RI 9171

Bureau of Mines Report of Investigations/1988

Beach Characteristics of Mine Waste Tailings

By C. M. K. Boldt

UNITED STATES DEPARTMENT OF THE INTERIOR

Report of Investigations 9171

Beach Characteristics of Mine Waste Tailings

By C. M. K. Boldt

UNITED STATES DEPARTMENT OF THE INTERIOR
Donald Paul Hodel, Secretary

BUREAU OF MINES
T S Ary, Director

Library of Congress Cataloging in Publication Data:

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

Beach characteristics of mine waste tailings.

(Report of investigations ; 9171)
Bibliography.
Supt. of Docs. no.: I 28.23:9171.
1. Mineral industries--Waste disposal. 2. Tailings (Metallurgy). 3. Tailings dams. I. Title. II. Series: Report of investigations (United States. Bureau of Mines) ; 9171.

TN23.U43 [TD899.M47] 622 s [622.7] 87-600437

CONTENTS

ILLUSTRATIONS

TABLES

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm/s	centimeter per second	gpm	gallon per minute
deg	degree	in	inch
ft	foot	pcf	pound per cubic foot
ft/s	foot per second	mm	millimeter
gal	gallon	psi	pound per square inch

BEACH CHARACTERISTICS OF MINE WASTE TAILINGS

By C. M. K. Boldt[1]

ABSTRACT

The Bureau of Mines surveyed waste disposal sites at 18 metal and nonmetal mines and conducted laboratory and full-scale field tests to determine the effects of tailings deposition techniques on physical properties of tailings pond beaches. Survey data included measurements of beach slopes, descriptions of deposition techniques, and measurements of beach physical properties taken at various distances from the point of discharge. Laboratory tests involved depositing two types of tailings, each with different grain-size distributions, into a settling trough and determining the resultant physical properties of settled materials along the length of the beach. Side confinement and the closeness of the water pool to the point of deposition caused the laboratory results to be inconclusive. Full-scale field deposition tests conducted at the tailings pond of a cooperating mine showed that there were similarities in relationships between exit velocities of tailings slurry and physical properties of the settled tailings on the beach.

[1]Civil engineer, Spokane Research Center, Bureau of Mines, Spokane, WA.

INTRODUCTION

Mill tailings usually are considered a useless byproduct of mining and milling processes. However, mining and milling methods have changed as more low-grade ores are now being mined. As a result, the quantity and quality of mill tailings have also changed. Tailings are ground more finely as ore dressing procedures pick up microscopic particles of minerals, and the ratio of recoverable minerals to waste tailings is decreasing because more lower grade ore is being processed.

In an effort to promote safety-oriented technologies for mine waste disposal, the Bureau of Mines has conducted an investigation to determine the effects of deposition techniques on the structural stability of tailings embankments. If the physical characteristics of impounded tailings could be altered without extraordinary costs, a more stable and/or useful form of mine waste may be produced. For example, deposited tailings could be used as a source of backfill material. Presently, particle separators, such as cyclones, are used to gather the sand fraction of tailings for use as hydraulically transported, underground backfill. This practice, however, leaves the fine fraction to be deposited on the surface. If the total tailings could be used as backfill, the need for a large surface disposal area would be minimized.[2]

By using mechanical dewaterers or by naturally dewatering the tailings via evaporation and percolation, mill tailings could become a useful source of backfill aggregate. This would be especially true if tailings settling could be controlled at deposition to produce an optimally segregated material that could be reclaimed with a minimum of effort.

It might also be possible to determine a relationship between the exit velocity of the tailings slurry and the factor of safety of tailings embankments. This correlation would help personnel to quantify any changes in the embankment factor of safety due to proposed changes in tailings deposition rates. The information produced in this study would be useful also in developing better deposited tailings for use as embankment material.

This investigation consisted of three phases. Phase I was a survey of the tailings impoundments of 18 metal and nonmetal mines. The results were evaluated for correlations between deposition and embankment characteristics. Phase II included laboratory model tests where tailings slurry was deposited into a long, narrow settling trough and the physical properties of the resultant beach were measured. Phase III consisted of full-scale field tests at a cooperating mine site where an auxiliary pipeline was installed to control tailings deposition flow rates. The beach formed by each controlled deposition was then analyzed, and its physical properties were measured. The measured physical properties, in conjunction with the relationship between each exit velocity of the discharged tailings slurry and stability of the resulting beach slope, were used to perform an iterative analysis of the factors of safety for an idealized embankment.

[2]Keren, L., and S. Kainian. Influence of Tailings Particles on Physical and Mechanical Properties to Fill. Paper in Mining with Backfill, ed. by S. Granholm (Proc. Int. Symp. on Mining With Backfill, Lulea, Sweden, June 7-9, 1983). A. A. Balkema, 1983, pp. 21-29.

Thomas, E. G. Characteristics of Cemented Deslimed Mill Tailing Fill Prepared from Finely Ground Tailings. Paper in Mining with Backfill, ed. by S. Granholm (Proc. Int. Symp. on Mining With Backfill, Lulea, Sweden, June 7-9, 1983). A. A. Balkhema, 1983, pp. 59-66.

ACKNOWLEDGMENTS

The author wishes to thank the following employees of the Bureau's Spokane Research Center: Paul McWilliams, mathematical statistician, and Douglas Tesarik, mathematician, for their invaluable guidance in the statistical treatment of test data and technical review; and Lynn Atkins, engineering technician, for conducting the extensive laboratory tests.

PHASE I.--MINE SURVEYS

TEST PROCEDURE

Surveys of waste disposal sites were conducted at 18 metal and nonmetal mines. A few of the deposition techniques used at the mines included upstream spigoting (type 1), centerline cycloning (type 2), and borrow dike with spigoting (type 3). Information was collected on each mine's operating procedure (fig. 1). Elevation surveys were conducted to determine beach slope, and distances were measured between sample locations where surface Shelby tube samples were taken perpendicular to the embankment crest. This measurement and sampling pattern produced a cross section of physical properties with respect to distance from the point of discharge. The samples were tested at the Bureau's Spokane (WA) Research Center for internal shear strength, permeability, and grain-size distribution. Table 1 summarizes the tailings impoundment characteristics at the 18 mine sites.

TEST RESULTS

The results of the field surveys were statistically analyzed to determine if there were any simple mathematical relationships among the predictive variables (spigot diameter, velocity, slurry density, and/or permeability), which could be used to predict the embankment's grain-size gradation away from the point of discharge. A stepwise regression analysis was used to pick the most highly correlated variables in descending order of correlation, thereby builing a linear mathematical model of the selected input variables. A set of products and squared terms were also candidates for the model. An important constraint was that the model be linear and additive. Therefore, many other candidate functions were not investigated, for example, exponential curves.[3]

Figure 2 shows a tabulation of one stepwise regression analysis. In this case, variables 1 to 3, the multiples of variables 1 to 3, and the squares of variables 1 to 3 were used to predict the grain-size distribution of the beach (i.e., the percentage of particles finer than 50 mesh).

As figure 2 indicates, there is a poor linear correlation between any one of the predictive variables and the grain-size values. This usually indicates that a highly correlated result will not be obtained even if many of the variables are included in the final mathematical equation. This stepwise regression run did provide a multiple correlation value $R^2 = 0.494$, where R^2 is a measure of how well the multidimensional plane described by the equation fits the data. Although this value of R^2 is statistically significant, it certainly is not outstanding. ($R^2 = 1.0$ is a perfect correlation value.)

---

[3]McWilliams, P. C., and D. R. Tesarik. Multivariate Analysis Techniques with Application in Mining. BuMines IC 8782, 1978, 40 pp.

OPTIMIZING SLURRIED MINE WASTE SEGREGATION CHARACTERISTICS

Field Reconnaissance

Name: ______________________ Date: ______________________

Mine: ______________________ Location: ______________________

Contact(s): ______________________ Address: ______________________

______________________ ______________________

Phone: ______________________

Type of Mine: ______________________ Daily Tonnage: ______________________

Quantity Tailings: ______________________ Slurry Density: ______________________

Delivery Pipe(s) Size: ______________________ Velocity: ______________________

Spigot Size: ______________________ Number of Spigots: ______________________

Spigot Spacing: ______________________

Sample Number	Location	Type of Sample

Tailings Pond

Length: ______________ Width: ______________ Height: ______________

Beach Slope: ______________

Additional Comments: ____

____

____

____

____

NOTE: Obtain a map or plan of the tailings deposit if available. Otherwise, sketch a plan and typical cross section on the back of this sheet.

FIGURE 1.--Mine survey form.

