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EFFECTS OF ORIFICE SPACING
ON THE FLUIDIZATION PROCESS

by

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ABSTRACT

In some circumstances, application of the fluidization phenomena in the coastal environment promises a long term alternative to dredging for channel maintenance. Fluidization in the coastal environment is the process where flow from a perforated pipe is introduced into overlying sand at a rate sufficient to suspend the sand into slurry. This slurry can be transported along the fluidization pipe by gravity, pumping, or shear of overlying ebb tidal flows. Fluidization systems offer permanent solution to the problem of tidal channel sedimentation and maintenance. Past laboratory and field studies have supported the feasibility of fluidization and offer data to aid in design. The present study examines the effect of fluidization pipe hole spacing on the fluidization process and provides data to aid in fluidization hole spacing selection.

Two-dimensional experiments are performed to evaluate 2.54 cm (1 in), 5.08 cm (2 in), 7.62 cm (3 in), and 10.16 cm (4 in) horizontally opposed orifice spacings. Each hole spacing is tested in uniform fine sand (d_50 = 0.16 mm) and uniform medium coarse sand (d_50 = 0.45 mm) of 42.0 cm (16.5 in) and 25.4 cm (10.0 in) bed depths resulting in sixteen unique experiments. Four parameters are monitored for evaluation. The excess hydraulic head distribution in the surrounding sand bed, flow rate, internal fluidization pipe pressure, and the resulting final trench geometry formed after sediment transportation simulation are examined to quantify the effect of orifice spacing on the fluidization process in the coastal environment. Additionally, the effects of varied bed condition, bed depth and sand size, is examined.

The present study shows that the 5.08 cm (2 in) hole spacing is optimal for fluidization of fine sands, and the 2.54 cm (1 in) hole spacing is optimal for fluidization of medium coarse sands. Finer sands are easier to fluidize than medium coarse sands for all hole spacings. Shallower bed depths are easier to fluidize than deeper bed depths for all hole spacings. Design recommendations are offered for site specific conditions and project objectives.
1.0 INTRODUCTION

The dredging of inlets, harbors, and navigation channels historically has been the primary method for sand management in the coastal environment. Dredging often is prohibitively expensive and does not yield permanent solution for channel maintenance. Manipulation of the phenomenon of fluidization offers a unique and long term solution for navigation channel maintenance.

1.1 The Fluidization Phenomena

Fluidization is the transformation of noncohesive material, subject to internal and upward flow, into slurry. The upward flow of any fluid through porous media results in a vertical pressure differential due to the viscous and inertial forces within the flow field. As the flow velocity increases, the pressure differential increases at a linear rate for laminar conditions and at a quadratic rate for transitional and turbulent conditions. If the pressure differential is sufficient to balance the existing overburden pressure, instability among the granular particles exists. At the point of instability a state of initiation of fluidization results (Amirtharajah, 1970). At higher flow velocities the granular media is suspended and expands into slurry. This condition is termed fluidization where the media and fluid together behaves as a highly viscous fluid.

The fluidization phenomena may be applied to the coastal environment by the introduction of flow through a perforated pipe into an overlying sand bed, Figure 1.1. At sufficient flow rates the overlying sand bed is fluidized and behaves as a highly viscous fluid. This overlying slurry may be controlled, directed, and transported through the incorporation of other mechanisms known within the hydraulic engineering discipline. Three mechanisms may be employed to aid in the transport of the slurry in a direction parallel to the fluidization pipe. First, if the fluidization pipe is sloped, the slurry is subject to a downstream component of gravitational force causing sediment transportation downstream along the pipe. Secondly, tidal or river currents apply an overlying shear stress to the slurry. Fluidization pipe placement parallel to the current direction would provide sediment transportation along the pipe. Thirdly, pumping of
the slurry from any point along the fluidization pipe would cause drawdown within the fluidized zone resulting in sediment transportation toward the pumping point.

Proper fluidization pipe placement, in conjunction with manipulation and possible combinations of the above mechanisms, offers a method for controlled sediment transportation. Application of fluidization may be employed to aid in channel navigation maintenance, sand by-passing, and other operations requiring sediment transport.

1.2 Stages of the Fluidization Process

The identification of stages of the fluidization process from a no-flow state through full-fluidization and to final trench formation enables understanding of the function of a prototype system designed for sand management in coastal environment. Roberts et al. (1986) and Clifford et al. (1989) identified five progressive stages encountered in the fluidization cycle as follows:

- The pre-fluidization stage begins at an original no flow condition. Flow rate is gradually increased without any physical changes in the sand bed, Figure 1.2 (a). The excess hydraulic head distribution within the bed and internal fluidization pipe pressure increases with increasing flow rate.

- The initiation of fluidization stage occurs at a higher flow rate as the maximum sustainable excess hydraulic head gradient is surpassed. At this point, the pore water pressure differential within the sand bed overcomes the overburden differential in local regions surrounding the fluidization pipe causing piping as shown in Figure 1.2 (b). The excess hydraulic head within the bed is redistributed. The internal pipe pressure may drop momentarily or continuously depending on the pipe/bed configuration.

- At higher flow rates, the full-fluidization stage is reached when the entire fluidized region is continuous slurry and berms form as shown in
Figure 1.2 (c). Horizontal planes of excess hydraulic head indicate a vertical flow gradient within the fluidized zone. At full-fluidization the internal pipe pressure may be at a maximum depending on pipe/bed configuration.

- The slurry removal stage simulates the previously mentioned sediment transport mechanisms. As the bed fluidized surface level drops during slurry removal, the surrounding berms and walls slump into the fluidized zone until the submerged angle of repose is met, Figure 1.2 (d).

- The final trench configuration stage is reached when all of the slurry is removed. The erosive power of the jets emanating from the fluidization pipe dictates the bottom width of the trench. This bottom width, along with the bed material's submerged angle of repose and the bed depth, controls the remaining trench dimensions, Figure 1.2 (e).

The first three stages were examined by Roberts et al. (1986). Extending the work of Roberts, Clifford et al. (1989) studied the last two stages. The five stages of the fluidization process applied in the coastal environment are not distinct but occur as continuous and progressive events.

1.3 Literature Review of Fluidization for Sand Management

The first proposal of fluidization as a sand management technique was offered by Hagyard et al. (1969). Two-dimensional fluidization of over-laying sand was proposed via a longitudinally and downwardly perforated source pipe sloping offshore and placed to intercept littoral drift approaching the harbor entrance of Westport, New Zealand. Before entering the harbor entrance, the littoral drift enters the fluidized region and flows downgrade and offshore as viscous slurry.

