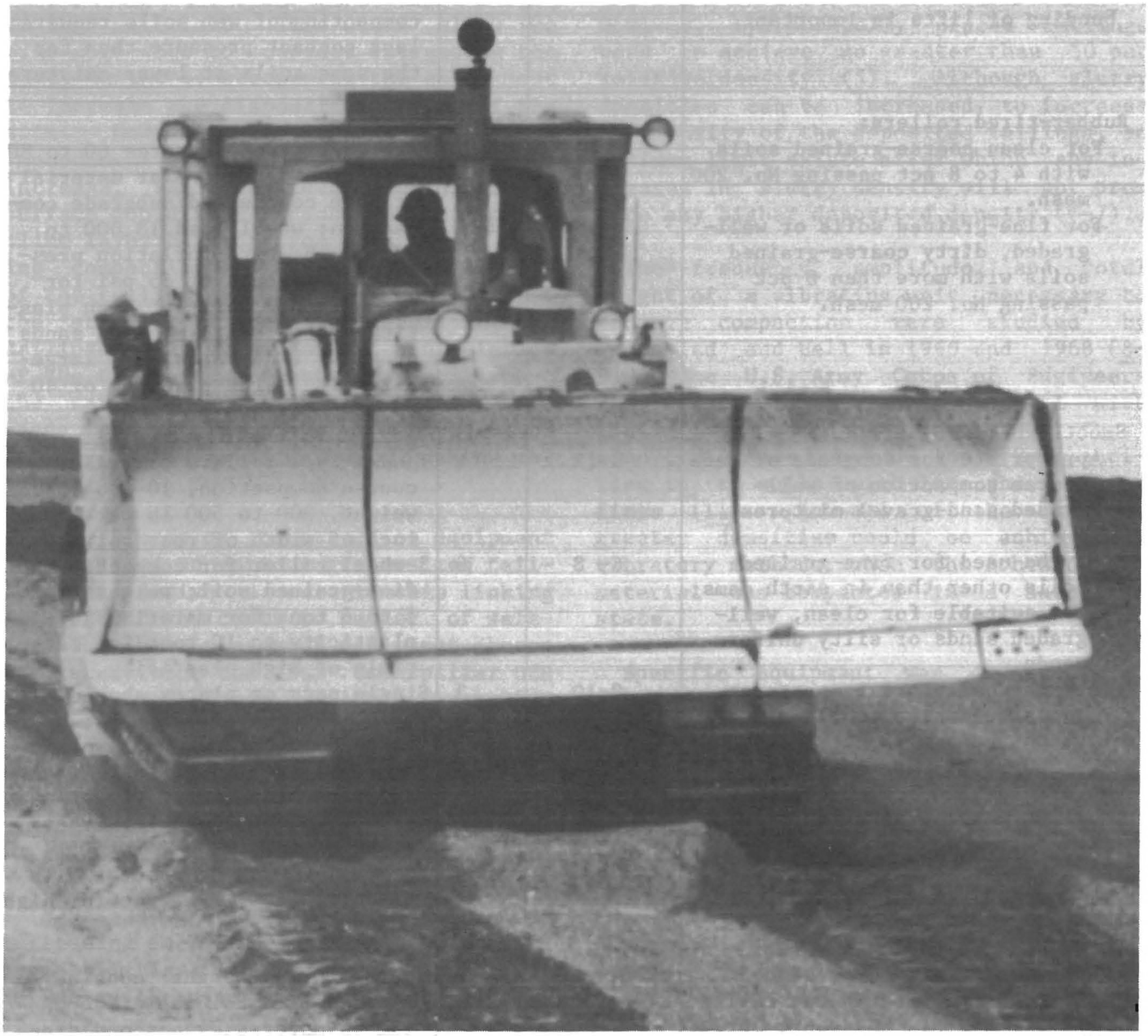

FIGURE 4. - D8H track-mounted dozer.

FIGURE 5. - D500 rubber-tired dozer.

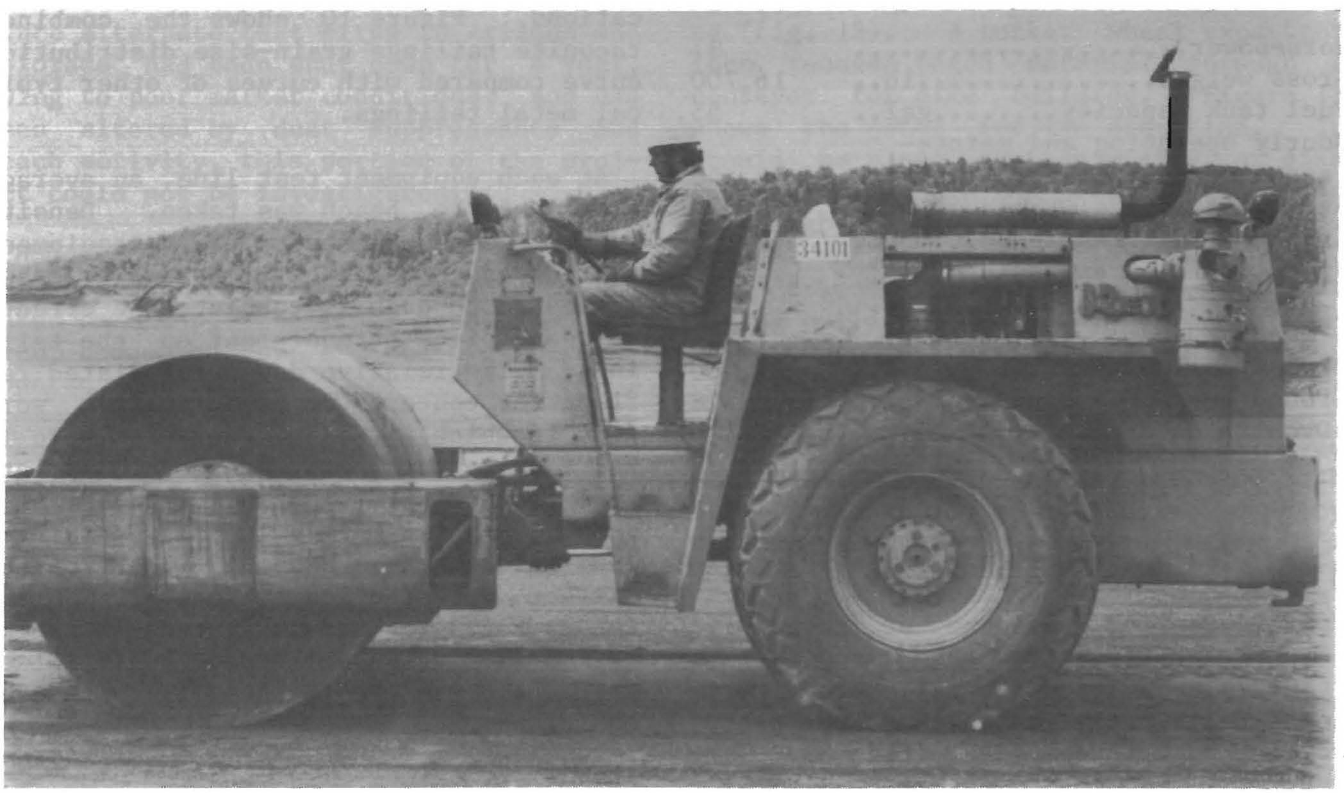

FIGURE 6. - SP848 vibratory smooth-drum roller.

