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Progress report on FAST: Fluidization Applied to Sediment Transport as an alternative to maintenance dredging of navigation channels in tidal inlets.

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Abstract. - Tidal inlets between barrier islands are strongly influenced by a bottom current regime varying in both direction and velocity that leads to frequent shoaling and meandering of navigation channels. The concept of keeping a channel open by fluidizing bottom sediments was suggested in 1969 in New Zealand, but the idea was not pursued there. Preliminary testing of this concept in the United States indicated fundamental difficulties in achieving longitudinally continuous fluidization.

Laboratory flume studies at Lehigh University have shown that fully continuous fluidization along the length of the distribution pipe can be achieved when adequate flow rates, on the order of 4 liters per second per meter of pipe length, are used. A two-dimensional physical model of a vertical transverse section across a fluidization system was used to determine the optimum configuration of fluidizing orifices (horizontally

opposed pairs) and the effects of different orifice sizes on two sands with different size characteristics. The studies were then extended to the third dimension in a flume (4.5 m long by 1.5 m wide by 1.2 m deep) with a 3 m fluidization distribution pipe buried in sand. A series of experiments were performed to determine quantitatively the relationships between the width of the fluidized zone and the flow rate through the pipe for different longitudinal spacing of orifices, different conditions of sand burial, and different means of removing fluidized sand from the channel.

A scaled-up field test is planned for the summer of 1980 near a tidal inlet in southern New Jersey, to determine the design parameters for a later full-scale demonstration in a small tidal inlet, and to perform experiments not easily managed within the confines of a laboratory flume. With a pump capable of delivering 2400 liters per minute (600 gal/min), we will fluidize through a 12.7 cm (5 in) diameter pipe with horizontally opposed pairs of 3.16 mm (4/32 in) orifices spaced at 5 cm (2 in) intervals over a 10 meter (33 feet) length.

INTRODUCTION

For much of the coastline from Massachusetts to Texas, tidal inlets between barrier islands are the principal means of access to the open ocean for recreational and commercial fishing boats from the harbors and marinas on the protected landward side of the islands. Maintaining navigable channels through these inlets is a problem: strong ebb and flow tidal currents move considerable sediment back and forth, forming shifting shoals in and near the inlets. Conventional methods -- frequent dredging or permanent jetties -- are quite expensive, and are often ineffective or have undesirable side-effects on nearby beaches. An economically and environmentally acceptable alternative to present methods of dredging and disposal, even if applicable to only a portion of the tidal inlets requiring deeper navigable channels, could have an appreciable national impact.

Hagyard et al (1969) first suggested a surprisingly simple solution to the problem of keeping a channel open through a sand bar closing an estuary harbor. They proposed burying a perforated pipe in the sand bar and pumping water through it at sufficient pressure and flow rate to fluidize the sand above the pipe: the sand would then flow as a liquid down a slight slope (1:400) to the seaward side of the bar. They estimated the power requirements to pump the fluidization water to be quite modest -- 96 horsepower for a dozen submerged pumps along a 7,000 foot long pipe (disregarding friction losses) -- as it is gravity that moves the sand and the fluidizing water merely provides lubrication. Some laboratory experimentation was done, but for various reasons including the death of the principal investigator, the concept of fluidization was not pursued further in New Zealand (I. A. Gilmour -- personal communication).

Wilson and Mudie (1970a) experimented at Scripps Beach with fluidization on an unsaturated beach face, where the sand surface was not covered by water. They used a distribution pipe of 19 mm inside diameter polyvinylchloride, with 2.4 mm holes spaced 5 cm apart, fed from a standard 16 mm inside diameter garden hose. In a series of experiments, they used fluidization pipe lengths from 1 to 3 meters, with the orifices pointed either up or down, burial depths to 0.5 m, and water flow rates from 0.15 to 0.94 liters per second per meter (ℓ/s/m). Under these conditions, they found that the fluidization was linearly inhomogeneous and unstable (Wilson and Mudie, 1970b), that is, along the length of the buried pipe there were several turbulent "fluid holes" separated by water saturated but not fluid "dams" that obstructed the longitudinal down-slope flow of sand. The deeper the fluidizing pipe was buried (up to 0.5 meter), the more distinct and widely spaced the fluid holes became, and they concluded that this vertical channeling effect was a serious impediment to the implementation of the fluidization concept. Most of their experiments involved digging a ditch, burying the pipe (with disturbed sand), and then turning the water on. They found that if the pipe were buried and allowed to sit overnight, the sand would achieve a natural dense compaction from the tidal cycle that washed over it, and they were then unable to achieve fluidization with the pressures and flow rates they had available (Wilson and Mudie, 1970a).

In part because of the vertical channeling problem, further research in the United States on sand transport by fluidization has been directed towards "duct-flow fluidization", in which jets of water from downward pointed orifices angled 45° forward "suspend and simultaneously transport sand as bed load within an artificial duct formed in the sand beneath the fluidizing pipe" (Bailard and Inman, 1975). The duct-flow fluidization process was first described by Harris _et al_ (1976): they explained that the forward momentum exchange between the 45° angle of water jets and the sand-water mixture beneath the fluidizing pipe effectively overcomes the flow instabilities inherent in the previous fluidization techniques. Duct-flow fluidization has been proposed for relatively short distances in conjunction with a crater-sink sand transfer system (Inman and Harris, 1971) as part of a coastal sand management system (Brush, 1972). As sand is removed from beneath the pipe, it is replaced by sand from the overburden immediately above the pipe, forming a crater or channel in the sand surface.

The simple fluidization concept of Hagyard _et al_ (1969) still appeared attractive, and preliminary non-quantitative experiments performed at Lehigh University in 1976-77 did not encounter the difficulties described by Wilson and Mudie (1970a). Our initial experiments were done in a flume under a cover of water, and longitudinally homogeneous and continuous fluidization was achieved without fail under a variety of conditions. This success encouraged us to undertake a more rigorous quantitative investigation, the results of which are reported in this paper.

The objective of this study was to investigate the feasibility of using sand fluidization to maintain a navigable channel in a tidal inlet. The navigation channel would first be dredged by conventional means, with a floor that slopes gently seaward. Two or more fluidization distribution pipes would then be laid parallel to the axis of the channel. Periodically, as sediment accumulated in the channel, the fluidization system would be activated to assist in moving this sediment seaward during ebb tide current flow. Sediment would not be allowed to accumulate to more than a few tens of centimeters in thickness before fluidizing it and allowing gravity (and perhaps ebb flow bottom currents) to move the sediment down the slope of the channel to deeper water beyond the seaward limits of the ebb delta but not beyond the influence of long-shore currents.

Fluidization is visualized as a means of keeping a navigable channel free of shoaling accumulations of sediment, and is thus an alternative to frequent maintenance dredging. In preventing shoals from developing in the channel, fluidization will further act to stabilize the position of the channel; to hold the axis of the channel in alignment with the fluidization distribution pipes and thus prevent the natural tendency of the ebb channel to shift laterally with time, or to meander within the confines of the inlet. The relatively straight navigable channel, maintained deeper than the rest of the inlet, will funnel and guide a major portion of the ebb tidal flow through the deeper channel, thus enhancing the scouring action of the strong ebb tide bottom currents. The action of the processes -- gravity flow of fluidized sediment down a slight slope, and scouring action of confined ebb tide bottom currents -- will reinforce each other to maintain the navigation channel in position, cross-section and longitudinal profiles, in a condition similar to the original dredged navigation channel. It may also be desirable to bend the seaward end of the channel in the downstream longshore current direction (Figure 1), to enhance the ability of the longshore current and wave action to move sand from the seaward terminus of the fluidized channel back shoreward to the beaches of the downstream barrier island. In this way sand removed from the inlet to maintain the navigation channel will be effectively by-passed around the inlet and not be lost to the barrier island beach system. If necessary, the fluidized sand could be pumped in its fluid state to a location closer to shore in shallower water where normal wave action would be able to move it onto the beach (see Figure 1).