The optimization of supply pipe hole configuration was investigated by Kelley (1977). Fluidization tests proved horizontally and symmetrically opposed
orifices, place along the sides of the pipe, most efficient. Fluidized zones 2.4 greater than the width of the Hagyard et al. (1969) configuration was achieved. All literature further reviewed employs the symmetrically and horizontally opposed hole configuration.

Murray and Collins (1978) conducted three-dimensional laboratory tests to qualify fluidization as a sediment transportation catalyst. Long supply pipes, placed both horizontally and inclined, fully fluidized overlying sand. Removal of the slurry via a stationary pump for the horizontal pipes or gravity flow along the inclined pipes proved fluidization as a viable technique for sediment transportation under controlled conditions. Weisman and Collins (1979) confirmed Murray and Collins (1978) and proved that removal of the slurry can be achieved by overlying flow along the supply pipe. Strong overlying flows are present in inlet channels during flood and ebb tides; therefore, fluidization offers a possible replacement to dredging for inlet channel maintenance.

Weisman et al. (1982) conducted field tests, located on the bay side of Corson's Inlet, New Jersey, to compliment previous laboratory findings. In addition, the effect of placing fluidization pipes in parallel to widen a maintained channel was investigated. All aspects of the previous laboratory testing programs were verified, but three unforeseen environmental factors were encountered. Firstly, algae entering pump intakes tended to clog the supply pipe holes. Secondly, sand entering the pump intakes accumulated in the supply pipe reducing the pipe cross-section with no clogging effect. Thirdly, clam shells, located throughout the sand bed, impeded the system's ability to achieve full trench width. The first two problems can be easily solved through pump intake location selection. The clam shell problem would be sight specific, and the effect in inlet channels is unknown.

Roberts et al. (1986) constructed a full scale two-dimensional fluidization tank to study the fluidization phenomena in significant detail. Through use of seventy-two head taps, the excess hydraulic head distribution surrounding the supply pipe was monitored during all stages of the fluidization process. Also, internal supply pipe pressure and flow rate were monitored. A more complete understanding of flow patterns and boundary
conditions of the fluidized/unfluidized interface was achieved. Specifically, the flow gradient was found to be vertical in the fluidized region, and leakage from the fluidized zone into the unfluidized region comprises less than five percent of the total flow rate.

Using the apparatus of Roberts et al. (1986), Clifford et al. (1989) studied the effects of slurry removal on trench formation and flow rate on the geometry of the fluidized region. Slurry removal reduces the depth of the slurry in the fluidized zone, and the fluidized/unfluidized interface progressively unravels to the submerged angle of repose. Thus, the final trench geometry is dictated by the erosive power of the jets emanating from the fluidization pipe, the bed depth, and the bed material’s submerged angle of repose. Clifford et al. (1989) found that a linear relation exists between increasing flow rate and fluidized zone width until a "threshold" flow rate is achieved. At this "threshold" flow rate, enough erosive power exists to eject slurry out of the fluidized zone forming "secondary" berms. A steeper linear relation between flow and zone width exists above the "threshold" flow rate.

Again using the experimental apparatus of Roberts et al. (1986), Ledwith et al. (1990) studied the effects of orifice size on two-dimensional fluidization efficiency. For a fine sand ($d_{50} = 0.15$ mm), Sand A, and a medium coarse sand ($d_{50} = 0.45$ mm), Sand B, at 25.4 cm (10 in) and 42.0 cm (16.5 in) overlying bed depths, supply pipe hole sizes of 1.59 mm (1/16 in), 3.18 mm (1/8 in), 4.76 mm (3/16 in), and 6.35 mm (1/4 in) were evaluated. Higher flow rates with lower corresponding internal pipe pressures were found to be necessary to achieve full-fluidization using larger hole sizes. In addition, wider trenches were formed with smaller hole sizes as a result of the erosive power of higher jet velocities emanating from the supply pipe. Specific data to aid in design and a recommendation of 3.18 mm (1/8 in) through 4.76 mm (3/16 in) hole spacing was offered.

A fluidization system to maintain a tidal inlet channel at a greater depth was installed at Anna Maria, Florida as presented by Collins et al. (1987). The formation of one fluidization trench 183 m (600 ft) in length, 4.9 m (16 ft) in top width, and 1.2 m (4 ft) in bed depth along the axis of the channel was achieved at the Lake
La Vista inlet. Placement of six 100 ft individual lengths of perforated conduit was achieved by rotating each length ninety degrees so that vertically opposed orifices result. Flow emanating downward from the lower holes allowed self-burial to the desired elevation. Once the elevation was achieved, the pipe was rotated back to the horizontally opposed hole orientation. During initial fluidization, surrounding turbidity levels were monitored and found to be low. After eight months of dormancy, the system was reactivated with no signs of biofouling of the pipe, but agitation of the surrounding trench was necessary to achieve full trench width since cementation of the overlaying bed occurred. As suggested by Weisman et al. (1987), more frequent fluidization would avoid the cementation problem. The Lake La Vista fluidization system proved that fluidization offers a permanent channel maintenance method.

1.4 Objective and Scope

The primary objective of this experimental study is to examine the effect of hole spacing on the fluidization process under the varied bed conditions encountered in the coastal environment. Hole spacing, sand bed depth, and bed material are varied to create sixteen unique fluidization pipe/bed condition configurations. In addition to the hole spacing examination, the effect of varied bed condition for a constant hole spacing is examined. By using the apparatus of Roberts et al. (1986), the current research specifically examines the following:

- Effects of hole spacing on initiation of fluidization flow rate, internal pipe pressure, and excess hydraulic head distribution for consistent bed conditions.

- Effects of hole spacing on minimum full-fluidization flow rate and internal pipe pressure for consistent bed conditions.

- Effects of hole spacing on minimum full-fluidization final trench geometry, flow rate, and internal pipe pressure for consistent bed conditions.
• Effects of bed depth and sand size on initiation of fluidization flow rate, internal pipe pressure, and excess hydraulic head distribution for consistent pipe configurations.

• Effects of bed depth and sand size on minimum full-fluidization flow rate and internal pipe pressure for consistent pipe configurations.

• Effects of bed depth and sand size on final trench geometry, flow rate, and internal pipe pressure for consistent pipe configurations.

• Monitoring of flow rate and internal pipe pressure to evaluate minimum hydraulic system performance standards for varied hole spacing and expected site conditions.

