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THE FEASIBILITY OF A SUBMARINE OUTFALL PIPE FOR MINERAL TAILINGS

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SUMMARY

Unusually large scale experiments are described which were carried out to investigate a submarine outfall pipe for China Clay residues which would be discharged as a slurry on a sea bed slope. The movement away from the outfall was critically important in assessing the life of the system. The difficulties of observation and interpretation of the results are described.

Two theoretical models were set up to predict the downhill movement of the slurry, and to find the probable rate of building of the underwater spoil heap. A tower type outfall was also investigated and its advantage assessed.

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It is sometimes desired to discharge mining tailings or other mineral refuse into the sea. To avoid serious contamination of the surroundings, the design and position of the outfall pipe must be selected with care, and some difficult decisions must be made.

Recently a proposal to dump 200 x 10^6 tons of the micaceous residue from the China Clay industry into the English Channel has been investigated, and the opportunity was taken to carry out some unusually large scale tests. The material was to be deposited over 60 years, at 1.8 x 10^6 tons/year now, rising in the future. The solids are mainly mica and the size distribution is shown in Fig. 1. The solids would be made into a slurry with fresh water to a maximum density of 1.4, the particles being deflocculated. A mean speed of about 3 m/sec in a 30 cm pipe is well known to keep the slurry mobile without settling out. At present, this waste is contained within bunds on land, or is discharged into rivers. Pollution of the rivers, and of the beaches at the mouths of rivers therefore occurs. The coastline is rocky with frequent high cliffs, and is a holiday area, so that it was necessary to be sure of the disposal into deep water of all the material, and to decrease as far as possible the visual pollution if the fines caused the sea to be converted to 'milk'.

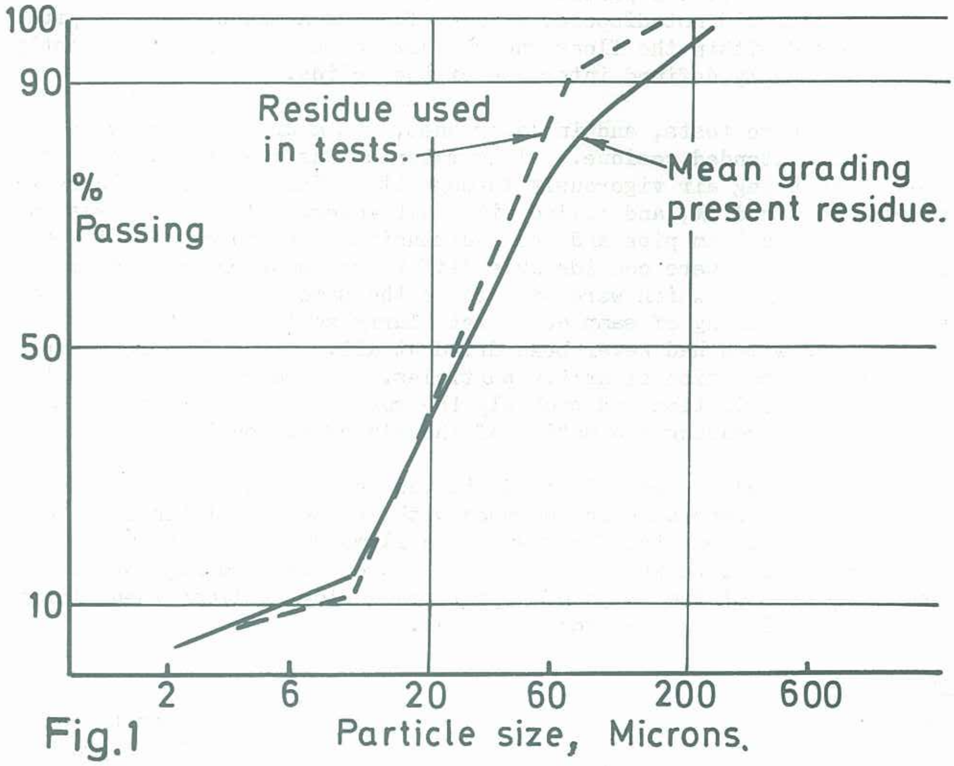

Fig.1

A convenient site, about 19 km from the workings, was 1.5 km offshore in 20 m of water, and at the head of a rocky 12% slope about 20 m deep again: at its foot, the sea bed was sloping only 2% and was smooth sand. The 30 cm dia pipe would be carried under the sea bed in a mined gallery, and then drilled upwards to a plain outlet close to the bed. The tidal currents in this position were some 0.5 m/sec at springs, with a tidal range of 2.5 m, and studies of sea currents using floats showed little likelihood of onshore drifts which would put slurry on the beaches.

