Acoustic measurement and morphological features of organic sediment deposits in combined sewer networks

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ABSTRACT

The performance of sewer networks has important consequences from an environmental and social point of view. Poor functioning can result in flood risk and pollution at a large scale.

Sediment deposits forming in sewer trunks might severely compromise the sewer line by affecting the flow field, reducing cross-sectional areas, and increasing roughness coefficients.

In spite of numerous efforts, the morphological features of these depositional environments remain poorly understood. The interface between water and sediment remains inefficiently identified and the estimation of the stock of deposit is frequently inaccurate. In part, this is due to technical issues connected to difficulties in collecting accurate field measurements without disrupting existing morphologies. In this paper, results from an extensive field campaign are presented; during the campaign a new survey methodology based on acoustic techniques has been tested. Furthermore, a new algorithm for the detection of the soil-water interface, and therefore for the correct esteem of sediment stocks is proposed. Finally, results in regard to bed topography, and morphological features at two different field sites are presented and reveal that a large variability in bed forms is present along sewer networks.

Keywords: sonar profiler, morphology, organic sediment, sewer deposits

1. INTRODUCTION

Sewer networks are essential for urban areas and their performance has important environmental consequences because it determines the quality of sanitation, and influence the risk of urban flooding (e.g. European standard NF EN 14654-1). Standard norms for environmental impact of sanitation facilities establish that sedimentation in sewer trunks should be prevented in order to avoid both flooding, and pollution issues. In fact, sediment accumulations have two main consequences: firstly, they reduce the ability to evacuate wastewater due to changes in friction and in cross sectional area; secondly, due to their organic nature, these sediments can be easily eroded and contaminate nearby areas. In spite of these deleterious effects, sediment deposits generally occur and interest large parts of sewer trunks; therefore, is important to understand their properties, and to identify effective methodologies aimed at characterizing their morphological features.

Difficulties arise when trying to study these depositional environments due to health and safety, as well as technical issues. Classically, sediment accumulations were detected using mechanical probes, i.e., point gauges, optical backscatter probes or endoscopes (Oms 2003). The limitations of these methodologies are connected to the fact that the sediment interface might be strongly perturbed leading to a misevaluation of the amount of sediments, especially in the presence of very soft fractions. Limitations are also caused by the fact that these instruments frequently necessitate the installation of large and unpractical equipment (Ahyerre et al. 2001). Moreover, these sensors are mostly punctual and difficult to use to trace fine resolution transverse profiles of the sewer trunks. More recently, Bertrand-Krajewski and Gibello, 2008 proposed the use of ultrasonic methodology to investigate the sediment bottom, and by using a rotating device showed that this technology could be potentially used inside sewer networks. However, no information about the nature of the sediment deposits was given, and preliminary results were only based probe outputs. (Gourmelen et al. 2010) also developed an acoustic system and provided new insights about sediment interface trough continuous observations; however observations were in part limited by their punctuality.

Within this context, this manuscript has a dual goal: first, a new technique, and procedure for the analysis of sediment deposits, and more accurate identification of the soft sediment interface is presented; the technique is based on an acoustic technology and a rotating sonar head. In this regard a new algorithm for a more accurate identification of the interface boundary is also defined. Measurements are then compared with results obtained with classical sediment gauges and sediment sampler.

Secondly, by using the aforementioned methodology, and fast Fourier analysis, new insights about the bathymetry, and morphology of combined sewer network bed forms are provided for two sewers in the city of Nantes (France).

2 LITTERATURE REVIEW

Characteristics of sediment interface

Combined sewer networks are characterized by a significant variability in sediment types and sediment transport patterns. (Crabtree 1989) classified sediment deposits based on the characteristics of their fractions; among those individuated by the Author, the two of interest for the present study are: Type A deposits: coarse, granular bed material-widespread; Type C deposit: mobile, fine grained found in slack zones in isolation and overlaying Type A. Type C deposits are characterised by larger fraction of organic material and a weak shear resistance.

During dry weather, a weak layer (type C) with organic content >90%, and of d_{50} around 0.5 mm is generally observed above a coarser type A layer. This weak layer is easily re-entrained when the shear stress is higher than 0.5-1 N/m^2.

Observation by (Oms 2003) confirm this multiple layers structure. According to endoscope measurements, coarser deposits are present at the bottom, and are covered by a layer of fine organic material having bulk density ρ_b in between 1046 kg/m^3 and 1315 kg/m^3. Herein, sediment interface is defined as the exterior boundary of the weak (type C) sediment layer.

(Ashley et al. 2004) further introduced two different definitions based on sampling technique, namely, near bed solids and dense undercurrent. In fact, apart from sediments in suspension, transport patterns are generally characterized by a combination of bed load over the settled bed and an inner suspension. The near bed organic solids which are transported over the settled bed, are generally detected trough sediment traps, and for dry weather flow are characterised by an organic content greater than 90% and sediment diameters d_{50} ranging from 30 mm to 50 mm. The inner suspension can be detected when sediments are collected with pipes, in form of a dense undercurrent, characterised by particles which are not in contact with the bed and which have a large dimension compared to that in the main flow field.

(Arthur et al. 1996) studied the characteristics of what has been defined as "organic near bed transport" in the Dundee combined sewage system. In this case, organic near bed fluid sediments were characterised by large volatile contents (up to 87.6%), small median radius d_{50} as 0.09mm<d_{50}<11 mm and bulk density ρ_b from 1000 kg/m^3 to 1998 kg/m^3.

Observation in the combined sewer system of Paris (Ahyerre et al. 2001), both visual and with suction systems, revealed the existence of high concentrated layer (total suspended solid concentrations up to 2 g/l) within the water column, in correspondence with what has been considered the organic layer. However, visual observation of the sediment water interface suggests that high concentrations might be linked to the survey methodology rather than to the presence of fluid sediment. In fact, direct observation during dry weather confirmed a clear distinction between water and organic layer, with only few particles moving on the top of the interface.

Laplace et al., 2003 showed that the deposits in sewers, and especially the organic layer at the water interface contribute to 40 to 70% of the total pollution from the wet weather combined sewer flow, and suggest that the organic layer formed at the surface of the deposit could be thus washed off trough flushing techniques before rainstorms. Gasperi et al., 2010 highlighted the significant role of sewer sediments as a source of Wet Weather Flow pollution, and suggested the possible importance of preventive managing service sewer actions to reduce the pollutant stocks. By using an extensive database of flow and turbidity measurements from Paris and Lyon, Hannouche et al., 2014 confirmed that the contribution of sewer depots to wet weather suspended solid discharge is important and up to 80%. By using laboratory experiments, it has been also shown that the stratification of the sediment bed can originate from biological mechanisms. Specifically, surface layers are influenced by environmental conditions and oxygen levels. A significantly weaker sediment layer with lower shear strength values is formed under more quiescent and oxygen richer conditions (Banasiak et al., 2005). Weather conditions are important for the characteristics of sediment deposits as well. Bersinger et al., 2015 showed that the sediment deposit is renewed after each rainfall event because, as the flow in pipes slows down, there is an accumulation of new sediments in the sewer. However, sedimentation processes are not the sole reason for stock renewal, and the authors suggest that the sewer network behaves as a bio-physicochemical reactor, and that biological processes leads to in-sewer transformation of deposits. Bersinger et al., 2015, also suggest that sediment stocks in sewer network during dry weather periods might be calculated by estimating the daily chemical oxygen demand fluxes brought about by the different rainfall events of the month.

In spite of numerous and valuable studies, there are still many uncertainties connected to grain size distribution, morphological features, as well as about the exact location of sediment interfaces. Many times, these uncertainties are connected to sampling techniques which are too invasive and disrupt the flow field.

