TAILINGS BEACH SLOPES

by

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ABSTRACT

This paper discusses the formation of tailings beach slopes from discharge point to pond bottom. Measurements from five operating tailings impoundments are compared and analyzed by normalizing the distance from the discharge and relative elevation to the pond. The slope data are compared with other published information and data trends are presented. The information presented in the paper provides a basis for comparison and developing similar relationships among slope parameters and *in situ* material properties.

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INTRODUCTION

The development of tailings deposition schemes to maximize basin filling, control pond locations, promote exposure and drying or for decommissioning requires, among other things, the prediction of tailings beach slopes. The selection of appropriate slope angles is most important at sites where long beach slopes can develop and where the relative elevation of the pond, discharge point(s) and surface of the tailings solids will effect basin construction activities as well as impoundment operations in general.

The purpose of this paper is to present a brief assessment of the dominant factors controlling tailings slope formation and to develop some behavioral trends. The information contained herein was prepared using published reports and project data collected as part of consulting assignments at five mine sites. It is the intention of this presentation to provide a data base which might be expanded to incorporate other minerals and depositional methods for other minerals and materials.

TAILINGS SLOPE FORMATION

DEPOSITIONAL REGIMES

The deposition of mine tailings is somewhat analogous to natural delta formation in that solids carried as a slurry settle and become deposited as the transporting medium loses energy when streams enter water bodies. It is often convenient to describe natural deltaic sedimentation in coastal environments in terms of topset, foreset and bottomset bed deposits as illustrated in Figure 1a. Each bed deposit is a reflection of the varying depositional regime from discharge to pond bottom. Borrowing this format a basis for terminology, this paper discusses the deposition at tailings impoundments using topset, foreset and bottomset bed to define different depositional regimes as discussed below.

The topset beds at tailings impoundments represent that portion of the tailings solids above the pond, which is more commonly referred to as the tailings beach, Figure 1b. The deposition of solids on the beach is observed to occur as three general flow systems: (i)a meandering channel flow part way down the slope where deposition of larger particles occurs by settling, followed by (ii) a network of tributary systems of small channels where the same depositional processes occur and which develop as the slope flattens and flow velocity decreases, followed by (iii) sheet flow over broad flat areas where only fine particles remain in suspension and only minor sorting occurs by processes similar to 'film sizing', a form of gravity concentration used in the mineral dressing industry (Taggart,1967). In all three flow regimes, some segregation occurs leading to a general reduction in mean particle size with distance from the discharge and layering of sediments as pond and discharge locations change.

Foreset beds develop as thin slurries enter the pond allowing particles to drop from suspension and roll down the advancing slope. The particle velocity decreases in static ponds creating a calm depositional environment which leads to temporary oversteepening of these slopes. The slope angle formed would be influenced by the rate of solids deposition which controls pore pressure development. No well documented sampling program of foreset beds has been undertaken to the writer's knowledge, but it would appear from excavations in disused tailings basins that some layering and segregation occurs parallel to the slope.

Bottomset beds accumulate as fine sediments settle from suspension. In addition, slope failures in foreset beds, which occur because of wave action or mass movements on soft foundations (i.e.,bottomset beds) as these beds advance into the pond, distribute coarser sediments throughout the pond bottom. The repeated deposition of coarse and finer sediments develops pronounced layering at many tailings impoundments.

CONTRIBUTING FACTORS TO SLOPE FORMATION

The geological factors that influence the engineering properties of sediments can be divided into three broad categories: (i)petrographic factors, (ii) modes of transportation and deposition, and (iii) post-depositional changes (Terzaghi, 1955). For mine tailings, the petrographic factors affecting slope formation include particle size distribution leaving the mill, grain shape and mineralogical composition. Tailings transportation in pipelines as a slurry at typical flow rates of 1 to 3 m/sec, for example, results in a pseudo-homogeneous flow regime giving a uniform distribution of particles throughout the pipe (Cabrera,1979). The changing depositional regimes at discharge on the topset beds was discussed above. The principal factor controlling tailings deposition is the slurry behavior after discharge which is principally controlled by the percentage of solids in the slurry, an observation which has been made by numerous investigators throughout the literature.

The variation in operating procedures and practices, and climatic conditions at different tailings impoundments results in sediment layering and overlapping of depositional environments. These factors complicate the assessment of tailings slopes. The discussions and slope data presented in the next section of this paper are 'unfiltered' field measurements which might account for some of the wide scatter in data trends.

DATA BASE AND TRENDS

The data base used in this study was assembled from five operating mines in Canada and a review of the literature. Topset bed slope measurements were obtained at all five sites. Foreset and bottomset bed slope profiles were obtained from two uranium mining operations in Elliot Lake, Ontario. Some of the relevant tailings management features from each mining operation is summarized in Table 1 below.

Table 1. Summary of Mine Sites Studied

mine	type	Specific Gravity	%sol.	average 'n' topset	foreset	bottomset
1.Agnico-Eagle(Que.)	gold	3.2	28	1.71	--	--
2.Doyon (Que.)	gold	2.85	48	2.18	--	--
3.Pine Point(NWT;est%sol)	Pb-Zn	3.5	25	1.01	--	--
4.Denison(Ont.)	uranium	2.65	33	1.51	3.53	2.0
5.Quirke(Ont.;4 profiles)	uranium	2.7	20	1.20	2.4	1.87

The change in elevation of topset beds with distance from the discharge for the five mines considered is summarized on Figure 2a. These data are similar to many published records and suggests overall slopes of 0.5% to 1.0% would be appropriate. Similarly, the change in elevation of foreset and bottomset beds with distance from the edge of the pond (i.e., discharge location into the pond) is presented in Figure 2b for several slope profiles obtained at the two uranium mines. This plot indicates that the initial slopes, which are considered to be foreset beds, are markedly steeper than the topset beds; this accounts for the development of a deep storage pond at many sites. The steeper foreset beds grade into flatter bottomset beds in the distant locations of the pond.