TABLE 1. - Tailings impoundment characterization at the test mine sites

Mine	Deposit technique[1]	Spigot diam, in	Spigot spacing, ft	Flow, gpm	Slurry density, % solids	Beach slope, %	Mill grind, % passing		Solids sp gr (G_s)	Distance from spigot, ft	Angle int. fric., deg	Permeability (K), cm/s	Beach sample, % passing	
							50 mesh	200 mesh					50 mesh	200 mesh
1....	1	6	25	705	29	2.2	92	47	2.8	0	40.5	0.00197	52	12
	1	6	25	705	29	2.2	92	47	2.8	100	38.7	.00222	60	14
	1	6	25	705	29	2.2	92	47	2.8	200	34.4	.0045	64	14
	1	6	25	705	29	2.2	92	47	2.8	300	40.9	.0069	59	12
2....	1	6	25	705	29	2.2	92	47	2.8	400	36.4	.00233	69	14
	1	6	25	705	20	.9	92	47	2.7	0	39.3	.00216	83	20
	1	6	25	705	20	.9	92	47	2.7	100	39.5	.00226	79	15
	1	6	25	705	20	.9	92	47	2.7	200	37.8	.000663	88	25
	1	6	25	705	20	.9	92	47	2.7	300	42	.000969	91	27
3....	1	6	25	705	20	.9	92	47	2.7	400	38	.000706	98	35
	1	6	24	580	30	1.7	95	55	2.7	0	42.9	.00268	60	10
	1	6	24	580	30	1.7	95	55	2.7	100	45.9	.000727	80	13
	1	6	24	580	30	1.7	95	55	2.7	200	43	.000095	81	23
	1	6	24	580	30	1.7	95	55	2.7	300	49.3	.00048	91	35
4....	1	6	24	580	30	1.7	95	55	2.7	400	40.5	.00013	96	44
	1	4	40	225	55	1.4	85	50	2.7	0	39	.00019	91	21
	1	4	40	225	55	1.4	85	50	2.7	100	39.4	.000688	90	21
	1	4	40	225	55	1.4	85	50	2.7	200	39	.000764	89	20
	1	4	40	225	55	1.4	85	50	2.7	300	37.1	.000554	94	25
5....	1	4	40	225	55	1.4	85	50	2.7	400	38	.000026	96	56
	2	12	52	530	50	NA	90	54	2.7	0	39.2	.000158	80	33
	2	12	52	530	50	NA	90	54	2.7	50	36	.000167	86	38
6....	2	12	52	530	50	NA	90	54	2.7	250	35.5	.000105	82	38
	2	10	25	230	35	NA	90	47	2.7	9	38.7	.00101	85	25
7....	2	10	25	230	35	NA	90	47	2.7	109	38	.000745	87	26
	2	10	25	230	35	NA	90	47	2.7	50	40.9	.000043	86	35
8....	2	10	25	230	35	NA	90	47	2.7	150	38.5	.00107	86	38
9....	2	10	25	230	35	NA	90	47	2.7	100	37.4	.000879	84	20
	1	1.25	40	667	48	.9	100	57	2.7	0	37.9	.000106	95	40
	1	1.25	40	667	48	.9	100	57	2.7	100	39	.000193	90	34
	1	1.25	40	667	48	.9	100	57	2.7	200	39.5	.000058	98	57
	1	1.25	40	667	48	.9	100	57	2.7	300	41	.000023	98	76
	1	1.25	40	667	48	.9	100	57	2.7	400	41.6	.000133	96	47

See explanatory notes at end of table.

TABLE 1. - Tailings impoundment characterization at the test mine sites--Continued

Mine	Deposit technique[1]	Spigot diam, in	Spigot spacing, ft	Flow, gpm	Slurry density, % solids	Beach slope, %	Mill grind, % passing		Solids sp gr (G_s)	Distance from spigot, ft	Angle int. fric., deg	Permeability (K), cm/s	Beach sample, % passing	
							50 mesh	200 mesh					50 mesh	200 mesh
10...	1	2.5	20	450	30	2.2	NA	NA	2.7	0	36.5	0.00244	74	21
	1	2.5	20	450	30	2.2	NA	NA	2.7	50	40	.000082	88	32
	1	2.5	20	450	30	2.2	NA	NA	2.7	100	36.6	.155	79	33
	1	2.5	20	450	30	2.2	NA	NA	2.7	150	31.1	.00176	90	29
	1	2.5	20	450	30	2.2	NA	NA	2.7	200	39	.000312	96	40
11...	5	12	0	2,000	38	NA	NA	NA	2.9	5	45	.00119	82	15
	5	12	0	2,000	38	NA	NA	NA	2.9	65	52.1	.0178	88	21
12...	6	14	0	2,200	30	28	95	58	2.9	0	46.9	.00159	99	24
	6	14	0	2,200	30	28	95	58	2.9	100	40	.0019	97	16
	6	14	0	2,200	30	28	95	58	2.9	200	40	.00146	97	21
13...	5	12	NA	1,600	35	2.5	91	48	2.9	0	41	.0025	63	14
	5	12	NA	1,600	35	2.5	91	48	2.9	100	43.8	.00171	66	17
	5	12	NA	1,600	35	2.5	91	48	2.9	200	40.2	.00183	70	20
	5	12	NA	1,600	35	2.5	91	48	2.9	300	40	.000594	84	35
	5	12	NA	1,600	35	2.5	91	48	2.9	400	43	.000517	78	25
14...	3	15	0	1,600	35	20	91	48	2.9	0	NA	NA	92	34
	3	15	0	1,600	35	20	91	48	2.9	100	NA	NA	85	17
	3	15	0	1,600	35	20	91	48	2.9	200	NA	NA	75	19
15...	3	15	0	1,600	40	2.7	NA	NA	2.9	75	35.9	.0129	70	15
	3	15	0	1,600	40	2.7	NA	NA	2.9	175	38.4	.000669	84	22
16...	4	14	0	2,446	15	.5	NA	65	2.6	0	31.5	.000119	71	23
	4	14	0	2,446	15	.5	NA	65	2.6	100	28.1	.000133	75	27
	4	14	0	2,446	15	.5	NA	65	2.6	200	NA	NA	98	86
	4	14	0	2,446	15	.5	NA	65	2.6	300	NA	.000010	99	89
	4	14	0	2,446	15	.5	NA	65	2.6	400	NA	NA	96	76
17...	4	14	0	2,446	15	.9	NA	65	2.6	0	31.3	.00795	76	16
	4	14	0	2,446	15	.9	NA	65	2.6	100	19.1	.000045	94	40
	4	14	0	2,446	15	.9	NA	65	2.6	200	21.9	.000073	90	25
	4	14	0	2,446	15	.9	NA	65	2.6	300	NA	.000006	98	72
	4	14	0	2,446	15	.9	NA	65	2.6	400	NA	NA	99	96
18...	4	2.5	20	567	10	.6	100	93	2.9	100	36	.000054	100	71
	4	2.5	20	567	10	.6	100	93	2.9	200	36.5	.000080	100	52
	4	2.5	20	567	10	.6	100	93	2.9	300	33.2	.000009	100	97
	4	2.5	20	567	10	.6	100	93	2.9	400	34.5	.000050	100	98

NA Not available.

[1] 1--upstream spigot; 2--upstream cyclone; 3--centerline cyclone; 4--borrow dike; 5--single point discharge; 6--downstream cyclone.

Data set = Beach data (% passing 50 mesh overall)

No. of observations = 67

No. of variables = 10

Grain size (% passing 50 mesh) = 175.16 - 0.10023 (velocity) - 3.40 (slurry density) - 0.00093 (spigot diameter x velocity) - 0.109 (spigot diameter x slurry density) + 0.0015 (velocity x slurry density) + 0.3074 (spigot diameter)^2 + 0.000023 (velocity)^2 + 0.042 (slurry density)^2

$$R^2 = \frac{\sum_{i=1}^{n} (\tilde{y}_i - \bar{y})^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2} = 0.494$$

where y_i = dependent variable

$\tilde{y}_i$ = "fitted" (derived) dependent variable

$\bar{y}$ = sample mean of y_i.

The variables and the individual linear correlation coefficients are listed:

Variable	Linear correlation coefficient with variable 4
1. Spigot diameter	-0.131067
2. Velocity	+0.045277
3. Slurry density	-0.073331
4. % passing 50 mesh	+1.000000
5. Spigot diameter x velocity	+0.039531
6. Spigot diameter x slurry density	-0.230344
7. Velocity x slurry density	-0.093970
8. (Spigot diameter)^2	+0.049857
9. (Velocity)^2	+0.109972
10. (Slurry density)^2	+0.029541

FIGURE 2.–Stepwise regression.

