Lehigh
University

Stabilization of Tidal Inlet Channels

CORSON INLET FIELD TEST

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Laboratory

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1. INTRODUCTION

Along the barrier islands off the east coast of the U.S. and at other locations, there exist many tidal inlet channels which connect the back bay areas to the ocean. The bay areas are ideal for harbors and marinas; however, navigation through the tidal inlets can be uncertain. The geometry and the stability of the geometry of the inlets is a function of river locations, discharges and sediment loads, offshore topography, onshore-offshore and longshore movement of sediment, tidal flows, and storm action, including setup and abnormal wave action. Thus, although a particular inlet may be a stable geomorphological feature, its geometry, especially its tidal channels, may be changing constantly.

The historical approach to maintaining a stable navigation channel through a tidal inlet has been (i) construction of jetties, and (ii) frequent dredging. Dredging is an expensive endeavor that needs to be repeated at unpredictable intervals.

This study concerns an alternative to dredging. A pipe with small holes drilled at frequent, uniform intervals along its entire length is placed in the ebb tide channel at a navigable depth. Several pipes in parallel would be necessary to maintain a sufficient width. When the channel begins to fill with sediment, water is pumped into the pipe and discharges from the holes in the pipe. At a sufficient flowrate in the pipe the discharge from the holes fluidizes the sand above the pipe. The fluidized sand is removed from the channel by (i) pumping the slurry, (ii) flowing down a gradient, or (iii) being swept out to the longshore current by the ebb current.

This report includes three distinct phases of research:

(i) a summary of laboratory studies undertaken to give information useful in the design of a prototype fluidization system in a tidal inlet.

(ii) results of a field study done near a tidal inlet whose aims were to confirm the results of the laboratory work and to assess unforeseen problems of working under natural conditions.

(iii) recommendations for a full-scale design of a fluidization system for a particular tidal inlet and cost comparison with that of a dredging operation at the same inlet.

1.1 Historical Background

The first investigators to suggest a fluidizing pipe for removal of sediment were Hagyard et al. (1969). Their concern was with an estuary and they hoped that the fluidized sand would flow down a slight slope to the ocean. Inman and Harris (1970), Baillard and Inman (1975), and Harris et al. (1976) hoped to achieve removal of sand by pointing the fluidization holes downward. The hole excavated would form a duct under the pipe through which the fluidized sand would flow by gravity. Caving of sand above the pipe would eventually create a channel. These investigators had trouble with "fluid holes", regions of well-fluidized sand with unfluidized sand dams between. These dams do not allow any longitudinal flow of slurry. Wilson and Mudie (1970) had a similar problem even with upward pointing discharges.

1.2 Previous Lehigh University Work

1.2.1 Kelley's Experiment (1977)

Kelley (1977), using a two-dimensional (2D) experimental apparatus, Figure 1, tested various fluidization hole configurations to determine which one gives the greatest fluidized width. The two-dimensional effect was achieved by having the depth and width dimensions of the apparatus an order of magnitude larger than the length dimension. Water is fed through a 'distribution' or fluidization pipe sample drilled with 2.54 cm holes at 2.54 cm centers. The distributor was placed at the center-bottom of the apparatus and covered with sand. Flow out of the holes in the distributor fluidized the sand. Kelley concluded that the widest fluidized region for a specific flowrate is given by holes horizontally opposed. Holes pointing upward or downward caused smaller fluidized regions.

1.2.2 Murray and Collins (1978)

Murray and Collins (1978) used a large flume to obtain a three-dimensional (3D) effect, Figure 2. The fluidization holes were horizontally opposed, spaced 2.54 cm apart and drilled 0.238 cm (3/32 in) in diameter. The entire flume was filled with sand to a depth of 15.25 cm above the pipe. Complete fluidization was achieved without the "holes and sand dams" observed by Wilson and Mudie (1970) or Inman and Harris (1970). The fluidized sand migrated down slope, creating a channel width of over 50.8 cm.

Some of the conclusions reached by Murray and Collins (1978) are as follows:

(i) The process leading to a fully fluidized channel is quite consistent. As the flowrate is increased through the system, individual areas of boiling sand enlarge and join until the whole channel is fluidized.

(ii) Fluidization is achievable under a variety of conditions, including (a) horizontal and nonhorizontal pipes, and (b) uniform and nonuniform sand coverage.

(iii) With the pipe on a slope and a fully fluidized channel, the sediment flows under the influence of gravity to the downstream end of the pipe.

(iv) The fully fluidized sediment could be rapidly removed by pumping the slurry from the downstream end.

Murray and Collins (1978) accomplished the intended purpose of their testing to show that a channel could be completely fluidized along the length of the fluidizing pipe. However, they took little data that could be used for the design of a prototype system.

1.2.3 Weisman and Collins (1979)

Weisman and Collins (1979) or Weisman, Collins, and Parks (1980) performed laboratory studies to give information useful in the design of a prototype fluidization system. Specifically, a designer must choose a fluidization hole size, hole spacing, flowrate through the system, distance between parallel pipes, pipe size, etc. based upon anticipated navigation channel requirements and site location.

The research had two basic aims:

(i) to investigate the relationship between flowrate per unit length of fluidization pipe and the width of the fluidized channel,

(ii) to assess the removal of fluidized sand from the channel by gravity flow, by pumping, or by the scouring action of an overlying flow.

2D Experiment

To accomplish the first part, the two-dimensional apparatus used by Kelley (1977), Figure 1, is particularly suitable. Each sample has fluidization holes of a particular diameter. The range of fluidization hole diameters tested was determined from practical considerations. By increasing the flowrate through the system, a relationship between flowrate per unit length of fluidization pipe and fluidized channel width can be established for a given fluidization hole size. (For the duration of this paper this relationship will simply be referred to as the flowrate/width relationship.) Hence, the effect of fluidization hole size can also be understood by comparison of data.

The effect of sand depth over the fluidization pipe on the flowrate/width relationship can also be readily investigated in the 2D apparatus. Once again comparative data analysis will be useful.

Specifically the following aspects were studied;

(i) the trend of the flowrate/width relationship

(ii) the effect of depth of burial of the fluidization pipe on the flowrate/width relationship

(iii) the effect of different fluidization hole diameters on the flowrate/width relationship.

The fluidized channel width recorded was a relatively arbitrary measurement, subject to individual interpretation. The width was basically that from peak to peak of the berms formed by the sand being ejected from the fluidized channel.

Specifically the model was a box, 122 cm long, 71 cm deep and 7.6 cm thick. It was constructed of 0.63 cm plexiglass with joints glued and screwed together. To provide rigidity to the front and rear faces of the model, 2.54 cm steel box supports span the length of the model at intervals of approximately 23 cm.

Water was introduced into the sand through the fluidization pipe sample using pressure-regulated city water as the source. An in-line pump was used at the end of each experimental run to boost the flowrate. The flowrate was determined by collecting the discharge from the weir in a graduated container over a known time.

The sand was placed in the model to the desired depth and packed down by rodding. The rodding was carried out under saturated conditions and was used only to eliminate large voids that may have occurred during placement.

The fluidization pipe samples were constructed from 3.81 cm diameter plastic pipe and were approximately 7 cm long. The fluidization holes were drilled on a horizontal plane spaced at 2.54 cm centers. This resulted in 6 holes per sample. The orientation of the holes on the horizontal plane was selected on the basis of the recommendation of Kelley (1977).

