Hydraulic Gradient of Sand-Water Mixture Flow for Different Sands and Pipes

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Abstract: One of the most important criteria in designing of pipelines which transport granular solid grains is the hydraulic gradient through these pipelines. The hydraulic gradient is considered as a main design parameter of the pump and its operational costs. The main characteristics of the transported granular solid grains are its density, median grain size, d_{50}, and its coefficient of uniformity, which has significant effect on the solid grains-water mixture flow hydraulic gradient. Whereas, the solid grains-water mixture flow hydraulic gradient is mainly function of the pipe material type. This paper carried out experimental runs to study the hydraulic gradient of sand-water mixture flow for different median grain size sands and 50.8 mm diameter horizontal pipes with different materials. This paper used three median grain sizes of sands having d_{50} values of 0.12, 0.23 and 0.42 mm, and also, three pipes with different materials, i.e. PVC, copper, and steel pipes. The experimental runs were designed to include the previous work conditions to facilitate the comparison of the obtaining results with the previous results. It was found that the sand-water mixture hydraulic gradient increase as the sand median grain size increases at low velocities, but correspondingly decreases at higher velocities. Also, the results showed that the sand-water mixture flow hydraulic gradient increase as the pipe roughness increases. The analysis of the obtained results have been conducted in the light of earlier published data and presented in the form of curves and equations.
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1- Introduction:

Chemical and mining industries widely use solid grains-water mixture flow in slurry pipelines. It is well known that the sand–water mixtures flows friction losses in pipeline depend on the nature of the flow in a pipeline. For low sand-water mixture velocity, the sand particles will be silted on the pipe wall forming sand bed which will be stationary if that velocity is below the critical velocity. The sand particles slide over the pipe wall for velocities bigger the critical one. It was found that, the range of the sand-water mixture flow velocity within which the contact bed occurs in depends on the sand median grain size, d_{50}, the pipe diameter, D, and the concentration of sand in water. One of the most important criteria in designing of pipelines which transport granular solid grains is the hydraulic gradient through these pipelines. In the present paper, the effect of sand median grain size and the type of the pipe materials on sand-water flow hydraulic gradient were investigated for different sand concentrations and flow velocities. The results of the experimental runs were compared with results collected in the previous work. A pipe loop system was built, allowing variation of sand type, pipe type, flow velocity, and sand concentration.

2- Overview of the Prior Published Data:

Transportation of solid particles by horizontal pipelines through sand-water mixture, the hydraulic gradient calculation is complicated in case of smaller flow rates to have low energy cost of solid particles transportation and the sand particles slide on the pipe wall because the sand-water mixture velocity is close to the critical velocity.

Mahmoud Eltoukhy (2013) carried out laboratory studies to investigate the effect of sand concentrations and the inclination angle of the pipeline on the sand-water mixture flow hydraulic gradient. Five values of the pipe inclination angle of 5, 10, 25, 35, and 45° upward and downward positions, in addition to the horizontal and vertical positions were used. Three values for the concentration of sand in the sand-water mixture of 5, 10, and 15% by volume were used for each inclination position. It was found that the values sand-water mixture flow hydraulic gradients through the pipeline laid upward sloping position are always greater than the corresponding values of each horizontal and downward pipeline positions for any value of the concentration of sand and inclination angle. The hydraulic gradient through the pipeline has directly proportion with the sand concentration.

Wasp et al. (1999) showed that the properties of the sand-water mixture flow in pipelines are different from the water without sand particles flow.

The three natures of flow i.e., laminar, transition, or turbulent, should be allowed which also depend on the fluid properties and the pipeline roughness. It was found also that the sand-water mixture flow is complicated comparing with the homogeneous water flow mainly for two reasons. The first reason is that, the sand particles affect the properties of the liquid and sand-water mixture. The second reason is depending on the conditions of the sand particles to have range of sand-water mixture behaviors.

Richardson, et al. (1999) studied homogenous flow systems showed that the presence of solid particles in fluid increase the solid-fluid mixture viscosity comparing to the pure fluid viscosity. On the other hand, the solid particle concentration gradient along the pipeline vertical axis was surveyed at high velocities in heterogeneous flow in which the solid particles are not uniformly distributed across the pipeline cross section. Each fluid and solid particles phase possesses their separate properties. Homogeneous solid-liquid mixture has smaller solid particles concentration with smaller particle sizes than the heterogeneous solid-liquid mixture.