Four groups of statistical analyses were performed. Table 2 provides descriptions of the analyses and summarizes the results. The results indicate that the data from the 18 mine sites are far too heterogeneous to be treated as a single data set. Attention should be focused on the fourth column in table 2, the R^2 values. The only good regression run was for code C (table 2), using only data obtained from type 1 depositional methods where embankments were built by upstream spigoting.

TABLE 2. - Stepwise regression

Code	Steps[1]	Observations	R^2	Av residual	Av deviation, %	Remarks
GRAIN SIZE, % PASSING 50 MESH						
A....	10	67	0.494	6.79	8.58	Too many terms required to achieve R^2 value (fig. 2).
B....	3	61	.096	9.24	12.09	Variable orders; diam, velocity, and slurry.
C....	4	25	.798	4.80	6.56	Variable order; permeability, diam, velocity, and slurry.
D....	3	47	.277	7.78	11.49	Variable order; diam, velocity, and slurry.
GRAIN SIZE, % PASSING 200 MESH						
A1...	10	67	0.542	11.36	37.56	None.
B1...	4	61	.170	14.26	55.93	Variable order; diam, slurry, velocity, and permeability.
C1...	3	25	.588	8.56	34.69	Variable order; diam, permeability, slurry.
D1...	3	47	.188	14.19	57.13	Do.

Code explanation:
A, A1--Spigot diam, velocity, slurry density, and powers of these variables.
B, B1--Spigot diam, velocity, slurry density, and permeability.
C, C1--Type 1 deposition; diam, velocity, slurry, and permeability.
D, D1--Spigot spacing >0; diam, velocity, slurry, and permeability.

[1]Number of variables, variables squared, and multiples of variables.

NOTE.--R^2 is a measure of how well the resulting multidimensional plane fits the data.

PHASE II.--LABORATORY TESTS

TEST PROCEDURE

After bulk tailings samples were obtained from two mine sites, laboratory testing commenced. The tailings were diluted with water to a specific slurry density, mixed in a large, 1,675-gal tank, and then pumped at a specified flow rate for discharge into a settling trough. Tailings A consisted of fine mill waste from a copper-silver mine. Tailings B was from a silver-lead-zinc mine and contained coarser particles. The grain-size distributions are plotted in figure 3.

It was hypothesized that depositional variables such as flow rate, slurry density, and beach physical properties, as well as relationships among variables, could be ranked according to their relative importance before full-scale field tests were undertaken.

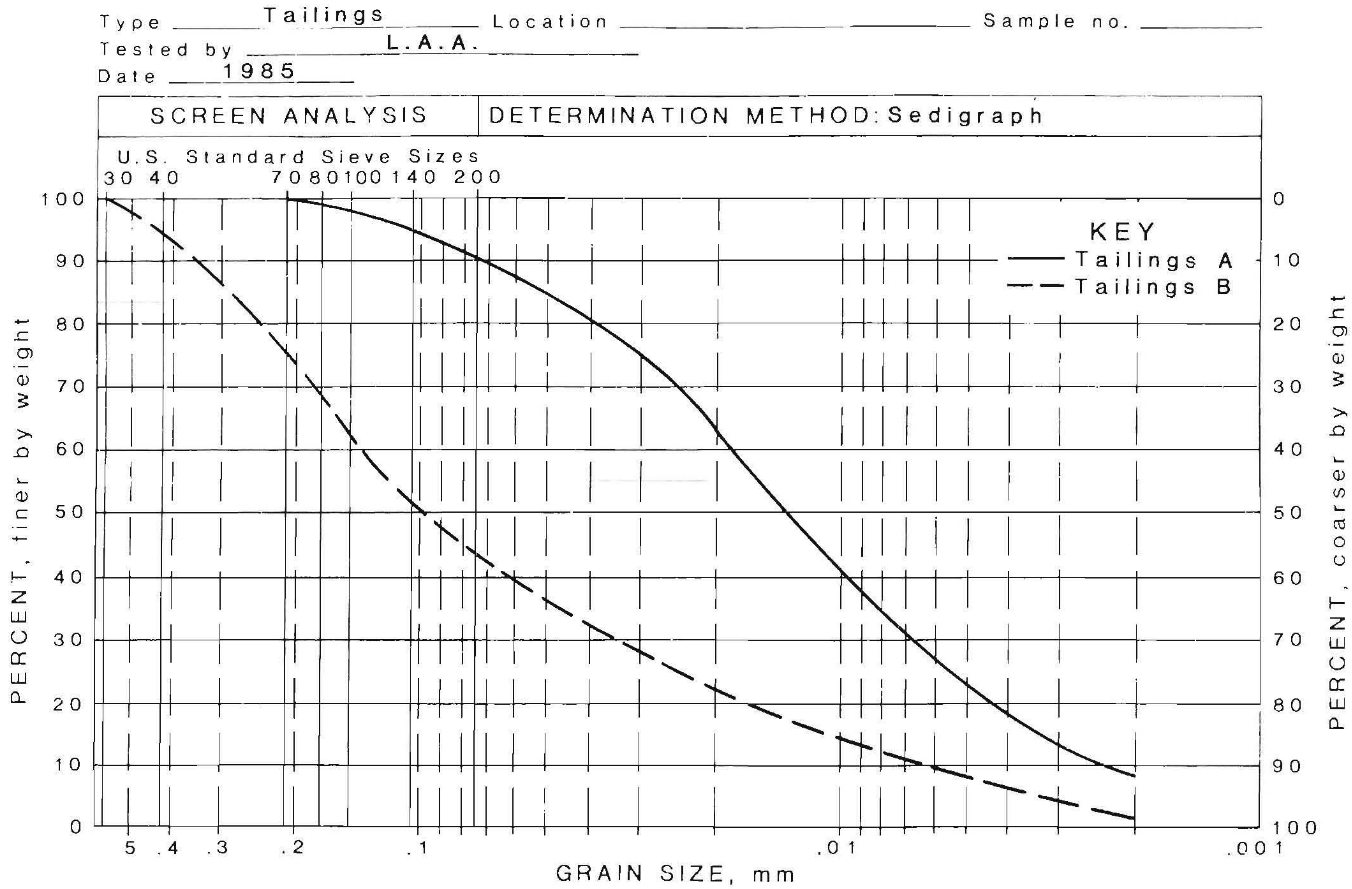

FIGURE 3.--Grain size of tailings A and B.

For each tailings sample, the slurry density was altered by changing the percentage of solids. The slurry was then pumped at controlled flow rates through a 1-1/4-in pipe opening. The tailings were deposited in a 2-ft-wide by 40-ft-long wooden trough. A burlap bulkhead at the far end permitted the water to drain. After the solids were sufficiently dewatered, Shelby tube samples were taken at designated distances along the length of the deposited tailings. The samples were then analyzed for permeability, internal shear strength, and grain size. Figures 4 through 6 show the bulk mixing tank, slurry loop system, and deposition of the tailings to form the beach.

TEST RESULTS

Tables 3 and 4 summarize the physical properties of the deposited tailings from mines A and B. The data in these tables indicate that the following relationships among the variables are valid:

1. For both mine tailings type g, the steepest beaches, reflecting the quickest settlement of the coarse particles, resulted from low flow rates (3-5 ft/s) in combination with high slurry densities (50%-57% solids).
2. The next steepest beaches resulted from low flow rates (3-5 ft/s) in combination with medium slurry densities (30%-45% solids).

FIGURE 4.–Bulk mixing tank.

3. The third steepest beaches were produced either by high flow rates (8-9 ft/s) and high densities (50%-55% solids) or by low flow rates (3-5 ft/s) and low densities (22%-26% solids).

4. The flattest beaches (least amount of particle segregation) were produced by high flow rates (8-9 ft/s) and medium to low slurry densities (22%-43% solids).

5. When the slurry density of the mine A tailings sample was increased by 28% (from 43% to 55% solids), the beach slope increased 21% (from 2.32% to 2.80%) under high flow rates.

6. Increasing the slurry density of the mine B tailings sample by 127% (from 22% to 50% solids) increased the beach slope by 9% (from 2.08% to 2.26%) under high flow rates. The relatively small change in beach slope after the change in slurry density in comparison with that of the mine A sample can be attributed to the higher specific gravity of the mine B tailings sample (2.84), which is higher than the specific gravity of mine A (2.68).

Although the two completed tests verified generalized relationships, no quantitative correlations could be seen. Apparently, the confined dimensions of the trough influenced the depositional trials. Side eddies and the closeness of the pond water to the point of discharge obscured any attempt to correlate tailings deposition conditions to resultant beach characteristics. Therefore, it was necessary to conduct full-scale field tests without the benefit of quantitative laboratory results.

