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STATIONARY WAVES MEASURED BEHIND A BEND IN HETEROGENEOUS TRANSPORT

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The results of laboratory experiments on the flow of concentrated sand-water-mixtures downstream of a 180 degree bend are described. Longitudinal pressure profiles reveal stationary standing waves in the heterogeneous transport regime. The waves occur at and around the deposit limit velocity. Under many prototype flow conditions the flow is just in this regime. Typical wave lengths are 40*D* to 60*D,* where *D* is pipe diameter. The measurements cover a distance of 80*D* behind the bend, measured waves appear to stretch further. These measurements reveal the very reason for the appearance of a restratification phenomenon in certain earlier laboratory tests.

KEY WORDS: pipe line, bend, sand-water-mixture, transient flow, measurements.

1. INTRODUCTION

Transient processes in stratified slurry pipe flow are a relatively unexplored area. Pressure gradient measurements in slurry pipes situated in laboratories are often based on the measurement of the pressure drop over relatively short stretches. Inevitably, the laboratory measurements are conducted a certain distance behind components, where the flow might still be transient.

A paper by Matousek and Krupicka (2013) led the author to the idea that earlier measured peaked hydraulic gradient curves (Matousek 1997, Matousek 2002, Gu et al. 2007) might reflect transient development of the flow, including standing harmonic waves. At these peak conditions a restratification was measured: the sliding bed layer is thicker (Matousek 1997).

In order to find out whether such a transient process occurs, it was decided to conduct detailed systematic longitudinal pressure profile measurements downstream of a bend, some of which are reported here. A preliminary laboratory measurement already revealed the presence of harmonic waves, Talmon (2015). The objective of the reported measurements is to quantify the waves and associated flow conditions.

To the author's knowledge, such detailed pressure profile measurements on hyperconcentrated sand-water mixtures have not been published before. The paper shows how this transient process changes with flow velocity, sand concentration and grain size. These measurements serve to validate theoretical developments.

2. TEST SET-UP

The tests are conducted in a Perspex slurry loop circuit situated at Delft University of Technology, see Figure 1. The internal diameter of the pipes is D=0.04 m. A straight pipe section, situated downstream of a 180 degree r/D=5 bend, is equipped with a series of 9 pressure taps approximately equidistantly distributed over a distance of 3 m. The pressure taps are situated at 45 degrees from the pipe's crest to prevent air entering in the impulse tubes during start-up.

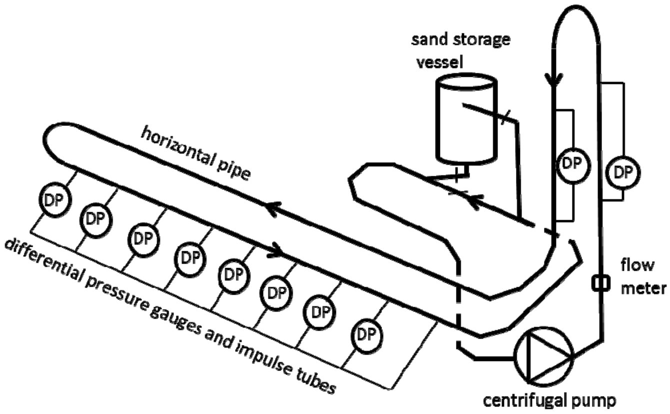

Figure 1 Schematisation of slurry loop circuit

The pump is connected with flexible hoses to the circuit. The discharge hose is connected to the riser. The flow meter is situated in the lower part of the riser: 7D from this flexible hose connection. The delivered solids concentration is measured in the vertical section U-loop section via gravitational slurry density measurement, Wilson et al. (2008).

The pipe line contains 9 pressure taps. The longitudinal pressure profile along the horizontal pipe is measured by 8 differential pressure gauges (7 * Rosemount DP4 and 1 * DP3), Figure 2. The last pressure tap serves as a reference: upstream pressures are measured against this (common) pressure.

The pressure taps have an internal diameter of 2 mm and are connected to sand pots for settling of sand eventually entering the pressure tap. The sand pots are connected with impulse tubes to the differential pressure gauges. By means of switching a set of valves and the opening of measuring chamber drains of the differential pressure gauges, the impulse tubes and differential pressure gauges are flushed with tap water to clear the measuring system of any air bubbles.