Detection of the sediment deposit interface

Different techniques have been employed to identify the sediment-water interface, but many times environmental and security constraints are present.

Development of optical and acoustical backscatter probes for marine applications allow the definition of sediment bottoms trough indirect measurements. For example, (Gallagher et al. 1996) defined the distance at which the seafloor was detected using a threshold criterion, and by means of 1 MHz sonar altimeter with voltage immediately below the automatic adjusted maximum gain level. After laboratory and field experiences, they defined an automatic gain adjustment algorithm, which included signal normalization and a threshold voltage employed to individuate the time at which the bottom-echo was detected. By means of the automatic gain adjustment algorithm, the authors were able to measure the seafloor with a precision of 0.03 m. Differently, (Bell and Thorne 1997), located the sediment bottom on the base of the maximum correlation calculated between the backscatter profile measured with a 2 MHz rotating head sonar and a model bed echo which reflects an ideal approximation of what is the actual bed echo.

According to (Bell and Thorne 1997) and (Thorne and Hanes 2002) the use of the algorithm improves the localisation of the sediment bottom if compared to threshold methodologies. Moreover, the authors provide a full review of acoustic measurements technique and methodologies to determine the sediment concentration from the backscatter profile.

(Webb and Vincent 1999), based on three frequency transducer experiments, defined the bed as the place where the strongest backscatter signal is measured.

Later on, (Green and Black 1999) define the base range as the range of the bin (i.e. one of the volumes in which the water column is divided in the sonar image) immediately above the break of slope in the temporal burst-averaged concentration profile. The burst-average concentration profile was based on the averaged root-mean-square backscattered pressure profiles. According to the nature of the surveyed bed, they namely located the sediment bottom at 0.01 m below the base range for rippled bed, and at 0.02 cm below the base range for transitional and “hummocky” beds (i.e., a stratification in which mounds of sand occur).

(Hoitink and Hoekstra 2005), compared the suspend concentration profiles obtained from acoustic Doppler current profiler (ADCP), acoustic backscatter signal and optical backscatter signal (OBS).

By also considering (Alexander et al. 1997) results, they observed that acoustic instruments have different degree of penetration inside fluid mud according to the signal frequency at which the backscatter is collected. Generally, 200 kHz signal is able to detect the top of the mud layer, corresponding to roughly 1050 kg/m^3, but the reflected signal is more properly associated to a gradient of concentration rather than to a specific density. Differently, lower signal of 20-40 kHz are able to penetrate the fluid mud reaching a more consolidated layer.

However, in terms of dredging volume definitions, none of the previous elevations seemed suitable and a more appropriate layer definition comes from intrusive instrumentations, such as sled transducer, which has been designed to travel along a physical horizon of constant density and viscosity (Alexander et al. 1997). More recently, (Dolphin and Vincent 2009), adopted the methodology proposed by (Green and Black 1999) and locate the sediment bottom as the level at which the “break-in-slope” of the sediment concentration curve was observed from acoustic backscatter measurements.

It is worth noticing that the majority of technical advancements in terms of acoustic instrumentations have been done in relation to marine environments, where sandy deposits are abundant. Sewer deposits are dramatically different with respect to marine sediments, as they have a much higher organic matter concentration (30% to 89% of volatile solids), and are less homogeneous. Acoustic measurement may represent an adequate solution in terms of installation feasibility (small dimensions and light < 5 kg, no needs of special equipment, and the ability to detect the interface with minimal interaction, a characteristic rather important in presence of soft sediments.

3 METHODS

Equipment

Herein, a sonar profiler is used to detect the interface of the sediment deposits, and then compare the acoustic measurements with data from a sediment gauge. Water samples were collected as well.

The use of a sonar profiler in sewer network is a relatively unexplored technology. Results from the sonar were improved by modifying the algorithm used to extract the sediment interface. In this regard, a sonar profiler (thereafter mentioned SONAR), manufactured by Marine Electronics ltd., and with 2 MHz working frequency was used to measure the bottom transverse and longitudinal acoustic response of the sediment bed.

The profiler consisted in an emitter and an acoustic receiver that rotates inside the probe case. The probe case consisted of an alloy cylinder of 70 mm of diameter and 445 mm of length. The sonar profiler has a rotating head that measure the acoustic backscatter along 400 beams of 0.9° each and for 250 control volumes, or bin, from the centre of the probe to the maximal measured distance or range $R_{\max}$, with a frequency of 1 Hz (i.e., a section each second).

The plane of rotation is located at around 4.5 cm from the edge of the PVC boot. The probe can detect the acoustic backscatter (ABS) with maximum distances (subscript "max") ranging between 0.125 m < $R_{\max}$ < 6 m, where R is the generic position of the control volume or bin from the SONAR centre (Figure 1c). The probe is able to detect both pitch and roll angles (right bottom of the frame), with a precision of ±0.1°. The main parameters to regulate were:

1) the "range" or maximum detectable distance, $R_{\max}$ (0.125 < $R_{\max}$ < 6 m); Since each radial beam is divided into 250 control volume between $0<R<R_{\max}$, the probe presents a geometrical resolution of 1/250 of the maximum range.

2) the "pulse length", P_L (4 μs <P_L<20 μs), which represent the duration of the pulse generated by the sonar; the vertical resolution δ_v is connected to P_L by $\delta_v=cP_L/2$.

The output generated by the software is given in counts using an 8-bit scale. The SONAR is equipped with a 70 dB logarithmic receiver, in which the output voltage (the voltage post-processed by the probe and which is latter converted in counts) produced by the probe is proportional to the logarithm of the input voltage (i.e., the row signal recorded by the piezoelectric transducer of the SONAR). The software automatically adjusts the gain to the largest detected backscatter. However, the output also gives the gain used for the automatic adjustment.

The software also allows for the regulation of the maximal intensity and the signal threshold, which, however, does not modify the accuracy of the measure. The temperature needs to be manually adjusted, as the probe has not been equipped with a thermometer. Hence, temperatures have been recorded by means of a digital thermometer installed in the network, with precision of 0.1°C and regularly calibrated.

The software elaborates separately each beam or sector of 0.9°. A profile of the bottom can be obtained by the recorded image using three different software algorithms: 1) “Max”, the profile is obtained from the points were the maximum ABS is detected; 2) “3/4”, the profile is obtained from the point were ¾ of the maximum ABS is detected; 3) “Area1”, the profile is obtained from the point were the largest energy is detected. Generally, “Max” shows a profile that is more extended compared to the other two. Slight differences occurs between them, generally less than 1 cm over hard bottom, while the profile individuated over soft deposits is more scattered.

In terms of sediment gauge measurements, when soft sediments (e.g. the type C organic layer) are present, the introduction of the gauge might interfere with the sediments and destroys the organic layer. To limit this issue, a point sediment gauge fixed at the bottom and with 25 cm disk diameter was used. When operating with a sediment gauge, the ability of the operator to detect the sediment represents a source of uncertainty as well. In this regard, to reach the top of the organic layer without entering it, the gauge should be introduced without any pressure on the disc. Water has been sampled using a suspended solid sampler device, made of four pipes of 10 mm of diameter, placed at different heights from the bottom (Jaumouillie et al. 2002). Each pipe is connected to a 2.5 l bottle with -0.07 MPa pressure. Once the pipes were connected to the bottles, the device was immersed, and the connectors opened for around 15 second.