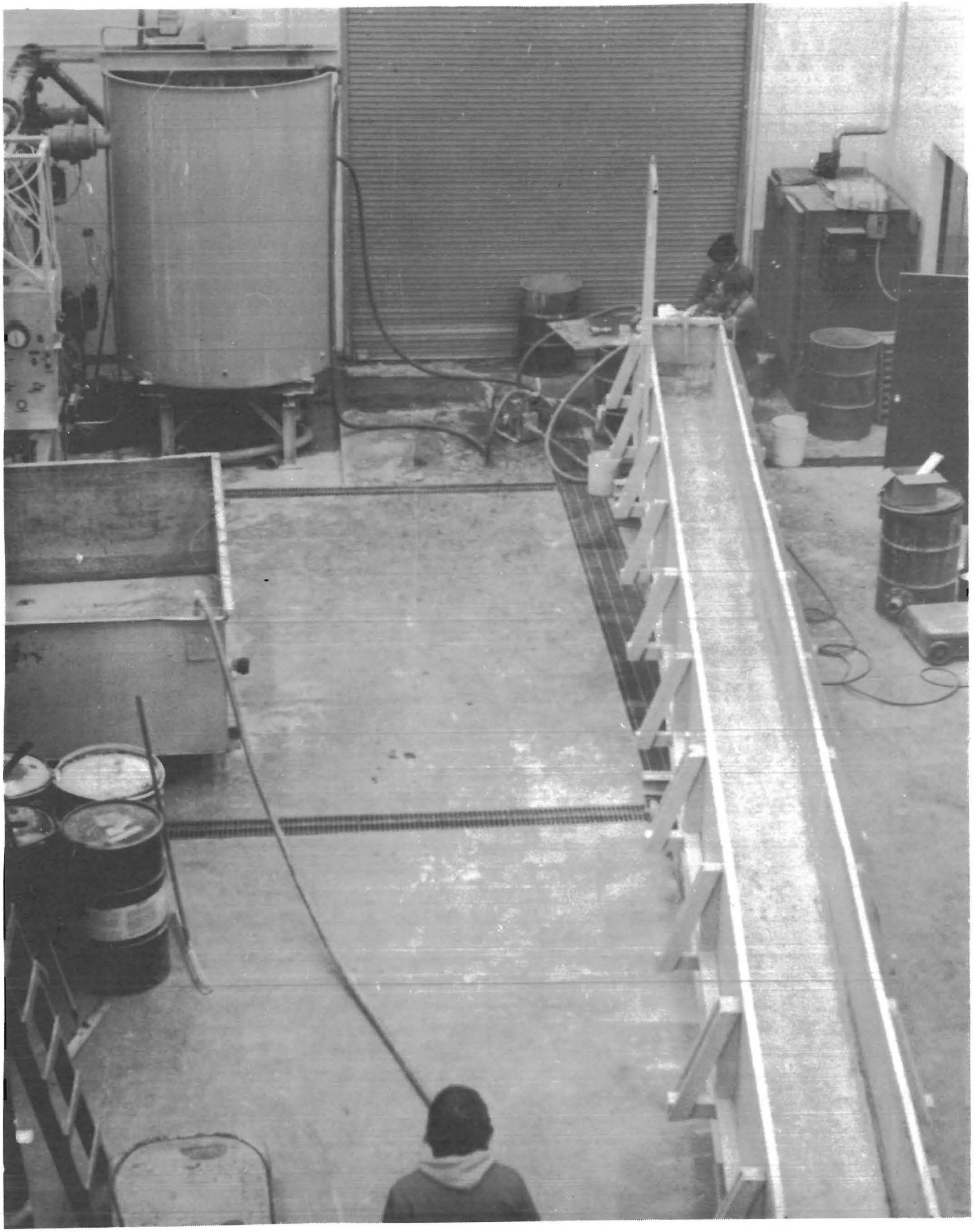

FIGURE 5.--Laboratory test system.

FIGURE 6.--Depositing tailings to form beach in trough.

TABLE 3. - Physical properties of deposited tailings from mine A

Run and slurry density	Exit velocity, ft/s	Av beach slope, %	Station, ft[1]	Shear angle, deg	Cohesion, psi	Grain size, % passing-- 30 mesh	50 mesh	70 mesh	100 mesh	140 mesh	200 mesh	Permeability (k), cm/s
A1: 45% solids	4	3.24	0+04	46	4	100	99	91	74	52	32	NA
			0+12	44	3	100	100	99	92	76	52	NA
			0+20	48	14	100	100	97	89	73	50	NA
			0+28	48	16	100	100	100	100	95	77	NA
			0+35	42	20	100	100	100	100	97	81	NA
A2: 43% solids	9	2.32	0+04	41	5	100	88	66	46	31	20	NA
			0+12	44	8	100	99	93	80	60	38	NA
			0+20	45	11	100	99	92	76	57	38	NA
			0+28	42	11	100	100	100	98	86	58	NA
			0+35	39	15	100	100	100	96	85	62	NA
A3: 57% solids	4	3.60	0+04	38	13	100	98	89	75	57	37	7.43×10^{-5}
			0+12	34	22	100	99	91	77	59	39	8.40×10^{-5}
			0+20	40	4	100	100	96	83	65	42	3.95×10^{-4}
			0+28	41	12	100	100	100	99	96	85	NA
			0+35	35	11	100	100	100	100	99	96	NA
A4: 55% solids	9	2.80	0+04	39	10	100	98	91	72	51	31	1.20×10^{-4}
			0+12	42	3	100	99	94	78	59	37	1.19×10^{-4}
			0+20	37	12	100	100	96	84	63	39	1.26×10^{-4}
			0+28	39	7	100	100	99	95	80	51	NA
			0+35	39	5	100	100	100	97	91	74	NA
A5: 26% solids	4	2.60	0+04	40	4	100	98	89	69	45	24	1.92×10^{-3}
			0+12	34	13	100	99	95	81	56	30	1.19×10^{-3}
			0+20	39	9	100	100	100	97	86	61	1.07×10^{-3}
			0+28	32	22	100	100	100	100	98	88	NA
			0+35	40	4	100	100	100	100	99	93	NA
A6: 27% solids	7	1.71	0+04	43	3	100	99	95	83	63	38	1.37×10^{-4}
			0+12	39	4	100	100	99	96	83	55	1.27×10^{-3}
			0+20	37	6	100	100	99	96	80	50	5.88×10^{-4}
			0+28	35	7	100	100	100	100	97	79	NA
			0+35	36	3	100	100	100	100	99	98	NA

NA Not available. [1]Distance from deposition point.

TABLE 4. - Physical properties of deposited tailings from mine B

Run and slurry density	Exit velocity, ft/s	Av beach slope, %	Station, ft[1]	Shear angle, deg	Cohesion, psi	Grain size, % passing-- 30 mesh	50 mesh	70 mesh	100 mesh	140 mesh	200 mesh	Permeability (k), cm/s
B1: 30% solids	5	2.74	0+04	41	1	100	93	81	62	41	25	NA
			0+12	43	6	100	97	87	67	45	27	NA
			0+20	38	9	100	99	92	73	51	33	NA
			0+28	37	4	100	100	99	95	80	56	NA
			0+35	37	2	100	100	100	98	89	70	NA
B2: 29% solids	9	1.21	0+04	40	2	100	86	64	41	24	13	2.26×10^{-3}
			0+12	39	0	100	93	76	50	29	15	1.32×10^{-3}
			0+20	32	12	100	100	96	85	66	43	1.67×10^{-4}
			0+28	31	8	100	100	100	96	84	59	NA
			0+35	33	3	100	100	100	100	99	90	NA
B3: 50% solids	8	2.26	0+04	36	11	100	81	61	43	28	19	2.66×10^{-3}
			0+12	37	7	100	91	72	50	33	22	5.08×10^{-4}
			0+20	35	0	100	98	90	70	48	32	4.24×10^{-4}
			0+28	37	0	100	100	97	85	65	44	NA
			0+35	40	3	100	100	99	92	74	54	NA
B4: 50% solids	5	2.86	0+04	34	2	100	89	73	53	36	25	4.22×10^{-4}
			0+12	41	1	100	98	88	70	49	31	4.24×10^{-4}
			0+20	36	1	100	99	91	71	48	31	3.81×10^{-4}
			0+28	39	0	100	99	94	82	66	49	NA
			0+35	35	4	100	100	99	93	80	63	NA
B5: 22% solids	8	2.08	0+04	42	1	100	91	74	52	33	20	8.26×10^{-4}
			0+12	35	6	100	96	85	67	47	29	3.71×10^{-4}
			0+20	34	10	100	98	90	69	46	26	NA
			0+28	38	3	100	99	95	84	63	40	NA
			0+35	37	5	100	99	97	90	73	48	NA
B6: 20% solids	5	2.38	0+04	38	3	100	91	75	52	32	17	3.56×10^{-3}
			0+12	40	2	100	97	88	71	49	30	8.17×10^{-4}
			0+20	38	0	100	99	97	89	75	58	5.19×10^{-4}
			0+28	38	0	100	99	98	90	75	55	NA
			0+35	35	3	100	99	99	99	99	97	NA

NA Not available. [1]Distance from deposition point.