TABLE 7. - Selected specifications for D8H track-mounted dozer

Horsepower....................	285
Blade type....................	8U
Gross weight plus blade....lb..	60,000
Fuel tank capacity........gal..	134
Hourly operating and maintenance costs..................	$130
Average downtime..........pct..	20
Average operating speed...mph..	2
Ground bearing pressure...psi..	8

TABLE 8. - Selected specifications for D500 rubber-tired dozer

Horsepower....................	635
Blade type....................	D500 coal
Gross weight plus blade....lb..	150,000
Fuel tank capacity........gal..	380
Hourly operating and maintenance costs..................	$229
Average downtime..........pct..	20
Average operating speed...mph..	4
Ground bearing pressure...psi..	58

TABLE 9. - Selected specifications for SP848 vibratory smooth-drum roller

Horsepower....................	87
Gross weight...............lb..	16,700
Fuel tank capacity........gal..	55
Hourly operating and maintenance costs..................	$48
Average downtime..........pct..	20
Average operating speed...mph..	2
Vibratory drum dimensions, in:	
Diameter....................	60
Width.......................	84
Drum dynamic force........psi..	27,000
Ground bearing pressure[1]..psi..	18

[1]Dynamic on drum only.

FIELD TEST DATA

Taconite Tailings--Site 1

Field testing was done at three different locations on the site 1 pond (fig. 7). The taconite tails are direct-deposited at the embankment periphery, forming an upstream beach (fig. 8). The

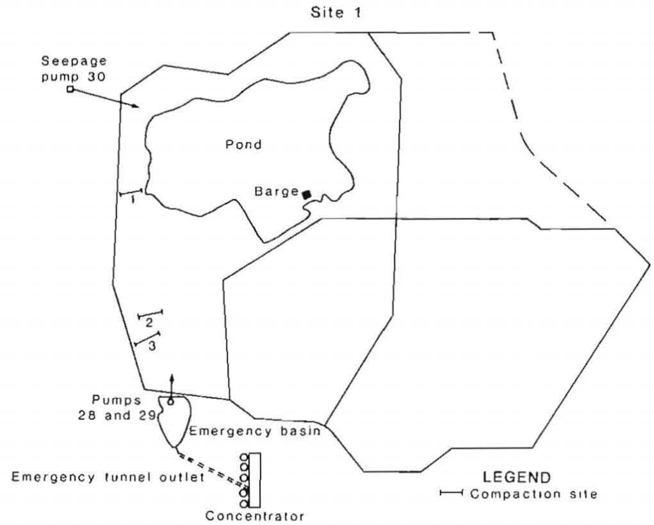

FIGURE 7. - Site 1 tailings basin plan.

beach is then pushed by D500 and D8H dozers to the next 5-ft lift on the crest (fig. 9).

The grain-size analysis showed no appreciable differences among samples from the three equipment test line locations. Therefore, laboratory tests were conducted on combined samples from all three locations. Figure 10 shows the combined taconite tailings grain-size distribution curve compared with curves of other typical metal tailings.

At each equipment test line, an average slope of the beach was taken. Density samples were obtained prior to equipment testing and after each consecutive pass. Tables 10 through 12 tabulate the effects of each piece of equipment on the tailings. The relative densities listed reflect the concerns of E. T. Selig's work (16) in which a random error of ±10 to 15 and a systematic error of 25 to 30 points were found. This makes values greater than 100-pct relative density possible. The net density change 12 in below the surface was also taken for the D8H and SP848 procedure and is listed in tables 10 and 12. Figure 11 graphically illustrates the change in density with each equipment pass.

FIGURE 8. - Taconite tailings, direct-deposited.

Copper Tailings

Field testing was started on lead-zinc tailings at a second site; however, the bearing capacity of the tailings was insufficient to support the test equipment. Since alternate test sites in Arizona and Colorado had been shut down for a year, owing to poor market conditions, and had been altered by dust suppressants and beach activity, this portion of the project could not be investigated.

However, during the course of the project, after-the-fact density readings were taken on a copper tailings pond that had been compacted by a modified track-mounted transporter.

Density readings were taken at three areas of the tailings pond. Area 1 had been upstream-spigoted a year earlier and had not been altered except by time and weather. Area 2 was compacted by a D8H dozer only as a consequence of building up a 15-ft lift on the dike. Area 3 was carefully compacted by a modified, four-track-mounted swamp transporter with a rated ground pressure of 2.5 psi, unloaded (fig. 12). A bucket wheel excavator then removed beach material through a conveyor for dike building. Figure 13 shows the setup for the operation. It should be noted that this type of dike building procedure has been questioned as a design consideration since the borrow area trench parallels the entire dike. This trench then acts as a catchment basin, building up a shell of less permeable composite tailings just within the embankment face (17).

The gradation of the tailings ranged from 52 to 10 pct passing the 200 mesh sieve. Table 13 summarizes the density readings.

FIGURE 9. - Embankment crest being built.