The sieves curves of tested silica sands (Dorsilit 9 and Dorsilit 8) are shown in Figure 2. Median grain sizes are: 0.325 mm and 0.57 mm respectively.

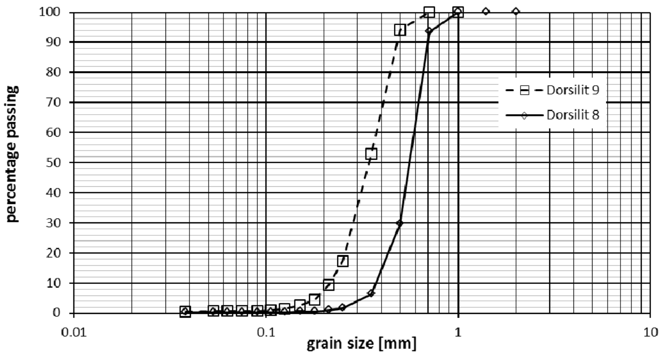

Figure 2 *Sieve curves of utilised sands*

Since traveling density waves may develop naturally in stratified long distance pipelines and loop circuits, Talmon et al. (2007), the measuring time needs to be sufficient to capture several passages of these. The data is recorded with a frequency of 10 Hz for a duration of 300 s. The content of the circuit is 28.9 litres (without storage vessel and auxiliary pipes). At a velocity of 1.5 m/s the circulation time is 15.3 s. For a 300 s measurement duration, the fluid is circulated circa 20 times, which is considered sufficient for subsequent processing.

3. TEST RESULTS

Before and after slurry measurements, water was run through the measuring section to monitor the performance of the measuring system under known conditions, showing data describing the hydraulically smooth curve of the Moody diagram.

3.1. DELIVERED CONCENTRATION

For a series of tests a known mass of sand is fed into the loop. At highest flow velocity the sand is distributed homogenously. In that case the concentration measured in the vertical U-loop is equal to the spatial averaged concentration in the recirculating loop. Stratification occurs at lower velocities and sediment transport is less efficient: the transport concentration becomes lower. Consequently the concentration measured in the vertical U-loop becomes smaller, see Figure 3, and the concentration in the horizontal sections becomes larger.

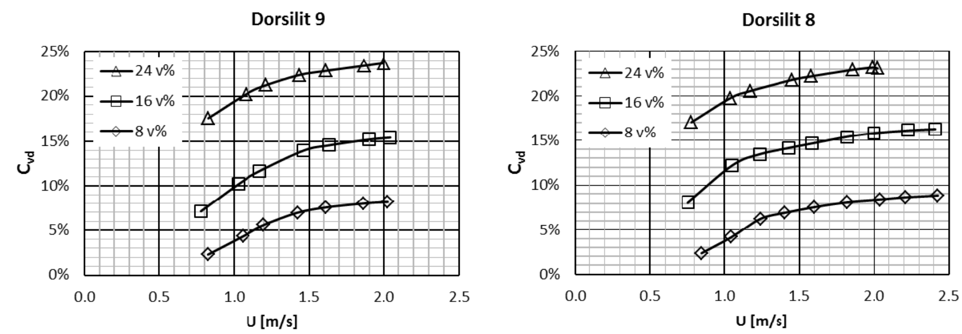

Figure 3 Delivered concentration C_{vd} measured in the vertical U-loop as a function of flow velocity and spatial concentration of solids in flow loop, mentioned in legend

Traveling density waves were seen in the vertical U-loop data, contrary to the situation in an earlier pilot measurement, Talmon (2015). These traveling waves may result from start-up of the flow, but also from velocity changes between measurements. Another cause could be a self-amplification mechanism, in that case the waves are a natural component of sand transport, Talmon et al. (2007) and won't disappear. Since the ultimately measured stationary pressure profiles in the horizontal pipe are similar to the pilot measurement, it does not make a fundamental difference if these travelling waves are still present.