A further objective of this study is to define and characterize, through laboratory-scale studies, the relationships and parameters needed for the engineering design of a prototype fluidization system for a real tidal inlet. The laboratory studies were not intended to model a tidal inlet. The experiments were meant to reveal relationships between the flow discharging from the fluidization pipe and the resulting fluidized sediments. Particular attention was devoted to determining quantitatively the relationships between:

(a) distribution pipe size (internal diameter);
(b) sand burial depth of distribution pipe;
(c) fluidization hole size;
(d) longitudinal hole spacing;
(e) configuration or orientation of holes; and
(f) flowrate through the system.

Other factors, such as the interactions between parallel distribution pipe and the effects of ebb flow currents on nonfluidized sand between the pipes, remain to be studied.

EXPERIMENTAL SETUP AND PROCEDURES

Two-dimensional model (Figure 2)

Two types of experimental setups were used in this study. The first type, referred to as the two-dimensional model, was designed (Kelley, 1977) to investigate the cross-sectional size and shape of the fluidized zone as related to fluidization hole size, the configuration or orientation of the holes, and flow rates of the fluidizing water. The model, constructed of 6.35 mm (0.25 in) thick plexiglass, has the shape of a thin vertical box, approximately 122 cm (48 in) wide, 71 cm (28 in) deep, and 7.6 cm (3 in) thick. To provide rigidity to the front and rear faces of the model, 2.54 cm steel box supports span the width of the model at vertical intervals of approximately 23 cm. A short section of 3.8 cm (1.5 in) internal diameter polyvinylchloride pipe, capped at both ends, simulates a cross-section of a fluidization distribution pipe: this is placed within the plexiglass box with the capped ends against the two viewing faces of the model. Fluidizing water flows into the distribution section under pressure through an inflow pipe. Outlet orifices, of different sizes and in different configurations for successive tests, were drilled into the short length of the distributor. Thirteen pressure taps, in a partial grid on the rear face of the model, were connected by plastic tubing to a manometer board to allow simultaneous pressure readings from all taps.

In operation, the section of fluidization distribution pipe was placed and clamped into position, sand was emplaced up to the desired level, saturated with water and carefully packed down, and then the experimental run was conducted by opening the inlet valve in small increments. Flow rates and pressures were recorded for each incremental step, after a short pause to allow equilibrium to be established. Each run was duplicated to provide additional data points and to check the repeatability of the process.

Three-dimensional model (Figure 3)

To investigate the longitudinal effects, a fluidization distribution pipe approximately 3 meters long (10 ft), capped at the downstream end, was placed in a flume approximately 4.5 m long by 1.5 m wide by 1.2 m deep (15 x 5 x 4 ft). The distribution pipe was galvanized steel of 3.8 cm (1.5 in) internal diameter, with orifices the same as in the most successful two-dimensional experiment: 2.38 mm holes at 2.54 cm intervals in the horizontally opposed configuration. Although the flume bottom was horizontal, either or both the pipe and the sand surface could be sloped toward the downstream end of the flume. The distribution pipe was supported off the bottom of the flume by blocks a few centimeters thick.

Later, the length of the distribution pipe was reduced to 1.5 meters. This length was sufficient to give the three-dimensional effect while reducing the total flowrate to half what it was with the longer pipe. This allowed the system to reach the higher flowrates per meter of pipe length that were needed to investigate the desired relationships and still remain within the capacity of the laboratory water system.

The flume was provided with overlying flowing water by a 35 hp pump capable of discharging 1600 gpm through a 20.32 cm diameter pipe into a header tank. The flow was streamlined by passing it through a basket of gravel and allowing it to discharge over the surface of the sand in the flume. Current velocities were estimated by timing the movement of a float over a measured distance.

Sediments used in models

The sediments naturally occurring in and near tidal inlets are mainly sand in a narrow range of sizes. Along the coasts of the United States, the median sand sizes found in inlets range from approximately 0.2 to 0.5 mm (Bruun and Gerritsen, 1959).

Two types of sand were used in these experiments (Figure 4):

(1) the Kelley sand was a clean well-sorted quartz sand with a median diameter of 0.5 mm (Figure 4);

(2) the New Jersey beach sand (commercial designation) was a "dirtier" less well-sorted quartz sand that initially had a mean grain size of 0.23 mm. Repeated use of this sand in fluidization experiments produced an obvious change in color and texture, and it was apparent that the finer sizes were being selectively washed out. A size analysis of this sand after several cycles of fluidization showed less fines, with a median diameter of about 0.4 mm (Figure 4).

Procedure with 2-dimensional model

For each run, a short length (7 cm) of 3.8 cm diameter plastic pipe was prepared with holes of the size and configuration to be tested, and was capped at both ends and connected to the vertical inlet pipe. This assembly was then placed in the plexiglass box and clamped into position. Sand was added to the box to the desired depth, and the box was flooded with water to the overflow level. A thin metal rod was thrust through the sand at several points from the open top of the box to insure removal of air pockets and uniformity of packing. The sand was leveled and depth of coverage checked. The experiment was run by opening the inlet valve in several small increments, with a brief pause between each incremental flowrate increase to allow equilibrium to be established and observations and measurements to be made. At each step, flowrate through the short fluidization pipe was measured by collecting the discharge from the overflow weir in a graduated container over a known length of time. The extent and shape of the fluidized zone could be observed through the plexiglass sides of the model, and the width of the fluidized zone was measured at the sediment-water interface. Each run was duplicated to provide additional data points and to check the repeatibility of the process.

Procedure with 3-dimensional model

Initially, the fluidization pipe was installed in the empty flume, and clamped into a fixed position on blocks a few centimeters off the bottom of the flume. Then sand was shovelled into the flume to a thickness of about 16.5 cm above the pipe. The flume was flooded with water and the sand carefully compacted by rodding and tamping. For subsequent runs with the pipe and sand already in place, it was only necessary to check and correct or adjust if necessary the position of the pipe, and to redistribute the sand in the flume to a desired condition, and tamp it into as uniform packing as possible. To change the orifice spacing, the pipe was exposed by shovelling the sand aside, and selected holes were closed by wrapping the pipe with tape.

With the pipe and the sand cover in the desired configuration and the flume flooded to the overflow level, the experiment was carried out by opening the inlet valve in small steps to increase the flow rate through the fluidization pipe in several small increments, with a pause of several minutes between each step to allow equilibrium to be attained and observations to be made. The flow rate was measured at each step by diverting the overflow from the flume into a volumetric tank over a known time interval. At low flow rates, only observations as to completeness and longitudinal uniformity of fluidization were made. At higher flow rates, after full fluidization was achieved, the width of fluidized channel was measured.

A typical test run would include about 8 flow rate increments, each with detailed observations and measurements. Each run lasted approximately an hour. Preparations for a run took anywhere from half-an-hour to several hours, depending on how many changes were made.

In a typical run, several stages of fluidization were observed in the following sequence:

(a) along the length of the fluidization pipe, a series of "pressure circles" or low-relief sand mounds 5 to 10 cm in diameter developed on the sand surface, at low pressures and flow rates;

(b) "sand boils" or point source eruptions of fluidized sand, 5 to 10 cm in diameter, began to appear on either side of the buried pipe.

These did not all appear at once, or begin every time in the same place, but in every run they eventually appeared along both sides of the entire length of the buried pipe;

(c) with increased, but still relatively low flow and pressure, a stage of "partial fluidization" was reached, corresponding perhaps to that described by Wilson and Mudie (1970a) as linearly inhomogeneous and unstable: there would be a small number (2 to 6) of large (30 to 50 cm) circular or elongate sand boils or turbulent fluidized areas, separated by dams or zones of clearly unfluidized or less-fluidized sand. These few large boils formed by the merging longitudinal and lateral expansion of a number of the smaller boils in a non-uniform manner. Intensity of color was a clue: the well-fluidized zones were distinctly lighter in color than the intervening poorly fluidized zones, and the turbulent areas showed streaky concentric patterns. If the flow rate were held constant for several minutes, the sand remained in a dynamic state of partial fluidization;

(d) with further increases in flow rate, full and complete fluidization was achieved, evidenced by a uniformly lighter color in an unbroken zone of equal width the full length of the buried pipe. On close inspection, individual grains of sand could be seen moving laterally out of this fluidized zone, and then stopping -- a fairly well-defined levee of unfluidized sand was thus built up on both sides of the fluidized zone;

(e) it was experimentally determined that once the stage of full fluidization was reached, it could be maintained in that condition (without breaking up into individual large sand boils) as the flow rate was decreased as much as 20%. A further reduction of 20% in the flow rate produced a state of partial fluidization, i.e., the uniform full fluidization broke up into a few (2 to 5) large elongate sand boils with short zones of less fluidized sand (darker in color) between the large sand boils.