A comparison of data from the five mine sites listed in Table 1 and other published data from the literature is presented in Figure 3. These plots indicate that although there would appear to be some trends in the data, the scatter is significant and might be attributed to several operational factors. A method of comparing different slope profiles and obtaining data for predictive purposes is presented below.

NORMALIZED BEHAVIOR

The work of Melent'ev et al (1973) and other Russian researchers have shown that the slope formed by hydraulically placed granular materials can be represented by a dimensionless "master profile". This concept was later discussed by Blight(1987), Wates, et al (1987), Blight et al (1985) and Blight and Bentel, (1983).

The master profile is considered to apply to all slopes in similar materials regardless of the beach length or elevation difference between the slurry discharge and the pond. The formation of a master profile suggests that the depostional characteristics, modes of sediment transport and profile formation are consistent for any slope. The master profile is simply a normalization of the slope profile by dividing the elevation difference between the pond and any point on the beach, h, by the total elevation difference between the discharge and the pond, y. Similarly, the distance between the discharge and any point on the beach, H, is divided by the total distance between the discharge and the pond, x. The relationship between these parameters is illustrated in Figure 4 and can be stated according to the following equation:

$$h/y = (1 - H/x)^n \qquad \text{[eqn 1]}$$

where the exponent 'n' is considered to be characteristic of a particular material and method of placement. The normalization of data allows direct comparison of many slopes regardless of beach length and site geometry. In addition, once the exponent 'n' is determined, one can use the above equation to develop site specific profiles, discharge elevations and pond locations for planning tailings deposition schemes. It is noted that Wates et al (1987) and Robinsky (1978), for example, have demonstrated the use of small scale laboratory tests in assessing the effects of slurry characteristics on the slope parameter 'n'.

The data from the five mine sites considered in this paper were plotted in this normalized fashion and the results appear as Figures 4 and 5 for topset beds and foreset-bottomset beds, respectively. The average value of the parameter 'n' for each tailings profile presented in Figures 4 and 5 is summarized in Table 1. Additional values of the exponent 'n' obtained from the literature are listed in Table 2 below.

Table 2. Reported Values of Normalized Slope Exponent 'n'(Topset Beds)

source	mineral	average 'n'	comments
Blight and Bentel(1983) {South Africa mine}	copper	1.4	cyclone underflow
"	diamond	1.5	beach slope
"	platinum	2.0	beach slope
"	gold	4.0	beach slope

The data summarized in Figures 4 and 5 and Tables 1 and 2 could be used to provide information for developing predictive equations for slope profiles at similar mining operations, although the scatter in data is rather large. There appears to be some general trends in the data set as discussed below.

TREND ANALYSIS AND POSSIBLE APPLICATIONS

If the slopes formed by sedimenting tailings are considered to be analogous to natural delta deposits and channel flow processes then the simplified qualitative relationship suggested by Lane (1955) would provide insight into the factors affecting slope formation. Lane observed that the slope of bottom sediments in channel flow follows the relationship:

$$i \sim (Qs \times d)/Qw \qquad \text{[eqn 2]}$$

where, i is the slope of the stream
Qs is the quantity of solids in the flow
Qw is the quantity of water (flow velocity)
d is the dominant particle size

This simple relationship confirms the common field and laboratory observation that the slope of a tailings beach increases when the volume of water is decreased (i.e., the flow velocity is decreased by using several spigots rather than a single end discharge point), and if the quantity of solids at the discharge is increased or the particle size is increased. Since most tailings considered herein have similar gradational characteristics, particularly in the coarser fraction, the percentage of solids in the slurry at discharge would be the dominant factor controlling slope formation. The quantity of water at the discharge also affects slope formation to a lesser extent but was not quantified in the data obtained; however, the operations studied have somewhat similar discharge methods and rates.

The effect on tailings slopes of the percentage of solids in the discharge is illustrated in Figure 6 for the five mine sites studied. The data suggests a consistent trend of increasing value of the exponent 'n' (i.e., increasing slope angle) as the slurry density increases for topset and foreset beds. Bottomset beds appear unaffected by the characteristics of the slurry discharge as anticipated. It should also be noted that the apparent specific gravities of each tailings is noted beside the data point in Figure 6 and indicates that specific gravity has a secondary influence on slope angle. These observations are consistent with other published data such as that presented by Blight et al (1985) and Robinsky (1978), among others. The use of the data in Figure 6 is for the selection of 'n' which provides a complete profile from discharge to pond base using the normalized slope relationship [eqn 1].

The segregation of particles along the beach was studied at several mines but more closely at the Denison Mine in Elliot Lake, Ontario. The change in various gradational sizes as referenced to the per cent passing size, d, is presented in Figure 7a for part of a long topset bed. These data demonstrate that over the initial 500 m of beach, the main change in particle size was in the coarser fraction (d50 to d80 sizes) and that the coefficient of curvature remains roughly constant while the coefficient of uniformity decreases with distance from the discharge.

The variation is gradational characteristics on topset beds for a variety of mines was plotted and it was observed that the rate of increase in the percentage of fines towards the pond could be used as an index of overall particle segregation (referred to herein as the 'segregation index'). When plotted against the percentage of solids by weight at the discharge, a data trend is apparent as shown in Figure 7b. The envelop of the data in Figure 7b represents the boundaries from several data sources and mine types.