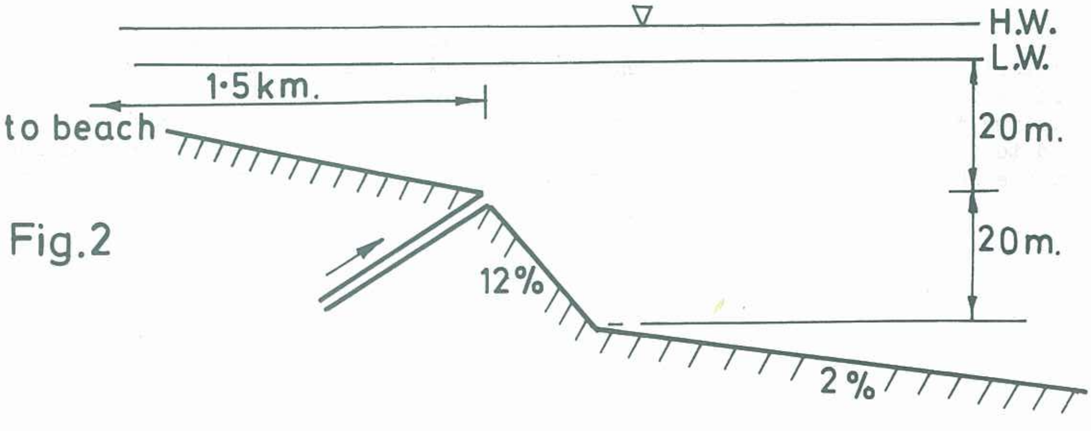

Fig.2

A heavy fluid discharged on a bed slope will undoubtedly run down-hill as a continually supplied 'turbidity' or density current. With a slurry, however, additional complications arise, since the solids constantly settle out (the largest particles nearest to the outfall), and there may be dilution on the upper side of the current. Both these matters were of importance in the design, since the first controls the distance travelled by particles, and so the total volume of storage available: and the second might affect the production of 'clouds' of fine particles that could be diffused by turbulent motions to the surface of the sea. An experimental programme was evolved to throw light on these features.

Laboratory experiments

Small scale experiments in a 3 m long by 10 cm wide laboratory channel showed that fresh water slurry fed into salt water on a 2% sloping bed soon accumulated over the end of the pipe, making a surface slope about some 4%. It was further observed that when the larger fraction of particles had settled from the slurry, the density became less than that of the sea water: convection started, appearing precisely like small cumulus clouds as the finest particles were carried upwards. At the same time it was found in this small scale that if slurry was very slowly fed under the salt water, the particles were flocculated by the salt, and they gripped together. The slurry thus did not disperse at all, forming a mound over the pipe. However, the fresh water was locked within the flocs and did not convect upwards: perfectly clear salt water stayed above the sharply defined interface of the solids.

The solids used in these tests, and in later ones, was a dried slurry with the same particle size distribution as the intended residue. This material was re-mixed with fresh tap water and kept in suspension by bubbling air vigorously through it. This re-mixed slurry was also tested in a 1 m square tray, inclined 2%, and filled with salt water. The slurry was introduced on the bottom of the tray through a 2 cm pipe and the 3-dimensional spreading of a fixed quantity of material was measured. There were considerable differences between slurries made up from different sacks of dry material which were said to be the same; and there were similar large differences between the spreading of samples of wet slurry sent directly from various units of the refining process, and which had never been dried at all. Indeed, some slurries rapidly choked the inlet pipe by deposition of gritty particles. It seemed clear that there were differences in the size distribution and probably the surface chemistry of all samples, and these had a large effect on the spreading and motion of the slurry at least on a 2% slope.

With these small scale experiments in mind, it was thought advisable to carry out more at much larger scales and these were done in the open with sea water, within large masonry settling tanks. Two series were arranged; the first was in a flume 20 m long and 60 cm wide, and was an attempt to find the critical slope which just kept all the slurry moving downhill; and the second was a three-dimensional test of the shape of deposit on a sloping floor when slurry was discharged from a 5 cm pipe, within a tank some 9 m wide.