Kaushal et al. (2005), and Kaushal and Tomita (2007) carried out experimental runs to study the concentration and distributions of solid in solid-water mixture flow through pipeline by using γ - ray. Their results show that, the pressure drop profiles of solid-water flow looks like that of pure water data, for finer solid particles except for solid concentration value of 50%, but for coarser solid particles, the pressure drop has skewed profiles of equivalent solid-water flow. Their experimental studies showed that, finer particles are absent near the pipeline wall and are in suspension state. Also, the presence coarser particles near the pipeline wall, is due to effect of viscous turbulent on the bottom particles which increases the interactions between particles.

Raudkivi (1989), found that for vertical pipeline downward flow, the solid particle velocity value is greater than the water velocity but the opposite results are obtained for upward flow. The variation is was found to approximately equal to the settling velocity value. Coiado and Diniz (2001), carried experimental runs to study the solid-water flow in inclined pipes. Through the analysis of the obtained results, it was concluded that the values of hydraulic gradient through upward sloping pipeline are greater than that of each horizontal and downward sloping pipelines for any value of the sand concentration and pipeline inclination angle.

Kim et al. (2008), conducted experimental studies on the transport of the sand-water mixtures through square ducts, focusing on the economic transport of solid particles. The measured data of the hydraulic gradient, sand effect, and deposition limit velocity for square duct were compared with that of corresponding to the mixture flow through circular pipe. The hydraulic gradient of pure water in the circular pipe was found larger than the hydraulic gradient through square duct because of the secondary flow in the square duct. As an opposite results were obtained in case of sand-water mixture flow. It was found that the hydraulic gradient of the sand-water flow in the circular and square pipelines is directly proportion with the sand concentration and Reynolds number.

Faraj et al. (2012) compared the Electrical Resistance Tomography system (ERT) in surveying the sand distributions in horizontal and vertical directions of sand-water mixture with the actual photographs of the sand-water mixture flow. The results of ERT showed good agreement between the two results. Therefore, it can be concluded that the ERT system could well be used for surveying the sand distributions through pipelines.

Kaushal, et al. (2012), compared between using of Eulerian and Mixture models of studying the sand-water mixture flow through pipeline with the experimental results. It was found that the obtained results by using both Mixture and Eulerian models in estimating of pressure drop for flow of water agree with the experimental results. Whereas, in case of sand-water mixture flow the pressure drops at different sand concentrations, namely, 30%, 40% and 50%, the Mixture model cannot correctly predict the pressure drops, the error increases with the sand concentration. But the predicted pressure drops by using Eulerian model were quite accurate values at all sand concentrations and sand-water mixture flow velocities.

The published materials about solid-liquid mixture flow were mostly conducted for horizontal pipeline with one pipe material. There are limited studies deals with the effect of sand median grain size on sand-water flow hydraulic gradient. Almost, no researchers studied the variation of the sand-water flow hydraulic gradient with the pipe roughness. In hits backdrop, this paper studies the effect of the sand median grain size, d_{50} and the roughness of the pipeline on the sand-water mixture flow hydraulic gradient for different sand concentrations. The obtained results were translated into forms of curves and equations to estimate the hydraulic gradient for given sand median grain size and pipeline roughness for sand-water mixture flow velocity and the sand concentration by volume.

3- Experimental Apparatus:

An experimental apparatus was set up where the flow rates and sand-water flow hydraulic gradient can be measured through a laid horizontal pipeline in the Hydraulic Laboratory. An elevation view of the used apparatus is shown in Fig. 1. The used pipeline inside diameter is 50.8 mm. This apparatus was prepared to conduct all runs which achieve the present paper objectives. The sand and water were mixed in main tank, with length of 0.80 m, width of 0.70 m and depth of 0.80 m and maintain this mixture to be homogeneous by using an auxiliary pump. Then, the main pump was used to pump the homogeneous sand-water mixture through the horizontal pipeline. The run should be allowed sufficient time before recording the run result to ensure steady state conditions. The sand-water mixture flow hydraulic gradient was measured through the pipelines between two points 2 m apart by differential manometer. The discharge was measured by dividing the collected volume of the outlet mixture by the corresponding time. The sand concentration in the sand-water mixture was estimated by using a tank to measure the sand volume and balance to weigh the sand sample. This paper used three sands in the experiments, which were uniform sands with median grain sizes, d_{50} of 0.12 mm (finer sand) , 0.23 mm (medium sand), and 0.42 mm (coarser sand), as shown in Fig. 2. The sand concentration varies from zero percent for water flow up to 25 % in volume for sand-water flow. Three pipes, i.e. PVC, copper, and steel were used to study the variation of the sand-water mixture flow hydraulic gradient with pipe roughness.

