Prepared for:
R W S- DGW Hydro-Instrumentation Department
Project TNW* FYSALG

Characterization of suspension samples Poortershavene

AFGEHANDELD

Development of silt measuring methods

July 1993

delft hydraulics
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SUMMARY AND CONCLUSIONS

Suspension samples and also samples of bottom material from the Poortershaven field location have been studied acoustically. It has been shown that acoustic characterization by attenuation and scattering spectroscopy gives quantitative as well as qualitative information about the particles in the samples. It is shown that the quantitative information, regarding the size distribution, is in general consistent with the results of particle size analysis by the optical diffraction method. Furthermore the acoustic characterization provides an extra parameter, the acoustic cross section, which can be interpreted as a particle shape parameter.

The results obtained present evidence that scattering measurements are likely to be more sensitive than attenuation measurements. This means that scattering measurements, although more limited as regards the feasible frequency range, can provide valuable complementary information, especially at low particle concentrations. This is valid even for particles in the silt size range, using frequencies up to 20 MHz. Therefore it is recommended to implement scattering measurements in the research-phase instrument.

If the suspension samples from the Poortershaven location, as taken for the present study, are representative as regards variability in concentration and sediment material (size range, silt to sand ratio etc.), than it should be concluded that this location is not a suitable test-site for the acoustic research-phase instrument.

A general conclusion is that laboratory measurements are a necessary first step in the development of a research-phase instrument. However, only in situ measurements in the field can provide information about the real field particle size distributions (etc.) directly. Such measurements are foreseen at the end of the SMART/ISUSAT (EC-MAST) project, where the acoustic research-phase instrument and an in situ optical diffraction particle sizer will be tested and compared.

1 INTRODUCTION

An acoustic measuring method for the concentration and size of suspended sediment particles has been developed during recent years [1-3]. The emphasis was on the measuring principle and the research was carried out in the laboratory. The programme was called "Development of silt measuring methods" and was funded by the Hydro-Instrumentation Department of RWS/DGW and by DELFT HYDRAULICS.

The present study is the last piece of work which is carried out within the framework of this programme and forms a link with a newly started project within the EC-MAST programme, SMART/ISUSAT [4]. In this new project the emphasis shifts to more applied research and to the development, in parallel, of a "first prototype field instrument", which has been called a "research-phase instrument".

The present study comprises the acoustic characterization in the laboratory of some field samples. The samples were taken from the river Rhine at Poortershaven, which is a field measuring location of RWS in the Rotterdam Waterway near to Maassluis-West [5]. The aim was to obtain relevant information for the first definition phase of the design of the research-phase instrument, as regards field conditions. Further, the study should provide some information on the suitability of the specific field location as a possible future test-site for the research-phase instrument.
In the following, the measurements which have been carried out are documented. It should be noted here that, unfortunately, the results of the study are of a rather limited value. The various reasons will be mentioned. However, it was still possible to draw some interesting specific and more general conclusions.

2 RESULTS AND DISCUSSION

2.1 Field samples as received

Suspension samples of 50 l have been taken at three different moments of the tide: high, low and in between. This was done at two different heights above the bottom: 0.5 m and 5 m. Also, one sample of bottom material was taken. The sampling was carried out by RWS, at the Poortershaven location, close to the measurement set-up of the Hydro-Instrumentation Department [Ref. evt.: RWS-rapportje].

The suspension samples were delivered at the laboratory in 25 l containers, two for each of the 50 l samples, labelled A and B. The water density and the sediment mass concentration of the samples were determined. They were practically equal for the two parts (A, B) of the samples. These data are collected in Table 1.

