# HYDRAULIC TRANSPORT OF COARSE GRAVEL－A LABORATORY INVESTIGATION INTO FLOW RESISTANCE

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## ABSTRACT

Flow resistance relating to the hydraulic transport of solids has attracted much attention from the dredging industry and related academic fields. Until now, a great deal of literature on the flow resistance of sand or fine particles hydraulically transported in a pipeline has been published. However, very little research on the hydraulic transport of coarse particles has been carried out, resulting in very limited understanding about the behavior of coarse particles. In recent years the hydraulic transport of coarse gravel or stone pieces has played an important role in the production control of several dredging projects in China. In order to investigate the basic characteristics of big particle transport, a series of laboratory tests were performed on the 315kW-DN200mm slurry pump-pipeline stand at Hohai University, China. Three types of gravel with diameters of 4.0~8.0mm, 8.0~16.0mm and 16.0~32.0mm were used. The delivered volume concentrations were controlled around 6~7% and 10~12%, respectively, forming gravel-water mixtures with specific densities of 1.1 and 1.2. Laboratory tests show that the behavior of the coarse gravel hydraulic transport differs somewhat from that of fine particles. The characteristics of flow resistance for the hydraulic transport of coarse gravel and the factors that affect the resistance are discussed in this paper. An empirical prediction model for this flow resistance is also presented.

**Keywords:** Hydraulic transport of coarse gravel, flow resistance, laboratory investigation

## INTRODUCTION

The transport of solids is one of the main processes in dredging engineering and a lot of studies have been carried out on the transport of sand or fine particles (Durand 1953, Wilson 1976, 1997, Sundqvist et al. 1996, Matousek 1997, Ni 2004). As is known to us, the most common type of slurry flow is the partially-stratified or heterogeneous case, in which turbulent suspension and inter-granular contact are the two significant mechanisms of particle support. However, relatively little research has been done on gravels or even bigger particles. In recent years the hydraulic transport of coarse gravel or stone pieces has played an important role in the production control of several dredging projects in China. Engineers are interested in what mechanisms of particle support are active in the gravel mixture flows.

This paper presents the measured data for flow resistance of three gravel groups tested in the newly-established closed pump-pipeline stand at Hohai University, China. The pipeline diameter is 200mm and the electrical engine

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power is 315kW with frequency controlled by the SIMENS ECO1-315k inverter. The tested gravels are listed in table 1 and the laboratory pump-pipeline system is shown in Figure1.

**Table 1. Gravels used in the laboratory tests.**

| Solids | Gravel 2 | Gravel 3 | Gravel 4 |
|---|---|---|---|
| Solid diameter *d* | 4.0-8.0 mm | 8.0-16.0 mm | 16.0-32.0 mm |
| Delivered volumetric concentration $C_{vd}$ | (1) 6－7%<br>(2) 10－12% | (1) 6－7%<br>(2) 10－12% | (1) 6－7%<br>(2) 10－12% |


**Figure 1. 315kW-DN200 pump-pipeline slurry transport stand at Hohai University, China.**

Differential pressure transmitters of Rosemount Model 1151 were used to measure the pressure drop over pipeline sections. The Rosemount magnetic-inductive flow meter 8711 was used to measure the mean slurry velocity $V_m$ in the circuit. The spatial solids concentration across the pipe cross-section $C_v$, which gives the fraction by volume of solids actually resident in slurry, was detected by a radiation density meter Berthold LB 444 with a Cs-137 source. In order to obtain the concentration distribution, a special support frame was installed on the horizontal pipeline to set continuously the radioactive source and the detector at different vertical positions across the pipeline cross-section. For determining the solids production or how much solid per hour is transported through a pipeline, the so-called delivered volumetric concentration $C_{vd}$ must be introduced, which gives the fraction by volume of solids delivered in slurry, and is calculated as the ratio between solids flow rate and the slurry flow rate. During each experimental run, the total amount of sand in the circuit was constant but the delivered concentration may increase slightly with the increasing mean slurry velocity.