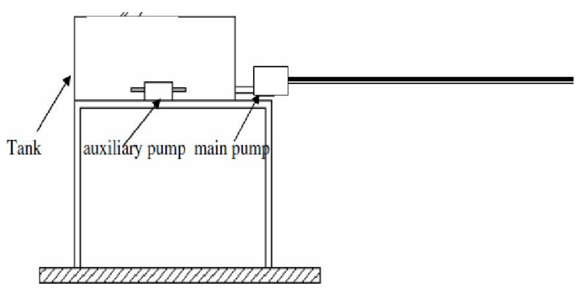

Fig. 1 Apparatus Layout

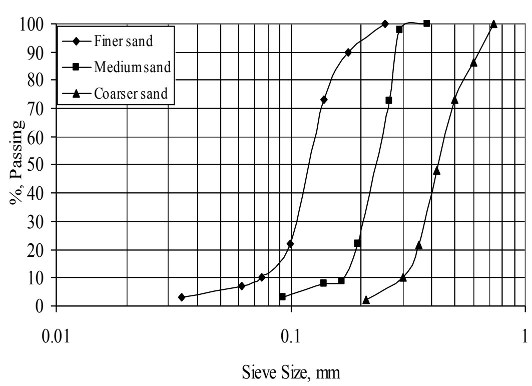

Fig. 2 Grain size distribution of different sands used in the pesent paper

4- Experimental Work:

The laboratory work consists of two main sets of experiments. The first set consists of 85 runs, and it used to measure the sand-water mixture hydraulic gradient through the PVC pipe for the three types of sands for different sand concentrations, (0 %, 5 %, 10 %, 15 %, 20 %, and 25 % in volume) and velocities. The second set of experiments consists of 58 runs for studying the effect of pipe roughness on the sand-water hydraulic gradient for different sand concentrations and velocities. Also, 29 runs were carried out using copper pipe and another 29 runs were carried out using steel pipe. In each experimental run the sand-water mixture velocity should have a value greater than the critical velocity to prevent silting of sand particles. Durand (1953) and Gibert (1960) found that, the sand-water mixture velocity should be greater than 0.75 m/s for the finer sand, 1.21 m/s for the medium sand, and 1.49 m/s for the coarser sand in the corresponding runs to maintain that the sand particles are always in suspension state.

5- Results and Discussion:

The experimental measurements were recorded by decreasing or increasing the sand-water mixture flow velocity, V_m for a known sand concentration. Each experimental run takes about 7 min to record the measurement for known sand concentration and sand-water mixture flow velocity.

5-1 Sand-water Mixture Hydraulic gradient for Different Sands:

Figs. 3–5 show the sand-water hydraulic gradient per unit length i = hydraulic gradient / corresponding length, (h/L), against flow Froude number, F_r. To check the accuracy of the experimental run results for recording the sand-water flow hydraulic gradient, experimental runs were carried out to measure the water without sand flow hydraulic gradient and the obtained results through PVC pipe with relative roughness, (k = 0.00324) were found to be agree with the Moody chart. The sand-water flow velocity values have ranges from the maximum allowable value to the minimum possible velocity, where each velocity value is greater than the settling velocity of the used sand. The flow velocity values at which the sand particles roll at the pipe wall is taken as ‘‘streaking at the bottom’’. Further reduction in the flow velocity value leads to make the sand particles at the pipe wall coming to rest and the corresponding velocity value is known as the deposition/critical velocity. Below this velocity value, a stationary bed is created and this results in pipe throttling and reducing the total pipe cross section.