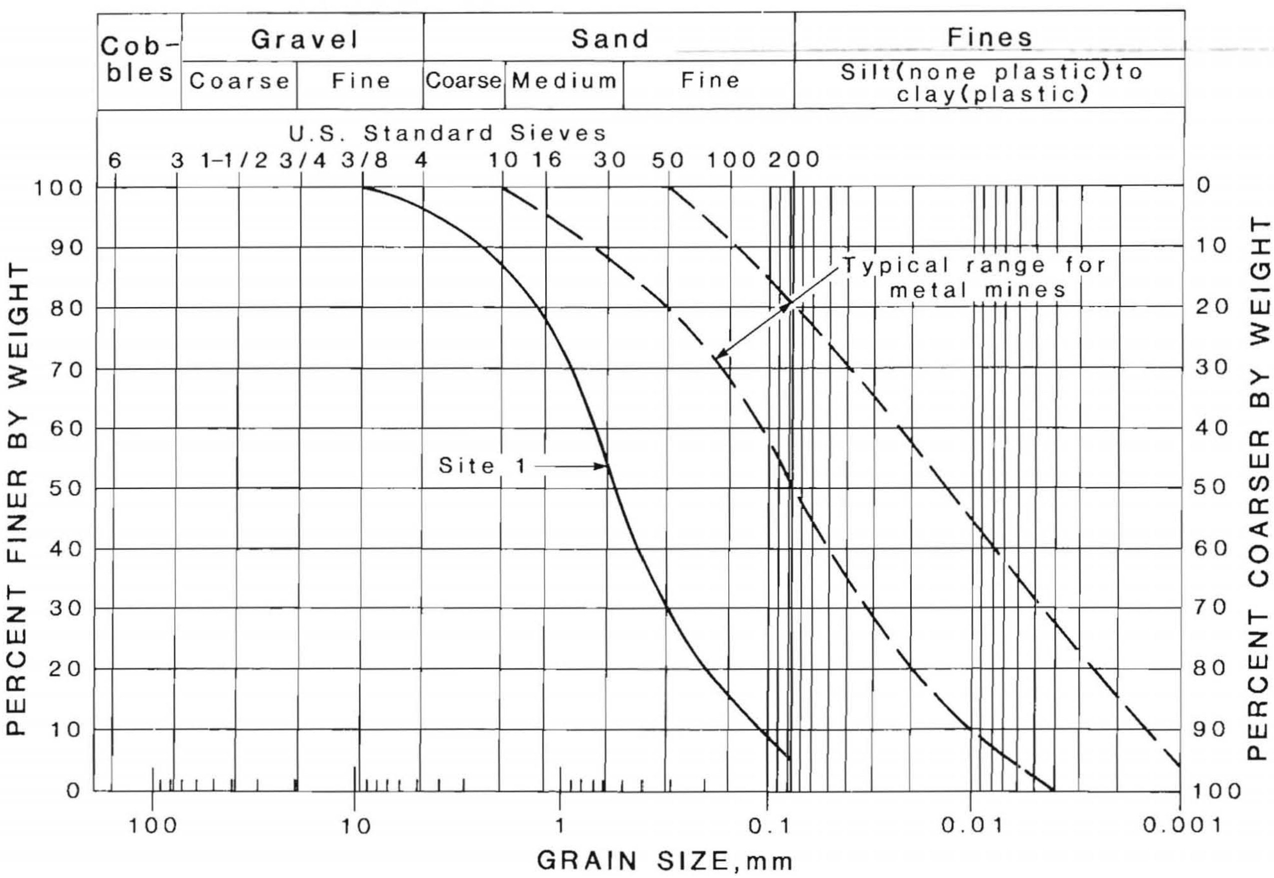

FIGURE 10. - Gradation curves of typical metal tailings.

TABLE 10. - Density change per pass for D8H track-mounted dozer

Station	Dry density (γ), pcf	Moisture, pct	Void ratio (e)	Relative density (D_r), pct	12-in depth (γ_{wet}), pcf	12-in depth (γ_{dry}), pcf
0+00:						
In situ...........	106.57	6.2	0.768	-23.0	NA	NA
1st pass..........	110.00	5.7	.713	-6.5	NA	NA
2d pass...........	128.52	6.0	.466	67.6	NA	NA
3d pass...........	115.23	7.3	.635	16.9	NA	NA
4th pass..........	114.41	6.7	.647	13.4	NA	NA
0+40:						
In situ...........	108.49	6.9	.737	-13.6	118.58	108.68
1st pass..........	117.90	4.4	.598	28.0	NA	NA
2d pass...........	122.83	4.6	.534	47.2	NA	NA
3d pass...........	110.85	5.3	.700	-2.5	NA	NA
4th pass..........	115.14	7.1	.637	16.5	132.91	128.38
0+88:						
In situ...........	115.95	3.8	.625	19.9	NA	NA
1st pass..........	124.27	5.7	.603	26.5	NA	NA
2d pass...........	112.53	7.1	.745	5.1	NA	NA
3d pass...........	97.33	7.3	.936	-73.3	NA	NA
4th pass..........	114.86	4.6	.641	15.3	NA	NA
1+50:						
In situ...........	112.15	7.2	.680	3.4	132.61	124.41
1st pass..........	115.62	6.9	.630	18.5	NA	NA
2d pass...........	99.16	10.0	.901	-62.6	NA	NA
3d pass...........	121.99	8.2	.545	44.0	NA	NA
4th pass..........	111.12	9.2	.696	-1.3	133.83	125.19

NA Not analyzed.

NOTE.--Summary of test factors:
Combined soil sample γ_{dry}max = 136.9 pcf, γ_{dry}min = 110.7 pcf.
Slope of sample line (average) = 1.5 pct.
Speed of machinery (average) = 1 to 2 mph.
Vibration: 0.55-g acceleration, 0.78-in/s velocity, 0.002-in displacement.
Tailings direct-deposited 4/3/82, tested 6/10/82.

LABORATORY TEST DATA

Prior to and after field testing, a series of laboratory experiments was conducted on tailings shipped from site 1. Since no field tests could be conducted on site 2, all laboratory tests were on site 1 tailings only. Modified Proctor tests and vibratory minimum and maximum density tests indicated the tailings reached a higher maximum density in the dry state using vibration. Tests were also conducted taking into consideration time, work, and density, where

$$W = FD,$$

where W = work,

F = force or weight of impactor,

and D = distance or displacement.

TABLE 11. - Density change per pass for D500 rubber-tired dozer

Station	Dry density (γ), pcf	Moisture, pct	Void ratio (e)	Relative density (D_r) pct
0+00:				
In situ......................	129.41	2.6	0.456	70.6
1st pass.....................	141.38	2.6	.333	170.6
2d pass......................	137.69	2.2	.376	95.8
3d pass......................	142.60	2.7	.145	111.0
4th pass.....................	138.47	2.7	.361	99.2
1+55:				
In situ......................	NA	NA	NA	NA
1st pass.....................	146.55	1.9	.289	121.7
2d pass......................	126.48	2.2	.490	60.5
3d pass......................	151.28	2.2	.246	133.7
4th pass.....................	132.75	1.1	.420	81.6
2+00:				
In situ......................	118.27	2.7	.593	29.5
1st pass.....................	116.58	3.3	.616	22.5

NA Not analyzed.

NOTE.--Summary of test factors:
Combined soil sample $\gamma_{dry}max$ = 139.08 pcf, $\gamma_{dry}min$ = 112.23 pcf.
Slope of sample line (average) = 4 pct.
Speed of machinery (average) = 3 to 5 mph.
No vibration test.
Tailings direct-deposited 1/22/82, tested 6/9/82.