## OBSERVED PHENOMENA

### Transport of Gravel 2 of d=4.0~8.0mm

The flow resistance or friction head loss over a pipe section is usually expressed as the dimensionless hydraulic gradient $I_m$ which is defined as the frictional head loss in meter-water-column over one meter pipeline. Plotting the curve of $I_m$ with the increasing slurry velocity $V_m$ shows the development of slurry flow resistance. Figure 2 shows the measured data of the gravel 2 mixture with the delivered concentration $C_{vd}$ equal to 6-7% and 10-12%, respectively. The mixture behavior is unusual. With the increase of mixture velocity, the solids-effect $I_m - I_w$, where subscripts m and w stand for mixture flow and clear water flow, respectively, neither monotonously increases nor monotonously decreases as most sand slurries. Above the deposition-limit velocity, the flow resistance experiences a second peak. This characteristic is very unusual and is called “double-peak” flow resistance, which was first measured and later confirmed in the slurry tests of coarse sand with $d_{50}$=1.84mm in the DN150mm pipeline circuit at the dredging laboratory of Delft University, The Netherlands (Matousek 1997, Ni 2004). What impressed us was that the gravels with d=4.0~8.0mm also demonstrated a “double-peak” flow resistance in the 200mm pipeline circuit at Hohai University, China.

The deposition-limit velocity $V_{dl}$ was observed visually through a transparent plexi-glass section, underneath which a mirror was placed, see Figure 3. For the mixture of gravel 2, the $V_{dl}$ was around 3.0m/s.

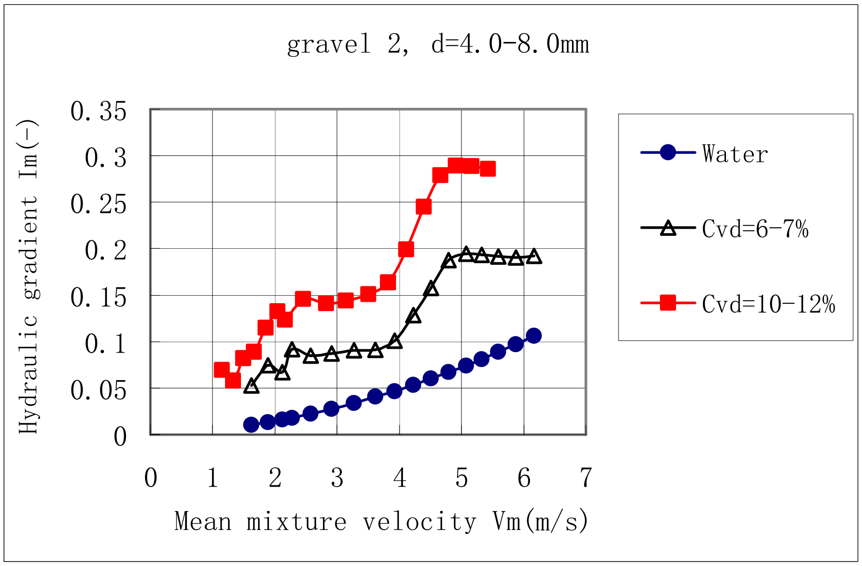


**Figure 2. Flow resistance of gravel 2 mixture in DN200mm pipeline.**

**Figure 3. Observation of the mixture flow with a mirror underneath the transparent plexi-glass pipe.**

**Transport of Gravel 3 of d=8.0~16.0mm and Gravel 4 of d=16.0~32.0**

Compared to the behavior of the gravel 2 mixture, the friction head losses due to gravel 3 mixture and gravel 4 mixture develop roughly monotonously with the mean mixture velocity, see Figures 4 & 5. No “double-peak” flow resistance was observed. Above the deposition velocity $V_{dl}$ the solid effect $I_m - I_w$ seems to be independent of the mean mixture velocity $V_m$. The mixture resistance curves are almost parallel to that of water flow. Regarding the deposition-limit velocity $V_{dl}$ for mixtures of gravel 3 and gravel 4, the visual observation revealed that it was impossible to develop a steady thin bed to determine the deposition-limit threshold in the transport of the lower delivered concentrations of $C_{vd}$=5-8%. Instead, the intermittent settling and flushing processes alternatively occurred, which resulted in the fluctuation of the flow resistance at the lower mixture velocities, see Figures 4 & 5. For higher delivered concentrations of $C_{vd}$=10-12%, a stable thin bed can be developed and the $V_{dl}$ is around 3.0m/s.

