

The Hydraulic Behavior of Vertical Jet Sediment Bed Fluidization from the Vortex Growth Point of View

M. Arsyad Thaha^{1,*}, Radiana Triatmadja², A. Ildha Dwipuspita¹

¹Civil Engineering, Hasanuddin University, Makassar, 90245, Indonesia
²Civil Engineering, Gadjah Mada University, Yogyakarta, 90245, Indonesia

Abstract Pressurized water flow through small holes in an embedded pipe in the sediment deposit will lead to increased sediment porosity and subsequently producing drag force that causes sediments to be lifted, agitated and expanded until it reaches the phase of incipient fluidization. This mechanism is an important part for the development of fluidization method as a new technique to overcome the water channel sedimentation. Two dimensional experimental works for vertical jet fluidization in unbounded domain of sediment deposit were performed in the laboratory of Gadjah Mada University, Indonesia. The results show that the hydraulic behaviors in all steps of prefluidization toward incipient fluidization can be explained in detail. Criteria to achieve initial fluidization given by a certain value of flow rate and hydraulic head in the fluidizer pipe that produces critical internal vortex. The critical height of vortex (z_c) about $0.5d_b$ where d_b is the thickness of the sediment deposit. Pressure distributions in the sediment bed indicate that approximately 90% of the head loss occurs within 10 cm in front of the jet hole. The hydraulic gradient (d_h/z) for incipient fluidization was found about 1 to 1.2, where the Darcy's law is still valid. The shape of fluidized zone can be clearly identified through measurement of equipotential contour line.

Keywords Hydraulics Behavior, Jet Flow, Sediment Bed, Fluidization

1. Introduction

In the fluidization process of granular sediment, fluid flow through the pores producing drag force acting on the grains of material that works in the direction of flow. Besides, the gravity force of material and buoyancy force also acting together on the materials. When the direction of flow is bottom up, both the drag force and buoyancy will lift the grains upward, while the gravity force will cause the grains move downward. In the conditions of an upward force is less than the downward force, the material will still stay on the bottom. In this case, Darcy's law and Cozeny-Carman equation is applied, where the amount of energy loss is proportional to the flow rate as in [6]. The increase of the supervisory velocity produces a drag force increase to a certain value until achieving a balanced condition in which upward force is equal to the downward force. This condition become the achievement marks of incipient fluidization.

On the basis of unbounded domain deposit, the fluidization becomes more complicated because a part of flow rate passes from reviewed domain. The objectives of this paper are to present the mechanism of fluidization in

each stages of the process from prefluidization to fully fluidization, the internal vortex shape, dimensions and its size development up to critical condition of fluidization, the assesment of prefluidization, initial condition and fully fluidization through equipotential contour map and to present the changes in the pattern of hydraulic gradient from pre to post-fluidization, the understanding of the changes of flow type and limitation of Darcy Law. The illustratif stages of prefluidization to incipient fluidization by a single vertical jet in unbounded domains is shown in Figure 1.

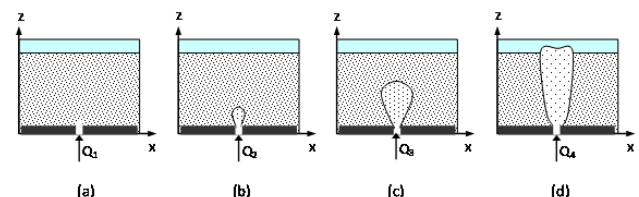


Figure 1. The stages of fluidization process from pre (a) to incipient condition (d)

2. References Review

Vertical jet fluidization has been investigated by several researcher such as Bear in [1]; Lennon et al. in [1], and Widiyanto in [4]. All researchers used requirement of hydraulic head parameter as the achievement criteria of fluidization. The head requirement to achieve initial

* Corresponding author:

athaha_99@yahoo.com (M. Arsyad Thaha)

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condition of fluidization in the common coastal sand characteristics were obtained about unity to the thickness of deposit or written as hydraulic gradient ($d_h/d_L \approx 1$). In the theoretical view, d_h/d_L can be larger than 2 depending on the porosity and mass density of sediment (ε and ρ_s). Thaha in[4] recommends the criteria for incipient fluidization in unlimited domains using Richardson-Zaki correlation (1971) as in[7].