Field sites

The “Duchesse Anne” combined sewer (DA) and the “Allée de l’Erdre” combined sewer (AE) were chosen based on their different flow characteristics as well as differences in bottom and suspended sediment concentrations

The DA site is characterised by a slope of S=0.3% (%), a catchments area of 4.11km^2, connected into a network of 21 km of length. The AE site has a slope of S=1.2 %, a catchments area of 1.41 km^2 ha and a network length of about 60 km. Table 1 summarizes flow characteristics, and sediment deposits characteristics for the two different sites and during the execution of the field campaign. Flow velocity at the DA site are, on average, 4 times higher than flow velocities at site AE, while the sediment stack at the AE site is on average 5 times higher than at the DA site (Table 1). All tests were executed in the absence of precipitation, and apart from test AE-S2 all tests were conducted after at least two days of dry weather (<0.2 mm precipitation, T_D Table 1). The number of dry weather days before the tests ranged from 0 to 10. During dry weather, the DA sewer sediment deposits have a mineral content (type A sediment, according to (Crabtree 1989)) higher than AE. The AE site generally shows, starting from the bottom, a first layer of type A sediments, a second layer of type C, and superimposed layer with high suspended sediments. Figure 1f presents an example, of sediment layering.

Both sewer pipes are characterised by an egg shaped transverse section with one lateral bank, allowing the passage of the operators, and preventing sediment disturbance (Figure 1 a,b).

Two different carriage systems have been installed inside the sewer in order to shift the probes both longitudinally and transversally. At the AE site, two rails have been installed longitudinally at the invert sides toward 10 m of length at about 1.2 m from the invert bottom, in order to reduce their inundation likelihood and the flow disturbance. The rails have been fixed starting from the manhole toward the upstream direction (Figure 1d), and consisted of 4 cm width squared alloy bars. A 1.08 m alloy bar of the same dimensions and section of that used for the rail has been fixed transversally over the rails and a mobile support, which can slide along all the channel width, held the vertical bars. In order to adjust the probe orientation, the vertical bar consisted of a cylindrical section that completely rotates in both directions. Differently, the experimental installation of DA site (Figure 1e) consisted of a single rail fixed at the top of the invert, over which a carriage has been arranged, allowing for longitudinal movements. Vertically, the position of the probes is regulated by means of a cylindrical bar, directly hanging from the small carriage, which again can be rotated in order to adjust the probe orientation. Small transverse regulations are possible to fix the probe at the dry weather channel centre. The longitudinal position of the probe is measured by means of a 1 cm precise scale fixed over the rail. A transverse bar has been used to stabilize the whole system, hence preventing and reducing lateral probe oscillations and tilting.

Measurements executions

Data presented here refer to sewer trunks in the DA-field site, and in the AE-field sites (trunks length ranging from 4 to 9km). For each transverse section, the probe centre has been fixed at the free surface over the invert centre, in order to minimize flow disturbance. For each sampled section, a SONAR image is recorded and the sewer profile extracted, with a resolution between 10 cm and 20 cm longitudinally. The image is thus made by the backscatter intensity detected at each sector of 0.9 rad. In real time conditions and based on the 8-bit backscatter intensity, the SONAR software shows the bottom profile using the max algorithms by considering the line connecting the point at which the maximum backscatter intensity is detected for each sector (Figure 2). The extensive measurement campaign was made between October 2010 and June 2011, generally between 7:30 am and 11:00 am, when the flow level was low enough to reduce the risk for the operators.

RESULTS

The algorithms developed by Marine Electronics shows a good correspondence with the observed geometry in laboratory conditions (Figure 2a) and, more in general with compacted material (concrete, sand,) as represented by white continuous lines representing the sewer contour (Figure 2a, b). However, these algorithms fail to detect the exact interface of the soft deposits (Figure 2b, the solid interface detected by the Marine Electronics algorithm is the red dashed line). Using a similar approach as (Green and Black 1999), a new algorithm has been defined which identifies the acoustic interface as the distance from the probe where the backscatter signal showed the largest gradient.

To reduce possible noise, and before gradient calculation, a Gaussian filter with 5 mm variance (equal to the instrumental variance) and of 10 cell extension was also applied for each beam (equation 1).

$$f'(R) = f * g(R) = \int_{r=0}^{r=R} f(R) \cdot g(\varsigma - R) dR \qquad (1)$$

This digital filtration aims at removing, from the original signal, spikes and noise possibly provoking a false detection. The interface is, thus calculated using eq. 2:

$$R_{\text{int}}{}^{j} = \max\left[f'(R^{j}) \right] \text{ for } 0<j<400 \qquad (2)$$

in which j represents the j^{th} beam of 0.9° detected by the SONAR. In this regard, an automated script has been developed.

Figure 2c shows an example of the application of eq. 1, 2 to the row signal (square symbols) for the detection of the interface. The original algorithm associate the solid interface to the value R=310 mm where the signal itself reaches the maximum. Differently, the new algorithm associates the solid interface to the maximum of the filtered signal gradient (continuous line), and consequently to *R*=255 mm (Figure 2c).

Figure 3a, b show filtration results, and the final soil interface detection. The sonar image blurs after the application of the filter (compare figure 3a and 3b), but also remove some noise and high spikes from the original source signal, which is advantageous to detect the interface. The final soil interface is indicated by the white circles in figure 3b (note that the number of circles in the figure has been reduced for readability), and is in better agreement with the image itself.

The profile obtained still contains some scatter, due to the presence of large cluster of debris flowing in the water. The automated script generated for this procedure also filters the scatter obtained by the previous procedure. The filter is based on both manual and automated procedure. The manual procedure allows the user to select the points to be eliminated using a rectangular box selection. The points included in the rectangular selection will be eliminated from the section. The automated procedure is based on a mobile median and standard deviation obtained from the z_{i-5} and z_{i+5} data, where z_i is the i-th point of the vertical component of the interface. Hence, the space of acceptable values is defined as the median value ± median absolute deviation obtained using a windows size of 7 points. Herein, the size of the windows has been used to better capture local patterns (Menold et al. 1999). If the value of z_i is outside the threshold is rejected, otherwise is retained. This procedure is done for all the points of the profile detected by the sonar. The algorithm is repeated until the differences between the n-step standard deviation and the n-1-step is zero.

Figure 3c shows the reconstructed morphology for one of the trunks, and by using the abovementioned methodologies. The black dots in the figure represent the row data after filtration, while the surface represents the interpolated surface using a least square interpolation algorithm.

Tests have been also conducted to verify the accuracy of the SONAR methodology with respect to gauge measurements. One of the test has been carried out at the DA site (section S1), were sediment characteristics were relatively constant (high mineral content). The SONAR rotating head has been stream wise oriented to measure a transverse profile of the sewer trunk (Figure 1d). Figure 4a shows the backscatter contour lines obtained from the SONAR image. Signal of less than 20 counts has been removed from the image, in order to increase the contrast between the water and the deposits. The image has been obtained with a pulse length of 4 μs and a range of 750 mm. According to the 8-bit backscatter amplitude, high backscatter signal corresponds to high amplitude recorded by the SONAR. The image clearly shows the lateral walls of the trunk, of which one is the vertical wall of the side bank. From this image it has been possible to obtain a 8-bit backscattered vertical profile from the centre of the probe (Figure 4b). In the plot, the range has been fixed from the centre of the probe. The centre of the probe relates to the probe dead zone, which is automatically filtered by the software and automatically set to 0 counts of amplitude. The first peak observed at about 15 cm from the centre related to a noise detected by the probe and not filtered.