RESULTS

Orifice Configuration (2-D Model)

A series of tests were run on the two-dimensional model to determine an optimum size of fluidization orifice, and an optimum configuration for the orifices. As a quantitative measure of the performance of the various combinations tested, we used the width of fluidized zone as observed at the upper sediment-water interface, for each measured flow rate through the fluidization distributor pipe. By increasing the flow rate through the system, a relationship between flow rate per unit length of fluidization pipe and fluidized zone width can be established for a given combination of fluidization hole size, spacing and configuration. Throughout the remainder of this report, this will be referred to as the flow rate/width relationship and will be depicted in graph form (see Figures 5 through 9).

The width of the fluidized zone is a somewhat arbitrary measurement, subject to individual interpretation. In practice, the width is measured from peak to peak of the levees formed on each side of the fluidized zone as sand is ejected laterally and is deposited when the sand comes out of fluidized suspension. At low flow rates, these levees are not well defined. In some later three-dimensional model experiments where the fluidized sand is removed down channel, the lateral levees never form and the width must be measured at a different point in the cross-sectional profile. Consequently, the width measurements should be considered only as an index of performance for comparative purposes.

Previous workers had utilized a single row of orifices, oriented either vertically upwards (Hagyard *et al*, 1969), or directed downwards (Mudie and Wilson, 1970a, 1970b). With the criterion of width of fluidized zone, we tested five configurations:

(1) orifices directed downwards;

(2) orifices directed upwards;

(3) orifices in pairs directed horizontally;

(4) orifices in pairs directed 45° downward from horizontal; and

(5) a combination of (1) and (3).

Along the short (7 cm) length of the two-dimensional model fluidization distribution pipe, orifices of 2.54 mm diameter (as used by Mudie and Wilson, 1970a) were spaced on 2.54 cm centers. There were a total of 3 orifices for configurations 1 and 2; 6 orifices for configurations 3 and 4; and 9 orifices for configuration 5.

The width of fluidized zone for a specific flow rate for each configuration tested is listed in Table 1.

Table 1. Width of Fluidized Zone for Orifice Configurations

Orifice Configuration	Width of Fluidized Zone
1	29.2 cm
2	27.9 cm
3	71.2 cm
4	50.8 cm
5	53.3 cm

As it was clearly evident that configuration 3 - horizontally opposed pairs of orifices, produced a significantly wider fluidized zone than any of the other configurations tested, this was the configuration used in all subsequent two-dimensional and three-dimensional model tests.

Orifice Size (2-D Model)

Four orifice sizes were tested in the two-dimensional model: 0.159 cm (2/32 in), 0.316 cm (4/32 in), 0.476 cm (6/32 in), and 0.635 cm (8/32 in). The smallest size was selected by considering the size of the sand grains and the need to provide a jet of water out of the fluidization hole of at least similar size to interact significantly with the grains. From a hydraulic point of view, the smaller the hole size the greater the internal fluidization pipe pressure will be required to force adequate flow rates through the fluidization holes. For Holes smaller than 0.159 cm diameter, the pressure required would be impractical. Hydraulic considerations also set a limit to the larger size, as initiation of fluidization is dependent upon achieving a certain minimum pressure in the sand. The total flow rate required to achieve the necessary pressure using holes larger than 0.635 cm diameter would also be impractical.

As shown in Figure 5, at a given flow rate, the smallest diameter holes produce the largest width of fluidized zone. This effect is probably related to the velocity of the water jet from the orifice, with larger orifices producing lower velocity jets. The width difference for the two larger hole sizes tested appears to be negligible.

Sediment Characteristics (2-D Model)

Sediment characteristics (mean grain size and degree of sorting) of different sands have a measurable influence on the flow rate/width relationship as shown in Figure 6. For a given flow rate and orifice size, the width of fluidized zone produced was about 20 percent larger for the New Jersey beach sand than for the Kelley sand. This effect was small as compared with that produced by other parameters.

Depth of Burial (2-D Model)

For a given hole size (3.16 mm), the effect of doubling the depth of sand burial (from 20.3 cm to 40.6 cm) appears to be insignificant (Figure 7).

Above a flow rate of about 4 liters/second/meter, the rate of increase in width of fluidized zone with increasing flow rate appears to level off, and relatively larger flow rate increments are required to produce small increases in fluidized zone widths.

Comparison of 2-D and 3-D Model Tests

All of the above described tests were made in the 2-D model. The remainder of the test program was performed in the 3-D model. Figure 8 shows a comparison of the flow rate/width relationship as determined in the two models for identical conditions of sand burial depth (20.3 cm), orifice size (3.16 mm), sand type (New Jersey beach sand), and orifice configuration (horizontally opposed pairs). At a given flow rate, a wider fluidized zone is produced in the 3-D model. This difference is probably accounted for by the relatively unconstrained nature of the 3-dimensional model. In the 2-dimensional model, the fluidizing flow was probably strongly influenced by wall effects.

In addition, the slope of the flow rate/width relationship is steeper for tests run in the 3-D model: i.e., the same increase in flow rate in the two models will produce a larger increase in fluidized zone width in the 3-D model.

Orifice Spacing (3-D Model)

Three orifice spacings were tested, 2.54 cm, 5.08 cm and 10.16 cm (Figure 9). The flow rate necessary to initiate fluidization does not appear to be significantly influenced by the spacing of the orifices. For a given flow rate, the intermediate spacing (5.08 cm) appears to produce a significantly larger width of fluidized zone than either the closest spacing (2.54 cm) or the widest spacing (10.16 cm).

Uneven Sand Burial (3-D Model)

Under natural conditions in a tidal inlet, sand deposited by tidal currents and wave action would not be expected to cover the fluidization distributor pipe evenly: i.e., at some points along the buried pipe the sand might well accumulate to thicknesses of as much as 20 cm, for example, while at other points there may be virtually no deposition and accumulation of sand. Laboratory flume experiments using an even thickness of sand covering the fluidization distributor pipe obviously is unrealistic. Several experiments were to test the ability of the 3-dimensional model fluidization system to achieve longitudinally continuous full fluidization under less than ideal conditions of even sand coverage.

With the pipe fixed in a horizontal position, sand was spread to an even thickness of approximately 12.7 cm (5 in) over the length of the pipe, and an additional 12.7 cm was built up over the central one-third of the pipe length in the form of a low hummock of 25.4 cm thickness. Fluidization flow was initiated in the distributor pipe, and the flow rate was increased in small increments as previously done. As expected, fluidization began to develop first in the upstream area of thin sand coverage, then appeared in the downstream area of thin sand coverage, and finally as the flow rate approached 3 to 4 liters per second per meter, the central area of thicker sand coverage became fluidized.

In subsequent runs, the area of thicker sand coverage was placed over the upstream third of the pipe, over the downstream third of the pipe, and over both ends of the pipe with the central third under thin sand cover. In all cases, fluidization began in the thin coverage areas, and in all cases, fluidization progressed to the usual final state of longitudinally continuous full fluidization at the higher flow rates.

Removal of Sand from Fluidized Zone (3-D Model)

Fluidizing the sand in a linearly continuous zone above the buried distributor pipe is only the first step in achieving a channel: the fluidized sand must be physically removed to produce the channel. Three ways of accomplishing removal of sand were tested:

(1) While the sand was kept in a fluidized state, a small submersible centrifugal pump was used to pump the fluidized sand through a short length of 1.25 cm internal diameter plastic hose to another portion of the flume. All of the fluidized sand could be pumped away from one position; i.e., the fluidized sand flowed to the pump intake location at one end of the distributor pipe from the entire length of the distributor pipe. As the level of the fluidized sand was lowered, the walls of the channel slumped down and that material was fluidized and pumped away, creating a channel significantly wider than the measured width of the fluidized zone. The sides of this channel stabilized at the low angle of repose of saturated sand.