It is observed that the trend in Figure 7b follows some form of a exponential equation and thus the logarithm of the 'segregation index' results in a fairly consistent linear relationship when plotted against the percentage of solids at the discharge as shown in Figure 8a. Again, the envelop was developed from data at several different mining operations. Combining this inferred trend in Figure 8a with the trend in the slope parameter 'n' shown on Figure 6 results in the relationship indicated in Figure 8b which suggests that the slope angle would increase as the segregation index decreases. This observation provides a numerical basis and is consistent with the published data of Robinsky (1978) and others which describes the dependance of slope angle on particle segregation.

Application of the data trends and analysis to the planning of basin filling schemes and preparing material balances is apparent. The initial data set presented in Figures 6,7 and 8 provides a methodology and data base for predicting tailings slopes from the discharge to the pond base. The influence of particle segregation on slope formation is demonstrated in Figures 7 and 8. These data also provide a basis for predicting tailings slope-segregation characteristics which controls, among other things, the *in situ* permeability (and hence position of the phreatic surface), the development and dissipation of pore water pressures, material compressibility, and dynamic resistance.

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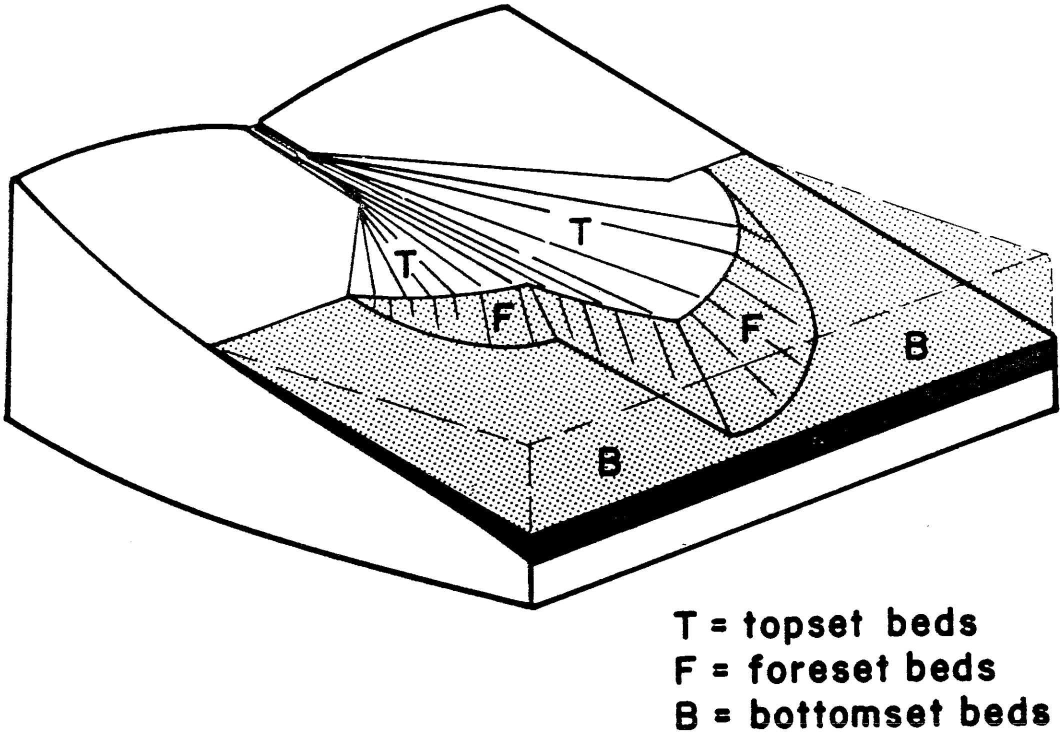
Figure 1. Tailings Slope Definition and Inferred Flow Regimes on Topset Beds

a)