For -0.15 m $<z_{SONAR}<$-0.35 m, the backscatter shows an almost constant value of about 20 counts. When the signal approaches the sediment bottom, the signal amplitude drops to about 181 counts and then reduces due to the presence of the sediment on the bottom. The signal shows a marked peak where the sediments have been detected by the gauge. The image shows that the sediment bottom is not perfectly flat, most likely connected to secondary current which could modify the shear stress and the sediment accumulation. In particular, it seems that the larger deposits are present near the left sidewall, whereas less sediment seems to accumulate at the bank wall, owing to larger velocity generally observed in this area for compound section as observed by (Larrarte 2006). According to gauge measurement, an average z_{SED} = 0.10 m of sediment has been detected, for a total water depth of δ=0.41 m. SONAR measurement shows a δ_{SONAR}= 0.44 m and a distance between the average sediment plane and the top of the bank of about 0.32 m. The total bank wall height was 0.45 m, therefore showing a sediment depth detected with the sonar of z_{BED}= 0.12 m. A comparison with the value detected with the gauge revealed a reasonable agreement. A slight difference of the order of 20% occurred, which is a satisfactory result. Inaccuracies may occur during gauging operations (the gauge may not reach the bottom, it can slightly sink in the sediment, the sediment morphology is not constant).

5.1 sediment deposits and their morphology

Figure 5a-d shows results obtained from the samples collected at the two different sites. The figure shows both the sediment concentrations in terms of TSS (total suspended solid) and VSS (volatile suspended solids) for two different sieve sizes (0.125 mm and 2 mm) and the bottom particle size distribution, in which *D* is the diameter for which the percent *P* in weight of sediment is finer. Figure 5 e-h shows the ratio between VSS and TSS at different water elevations, and for the same tests. TSS, VSS and particle size distribution were determined according to the procedure suggested in French norms: NF EN 872 and NF T 90-105-2, and water samples were collected according to (Larrarte 2008). Standard deviation values for each data point were less than 10 mg/l;

this is in agreement with accuracy values presented with the same technique by Larrarte and Pons, 2011, and Larrarte, 2015. This technique allows collecting samples of water at different levels from the free surface, and at the same time. The particle size distribution has been evaluated manually for fractions D>0.560 mm and by a MALVERN MS 2000 laser granulometer for fractions D<0.560 mm.

Bottom sediments show average diameter of about d_{50}=0.1 mm at DA, whilst AE generally shows a smaller diameter of d_{50}=0.025 mm and a sediment uniformity parameter of $\sigma_s=(d_{84}/d_{16})^{0.5}$ of $\sigma_s\approx1.41$ and $\sigma_s\approx6$ respectively, i.e., the bottom sediment particle size distribution for DA is rather uniform compared to AE conditions. The difference in the average particle sizes is linked to the averaged velocities observed at the two sites, as shown in table 1. Velocities have been recorder using an acoustic Nivus® PVM-PD of 1 cm/s of precision. The instrument provides averaged velocity but no information about the velocity fluctuation is available. However, three independent measurements have been taken per each survey point, to check their quality and to avoid any influence from suspended material clogging the probe. The standard deviation σ_u has been reported in the table, together with the temperature measurements, necessary to both calibrate the probe and characterise the biological activity of the network. This latter is important as it can deeply modify the characteristics of the surface of the invert and its roughness, e.g., presence of bio-film. Velocity around u=0.4 cm/s occurred at the DA site, in which the sediment thickness was limited to few centimetres. Conversely, AE shows velocities slightly below 10 cm/s during the morning, with sediment deposits thickness larger compared to that observed at DA. Long survey lasting for more than 12 hours shows that generally, later in the morning, the flow velocity increases, while the deposit thickness may considerably reduce. It is worth noticing that a slight change in flow velocity is sufficient to erode the soft deposits.

The two sites are also characterised by different concentrations and bottom sediment particle distributions. Both sites are characterised by a large percent of organic matter, as the suspended solids are composed by a volatile fraction generally larger than 70%. However, what clearly distinguish the two sites are the sediment concentrations observed in both the water column and near the bottom (Figure 5). TSS concentrations generally show almost constant values at the DA site of $TSS_{<}$2mm of 200 mg/l<TSS<350 mg/l, with a slight scatter toward the average observed for each survey. Differently, the AE site shows a strong concentration gradient, with $TSS_{<2mm}$ > 1000 mg/l and peaks larger than $TSS_{<2mm}$ > 3000 mg/l, clearly indicating the presence of a mudflow toward the bottom. (Larrarte 2008) also obtained similar results, in which maximum concentration of TSS<600 mg/l and reduced gradients were observed for inverts with few sediment deposits.

A sample of sediment deposits typically observed the AE site was presented in Figure 1f. According to field observations, the interface may settle of about 10 cm during the first minute after sampling, demonstrating the presence the rather soft, non-compact type C deposit, easily eroded by slight change in flow velocity (Ashley et al. 1992) and easily suspended during surveys with invasive instrumentation.

Figure 6 shows results for 4 morphological surveys, one from the DA site and 3 from the AE: DA-S5, AE-S6, AE-S7, and AE-S8 respectively. Each panel represents the morphology of sediment deposits over a length, x, of several km, and over entire cross sections. In the figure, data are displayed in terms of z_{plane}, i.e., the vertical coordinate measured from the average plane passing trough the measured points. An almost bi-dimensional shape characterizes the survey of DA site. Two depression are clearly visible at around x=-1.5 m and x=-7 m, in which observed maximum negative z_{plane} = -40 mm. the central zone of the survey, however, is rather flat and characterized by a maximum deviation of about z_{plane} =40 mm near x=-5.8m.

Differently, for the AE sites, the presence of a much higher organic content (Figure 5) alters the previous bi-dimensional patterns observed in case in the DA field site. Test AE-S6 presented a large depressions near x=-500 mm. A similar pattern occurs near x=-1000 mm for AE-S7.

The average plane representing the morphology, $z_{average}$, has been further decomposed as $z_{average} = \alpha+\beta x+\gamma y$, where α, β, and γ are the minimum squared error coefficients evaluated on the points

z_{BED} obtained from the SONAR output. It follows that $z_{plane} = z_{BED}-z_{average}$. The horizontal resolution of the survey has been fixed in about 20 cm. Table 2 summarizes coefficients α, β, and γ relative of each survey. Coefficients α represent the thickness of the sediment at the point x=0 m and y=0 and β and γ represent the local longitudinal and transverse slopes respectively. The coefficients of the two sites clearly show large differences.

Longitudinal slope coefficients also highlight how sediment deposits may locally presents larger bottom slopes compared to the average invert slope. In particular, DA data shows β of the same order of the bottom invert, due to the low sediment accumulation observed during the survey. Differently, AE presented average slope up to several times larger compared to the bottom slope, where negative beta values correspond to a sediment height decreasing from upstream to downstream. Transverse slope are generally larger than 0.01 for both the sites, indicating the presence of local tridimensional flow patterns. Maximum average transverse may reach up to 7-8% in both sites, regardless the nature of the sediment flow. It is worth noticing that major three-dimensional patterns may be locally generated by the presence of bends and other discontinuities, although these latter are generally more than 10 m upstream the site of measurements.

Generally, complicated 3D morphologies have been identified, especially for the AE field sites. Maximum deviations from the average plane may reach larger values, up to z_{plane} =-60 (Figure 6c x=-1000 mm) mm and z_{plane} =+80 mm (Figure 6c x=-2000 mm).

These complicated three-dimensional features are characterized by the occurrence of bed forms as well. According to (El Kheiashy et al. 2000; Rauen et al. 2008) bed forms formation are characterized by two main features, i.e., length λ and height η. (Raudkivi 1997; Rauen et al. 2008) proposed several equations correlating the average grain diameter with the former parameters. Accordingly, at equilibrium conditions λ and η are independent from the flow. As an example, for 0.1 mm sand, equilibrium λ, and η are 109 mm and 14 mm respectively (Raudkivi 1997). Moreover, if the velocity u<40 cm/s and d_{50}<0.1 mm, bed morphology should be mainly characterized by ripples.