PHASE III.--FULL-SCALE FIELD TESTING

TEST PROCEDURE

A memorandum of agreement was formalized with the copper-silver mine from which the mine A tailings sample was obtained. The mine provided access to its tailings, a site at its pond on which to build an auxiliary tailings discharge spigot (fig. 7), and the use of its labor and equipment to set up and tend the test site. Once the test pipeline was installed, tailings were deposited at regulated exit flow velocities of 7, 13, and 26 ft/s, and at 13 ft/s with a spray plate attachment. The mine's standard deposits, made at 92 ft/s, were also sampled. All regulated flow deposits were made through a 1-1/4-in orifice so that exit velocities could be more readily compared with those of previous laboratory tests.

After at least 18 in of tailings had accumulated for each flow velocity, Shelby tube samples were retrieved and sent to the Bureau's laboratories to be analyzed for permeability, internal shear strength, and grain-size distribution. Figure 8 shows the auxiliary spigot arrangement that controlled the flow of tailings. Figure 9 shows the spray and beach resulting from the use of the spray plate attachment on the spigots depositing tailings at 13 ft/s. The spray plate was used to determine if an energy dissipator would significantly alter the physical properties of the beach.

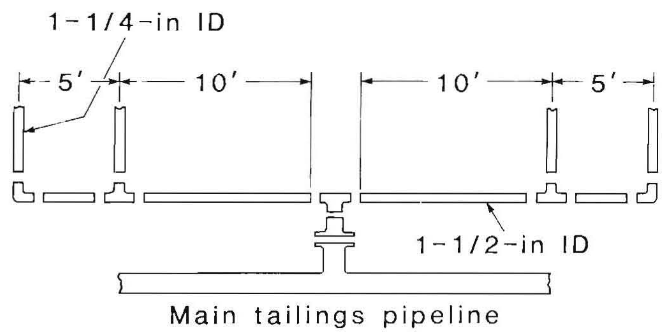

FIGURE 7.--Schematic of field test spigot arrangement.

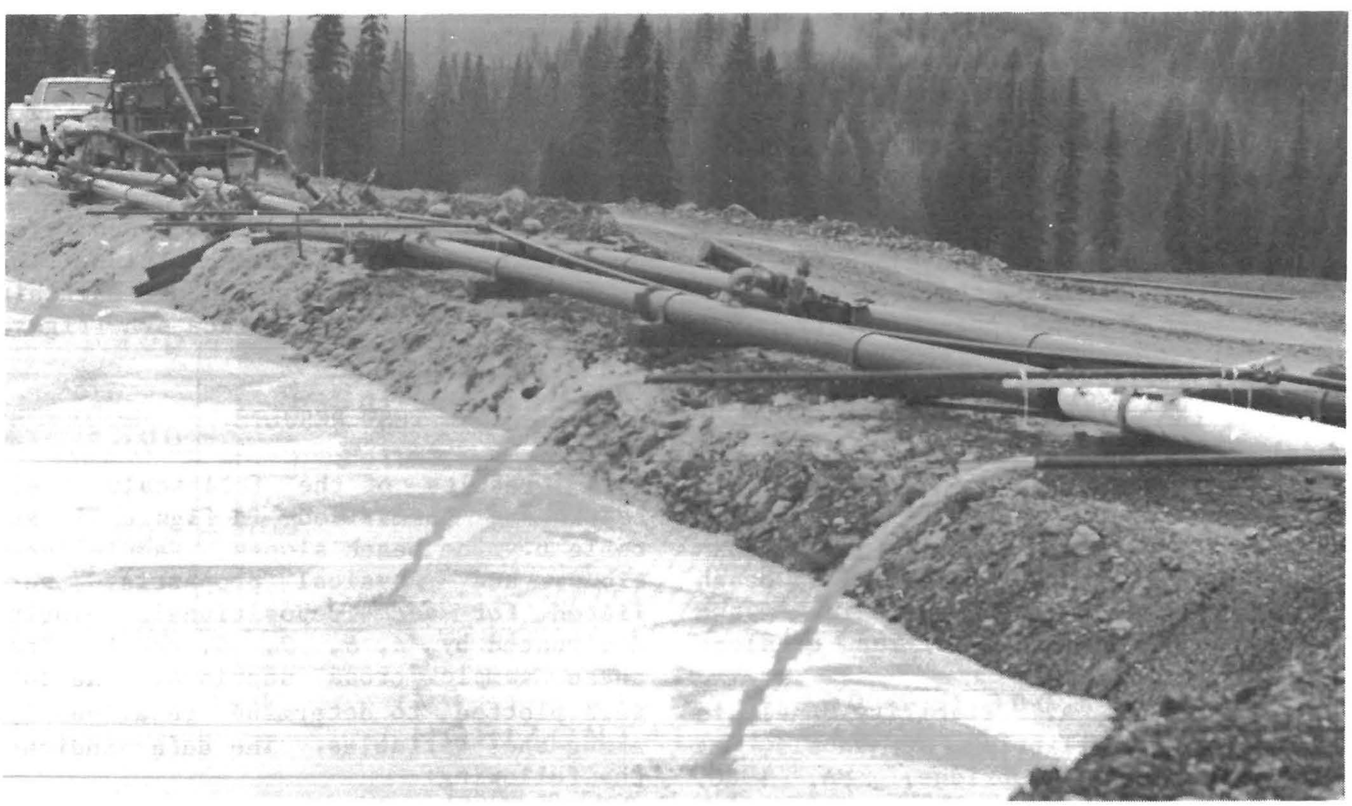

FIGURE 8.--Auxiliary spigot arrangement.

FIGURE 9.–Spray plate attachment.

After the data were compiled, an idealized embankment was modeled using the physical properties of the beaches generated at each depositional velocity. The factor of safety analysis used Bishop's method of slices[4] to determine circular failures in an embankment. The computer model simulated a 1.5:1 face slope, a 300-ft height, an impermeable foundation, constant phreatic and soils interface locations, and a pond elevation 400 horizontal ft from the crest. The beach slopes and physical properties were changed for each computer run of slope stability to reflect each beach condition found after full-scale deposition. The slip circle was held constant to maintain a through-the-embankment-face arc (figure 10, table 5).

[4]Bailey, W. A. Stability Analysis by Limiting Equilibrium. CE Thesis, MA Inst. Technol., Cambridge, MA, 1966, 153 pp.

TEST RESULTS

The results of the full-scale field tests are summarized in figure 11 and table 6. The beach slopes, sample locations, and physical properties were listed for each depositional velocity designated by *A*, *B*, *C*, *D*, and *E*. From these sample cross sections, the data were plotted to determine relationships among the variables. The data indicate the following:

TABLE 5. - Factor of safety summary for figure 10

Velocity at beach slope[1]	Angle of internal friction (ϕ), deg	Tan ϕ	Density, pcf		Factor of safety
			γdry	γsat	
7 ft/s at 2 pct:					
Soil 1	39	0.8098	83	NAp	1.18
Soil 2	38	.7813	87	NAp	
Soil 3	39	.8098	NAp	115	
Soil 4	38	.7813	NAp	117	
13 ft/s at 1.2 pct:					
Soil 1	35	.7002	90	NAp	1.04
Soil 2	33	.6494	87	NAp	
Soil 3	35	.7002	NAp	119	
Soil 4	33	.6494	NAp	117	
13 ft/s at 1.5 pct:[2]					
Soil 1	37	.7536	81	NAp	1.10
Soil 2	38	.7813	95	NAp	
Soil 3	37	.7536	NAp	113	
Soil 4	38	.7813	NAp	121	
26 ft/s at 0.2 pct:					
Soil 1	40	.8391	84	NAp	1.23
Soil 2	39	.8098	86	NAp	
Soil 3	40	.8391	NAp	115	
Soil 4	39	.8098	NAp	116	
92 ft/s at 0.2 pct:					
Soil 1			83	NAp	1.14
Soil 2	38	.7813	86	NAp	
Soil 3			NAp	115	
Soil 4			NAp	116	

NAp Not applicable.
γdry Dry unit weight.
γsat Saturated unit weight.

[1]c = 0 in all cases.
[2]With spray plate.