(2) The fluidized sand could also move down a gentle slope by gravity flow. In all previous tests in the 3-D model, the distributor pipe had been placed in a horizontal position: for this experiment the pipe was sloped from the inlet end down to the closed end at a 5% gradient, with a uniform thickness of sand coverage (20.3 cm) whose upper surface also sloped at a 5% gradient. A fluidization flow rate of 3 liters/meter/second in the buried distributor pipe initially produced the usual fluidized zone with a width of 70 cm. The flow in the fluidization pipe was maintained for 30 minutes. The fluidized sand was observed to move downslope by gravity flow until halted by the building of a dam and delta across the downstream end of the channel. This obstruction was built in a manner similar to the side-channel levees, as the fluidized sand overflowed the channel end, it quickly reverted to an unfluidized condition. When this dam was continuously removed by hand, the fluidized sand drained unimpeded from the channel, and the sides of the channel slumped down to increase the channel width from 70 to 100 cm.

(3) Although the laboratory flume and apparatus for providing overlying flowing water was only marginally suitable for simulating the behavior of a fluidized channel under ebb tide flow conditions, encouraging results were obtained. For this experiment, the fluidization pipe was set horizontally with 3.16 mm holes spaced at 5.04 cm, covered by a uniform 20.3 cm thickness of sand. A fluidized channel was created at a fluidization pipe flow rate of 3.06 ℓ/m/s, and the valve was opened to the overlying flow apparatus.

With this flow extending across the entire width of the flume, a scour velocity of about 30 cm/sec was attained. Although this flow was sufficient to create ripple marks on the sand surface outside the fluidized channel, there appeared to be little tendency of the overlying flow to entrain the fluidized sand. Baffles were then used to direct the overlying flow over the fluidized channel, and a surface velocity estimated at 80 cm/sec was attained. The scouring capacity of the overlying flow was dramatically increased, sweeping all the fluidized sand out of the channel. The walls of the channel simultaneously slumped, were fluidized and swept out by the overlying current, creating a wider and deeper channel. A low dam and delta eventually accumulated at the downstream end. When the baffles were moved downstream to direct the higher velocity flow over the dam and delta, only a small erosive effect was noted: apparently a higher velocity is required to erode the unfluidized sand of the dam and delta than is required to transport the fluidized sand.

DISCUSSION

It is apparent from the results reported here that the problems of linearly inhomogeneous fluidization and the isolation of fluidized holes by non-fluidized dams reported by Wilson and Mudie (1970 a, b) are not serious impediments to the implementation of the fluidization concept. Our laboratory 3-dimensional experiments invariably achieved a final state of longitudinally continuous and full fluidization over a wide variety of conditions. Three differences between our procedures and those of previous workers probably account for the difference in results:

(1) We used a configuration of fluidization orifices in horizontally opposed pairs, instead of a single row of orifices directed either upwards or downwards as used by Mudie and Wilson (1970a);

(2) We ran our experiments in water-saturated sand covered by a significant depth of standing or flowing water, instead of on an unsaturated beach face with a sand-air interface as used by Mudie and Wilson (1970a); and perhaps most importantly,

(3) We used flow rates through the buried distributor pipe in a range from 1 to 6 liters/second/meter, whereas Mudie and Wilson (1970 a, b) used flow rates of less than 1 ℓ/s/m. We found that flow rates on the order of 3 to 4 ℓ/s/m were required to attain fully continuous fluidization. Wilson and Mudie (1970 a, b) were limited in the flow rates they could achieve by the capacity of their pump, by the small diameter (19 mm) of their distributor pipe, and particularly by the small internal diameter (16 mm) of the ordinary garden hose connecting pump to distributor pipe.

CONCLUSIONS AND RECOMMENDATIONS

1. A configuration of fluidization orifices in horizontally opposed pairs produces the widest and most uniform fluidized zone of those arrangements tested.
2. Orifice diameters in the 3 to 5 mm range are the best compromise between the need for high water jet velocities (favoring small holes),

the need to minimize clogging (favoring holes larger than the maximum sand size to be encountered), and the need to balance pump pressure and volume capabilities and costs.

3. Orifice spacing on 5 cm centers appears to be nearly optimum, as this spacing has a steeper flow rate/width curve (largest width increase per additional flow rate increment) than either closer or wider spacings.
4. For a given set of specifications (orifice diameter, spacing and configuration, sand type and burial depth), there is a well-defined relationship between flow rate per unit length of distributor pipe and the width of the resulting fluidized zone. This relation is steep at first and then flattens out so that finally a large increase in flow results in only a small increase in width.
5. A fluidization flow rate of about 3 to 4 ℓ/s/m is required to produce longitudinally continuous and full fluidization over a zone 40 to 60 cm wide.
6. When the fluidized sand is removed from the fluidized zone, the sides of the resulting channel slump down and are also fluidized and removed, increasing the channel width by 50%.
7. Fluidized sand can be moved by pumping, by flowing down a gentle (5%) slope, or by being eroded and transported by bottom currents of sufficient velocity. In a laboratory flume, currents of about 80 cm/sec velocity appear able to erode fluidized sediment without significant erosion of nearby unfluidized sediment.

8. Design parameters for a scaled up in size field test near a tidal inlet in southern New Jersey, planned for the summer of 1980, include:
   a. Fluidization distributor pipe 10 m long, 12.7 cm diameter, with horizontally opposed pairs of 3.16 mm diameter orifices, spaced at 5 cm intervals,
   b. Centrifugal submersible pump capable of delivering at least 40 liters per second (600 gal/min).

In addition to repeating the laboratory experiments on a larger scale under natural conditions, some further tests that cannot easily be done in the laboratory flume, such as investigating the interactive effects of parallel distributor pipes separated by various distances, will also be conducted during this season.

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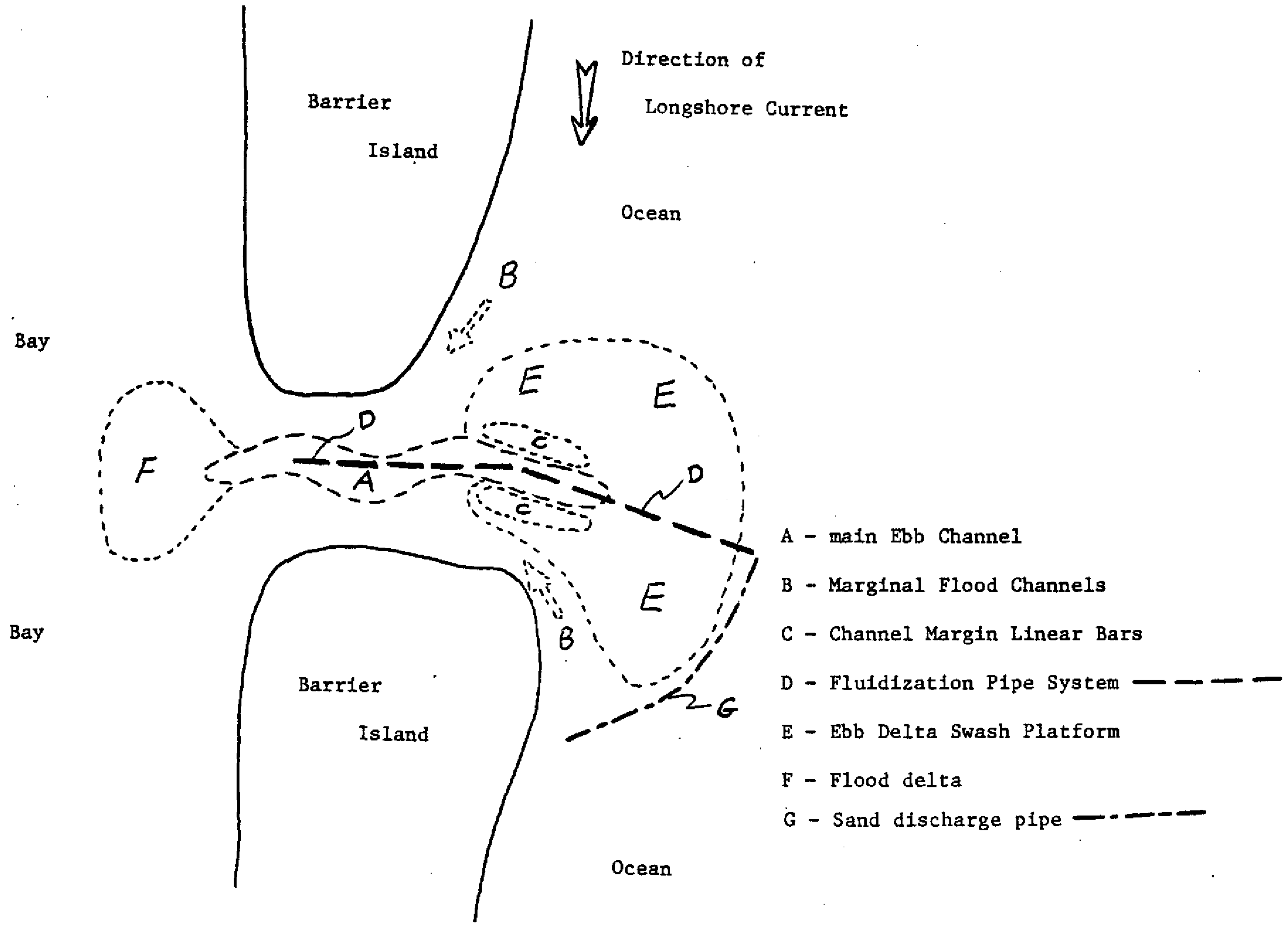