The flowrate/width relationship shows remarkable smoothness and repeatability. The trend of the relationship is identical for all fluidization hole diameters and sand depths tested, Figure 3.

Initially the fluidized channel width increases rapidly with small incremental fluidized pipe flowrates. The relationship levels off and large flowrate increments are required for relatively small fluidized channel width increases.

There are two different depths of sand tested, namely 20.3 cm and 40.6 cm. The greater depth of sand coverage slightly retards the initiation of fluidization. More importantly, in general, within the limits of the experiment conducted, the flowrate/width relationship was not affected by the depth of sand above the pipe.

Perhaps the most important variable tested was the diameter of the fluidization holes. Four different hole sizes were tested, namely 0.159 cm (2/32 in), 0.316 cm (4/32 in), 0.476 cm (6/32 in), 0.635 cm (8/32 in). From Figure 3, it is evident that, for a given flowrate, the smaller hole size gives a larger fluidized width. This is due to the high velocity or erosive power of the individual jets. However, from a consideration of the hydraulics, holes that are too small would require extremely high pressures to force adequate flowrate through the system.

The effect on the channel cross section when the fluidized sand was removed was investigated by syphoning the slurry from the middle of the fluidized channel. The slurry syphoned readily and there was a dramatic slumping of the sand into the channel and consequent enlargement of the channel. The original vertical sides of the fluidized channel were completely removed.

3D Experiment

To test the second objective of the study by Weisman and Collins (1979), that of sand removal from the fluidized channel, a larger 3D facility is necessary, Figure 2. A fluidization pipe in excess of 1.5 m in length was used to obtain the 3D effect.

Initially it was necessary to establish a correlation between the two models. This was achieved by conducting similar experiments in the 2D and 3D models and comparing the data. The 3D apparatus also allowed further investigation of the fluidization hole spacing by running a series of tests at different spacings. The tests consisted of gathering flowrate per unit length of fluidization pipe and fluidized channel width data and making graphical comparisons.

Once these further aspects of the fluidization channel phenomena had been studied the removal mechanisms of the fluidized sand were tested. Gravity flow and pumping of the fluidized sand slurry were investigated. Most importantly, because of the known existence of strong ebb tides in most tidal inlets, scouring by the overlying flow was simulated.

Specifically the following situations were studied:

(i) a comparison of flowrate/width relationship data for the same (3D) sand for identical tests conducted in the 2D and 3D experiments.

(ii) the effect at various fluidization hole spacings on the flowrate/width relationship.

(iii) the movement of the fluidized sand by gravity above a sloped fluidization pipe and any change in channel cross section.

(iv) the movement of the fluidized sand when removed (pumped) as a slurry from the channel and any change in channel cross section.

(v) the movement of the fluidized sand when subjected to an overlying flow and any change in channel cross section.

In a similar fashion to the 2D tests the experimental runs were observed with the aim of gaining qualitative knowledge about the fluidization process.

The 3D experiments were conducted in a steel tank shown in Figure 2. The flume was 7.47 m long, 1.52 m wide and 0.61 m deep. The fluidization pipe was a 3.81 cm diameter galvanized steel pipe, 3.05 m long and was fed by a 5.08 cm diameter galvanized steel pipe.

The water supply was from the city water main and was controlled by a valve at the upstream end of the fluidization pipe. The flowrate was determined by diverting the discharge from the flume to a volumetric tank over a known time interval.

The overlying flow was provided by a 35 HP pump capable of discharging 1600 gpm at 60 ft. The water was pumped to the end of the flume through a 20.32 cm diameter steel pipeline and discharged into a header tank.

The sand was placed at the desired depth over the fluidization pipe and extended downstream about 0.5 m past the end of the fluidization pipe. Usually, the sand was compacted by a combination of the shovelling, leveling, and smoothing processes.

The trend of the flowrate/width data for the 3D test is identical to that obtained in the 2D apparatus. The data is almost identical for both tests and the small variation can probably be explained by the 3D aspects of the larger tank. After testing, the flume was drained and this is shown in Figure 4. The berms built up by the ejection of finer material can be clearly seen around the perimeter of the fluidized channel area. Particular attention should be taken of the berm built up at the lower end of the fluidized channel (perpendicular to the fluidized pipe). This berm formed a dam which inhibits the movement of fluidized sand downstream in later tests.

There are three important effects to be noted from the tests with varying fluidization hole spacing. The flowrate/width data from these tests is shown in Figure 5. First, fluidization hole spacing appears to have little influence on the flowrate per unit length of fluidization pipe necessary to initiate a fluidized channel. Second, the flowrate per unit length of fluidization pipe necessary to achieve any given fluidized channel width is independent of fluidization hole spacing. Third, the wider the fluidization hole spacing, the more dense the "fluidized" sand becomes. Given that the aim of the project is to produce the widest possible fluidized channel at the lowest practical flowrate per unit length of fluidization pipe, then the third result appears to be the only one of significance.

The ability to remove the fluidized sand from the channel is of major importance to the successful implementation of the system. The apparatus, as described, was not entirely suitable for full evaluation of this aspect of the project but it was felt that enough work was done to justify considerable optimism. The principal shortcoming of the experimental setup was that only the lower values of the expected ebb tide scour velocity range could be achieved. A number of important conclusions could, however, be drawn.

Initially the fluidization pipe was placed in the flume at a 5% slope with a uniform sand coverage of 20.3 cm over the fluidization holes which were spaced at 5.04 cm centers. The fluidization pipe valve was fully opened. A flowrate of 3.04 ℓ/m-sec was obtained and a fluidized channel 0.70 m in width developed. The flow in the fluidization pipe was continued for about 30 minutes. A sand dam existed at the downstream end of the fluidized channel between the end of the fluidization pipe and the downstream extremity of the sand coverage, Figure 6. In addition, a sand delta formed on this dam as the fluidized sand migrated down the channel. Clearly the fluidized sand migrates down the channel under the influence of gravity. The sides of the channel have slumped and the width increased from 0.70 m to 1.04 m.

After testing the effect of sloping the pipe, it was returned to the horizontal and set up under the same conditions; 5.04 cm fluidization hole spacing and 20.3 cm sand coverage. The flowrate in the fluidization pipe was set at about 3.0 ℓ/m-sec and fully fluidized channel developed. The overlying flow-apparatus was turned on and once again the dam was broken and the fluidized sand was removed by hand. The overlying flow was estimated at 0.3 m/sec. The fluidization pipe flowrate and the overlying flow were turned off and the flume drained. The results are shown in Figure 7 and are similar to the sloped fluidization pipe results. The fluidization sand is so "fluid" that even with the fluidization pipe in the horizontal position, removal of the sand (by pump or other means) at the downstream end of the fluidized channel caused the fluidized sand to flow out of the channel. In the process, the sides slumped causing an approximate channel width increase of 50%.

1.3 Conclusions of Laboratory Studies and Design Recommendations

1.3.1 Conclusions

(i) For a given sand type, sand depth, and fluidization hole size, a well-defined relationship between flowrate per unit length of fluidization pipe and fluidized channel width exists.

(ii) Sand depth affects the flowrate per unit length necessary for initial fluidization; at greater sand depths a slightly higher flowrate per unit length is necessary. Sand depth has a minor effect on the flowrate/width relationship.

(iii) For a given flowrate per unit length, the smaller the fluidization hole diameter the larger the fluidized channel width that will result.