• Data and design recommendations for expected bed and supporting equipment conditions.

Optimum design hole spacing is expected to be site specific on such factors as bed material, bed depth, and desired channel width. The data provided in this study is intended to facilitate hole space selection for expected site conditions. The necessary performance capacity of the fluidization pipe and its supporting equipment may then be evaluated and incorporated into the final design of a fluidization system for sand management in the coastal environment.
2.0 METHOD OF INVESTIGATION

This study consists of full-scale modeling of expected prototype fluidization systems for sand management of inlets and harbors. Review of the experimental equipment, test preparations and procedures, and summary of testing program briefly offers the reader a general overview of the equipment and methodology of this study.

2.1 Experimental System

The two-dimensional experimental equipment utilized in the present study was designed and built as stated by Roberts et al. (1986). Clifford et al. (1989) and Ledwith et al. (1990) also used this system. The experimental equipment can be divided into four systems: fluidization tank, hydraulic support, slurry removal, and data acquisition. A detailed description, for construction purposes, is not warranted; therefore, only a brief overview for operational understanding is offered. See Roberts et al. (1986) for more detailed description of the experimental equipment.

The sand bed system is contained in the fluidization tank, Figure 2.1. This fluidization tank, encased in a square steel tube box frame, is made primarily of plate steel with internal dimensions of 121.92 cm (48 in) vertical height, 365.76 cm (144 in) horizontal width, and 30.48 cm (12 in) horizontal depth. A steel plate, comprising most of the back wall, is removable to ease maintenance and repair. A large portion of the front panel is constructed of 1.91 cm (3/4 in) tempered glass plate to facilitate visual observation of the fluidization process from initiation of fluidization to final trench formation.

The hydraulic system consists mainly of the fluidization pipe and the supporting equipment to supply the pipe with recirculated water. The fluidization pipe is interchangeable and placed parallel to the short axis of the tank, midpoint along the long axis and 45.7 cm (18 in) along the medium axis from the floor of the tank, Figure 2.2. Following an upstream path, review of the hardware supplying the fluidization pipe is presented as follows: At the same elevation and immediately outside
the fluidization pipe are bleedable taps feeding a mercury manometer that monitors the internal fluidization pipe pressure. A 1.27 cm (1/2 in) needle valve regulates flow rate through the fluidization pipe. A 2237 Watt (3 hp) centrifugal pump supplies the hydraulic system with mechanical energy. This particular pump is oversized, and a wastegate is used to reduce heating of the pump and to bleed air from the system. A settling tank supplies the pump with intake head that can be easily monitored for consistency. The settling tank receives overflow from the fluidization tank. This overflow is regulated by an adjustable weir on the outfall chute that maintains constant water surface elevation overlying the sand bed. Flow rate through the fluidization pipe is calculated by timed volumetric flows into graduated containers during steady state conditions, Figure 2.3.

The slurry removal system is essentially a recirculating siphoning system that removes the bed material from the fluidized zone, Figure 2.4. Once the bed is fully fluidized, siphoning of the slurry into an external storage facility simulates the various natural sediment transportation mechanisms that may be utilized in a prototype system. Additional water, equal in volume to the removed slurry solids and any retained pore water, must be added to keep the hydraulic conditions consistent.

The data acquisition system monitors the excess hydraulic head distribution within the sand bed. The distribution is inferred from 72 of a possible 135 distinct pressure taps located across the back plate on one side of the fluidization pipe, Figure 2.5. Symmetry across a vertical plane dividing the length of the fluidization pipe is assumed. Each tap is hydraulically connected to a single pressure transducer through a cyclic switching and valving controller. The pressure transducer modifies a distinct voltage from a voltage supply, see Figure 2.6. This modified voltage is easily read from a digital multimeter and converted into pressure or head. Excess head distribution contour plots are created by a three-dimensional plotting package. The excess hydraulic head contours allow determination of the vertical pressure gradient and flow pattern within the sand bed just prior to initiation of fluidization.
2.2 Test Preparations and Procedures

A detailed review of the testing preparations and procedures is given, and solutions to typically encountered problems are additionally offered below. The test preparations are presented separately for each system. Sand bed system preparation consists of the following:

• With the fluidization tank empty of both sand and water, attach the desired fluidization pipe.

• Fill the fluidization tank with room temperature water that is to a level higher than the sand. The temperature constraint of this step eliminates dissolved oxygen that comes out of solution of water placed at typical tap temperatures. If low temperature water is used, the sand bed reaches a less than fully saturated state.

• Slowly pour the sand through the depth of water. This step allows entrained air to be stripped during settling of the sand. Rake at small lifts along the length of the bed to release any additional air that may be trapped.

• Dynamically compact the sand, in small lifts, by driving a tapered-end rod until it "walks out" of the bed as would a sheepsfoot roller. Use of a concrete vibrator allows quick compaction. Care must be taken in the area of the fluidization pipe to minimize clogging of the pipe by the entrance of sand through the orifices.

• Repeat the previous two steps until the desired bed depth is met. At this depth drain the overlying water to approximately one-half inch above the sand surface. This small layer of water behaves as a water level to ease finish grading of the sand surface.
• Adjust the overflow weir to the correct final overlying water level and fill the tank.

Hydraulic system preparation consists of the following:

• Fill the settling tank to the desired level with water equal to the sand bed temperature. This precaution minimizes the amount of oxygen introduced to the bed during pre-fluidization flows.

• Power the pump and open the wastegate to allow any air within the pump to be released before entering the fluidization pipe.

• Slowly open the needle valve to allow a pre-initiation of fluidization flow rate to pass through the fluidization pipe.

• Bleed the internal pipe pressure manometer and associated taps on the pipe.

• If significant particle breakdown occurs during the bed placement, allow the pre-initiation of fluidization flow rate to continue until all cloudy water containing suspended fines flows from the bed. Replace the cloudy overlying water with clean water. This step keeps the overlying water clear during testing allowing visual observation of the sand bed, fluidized zone surface, and the final trench geometry through the tank’s glass face.

The slurry removal system preparation consists of the construction of the siphoning apparatus as shown in Figure 2.4. The preparation procedure is highly dependent on available equipment. Details of system preparation have no bearing on the testing method and no specific procedure is offered. Data acquisition system preparation consists of the following:

• Establish a water column to supply the fluid switching valves with the proper balancing pressure for the particular valving system being used.
• Bleed all taps, lines, and switches supplying the single pressure transducer. Creation of a vacuum greatly speeds bleeding the lines.