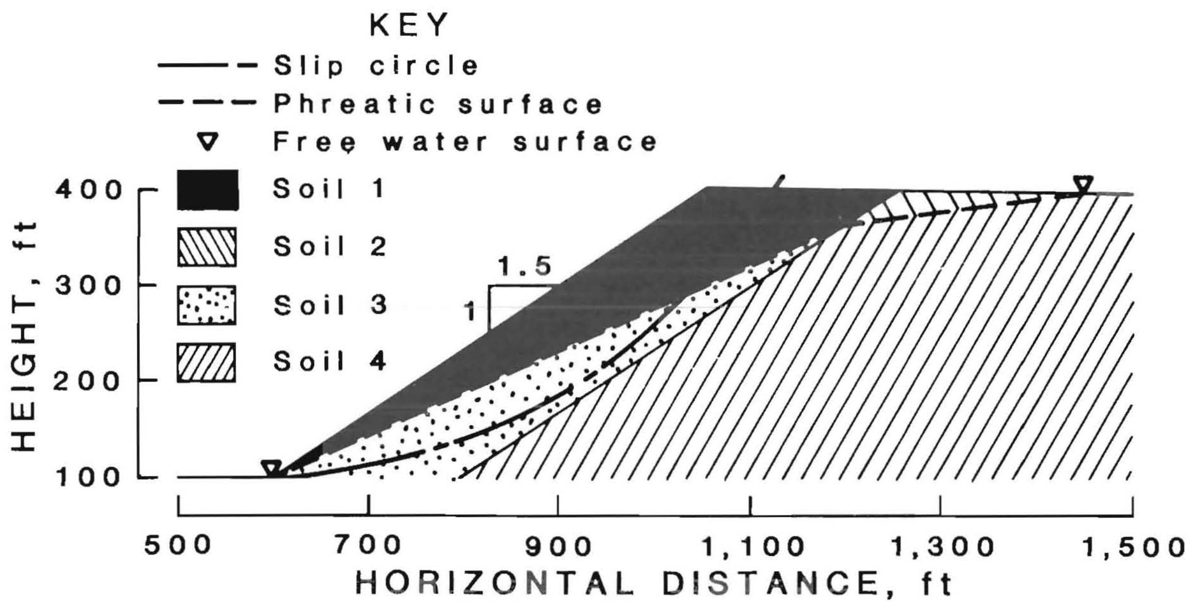

FIGURE 10.–Factor of safety summary.

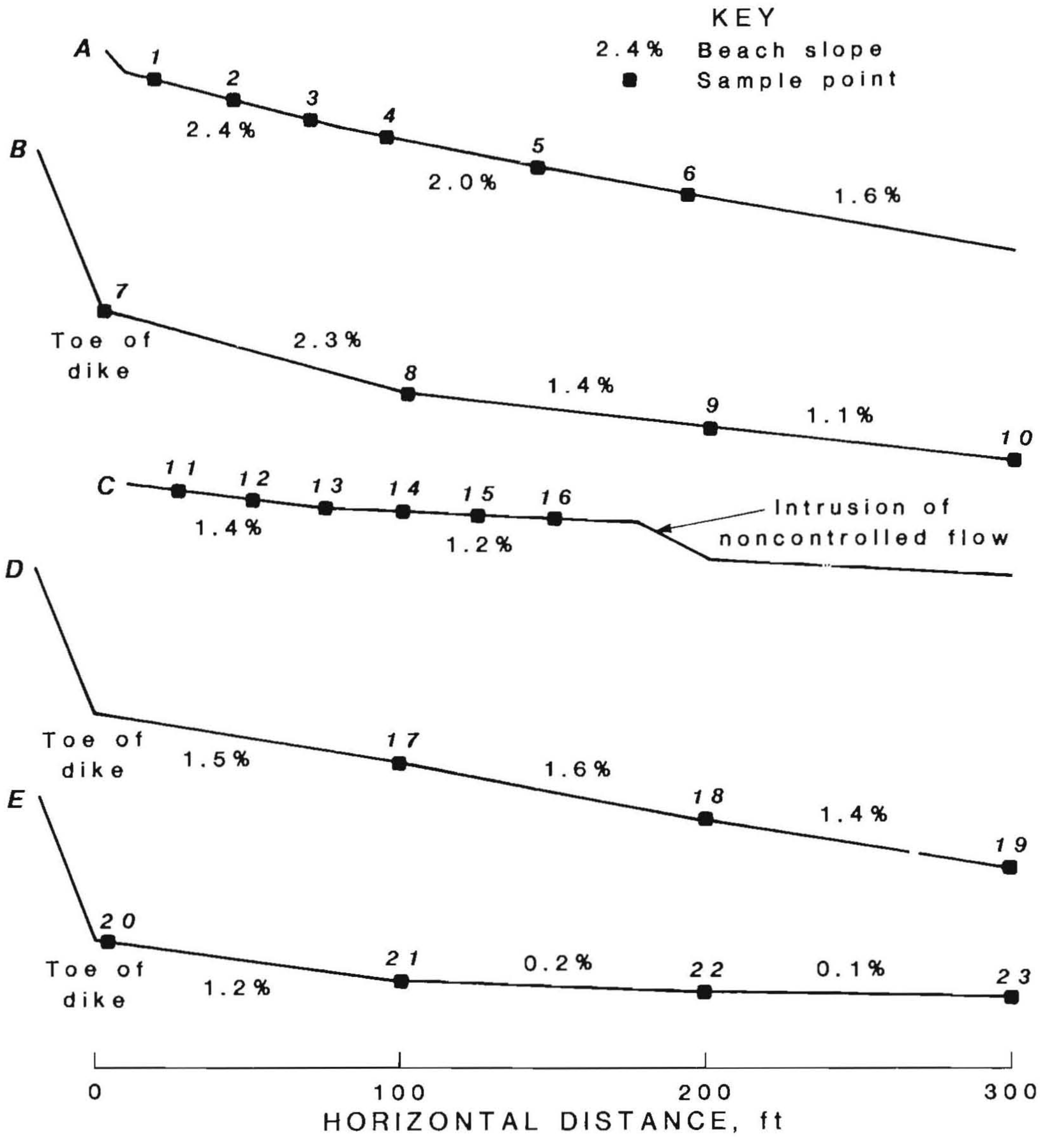

FIGURE 11.–Test beach properties.

TABLE 6. - Test beach properties for figure 11

Sample point	Permeability (k), cm/s	D_{60}/D_{10} (C_u)	D_{10}, mm	ϕ, deg	Cohesion (c), psi	γdry, pcf
A, VELOCITY, 7 ft/s						
1.	9.91×10^{-5}	9.4	0.008	35	3.4	88.7
2.	1.58×10^{-4}	8.5	.01	38	.8	83.4
3.	1.34×10^{-5}	10.4	.0071	41	0	83.3
4.	6.92×10^{-5}	8.5	.01	38	0	91.6
5.	9.12×10^{-5}	7.4	.0053	37	.6	86.9
6.	8.1×10^{-5}	9.5	.006	38	3.0	88.5
B, VELOCITY, 13 ft/s						
7.	1.36×10^{-4}	7.6	0.01	34	3.0	77.3
8.	1.39×10^{-4}	9.0	.007	35	5.6	88.4
9.	1.16×10^{-4}	10.0	.0078	35	5.6	90.8
10.	3.15×10^{-4}	9.2	.012	31	9.7	83.6
C, VELOCITY, 13 ft/s WITH SPRAY PLATE						
11.	1.04×10^{-4}	9.2	0.0069	36	1.1	81.5
12.	9.88×10^{-5}	9.4	.0064	38	0	80.7
13.	1.28×10^{-4}	6.3	.0079	38	0	84.5
14.	5.92×10^{-5}	7.1	.007	40	1.6	88.3
15.	8.82×10^{-5}	8.4	.011	40	0	92.6
16.	1.26×10^{-4}	7.7	.013	35	5.5	97.1
D, VELOCITY, 26 ft/s						
17.	7.3×10^{-4}	13.3	0.009	39	4.9	83.7
18.	1.87×10^{-4}	8.5	.013	40	.1	83.6
19.	9.49×10^{-5}	14.9	.0067	37	5.1	87.7
E, VELOCITY, 92 ft/s						
20.	8.74×10^{-5}	7.5	0.016	37	3.0	84.7
21.	4.85×10^{-4}	4.0	.035	40	.7	NA
22.	9.8×10^{-5}	4.0	.03	37	9.7	82.7
23.	1.19×10^{-4}	5.7	.021	38	1.9	89.6

NA Not available.
C_u Coefficient of uniformity.
D_{10} Grain size 10% finer.
D_{60} Grain size 60% finer.
ϕ Angle of internal friction.
γdry Dry unit weight.