(iv) By pumping or siphoning the fluidized sediment out of the system, the fluidized region is expanded by about 50%. Slumping of the sides occurs until the angle of repose is reached.

(v) If the fluidized sand can be removed and the sides slump then fluidization hole diameter and flowrate per unit length have little influence on the final bed configuration because the fluidized channel width is smaller than the ultimate width. Hence, fluidization hole diameter has a real significance for two reasons: (a) to maintain fluidization with an appropriate flowrate per unit length, (b) to minimize clogging.

(vi) Fluidization hole spacing apparently has no effect on initiation of a fluidized channel.

(vii) Flow rate per unit length of fluidization pipe necessary to achieve any given fluidized channel width is independent of fluidization hole spacing.

1.3.2 Design Recommendations

(i) Fluidization hole size: In order to minimize total flowrate, the smallest fluidization hole size as possible is required. However, holes too small in diameter would require large pressures within the pipe to emit a given flowrate. Also, small holes clog easily; hence, a hole size greater than the larger sediment sizes is recommended.

(ii) Fluidization hole spacing: A spacing of 5.08 cm is probably adequate for full fluidization. Advantage is taken of high individual jet velocity to prevent clogging, while a wider spacing leads to regions of high density fluidized sand.

(iii) Fluidization pipe flowrate: A flowrate in the order of 4 $\ell/(s\text{-}m)$ is recommended for good fluidization and sufficient fluidized channel width. This value is conservative when used with sand whose D_{50} is around 0.40 mm. For smaller sands, a lower flowrate would be in order; vice-versa for larger sands.

(iv) The pipe should be sloped seaward and, perhaps, an additional pump provided to pump the fluidized region empty. Removal of the delta formed by the scouring of the fluidized sand should be considered.

(v) A special valve at the downstream end should be installed to clear the line of sand when necessary. Maintaining a small flow through the fluidization pipe would also help to keep the fluidization pipe free of sand.

(vi) To maintain a navigable width of forty feet, it appears that at least two or three parallel pipes must operate.

(vii) The fluidization pipe diameter is totally independent of the fluidization process and is sized only on hydraulic considerations.

(viii) The smaller the number of fluidization holes per unit length used to discharge a given flowrate per unit length, the higher the fluidization pipe pressure will be.

(ix) The pump and pipe system must be designed such that an adequate pressure exists throughout the fluidization pipe to ensure the design flowrate per unit length of fluidization pipe.

2. FIELD TEST

A field test was conducted at Corson Inlet, New Jersey, during the last two weeks of June 1980 to study the stabilization of tidal inlet channels by fluidization.

2.1 Aims

There were two aims of the field test.

(i) Confirmation, under field test conditions, of the previously accumulated laboratory experience. It was intended that this confirmation would be phenomenological rather than quantitative.

(ii) Proof of the technical feasibility of maintaining a tidal channel by fluidization, especially to identify operational problems and field scale limitations.

Some quantitative information would be possible in the sense that the test equipment was sized based on the results of Weisman and Collins (1979) and successful field testing would indicate the ability to design systems from previously documented test results.

2.2 Field Test Design

The following steps were taken in the design of the field test apparatus. These steps are based on the Design Recommendations discussed previously, section 1.3.2.

(i) Fluidization hole size - 0.316 cm (1/8 in). This size was chosen from a consideration of the need to prevent clogging while maintaining a reasonable head loss through the hole and ensuring a reasonably erosive jet.

(ii) Fluidization hole spacing - 5.08 cm

(iii) Fluidization pipe flowrate - 4ℓ/(s-m)

(iv) Length of fluidization pipe - 12.2 m single; 6.1 m parallel. These lengths were decided upon based on a number of considerations. The entire system had to be manually placed in position and buried. Plastic (PVC) pipe 15.2 cm in diameter was selected to minimize head loss. The weight of the individual 3.05 m pipe lengths and the submersible pump were just capable of being manually positioned. Of course an overriding consideration was the budget limitation.

(v) Total fluidization pipe flowrate - 48.8 ℓ/s.

(vi) Pump Operating Head - 9 m. Once the total fluidization pipe flowrate is known the individual fluidization hole velocity can be calculated as 1283 cm/s. The head loss through the fluidization hole is of the order of 6.7 m. The head loss through the delivery pipe and the fluidization pipe itself is of the order of 2.4 m. Hence, the total head is about 9 m.

(vii) Pump Characteristic Curve - Flowrate ≈ 48.8 ℓ/s, Head = 9 m. The pump characteristic curve should be such that the pump operates close to the desired flowrate over a reasonably wide head range.

(viii) Parallel system separation - 1.83 m. To achieve interaction between fluidized channels the width between parallel fluidization pipes must be selected so that when the internal sides of the fluidized channels slump at their angle of repose their combined peak is below the original sand level. The width between pipes, then, is dependent on the depth of sand over the pipes. The width of 1.83 m was determined assuming a sand coverage of 60 cm.

An alternative approach to selecting the fluidization pipe flow is to consider the settling velocity of the sediment. The following relationship between minimum fluidization velocity (v_f) and unhindered settling velocity (v_s) has been proposed by Rowe and Henwood (1961).

$$v_s = 8.45\ v_f$$

The sieve analysis of the Corson Inlet sand is discussed in Section 2.3.1. The sand was very uniform and had a d_{50} of 0.25 mm. This sand has a settling velocity of approximately 1.3 cm/sec from Graf (1971). Using the equation of Rowe and Henwood a minimum fluidization velocity of 0.154 cm/sec would be necessary.

Assuming that at the sand surface the sand would be fluidized over a width of 1 m then the flowrate required per unit length of fluidized pipe would be 1.54 ℓ/(s-m). The value of 4ℓ/(s-m) chosen has a substantial factor of safety.

2.3 Procedures

2.3.1 Geographic Location

The site selected for the field tests was the bay side of the northern headland forming Corson Inlet, Figure 8. The inlet is located approximately 32 km south of Atlantic City, New Jersey. The back bay area which gains access to the ocean through Corson Inlet is small when compared to other areas along the coast. Consequently the volume of water exchanged over a tidal cycle was not large, hence correspondingly moderate tidal velocities were experienced. The tidal range during the testing period was about 1.5 m.

The site was selected because it offered;

(i) a sedimentary environment similar to the channels of a tidal inlet.

(ii) good access for the delivery and retrieval of equipment

(iii) a large expanse of gently sloping beach face between low and high water.

The results of a sieve analysis of the beach sand are shown in Figure 9. It can be seen that the sand is very uniform and is quite similar to that used in the laboratory experiments.

2.3.2 Equipment

There were four major pieces of equipment used in the field test, Figure 10. The supply pump was a submersible dewatering Flygt Series B pump. It had a 10.2 cm discharge diameter and was rated at 13 HP. The power supply was 230 volt, 3-phase trailer mounted unit, powered by a gasoline engine. A small gasoline powered dewatering pump, rated at 3 HP was used to pump the slurry.

The fluidization pipe was 15.2 cm diameter PVC flanged pipe. The individual pipe sections were 3.05 m in length and could be bolted together to form a single or parallel pipe system. A short length of 10.2 cm diameter PVC pipe was used to deliver water from the pump discharge to the fluidization pipe system.