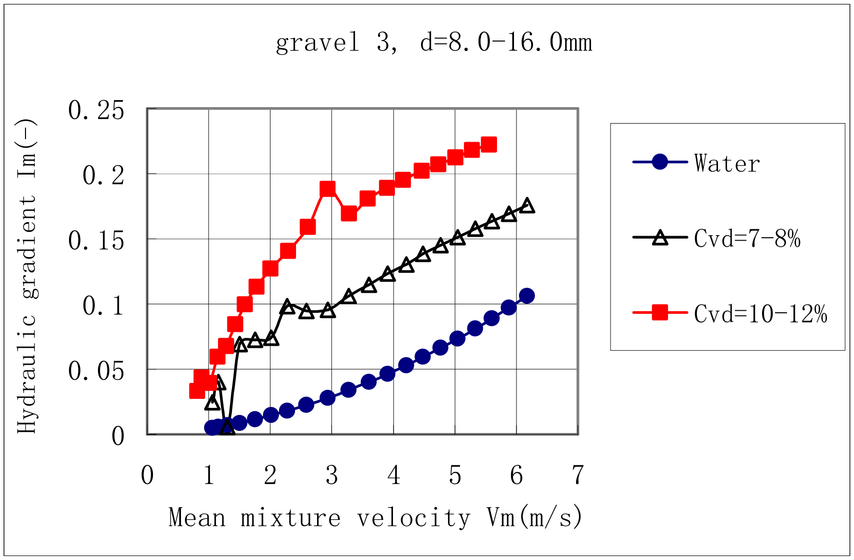


**Figure 4. Flow resistance of gravel 3 mixture in DN200mm pipeline.**

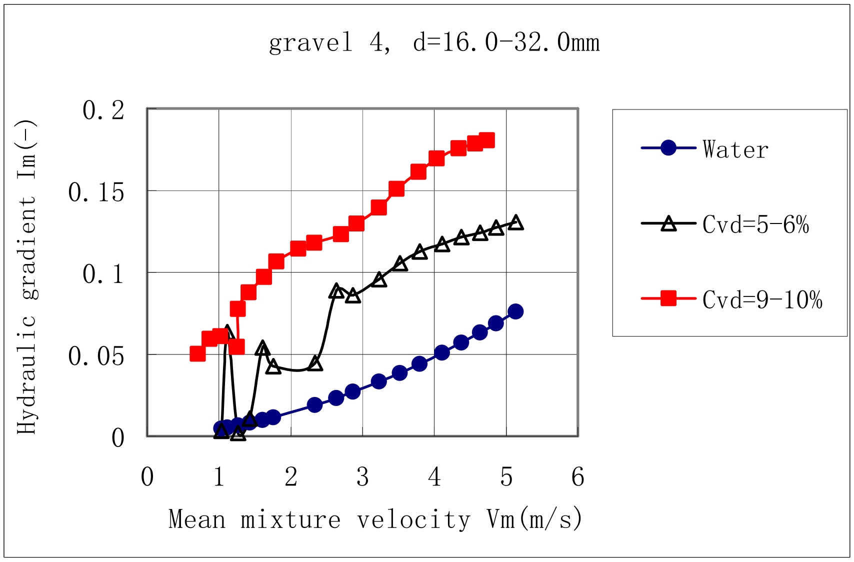


**Figure 5. Flow resistance of gravel 4 mixture in DN200mm pipeline.**

## EMPIRICAL MODELING OF THE FLOW RESISTANCE

There have been a great number of empirical models to predict solid-liquid slurry flow resistances. Therefore several representative empirical models were firstly employed to check our experimental data. One of them was the Durand model (Durand, 1953), which can be stated as below:

$$I_m = I_w + KC_{vd}\left(\frac{\sqrt{gD}}{V_m}\right)^3\left(\frac{\omega}{\sqrt{gd_{50}}}\right)^{1.5} I_w \quad (1)$$

where $I_m$, $I_w$ denote the hydraulic gradients of gravel mixture flow and water flow, respectively, $C_{vd}$ the delivered volumetric concentration, $D$ the diameter of pipeline, $V_m$ the mean mixture velocity, $g$ the gravity acceleration, $\omega$ the particle settling velocity, and $K$ the coefficient. In the original Durand model, $K$=180.

As is known to us, Durand model has been widely used to calculate the friction head loss in the pipeline heterogeneous slurries. Like other popular models, however, it couldn't give reasonable predictions to the big gravel particles flow either. Figures 6, 7 & 8 show that the Durand model neither simulates the "double-peak" flow of gravel 2 mixture, nor predicts the flow resistances of gravel 3 and gravel 4 mixtures.