3.2. PRESSURE PROFILES

The stationary wave pattern is already revealed in the longitudinal pressure profiles, Figure 4a and 5a, but becomes clearer when local pressure gradients are considered, Figure 4b and 5b. The wave length at velocities of U=0.8 m/s to 1.0 m/s is about 40*D*. The wave length increases for higher velocities.

Figure 6 and 7 show how the pressure gradient varies with flow velocity if it is measured with a pair of closely spaced pressure taps at different distances behind the bend. At closest distance the clean sweeping action of the bend with increasing flow velocity is seen. At a location of 23*D* to about 40*D* the typical restratification signature is found (resembling I-U graphs in Matousek 1997). At 50*D* to 70*D* even double peaked results are found (resembling results in Gu et al. 2007). These double peaks are a result of a downstream shifting of the wave pattern with velocity over the measuring location.

It is to be pointed out that the presented dP/dx-U (pressure gradient - velocity) diagrams should not be interpreted as I-U (hydraulic energy gradient - velocity) diagrams. In varying flow conditions the total energy consists of downstream varying contributions from potential (pressure) and kinetic energy. I-U diagrams should be determined at further distances behind components and over greater pressure tap intervals.

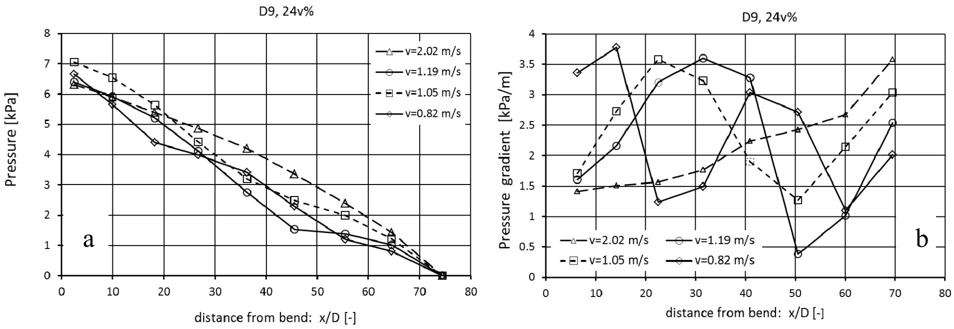

Figure 4ab *Longitudinal pressure profiles and pressure gradient profiles calculated from these longitudinal pressure profiles*

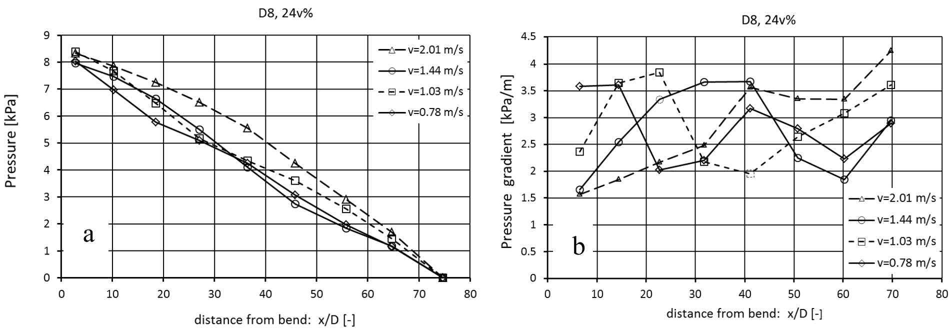

Figure 5ab *Longitudinal pressure profiles and pressure gradient profiles calculated from these longitudinal pressure profiles*

4. EVALUATION

A stationary wave pattern is measured. With increasing flow velocity the wave pattern is found to shift downstream. This appears to be caused by a clean sweeping action of flow exiting the bend. The restratification effect appears when internal structure and fluid pressures are measured too close to disturbances. It shows up when the measurement takes place between the trough and crest of the stationary wave pattern, of which the pattern shifts with flow velocity.

Furthermore, the wave pattern may repeat itself one wave period downstream. This was probably the case in the pressure gradient measurements at 35*D* and 75*D* reported by Brouwer et al. (2013). Within the 80*D* of our test set-up no asymptotic equilibrium is reached. An exception might be at highest flow velocities, but this cannot be ascertained because of lack of further downstream pipe length. For practical flow conditions, usually a bit higher than the deposit limit velocity, adaptation lengths are more than 80*D* for the solids employed in our tests.