Large scale experiments

In the flume test, 20 tonnes of dry material was mixed with sea water to densities 1.2 or 1.4 and discharged in 50 min so that the flow was about 1/12 of that of the proposed full scale pipeline. It entered under a sluice 7 cm open at the higher end of the flume, and the bed formation at the end of each run was recorded. It was thought that such a 2-dimensional test would represent the motion of slurry as it ran down a slope, when salt had replaced fresh water; and when (as had been noticed in small scale tests) the river of slurry had concentrated along a bed and was not fanning out in all directions. The sea water was clouded from the outset so that little visual observation could be made of the deposition. A diver reported moving depths of slurry of about 8 cm and speeds of about 15 cm/sec, while samples taken all along the 20 m length showed little dilution of the slurry.

The tests showed clearly that the 1.4 density slurry travelled further than the 1.2 density, and less material remained in the 20 m length. At a 6% slope, all material was swept the full length, but as the slope decreased, the larger particles were deposited. At 2% slope, and density 1.4 two tests were done, each at the same discharge rate, but one lasting 110 minutes as compared to the standard 50 mins. The centreline profiles, measured after draining away the sea water, are shown in fig. 3, and the proportion of solids left in the flume are shown in Table 1.

Table 1 Test on 2% slope, Density 1.4 - Proportion of Particles remaining in Flume.

	50 min Test	110 min Test
All particles	13%	10%
Particles 150	100%	100%
75 - 150	70%	98%
53 - 75	36%	19%

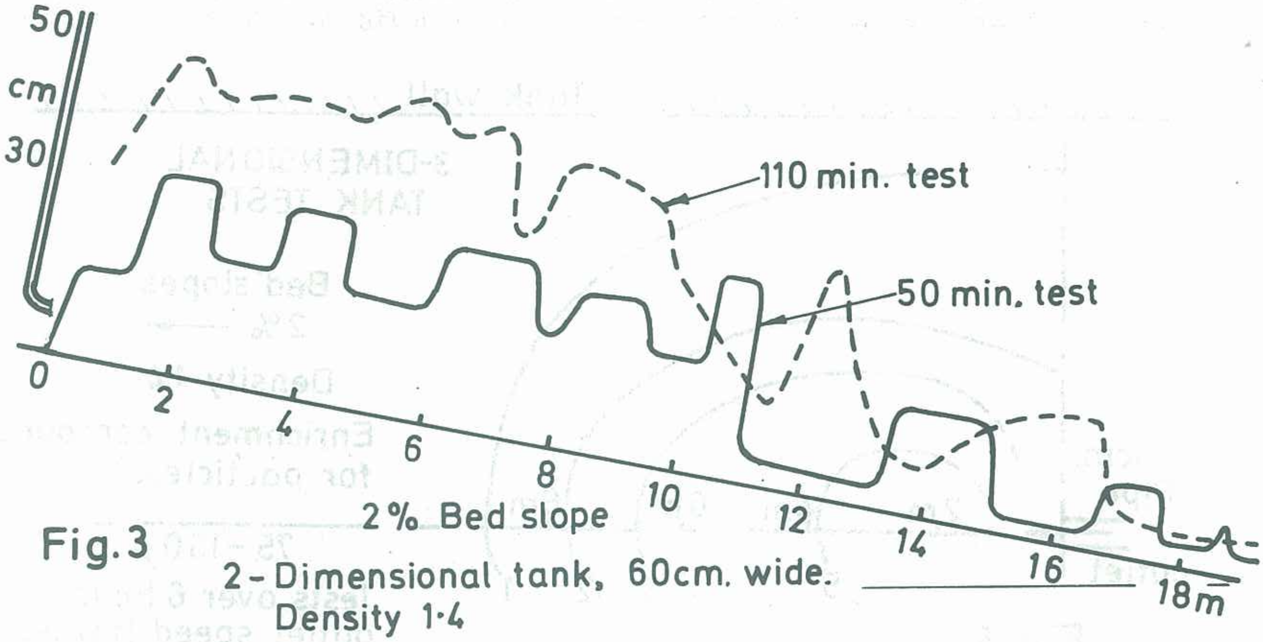

Fig.3 2-Dimensional tank, 60cm. wide.
Density 1·4

The proportions remaining are those compared to the total of particles in the size group shown, fed into the slurry during the whole test. One way of interpreting the result is to say that after 50 minutes 87% of all particles (90% in 110 mins) travelled more than 20 m down 2% slope, Alternatively, a more pessimistic interpretation is to observe that in both tests all the large particles were retained in the 20 m.

