Erosion Characteristics of Underwater Deposited Mine Tailings

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Abstract

The erosion characteristics of underwater deposited mine tailings were measured using two separate techniques: 1) a rotating circular flume and 2) a research wave flume, located, respectively, at the National Water Research Institute, Burlington, Ontario and Canadian Hydraulics Centre, National Research Council, Ottawa, Ontario. The experimental tailings for both studies were obtained from the nickel mining operations of INCO Limited, Copper Cliff, Ontario. For the circular flume study, total mill tailings, as discharged, along with their process water were used. For the wave flume study, the erosion characteristics were measured separately for coarse, fine tailings, and fine tailings covered with a 5-cm layer of fine silica sand.

For measuring erosion characteristics using a circular flume, a uniform bed of mine tailings, approximately 3 cm in thickness, in contact with their process water was prepared and allowed to settle. The flume and its cover plate were rotated in the opposite directions relative to the stationary fluid column producing a uniform shear stress on the tailings bed. By increasing the speed of the rotating flume assembly in uniform incremental steps, the critical shear stress at which the tailings became mobile was measured by determining the mass of the re-suspended tailings in the water column. For the experimental tailings, the critical shear stress using the circular flume was measured as ~ 0.16 N/m^2.

In the wave flume, the mine tailings were placed in the flume test area and exposed to a range of regular and irregular wave conditions, and their mobility was measured in terms of critical shear stress exceeding the motion threshold. For coarse and fine tailings, the measured critical shear stresses were, respectively, 0.21-0.25 N/m^2 and 0.20-0.22 N/m^2. The mobility of the tailings was observed to be independent of their particle size distribution, the nature of sediment placement or their degree of consolidation. No upward migration of the tailings was seen when the tailings were covered with a thin layer of silica sand.

Introduction

Underwater disposal of sulphidic (reactive) mine tailings in man-made or natural water bodies, or establishment of an in-situ water cover on the deposited tailings for controlling acidic drainage is a very attractive option at sites where local climatic and topographic conditions permit establishment and maintenance of such covers. The advantage of the water cover in controlling sulphide oxidation, and hence acid generation, lies in its ability to limit the availability of dissolved oxygen through its low solubility and diffusivity of molecular oxygen at ~ 8.6 mg/L (at 25 ºC) and 2×10^{-9} m^2/s, respectively, compared to those for the air at ~ 285 mg/L (21.5% v/v at STD) and 1.82×10^{-5} m^2/s, respectively.

For the successful management of underwater deposited mine tailings under shallow water cover

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conditions, it is essential to provide and maintain the depth of the water cover at a level sufficient to ensure that the deposited tailings are physically stable at the surface and no re-suspension of the tailings occurs due to wind induced wave action. The physical stability of the tailings surface is primarily influenced by wave action.

The role of wave action on the suspension/re-suspension of mine tailings was investigated by Lawrence et al. (1991) for the oil-sand mining operations of Syncrude Limited in northern Alberta, and by Yanful and Varma (1998) for the reactive, base-metal mine tailings. Atkins et al. (1997) have examined the problem of wave action on the surface stability of underwater deposited mine tailings, and have proposed a design methodology for tailings facilities for determining the minimum depth of water cover required to adequately cover a given set of tailings characteristics.

While designing water-covered, tailings management facilities, the knowledge of the erosion characteristics of mine tailings under various water depth and wave conditions is essential. More specifically, the critical velocity or shear stress for the tailings bed mobility is required for calculating the required minimum depth of the water cover.

This study investigated the erosion characteristics of underwater deposited mine tailings, and determined their critical shear stress using two different test methods and various water cover conditions.

Experimental Methods

Experimental facilities

The erosion characteristics of underwater deposited mine tailings were studied using two state of the art techniques: 1) a rotating circular flume, and 2) a research wave flume as briefly described below:

1. Rotating Circular Flume

The rotating circular flume and its associated test facilities are located at the National Water Research Institute, Burlington, Ontario, Canada. The facility was designed to undertake basic research on fine-sediment dynamics, specifically for cohesive sediments such as silt and clay without compromising their particle integrity. In a rotating circular flume the fluid is kept stationary and the flow is generated by moving the flow boundaries, i.e. flume. In a conventional straight or linear flume, a fluid flow is provided in a stationary flume.