Weisman *et al.* in[10] conducted two-dimensional experiments with serial horizontal jet in a bath size of 365.7 cm x 121.9 cm x 30.4 cm using fine sand with $d_{50} = 0.15$ mm, $\rho_s = 2.67$ t/m³ and $\varepsilon = 0.39$ in order to determine the boundary line between fluidized-unfluidized zone. By using pressure sensors, the distribution of hydraulic head in the sand bed can be measured and mapped. Other findings are about 40% of flow rate exits through the boundary wall from fluidization zone just prior incipient condition and drops to about 5% at the beginning of fluidization. Hydraulic gradient values ranged in initial fluidization condition $d\phi/dy = 1.06$ for $d_b = 25.4$ cm and $d\phi/dy = 1.25$ for $d_b = 45$ cm. This result is slightly larger than the 1D fluidization results that give dh/dy around 1. Lennon and Weisman in[2] conducted a three-dimensional study using finite difference method to determine the need for initial fluidization hydraulic head. By

using diameter and holes space 3.175 mm and 50.8 mm respectively, the simulation results showed that 80% of pressure dissipation occurred within 3 cm in front of the hole. Field application design of fluidization system for channel maintenance of Panoang river estuary in Bantaeng coastline Indonesia as in[3] has been performed based on the formulation of the required hydraulic head and flow rate for fluidization obtained by Thaha as in[4].

3. Research Method

Experimental research was conducted at the Laboratory of Hydraulics and Hydrology in Center Study of Science & Engineering, Gadjah Mada University, Indonesia. Two dimensional experimental study had been carried out in 120 cm x 50 cm x 80 cm sand bath size which were made from transparent acrylic and completed with flow circulation system. Flow rate was measured by flow meter and hydraulic pressure was measured by a manometer bank connected to pressure gauge. The sediment sample using medium sand with $d_{50} = 0.344$ mm, $\rho_s = 3.073$ t/m³ and $\varepsilon = 0.307$. Figure 2 shows the experimental conditions.