• Bleed the pressure transducer for accurate readings.

• With no flow through the experimental system, monitor the pressure transducer readings for all taps. Any deviation indicates continued presence of air within the data acquisition system, and re-bleeding is necessary. Process the pressure transducer reading to ensure agreement with fluidization tank water level.

The testing procedure applies only to the scope of this project. The testing procedure consists of the following:

• Ensure all water levels are correct.

• Power the pump and allow some by-pass through the wastegate to self-cool the pump.

• Slowly open the needle valve to allow flow through the fluidization pipe at a pre-initiation of fluidization flow rate. Note that increases in flow rate must be gradual to avoid significant pressure waves that may rupture the sand bed resulting in a local premature initiation condition.

• Adjust the overflow weir to maintain the desired water level within the fluidization tank.

• Allow the entire system to reach steady state.

• At steady state, record all tap readings for the excess head distribution, volumetric flow rate at the overflow wier, and the internal pipe pressure manometer deflections.
• Repeat the previous four steps until initiation of fluidization occurs. Initiation of fluidization is indicated by a permanent drop in excess head within the sand bed and vertical expansion of the bed, Figure 1.2 (c).

• Trace and label the sand bed surface profile on the tempered glass tank facing.

• Increase the flow rate and allow the system to reach steady state. At steady state, record only the flow rate and the internal pipe pressure manometer deflections. Monitoring of the excess head distribution during fluidization flow rates is not within the scope of this study.

• In addition to the above data collection, trace and label significant changes in the cross-section of the fluidized zone.

• Continue the previous two steps until the minimum full-fluidization condition is reached. Minimum full-fluidization can be defined as that condition where the entire fluidized region first behaves as a viscous fluid in that no solid or near solid areas exist.

• At minimum full-fluidization, siphon the slurry from the fluidized region with the slurry removal apparatus. Replace the volume of water lost to keep hydraulic conditions consistent. The bed surrounding the fluidized zone begins to slope into the slurry until the submerged angle of repose is met, Figure 1.2 (d).

• Continue slurry removal until the final trench geometry is established, Figure 1.2 (e). Trace this final trench geometry and record flow rate and internal pipe pressure.

These testing preparations and procedures closely imitate prototype conditions. The method allows concise prediction and reproduction of prototype performance under easily variable pipe and bed conditions. The primary results include pertinent flow
rates, pipe pressures, and resulting trench geometry.

2.3 Summary of Tests

Four fluidization pipe configurations were evaluated under four sand bed configurations. All fluidization pipes were constructed of 5.08 cm (2 in) schedule 80 PVC and employed horizontally and symmetrically opposed 0.318 cm (1/8 in) holes. Varied hole spacings of 2.54 cm (1 in), 5.08 cm (2 in), 7.62 cm (3 in), and 10.16 cm (4 in) constituted the difference in pipe configuration. Each pipe configuration was tested and evaluated in fine uniform sand ($d_{50} = 0.16$ mm) and coarse uniform sand ($d_{50} = 0.45$ mm) of 42.0 cm (16.5 in) and 25.4 cm (10 in) bed depths. The four pipe samples, two bed depths, and two sand sizes results in sixteen unique tests. The primary objective of the testing program is to quantify the effect of varied hole spacing on the fluidization process under different bed depth and sand size conditions. In addition, the effect of the different bed conditions for constant pipe configuration is examined.

Each test included the monitoring of flow rate, internal fluidization pipe pressure, and excess head distribution within the sand bed during pre-initiation of fluidization flow rates. During post-initiation conditions flow rate, internal fluidization pipe pressure, and significant geometric changes in the fluidized region were monitored. At minimum full-fluidization and after slurry removal flow rate, internal fluidization pipe pressure, and final trench geometry were monitored. From the above data collection, hydraulic performance can be predicted for prototype systems. Record of all data collection events for all tests are shown in Table 1.1.
3.0 EXPERIMENTAL RESULTS

Evaluation of the effect of varied hole spacing on the fluidization process is made through the analysis of four parameters: excess hydraulic head distribution within the sand bed, flow rate, internal fluidization pipe pressure, and final trench geometry. Although these parameters are closely interrelated, comparison of varied hole spacing conditions is made independently for each of the four parameters. The excess hydraulic head distribution in the sand bed surrounding the fluidization pipe is obtained and evaluated just prior to the initiation of fluidization stage. Both flow rate and internal fluidization pipe pressure are monitored at all stages of the fluidization process, but only the initiation of fluidization and minimum full-fluidization stages are evaluated and compared. The post-slurry removal final trench geometry is examined at the minimum full-fluidization flow rate. Evaluation of the minimum full-fluidization condition is highly subjective. For each parameter, the observations of the effect of hole spacing for constant bed conditions, bed depth and sand size, are first addressed. Then, the effect of varied bed conditions, bed depth and sand size, are observed.

3.1 Excess Hydraulic Head Distribution

The excess hydraulic head distribution is defined as the distribution of piezometric head above the static no-flow condition. The two-dimensional excess hydraulic head distribution within the sand bed surrounding the fluidization pipe is monitored by the procedure outlined in Chapter 2.2 using the data acquisition system described in Chapter 2.1. The contour plots, Figures 3.1 through 3.4, show the excess hydraulic head distribution on the back plate of the fluidization tank. The assumption that the plots are representative of the distribution along the entire length of the fluidization pipe is made. Table 3.1 summarizes the pre-initiation of fluidization flow rate and corresponding excess hydraulic head at the number fourteen pressure tap which is closest to the fluidization pipe, as shown in Figure 2.5. In this study, the distribution is monitored for pre-initiation of fluidization conditions to examine the effect of hole spacing on the flow pattern within the sand bed and the resulting pressure gradient. The excess hydraulic head distribution from initiation of fluidization through full-
fluidization to final trench formation has been treated in detail by Clifford et al. (1989) and is not examined in this study.

The excess head distribution plots, shown in Figures 3.1 through 3.4, present equipotential lines of constant head approaching near elliptical shape surrounding the fluidization pipe during pre-initiation of fluidization conditions. This near elliptical shape diminishes at greater distances from the pipe since the fluidization tank provides boundaries to the seepage flow. For prototype conditions, proximal boundaries are unlikely, resulting in near elliptical equipotential shape at greater distances.

Again, the primary objective of this study is to qualify the effect of hole spacing on the fluidization process for varied bed conditions. Additionally, the varied bed condition effects are examined for constant hole spacing.