The rotating circular flume assembly, shown in Figure 1, consists of a circular flume, 5.0 m in mean diameter, 0.30 m in width and 0.3 m in depth. It rests on a rotating platform having a diameter of 7.0 m. An annular cover plate (ring), attached to an upper turntable, fits inside the flume with a radial clearance of 1.5 mm on either side. The rotating platform and the upper turntable are supported in a “king-post configuration”, where the support for the entire structure is provided within a king post that also houses two independent drive assemblies for the lower rotating platform and the upper turntable containing the ring. Both the flume and the ring could be rotated independently in either direction with a speed range of 0 to 3.0 rpm. A 10 t capacity jackscrew, mounted at the center of the upper turntable, is used for raising or lowering the position of the ring in the flume, and for removing the ring completely for filling or emptying the flume.

The flume operates smoothly without any detectable wobble or vibration. The horizontal level of the flume bottom and the underside of the top cover-ring surface are true within ± 1.5 mm. The total dead weight of the flume is ~ 10 t and the total height of the flume structure is ~3.5 m from the foundation level.

The flume is also fitted with glass windows for instruments, and for visual observations. Electrical power is provided to the lower rotating platform to power instruments such as a laser Doppler anemometer and a laser particle size analyzer, used respectively, for measuring the tangential velocity component, and for particle size distribution of the suspended particles. The bed shear stress is measured using a Preston tube, which is a simple pitot tube resting on the bed surface, and a 2 mm diameter fixed tube, mounted through the outer wall of the flume. The bed shear stress is computed by the measured difference between the pitot and static pressures. The pressure difference is measured using a diaphragm pressure transducer.

By rotating the flume and its upper cover plate (ring) in opposite directions at rotational speeds ranging from 0 to 3 rpm, the flume assembly could be operated to provide reasonably uniform bed shear stresses over the entire flume width. Details of the rotating circular flume, its accessories and measuring techniques are provided in Krishnappan (1993).

2. Research Wave Flume

The research wave flume and its associated test facilities are located at the Canadian Hydraulics Center (CHC) of the National Research Council of Canada (NRC), Ottawa, Ontario, Canada. The research wave flume, shown in Figure 2, is 97 m long, 2 m wide and 2.75 m deep. It has a programmable, multi-mode wave generator machine and an active wave absorption capability, and can generate waves up to 1.1 m high. The wave absorber at the opposite end of the flume is a progressive, porosity expanded-metal absorber, which has reflection coefficients of less than 5% over a large range of wave conditions. Along the flume floor, a 1-m wide, 2-m long and 0.085-m deep test section was built to contain mine tailings for testing under various water depth and wave conditions.

Waves in the flume are measured using capacitance-wire wave gauges. These gauges consist of a wire probe and a capacitor head that generates a voltage signal that is linearly proportional to the elevation of the free surface of water. As the water level in the flume varies with propagating waves, the voltage reading from the probe also varies and is recorded. A series of voltage records is used to determine wave heights and periods. The location of the wave probes along the flume are also shown in Figure 2. Wave gauges 1 and 2 were stationed near the wave generator, whereas an array of wave gauges, 1 through 6, was stationed directly above the test section.

Wave orbital velocity near the tailings test bed are measured using a Sontek ADV current meter, which is a single point, high resolution, 3 D Doppler current meter. The current meter is programmable to measure velocities in the range: ±3, 10, 30, 100 or 250 cm/s, having a velocity resolution of 0.1 mm/s and a sample volume of less than 0.2 cm^3.

Suspended sediment concentration measurements through the height of the water column are measured using a transversely mounted sediment suction sampler, consisting of eight intakes that are vertically aligned in an exponential distribution above the test bed. The sampler is mounted near the down-wave limit of the test section.

Observations, and video and photographic records of the tests are made through glass windows in front of the test area. Details of the research wave flume, its accessories and testing procedures for determining the mobility of mine tailings under wave action are given in Davies and Reid (2000).

Experimental procedures

The experimental tailings for the erosion studies were obtained from the nickel mining operations of INCO Limited, Copper Cliff, Ontario, Canada. For the circular flume study, total mill tailings, as discharged without particle size segregation, along with their process water were used. The tailings were obtained from the mill, by bleeding a small stream of tailings from the tailings discharge pipeline as the tailings were being discharged. The tailings were kept covered with their process water to minimize surface oxidation prior to testing.