The profiles show two features of importance; first that the mean surface slope was greater after the longer test, and so gave higher slurry speeds which deposited less of the fine fraction; and second, that the final surface was by no means a uniform slope. There were dunes and hollows, often noticeably 3-dimensional, so that the slurry stream must have meandered over the 60 cm wide flume. Thus despite the 2-dimensional inlet of slurry, the stream must have soon concentrated into only part of the 60 cm width. It has been noticed in the small scale tests (in which the flume was only 4 cm wide and the slurry surface could be seen through the glass walls) that the slurry did not flow uniformly over the whole width. There seems to be a strong tendency towards concentration of slurry streams, into a few narrow 'rivers', rather than a uniform sheet of movement over a wider area.

The deliberately 3-dimensional tests were carried out at slopes of 2% and 4%, but the pipe was always 5 cm diameter with 1.2 m of water over it. Tests were done with a mean slurry outlet speed of 1.5 and 1.0 m/sec. Tests were done at 1/40 of the prototype discharge for 6 hours, following which the tank was carefully emptied and the profile measured and sampled. During the test, numerous samplings were made in the diffusing jets, to find how high the dispersed slurry would be found above the bed, and to determine the density of the moving slurry stream. These samples showed clearly that the slurry did not continue to diffuse linearly with distance (as occurs in a freely discharging jet of the same density as the ambient); it reached a height of only about 8 pipe diameters, and then rapidly fell back to the bed. There was no sign that the diffusion process brought quantities of solids near the water surface, some 1.5 m (i.e. 30 pipe diameters) above. On the other hand, the sea water (which started somewhat opaque) rapidly became generally milky, the Secchi disc visibility decreasing from about 1 m to 20 cm in 20 minutes. This was doubtless due to the fines, perhaps convecting as was seen in the laboratory tests. Although this effect seems to indicate an undesirable visual pollution in the prototype, it was noticeable that later in the 6 hour tests the visibility did not become steadily worse: in fact there were signs of a small improvement towards the end of a test. It seems possible that large scale slow circulations or density layerings were set up in the tank which in some complex manner obscure or inhibit the 'milkiness'. Whether the same would occur in the ocean, with strong tidal and wind blown surface currents, is a matter for conjecture and further experiment.

The resultant pattern of the sedimented material was plotted as enrichment curves for each size range. A typical result for coarse material is shown in fig. 4. An enrichment curve is a contour within which the proportion of solids of the given size is more than the stated number of times greater than the proportion of the solids in the original slurry. Thus it will be seen that particles of sizes 75-150 µ are at least 5 times as prevalent within the 5 contour as they are in slurry. The patterns showed that in 3-dimensional spreading on the bed slope, the large particles were still deposited close to the outlet, but that the fines travelled to the end of the available tank (and presumably much further if a long enough tank were available).