3.1.1 Effects of Hole Spacing on Excess Hydraulic Head Distribution

Upon detailed examination and comparison of Figures 3.1 through 3.4 and Table 3.1, observations are made of the effect of hole spacing on the excess hydraulic head distribution as follows:

- Hole spacing has no apparent effect on the vertical pressure head gradient that initiates fluidization over the fluidization pipe. For example, the vertical excess head gradients over the fluidization pipe in the 42.0 cm (16.5 in) of fine sand bed shown in Figures 3.1 (a) through (d) are 0.88 for the 2.54 cm (1 in) hole spacing at a 51.0 cc/s flow rate, 0.84 for the 5.05 cm (2 in) hole spacing at a 44.6 cc/s flow rate, 1.00 for the 7.62 cm (3 in) hole spacing at a 52.8 cc/s flow rate, and 0.88 for the 10.16 cm (4 in) hole spacing at a 51.4 cc/s flow rate. The small variations are more a result of flow rate than hole spacing. All vertical excess head gradients above the fluidization pipe are consistent for all other bed conditions.
• Increased hole spacing, thus decreased total orifice area and increased jet velocity, increases the excess head immediately outside the fluidization pipe, yet this influence is quickly diminished as the flow field emanating from each hole disperses. This observation is apparent upon inspection of Table 3.1 where the excess head at the number fourteen pressure tap is fairly constant for the range in hole spacings.

• Increased hole spacing, thus increased jet velocity, only slightly elongates the equipotential contours in the area immediately surrounding the fluidization pipe. This effect is more pronounced for shallower bed depths due to shorter flow path lengths. The elliptical excess head contour lines in the deeper bed of coarse sand shown in Figures 3.3 (a) through (d) change little with increasing hole spacing. Yet, the elliptical excess head contour lines in the shallower bed depth of coarse sand, shown in Figures 3.4 (a) through (d), tend to elongate with increased hole spacing.

From the above observations, the effect of hole spacing is seen as negligible to the excess hydraulic head distribution in the sand bed for pre-initiation of fluidization.

3.1.2 Effects of Bed Condition on Excess Hydraulic Head Distribution

Several observations of the effect of bed condition, bed depth and sand size, on the excess hydraulic head distribution can be made from Figures 3.1 through 3.4 and Table 3.1 as follows:

• Shallow bed depths appear to reach initiation of fluidization at lower vertical pressure head gradients for both fine and coarse sands. The average initiation of fluidization vertical pressure head gradient is 0.90 for the 42.0 cm (16.5 cm) bed depth of fine sand, Figures 3.1 (a) through (d). The average initiation of fluidization vertical pressure head gradient is 0.70 for the 25.4 cm (10.0 in) bed depth of fine sand, Figures 3.2 (a) through (d). This difference in initiation pressure head gradient is credited to the sensitivity of the needle valve controlling the flow rate.
• For the sands used in the present study, the finer sand reaches initiation of fluidization at lower vertical pressure head gradients. The average initiation of fluidization vertical pressure head gradient is 0.80 for the fine sands, Figures 3.1 (a) through (d) and 3.2 (a) through (d). The average initiation of fluidization vertical pressure head gradient is 0.97 for the coarse sands, Figures 3.3 (a) through (d) and 3.4 (a) through (d).

• The equipotential contour lines are more elliptic for the coarse sand indicating greater anisotropic permeability. Comparisons of Figures 3.2 (b) and 3.4 (b) show broader and flatter contour lines of constant excess head in the coarse sand.

• Local curvature and discontinuity of the equipotential lines indicates nonhomogeneity in permeability due to nonuniform compaction of the sand bed during test preparation. Figures 3.1 (d), 3.3 (c), and 3.3 (d) show local discontinuities, but these imperfections fluctuate in direction, thus discounting a data error.

From the above observations, the bed condition proves to influence the excess hydraulic head distribution more than fluidization pipe hole spacing for pre-initiation of fluidization.

3.2 Flow Rate

Flow rate was monitored at all stages of the fluidization process by the procedure outline in Chapter 2.2 using the overflow weir described in Chapter 2.1. The flow rate parameter is of primary importance since the necessary flow rate capacity of piping and pumping equipment is needed for a prototype system design. Initiation of fluidization and minimum full-fluidization flow rates obtained in the present study are presented in Table 3.2. The effect of hole spacing on initiation of fluidization and minimum full-fluidization flow rates is discussed. In addition, the effect of bed condition, bed depth and sand size, is addressed for initiation of fluidization and minimum full-fluidization flow rates.
3.2.1 Effects of Hole Spacing on Flow Rate

From the data presented in Table 3.2, the following observations of the effect of hole spacing on initiation of fluidization and minimum full-fluidization flow rates are made as follows:

- The 5.08 cm (2 in) hole spacing induces initiation of fluidization at lower flow rates for both bed depths of the fine sand.
- The 5.08 cm (2 in) hole spacing reaches full-fluidization at lower flow rates for both bed depths of the fine sand.
- The 2.54 cm (1 in) hole spacing induces initiation of fluidization at lower flow rates for both bed depths of the coarse sand.
- The 2.54 cm (1 in) hole spacing reaches full-fluidization at lower flow rates for both bed depths of coarse sand.
- No consistent hole spacing/flow rate trend exists for all bed conditions at initiation of fluidization and minimum full-fluidization conditions, noting that the latter condition is subject to interpretation by the observer.

From the above observations, greater hole spacings appear to be inefficient for both initiation of fluidization and full-fluidization. An optimum inverse hole spacing/sand size relation may exist for the flow rate parameter.

3.2.2 Effects of Bed Condition on Flow Rate

Again, from the data presented in Table 3.2, the effects of bed condition on initiation of fluidization and minimum full-fluidization flow rates are made as follows:

- The finer sand consistently reaches initiation of fluidization condition at lower flow rates for both bed depths.
• The finer sand consistently achieves minimum full-fluidization at lower flow rates for both bed depths.

• The shallower bed depths reach the intitiation of fluidization at lower flow rates for both sand sizes.

• The shallower bed depths reach the minimum full-fluidization at lower flow rates for both sand sizes.

The relative ease of fluidization of the fine sand is significant in the coastal environment where fine sands are prevalent. Flow rate per length of fluidization pipe is low, thus requiring low flow rate capacity piping and pumping equipment for prototype systems.