Fig. 1 Map view of idealized tidal inlet, with fluidization pipe system along axis of main ebb channel and through ebb delta swash platform.

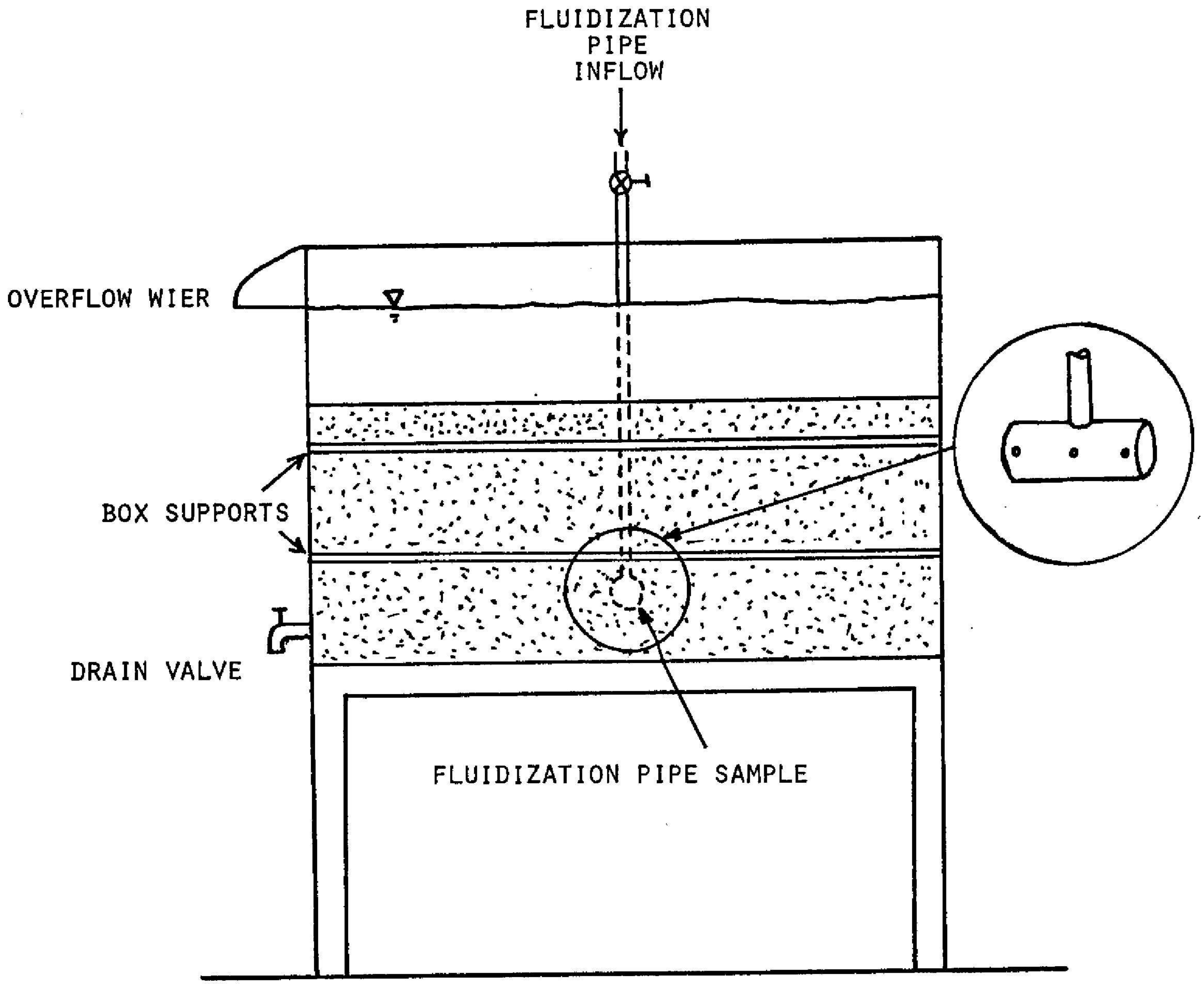

Fig. 2 Diagrammatic sketch of two-dimensional model.

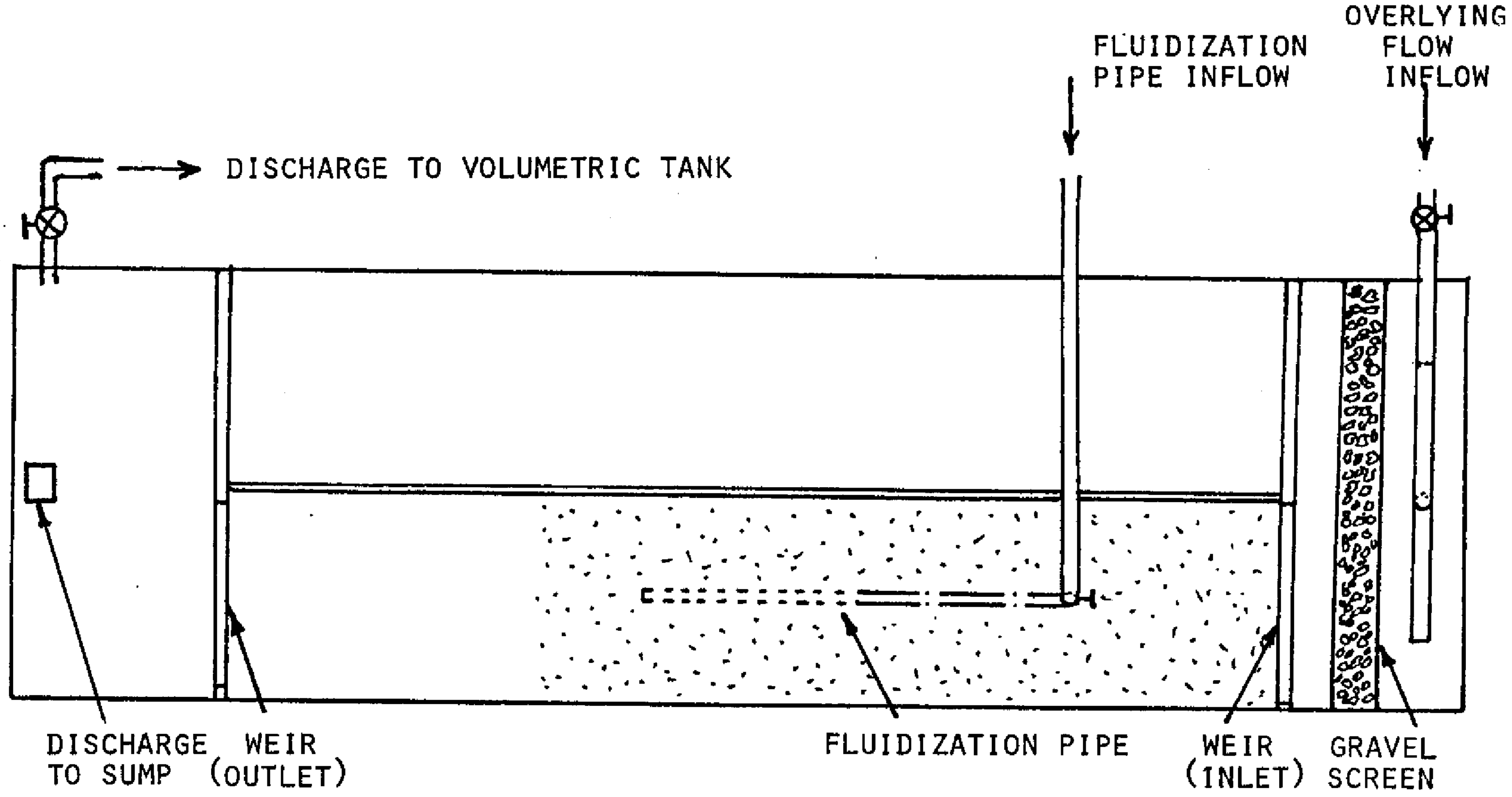

Fig. 3 Diagrammatic sketch of three-dimensional model.