For the wave flume study, the erosion characteristics were measured separately for coarse and fine tailings, and for fine tailings covered with a 5-cm layer of fine silica sand. Both the coarse and fine tailings were obtained from a freshly deposited area in the tailings basin. The coarse tailings were obtained from an area immediately in the vicinity of the tailings discharge point. The fine tailings were obtained from a distant area far removed from the discharge end. The fine silica sand used for covering the fine tailings bed was from the Canada Hydraulics Center’s laboratory. The experiments were conducted using municipal tap water.

The experimental procedures for the two studies were as follows:

Circular flume study

For determining the erosion characteristics using the circular flume, a uniform bed of mine tailings, approximately 3 cm in thickness, in contact with their process water was prepared and allowed to settle. The tailings were first mixed and homogenized using an industrial mixer, and slurried using their own process water. The tailings slurry was then poured into the circular flume. Before letting the tailings to settle, the flume and the ring were rotated at near maximum speeds of 2 and 2.5 rpm, respectively, for about 20 minutes. The speed of the flume and the ring was then gradually decreased to zero. This procedure allowed the tailings to distribute and settle evenly over the entire flume bed. The tailings were allowed to settle for five days before conducting the erosion test.

The flume and its cover plate (ring) were rotated in opposite directions relatively to the stationary fluid column to produce a uniform, tangential shear stress on the tailings bed. By increasing the speed of the rotating flume assembly in uniform incremental steps, the critical shear stress at which the tailings became mobile was measured by sampling the water column above the tailings bed and determining the mass concentration (dry mass) of the re-suspended tailings in the water column. A background concentration of the suspended tailings mass in the water column prior to starting the flume was also measured. The critical shear stress for the bed mobility was obtained by plotting the measured mass concentration of the re-suspended tailings as a function of the applied shear stress and determining the required shear stress at the mobility threshold.

Wave flume study

In the wave flume, the mine tailings were placed in the flume test area and the flume was filled with municipal tap water. The test tailings were exposed to a range of regular and irregular wave conditions, and their mobility was measured in terms of the critical shear stress exceeding the motion threshold.

The established tailings bed was subjected to a series of storm sequences of increasing intensity. Hydrodynamic conditions and bed response was monitored using photography and video recording, and by sediment suction sampling. The coarse tailings were tested first, followed by fine tailings. The fine tailings were tested under three different conditions: densely packed, a loosely placed slurry and a consolidated slurry covered with a 5-cm layer of fine silica sand (D_{50} = 120 µm). A summary of the test materials, established water cover depths and wave conditions are given in Table 1.

Table 1. Summary of test materials, and established water depth and wave conditions for the wave flume study.

Material	Depth of water (m)
Coarse tailings	2.0
Coarse tailings	1.5
Coarse tailings	1.5 (regular waves)
Coarse tailings	1.0
Fine tailings	1.5
Fine tailings slurry	1.0
Fine tailings slurry with a 5-cm cover of fine silica sand	1.0

For a given test material and water depth, a Shields rating from 0 to 5 was assigned to each hydrodynamic test condition in the order of increasing waveform energy, and hence bed mobility, where ‘0’ represented no motion, ‘3’ represented the motion threshold and ‘5’ the onset of sediment transport with suspension clouds. The Shields ratings were then plotted based on the dimensionless grain size of the tailings/sand and the calculated Shields parameter (Shields, 1937). The Shields parameter represented the shear stress that was acting on the test bed and differed with each magnitude of the wave, water depth, and grain size. The Shields rating was then compared with the Soulsby and Whitehouse (1998) prediction of the mobility threshold.

Results and Discussion

Circular flume study

The total mill tailings used in the circular flume study were somewhat coarse having a D_{50} diameter of ~150 µm. The tailings contact or process water used in the testing contained a high concentration of total dissolved solids (TDS) exceeding 1,500 mg/L, mostly as dissolved gypsum ($CaSO_4.2H_2O$). The erosion characteristics of the tailings, plotted as the mass concentration (dry weight) of the re-suspended tailings as a function of the applied bed shear stress, are shown in Figure 3. Based on the criterion for the motion threshold, the critical shear stress for the total mill tailings in contact with their process water was obtained as 0.16 N/m^2.