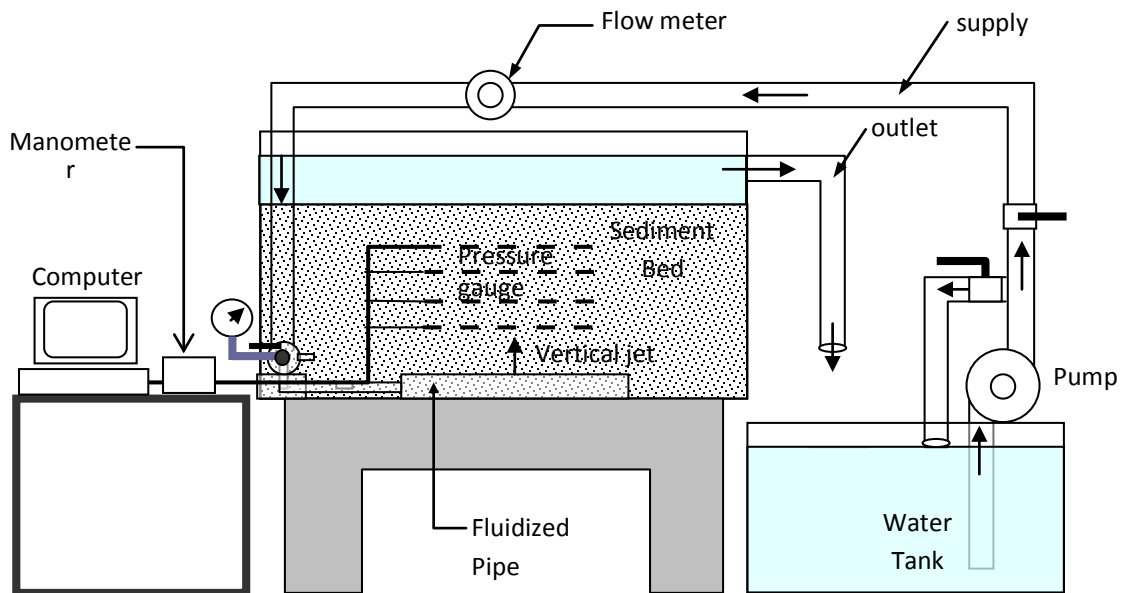


Figure 2. Experimental conditions

4. Results and Discussion

4.1. Initial Fluidization

The detailed process in prefluidization stages is not fully known ahead of this study. Although the mechanism of this prefluidization stage can be explained theoretically by Darcy's law, but there is a vortex and an internal scouring occurred accompanying the process. This phenomenon seems to be an important part of the process and needs to be explained in detail. As the discharge is still relatively low, the scouring process that occurs in the walls of the vortex has not significantly increased the volume of scour. But if the jet flow further increased up to a certain value, then the process of scouring especially on edge vortex (see Figure 3a) began to significantly reduce the thickness of the visible unity of sediment in it.

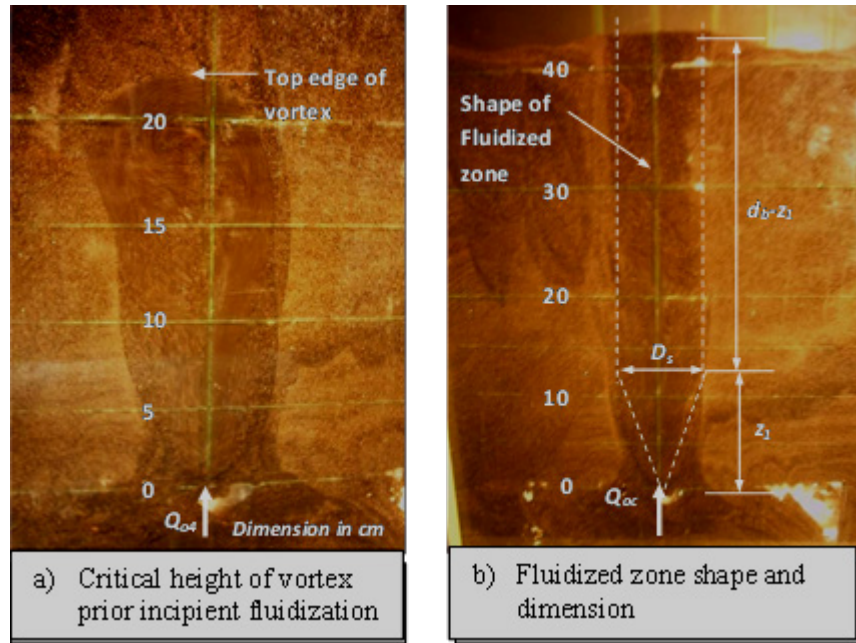


Figure 3. Shapes and sizes of initial to full fluidization condition

Incipient fluidization will occur depending on the rate of scouring by the internal flow velocity. At relatively low flow rate, achieving initial fluidization may take a relatively long time, and vice versa at a relatively high discharge the fluidization will be quickly achieved. Figure 3b shows the geometry of the fluidized zone shortly after the first outburst occurred on the sediment surface marking the achievement of incipient fluidization. Discharge leading to initial fluidization called critical flow rate (Q_{oc}). Figure 3b presents the shape and dimension of fluidized zone for 40 cm deposit thickness which consists of two parts, namely inverted cone-shaped as the bottom part near from hole jet with a diameter and height of each D_s and z_1 and cylindrical shaped at upper part with diameter and height are D_s and $(d_b - z_1)$ respectively. The characteristics of core flow in Figure 3b seems difficult to be described due to the fluctuation in sediment movement, but it can be identified by the shape which is averagely similar to fluidized zone despite the diameter (D_c) is smaller than D_s . In order to accommodate the parameter D_s , z_1 and $(d_b - z_1)$ easily, it is necessary to convert those parameter in the function of sediment thickness (d_b).