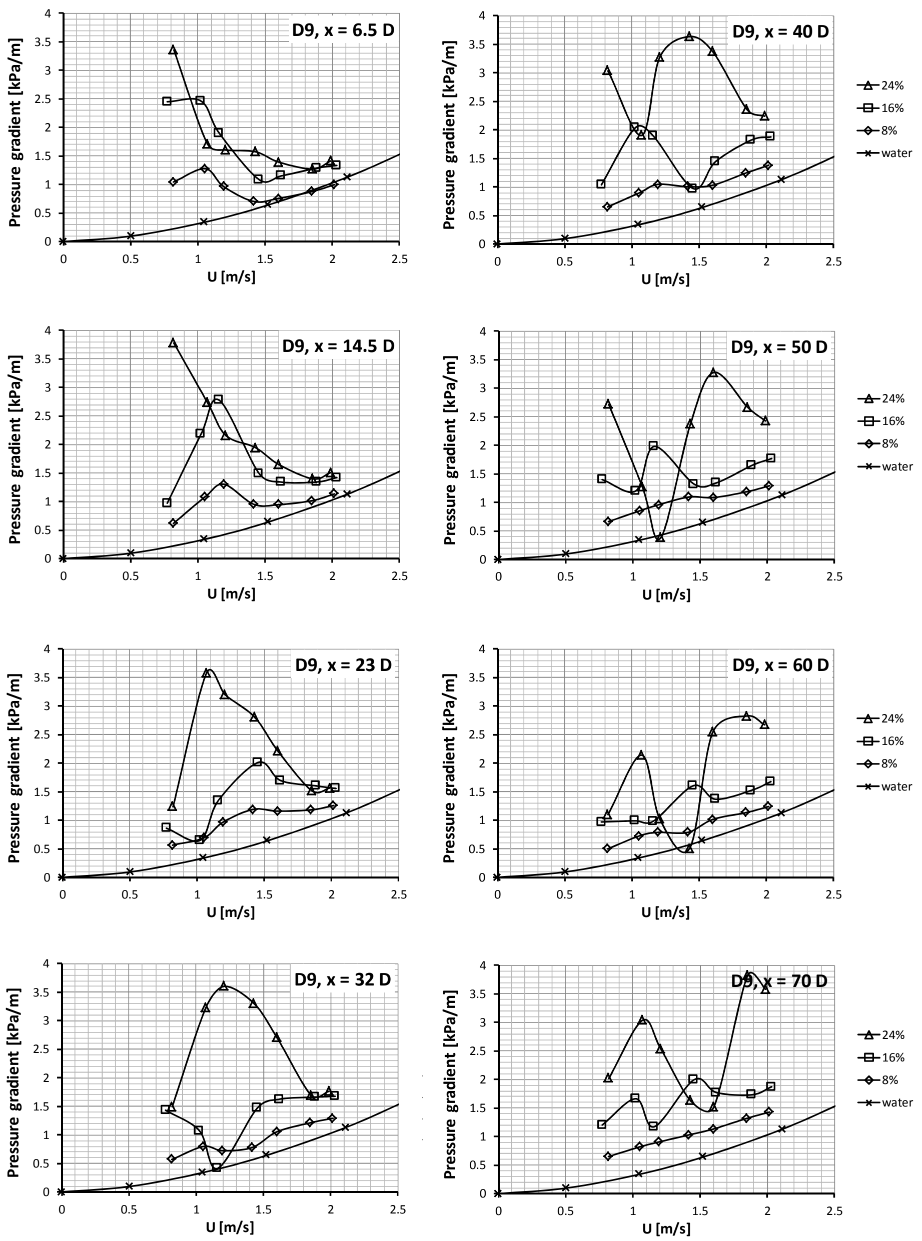

Figure 6 Local pressure gradient for Dorsilit 9 sand measured at different distances from the bend. Interval of pressure taps is of the order of 8 to 10 D