<table>
<thead>
<tr>
<th>sample no.</th>
<th>relative time (h)</th>
<th>tide</th>
<th>height above bottom (m)</th>
<th>density (kg/m³)</th>
<th>sediment concentration (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A, B</td>
<td>0</td>
<td>high</td>
<td>0.5</td>
<td>1019.6 (A), 1019.9 (B)</td>
<td>0.193</td>
</tr>
<tr>
<td>4A, B</td>
<td>0</td>
<td>high</td>
<td>5</td>
<td>1019.7 (A), 1018.8 (B)</td>
<td>0.067</td>
</tr>
<tr>
<td>2A, B</td>
<td>4</td>
<td>mean</td>
<td>0.5</td>
<td>1012.2 (A), 1014.0 (B)</td>
<td>0.058</td>
</tr>
<tr>
<td>5A, B</td>
<td>4</td>
<td>mean</td>
<td>5</td>
<td>1004.3 (A), 1004.6 (B)</td>
<td>0.023</td>
</tr>
<tr>
<td>3A, B</td>
<td>7</td>
<td>low</td>
<td>0.5</td>
<td>1011.3 (A), 1010.0 (B)</td>
<td>0.027</td>
</tr>
<tr>
<td>6A, B</td>
<td>7</td>
<td>low</td>
<td>5</td>
<td>1000.9 (A), 1001.2 (B)</td>
<td>0.015</td>
</tr>
</tbody>
</table>

A first judgment of the suspension samples was made by visual inspection of small amounts in glass cylinders. The sediment material was of the same type for all six samples. The individual particles were clearly visible, relatively coarse with respect to clay and had a brownish colour. The settling behaviour was very similar for all samples, the particles were relatively light with respect to sand. A particle size analysis by optical diffraction of as received samples 1A and 1B gave a d₅₀ of about 40 μm (see Table 2).

It was concluded that all suspended sediment samples contained the same (unknown) material. This material was not sand, neither (pure) clay and was also different from the bottom material.

It should be noted here that the above conclusion was the main reason to use only the first out of the six available suspensions samples for acoustic measurements. Furthermore, this was the sample with the highest concentration. In fact, the concentrations of the other samples were so low that it would
have been impossible to detect relatively small differences in the particle size distributions.

The bottom material (about 1 l) contained silt, sand, stones and pieces of pottery. The silt was black and sticky and different from the material in the suspension samples. The sand was of a grey colour.

About 40 g of the bottom sample was analyzed further. It contained about 40% water, 35% silt and 25% sand. Of the sand, the fraction greater than 500 µm (about 40% of the sand fraction) was removed by sieving. Of the remaining (< 500 µm) sand fraction the d$_{50}$ as determined by optical diffraction was about 200 µm. The silt fraction had a d$_{50}$ of about 10 µm (see Table 2).

2.2 Characterization by acoustic spectroscopy

Acoustic measurements were carried out on the suspension sample 1 (A,B) in different conditions. Further, the bottom sample was studied acoustically. From the suspension circuit of the experimental set-up, which has a volume of about 15 l, (small) samples can be taken with a suction device for reference purposes (see Fig. 1). The reference samples were analyzed by optical diffraction (Malvern Particle Sizer) to obtain estimates of the particle size distribution by volume. Further, the mass concentration was determined. First it is useful to discuss briefly the results of the reference measurements, as collected in Table 2.