4.2. Critical Vortex Dimension

The vortex size in prefluidization stage will be enlarged along with the increasing flow through the jet hole. Figure 4 shows the development graph of vortex height (z_p) until it reaches a critical height (z_c) and finally followed by bursts at the sediment surface as the mark for fully fluidization stage. Six test results at different sediment thickness were described in the relationship of $Q_o - z_p$. The thicker the sediment the greater the flow rate required to produce critical height of vortex. The critical height of vortex will grow itself at a constant flow rate up to bursts occurred at the sediment surface. By calculating the ratio of z_c to d_b on 16 test results,

it is obtained that the incipient fluidization will be achieved in the average ratio of $z_c/d_b = 0.5$.

When z_p is approximate to $0.5d_b$, than the scouring at the top edge of vortex will develop dynamically to increase the vortex height at a constant discharge. The duration of this critical condition until bursts occurred in experimental conditions ranging from 0.5 - 3 minutes.

Description of detailed processes in all stages under pre to initial fluidization have given well understanding in the mechanism of single vertical jet fluidization as the basic references for further development research of fluidization system. Graph model for the mechanism of vertical jet fluidization using internal vortex characteristics observed from 2 dimensional experiments can be explained in the Figure 5.

At the low discharge (Q_{o1}), the maximum height of vortex is formed in front of jet hole within time t_1 is $z_p - 1$. If the discharge increasing to Q_{o2} than the height of vortex increases logarithmically until it reaches a maximum value of $z_p - 2$ and will be constant after reaching the time t_2 . If the critical height of vortex (z_c) is a little bit above the $z_p - 2$ then a slight increase of discharge may make the flow rate will become a critical flow rate for fluidization (Q_{oc}). Processes observed at Q_{oc} can be seen in Figure 5 where from point A to B in time ($t_3 - t_2$) scouring speed becomes very high at the top edge of the vortex then become slow in the time of ($t_4 - t_3$) until reaching point C. When the vortex has reached the point C then a surface layer of sediment is slowly lifted causing the sediment surface becomes higher than surrounding area. Within a very short time ($t_5 - t_4$) bursts occurred on the surface of the bed as indication that the full fluidization is reached and the flow system changed from Darcy to non-Darcy flow having characteristics like flow in tube. As known that the fluidization is achieved when the weight of the sediment in the water has been compensated by the pressure of working

from the bottom. This can be explained that scouring mechanism serves to reduce the volume of sediment layers on it until the bottom pressure can finally balanced even greater than the weight of these sediments.

4.3. Fluidization Gradient Hydraulics

When the vortex reaches a critical height ratio $z_c/d_b = 0.5$ the flow and pressure at the time of discharge and the critical pressure is causing fluidization. Phenomenon at this moment

is interesting to be investigated in more detail therefore the experiment was continued to measure the hydraulic head at a point surrounding $0.5d_b$ above jet hole using a piezometer. This test is intended to get an idea of the development of the hydraulic gradient (dh/z) ranging from prefluidization to full fluidization. Figure 6 presents the experimental results the relationship of Q_o with dh/z for sediment thickness of 30 cm and 40 cm of each with 2 tests in the position of the observation point A.