2.3.3 Experimental Setup

In general the fluidization pipe system was assembled on the beach, Figure 11. The pipe sections were bolted together and an endplate was bolted on the end of the fluidization pipe. A 5.08 cm plug was screwed into the endplate. This allowed for clearing the line. The fluidization holes were predrilled 0.316 cm (1/8 in) holes at 5.08 cm spacing on a horizontal plane.

Burial of the pipe system was achieved by scouring a channel on the beach face with a 5.1 cm diameter hose connected to the submersible pump. The preassembled pipe system was then lowered into the channel, Figure 12, and the channel was backfilled with sand. This was achieved by scouring sand from higher up the beach face and washing the sand into the channel. Initially the small dewatering pump was used but the larger pump with a 10.2 cm hose was found to be much more efficient.

2.4 Results

Four different experimental configurations were tested, and three different locations were used for the tests. While the sites were adjacent they presented a range of beach conditions.

2.4.1 Horizontal Fluidization Pipe (Single)

The 12.2 m fluidization pipe was assembled on the beach, Figure 11, and rolled into the channel which had been excavated with the 10.2 cm diameter hose connected to the submersible pump. This excavation was carried out at low tide, under between 0.3 and 0.6 m of water. Once the pipe was in position it was connected to the pump, Figure 13, and covered with sand. The sand was backfilled into the trench by shovelling and scouring sand towards the excavation using the small dewatering pump. The depth of sand varied between 23 and 33 cm above the fluidization holes. All operations, excavation, connection and coverage were extremely difficult under water.

The fluidization experiment was equivalent in all aspects to the laboratory studies. When the pump was turned on sand boils formed above the buired pipe and then, very rapidly, full fluidization was achieved. Unlike the laboratory experiments, no berms were formed at the outer edges of the fluidized channel. It appeared that the small tidal current and more importantly, the wave action rapidly dispersed the fine material ejected from the fluidized channel. The pump was turned off and the channel width was found to be approximately 1.07 m (Figure 14).

The pump was turned on again and the full fluidization was quickly achieved (Figure 15). The suction line of the small dewatering pump was placed in the fluidized sand at the downstream end of the pipe system and the sand slurry was pumped out of the fluidized channel, Figure 16. The migration of fluidized sand down the channel was rapid and substantial. Within 10 to 15 minutes virtually all fluidized sand was removed from the channel leaving the entire 12.2 m of fluidization pipe exposed, Figure 17. The downstream berm, which had been apparent in the laboratory studies was once again formed.

The width of the channel increased to a maximum of 1.90 m as the sides of the fluidized channel slumped into the channel during the slurry pumping. The sides of the channel eventually took the natural angle of repose to within a few inches of the pipe. The depth of the channel was between 38.1 and 45.7 cm, Figure 18.

2.4.2 Sloped Fluidization Pipe (Single)

A channel was scoured on the beach face between the high and low tide water lines. The 12.2 m fluidization pipe was placed in the channel at a slope of about 2%. The pipe was covered by scouring the surrounding beach face and washing sand over the pipe. The sand coverage above the fluidization holes was about 38 cm.

Initially the 5.08 cm plug in the endplate was removed and the pump was switched on. The bulk of the flow discharged through this opening, excavating a large hole at the end of the pipe line. Some fluidization occurred along the pipe during this operation. The plug was replaced in the endplate and the system turned on. Full fluidization was rapidly achieved and a channel width of about 1.07 m was obtained. Many clam shells were evident but did not adversely affect the experiment. The previously excavated hole at the end of the fluidization pipe filled with sand migrating down the channel, Figure 19, under the influence of gravity within 2 minutes. A dam formed at the end of the channel retarding, to a large extent, the down slope migration of the fluidized sand.

The experiment was repeated after scouring a new hole at the end of the fluidization pipe. In spite of the fact that some holes appeared to be clogged, the fluidized sand rapidly migrated down the channel with a consequent increase in width to approximately 1.52 m, Figure 20. A number of clam shells were present but again did not appear to adversely interfere with the experiment.

The drained channel, Figure 21, showed migration of the fluidized sand and that the side slopes had taken the natural angle of repose. Examination of the pipes when they were excavated showed that algae had blocked a large number of the fluidization holes, Figure 22. This problem has two important considerations. First, the fact that algae entered the fluidization pipe was really an experimental design oversight. The on-shore winds and lack of substantial tidal velocity concentrated the algae in the shallow waters around the pump. No prescreening of the algae was attempted resulting in the pump sucking in and passing the algae into the system. Secondly, if poor intake conditions exist and algae passes into the fluidization pump then the algae very effectively blocks the 0.316 cm (1/8 in) diameter holes.

2.4.3 Sloped Fluidization Pipe (Parallel)

The same procedure as for the second test was followed for this test. The beach face was scoured, the fluidization pipe was assembled and placed in the excavation, Figure 12, and then sand from the surrounding beach face was used to backfill and bury the fluidization pipe. The 6.1 m parallel fluidization pipes were on a slope of approximately 2%, spaced 1.83 m apart, and the depth of sand to the fluidization holes was between 38.1 and 45.7 cm. A layer of clam shells had been encountered during the excavation and backfilling operations resulting in an extremely large concentration of the shells in the material covering the pipes.

The actual experiment was plagued with problems. Initially the pump sucked in large amounts of algae despite attempts to clear the channel to the pump intake. This led to the fluidization holes along the upper 3.05 m on both legs of the fluidization pipe system being clogged. The system was excavated and the endplate on the left side fluidization pipe and the end plug on the right side fluidization pipe were removed. The clogged fluidization holes were cleaned. Then holes were excavated at the end of the fluidization pipes. The endplate and the plug were replaced and the system covered with sand and another test was run.

Attempts to keep the algae away from the pump intake with a screen of hardware cloth were only partly successful. A large number of holes were clogged and in addition the clam shells were packed down tightly, particularly around the upper right side fluidization pipe. Despite these problems there was good fluidization, Figure 23, extensive migration of the fluidized sand down the pipe system, but the parallel pipes did not completely interact. The widths of the fluidized channels were in the order of 1.52 m. The drained channels showed both substantial sand migration and some interaction, Figure 24.

The system was excavated prior to the fourth experimental setup and it was noticed that the pipes were half full of sand. This was not surprising as the pump intake had been lowered to be in direct contact with sand, in an attempt to keep pumping as the tide went out. Consequently a substantial amount of sand was pumped into the fluidization pipe system. An important point was that the sand did not cause any blocking of the holes. Those holes which were blocked were blocked due to algae.

2.4.4 Sloped Fluidization Pipe (Parallel - 0.632 cm Fluidization Holes)

The fluidization holes were drilled out to a 0.632 cm (1/4 in) diameter and the pipe system was buried. The slope of the fluidization pipes remained at about 2% and the depth of sand coverage to the fluidization holes was about 45.7 to 50.8 cm. Holes were excavated at the ends of the fluidization pipes in the normal fashion and an inlet channel to the pump intake was excavated to allow the test to run for the maximum possible time as the tide went out.

When the system was turned on fluidization took longer than previously experienced with the 0.316 cm (1/8 in) diameter fluidization holes. The fluidized sand moved freely down the fluidization pipes and there appeared to be little algae sucked into the pump intake through the hardware cloth screen. Where the clam shells were at their densest the horizontal erosive nature of the fluidization jets was severely impaired, Figure 25. Despite this, there was some interaction of the parallel fluidization pipes. An attempt to increase the interaction was made by removing a number of the clam shells which were deflecting the fluidization jets. This led to a noticeable increase in the width of the channels.