**Table 2** Particle size analysis data (using a Malvern optical diffraction particle sizer) for the suspension sample 1 (A, B) under different conditions and bottom sample material. Reference is made to the figures in which the corresponding acoustic measurements can be found, identified by their acoustic measurement number. C$_{m}$ is the sediment mass concentration for the acoustic measurements.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Note</th>
<th>$d_{16}$ (µm)</th>
<th>$d_{50}$ (µm)</th>
<th>$d_{94}$ (µm)</th>
<th>C$_{m}$ (kg/m$^{3}$)</th>
<th>Acoustic meas. no.</th>
<th>Fig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>as received</td>
<td>15</td>
<td>42</td>
<td>98</td>
<td>0.193</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1B</td>
<td>as received</td>
<td>15</td>
<td>39</td>
<td>93</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1A</td>
<td>pump velocity 6</td>
<td>5.6</td>
<td>14</td>
<td>28</td>
<td>0.170</td>
<td>7</td>
<td>4, 5, 7, 8</td>
</tr>
<tr>
<td>1B</td>
<td>pump velocity 3</td>
<td>7.9</td>
<td>19</td>
<td>35</td>
<td>0.150</td>
<td>11</td>
<td>4, 5</td>
</tr>
<tr>
<td>1B</td>
<td>pump velocity 6</td>
<td>4.5</td>
<td>11</td>
<td>22</td>
<td>0.130</td>
<td>12</td>
<td>4, 5</td>
</tr>
<tr>
<td>Bottom</td>
<td>silt fraction as received</td>
<td>3.8</td>
<td>10</td>
<td>36</td>
<td>0.713</td>
<td>13</td>
<td>6, 7, 8</td>
</tr>
<tr>
<td>Bottom</td>
<td>silt fraction as received</td>
<td></td>
<td></td>
<td></td>
<td>0.400</td>
<td>16</td>
<td>7</td>
</tr>
<tr>
<td>Bottom</td>
<td>sand fraction &lt; 500 µm</td>
<td>120</td>
<td>197</td>
<td>270</td>
<td>3.765</td>
<td>14</td>
<td>6</td>
</tr>
<tr>
<td>Bottom</td>
<td>mixture of sand: and silt:</td>
<td>133</td>
<td>204</td>
<td>274</td>
<td>2.150</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>China clay</td>
<td>for comparison</td>
<td>3.3</td>
<td>8.0</td>
<td>16</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Reference measurements

In the experimental set-up for acoustic spectroscopy, the suspension is pumped around by a slurry pump, in order to enable the water temperature to be regulated. The effect that the slurry pump has on the particle size distribution of the Poothershaven suspension samples has been studied. Representative results for a "standard" pump velocity 6 were compared with those for a relatively low pump velocity 3. It is clear from the particle size distributions shown in Figures 2 and 3 and the corresponding parameters $d_{16}$, $d_{50}$ and $d_{84}$ (Table 2), that the pumping reduces the size of the particles. Already at a relatively low flow speed, corresponding to the pump velocity 3, the sizes are strongly reduced with respect to the as received sample. Two remarks should be made.

1. It is questionable how representative the as received suspension samples were (as regards particle size distribution) for the field situation. They were allowed to settle for a relatively long time in the containers.
2. The optical diffraction measurements are carried out in a suspension cell, which is mechanically stirred to suspend the particles.

A conclusion is that it may be worthwhile to study the possibility to further reduce the pump velocity in the laboratory set-up, which would also lead to more and more settling of the particles in the circuit. The limit would be no pumping at all, where due to the settling and possible temperature changes, there would be a stationary measuring condition only for a limited time.

A general conclusion is that laboratory measurements are a necessary first step, but only in situ measurements in the field can provide information about the real field particle size distributions (etc.) directly. Such measurements are foreseen at the end of the SMART/ISUSAT project, where the acoustic research-phase instrument and an in situ optical diffraction particle sizer will be tested and compared.

Suspension samples

Acoustic attenuation spectra for the samples 1A and B are shown in Fig. 4. Sample 1B was first measured with a pump velocity 3 (no. 11) and then with a pump velocity 6 (no. 12). The three acoustic measurements are equal the within experimental error. Thus, although a difference is expected between the two measurements at different pump speeds, the statistical error is too large to see it.

It should be noted that the statistical error in these two measurements (no. 11 and 12) was relatively large, due to a known but unrepairable noise source in the electronic system. The measurement on sample 1A (no. 7) shows the smaller statistical variations that are obtained in the absence of this extra noise source.

Acoustic scattering measurements, under an angle of 120° with the source beam direction, were carried out simultaneously with the attenuation measurements and are shown in Fig. 5. The frequency range is 1 - 20 MHz, smaller than for the attenuation measurements, but still very large: usually only one or a few frequencies are measured [6]. The scattered received signal intensities are shown as they are measured, i.e. without correcting for the transducer transfer functions. (The correction procedure should still be developed.) This means that the relative signal levels for the different transducers in a given spectrum have no meaning. One should compare the signal levels for each transducer pair in the different spectra.