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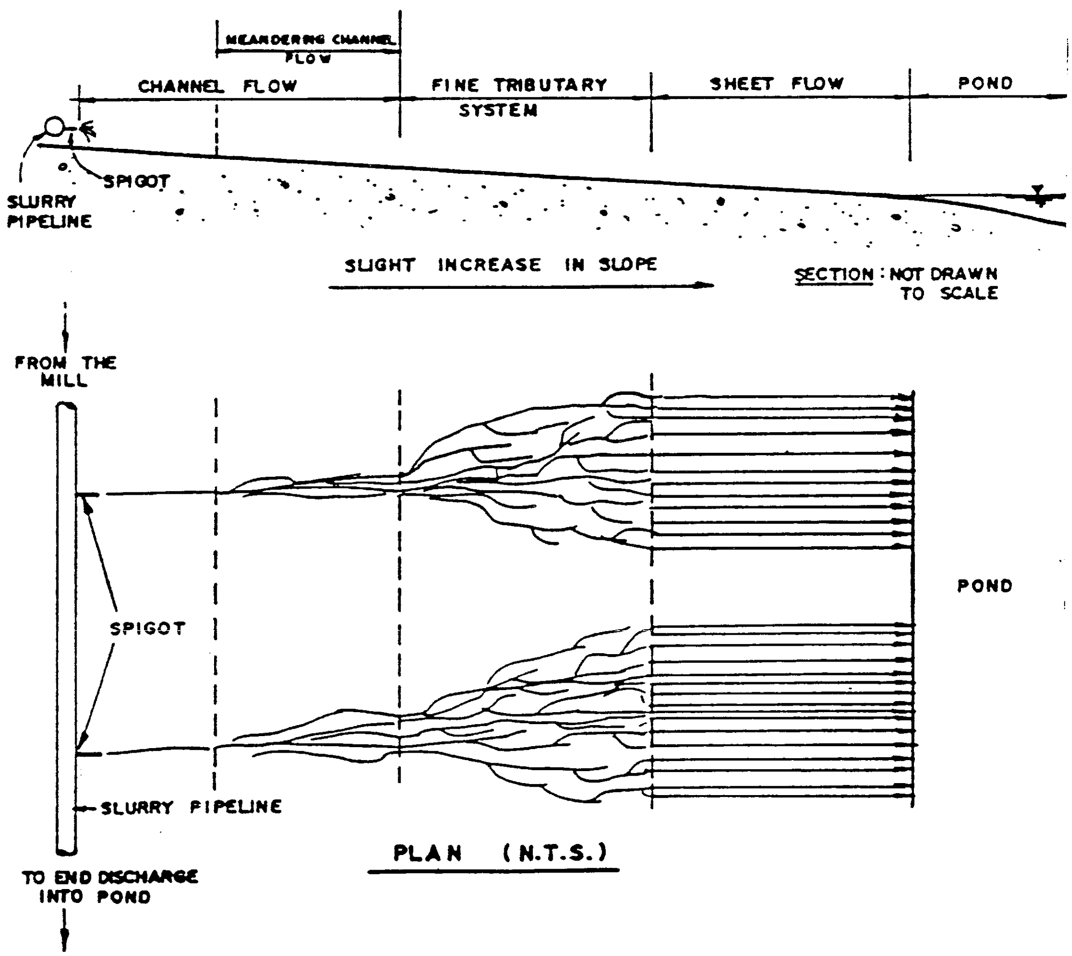
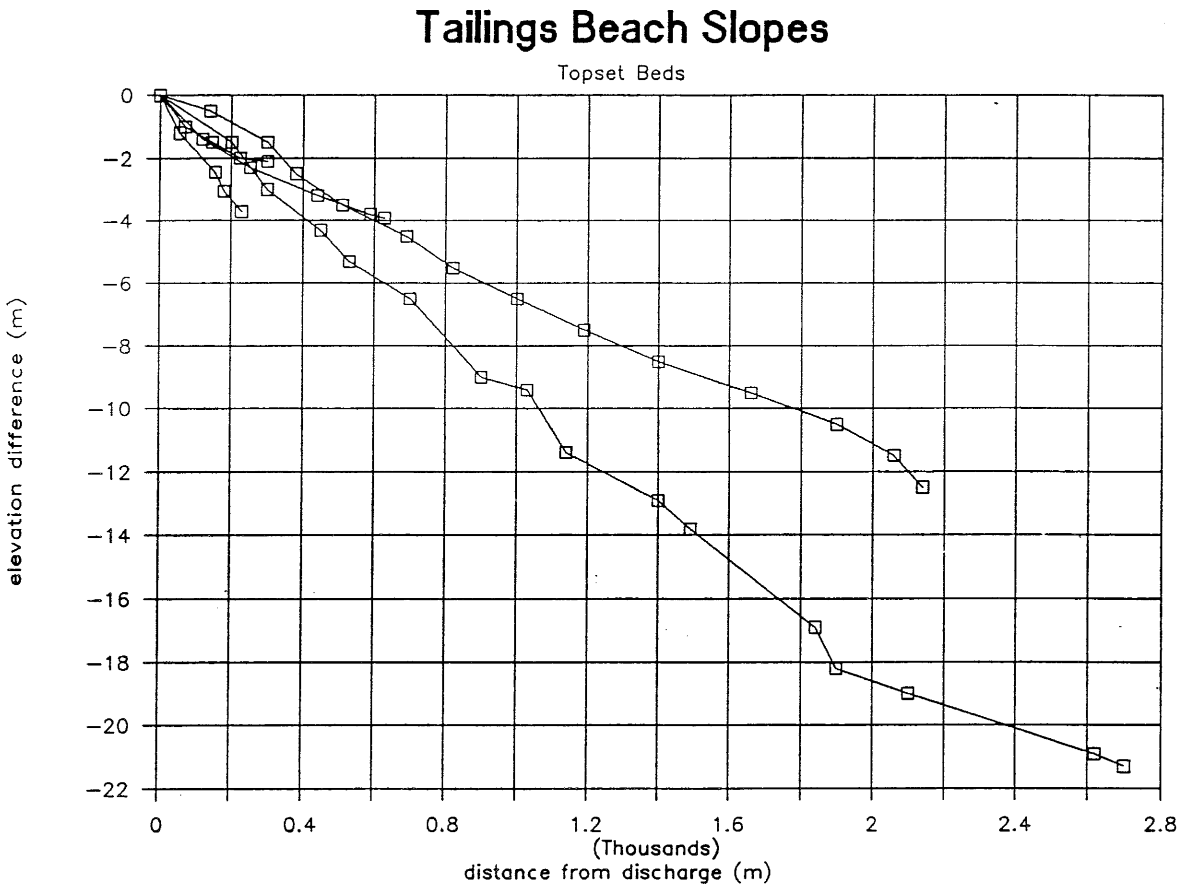


Figure 2. Tailings Slope Profiles

(mine sites listed in Table 1)