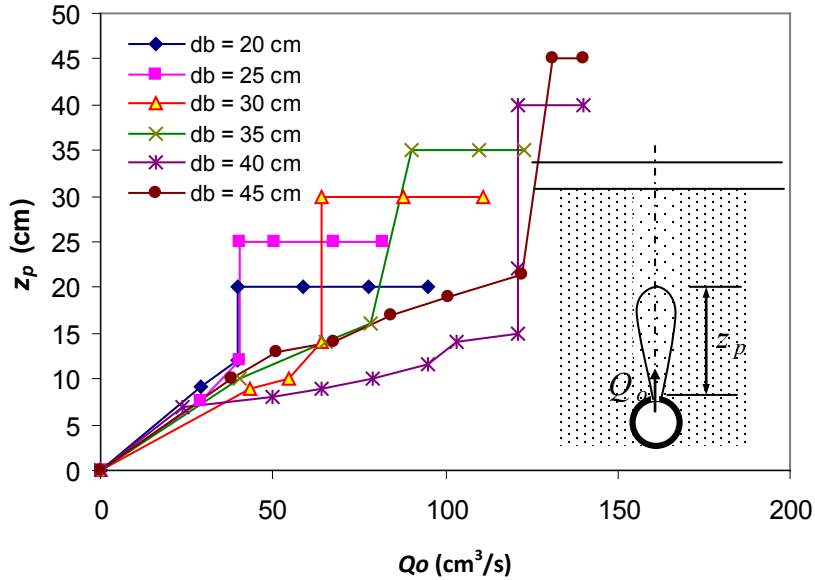


Figure 4. The development of vortex height in the pre to fully fluidization stage

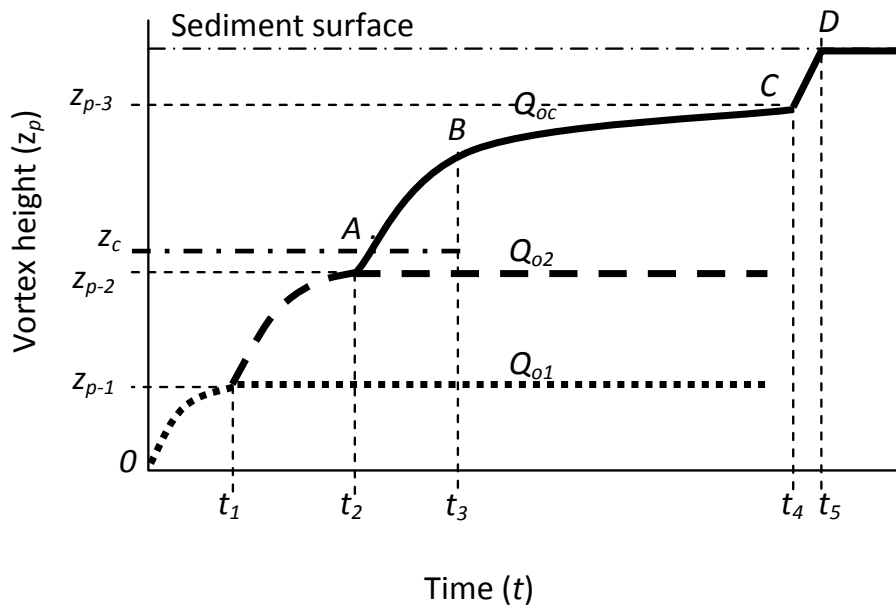


Figure 5. The model of pre to fully fluidization mechanism using vortex characteristics in relationship of z_p , t & Q_{oc}