1. Dry density did not significantly change for distances greater than 200 ft from the point of deposition regardless of tailings exit velocity (fig. 12*A*).

2. When the spray plate dissipator was used, the dry density increased after 200 ft, but decreased when the distance was less than 200 ft from the point of deposition (fig. 12*A*).

3. The velocity versus the coefficient of friction (tan ϕ) trends were also seen in the velocity versus beach slope relationship (figs. 12*B* and 12*C*).

4. The tan ϕ values were greater for distances less than 200 ft from the point of deposition than they were for distances more than 200 ft (fig. 12*B*).

5. Tan ϕ was the same for distances either less than or greater than 200 ft for the maximum exit velocity studied (fig. 12*B*).

6. Tan ϕ of the beach formed with the spray plate dissipator was greater than that formed by the spigots without the spray plate attachment (fig. 12*B*).

7. The beach that formed when the spray plate dissipator was used was flatter than the spigot-formed beach at all distances from the point of discharge (fig. 12*C*).

8. At all the velocities studied, the beach slopes were progressively flatter with increased distance from the point of discharge (fig. 12*C*).

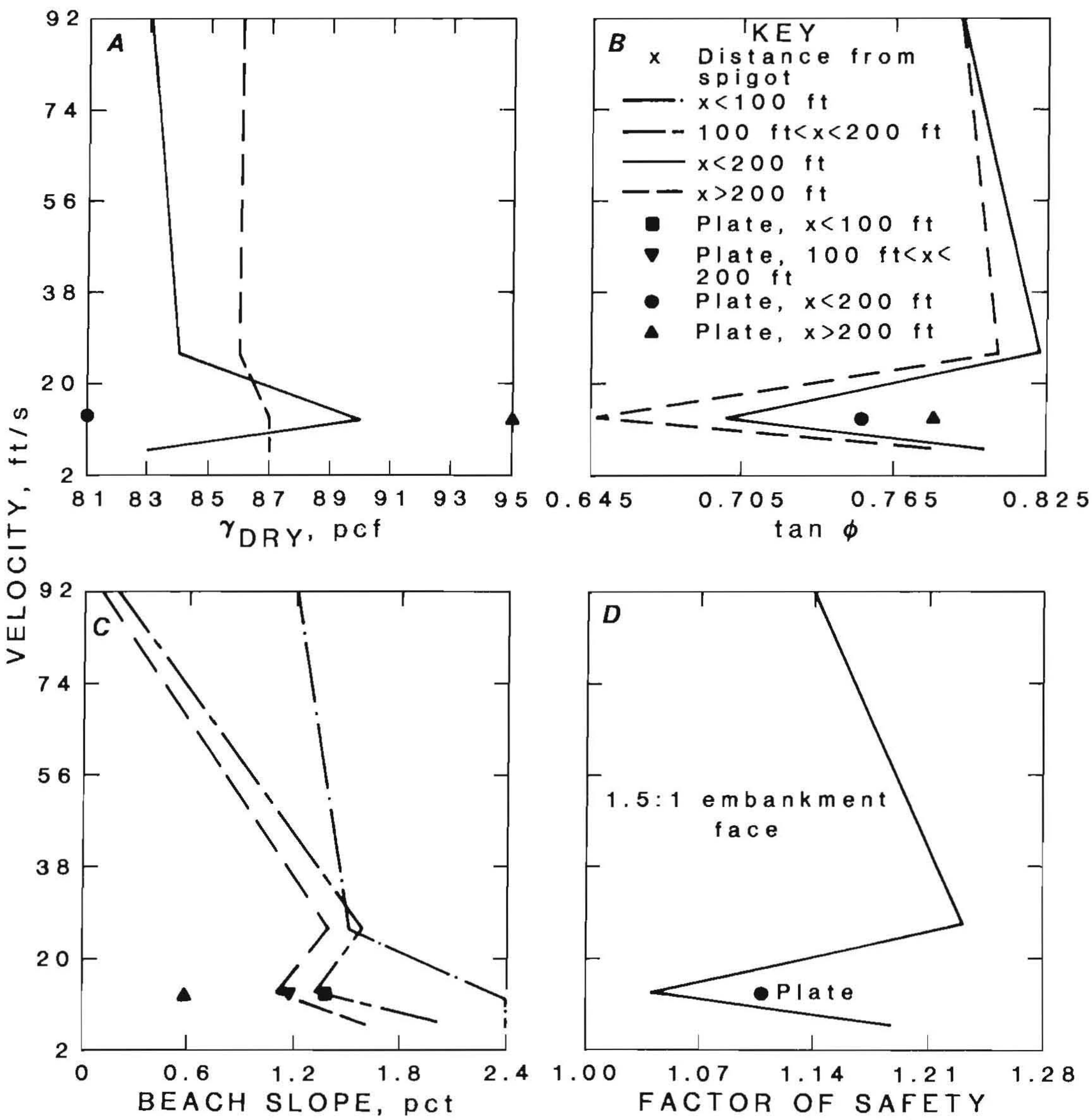

FIGURE 12.—Relationships between velocity and *A*, dry density; *B*, tan ϕ; *C*, beach slope; *D*, factor of safety.

DISCUSSION OF RESULTS

This Bureau study analyzed surface tailings deposition characteristics using three types of data gathering techniques. Phase I consisted of random sampling at 18 different surface waste disposal sites. Phase II used a 40-ft-long trough into which two tailings types were deposited at controlled velocities and slurry densities. Phase III required building an auxiliary pipeline on an active tailings pond and controlling the exit velocities of the mill tailings. For all three types of deposition tests, engineering properties were determined for the resulting beaches. These properties were then analyzed to determine if relationships existed between the depositional variables (flow rate, slurry density, etc.) and the resultant beaches (beach slope, grain-size gradation, etc.).

The statistical analysis of the data collected from the phase I field survey of 18 mine sites was inconclusive. Too many different types of depositional techniques were analyzed together to determine individual nuances. For instance, the largest family of depositional type--upstream spigoting--contained six mine sites for consideration. Of these six sites, each exhibited individual differences that may have affected the survey differently, i.e., specific gravity, exit velocity, slurry density. Two-dimensional correlation coefficients (r) were computed for two reasons: (1) to establish whether there were strong correlations between any pairs of variables and (2) to determine if it were feasible to use stepwise regression techniques on the data. Table 7 summarizes the correlation coefficient matrix for the upstream spigot sites only. The strongly paired correlations between spigot spacing and slurry density ($r = +0.89$) most likely occurred as a result of common depositional practices in the industry.

Phase II laboratory trough tests indicated that there were even fewer linear relationships between the variables (table 8). One relationship worth noting was the correlation between distances from the point of discharge and the percent passing 200 mesh grain size (correlation coefficient = +0.818). However, the angle of internal friction ϕ and the cohesion did not correspondingly change. Boundary condition constraints seem to have influenced the tailings depositions. For example, the wooden settling trough was apparently too short and narrow, creating back eddies and premature settling of fines. The correlation coefficients of 1.0 should be ignored for relationships between percent passing 50 mesh, mill grind, and percent passing 200 mesh, mill grind; percent passing 50 mesh, mill grind, and specific gravity of solids; and percent passing 200 mesh, mill grind, and specific gravity of solids. The relationships were paired because the material properties were compared to themselves since the same mill source was reflected.

The results of the phase III full-scale field trials are promising, but not complete. The tailings used in the study had a very fine grain size, which did not readily yield definitive differences in material properties. However, because of the fine grain size, the tailings can be taken as the lower limit of a range of tailings sample sizes where the measurements of physical properties also provide limiting values. The correlation coefficient matrix for the tests is summarized in table 9. The strongly paired correlations were as follows:

- $r = -0.98$ for deposition flow rate and average beach slope. As the exit velocity decreases, the ensuing beach velocity also decreases, causing particles to settle at a faster rate, thus creating a steeper beach.
- $r = +0.84$ between average beach slope and percent passing 200 mesh, beach sample. An increase in the beach slope angle is related to slowed beach velocity, which in turn causes faster settling of tailings particles. The fines fraction of the tailings are influenced more by the decrease in beach velocity than the coarser (percent passing 50 mesh, beach sample) sands, $r = 0.507$.