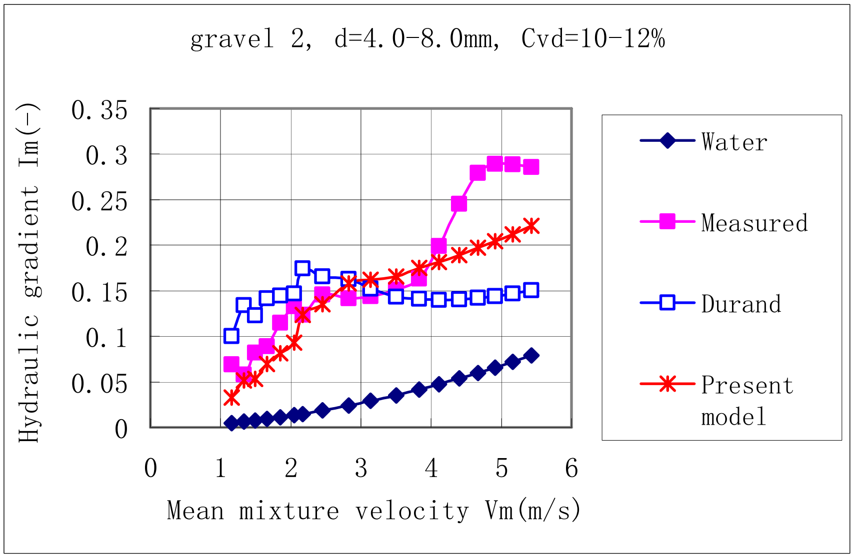


**Figure 6. Modeling of the flow resistance of gravel 2 mixture.**

From the measured curves shown in Figures 2, 4 & 5, one can reach the following two points about the solid-effect or the excess energy loss caused by the presence of gravels in the mixture flows. One is that the excess energy loss is proportional to the solid volume concentration $C_{vd}$, the other is that within the measured velocities of the mean mixture the solid-effect almost remains constant with the increase of the mean mixture velocity $V_m$. These phenomena suggest that the mechanical friction between the sliding gravels bed and the pipe wall would mainly contribute to the excess energy loss. In other words, the main mechanism of particle support is the inter-granular contact. Most particles are in continuous or sporadic contact with the pipe bottom, which is the case with sliding, rolling and jumping particles. These particles move along the pipe bottom with a velocity slower than the carrying fluid (Sundqvist et al. 1996).

Based on the above understanding and that the particle drag coefficient $C_D$ or the particle Froude number

$F_{rd} = \frac{\omega}{\sqrt{gd}}$ becomes constant when particle diameter is bigger enough, an empirical model modified from the Durand formula (1) is proposed as follows:

$$\frac{I_m - I_w}{I_w} = K \frac{C_{vd}}{(F_{rD})^2}, \quad K = 220 \qquad (2)$$

where $F_{rD} = \frac{V_m}{\sqrt{gD}}$ is called pipeline Froude number, representing the influence of pipeline diameter and the mean mixture velocity. The Froude number is a criterion of dynamic similarity for flows with a dominant of inertia and gravity. It relates slurry flows of different mean velocities in different pipe diameters. Now we use the proposed model (2) to predict the gravel mixture flow resistances, see Figures 6, 7 & 8. It is found that the calculated resistances given by the modified model agree well with the measured data. As for the "double-peak" flow resistance, the formula (2) does not produce a reasonable result. This type of flow is governed by the so-called shear layer mechanism (Matousek 1997) and until today the mechanism can not be modeled quantitatively and is to be subjected to further investigation.