Wave flume study

The wave flume study was conducted using three types of test materials; coarse tailings, fine tailings, and fine tailings covered with a 5-cm layer of fine silica sand. The grain size characteristics, represented by D_{50} diameter, and specific gravity of these materials were, respectively, 0.230 µm, 0.083 µm and 0.120 µm (silica sand), and 2.61, 2.37 and 2.40. The fluid media in the flume was from the municipal tap water supply.

The erosion characteristics of the tailings under wave motion were determined based on the assigned Shields rating (as discussed above) to the observations made on the response of the tailings bed to the applied wave conditions. Figure 4, shows a typical Shield parameter plot based on the dimensionless grain size parameter, and the predicted threshold mobility according to Soulsby and Whitehouse (1998) and the assigned Shields rating parameter for coarse tailings under a 2.0 m deep water cover.

The observed and predicted mobility threshold wave conditions, and the calculated critical shear stress associated with the mobility threshold for the coarse and fine tailings, and for the silica sand covering the fine tailings under various test conditions are summarized in Table 2.

Under the applied waveform conditions that exceeded the motion threshold, both the coarse and fine tailings were mobilized, irrespective of their degree of consolidation. However, for the fine tailings covered with a 5-cm layer of fine silica sand no mobility of the underlying tailings was seen under the applied wave conditions. The wave form parameter listed in Table 2 are thus for the mobility of the fine silica sand.

It is seen from these results that although the circular flume and the wave flume methods are quite different in their underlying principles and operating methods, the critical shear stress values obtained by the two methods are comparable. The critical shear stress value of 0.16 N/m^2 obtained for the total mill tailings in contact with their process water using the circular flume was, however, lower than the values obtained in ranges of 0.21-0.25 N/m^2 and 0.20-0.22 N/m^2, respectively, for the coarse and fine tailings using the wave flume and municipal tap water (Table 2). These values are comparable or slightly lower than the critical shear stress values of 0.12 to 0.17 N/m^2, obtained by Yanful and Catalan (2002) from field observations of re-suspension of base-metal tailings at maximum wind speeds averaging about 10m/s in a shallow end of a tailings impoundment.

In both cases, the tailings were observed to behave like a non-cohesive material, similar to a fine sand, where the intermediate fine fraction was mobilized irrespective of their particle size distributions. It is, however, believed that the high total dissolved solids (TDS) concentration of >1,500 mg/L for the tailings process water, used in the circular flume study, may have contributed to lowering of the threshold mobility due to its slightly increased buoyancy in comparison to that of the municipal tap water having a TDS of ~ 150-200 mg/L. The large volume capacity of the wave flume, at ~ 533.5 m^3, precluded testing of the mine tailings in contact with their process water as it would have required shipping and handling of a large quantity of mill process water.

The results of the wave flume study further showed that for both the coarse and fine tailings the mobility threshold parameters were nearly the same and no impact of their grain size distribution or particle cohesion was seen. Their mobility thresholds could be well predicted using the Shields curve and general relationships for non-cohesive materials. The tailings mobility was also seen to be independent upon the nature of sediment placement or their degree of consolidation.

Depending upon the availability of the test materials and the type of parameters required, either method could be suitably used for measuring threshold mobility parameters. These values are required in the design of water-covered, tailings management facilities for obtaining minimum water depth requirements for given wind velocity and wave fetch conditions. Davies and Reid (2000) have developed an algorithm based on Soulsby and Whitehouse's theory of critical shear stress (Soulsby and Whitehouse, 1998) for calculating the minimum water depth for a tailings basin to prevent re-suspension of the tailings due to wave action. These results are compared with those of Atkins et al. (1997).

Summary and Conclusions

The erosion characteristics of the mine tailings were measured using a rotating circular flume and a research wave flume. Total mill tailings in contact with their process water were used in the circular flume study. The wave flume study was carried out separately using coarse and fine tailings, and fine tailings covered with a 5-cm layer of fine silica sand.

The critical shear stress measured for the total mill tailings in contact with their process water was 0.16 N/m^2. For the coarse and fine tailings, the measured critical stresses using the wave flume and municipal tap water were in ranges of 0.21-25 N/m^2 and 0.20-0.22 N/m^2, respectively.