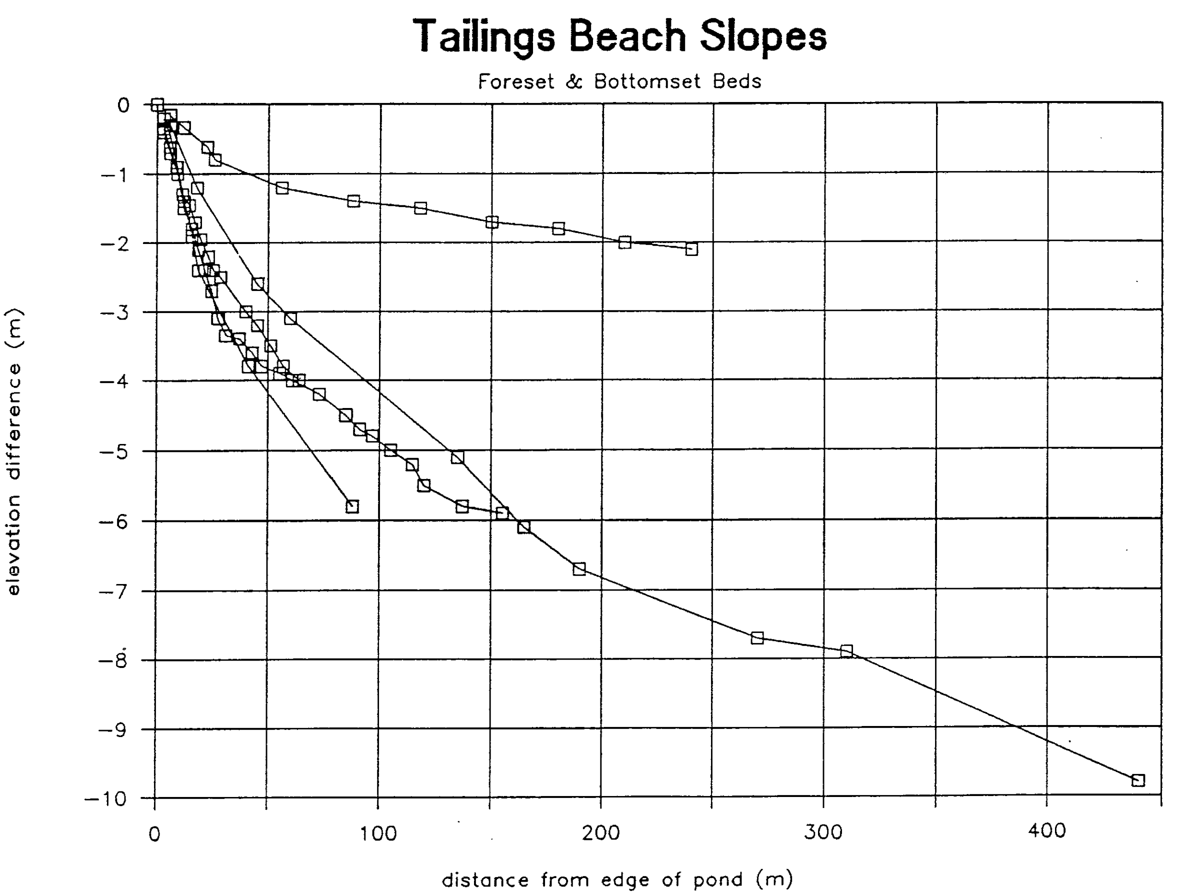


Figure 3. Summary of Tailings Slope Data

(from literature and data base in Table 1)