3.3 Internal Fluidization Pipe Pressure

The internal fluidization pipe pressure is monitored by the procedure outlined in Chapter 2.2 using the mercury manometer described in Chapter 2.1. The pipe pressure is highly dependent on flow rate and the total head grade line along any flow path from the pump to the sand bed surface. Head losses encountered from flow emanating from the fluidization pipe orifices and from flow through the bed in either a fluidized or nonfluidized state dominate the total head grade line. Variation in hole spacing, thus variation in orifice number per length of fluidization pipe, effects the influence that exit losses have. Bed depth and sand size affect the losses once flow leaves the fluidization pipe. Comparison of the internal pipe pressure versus flow rate at all stages of fluidization is presented in Figures 3.5 (a) through (d) and 3.6 (a) through (d). Figures 3.5 (a) through (d) show varied hole spacing for each bed condition, bed depth and sand size, tested. Figures 3.6 (a) through (d) show varied bed condition, bed depth and sand size, for each hole spacing. Summary of the internal fluidization pipe pressure just prior to initiation of fluidization and minimum full fluidization is shown in Table 3.3. Both the effects of varied hole spacing and bed condition are addressed.
3.3.1 Effects of Hole Spacing on Internal Fluidization Pipe Pressure

From examination of the internal pipe pressure versus flow rate comparisons of Figures 3.5 (a) through 3.5 (d), Figures 3.6 (a) through 3.6 (d), and Table 3.3, several observations of the effect of hole spacing on the internal pipe pressure are made as follows:

- Greater hole spacing, thus lesser orifice numbers per length of pipe, results in a steeper pipe pressure versus flow rate relationship for pre-initiation of fluidization conditions. For the bed conditions shown in Figures 3.5 (a) through (d), larger hole spacings generally yield higher pipe pressures at given pre-initiation of fluidization flow rates, because of more flow per hole.

- Greater hole spacing, thus lesser orifice number per length of pipe, results in a steeper pipe pressure versus flow rate relationship for full-fluidization conditions. For all the bed conditions shown in Figures 3.5 (a) through (d), larger hole spacing generally yield higher pipe pressures at post-initiation of fluidization flow rates, because of more flow per hole.

- For most bed conditions, pipe pressure drops momentarily at initiation of fluidization until flow rate is further increased as seen in Figures 3.5 and 3.6.

From the Figures 3.5 (a) through 3.5 (d), Figures 3.6 (a) through 3.6 (d), and Table 3.3, it can be seen that smaller hole spacing, thus greater orifice area per length of pipe, provides fluidization at much lower pressure requirements for all bed conditions.

3.3.2 Effects of Bed Condition on Internal Fluidization Pipe Pressure

From examination of the internal pipe pressure versus flow rate comparisons of Figures 3.5 (a) through (d), Figures 3.6 (a) through (d), and Table 3.3, several observations of the effect of bed condition, bed depth and sand size, are made as follows:
• Pipe pressure momentarily drops at initiation of fluidization for all bed conditions except the 5.08 cm (2 in), 7.62 cm (3 in), and 10.16 cm (4 in) hole spacings in coarse sand of 42.0 cm (16.5 in) bed depth where both high flow rates and corresponding pipe pressures are necessary to induce initiation of fluidization, Figure 3.5 (c).

• For the 2.54 cm (1 in) hole spacing in both bed depths of fine sand, the maximum internal pipe pressure is reached at the initiation of fluidization condition indicating that the head loss through the fixed bed dominates the hydraulic grade line at those flow conditions, Table 3.3.

• As hole spacing is increased the internal pipe pressure versus flow rate relationship is more predictable and dependent on head loss through the orifices regardless of bed condition. Comparison of Figures 3.6 (a) through (d) show less variation is the relationships at higher hole spacings.

With the above observations and associated figures, it can be seen that the fine sand is fluidized with significantly lower pipe pressures regardless of hole spacing. For the fine sand, bed depth has a lesser effect on the pipe pressure needed to provide full-fluidization flow rates. For the coarse sand, bed depth is a significant factor.

3.4 Final Trench Geometry at Minimum Full-Fluidization Flow Rates

The ultimate desired effect of fluidization, applied in the coastal environment, is the maintenance of navigation channels by direct formation of a channel or by sand bypassing. This can occur by trench formation from slurry removal of the fluidized zone. In the present study, slurry removal proceeded as indicated in Chapter 2.2 using the slurry removal system described in Chapter 2.1. Upon complete slurry removal, the resulting trench geometry is reached reproducing a prototype system subjected to any of the sediment transportation mechanisms discussed in Chapter 1.1.
Final trench geometry is controlled by the bottom width produced by the erosive power of the jets emanating from the fluidization pipe orifices. From this bottom width, the trench widens to the top width at a rate dictated by the submerged angle of repose of the sand bed. Thus, the entire trench geometry is governed by three parameters: the erosive power of the jets emanating from the fluidization pipe, the submerged angle of repose of the sand bed, and the bed depth overlying the fluidization pipe.

Comparison of the jet velocity versus bottom width is presented in Figure 3.7 and Table 3.4. The flow rate versus bottom width data for 5.08 cm (2 in) hole spacing and comparison of data from Ledwith et al. (1990) is shown in Figures 3.8 (a) and 3.8 (b). The flow rate versus top width data from 5.08 cm (2 in) hole spacing in fine sand and comparison to data of Ledwith et al. (1990) and Clifford et al. (1989) is presented in Figures 3.9 (a) and 3.9 (b). The flow rate versus top width data for 5.08 cm (2 in) hole spacing in coarse sand and data from Ledwith et al. (1990) is presented in Figure 3.9 (c). A summary of the bottom width and minimum full-fluidization flow rate data is made in Table 3.5. From the data presented in the figures and tables, the effects of hole spacing and bed condition, bed depth and sand size, are observed and presented below.

3.4.1 Effects of Hole Spacing on Final Trench Geometry

Upon examination of the figures and tables described above, several observations are made of the effect of hole spacing on final trench geometry, formed at minimum full-fluidization flow rates, as follows:

- From continuity, the jet velocity is proportional to hole spacing, since the number of orifices per length of fluidization pipe is reduced for increased hole spacing.

- The jet velocity versus bottom width relationship is linear as stated by Clifford et al. (1989) and verified by Ledwith et al. (1990). For the jet velocity versus bottom width relationships shown in Figure 3.7, linear best
fit interpretation of the data for each bed condition yields little error.

It can be seen from the above observations and data presented, that increases in hole spacing yields significant increases in final post slurry removal trench geometry at minimum full-fluidization flow rates.