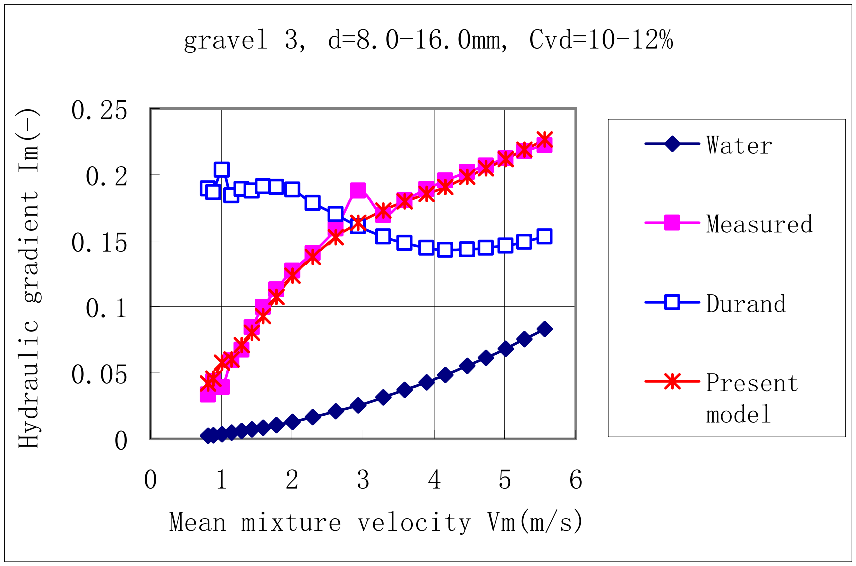


**Figure 7. Modeling of the flow resistance of gravel 3 mixture.**

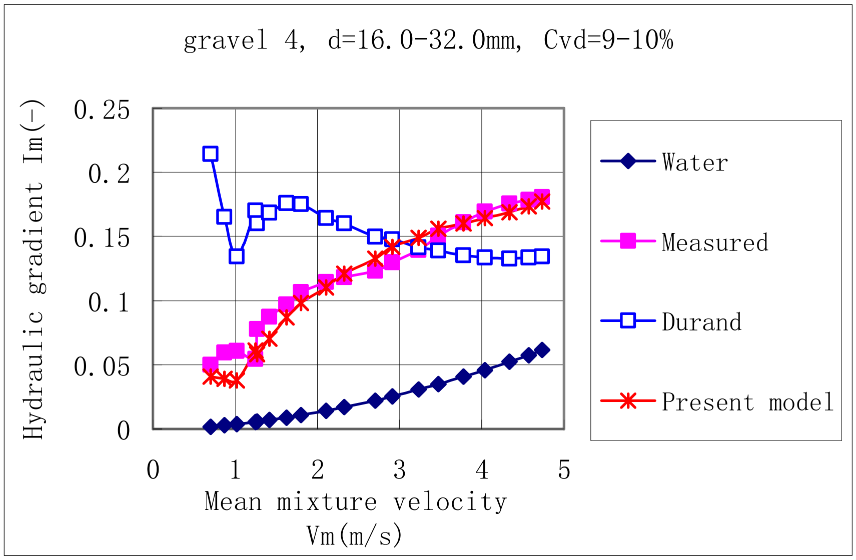


**Figure 8. Modeling of the flow resistance of gravel 4 mixture.**

## CONCLUSIONS

The laboratory investigation in the newly established 315kW-DN200mm pump-pipeline circuit indicates that the flow behavior of gravel-water mixtures is different from that of sand-water flow. For the cases with lower delivered concentrations of $C_{vd}$=5-8%, the intermittent settling and flushing processes alternatively occurred and resulted in instability at lower mean mixture velocities. For the gravels of d=4.0-8.0mm, the mixture flow resistance exhibited a "double-peak" characteristic, whose mechanism is actually not very clear yet and still can not be quantitatively modeled. For the gravels of d=8.0-16.0mm and d=16.0-32.0mm, the solid-effect $I_m - I_w$ figures are almost constant with the increase of the mean mixture velocity. Most of the gravels can be classified as contact load which are in continuous or sporadic contact. These gravels slide, roll and jump in the lower layer across the pipe cross-section. The mechanical friction mainly contributes to the total friction head loss. The friction head losses given by the proposed model in this paper agree well the measured data.

## REFERENCES

Durand, R. (1953). "Basic relationships of the transportation of solids in pipes-experimental research." *Proceedings of Minnesota International Hydraulics Convention*. Minnesota, USA, 89-103.

Matousek, V. (1997). *Flow mechanism of sand-water mixtures in pipelines.* Delft University Press. The Netherlands, 1997.

Ni, F., Zhao, L., Matousek, V., Vlasblom, W. J., and Zwartbol, A. (2004). "Two-phase flow of highly concentrated slurry in a pipeline." *Journal of Hydrodynamics, Series B*, 16(3), 325-331.

Sundqvist, A., Sellgren, A., and Addie, G.R. (1996). "Slurry pipeline friction losses for coarse and high density industrial products." *Powder Technology*, 89, 19-28.

Wilson, K. C. (1976). "A unified physically-based analysis of solid-liquid pipeline flow." *Proceedings of*

*Hydrotransport 4*, BHRA, Cranfield, UK, 1-16.

Wilson, K, C., Addie, G.R. (1997). "Coarse-particle pipeline transport: effect of particle degradation on friction." *Powder Technology*, 94, 235-238.

Wilson, K. C., Addie, G. R., Sellgren, A., and Clift, R. (1997). *Slurry Transport Using Centrifugal Pumps*. London: Blackie Academic and Professional.

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