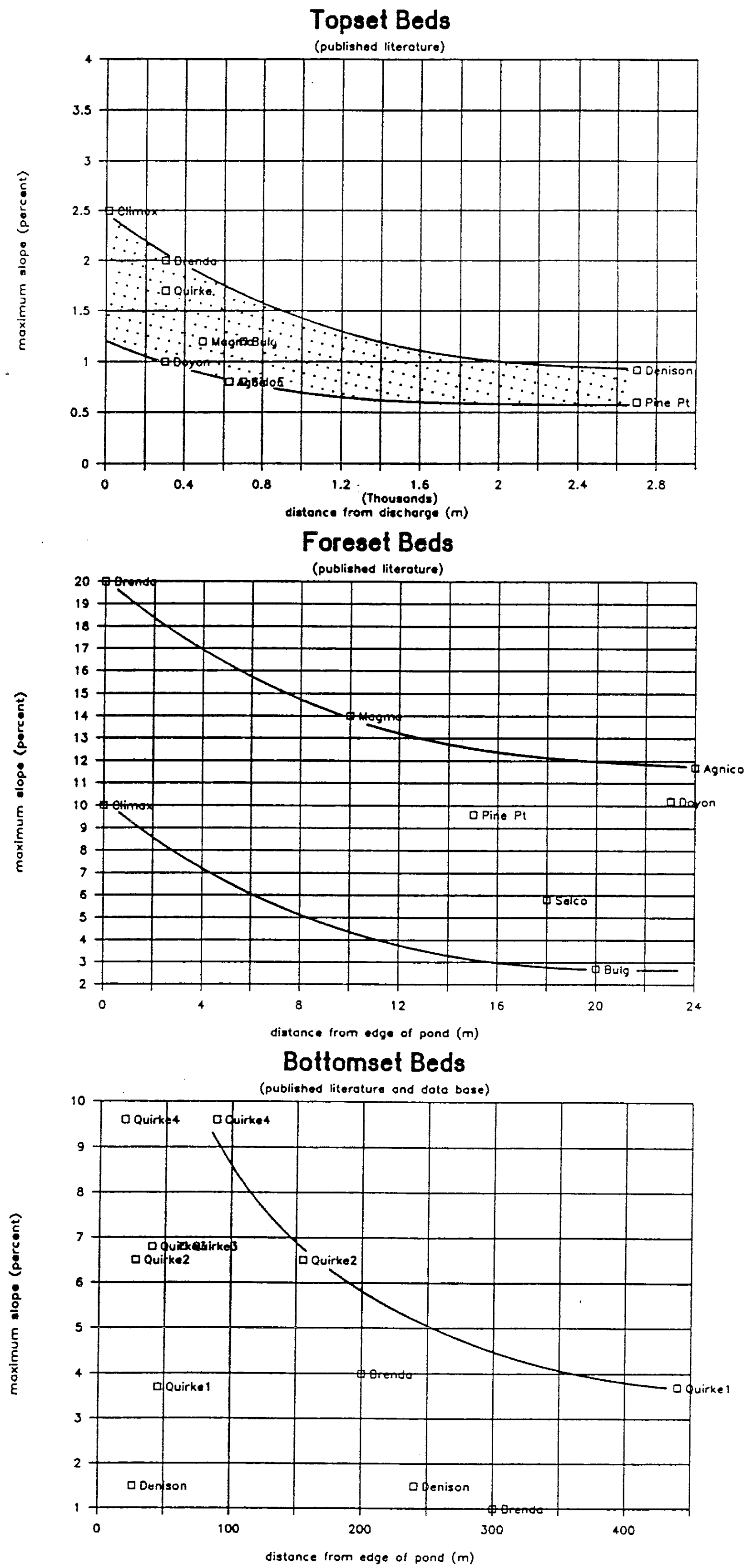


Figure 4. Normalized Topset Bed Slope Data

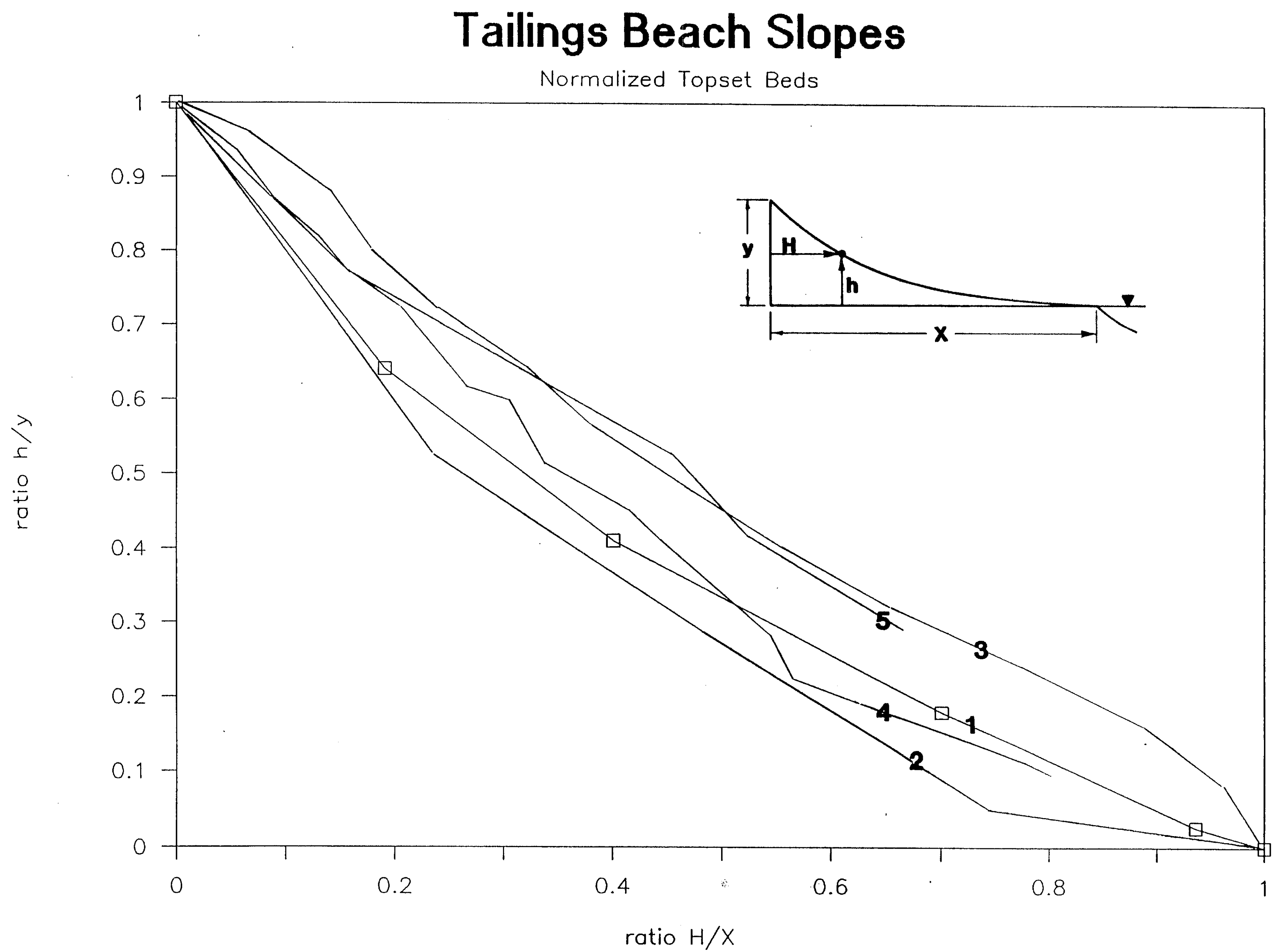


Figure 5. Normalized Foreset & Bottomset Slope Data
(all profiles from Quirke Mine)