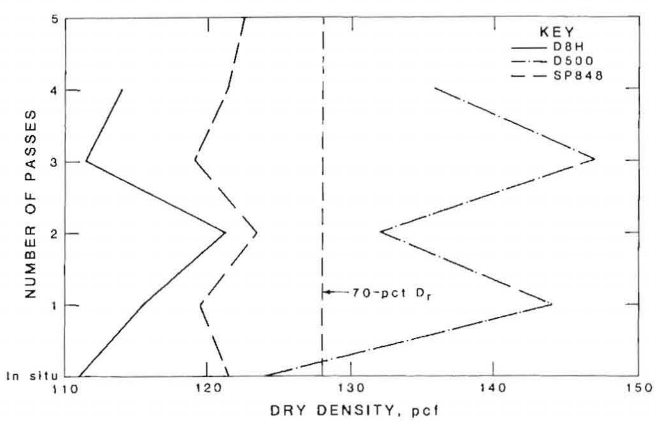

FIGURE 11. - Average surface density per equipment pass.

The vibration was analyzed using a portable vibration meter capable of reading acceleration, velocity, and displacement.

Figure 14 charts the change in dry density in relation to time on the vibration table, which was set at a given velocity, acceleration, and displacement.

Falling-head permeability results ranged from 2.77×10^{-3} cm/s at minimum density to 4.36×10^{-4} cm/s at maximum density. This range would put the tailings in the medium to low permeability classification of sand. Figure 15 shows the relationship between density and permeability.

TABLE 12. - Density change per pass for SP848 vibratory smooth-drum roller

Station	Dry density (γ), pcf	Moisture, pct	Void ratio (e)	Relative density (D_r), pct	12-in depth (γ_{wet}), pcf	12-in depth (γ_{dry}), pcf
0+00:						
In situ	122.99	4.7	0.532	47.8	134.25	126.92
1st pass	122.15	5.0	.543	44.6	NA	NA
2d pass	118.82	4.8	.586	31.7	NA	NA
3d pass	120.93	5.5	.558	40.0	NA	NA
4th pass	120.93	5.0	.558	40.0	NA	NA
5th pass	118.02	5.5	.597	28.5	144.40	133.22
0+45:						
In situ	109.72	6.3	.717	-7.8	141.56	134.32
1st pass	119.09	4.2	.582	32.8	NA	NA
2d pass	126.95	5.8	.484	62.1	NA	NA
3d pass	112.36	5.4	.677	4.3	NA	NA
4th pass	116.31	4.2	.620	21.4	NA	NA
5th pass	125.71	4.6	.499	57.8	145.12	135.90
0+90:						
In situ	132.51	4.6	.422	80.8	NA	NA
1st pass	116.98	4.9	.611	24.1	NA	NA
2d pass	123.95	4.8	.520	51.4	NA	NA
3d pass	123.44	5.1	.527	49.5	NA	NA
4th pass	126.36	5.0	.491	60.1	NA	NA
5th pass	123.14	4.8	.530	48.4	NA	NA

NA Not analyzed.

NOTE.--Summary of test factors:
Combined soil sample γ_{dry}max = 140.28 pcf, γ_{dry}min = 111.27 pcf.
Slope of sample line (average) = 2.8 pct.
Speed of machinery = 1 to 2 mph.
Vibration: 1.1-g acceleration, 1.4-in/s velocity, 0.02-in displacement.
Tailings direct-deposited 4/82, tested 6/11/82.

TABLE 13. - Density changes of copper tailings

Location and depth	Dike crest		Beach	
	Density (γ_{dry}), pcf	Relative density (D_r),[1,2] pct	Density (γ_{dry}), pcf	Relative density (d_r),[1] pct
Area 1, not altered:				
Surface	109	100	92	59
1 ft	105	NA	91	NA
2 ft	95	NA	85	29
3 ft	83	20	NA	NA
Area 2, D8H dozer:				
Surface	105	100	92	59
1 ft	95	NA	89	NA
2 ft	92	NA	81	10
3 ft	85	29	NA	NA
Area 3, low-ground-pressure tracked vehicle:				
Surface	98	81	106	100
1 ft	96	NA	NA	NA
2 ft	89	NA	NA	NA
3 ft	81	10	91	55

NA Not analyzed.

[1] $D_r = \frac{\gamma_{max}(\gamma - \gamma_{min})}{\gamma(\gamma_{max} - \gamma_{min})}$.

[2] Average γ_{min} = 79 pcf; average γ_{max} = 106 pcf.

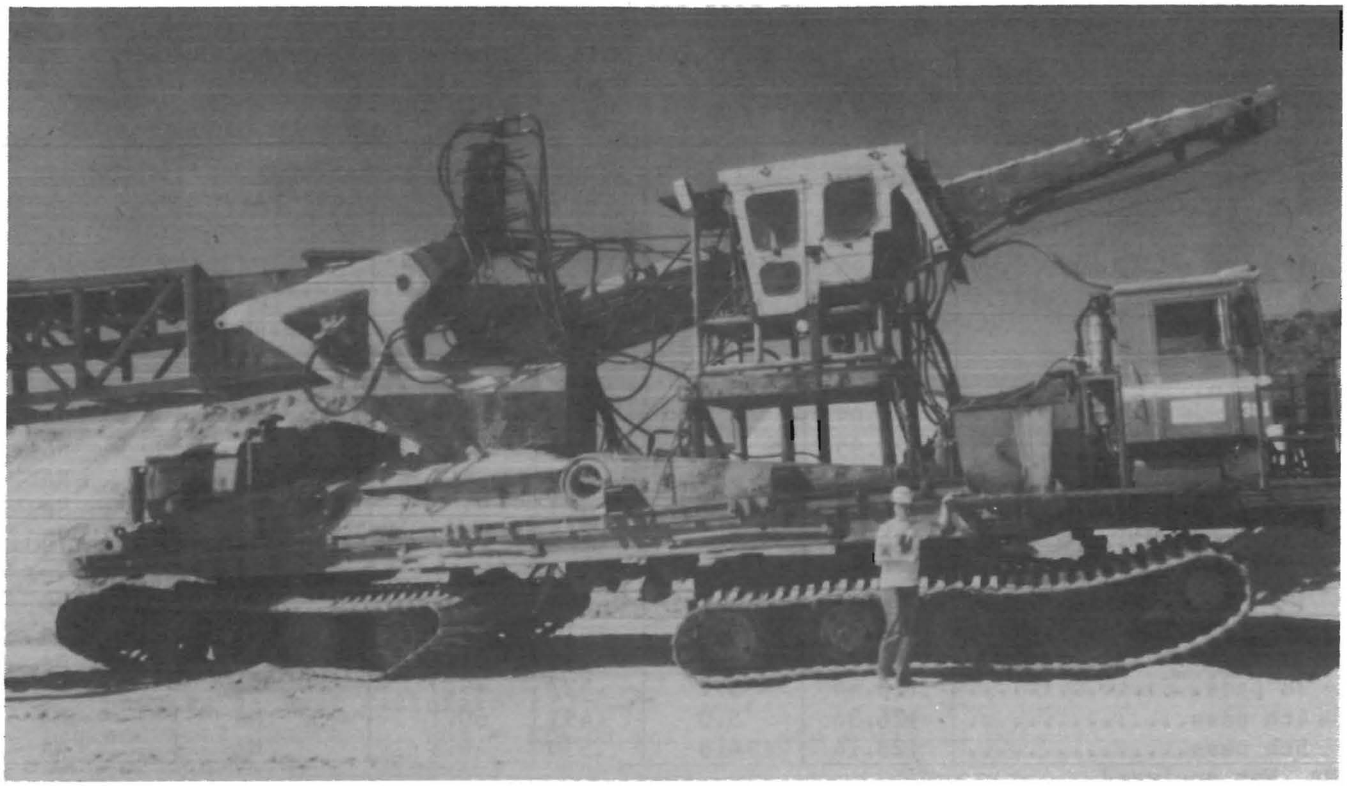

FIGURE 12. - Low-ground-pressure, modified transporter.