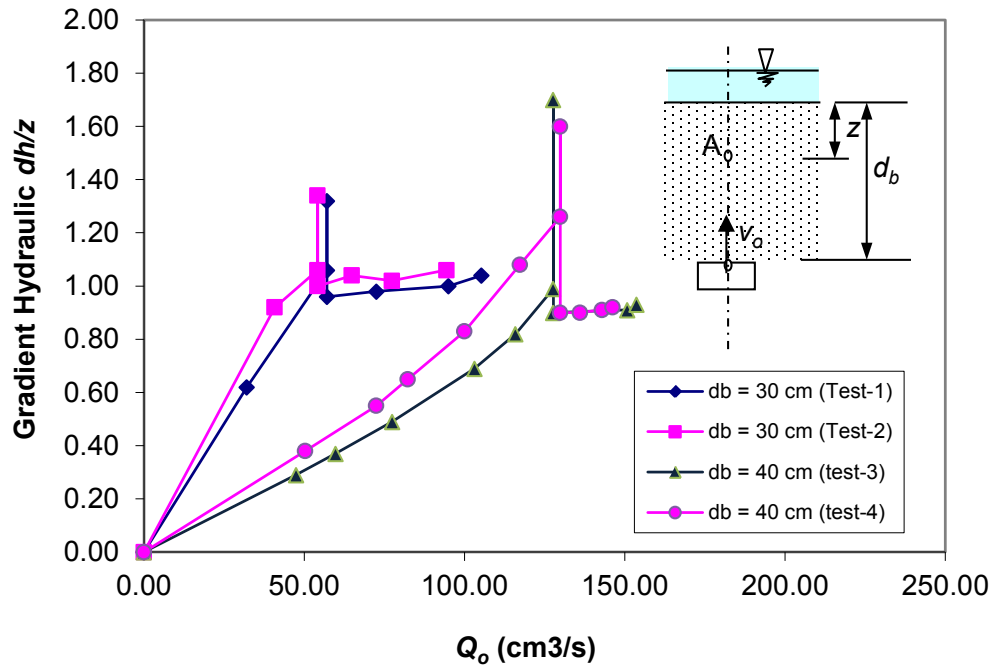


Figure 6. Characteristics of gradient hydraulic for $d_b = 30$ cm and $d_b = 40$ cm

The shape and pattern of hydraulic gradient (dh/z) for all tests such shown in Figure 6 relatively same in which dh/z is proportional to Q_o in the low to certain value of flow rate. At the critical value of flow rate (Q_{oc}) about $55 \text{ cm}^3/\text{s}$ for $d_b = 30$ cm and $128 \text{ cm}^3/\text{s}$ for $d_b = 40$ cm, dh/z increased sharply reaching a maximum value about 1.3 for $d_b = 30$ cm and 1.7 for $d_b = 40$ cm and then dropped down suddenly to values of 1 for both. In the subsequent increase of flow rate, the dh/z tends to a constant. Increase values of dh/z are linear up to Q_{oc} indicating that the prefluidization stage still follows the Darcy Equation. In Q_o value reaches Q_{oc} , the value of dh/z which increase sharply demonstrates the critical conditions of fluidization. The sharply increase of dh/z takes place within a few seconds to minutes along with the increasing of scouring works at the top edge of internal vortex and finally superficial flow will eventually spurting on the surface of sediment and drastically fall down value of dh/z indicates the fully fluidization is achieved. At this stage there is a change from Darcy flow type to non-Darcy flow. Flow type is getting changed to resemble the turbulent flow of fluid in the tube on $Q_o > Q_{oc}$ condition.

4.4. Hydraulics Head Distribution

Vertical jet fluidization experiments on 40 cm thickness of sand layer had been performed to describe the distribution of hydraulic head on three conditions, namely prefluidization conditions, incipient fluidization and fully fluidization. Figure 7 presents the contour map equipotential in the medium sand bath.

Hydraulics head were measured at 42 points using

piezometer. Distribution of hydraulics pressure for the stage of prefluidization with $Q_{oc} = 0.072 \text{ l/sec}$ are shown in Figure 7a, the incipient fluidization stages by $Q_{oc} = 0.104 \text{ l/sec}$ are shown in Figure 7b and fully fluidization by $Q_{oc} = 0.142 \text{ l/sec}$ are shown in Figure 7c. The equipotential contour approaching a circle on prefluidization stage indicates that the distribution of the flow is spread fairly even. The hydraulic head contour lines on the area near the hole jet (Figure 7b) are more dense than the outer regions, showing a loss of energy in this area is greater than the outer regions.