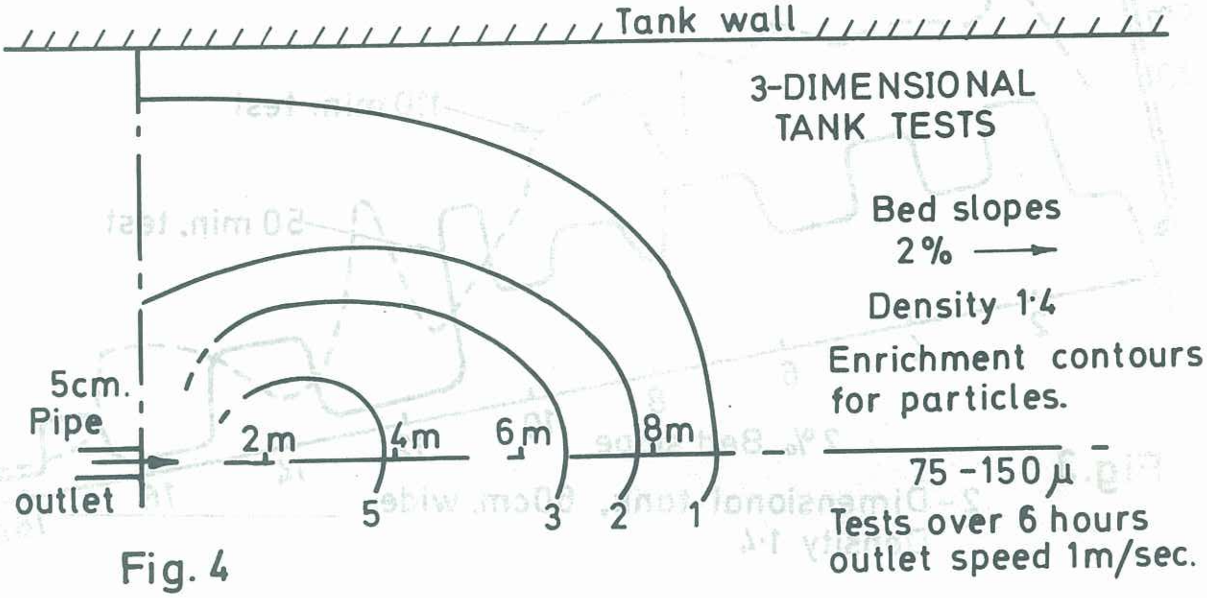

Fig. 4

Field Observations

An extensive programme of field observations of currents in the sea was arranged, to determine the likelihood of suspended material being carried towards the shoreline. In addition a slurry test was carried out where 130 tonnes of freshwater slurry was pumped to the sea bottom during a 10 hour period. A total of 800 gm of ground glass, irradiated with Scandium 46 (half-life 84 days) was added to the slurry at regular intervals during injection. Over the succeeding 6 months the radioactivity was determined over a wide area, and the nearby beaches searched for any signs of this material. Although some 40% of the radioactive material remained within 30 m of the dispersal point, evidence was found that some was carried as far as 8 km away in the SW direction - where there was a residual tidal current. None was found on the beaches. This experiment gives some clue as to whether the material, once put on the sea bed, will spread still further by tidal current action.

Interpretation of Results

After these rather large scale experiments, two theoretical models were derived to predict the rate at which the slurry would collect in the prototype. Each model presumed that on slopes of 6% and more all the slurry will move downhill, but when the slope had become less, some deposition will occur.

Model 1 assumed that the slurry travelled in 10 parallel streams each of the size of that in the 2-dimensional test; that on discharge from the pipe all the particles are uniformly distributed in the whole stream; that the particles sediment by Stokes Law and on reaching the stream bed don't roll any further; that there was no dilution of the stream from above; and the depth-speed-slope relationship was of the Manning type. The distances that various particle sizes will travel, and the consequent enrichment can be calculated. Using this model, the time required for the slope of the pile of material to decrease from the original 12% sea bed slope to 6% was calculated and found to be 6 months. After this stage had been reached the end of the pipe would be covered with residue and the pile would grow progressively larger in the form of a volcano.