Hydraulic gradient of sand-water mixture flow results for the sand with median grain size, d_{50} of 0.12

mm are presented in Fig. 3 by using different sand concentrations of 5%, 10%, 15%, 20% and 25%. It was found that the sand-water mixture flow hydraulic gradient at any flow velocity value increases with the increase in sand concentration. All curves have the same trend for all sand concentrations at all flow velocities. The rate of increase in the sand-water flow hydraulic gradient with different sand concentrations is small at low velocities but it increases rapidly at higher velocities.

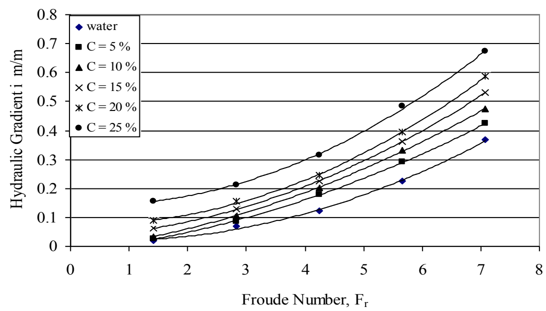

Fig. 3. Hydraulic gradient for finer sand, d_{50} = 0.12 mm through PVC pipe for different concentrations

Fig. 4 presents the sand-water mixture hydraulic gradient for the coarser sand with median grain size, d_{50} of 0.42 mm for different sand concentrations which its values range from 5 % to 25 %. From this figure, it is observed also, that at a given value of the flow velocity increasing in the sand concentration results in increasing in the sand-water mixture flow hydraulic gradient, but the increasing rate is comparatively smaller at higher flow velocities. Furthermore, at lower velocities, the sand-water mixture hydraulic gradient has a slit increasing at lower sand concentrations and it decreases with sand-water mixture flow velocity at higher sand concentrations. It is obvious, at the largest used sand concentration in this paper i.e. 25%, increasing the flow velocity results in decreasing sand-water mixture hydraulic gradient even up to the largest used flow velocity.

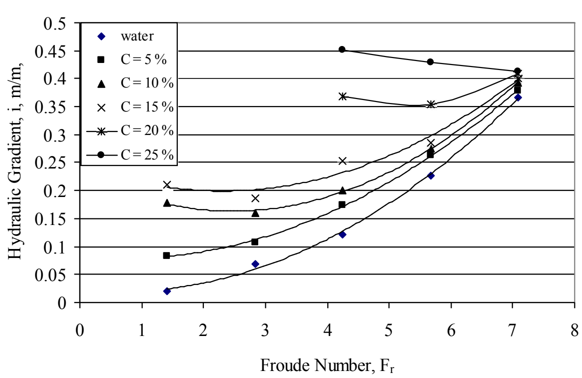

Fig. 4 Hydraulic gradient for coarser sand, d_{50} = 0.42 mm through PVC pipe for different concentrations

The results of the runs, which were carried out for the medium sand, d_{50} = 0.23 mm are depicted in Fig.5. The sand-water mixture hydraulic gradient increases as the flow velocity increases for at overall concentrations around 5 %, 10 %, 15 %, 20 % and 25 %. But the rate of increasing in the sand-water mixture hydraulic gradient for the medium sand is less than that of the finer sand.

Fig. 6 displays the effect of the median grain size, d_{50} on the sand-water mixture hydraulic gradient, for sand concentration of 10 % and PVC pipe. It is observed that the sand-water mixture hydraulic gradient has less value in the case of using finer sand, d_{50} =0.12 mm than using coarser sand, d_{50} = 0.42 mm at lower flow velocities but its values for finer sand are greater than that of coarser sand at higher flow velocity.