TABLE 7. - Correlation coefficient matrix for upstream spigot sites

	SPDIAM, in	SPSPAC, ft	FLOW, gpm	SLDEN, % solids	BCHSLP, %	MLL%-50	MLL%-200	SOLSG	DIST, ft	ANGL, deg	COHSN, psi	PERM, cm/s	BCH%-50
SPSPAC..	-0.475												
FLOW....	.256	-0.338											
SLDEN...	-.591	.894	-0.631										
BCHSLP..	.183	-.600	-.158	-0.246									
MLL%-50.	.409	-.061	.722	.179	-0.263								
MLL%-200	-.654	.421	-.032	.450	-.296	0.660							
SOLSG...	.405	-.225	.389	-.234	.541	-.082	-0.510						
DIST....	.115	.137	.074	.053	-.147	.000	.000	0.054					
SHEAR...	.276	-.000	.166	-.064	-.183	.299	.447	-.176	0.073				
COHSN...	-.367	-.219	-.125	-.052	.252	.458	.437	-.152	-.129	-0.511			
PERM....	-.153	-.231	-.096	-.104	.249	-.125	-.535	-.045	-.117	-.173	0.445		
BCH%-50.	-.511	.458	-.326	.410	-.597	.087	.444	-.775	.360	.016	.114	-0.109	
BCH%-200	-.640	.433	-.050	.402	-.416	.414	.577	-.454	.426	.033	.092	.018	0.733

SPDIAM--Spigot diameter,
SPSPAC--Spigot spacing,
FLOW--Deposition flow rate,
SLDEN--Slurry density,
BCHSLP--Beach slope,
MLL%--percent passing 50 mesh, mill grind;
MLL%-200--percent passing 200 mesh, mill grind,
SOLSG--Specific gravity of solids,
DIST--Distance,
ANGL--Angle of internal friction,
COHSN--Cohesion,
PERM--Permeability,
BCH%-50--passing 50 mesh, beach sample,
BCH%-200--percent passing 200 mesh, beach sample.

TABLE 8. - Correlation coefficient matrix for laboratory trough tests

	FLOW, gpm	SLDEN, % solids	BCHSLP, %	MLL%-50	MLL%-200	SOLSG	DIST, ft	ANGL, deg	COHSN, psi	PERM, cm/s	BCH%-50
SLDEN...........	0.052										
BCHSLP..........	-.568	0.348									
MLL%-50.........	-.125	.336	0.636								
MLL%-200........	-.125	.336	.636	1.000							
SOLSG...........	.125	-.336	-.636	-1.000	-1.000						
DIST............	.000	-.000	-.000	0.000	-0.000	0.000					
SHEAR...........	-.108	.191	.391	.367	.367	-.367	-0.238				
COHSN...........	-.154	.249	.434	.520	.520	-.520	.117	-0.030			
PERM............	-.065	-.440	-.219	-.276	-.276	.276	-.426	.073	-0.162		
BCH%-50.........	-.202	.039	.330	.354	.354	-.354	.611	.017	.181	-0.618	
BCH%-200........	-.251	.036	.223	.240	.240	-.240	.818	-.155	.175	-.460	0.582

FLOW--Deposition flow rate,
SLDEN--Slurry density,
BCHSLP--Beach slope,
MLL%-50--percent passing 50 mesh, mill grind,
MLL%-200--percent passing 200 mesh, mill grind,
SOLSG--Specific gravity of solids,
DIST--Distance,
ANGL--Angle of internal friction, beach sample,
COHSN--Cohesion,
PERM--Permeability,
BCH%-50--percent passing 50 mesh,
BCH%-200--percent passing 200 mesh, beach sample.

TABLE 9. - Correlation coefficient matrix for full-scale beach deposition

	FLOW, gpm	BCHSLP, %	DIST, ft	ANGL, deg	COHSN, psi	PERM, cm/s	BCH%-50
BCHSLP.......	-0.980						
DIST.........	.147	-0.190					
SHEAR........	.251	-.150	-0.193				
COHSN........	.132	-.241	.398	-0.647			
PERM.........	.122	-.178	-.146	.161	0.125		
BCH%-50......	-.503	.507	-.077	-.456	.060	-0.154	
BCH%-200.....	-.831	.841	-.197	-.192	-.211	-.362	0.618

FLOW--Deposition flow rate,
BCHSLP--Av beach slope,
DIST--Distance,
ANGL--Angle of internal friction,
COHSN--Cohesion,
PERM--Permeability,
BCH%-50--percent passing 50 mesh, beach sample,
BCH%-200--percent passing 200 mesh, beach sample.

° r = -0.83 between deposition flow rate and percent passing 200 mesh, beach sample. This again points to the interdependency of initial velocity, beach velocity, and the settling rate of the tailings particles.

The test results showed that the dry densities did not change significantly for distances greater than 200 ft. Therefore, tailings particles segregated, and most of the coarse particles settled out within the first 200 ft of deposition. This observation confirms Bentel's findings that beach slopes conform to a parabolic shape.[5]

The spray plate dissipator affected beach properties by decreasing the dry density and increasing the angle of internal friction. This would indicate greater segregation, causing the coarse particles to settle out earlier. However, as shown in table 6, this beach had the smallest diameter particle size when compared with the other spigot-deposited beaches. Also, the beach slope was consistently less than that of the spigoted beach slopes at any given distance from the point of deposition. These observations support the assumption that energy dissipators allow the particles to flow and settle out in a more heterogeneous manner. This would be advantageous if the tailings were to be used as a source for total tailings backfill.

The angles of internal friction appeared to be related to the beach slopes, as expected. However, there did not appear to be a direct relationship between velocity and factor of safety for this particular tailings (fig. 12*D*). In fact, there appeared to be a deposition rate that was actually detrimental to the model embankments. At an exit velocity of 12 ft/s, the factor of safety decreased to 1.04. The addition of the spray plate increased the factor of safety to 1.10, but this is still lower than the 1.14 factor of safety of the beach deposited at 92 ft/s. This means that for this particular tailings type, some rates of deposition can have detrimental effects. More field tests are required to confirm whether this phenomenon exists for any other tailings. Figure 10 shows the embankment schematic and resultant factors of safety for the various exit velocities studied.

[5] Bentel, G. M. Some Aspects of the Behaviour of Hydraulically Deposited Tailings. MS Thesis, Univ. Witwatersrand, Johannesburg, Rep. S. Africa, 1981, 141 pp.

CONCLUSIONS

To determine any relationships that may have affected the results in all of the three different test phases, linear regressions were calculated and compared. Table 10 summarizes the R^2 values of each regression in each test phase. Through this analysis, it was possible to predict the beach slope by knowing the flow rate of deposition, the R^2 value being 0.958 using the full-scale field data. This relationship dropped to 0.620 when a group of similarly deposited tailings sites were analyzed using the mine survey data, even when parameters of slurry density, specific gravity of the solids, and the mill grind were included. The same relationship between the dependent variable (beach slope) and the independent variables (flow and slurry density) was only 0.446 for the laboratory trough tests. It may very well be that any relationships that do exist between deposition techniques and beach characteristics are nonlinear, in which case higher order analysis techniques and more sample data are needed. One important general observation of the full-scale field test results should be stated. Changes in deposition parameters changed the embankment factor of safety. Considering the high cost of cleanup for a failed tailings pond, any changes in tailings deposition parameters should be evaluated prior to implementation.

TABLE 10. - Linear regression summary of all three phases

Sample and phase	Linear regression equation	R^2
Mine survey, upstream spigoting deposition only:		
Beach slope........	-24.2 - 0.261 (SLDEN) + 10.3 (SOLSG) - 0.00252 (FLOW)	0.620
BCH% 50............	806 + 0.388 (SLDEN) - 274 (SOLSG) + 0.0151 (FLOW)	.639
BCH%-200...........	557 + 0.795 (SLDEN) - 215 (SOLSG) + 0.0488 (FLOW)	.397
Laboratory trough:		
Beach slope[1].......	2.89 + 0.0248 (SLDEN) - 0.068 (FLOW)	.446
BCH%-50............	99.9 + 0.0151 (SLDEN) - 0.11 (FLOW)	.010
BCH%-200...........	66.4 + 0.093 (SLDEN) - 0.845 (FLOW)	.032
Full-scale field depositions:[2]		
Beach slope........	1.98 - 0.0043 (FLOW)	.958
BCH%-50............	98.7 - 0.00465 (FLOW)	.206
BCH%-200...........	61 - 0.0844 (FLOW)	.672

[1](SOLSG) and (MLL%-200) held constant.
[2](SOLSG), (SLDEN), and (MLL%-200) held constant.

SLDEN--Slurry density, percent solids,
SOLSG--Solids specific gravity,
MLL%-200--percent passing 200 mesh, mill grind,
FLOW--Flow rate, gpm,
BCH%-50--percent passing 50 mesh, beach sample,
BCH%-200--percent passing 200 mesh, beach sample.

U.S. GOVERNMENT PRINTING OFFICE: 1988 — 547-000/80,039

INT.-BU.OF MINES,PGH.,PA. 28718