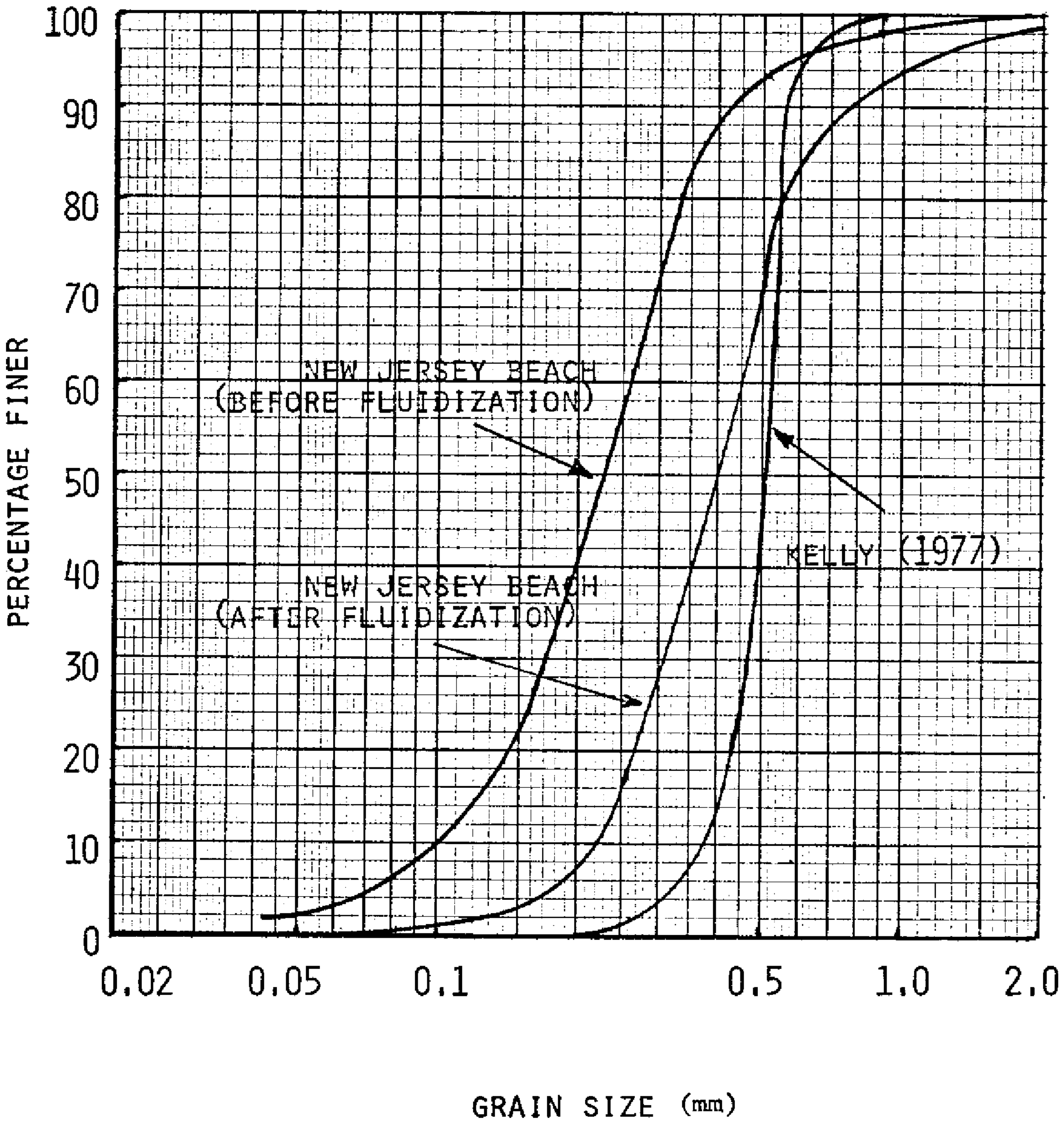

Fig. 4 Cumulative size analysis of sands used in experiments.

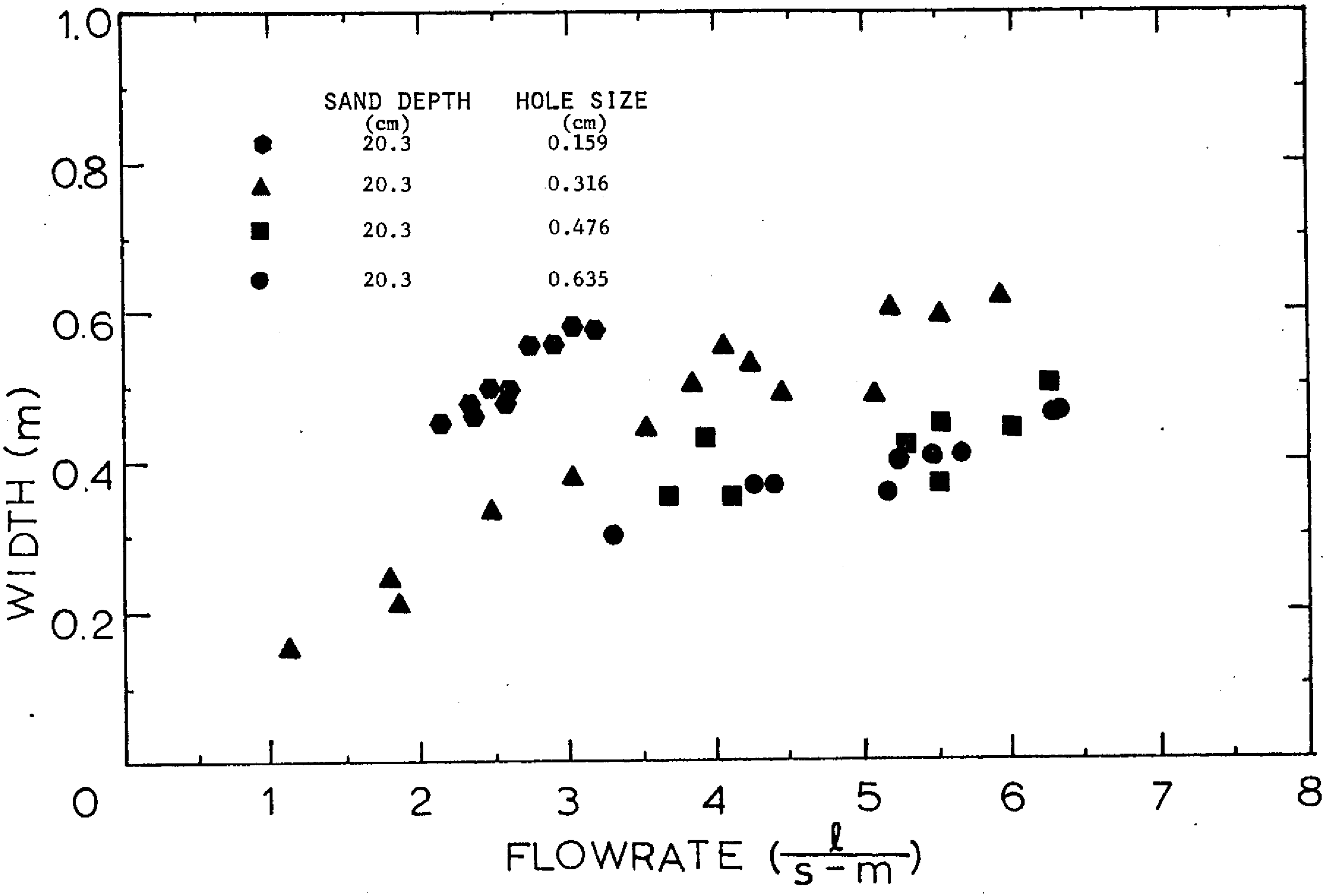

Fig. 5 Flowrate/width relationships for four orifice sizes in 2-D model.