Figure 7a-d shows the longitudinal profiles along sewer centreline (y=0 m), and relative to test DA-S5, AE-S6, AE-S7, AE-S8 respectively. The figure also shows the same longitudinal profiles filtered using a Gaussian filter of σ=50 mm of variance. It is possible to distinguish the formation of a long dune having large amplitude, and characterized by the superimposition of ripples. The dune is characterized by a steep leading edge (-7000 mm<x<-5500 mm), followed by a milder slope (-5500 mm<x<-2200 mm) and again by a steep part on the downstream side (-8000 mm<x<-7000 mm and -2200 mm<x<-1500 mm). On the contrary, AE longitudinal profiles are characterized by long dunes having smaller amplitudes, and shorter bed forms superimposed. For the latter, the upstream portions are generally steeper than the downstream ones. This particular pattern contrasts what generally occurs in the presence of sand dunes, and unidirectional flows, where a mild upstream slope is present which is the followed by a steeper side (Wren and Kuhnle 2008). This difference might be linked to the flow hydrograph typically observed in sewer networks, characterized by relatively low velocities and regular flow fluctuation during dry period and higher velocity during rain periods (i.e. flushing, with a steep rising limb and a relatively milder receding limb). (Campisano et al. 2004) observed similar morphologies in presence of flushing waves over isolated sediment deposits, and (Ristenpart 1995) described similar sediment morphologies with height of 5-20 cm along sewer trunk of 1500 mm of diameter.

Further insight and comparison of bed morphology can be made using Fast Fourier Analysis (FFA). Fast Fourier analysis has been successfully used by (Catano-Lopera and Garcia 2006a; Catano-Lopera and Garcia 2006b; Smith and Sleath 2005) to characterize the bed morphology for both oscillatory and combined flows. This technique allows understanding the largest component of the profile that can be assimilated to a sinusoid. Accordingly, the bottom profile can be considered as the sum of the sinusoid of wave length λ and amplitude η/2, both in mm.

The bed morphology can be approximated using a discrete sum of sinusoids:

$$z_{\mathrm{BED}}(\lambda) = \sum_{N} z_n e^{-i2\pi(\lambda/N)n} \tag{3}$$

where N is the number of simples, y_n is the n-th Fourier coefficient and:

$$\eta / 2 = \left| z_{\mathrm{BED}}(\lambda) \right| / N \tag{4}$$

Figure 8 shows the fast Fourier transform (FFT) for the longitudinal profiles shown in Figure 7. The test at DA is characterised by longer amplitudes of around 7 m of wavelength, and maximum amplitude of 25 mm, while the AE test are characterised by slightly lower amplitudes of shorter wavelength, around 3.5 m. Moreover, the in case of DA test the peak can be well distinguished from the shorter wavelengths, while in case of AE the bottom centreline profile the largest harmonics is slightly larger compared to that of smaller wavelengths, most likely due to the presence of the mud layer observed in AE tests. AE tests slightly differ one each other depending on flow conditions and water depth observed during the survey. Test AE-S7 and AE-S8 shows similar peak wavelength and height of λ= 4291 mm and λ= 3362 mm and η/2= 8.5 mm and η/2= 9.2 mm respectively, although velocities and sediment height differ significantly. In contrast, test AE-S6 presented two distinct main patterns of λ= 1663 mm and λ= 3239 mm and η/2= 15.6 mm and η/2 = 17 mm respectively, that may suggest the presence of two different morphologies formed at different time. Dry days before the surveys seem to play a secondary role on the morphology, as the lowest values η/2 is observed for test AE-S8, i.e., 4 dry days from the last significant event. However, the shape and intensity of the hydrograph prior to the survey should be further analysed to better assess its role on the formation of the mud layer.

CONCLUSION

A new application of acoustic techniques to the study of morphologies, and sediment deposits in combined sewer networks has been presented. Understanding the morphological features, bed forms, and sediment characteristics of these network systems is essential as the latter highly affect the flow field, sanitation performance, as well as the risk of urban flooding.

The use of Sonars to investigate the morphology of sediment deposits in sewer networks has been relatively unexplored but presents several advantages with respect to previous techniques, in terms of both accuracy, and ease of execution. Specifically, several difficulties are associated to the use of optical instruments in sewer networks due to the high suspended sediment concentrations, and problems connected to the perturbation of sediment deposits when deploying the instruments. On the other hand, gauge measurements can be highly subject to human errors, and are labour consuming. The automated technique, and deployment presented in this paper doesn't cause any perturbation of the sediment deposits, and also allowed a relatively fast reconstruction of the morphology. Furthermore, a new algorithm is proposed which is aimed at identifying the sediment interface by using the maximum of the gradient (rather than just the maximum) of the amplitude counts. The new algorithm performs well (Figure 3b, 4), and has been applied at different sites.

All tests were conducted in the absence of precipitation, and after at least two days of dry weather (<0.2 mm precipitation) apart from one test conducted the day after it rained. Analysing the influence of rainfall events (e.g. intensity and frequency) on the sediment deposit is outside from the scope of this work but is a very important aspect and deserves further investigations. In fact, rainfall events influence sediment deposits and flow conditions by removing the sediment stack and causing its subsequent renewal, and by influencing the bio-physicochemical conditions in the sewer (e.g. Bersinger et al., 2015). Consequently, rainfall events might affect sediment reactivity, and biological processes (e.g. Bersinger et al., 2015; Hannouche et al., 2014). For example, it has been shown trough laboratory experiments that sediment deposits formed under flow conditions are more resistant than the ones formed under quiescent water (e.g. Lau and Droppo, 2000). Bio-processes are also relevant in determining the weakening or hardening of the sediment deposits. As an example, nutrient depletion or high carbon to nitrogen ratio have been found to promote the secretion of polymeric substances which might help the development of an organic biofilm on the top of the loose sediment, and thus increase the shear threshold for erosion. In case of high oxygen levels, when aerobic sediment are dominant the exopolymeric production becomes small, and an intensive production of CO_2 bubbles counteracts stabilizing processes. On the other hand, when the oxygen levels drops, exoploymeric production increases, and anaerobic metabolisms are favoured. The latter have a weakening effect on the sediment strength due to biodegradation, and production of substances such as methane which can form gas bubbles, and disturb the natural structure of the sediment deposit (Baniasak et al., 2005). Further studies might address the monitoring of sediment deposits characteristics and biological reactivity using acoustic measurements. For example, acoustic backscatter has been related to sediment density, grain size, and sediment porosity, which might be useful indicators for the biological state of the stack of deposits (Richardson and Briggs, 1993). Monitoring changes in such variables might also be useful to monitor the reactivity of the deposit when combined with measurements of oxygen, and nutrient levels within the sewer."

The basic morphological features of sediment deposits have been presented for different trunks, and for two field locations characterized by large differences in suspended sediment concentrations, and sediment composition. Results showed that for the site with reduced suspended sediment concentrations, and more non-cohesive deposits, the bed mostly displays 2D features, while in the presence of a mud layer more three-dimensional patterns are present. In spite of small grain diameter, the analysis of deposits centreline shows the formation of large dunes, over which smaller feature superimpose. The hydraulic regime that occurs in the sewer network and the organic nature of the sediment might have strongly affected dunes features which differ from those observed for sandy deposits and unidirectional flow.

AKNOWLEDGMENT

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LIST OF FIGURES

interface detected with the old (black line), and new method (white dots). Note: In the figure, the number of detected points (white dots) has been reduced to improve the readability; the actual algorithm detects the interface with 0.9° resolution. (d) AE-S6 bottom morphology after filter application.

Figure 4 Test DA- S1 output; (a) the contour lines represent the 8 bit signal amplitude observed by the sonar, (●) gauge position; pulse length of 4 μs, x=0 m, (b) 8 bit signal amplitude at y=0 cm, section x=0.