Enlarging the fluidization holes from 0.316 cm (1/8 in) diameter to 0.632 cm (1/4 in) diameter seemed to have the predictable effects of having less clogging problems while losing some errosive power due to the lower exit velocity of the fluidization jets.

2.5 Conclusions from the Field Test

2.5.1 The laboratory experiments and the field tests exhibited identical phenomenological results.

(i) Full and uniform fluidization was achieved over the entire length of fluidization pipe.

(ii) Pumping the fluidized sand from the end of the channel caused a migration of the sand to the end of the pipe, slumping of the channel sides, and consequently a widening of the channel.

(iii) Placing the pipe on a slope caused the fluidized sand to flow to the end of the channel; the same process of side slumping and increased channel width was observed.

2.5.2 Design data obtained from the laboratory experiments were sufficient to ensure a proper design for the field test.

(i) Hole size, hole spacing, and total flowrate for the fluidization pipe were correct given the success of the field test.

(ii) The hydraulic design of the fluidization system, e.g., fluidization pipe diameter, pump type and characteristics was successful.

(iii) The parallel pipe system would have shown more interaction if more sand coverage could have been accomplished. The spacing between parallel pipes was chosen to achieve interaction for a sand coverage of 60 cm. Some interaction occurred with a sand depth of 38 to 45 cm.

2.5.3 The field testing broached some problems that did not exist in the laboratory but must be addressed if inlet channel stabilization by fluidization is to be implemented.

(i) Clogging of fluidization holes occurred because algae was sucked into the pump and discharged to the fluidization pipe rather than sand, as had been anticipated. The hole size, 3.175 mm, was much greater than the larger sand sizes, d_{90} of 0.35 mm; hence, clogging by sand did not occur. Proper screening around the pump intake should prevent algae from getting into the fluidization pipe.

(ii) When the pump was set on the sand or on a board on top of the sand, sand was sucked into the pump and deposited in the fluidization pipe. No clogging occurred. However, the effective cross-sectional area of the pipe was reduced and the roughness of the wetted perimeter increased, both of which cause the headloss through the pipe to increase. This headloss increase can cause a pressure drop along the pipe leading to little fluidization at the downstream end of the pipe. A simple remedy is to protect the intake of the pump from sucking in sand as well as algae. No problem of sand entering the pump was observed as long as the pump was elevated sufficiently above the water-sand interface.

(iii) The beach face contained several layers of clam shells. The technique used to cover the fluidization pipe with sand caused a concentration of shells around the pipe. The shells then armored the channel during testing and prevented widening of the channel to a size anticipated in pure sand. At this time, the authors do not know if this is likely to be a problem in tidal inlet channels.

2.5.4 Because the experiment was performed on the beach face, no conclusion can be reached about the effect of strong tidal current on the shape of the fluidized channel. It is suspected by the authors that a tidal current will help scour the fluidized sand from the channel resulting in further widening of the channel and removal of the mounds between the parallel pipes.

2.5.5 Finally, based on the experience of the field test, the authors feel that the next stage of the research should be conducted in an ebb-tidal channel over a long period of time, at least spring to fall, to ultimately test the feasibility of a fluidization system to maintain a navigable channel through a tidal inlet.

2.5.6 The preliminary design recommendations for a full scale system are as follows.

(i) Many parallel pipes, spaced 3 m apart, should be placed in a dredged channel.

(ii) The methodology used to operate the system would involve sequentially pumping water through two parallel pipes. When the channel has widened and interaction achieved, one pipe is valved off and the next parallel pipe is brought on line. This is continued across the whole channel.

(iii) The system component dimensions, e.g., pipe diameter and lengths and pump capacity, will depend on an economic evaluation. A number of alternative configurations are possible. For example, if continuous parallel pipes running the whole channel length are chosen, large diameter pipes would be required to minimize head loss and a relatively large pump would be necessary. Alternatively, each full length of pipe can be segmented allowing smaller diameter fluidization pipes and a series of smaller pumps.

2.5.7 Based on a rudimentary economic analysis, it is felt that a fluidization system is a viable alternative to dredging [see Appendix].