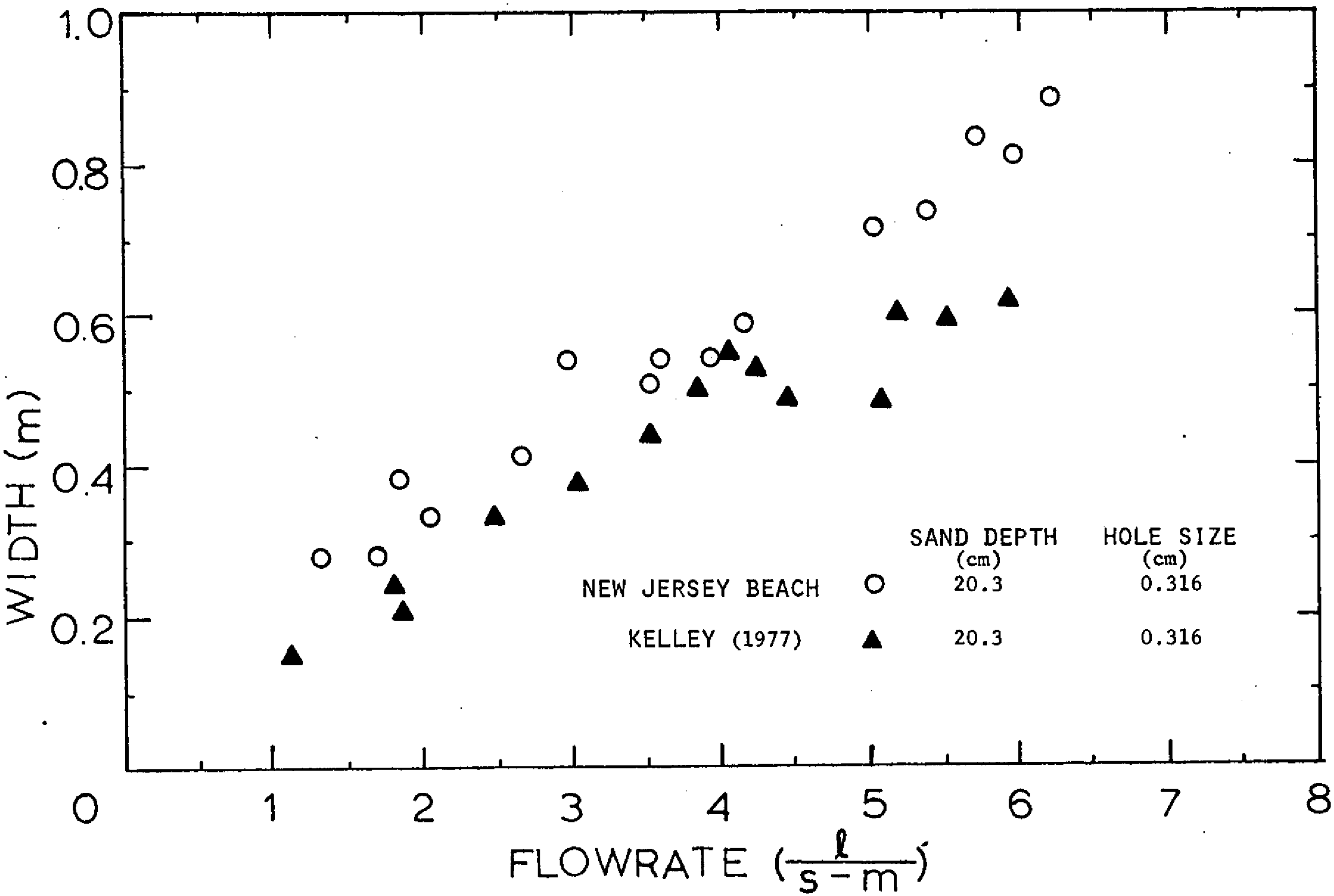

Fig. 6 Flowrate/width relationships for the two sands used in 2-D model.

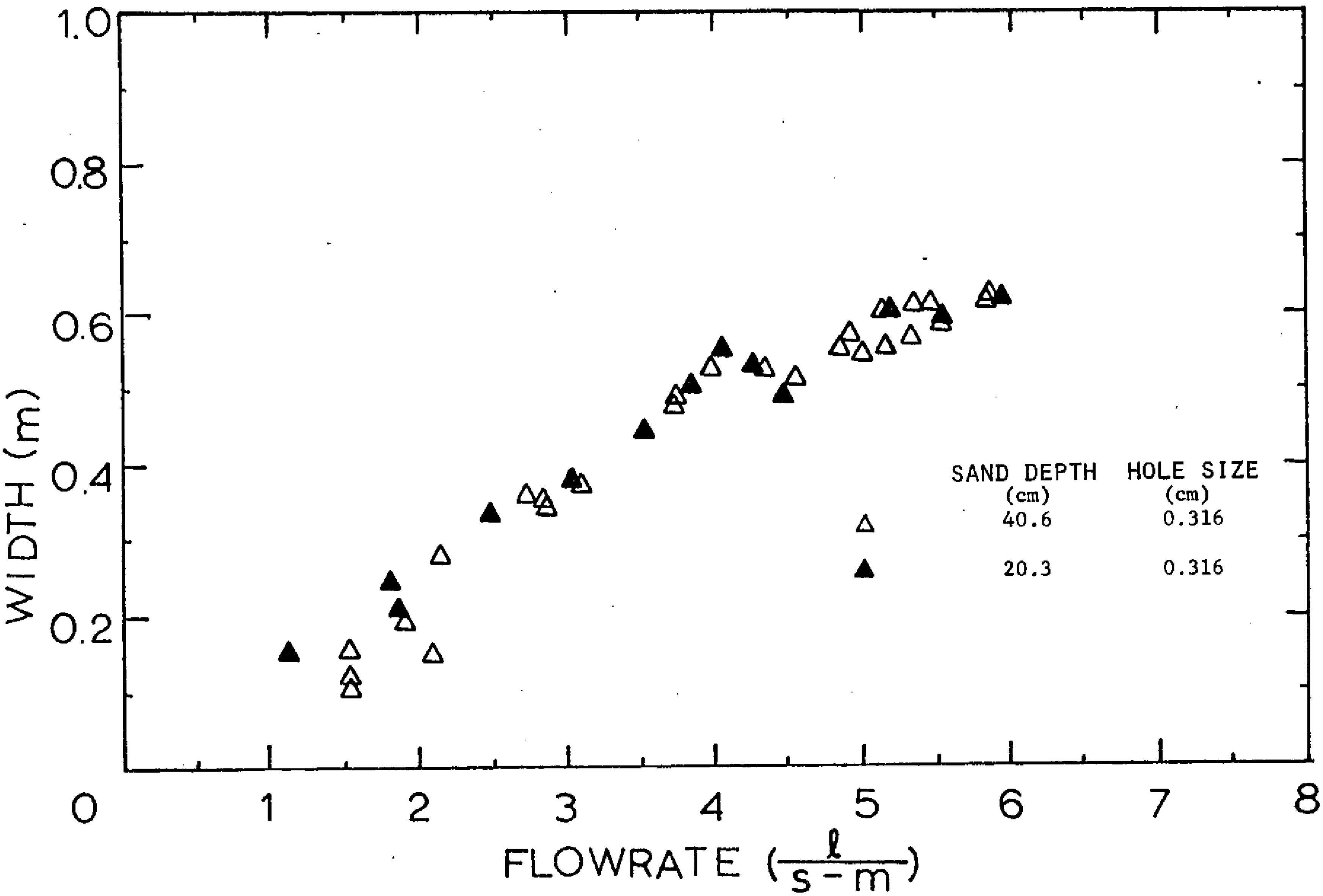

Fig. 7 Flowrate/width relationships for two burial depths in 2-D model.