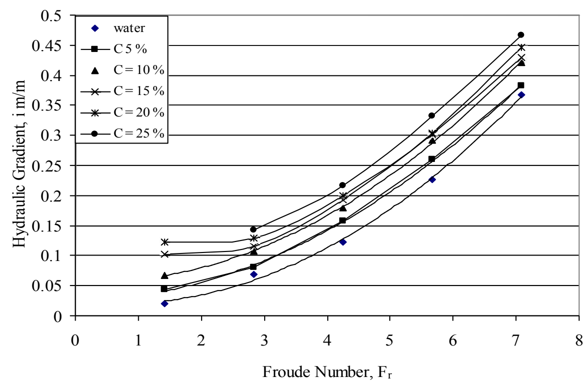

Fig. 5 Hydrulic gradient for medium sand, d_{50} = 0.23 mm through PVC pipe for different concentrations

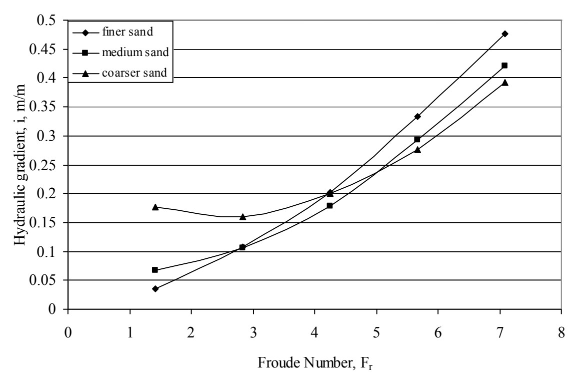

Fig. 6 Hydraulic gradient for PVC pipe and 10 % sand concentration for different sands

The reason of the sand-water mixture flow hydraulic gradient increases for coarser sand at lower velocities is because the gravitational effect which results in increasing the amount of sand particles moving in the bed, while, in case of using finer sand at higher velocities, greater surface area was obtained which cause more frictional losses in suspension and leads to more flow hydraulic gradient.

5-2 Sand-water Mixture Hydraulic gradient for Different pipes:

Experimental runs were conducted to investigate the effect of the pipe material roughness on the sand-water mixture hydraulic gradient. The inside surface state of the used pipe also has a major effect on the sand-water mixture flow hydraulic gradient. As the pipe roughness increases the thickness of non moving fluid near the pipe wall increases. Hence the pipe inside diameter will be reduced which results in increasing the fluid velocity, and consequently increasing in friction losses. The friction losses have more increase in the case of sand-water mixture flow than the pure water flow.

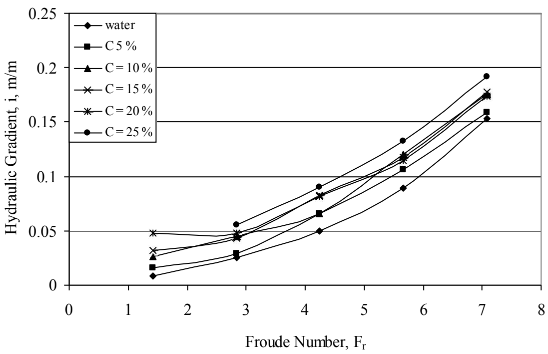

Fig. 7 Hydraulic gradient for medium sand, d_{50} = 0.23 mm through copper pipe for different concentrations

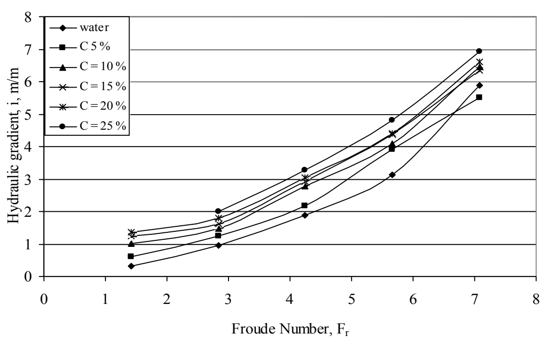

Fig. 8 Hydraulic gradient for medium sand d_{50} = 0.23 mm through steel pipe for different concentrations

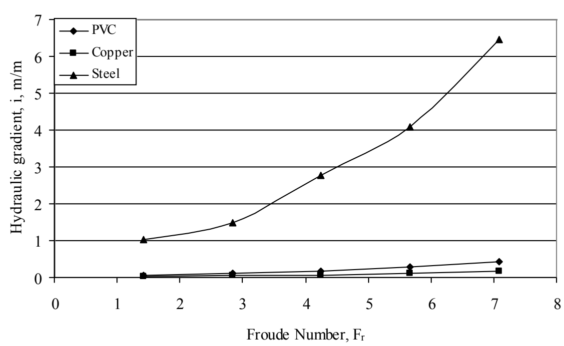

Fig. 9 Hydraulic gradient for 10 %, of medium sand concentration for different pipes

Copper and steel pipes were used in this paper with the PVC pipe. It was found that the sand-water mixture hydraulic gradient trends are the same for the three pipes, Figs. 5, 7, and 8. The analysis of the obtained data, show that increasing in pipe roughness results in increasing in the sand-water mixture hydraulic gradient, as shown in Fig. 9.