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4. FIGURES

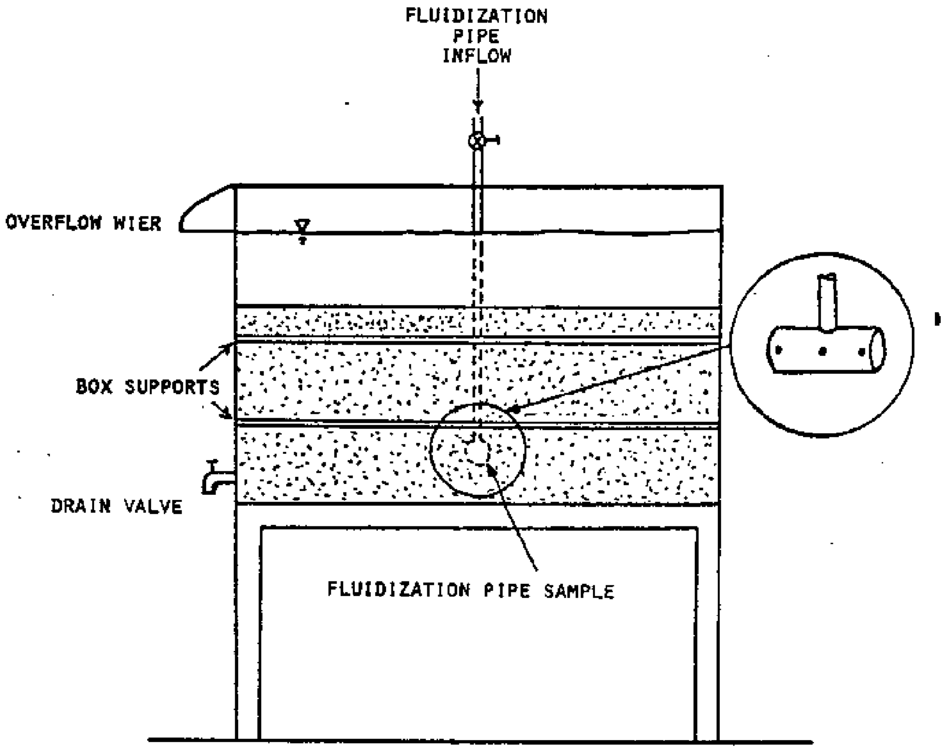

Figure 1: 2D experimental apparatus

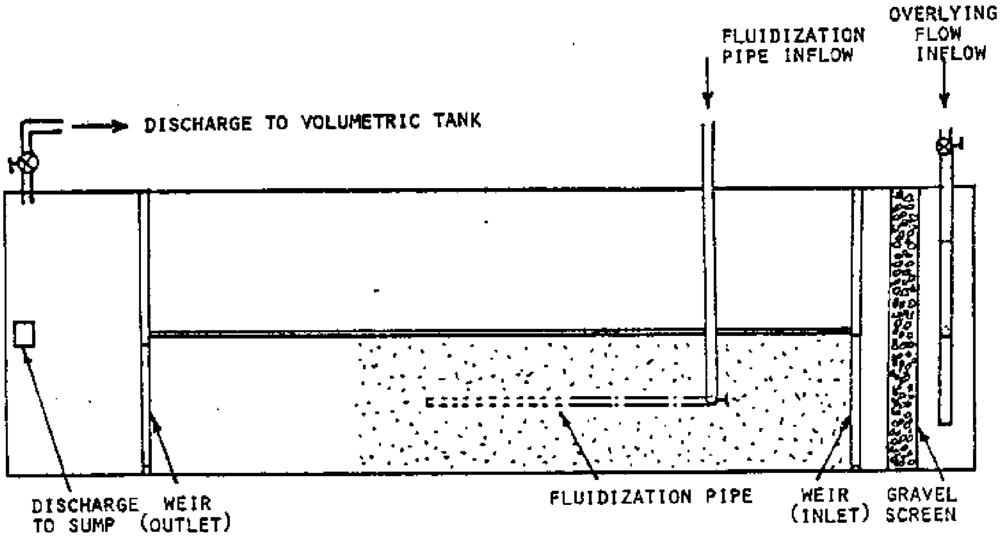

Figure 2: 3D experimental apparatus

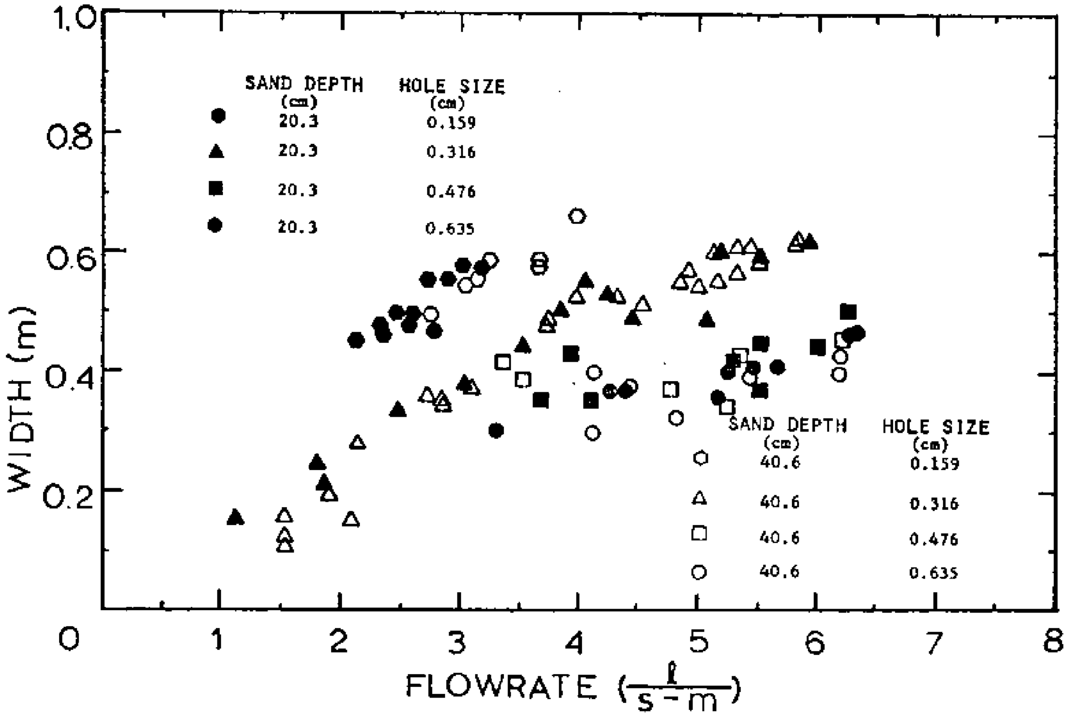

Figure 3: Flowrate versus width of fluidized channel for two sand depths and four hole sizes

Figure 4: Typical configuration of fluidized region and berm in laboratory experiment

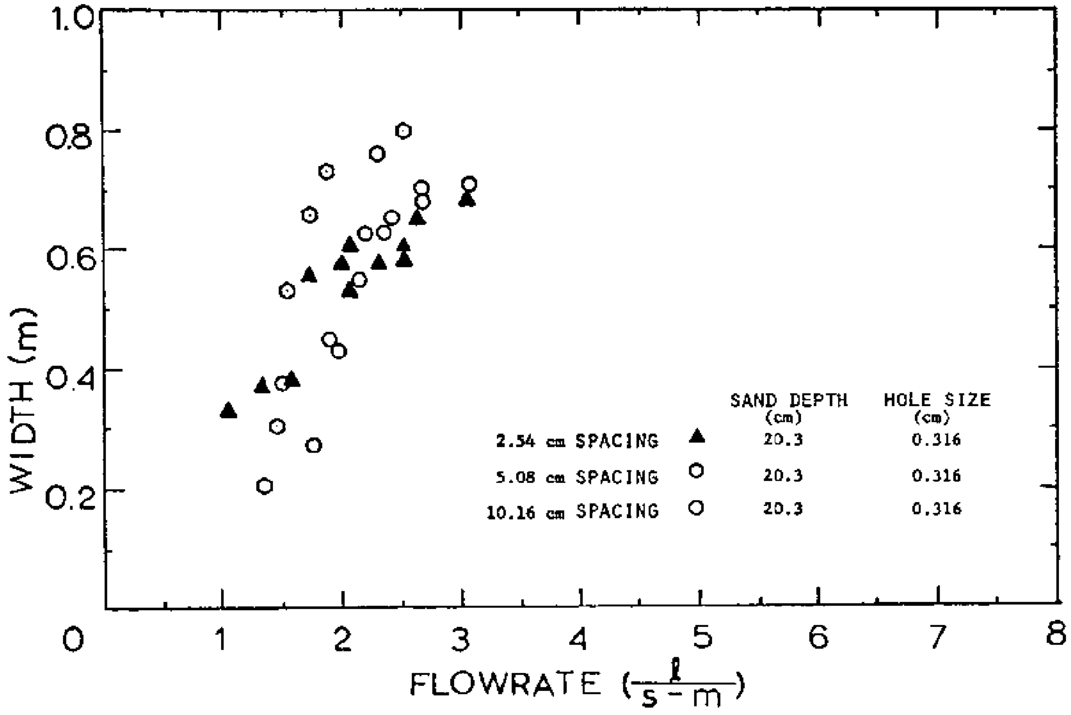

Figure 5: The effect of hole spacing on the flowrate-width relationship

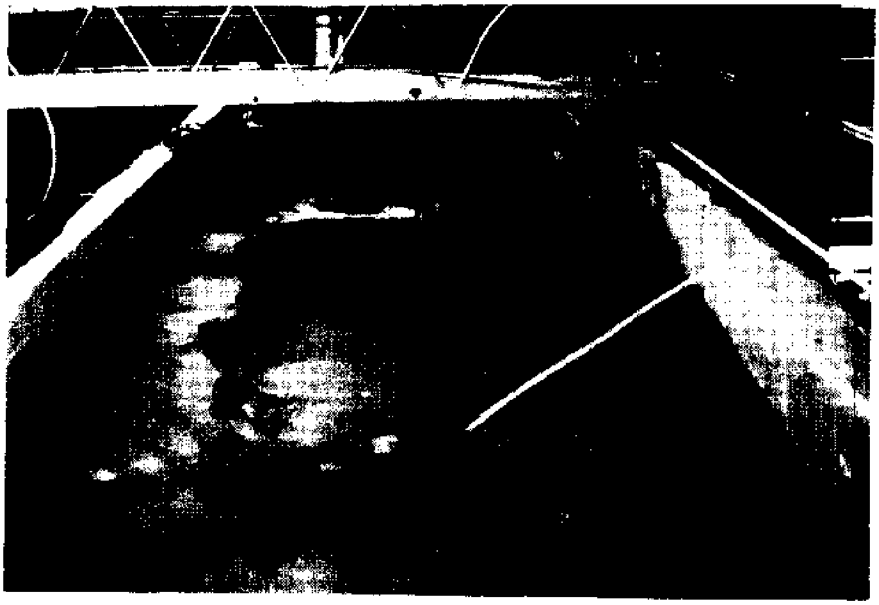

Figure 6: The effect of sloping the fluidization pipe on the channel configuration in the laboratory experiment