Changes in equipotential contour lines from a circle on the prefluidization to the elliptical shape in the stages of Incipient fluidization, indicate the mobilization of concentrated flow increase is due to rising of hydraulic works. Flow core is formed after the tube flow bursts on the surface and the fluidized sediment became separated from the unity of the deposit. Elliptical shapes in Figure 7b were changed to a boxy shape when discharge is increased from initial to full fluidization (Figure 7c), characterized by hydraulic head contour lines in the flat zone flow axis. Larger flow rates exacerbated the flow tube cross section as well as enlarged the fluidized zone diameter anyway.

Figure 8 presents the results of other tests with 3 kinds of deposite thickness of 20 cm, 30 cm and 40 cm in which the hydraulic head in vertical distribution is described in the flow axis to show the hydraulic head changes from jet hole to the surface sediments.

Figure 8 shows that the largest portion of energy loss during the initial fluidization between the hole to a distance of 10 cm in front of the hole with a loss of head about 90%.

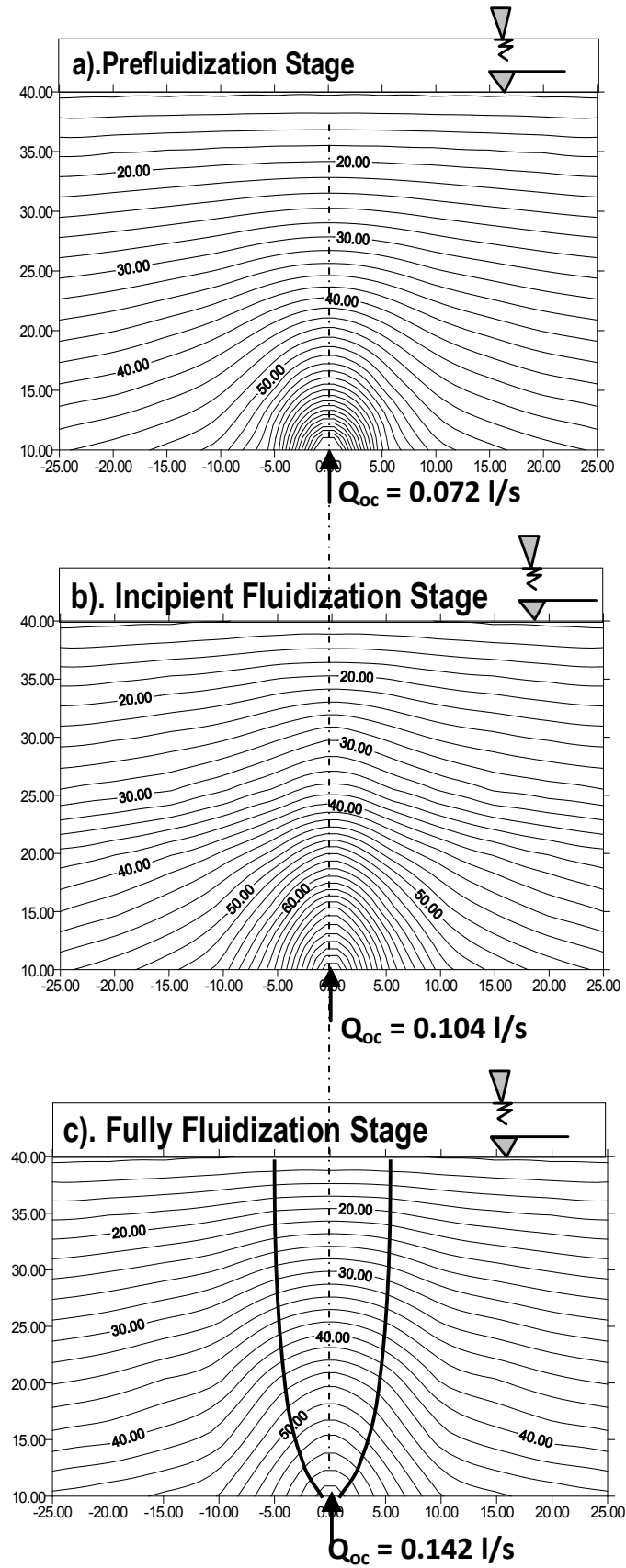


Figure 7. Contour map of equipotential distribution in 3 stage of vertical jet fluidization