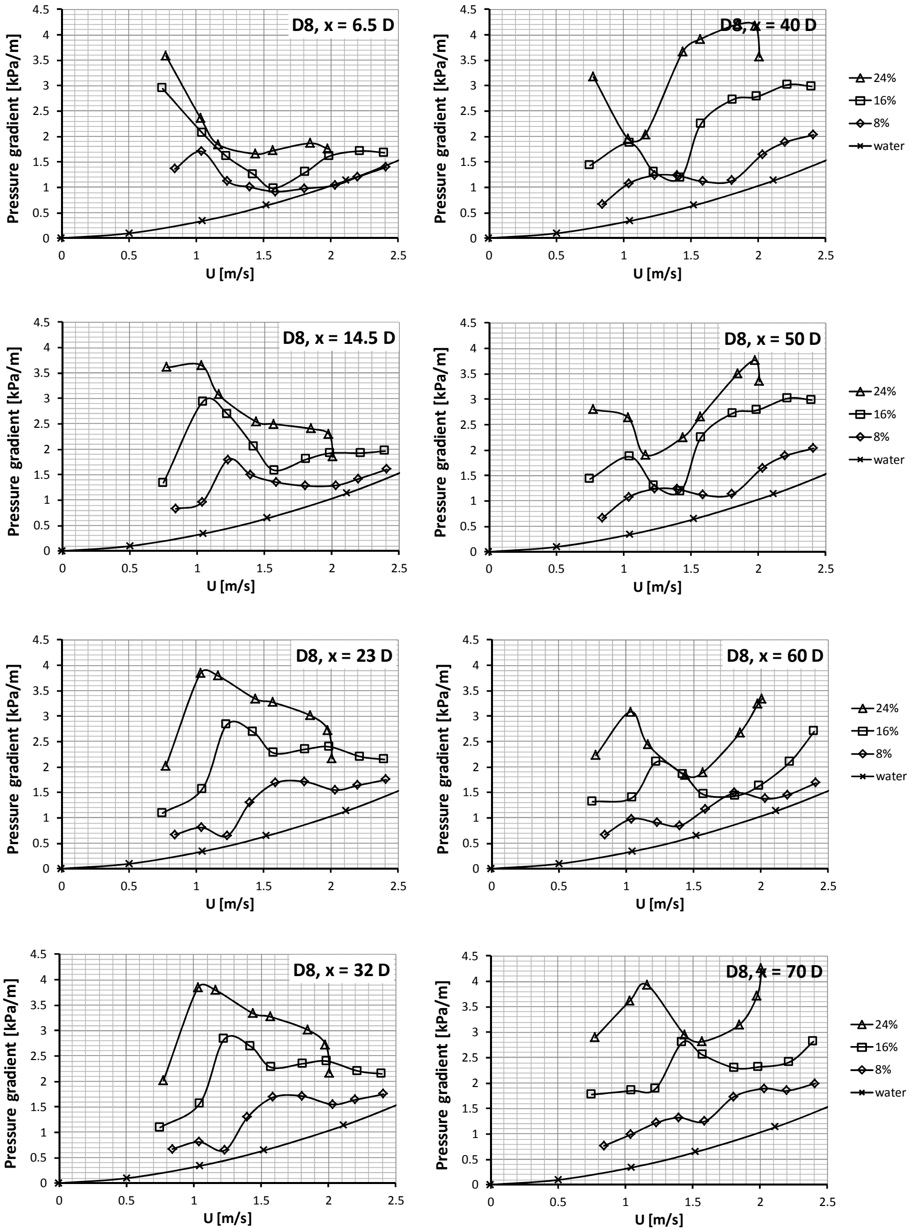

Figure 7 Local pressure gradient for Dorsilit 8 sand measured at different distances from the bend. Interval of pressure taps is of the order of 8 to 10 D

5. CONCLUSIONS

Significant stationary longitudinal pressure variations downstream of a 180 degrees bend have been measured. The restratification effect appears when internal structure and fluid pressures are measured too close to disturbances, such as a bend. Pressure drops measured under such conditions should not be interpreted as hydraulic energy gradient. Hydraulic energy gradients should be measured distant from disturbances, and over large intervals to minimize the influence of eventual stationary waves. To determine the extent of waves with distance a longer test set-up is necessary, an extension is already built.

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