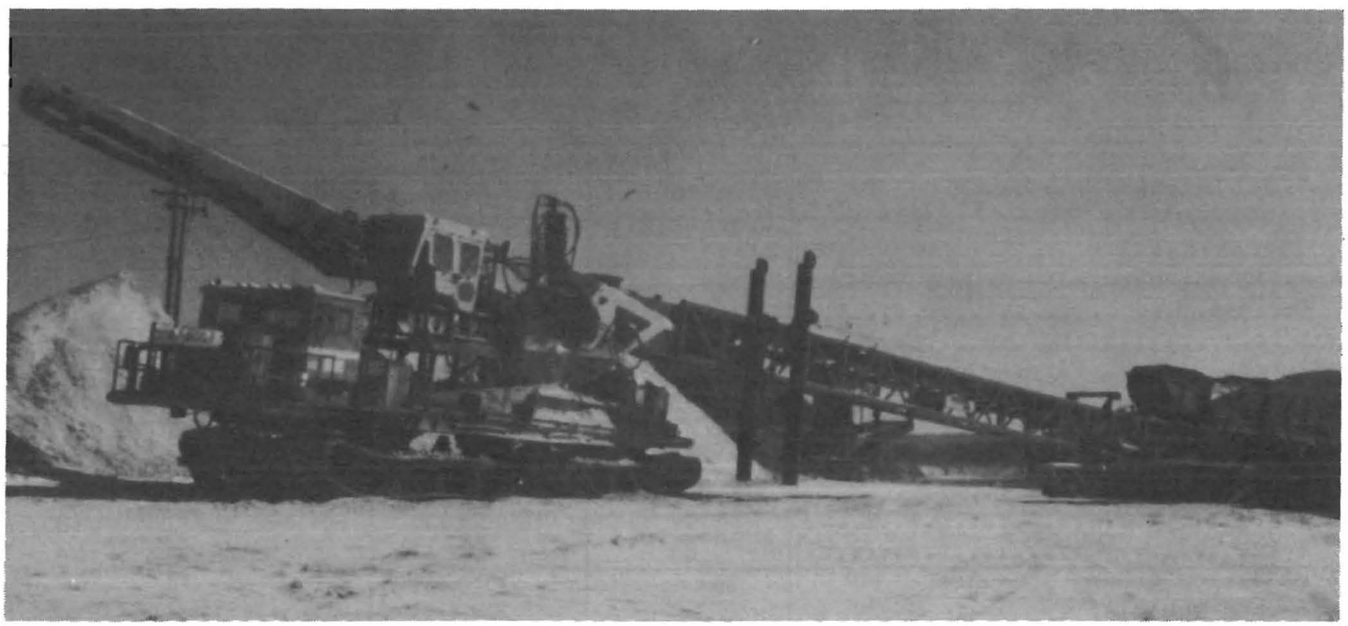

FIGURE 13. - Conveyor system.

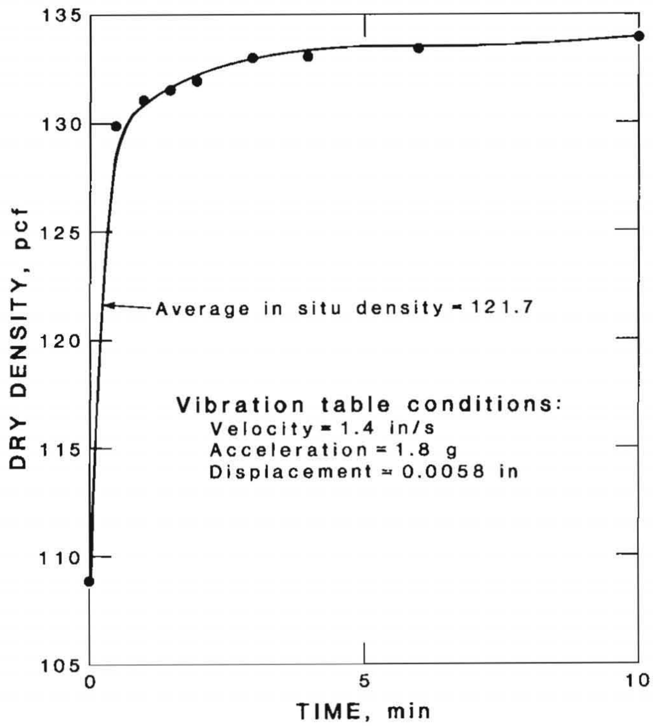

FIGURE 14. - Time-density curve for site 1 tailings.

	A	B	C
Permeability...ft/yr..	3,003	1,029	477
cm/s..	2.77×10^{-3}	9.40×10^{-4}	4.36×10^{-4}
Density...............	Min	50 pct max	95 pct max

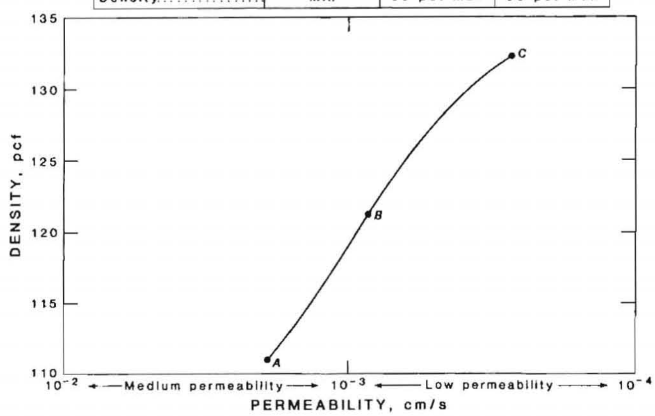

FIGURE 15. - Density-permeability curve for site 1 tailings.

Drained, triaxial shear tests were conducted on the combined tailings sample to determine shear strengths at different densities. The results are shown in figure 16.