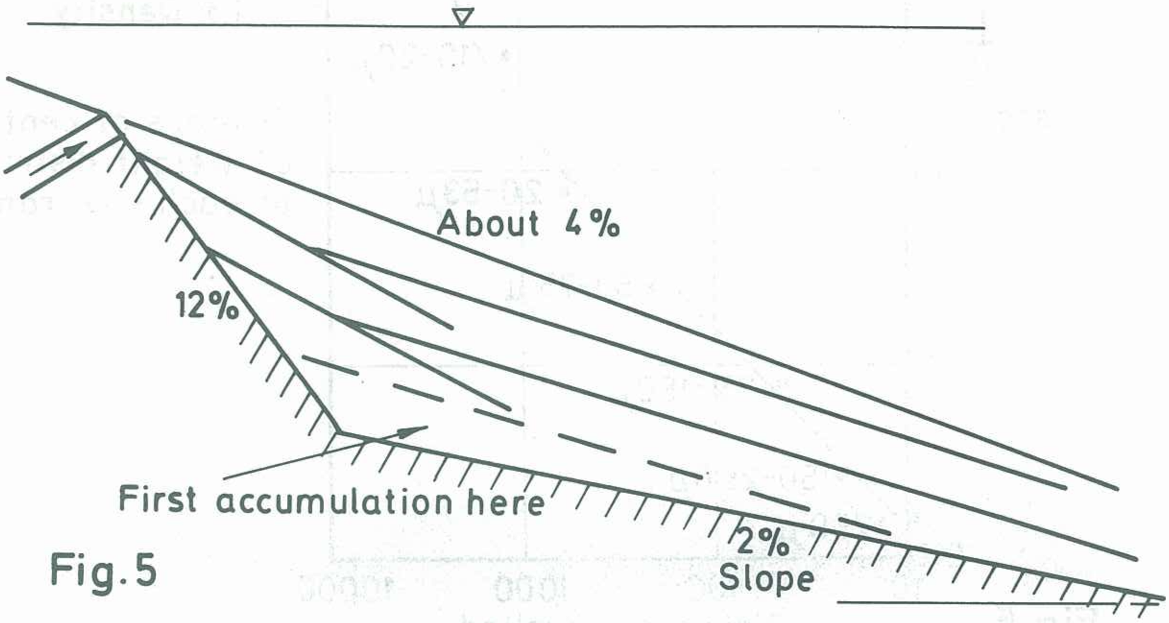

Fig.5

The second model depends more directly on the test results, but demands extensive extrapolation, with its consequent uncertainties. From the 2-dimensional tests the distribution along the flume of each size range of particles was determined. Then the centre of gravity of each size group was found, and plotted (logarithmically) against the reciprocal of its mean Stokes fall velocity. For size groups where only a portion of the material supplied had settled in the 20 m length, it was assumed that the whole quantity was uniformly distributed and the mean travel distance used. One such plot is shown in fig. 6. Then for the prototype outfall it was assumed that the distribution of particles would be the same as in the flume, and the build-up of arbitrary quantities of slurry could be compiled. Using this model, and making the additional assumption that a conical deposit would be formed, it was found that the 6% slope would be formed over the pipe in only 1½ years. (See next page for fig. 6).

In both models it was assumed that particles once having been deposited were not set in motion again by tidal currents. Evidence on this matter was difficult to assess; whereas the site experiment showed radioactive slurry undoubtedly spread over several square miles, application of the Sheilds' bed stability equation for the larger particles showed that the critical shear stress would be barely exceeded even at spring tides. A laboratory experiment where a sea-water stream was flowing over a flocculated bed of slurry showed that some fine material moved in suspension at the spring tide velocities, and that a few large flocculated aggregations rolled along the bed. The well-known difficulties of making accurate bed load transport measurements are increased with this material, since its behaviour may depend upon the way in which it has been laid down and the degree of flocculation that has occurred. No conclusive estimate could be made therefore of the effect of the tides on the further spreading of the residue.

Another cause of spreading of the sediment would be by wave action. A laboratory study was made in a 2-dimensional wave flume, at a scale of 1/25. There was a continuous supply at one point of the heavier sandy particles (i.e. not the whole size-range of the slurry). With little or no wave action, the sand particles accumulate to a mole-hill with steep sides, until the sand comes to low-water level. With waves of storm size, Froudian scaled, the mole-hill is slowly eroded down until an equilibrium is reached about 5 m below low water level. The time required for this decrease would be about 30 hours by the Froude scale of time, but it is by no means clear that this scaling time for water movements is necessarily true for the unsteady movement of sand.