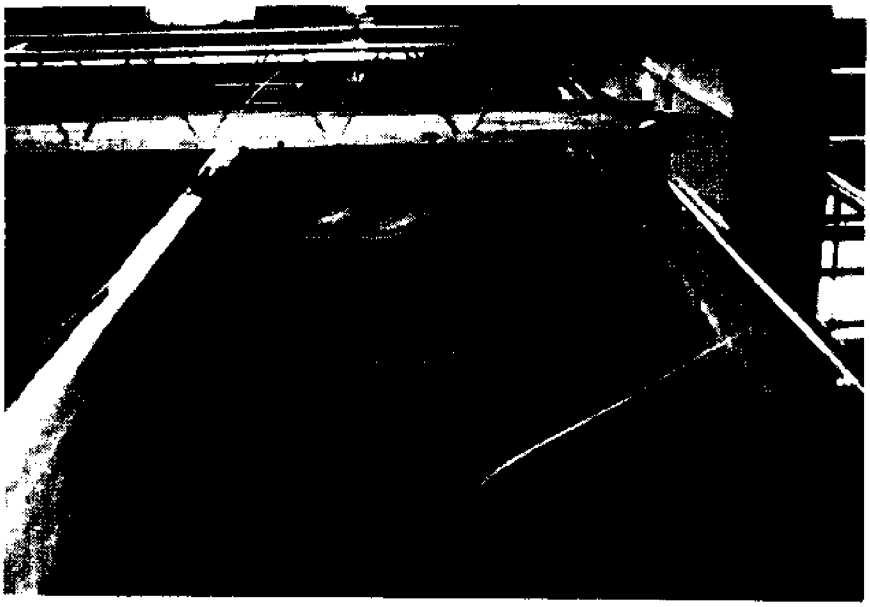

Figure 7: The effect of an overlying flow on channel configuration in the laboratory experiment

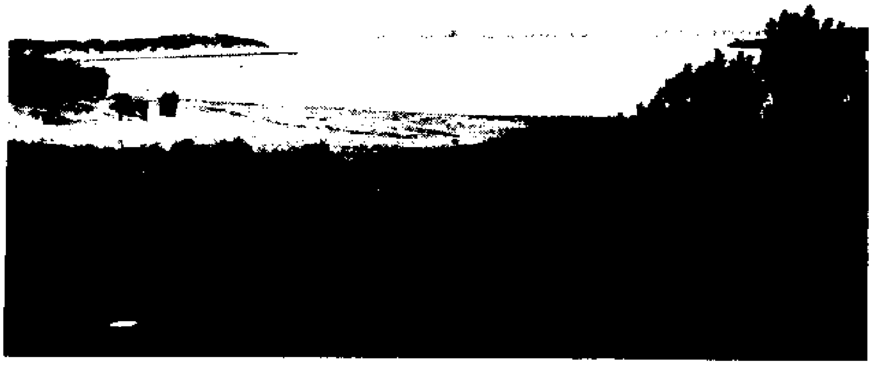

Figure 8: Field test site, Corson Inlet, New Jersey

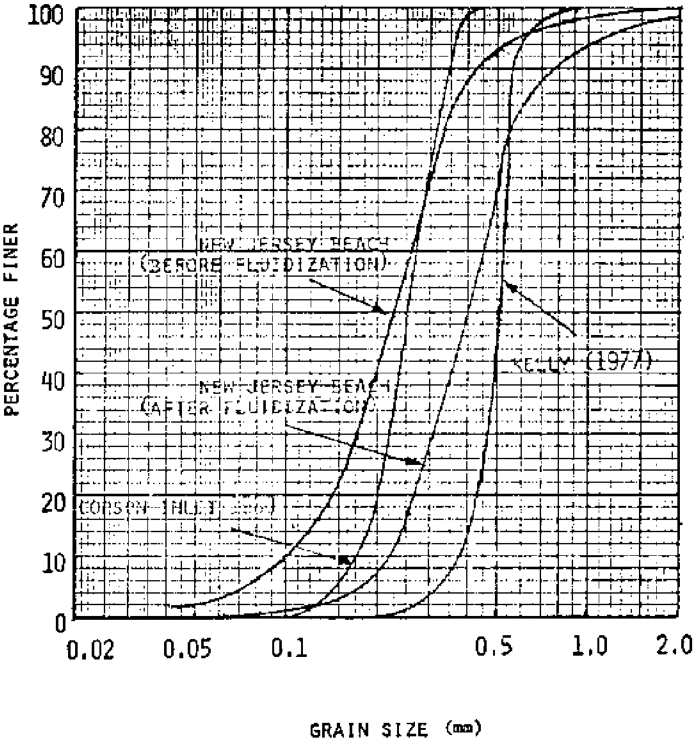

Figure 9: Sieve analysis of sediments

Figure 10: Field test equipment

Figure 11: Pipe assembly

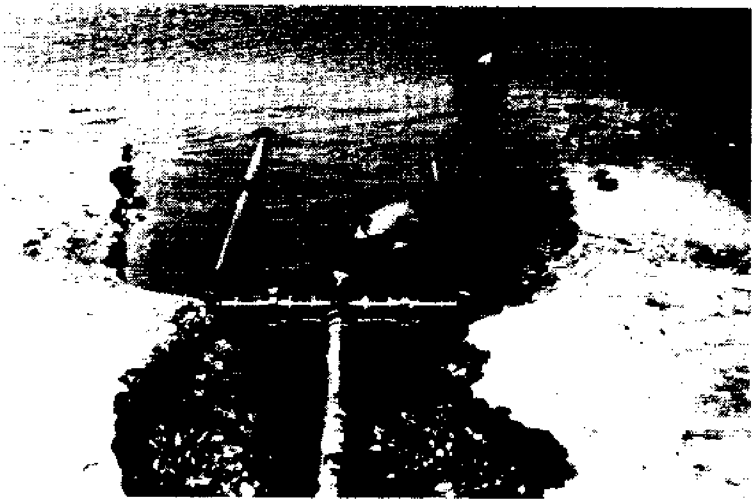

Figure 12: Excavation and placement of pipe system

Figure 13: Completely assembled fluidization system

Figure 14: Result of initial fluidization, horizontal pipe

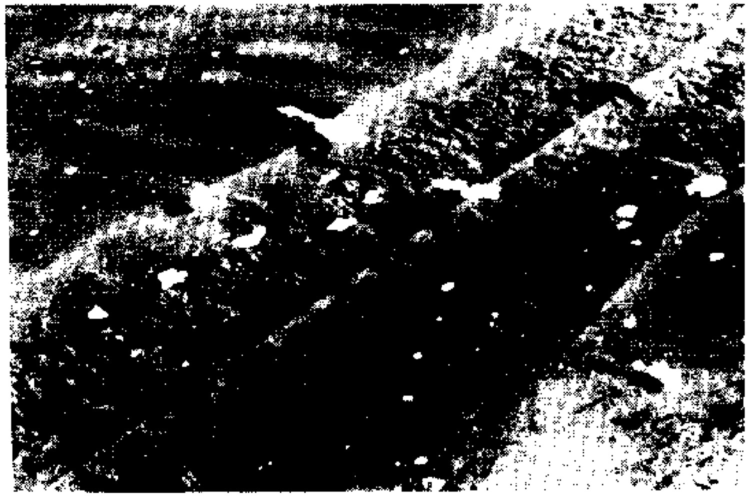

Figure 15: Fluidized channel, horizontal pipe

Figure 16: Pumping slurry from fluidized channel (horizontal pipe)