With a view to accomplish the objectives set for this study, several curve fittings were done and sound relationship was established between hydraulic gradient and the affecting variables, i..e., the Froude's number, F_r the sand median grain size, d_{50} the sand concentration, C, and the pipe roughness, k, see Fig. 10. In this figure all variables may be presented as variables factor I_V on the horizontal axis and the hydraulic gradient on the vertical axis:

$$I_V = \left(4.7\left(\frac{k}{d_{50}}\right) - 0.02\right)F_r - \left(5.4\left(\frac{k}{d_{50}}\right) - 1.1\right)C^2 - \left(16.1\left(\frac{k}{d_{50}}\right) + 0.06\right)C + 0.11 \quad (1)$$

Where:

$$F_r = \frac{v}{\sqrt{2gD}} \quad (2)$$

v : the velocity of sand-water mixture flow, (m/s)
D : diameter of pipe, (m)
g: gravitational acceleration, (m/s^2).

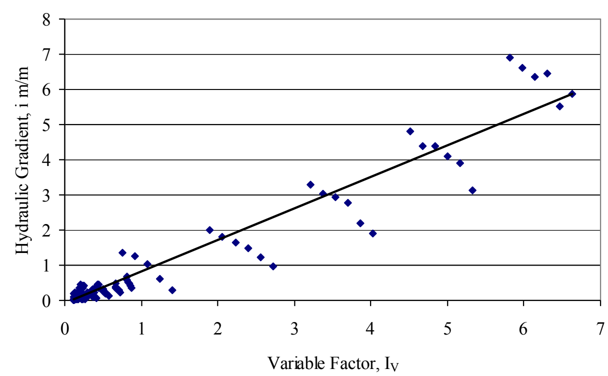

Fig. 10 Hydraulic gradient variations with the affecting variables

The hydraulic gradient, *i*, may be calculated for any I_V for a given sand-water mixture velocity, sand median grain size, pipe roughness, and the sand concentration from Fig. 10. Through curve fitting for data in Fig. 10, the following equation was obtained:

$$i = 0.897\, I_V - 0.082 \quad (3)$$

By substituting the value of I_V from Equation 1 into Equation 3, the hydraulic gradient can be directly calculated as:

$$i = \left(4.2\left(\frac{k}{d_{50}}\right) - 0.018\right)F_r - \left(4.8\left(\frac{k}{d_{50}}\right) - 0.99\right)C^2 - \left(14.4\left(\frac{k}{d_{50}}\right) + 0.05\right)C + 0.013 \quad (4)$$

Conclusions:

This paper studied the experimental results to determine the effects of sand-water mixture velocity, sand median grain size, the pipe roughness, and the sand concentration on the hydraulic gradient in the pipeline. Based on the experimental data, the results of curve fitting, and the resulting mathematical expressions, the following conclusions are reached:

1- For the finer and medium sands at a given flow velocity the sand-water mixture hydraulic gradient has directly proportional relationship with sand concentration.
2- For finer sand, the increasing rate in the sand-water mixture flow hydraulic gradient with the sand concentration is small at low velocities but at higher velocities, it increases rapidly.
3- For coarser sand at given flow velocity, increasing in sand concentration leads to increasing in the sand-water hydraulic gradient, but the increasing rate is comparatively smaller at higher flow velocities.
4- The coarser sand-water mixture hydraulic gradient has a slit increasing at lower sand concentrations and decreases with flow velocity at higher sand concentrations.
5- The coarser sand has more sand-water mixture hydraulic gradient at lower flow velocities and has less hydraulic gradient at higher flow velocities than finer sand.
6- Increasing in pipe roughness, results in increasing in the sand-water mixture hydraulic gradient
7- The curve fitting results and the corresponding equations developed can be used for calculating the sand-water mixture hydraulic gradient for given flow velocity, sand median grain size, the pipe roughness, and the sand concentration.

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