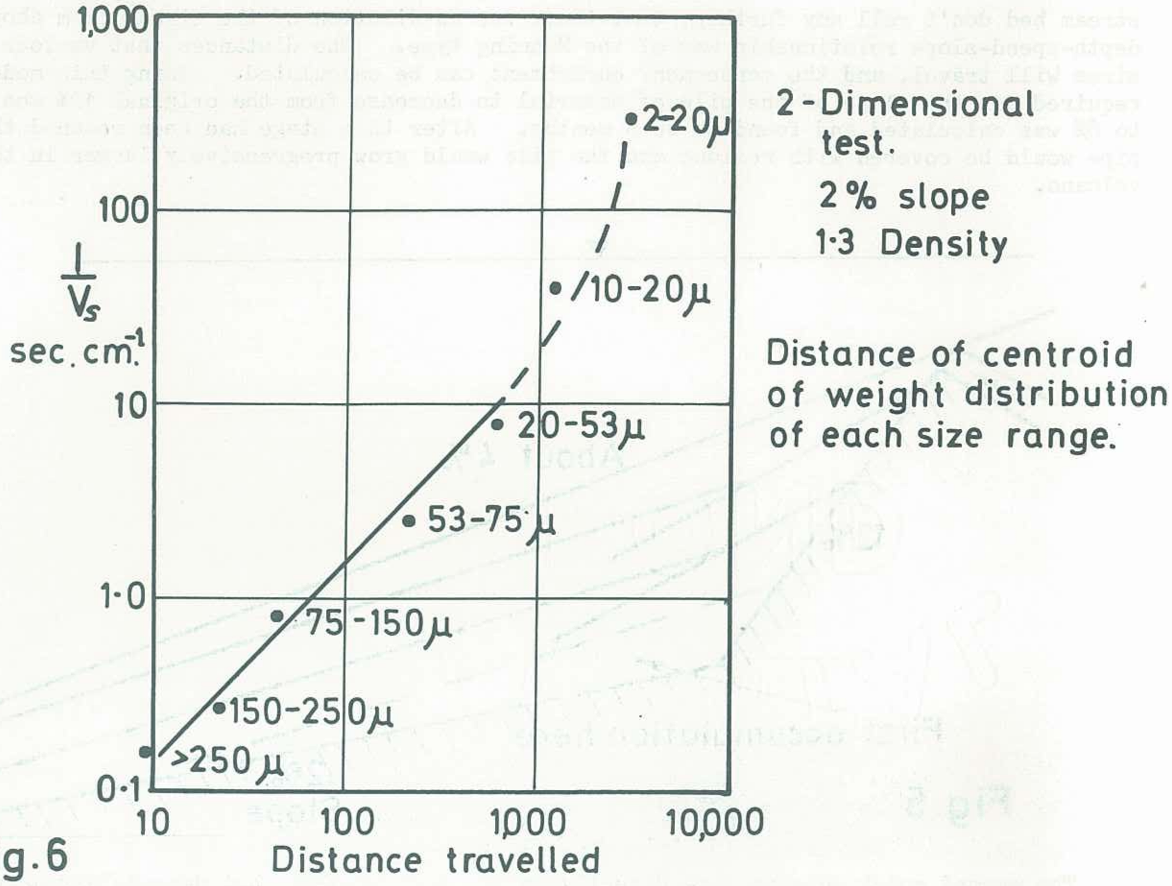

Fig.6

Because of the limitations of the available information, it had to be assumed that an outfall of this simple type could quickly become deeply buried by deposits, and that the mound would in a comparatively short time appear at sea level during calm periods. These effects of the scheme would be unacceptable for reasons of amenity and safety of shipping, and, subject to the results of additional experiments, raised doubts about the possibility of the outfall pipe becoming clogged.

Alternative Solution

With a relatively small increase in capital cost, an alternative form of outfall is possible by extending the pipeline another 1 km to seaward, where the bed is nearly horizontal at a depth of some 50 m. It was proposed to sink a 30 m high steel tower to the bed, thus leaving 20 m depth over its top. The pipe would discharge slurry from the top of the tower, probably having been mixed with sea water in a suitable diffuser. Every effort would be made to ensure that the particles were fully diffused so that they sink independently by Stokes' Law. The fairly strong tidal currents will then disperse the particles over a wide area.

Assuming Stokes' Law, it was possible to estimate (using the detailed knowledge of currents that had been gained) the places where particles would reach the bottom, and the rate at which the sediment would build up. By these calculations, a life of some 13 years was found for the sediment to reach the top of the tower, if none of the particles moved after first reaching the sea bed. If particles, having reached the bottom, were rolled further by the tidal currents, spreading only 25% of that actually observed in the radioactive field tests, then the life is extended to well over the desired 60 years.

This tower type outfall has the advantage of a longer life, and of a far greater certainty of success whatever the size distribution or chemistry of the particles may be in the future. However, it would be more costly, and because it deliberately disperses the slurry, would carry with it a risk that the fines will create a 'cloud' nuisance. This latter possibility is mitigated only by reason that developments of refining technique are likely to decrease the proportion of clays in the residue. The stronger tidal currents experienced in this arrangement compared to those in a sea bed outfall carry a greater likelihood that slurry may be carried to areas far from the outfall. In some situations this might be a disadvantage, but in the particular position chosen the tidal currents are such that any cloud of particles would be taken away from the coastline.

ACKNOWLEDGEMENTS

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