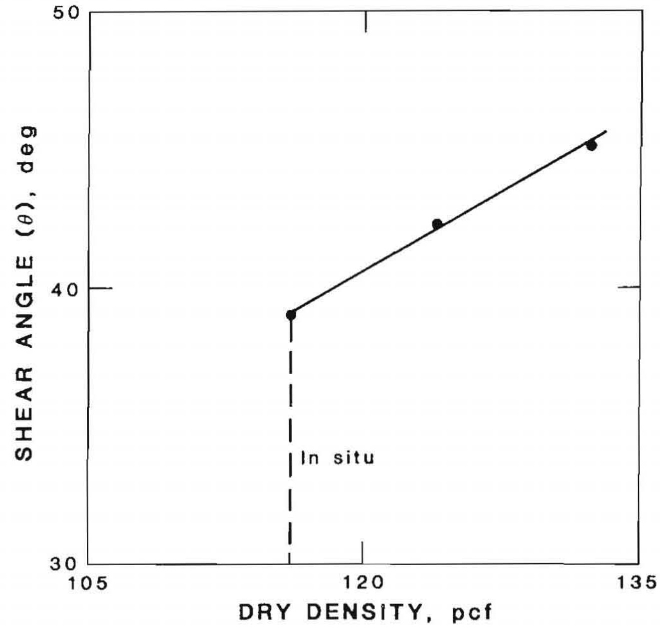

FIGURE 16. - Density-shear angles for site 1 tailings.

In order to compare changes in factor of safety with increased density, an idealized embankment was assumed. The embankment (fig. 17) was assumed to have a 3-to-1 sloping embankment face, a vertical height of 300 ft, and an upstream-spigoted beach slope of 2 pct. It also included layers of less pervious materials in the substrata and was homogeneous in the beach area, isotropic, and not affected by consolidation.

The pond was assumed to be in a steady-state flow situation with an impermeable layer at the base of the embankment and no perched water.

TEST RESULTS

To effectively compare the changes in density on a given material that were due to a given machine, each piece of equipment was analyzed for influence zone of compaction, change in density produced per pass, and cost per cubic yard to compact the coarse-grained tailings.

	Soil I[1]	Soil II	Soil III	Soil IV
Soil type....................	Coarse	Fine	Slime	Base
Dry density (γ_{dry})....pcf ..	111-138	130	130	130
Permeability (K)...ft/min ..	0.011-0.0034	0.00098	0.000098	0.0098
Shear angle (θ).......deg ..	39-46	38	30	40

[1]Varies with compaction.

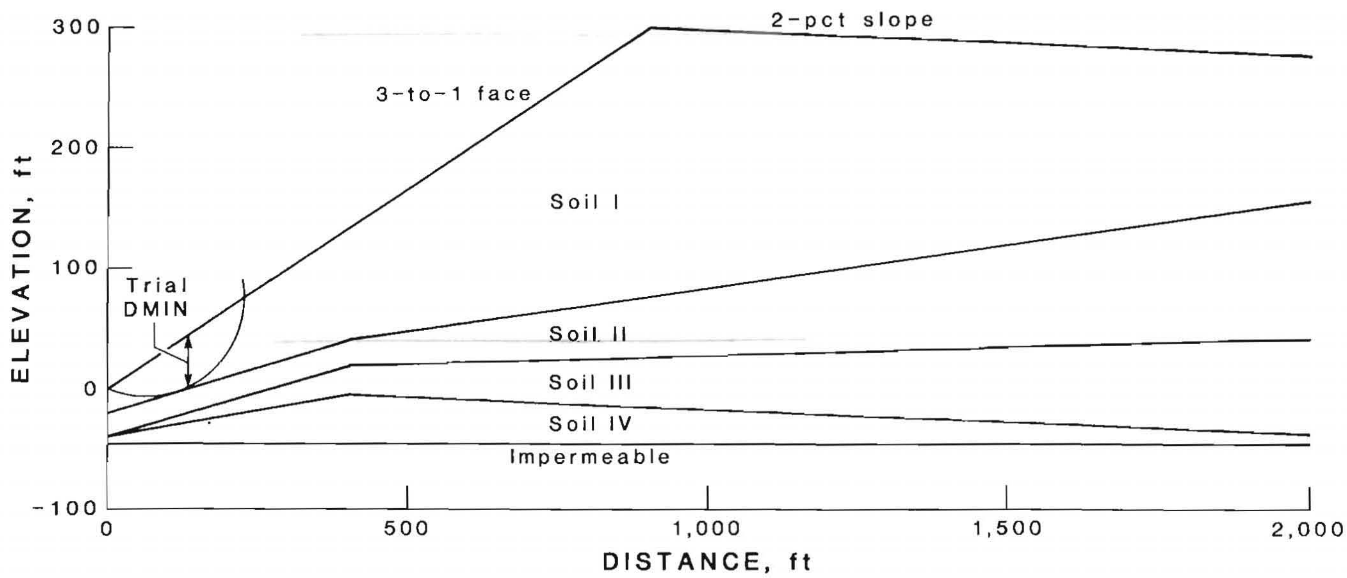

FIGURE 17. - Idealized 300-ft embankment.

The information from tables 10, 11, and 12, documenting the change in surface density after every pass, combined with an economic analysis of the cost to operate each machine (table 14), indicates that the vibratory smooth-drum roller, while having the lowest cost per cubic yard, did not increasingly compact the tails. The D500 significantly increased the density of the tails after the first pass but only undid what was done on subsequent passes, owing to excessive weight and shearing of the material, and the D8H alternately compacted and sheared the tails (fig. 18). Forssblad (8) mentioned the effects of vibratory compaction on the immediate surface of sand and gravelly soils with very little binder. In vibratory roller compaction, the density of the surface layer was not affected by variations in the intensity of vibration of the unit, but at the same time, the density achieved with vibration was higher than without vibration. And, while surface densities changed little or even decreased with continued vibratory compaction, subsurface densities increased to a maximum reached in approximately 6 to 10 passes. This phenonenon can describe the change in density per pass of the D8H and the SP848.

TABLE 14. - Costs of compacting equipment[1]

	D8H track-mounted dozer	D500 rubber-tired dozer	SP848 vibratory smooth-drum roller
Original equipment cost.............	$300,000	$600,000	$70,000
Annual cost[2].......................	$150,000	$300,000	$35,000
Hourly operating cost:			
Ownership.........................	$94	$188	$22
Fuel..............................	15	20	5
Operator..........................	21	21	21
Total........................	130	229	48
Distance covered in 1 h..........mi.	1.0	2.5	0.75
Compactive influence..........yd^3/h.	307	1,467	1,027
Cost per yd^3 per pass[3]..............	$0.42	$0.16	$0.05
Cost per yd^3 for 70-pct D_r[4].........	$1.26	$0.16	([5])

[1]Useful life of each piece of equipment: 7 yr; usage: 1,600 h/yr = 2,000 h/yr - 20 pct downtime was used for all equipment, assuming the equipment is used for continuous compacting.