3.4.2 Effects of Bed Condition on Final Trench Geometry

Upon examination of the figures and tables described above, several observations are made of the effect of bed configuration on final trench geometry, formed at minimum full-fluidization flow rates, as follows:

- Sand size affects the erosive power of the jets emanating from the fluidization pipe. The larger sand is more resistant to erosion; thus, decreased bottom width result from corresponding jet velocities. Extrapolation of the linear best fit interpretation of the data for the fine sand presented in Figure 3.7 shows that larger bottom widths result from corresponding jet velocities than for the medium coarse sand.

- Bed depth has no effect on the linear jet velocity versus bottom width relationship in fine sand. The linear best fit interpretation of the data for both bed depths of fine sand are coincident, Figure 3.7.

- Increased bed depth reduces the linear rate of the jet velocity versus bottom width relationship in the coarse sand. The linear best fit interpretation for each bed depth of coarse sand varies in slope, Figure 3.7.

- Bottom width data of Ledwith et al. (1990) for the fine and coarse sands is verified. Data presented in Figure 3.8 (a) shows agreement with the bottom width versus flow rate relationship.

- Compared to the findings of Ledwith et al. (1990), bottom width data for the coarse sand presented in Figure 3.8 (b) shows agreement for the
shallow bed depth and little agreement for the deeper bed depth.

- The top width versus flow rate relationship for both sands verifies the findings of Clifford et al. (1989) and Ledwith et al. (1990) at flow rates below the "threshold" condition described by Clifford et al. (1989), Figures 3.9 (a) through (c).

From the above observations and data, the effect of bed condition, bed depth and sand size, proves significant on the final post slurry removal trench geometry formed at minimum full-fluidization. Further, final trench geometry in fine sands appears to be accurately predictable.
4.0 CONCLUSIONS AND RECOMMENDATIONS

The full-scale modeling in the present study identifies the effects of hole spacing on the fluidization process in the coastal environment. Since the varied hole spacings are evaluated under different bed conditions, bed depth and sand size, the effects of bed condition are additionally evaluated. The effects of hole spacing and bed condition are quantified through four parameters: excess hydraulic head distribution, flow rate, pipe pressure, and final trench geometry. The latter three are essential parameters in fluidization system design. Since the majority of prototype operation is at full-fluidization conditions, a summary of the three essential parameters is presented in Table 4.1. Using all the data obtained and the observations of Chapter 3.0, conclusions of this experimental study, design recommendations, and recommendations for future work are expressed below.

4.1 Conclusions

The variation of hole spacing and bed condition shows strong interrelation among the significant parameters monitored in the present study. Several conclusions of the effect of hole spacing and bed condition on the fluidization process in the coastal environment are made as follows:

- The effect of hole spacing on initiation of fluidization and minimum full-fluidization flow rates is minimal.

- In larger sands, higher flow rates are necessary for initiation of fluidization and minimum full-fluidization.

- In deeper bed depths, higher flow rates are necessary for initiation of fluidization and minimum full-fluidization.

- Increased hole spacing increases the internal pipe pressure needed to provide initiation of fluidization and minimum full-fluidization flow rates.
Increased hole spacing, thus decreased orifice number per length of fluidization pipe, increases jet velocities providing wider trench widths.

4.2 Design Recommendations

In hole space selection, the designer must first determine the project objective. If only a narrow fluidization trench is necessary to maintain the targeted channel, a single fluidization pipe may suffice, and internal pipe pressure may dominate design considerations dictating smaller hole spacing. If a wide channel is to be maintained, series of parallel fluidization pipes may be necessary, and greater trench widths may dominate design considerations dictating greater hole spacing. Regardless of design objectives, two hole spacing conclusions can be made as follows:

- In terms of flow rate, pipe pressure, and final trench geometry, the 5.08 cm (2 in) hole spacing is optimal in fine sands.

- In terms of flow rate, pipe pressure, and final trench geometry, the 2.54 cm (1 in) hole spacing is optimal in coarse sands.

Long term performance of fluidization systems is unknown, yet several advantages of the smaller hole spacings add endurance credibility to the smaller hole spacings. Firstly, if biofouling and clogging of the fluidization pipe occurs, smaller hole spacings offer redundancy. Secondly, fluidization systems with smaller hole spacings operate at lower pipe pressures, thus reducing the impact of cavitation at the orifice. Thirdly, smaller hole spacing may facilitate easier sediment transportation along the fluidization pipe during gravitational or pumping slurry flows.

The data supplied in this study, provides the designer with sufficient information for hole space selection. No one particular hole spacing is optimal under the varied conditions a prototype system would endure, but the hole space selection should be controlled by expected bed conditions and desired channel width.
4.3 Recommendations for Future Work

Laboratory and field studies have proven fluidization to be an effective tool for sand management in the coastal environment. Extensive laboratory data exists to aid in the design of prototype systems. Yet, long term performance concerns suggest several recommendations for future work as follows:

- Examination of the fluidization process under rapid flow rate increases.

- Examination of the fluidization process in a range of bed materials that represent the variety of sediments encountered in the coastal environment.

- Examination of sediment transportation rates along fluidization pipes placed at varied slopes, subject to varied pumping drawdown, and sheared by varied overlaying tidal flow velocities.

- Examination of the effects of shell debris on final trench geometry.

- Examination of the effects of parallel pipe placement on flow rate, pipe pressure, and final trench geometry.

- Examination of optimal pipe material and the effects of long term pressure differentials on the orifice material.

- Examination of pipe configuration and bed conditions to the above concerns.
TABLES
Table 2.1: Summary of Tests

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<tr>
<th>Hole Spacing (in)</th>
<th>Sand Size (d\textsubscript{50}, mm)</th>
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### Table 3.1: Flow Rate and Sample Tap Data at Pre-Initiation of Fluidization

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Table 3.2: Flow Rate at Pre-Initiation and Minimum Full-Fluidization

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Table 3.3: Internal Pipe Pressure at Pre-Initiation and Minimum Full-Fluidization

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Table 3.4: Jet Velocity and Bottom Width Minimum at Full-Fluidization PostSlurry Removal

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Table 3.5: Trench Geometry at Minimum Full-Fluidization Post Slurry Removal

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Table 4.1: Summary of the Most Significant Parameters at Minimum Full-Fluidization

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Figure 1.1 Two-Dimensional Fluidization in the Coastal Environment. From Roberts et al. (1986).
Figure 1.2 Five Stages of Fluidization in the Coastal Environment.