The mobility of the tailings was observed to be independent of their particle size distribution, the nature of sediment placement or their degree of consolidation. No upward migration of the tailings was seen when the tailings were covered with a thin layer of silica sand.

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Table 2. Summary of test materials, water depths, observed and predicted values of wave height (H_s) and peak period (T_p) at which the mobility threshold was observed, and the calculated critical shear stress for the coarse and fine tailings for the wave flume study.

Materials	Water depth (m)	Wave height (H_s) and peak period (T_p) at the observed mobility threshold		Wave height (H_s) and peak period (T_p) at the predicted mobility threshold by Soulsby and Whitehouse (1998)		Calculated critical shear stress (N/m^2)
		H_s (m)	T_p (s)	H_s (m)	T_p (s)	
Coarse tailings	2.0	0.22	2.10	0.22	1.95	0.21
	1.5	0.18	1.90	0.17	1.71	0.23
	1.5 (regular waves)	0.32	1.53	0.29	1.41	0.25
	1.0	0.14	1.63	0.12	1.45	0.23
Fine tailings	1.5	0.13	1.65	0.14	1.57	0.20
Fine tailings slurry	1.0	0.13	1.64	0.10	1.33	0.22
Fine tailings covered with a 5-cm layer of fine sand*	1.0	0.13	1.63	0.11	1.37	0.16

*During the tests with the sand cover, the underlying tailings were not seen to move. Therefore, the values given in the table are for sand mobility only.

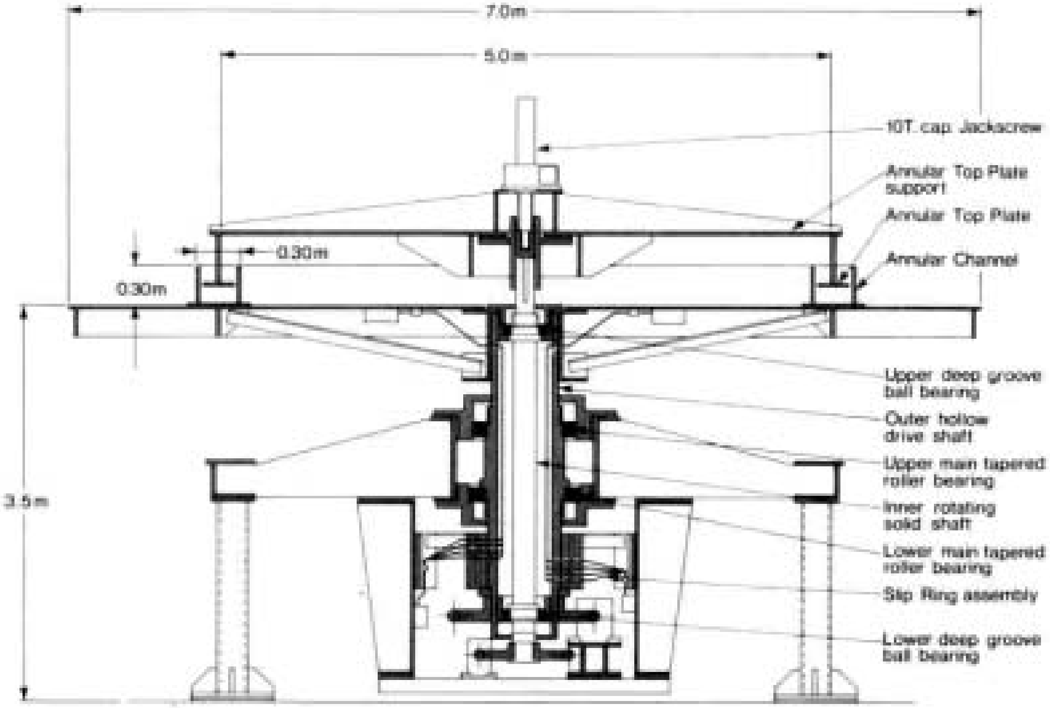

Figure 1. Schematics of the rotating circular flume at the National Water Research Institute, Burlington, Ontario, Canada.