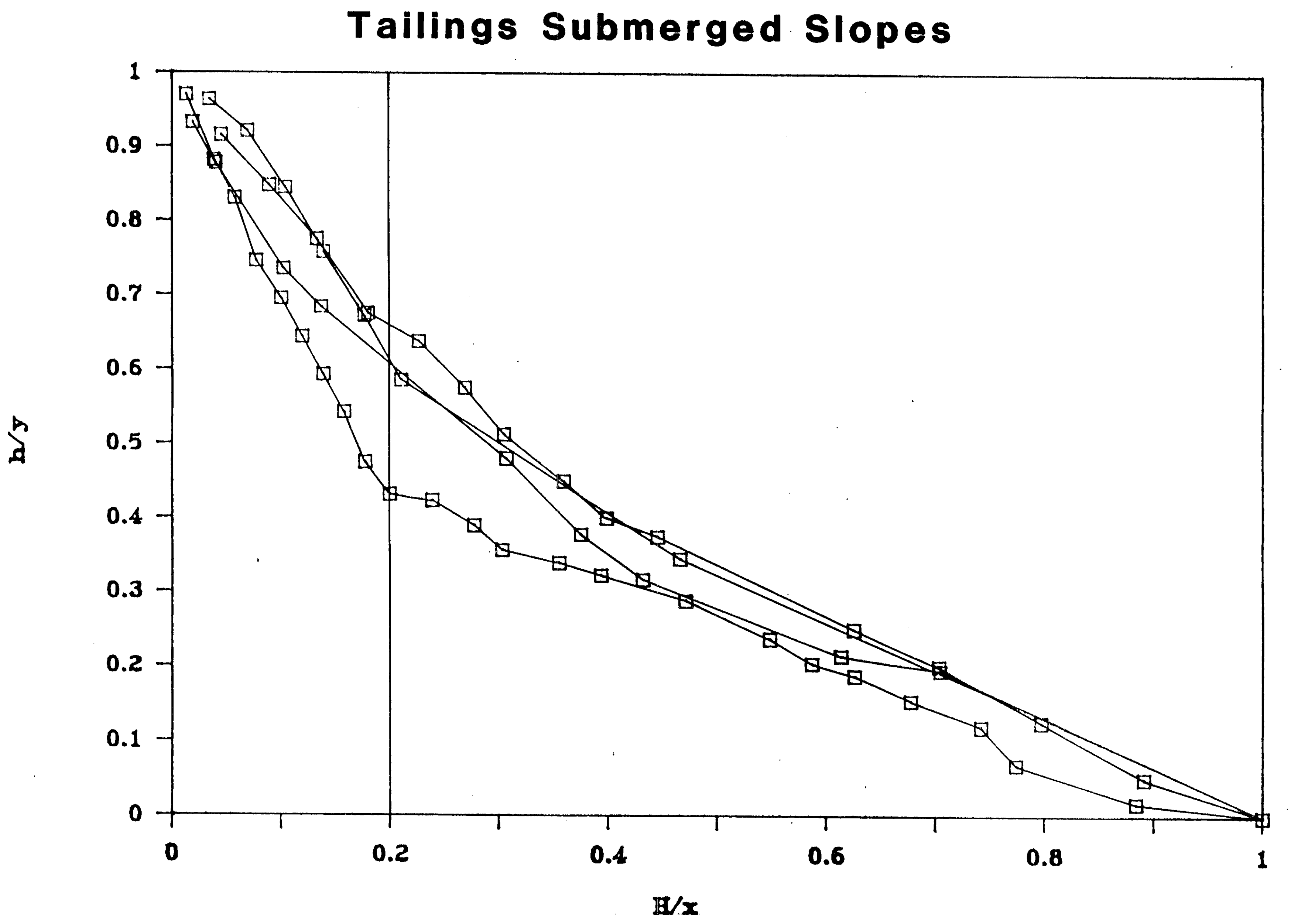


Figure 6. Changes in Tailings Slopes with Slurry Density at Discharge

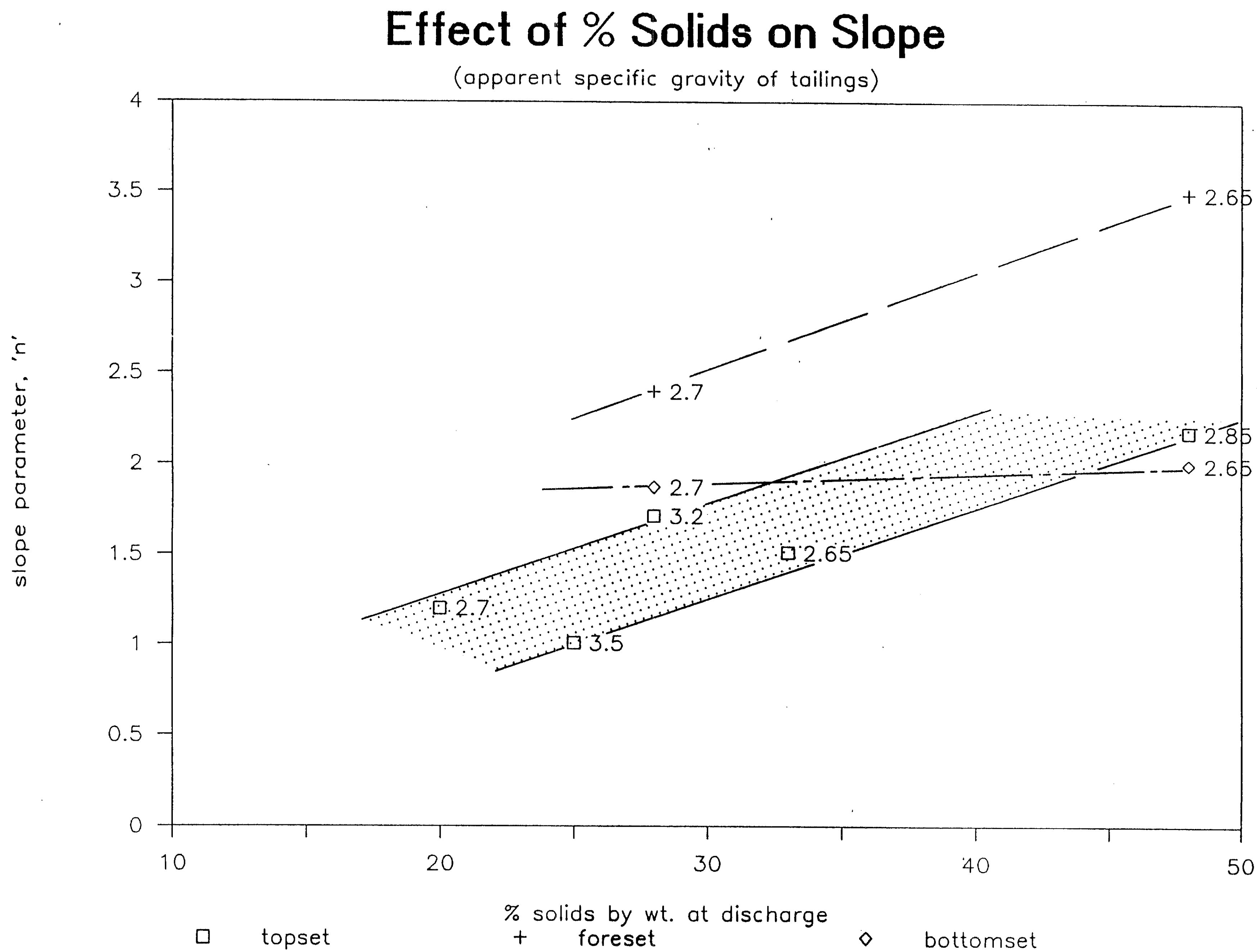