From Clifford et al. (1989).
Figure 2.1 Sketch of Two-Dimensional Fluidization Tank.
Modified from Roberts et al. (1986).
Figure 2.2 Fluidization Pipe Detail with 5.08 cm (2 in) Hole Spacing. Modified from Roberts et al. (1986).
Figure 2.3 Sketch of Recirculating Hydraulic System. Modified from Roberts et al. (1986).
Figure 2.4 Sketch of Slurry Removal System.
Modified from Clifford et al. (1989).
Figure 2.5 Schematic of Pressure Tap Locations.
From Roberts et al. (1986).
Figure 2.6 Schematic of Data Acquisition System.
Modified from Roberts et al. (1986).
Figure 3.1 (a) Excess Hydraulic Head Distribution in Fine Sand, Bed Depth = 42.0 cm, and 2.54 cm (1 in) Hole Spacing.

Figure 3.1 (b) Excess Hydraulic Head Distribution in Fine Sand, Bed Depth = 42.0 cm, and 5.08 cm (2 in) Hole Spacing.
Figure 3.1 (c) Excess Hydraulic Head Distribution in Fine Sand, Bed Depth = 42.0 cm, and 7.62 cm (3 in) Hole Spacing.

Figure 3.1 (d) Excess Hydraulic Head Distribution in Fine Sand, Bed Depth = 42.0 cm, and 10.16 cm (4 in) Hole Spacing.
Figure 3.2 (a) Excess Hydraulic Head Distribution in Fine Sand, Bed Depth = 25.4 cm, and 2.54 cm (1 in) Hole Spacing.

Figure 3.2 (b) Excess Hydraulic Head Distribution in Fine Sand, Bed Depth = 25.4 cm, and 5.08 cm (2 in) Hole Spacing.
Figure 3.2 (c) Excess Hydraulic Head Distribution in Fine Sand, Bed Depth = 25.4 cm, and 7.62 cm (3 in) Hole Spacing.

Figure 3.2 (d) Excess Hydraulic Head Distribution in Fine Sand, Bed Depth = 25.4 cm, and 10.16 cm (4 in) Hole Spacing.
Figure 3.3 (a) Excess Hydraulic Head Distribution in Coarse Sand, Bed Depth = 42.0 cm, and 2.54 cm (1 in) Hole Spacing.

Figure 3.3 (b) Excess Hydraulic Head Distribution in Coarse Sand, Bed Depth = 42.0 cm, and 5.08 cm (2 in) Hole Spacing.
Figure 3.3 (c) Excess Hydraulic Head Distribution in Coarse Sand, Bed Depth = 42.0 cm, and 7.62 cm (3 in) Hole Spacing.

Figure 3.3 (d) Excess Hydraulic Head Distribution in Coarse Sand, Bed Depth = 42.0 cm, and 10.16 cm (4 in) Hole Spacing.
Figure 3.4 (a) Excess Hydraulic Head Distribution in Coarse Sand, Bed Depth = 25.4 cm, and 2.54 cm (1 in) Hole Spacing.

Figure 3.4 (b) Excess Hydraulic Head Distribution in Coarse Sand, Bed Depth = 25.4 cm, and 2.54 cm (2 in) Hole Spacing.
Figure 3.4 (c) Excess Hydraulic Head Distribution in Coarse Sand, Bed Depth = 25.4 cm, and 2.54 cm (3 in) Hole Spacing.

Figure 3.4 (d) Excess Hydraulic Head Distribution in Coarse Sand, Bed Depth = 25.4 cm, and 10.16 cm (4 in) Hole Spacing.
PIPE PRESSURE V. FLOW RATE
SAND A  BED DEPTH = 42 cm

Figure 3.5 (a) Internal Fluidization Pipe Pressure Versus Flow Rate for Varied Hole Spacing in Fine Sand of 42.0 cm Bed Depth.
Figure 3.5 (b) Internal Fluidization Pipe Pressure Versus Flow Rate for Varied Hole Spacing in Fine Sand of 25.4 cm Bed Depth.
Figure 3.5 (c) Internal Fluidization Pipe Pressure Versus Flow Rate for Varied Hole Spacing in Coarse Sand of 42.0 cm Bed Depth.
Figure 3.5 (d) Internal Fluidization Pipe Pressure Versus Flow Rate for Varied Hole Spacing in Coarse Sand of 25.4 cm Bed Depth.
PIPE PRESSURE V. FLOW RATE
HOLE SPACING = 1 in

Figure 3.6 (a) Internal Fluidization Pipe Pressure Versus Flow Rate for Varied Bed Conditions with 2.54 cm (1 in) Hole Spacing.
Figure 3.6 (b) Internal Fluidization Pipe Pressure Versus Flow Rate for Varied Bed Conditions with 5.08 cm (2 in) Hole Spacing.
PIPE PRESSURE V. FLOW RATE
HOLE SPACING = 3 in

Figure 3.6 (c) Internal Fluidization Pipe Pressure Versus Flow Rate for Varied Bed Conditions with 7.62 cm (3 in) Hole Spacing.
Figure 3.6 (d) Internal Fluidization Pipe Pressure Versus Flow Rate for Varied Bed Conditions with 10.16 cm (4 in) Hole Spacing.
Figure 3.7 Bottom Width Versus Jet Velocity Relationships Post Slurry Removal for Varied Hole Spacings for All Bed Configurations.
Figure 3.8 (a) Bottom Width Versus Flow Rate Relationships Post Slurry Removal for 5.08 cm (2 in) Hole Spacing in Fine Sand.
Figure 3.8 (b) Bottom Width Versus Flow Rate Relationships Post Slurry Removal for 5.08 cm (2 in) Hole Spacing in Coarse Sand.
TOP WIDTH / FLOW RATE RELATION
SAND A   BED DEPTH = 42.0 cm
POST-SLURRY REMOVAL

Figure 3.9 (a) Top Width Versus Flow Rate Relationship Post Slurry
Removal for 5.08 cm (2 in) Hole Spacing in Fine
Sand of 42.0 cm Bed Depth.
TOP WIDTH / FLOW RATE RELATION
SAND A Bed Depth = 25.4 cm
POST-SLURRY REMOVAL

Figure 3.9 (b) Top Width Versus Flow Rate Relationship Post Slurry Removal for 5.08 cm (2 in) Hole Spacing in Fine Sand of 25.4 cm Bed Depth.
Figure 3.9 (c) Top Width Versus Flow Rate Relationships Post Slurry Removal for 5.08 cm (2 in) Hole Spacing in Coarse Sand of 42.0 cm and 25.4 cm Bed Depths.
REFERENCES