The results are quit interesting. Clear differences are observed. Only a qualitative interpretation can be attempted, which is partly consistent with the result of the optical diffraction size analysis on the suction samples. One should realize that for the scattering measurements, as for the attenuation measurements, the lower frequencies are more sensitive for larger particles. Similarly, the higher frequencies are more sensitive for smaller particles. At 10 MHz the maximum sensitivity is attained for a size of the order of 100 μm [7].

Comparing first the measurements at the two different pump velocities. The measurement at pump
velocity 3 (no. 11), shows a higher scattering in the frequency range of 4 - 15 MHz than that at pump velocity 6 for the same suspension (no. 12). This is consistent with a shift of the whole particle size distribution to smaller sizes, such that the part of the scattering above the measured range (i.e. above 20 MHz) is increased. This result is consistent with the optical diffraction result.

Comparing now the two measurements at the same pump velocity taken at samples 1A (no. 7) and 1B (no. 12) respectively. Clearly the ratio of the scattering at about 10 MHz to that at 4 - 5 MHz is higher for sample 1A than for sample 1B. This is consistent with finer particles in sample 1A than in sample 1B. This result is not consistent with the optical diffraction size analysis.

An important conclusion from the scattering measurements is that it turns out that they are probably more sensitive than attenuation measurements. Therefore they can give valuable complementary information, especially at low particle concentrations (as in the present case), even for particles in the silt size range.

Samples of bottom material

The results of the acoustic characterization of the bottom sample material are as follows. The attenuation spectra of the silt and sand size fraction, shown in Fig. 6, exhibit the characteristic shape expected for the corresponding sizes.

Further, a mixture was prepared from the silt and sand fractions in a mass ratio given in Table 2. The spectrum of this suspension of bottom material, shown in Fig. 6, is a linear combination of the sand and the silt fraction spectra. A good fit can be obtained by a simple least-squares procedure [8]. Instead of this fitted spectrum, the calculated linear combination, using the as-prepared mass concentrations of the 2 mixture components as coefficients, is shown in Fig. 6, to point out an effect relevant to future measurements of this type with field material. It is seen that the agreement is not very good. The calculated spectrum is too high at higher frequencies, which reflects an overestimation of the silt component. The conclusion must be that silt has disappeared from the actual mixture.

This can be due to two effects. The first effect, which is believed to be the most important, is that the silt is actually disappearing in the suspension circuit, until some equilibrium situation is reached. This means that the silt is sticking in corners and at surfaces where the flow velocity is low. This effect has actually been observed for the pure silt fraction and can be taken into account in that case by measuring the concentration, until equilibrium is reached and perform the acoustic measurement afterwards. This was not attempted for the mixture case. The second effect that may occur is that part of the silt sticks to the sand particles.

In order to check the homogeneity of the bottom silt material, acoustic spectra were obtained for suspensions prepared out of different samples from the bottom silt fraction. The acoustic spectra reproduced well, confirming sufficient homogeneity, as is illustrated in the upper graph of Fig. 7.

Comparison of suspension and bottom silt material

It has been demonstrated before that acoustic attenuation spectra can be interpreted quantitatively in terms of size and shape of the particles [9, 10]. For the present purpose a semi-quantitative discussion is sufficient and appropriate in view of the limited scope of the project.

The measured spectra for the silt bottom fraction and for the suspension material are reproduced in Fig. 7 (lower 2 graphs), where a comparison is made with China clay, a standard reference material in the silt size range. Since the vertical scale of these spectra is normalized (per unit of concentration), the differences in magnitude are relevant. The conclusion is that the three spectra are different. Therefore, also the corresponding suspensions are different.

What the differences are, can be explained using the results of the quantitative analysis referred to
above. In this analysis a slightly different normalization of the spectra is used, per unit of frequency and concentration, as is shown in Fig. 8. The general shape of a spectrum in this normalization is a, relatively broad, peak. The peak position is inversely proportional to the average particle size. The width of the peak is proportional to the width of the particle size distribution and its magnitude is related to the attenuation geometric cross section and therefore to the shape of a particle.