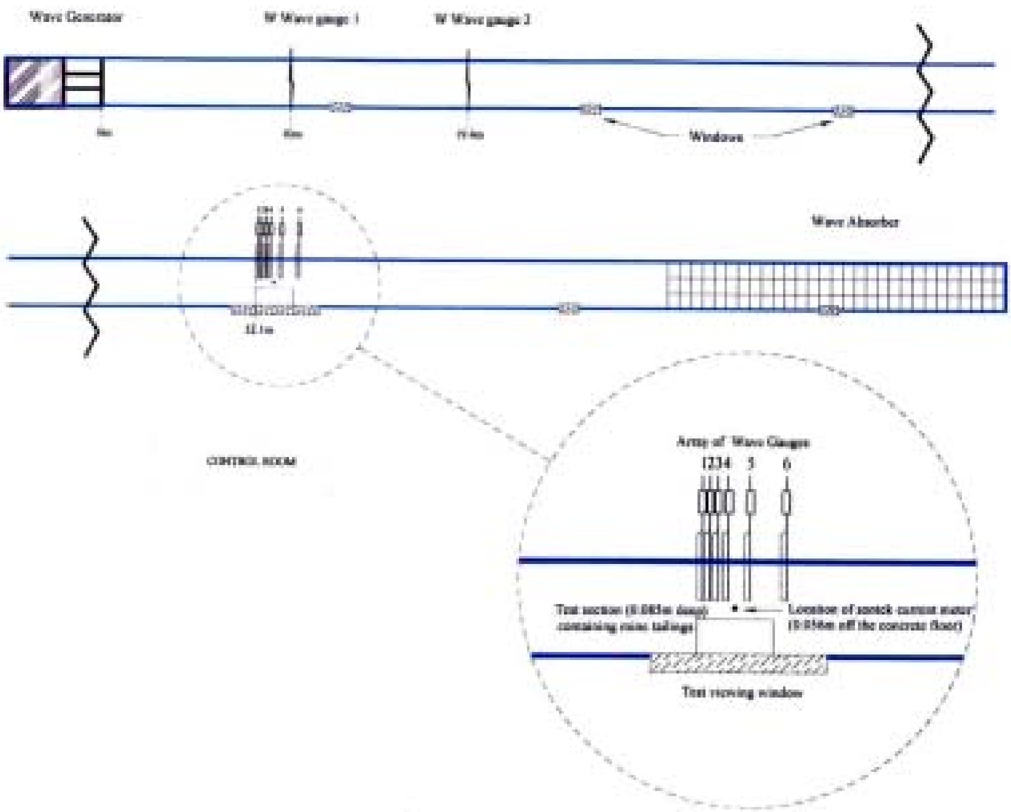

Figure 2. Schematics of the research wave flume at the Canadian Hydraulic Center, National Research Council Canada, Ottawa, Ontario, Canada.