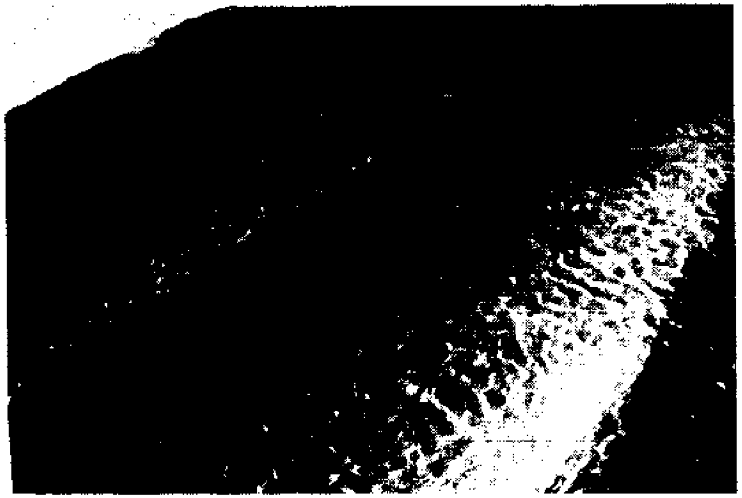

Figure 17: Full channel development following slurry removal (horizontal pipe)

Figure 18: Depth indication, horizontal pipe

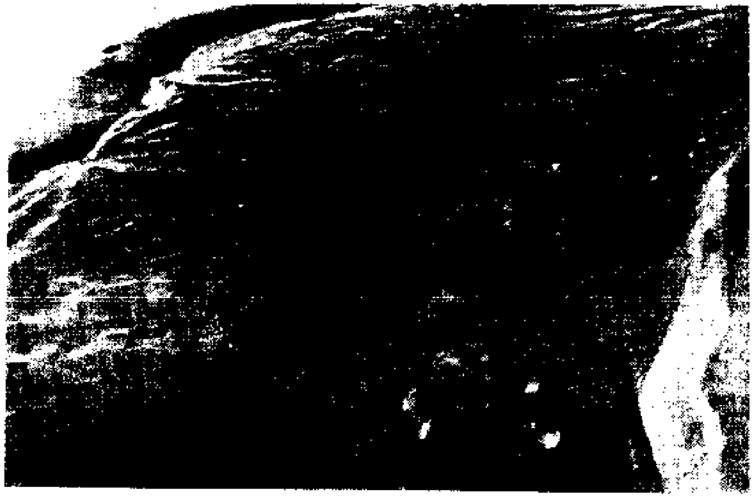

Figure 19: Migration of fluidized sand, to end excavation, sloped pipe

Figure 20: Channel width increase due to sand migration, sloped pipe

Figure 21: Drained channel, sloped pipe

Figure 22: Clogging of fluidization holes by algae

Figure 23: Fluidized parallel system with incomplete interaction

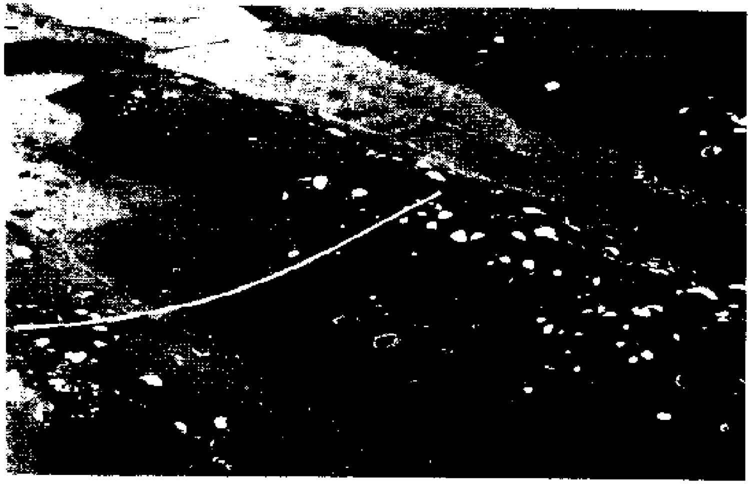

Figure 24: Drained parallel channels

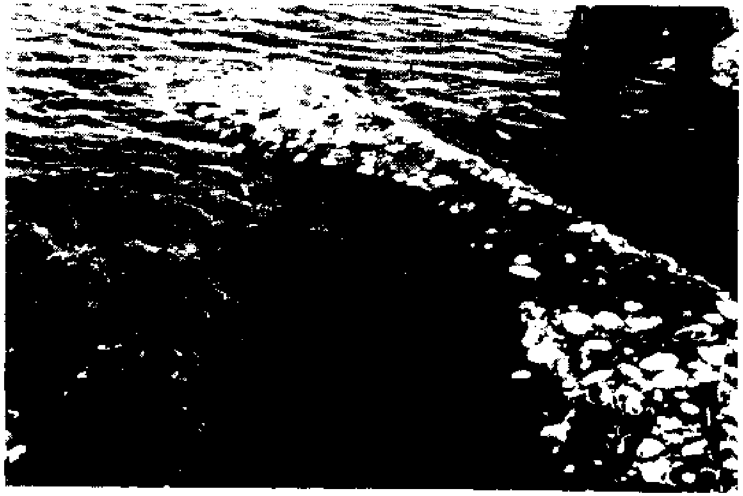

Figure 25: Clamshells impeding channel widening

5. APPENDIX

Further research to determine the technical feasibility of the fluidization technique for maintaining navigable channels in tidal inlets is only justified if the system can compete in an economically favorable manner with the traditional dredging procedure. The following analysis is rudimentary but justifies considerable optimism for the fluidization technique. The inlet considered for the comparison is Hereford Inlet, New Jersey.

(i) Dredging

A navigation channel approximately 45 m wide and 660 m long was dredged in 1980 at a cost of $465,000. A total volume of 76500 m^3 of sand was removed. This represents slightly less than a 1 m depth of sand being dredged. The channel had been dredged two years earlier.

(ii) Fluidization System

To obtain an equivalent channel using the fluidization technique there would be 14 parallel fluidization pipes broken into 22 segments. Each 30 m segment of the system will be supplied by one pump, for instance a Flygt Series B 2250 dewatering pump. A cost estimate for the system is,

22 Pumps	$ 330,000
Pipe system (8 in. PVC)	600,000
Installation	70,000
	$1,000,000

The expected life of the system would be 15 to 20 years. The annual operating cost will depend on the frequency at which sand covers the system and needs to be removed.

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