Figure 5 (a), (b), (c), (d): total suspended solid concentration, and volatile suspended solid concentration (horizontal axis), free surface (vertical axis); (e), (f), (g), (h): ratio between volatile suspended solids (VSS) and total suspended solids (TSS). (a), and (e) test DA-S5; (b) and (f) test DA-S4; (c) and (g) test AE-S4; (d) and (h) test AE-S8. Standard deviation values for both VSS, and TSS are less than 10 mg/l.

Figure 6 Bottom morphology measured by the sonar profiler, z_{plane} in [mm] (a) DA-S5 (b) AE-S6, (c) AE-S7, (d) AE-S8.

Figure 8 longitudinal profile for y=0 m: (a) DA-S5, (b) AE-S6, (c) AE-S7, (d) AE-S8.

Figure 9 FFT of the centreline profile.

LIST OF TABLES

Table 1. Flow velocity recorded before the morphological survey at the section x=0 m.

"site-ID" indicates the site of the measurement (DA, or AE) as well as different locations (S); Time is the hour when measurements were collected; T_D is the number of dry days before the survey (i.e., less than 0.2 mm of precipitation); T is the temperature at the moment of the survey; z_{probe} indicates the position of the acoustic velocity probe relative to the free surface, h is the distance from the probe to the sediment interface, u is the longitudinal velocity, z_{SED} is the position of the sediment detected by the point gage from the invert, δ is the total water depth between the sediment bottom and the free surface.

Table 2. Average sediment thickness, longitudinal and transversal slopes.

NOTATION

a_s = diameter of the particles;

C = sediment concentration;

c = sound speed;

d_{xx} = diameter for which xx percent of sediment in weight is smaller;

h = distance from the probe to the sediment interface;

k = acoustic wave number;

$P_{L\,=}$ pulse length;

R is the distance of the generic acoustic beam from the sonar centre;

R_{MAX} = maximum distance that can be detected by the SONAR;

S= slope;

S_v= scattered signal in decibel;

S_v= scattered signal in decibel;

u = longitudinal velocity;

x,y, and z = longitudinal, transverse and vertical coordinates;

y_{SONAR} = transverse distance from the centre of the instrument;

$z_{average}$ = average surface trough the sediment bed;

z_{BED} = position of the sediments interface detected by the SONAR;

z_{plane} = sediment surface referenced from $z_{average}$;

z_{PROBE} = position of the velocity probe;

z_{SED} = position of the sediment detected by the point gage from the invert;

z_{SONAR} = vertical distance from the centre of the instrument;

α, β, and y= interpolation coefficients;

δ= total water depth between the sediment bottom and the free surface;

δ_v = vertical resolution;

η =wave height;

θ = angle between z_{SONAR} and the measured beam;

λ = wave length;

ρ_b = sediment bulk density

σ = standard deviation of the Gaussian filter and;

$\sigma_s=(d_{84}/d_{16})^{0.5}$ = uniformity parameter.

Table 1 Flow velocity recorded before the morphological survey at the section x=0 m

Date	Site-ID	Time	z_{probe}	h	u	σ_u	z_{SED}	δ	T_{D}.	T
-	-	hours	m	m	m/s	m/s	m	m	days	°C
20-10-2010	DA-S1	8:00	-	-	0.35*	-	0.1	041	8	22
11-05-2011	DA-S5	8.00	0.1	0.34	0.41	-	0.02	0.44	2	20
11-05-2011	DA-S5	8.00	0.25	0.19	0.46	-	0.02	0.44	2	20
25-11-2010	AE-S2	8:00	-	-	0.10*	-	0.2	0.93	0	19
10-03-2011	AE-S6	7.50	0.1	0.37	0.116	0.026	0.35	0.47	10	15.6
10-03-2011	AE-S6	7.50	0.2	0.27	0.086	0.003	0.35	0.47	10	15.6
24-03-2011	AE-S7	10.18	0.5	0.11	0.0695	0.015	0.12	0.61	7	16
24-03-2011	AE-S7	10.19	0.4	0.21	0.1085	0.004	0.12	0.61	7	16
24-03-2011	AE-S7	10.19	0.3	0.31	0.1285	0.006	0.12	0.61	7	16
24-03-2011	AE-S7	10.21	0.2	0.41	0.1355	0.008	0.12	0.61	7	16
24-03-2011	AE-S7	10.21	0.1	0.51	0.1445	0.004	0.12	0.61	7	16
04-05-2011	AE-S8	10.18	0.2	0.21	0.097	0.004	0.35	0.41	4	19
04-05-2011	AE-S8	10.19	0.3	0.11	0.085	-	0.35	0.61	4	19

* average velocity from discharge measurements

Table 2. *Average* sediment thickness, longitudinal and transversal slopes.

Survey [-]	α [mm]	β [-]	γ [-]
DA-S5	16	-0.002	-0.072
AE-S6	302	-0.035	-0.081
AE-S7	297	-0.006	-0.014
AE-S8	355	-0.022	0.045