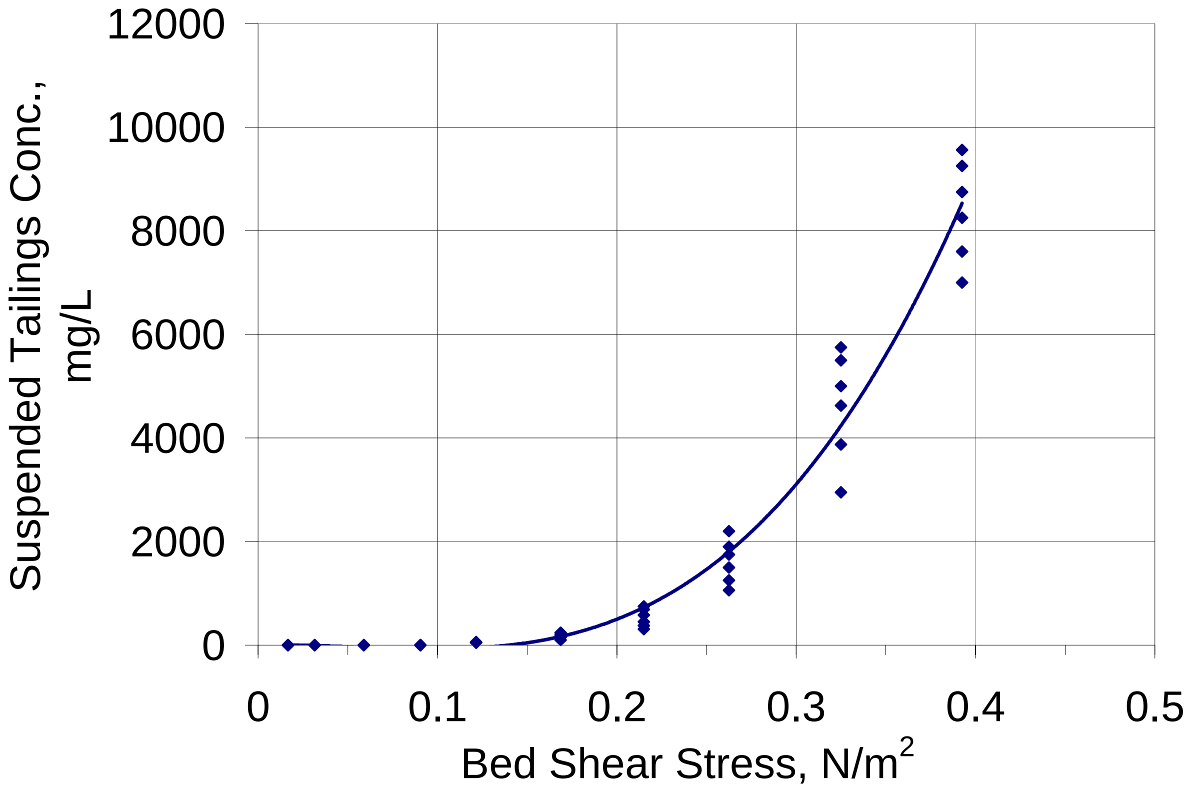

Figure 3. Erosion characteristics of the total mill tailings in contact with their process water using the circular flume.

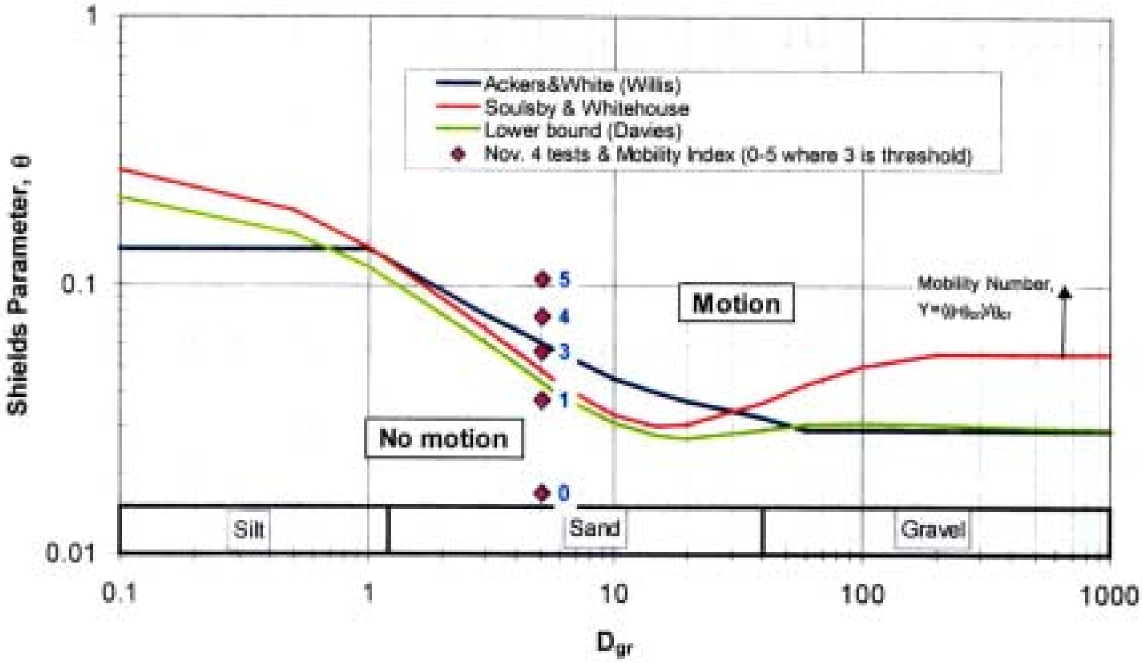

Figure 4. Shields parameter plot showing the observed and predicted mobility thresholds for the coarse tailings under a 2.0 m deep water cover.