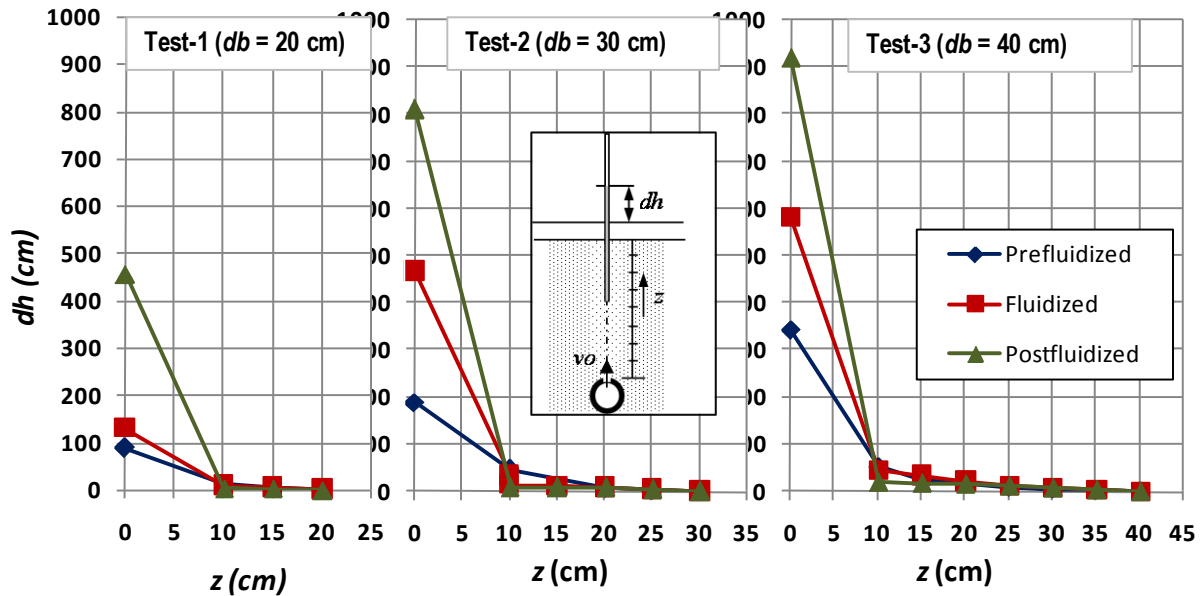


Figure 8. Vertical distribution of hydraulic heads for sediment thickness of 20 cm; 30 cm and 40 cm

5. Conclusions

1. The achievement of unbounded domain incipient fluidization can be explained by the height dimensions of internal vortex where the critical height of vortex (z_c) is obtained at least half of the thickness of the sediment (d_b).

2. Experiment results show that about 90% of high-energy loss occurs within 10 cm of the hole. There is closed sufficient to the results of Lennon and Weisman in[2].

3. The shaped of equipotential line spacing at initial and full fluidization stage can be one indication that the theory of net flows based on Darcy's law is no longer suitable in fluidization conditions.

4. Linear increase in the value of the pressure gradient (dh/z) were measured in sediment deposition on Q_o indicates the flow conditions at the pre fluidization stage still follows Darcy equation. At the higher value of Q_o approach to critical condition, the value of dh/z values increase sharply from 1 to 1.3 for $d = 30$ cm and from 1.2 to 1.7 for the value of $d = 40$ cm shows that the fluidization is in critical condition. Increased dh/z takes place in a few seconds with the increase in the culmination of work scouring internal vortex flow eventually sprayed on the surface and the value of dh/z dropped dramatically to a value ranging from 1 indicating fluidization has occurred. At this stage there is a change of flow type Darcy flow to non-Darcy flow. The results also correspond well with the results obtained by Weisman et al. in[10] and the theoretical value $dh/z = 1$.

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