Figure_1

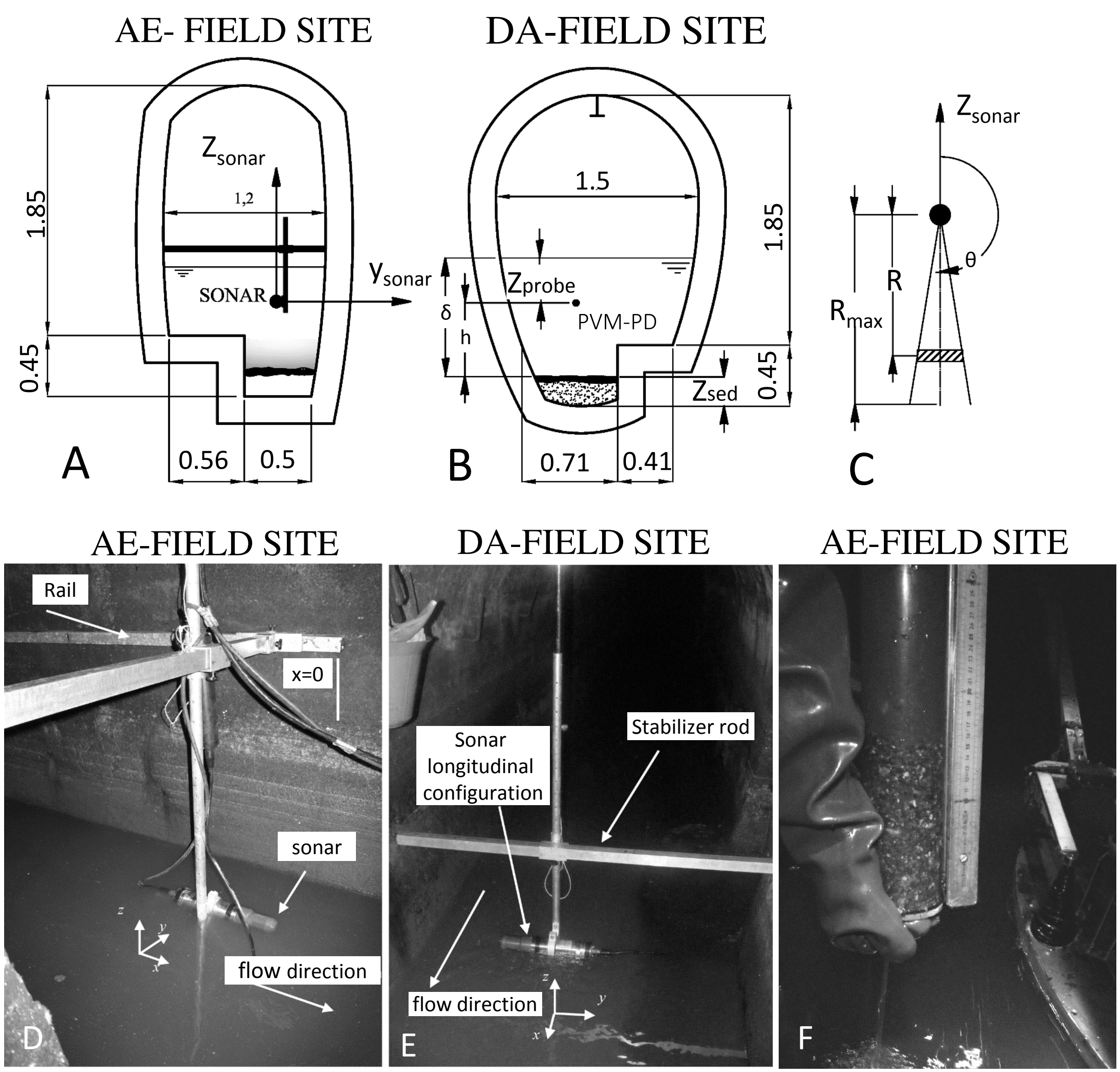
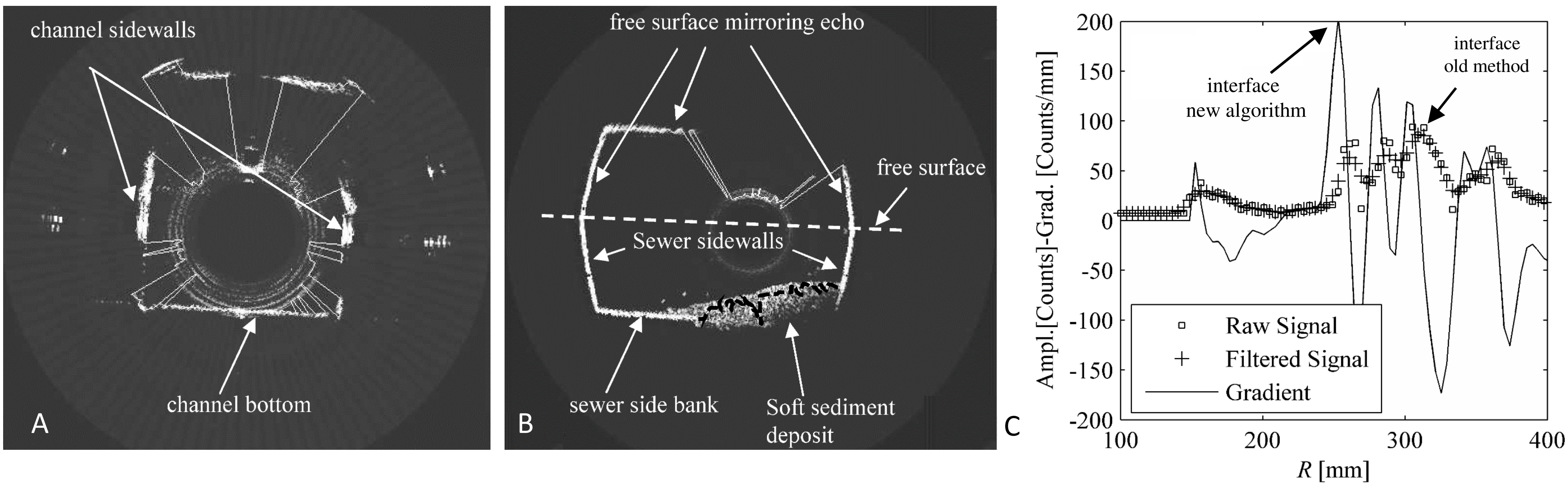
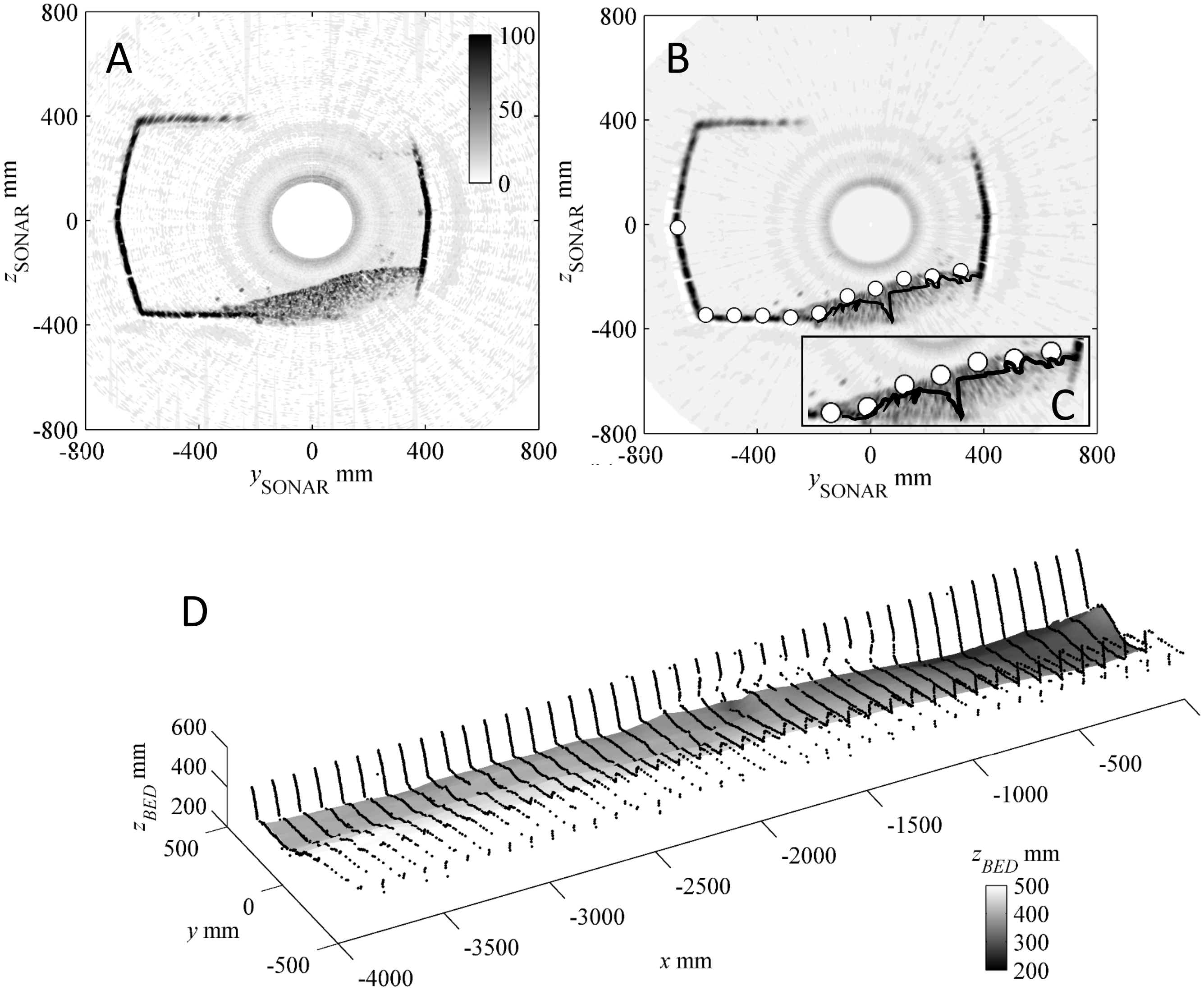

AE- FIELD SITE
DA-FIELD SITE
Zsonar
1,2
1.85
0.45
SONAR
ysonar
0.56
0.5
A
1.5
Zprobe
δ
h
PVM-PD
1.85
0.45
Zsed
0.71
0.41
B
Zsonar
θ
R
Rmax
C
AE-FIELD SITE
DA-FIELD SITE
AE-FIELD SITE
Rail
x=0
sonar
flow direction
D
Sonar longitudinal configuration
Stabilizer rod
flow direction
E
F