[2]Annual costs, as a percentage of original equipment cost: depreciation, 15 pct; repairs, 15 pct; interest and taxes, 20 pct; total, 50 pct.

[3]Distance covered in 1 pass = forward and reverse.

[4]D_r = relative density.

[5]The SP 484 was not capable of compacting the tailings to 70-pct D_r.

Table 6 recommends either a rubber-tired roller or heavy-tracked vehicle on coarse-grained materials. Although the tails at site 1 are considered coarse and wet, it was not possible to keep them in a saturated condition because of their high permeability. Therefore, the D8H dozer would probably do better on a finer grained material, which would be able to hold water through the compactive effort.

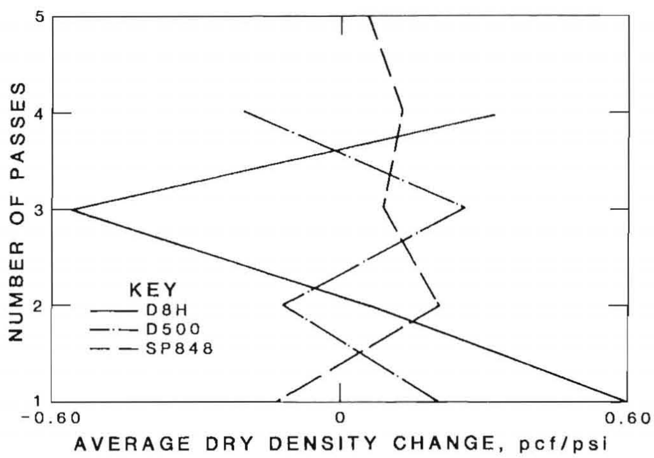

FIGURE 18. - Average density change for each equipment pass.

Rudimentary vibratory readings were taken on the D8H, SP848, and laboratory vibratory table in an effort to correlate work to change in density (fig. 19). Vibration readings were not taken on the D500 because there was no safe spot on which to mount the transducer and obtain readings while the unit was in motion. The vibratory table produced a classic, asymptotic relationship between work and cumulative change in density. The D8H and SP848 gave no indication of a similar relationship, although the SP848 did have fewer variations than the D8H. This could be attributed to the dozer's secondary and ineffective vibratory effort compared with the vibratory efficiency of the smooth-drum roller.

Computer analyses using two-dimensional finite-element programs were used to locate the phreatic surface in an idealized 300-ft embankment. The program is based on Darcy's law for steady-state flow and was developed by the U.S. Army Corp of Engineers Waterways Experiment Station (2). Embankment geometry, density (permeability at given densities),

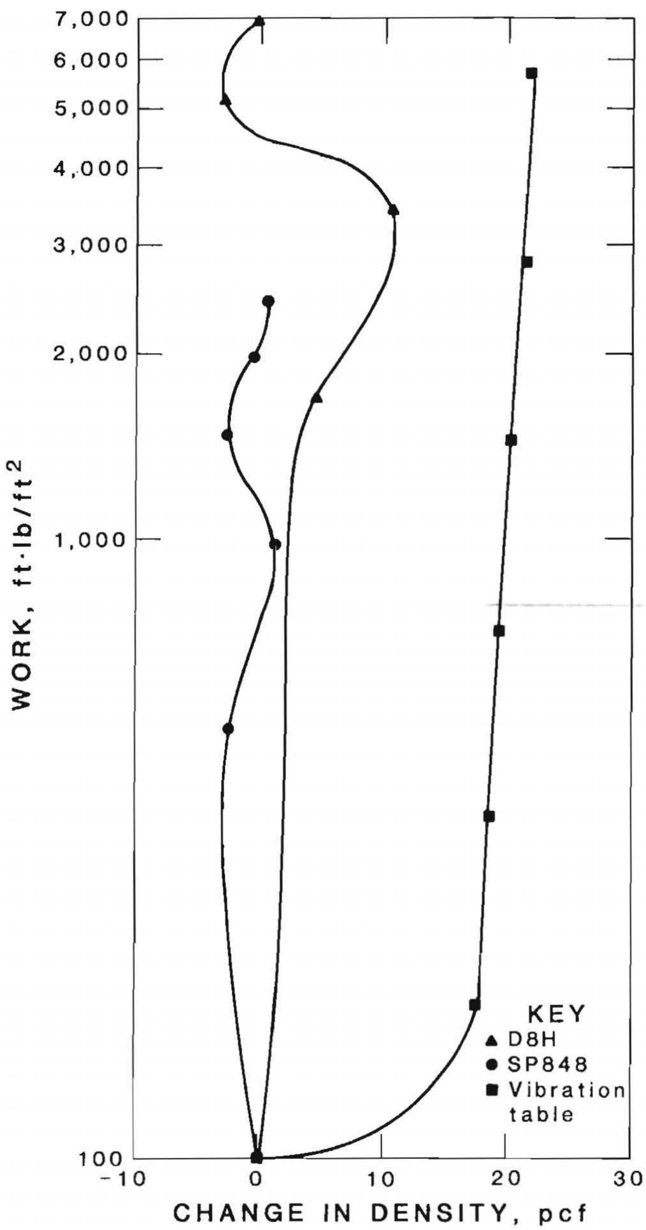

FIGURE 19. - Work to produce changes in density.

headwater level (pond elevation), and tail water level were input. Various pond elevations were input to reflect beach distances of 230 to 930 ft from the crest of the embankment.[5] The permeability-density relationship was taken from figure 15. Figure 17 describes the embankment geometry used.

After the phreatic level was located for each given parameter, a factor of safety analysis was run using Bishop's method of slices (3). Bishop's and Fellinius' factors of safety are computed for circular failure by inputing minimum failure circle dimension, embankment geometry, soil properties--density (γ), cohesion (c), and shear angle (ϕ)--and phreatic surface location. Figure 20 shows the relationship between changes in density and factor of safety for various assumed pond elevations.

According to the factor of safety (FS) analysis, the idealized 300-ft embankment would be considered "safe" (FS >1.5) for pond levels reflecting minimum beach distances of 200 ft when the tailings are compacted to 70-pct relative density. For noncompacted tailings, the beach distance is 600 ft. To compact the tailings from an in situ density of 117 pcf to 70-pct relative density of 128 pcf would cost \$0.16/yd^3 for the D500 and \$1.26/yd^3 for the D8H; the SP848 would never achieve 70-pct relative density.

If the D8H were used to compact an embankment 300 ft high by 1,500 ft long by 200 ft deep in order to take advantage of a smaller beach, the extra cost would be \$4,200,000, versus noncompaction and a beach distance of 600 ft.