Figure 7. Example of Segregation on Beach (Topset) Slopes

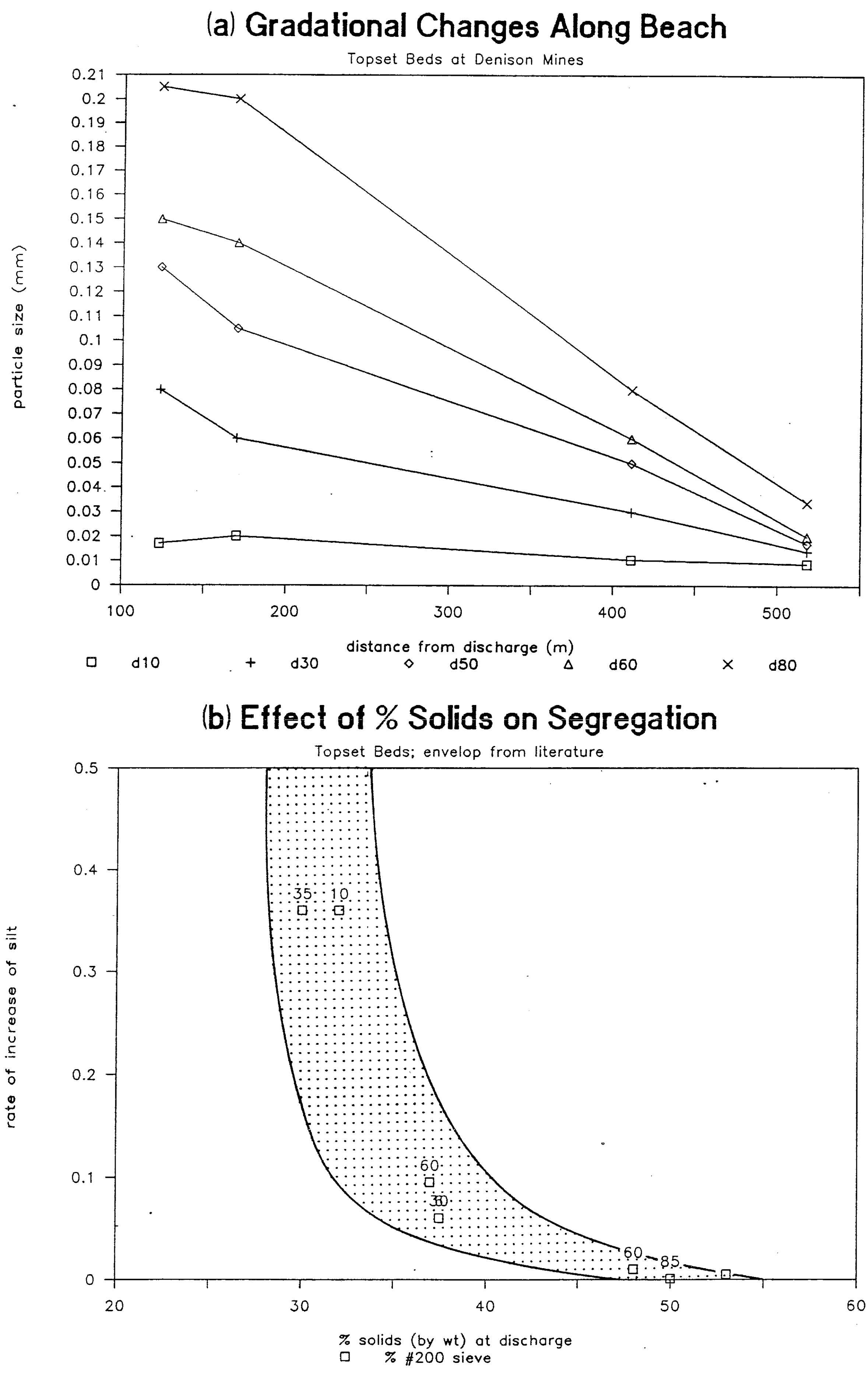


Figure 8. Example of Effects of Slurry Density on Segregation and Relationship to Tailings Slope Formation