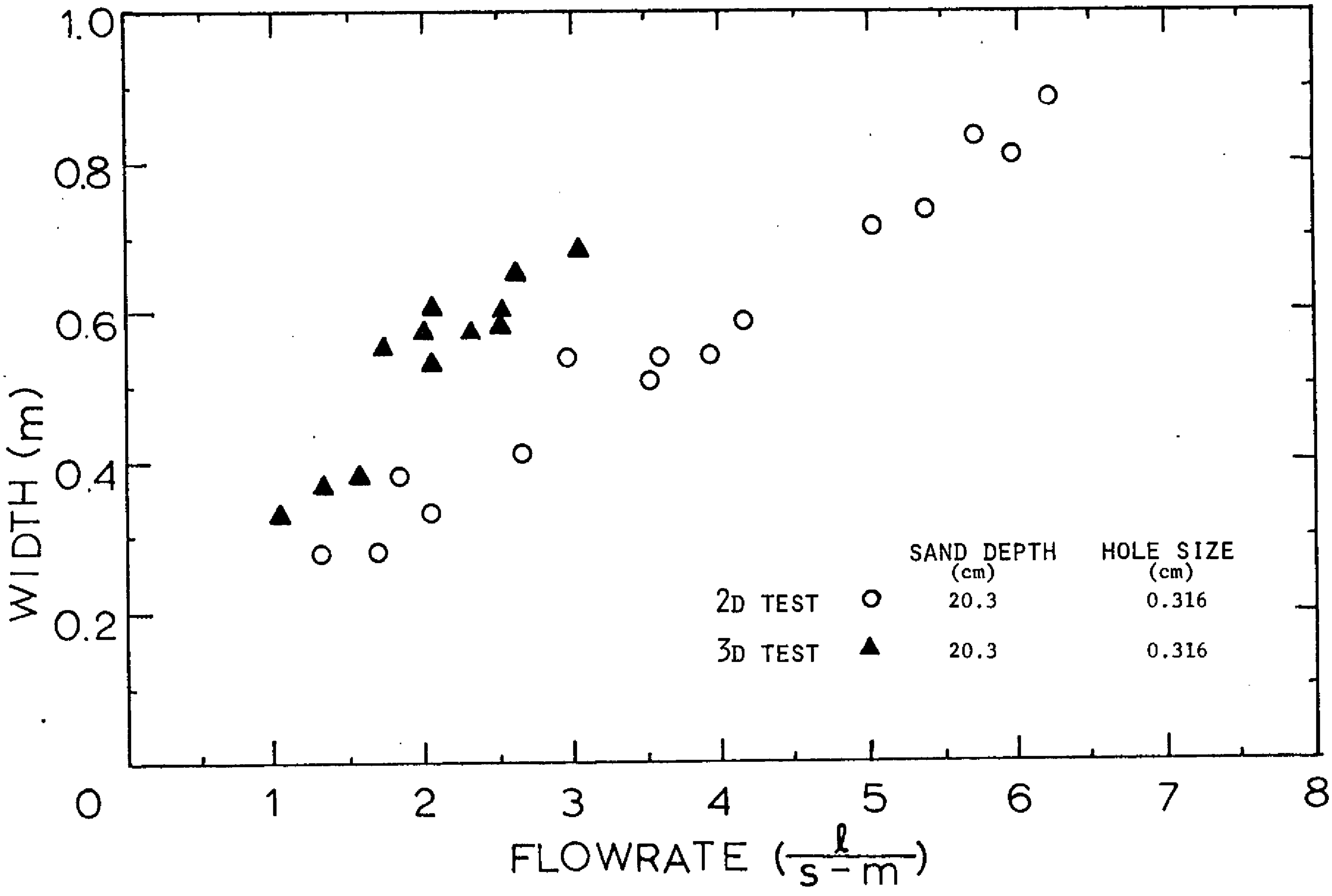

Fig. 8 Comparison of flowrate/width relationships for 2-D and 3-D models.

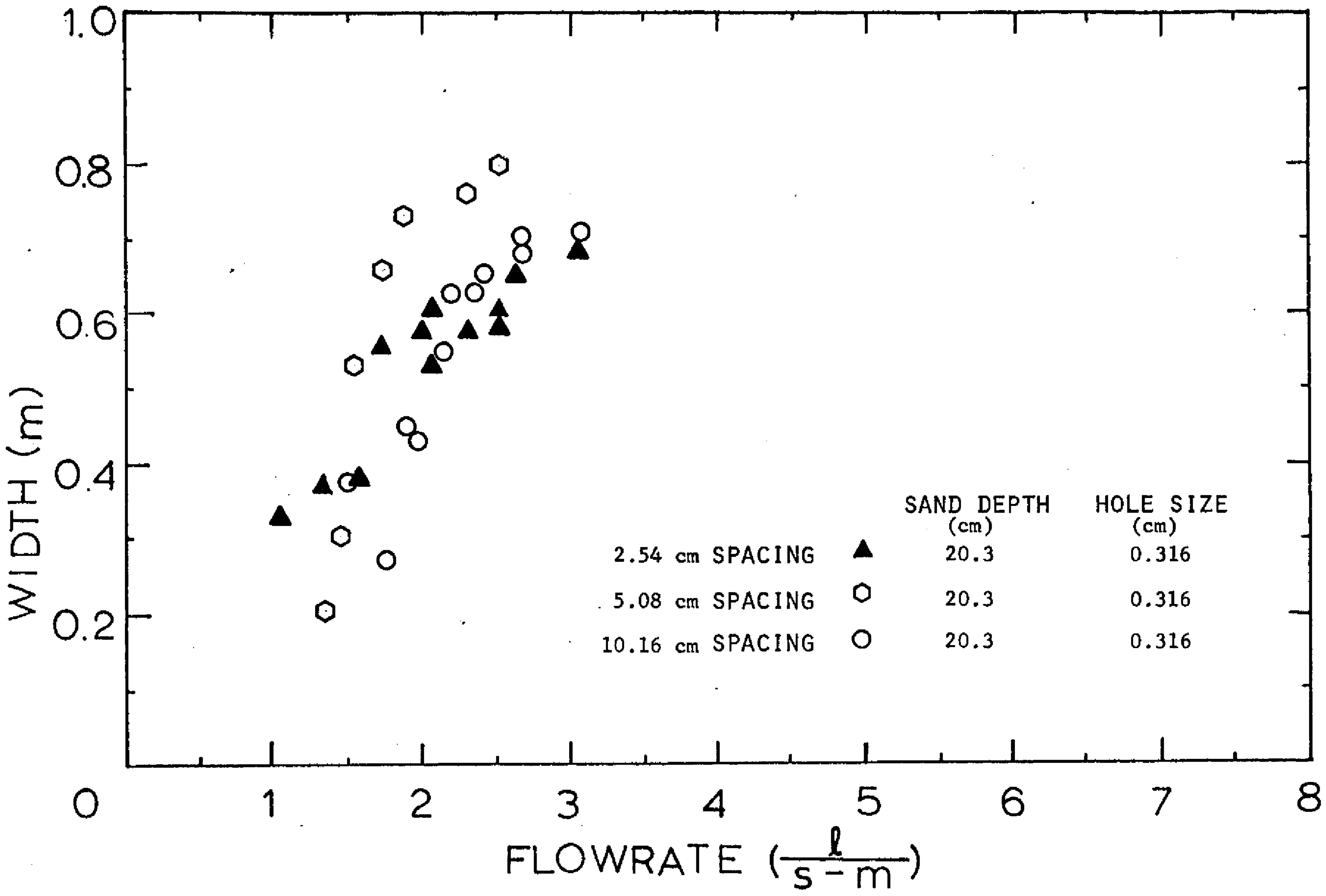

Fig. 9 Flowrate/width relationships for three orifice spacings in 3-D model.