In running iterative factors of safety with varying pond heads, a correlation became apparent. As the pond level increased (headwater closer to the embankment crest), the factor of safety did not continue to change as anticipated. Figure 20 shows a progressing relationship between factor of safety and increasing density until the head reached 291 ft (530 ft from the crest). With the head at 297 ft, the factor of safety relationship began regressing.

The hypothesis is that, as the phreatic surface reaches an optimum location at the bottom one-third of the embankment, all higher pond levels fail to

[5]This was necessary since the program altered the velocity of seepage through the embankment to reflect decreasing permeability, rather than raising the pond level. If it had been possible to show a rise in pond level, this rise could have then been directly related to a higher phreatic surface and a subsequently affected factor of safety.

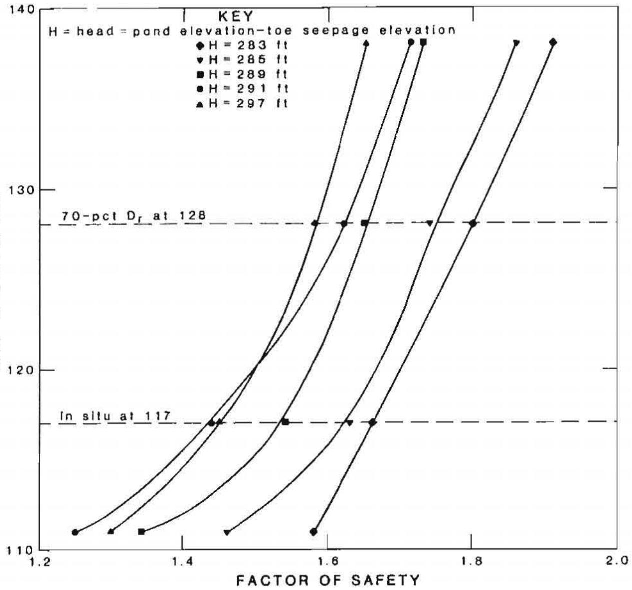

FIGURE 20. - Density-factor of safety relationship.

substantially change this location. This hypothesis, combined with the relatively small zone of influence of the failure circle (DMIN), was used in solving for the factor of safety. In the factor of safety analysis for the idealized 300-ft embankment, a DMIN equal to 20 ft was used, where DMIN is the vertical distance between the embankment face and the slip circle for the maximum slice (fig. 17).

A sensitivity analysis shows the influence of DMIN on a cohesionless embankment (table 15). A failure where DMIN equals 20 ft gave a factor of safety of 1.26, while a DMIN of 40 ft produced a factor of safety of 1.44. In tailings embankments that easily exceed 300 ft in height, failure circle depths must be carefully chosen to reflect the severity of the failure and its relationship to the actual stability of the structure.

TABLE 15. - Results of varying DMIN[1]

DMIN, ft	FS[2]	DMIN, ft	FS[2]	DMIN, ft	FS[2]	DMIN, ft	FS[2]
1......	1.174	11......	1.213	21......	1.262	31......	1.346
2......	1.177	12......	1.218	22......	1.266	32......	1.359
3......	1.182	13......	1.225	23......	1.270	33......	1.366
4......	1.185	14......	1.231	24......	1.275	34......	1.373
5......	1.189	15......	1.236	25......	1.280	35......	1.381
6......	1.193	16......	1.240	26......	1.285	36......	1.388
7......	1.196	17......	1.245	27......	1.290	37......	1.414
8......	1.200	18......	1.249	28......	1.329	38......	1.422
9......	1.204	19......	1.253	29......	1.336	39......	1.429
10......	1.208	20......	1.257	30......	1.341	40......	1.437

[1]Vertical distance between the embankment face and the slip circle for the maximum slice.
[2]Factor of safety.

NOTE.--Summary of test factors:
γ = 100 pcf
ϕ = 30°,
c = 0,
slope of embankment face = 2 to 1.

CONCLUSIONS

Based on the field and laboratory data collected and the assumptions made during the analysis of the data, the following conclusions can be drawn:

1. If all three types of equipment started at the same in situ density, the D8H track-mounted dozer and the D500 rubber-tired dozer would increase the density of the coarse tailings to at least the 70-pct relative density point. The SP848 vibratory smooth-drum roller would not increase the density to the 70-pct relative density point.

2. There was a net gain in surface density, comparing in situ with final pass, for all three pieces of equipment. However, the D8H produced sinusoidal density readings reflecting compaction, then shearing of the material after each pass. The D500 compacted the material on the first pass, then sheared for the following two passes. The SP848 compacted on the first pass, then achieved very little change on all subsequent passes.

3. The low-ground-pressure, four-tracked, converted transporter increased the surface density of the finer grained tailings beach significantly--from an average 59-pct relative density for spigoted only tails to 100-pct relative density. It was estimated to take between four to six passes of the machine to achieve the increases in density.

4. Visual observation of the condition of the copper tailings indicated the fines tended to migrate to the surface with compaction. This type of potential horizontal layering could lead to higher water surfaces throughout an embankment, owing to perched water, than would be the case if the embankment were more homogeneous and noncompacted.

5. The coarse coal waste compaction study (1) determined that the vibratory smooth-drum roller showed the most promise for effective compaction (grain size, minus 3 in with 60 pct passing 3/4-in mesh and 0 passing 200 mesh). In this study, the vibratory smooth-drum roller was the least desirable method of increasing density on coarse tailings (grain size, minus 3/8 in with 60 pct passing 40 mesh and 6 pct passing 200 mesh).

6. Shear strength test results indicated an increase from 30° for the uncompacted coarse tailings to 43° for tailings compacted at 70-pct relative density.

7. None of the equipment tested on the coarse tailings (D500, D8H, and SP848), or the low-ground-pressure tractor transporter on the finer grained tailings, possessed a compactive influence zone deeper than 12 in. Therefore, compaction efforts must be continuous while the tailings are being discharged. Compaction only after an embankment lift is completed is ineffective. However, deeper compaction depths are obtainable. Broms and Forssblad (18) cited a maximum depth of compaction of 8.5 to 10 ft (2.5 to 3.0 m) on natural sand deposits compacted with much larger 10- to 15-ton vibratory units, but 20 to 30 passes were required to achieve the depth.

In a mining environment, daily tonnages to the tailings pond are assumed to be constant. Therefore, decreasing the permeability of the embankment by compaction would raise the pond water level if pumping, evaporation, and seepage remained constant. Increasing pond levels, owing to added compaction, did increase the factor of safety number for a denser material; however, the DMIN had more of an impact. The slip circle, in this study, occurred in approximately the same location for all iterations on the saturated face and was shallow in depth. Therefore, once the face reached a minimum saturated condition, the factor of safety numbers did not significantly change.

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