As regards the bottom silt material the following conclusions can be drawn from the comparison with China clay in the upper graph of Fig. 8.
The average sizes are about the same (about 10 μm, corresponding to a peak position of 100 MHz). The width of the size distribution for the bottom silt material extends to larger sizes (lower frequencies) than for China clay. These conclusions are consistent with the optical diffraction size analysis results (Table 2). Further, the acoustic measurements indicate a larger acoustic cross section (by about 50%) for the bottom silt material (with respect to China clay), which can be due to a more irregular shape.
The same type of interpretation of the lower graph of Fig. 8, comparing the suspension sample material and China clay, can be given. The suspension sample has a larger average size (20 - 40%) than China clay and the size distribution extends to larger sizes. Again these results are consistent with the size analysis by optical diffraction. In contrast to the bottom sample material, the suspension material has about the same acoustic cross section as China clay.
Therefore, comparing suspension and bottom silt samples, the suspension particles have a larger average size and a smaller acoustic cross section, corresponding to a less irregular shape, than the bottom silt particles.

3 CONCLUSIONS

It has been shown that acoustic characterization by attenuation and scattering spectroscopy of the suspension samples and also of bottom sample material gives information about the particle size distribution, which is, in general, consistent with the results of particle size analysis by the optical diffraction method. Furthermore the acoustic characterization provides an extra parameter, the acoustic cross section, which can be interpreted as a particle shape parameter.

The results obtained present evidence that scattering measurements are likely to be more sensitive than attenuation measurements. This means that scattering measurements, although more limited as regards the feasible frequency range, can provide valuable complementary information, especially at low particle concentrations, even for particles in the silt size range, using frequencies up to 20 MHz. Therefore it is recommended to implement scattering measurements in the research-phase instrument.

If the suspension samples from the Poortershaven location, as taken for the present study, are representative as regards variability in concentration and sediment material (size range, silt sand ratio etc.), than it should be concluded that this location is not a suitable test-site for the acoustic research-phase instrument.

A general conclusion is that laboratory measurements are a necessary first step, but only in situ measurements in the field can provide information about the real field particle size distributions (etc.) directly.
ACKNOWLEDGEMENTS

All the acoustic experiments and laboratory analysis work was done by J.C.A. Wenneker. The necessary support of the electronic system and processing software was provided by N. Berkhoudt and W.J. Taal.

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Fig. 1 Diagram of the laboratory experimental set-up for acoustic attenuation and scattering spectroscopy, showing the suspension circuit and a block diagram of the electronics.
Fig. 2  Particle size distributions measured by optical diffraction (Malvern Particle Sizer), for suspension samples (upper graph) and silt and sand fraction of a bottom sample. Characteristic sizes are summarized in Table 2.
Fig. 3 This figure shows the same data as Fig. 2, using a logarithmic size scale.
Fig. 4 Measured attenuation spectra, normalized per unit of concentration, for suspension sample 1A (top graph) and suspension sample 1B (bottom graph) at normal pump velocity of the suspension circuit, and suspension sample 1B (middle graph) at a lower pump velocity of the suspension circuit. See also Table 2.
Fig. 5 Measured spectra of the scattering, at an angle of 120° with the forward direction, for the same suspensions as shown in Fig. 4. The scattering is given as an intensity and is not corrected for the transfer functions of the emitting and receiving transducers.
Fig. 6 Measured attenuation spectra for the silt and sand size fractions of the bottom sample, separately (upper 2 graphs) and for a prepared mixture (lower graph). For further explanation see text and Table 2.
Fig. 7 Measured attenuation spectra showing (from top to bottom): the reproducibility of different measurements of the silt bottom sample, the silt bottom sample compared with China clay and a measurement of a suspension sample compared with China clay. See Table 2 for size and concentration data.
Fig. 8 Measured attenuation spectra as in the 2 lower graphs of Fig. 7, but normalized in a different way, i.e. the vertical scale is divided by the frequency. For further explanation see text.