Figure_2



channel sidewalls
channel bottom
A
free surface mirroring echo
free surface
Sewer sidewalls
sewer side bank
Soft sediment deposit
B
C
interface new algorithm
interface old method
Raw Signal
Filtered Signal
Gradient
Ampl.[Counts]-Grad. [Counts/mm]
R [mm]
200
150
100
50
0
-50
-100
-150
-200
100
200
300
400

Figure_3



A
B
C
D
800
400
0
-400
-800
-800
-400
0
400
800
100
50
0
z_{SONAR} mm
y_{SONAR} mm
600
400
200
z_{BED} mm
500
0
-500
y mm
-4000
-3500
-3000
-2500
-2000
-1500
-1000
-500
x mm
z_{BED} mm
500
400
300
200

Figure_4

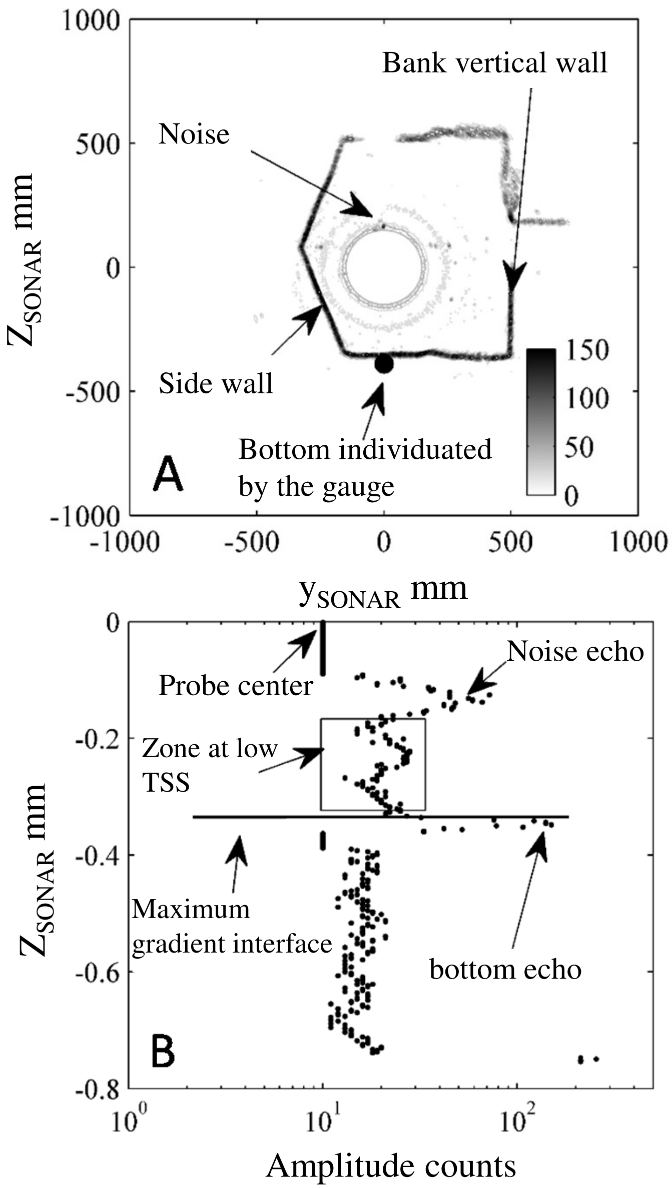
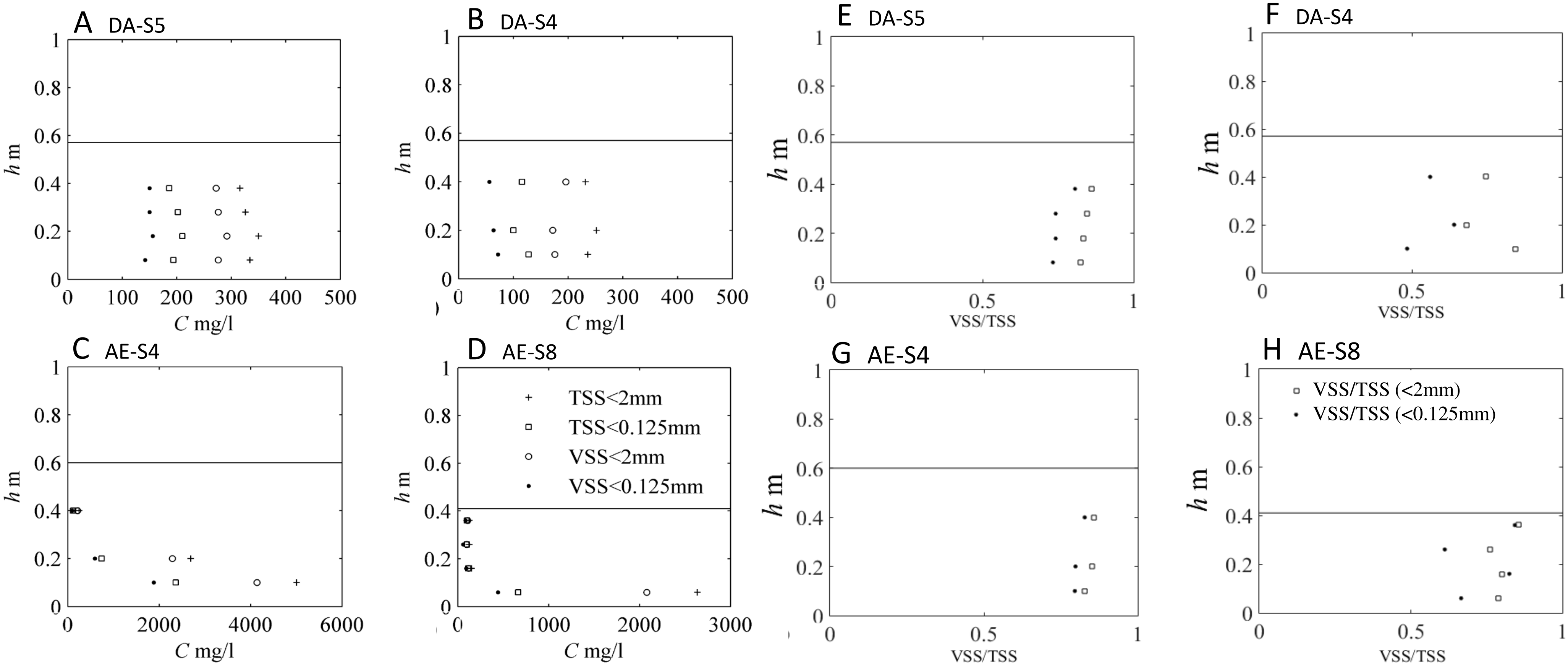

1000
500
0
-500
-1000
-1000
-500
0
500
1000
z_{SONAR} mm
y_{SONAR} mm
Bank vertical wall
Noise
Side wall
Bottom individuated
by the gauge
A
150
100
50
0
z_{SONAR} mm
Amplitude counts
10^0
10^1
10^2
0
-0.2
-0.4
-0.6
-0.8
Probe center
Noise echo
Zone at low
TSS
Maximum
gradient interface
bottom echo
B

Figure_5



A DA-S5
B DA-S4
E DA-S5
F DA-S4
C AE-S4
D AE-S8
G AE-S4
H AE-S8
h m
C mg/l
VSS/TSS
TSS<2mm
TSS<0.125mm
VSS<2mm
VSS<0.125mm
VSS/TSS (<2mm)
VSS/TSS (<0.125mm)

Figure_6

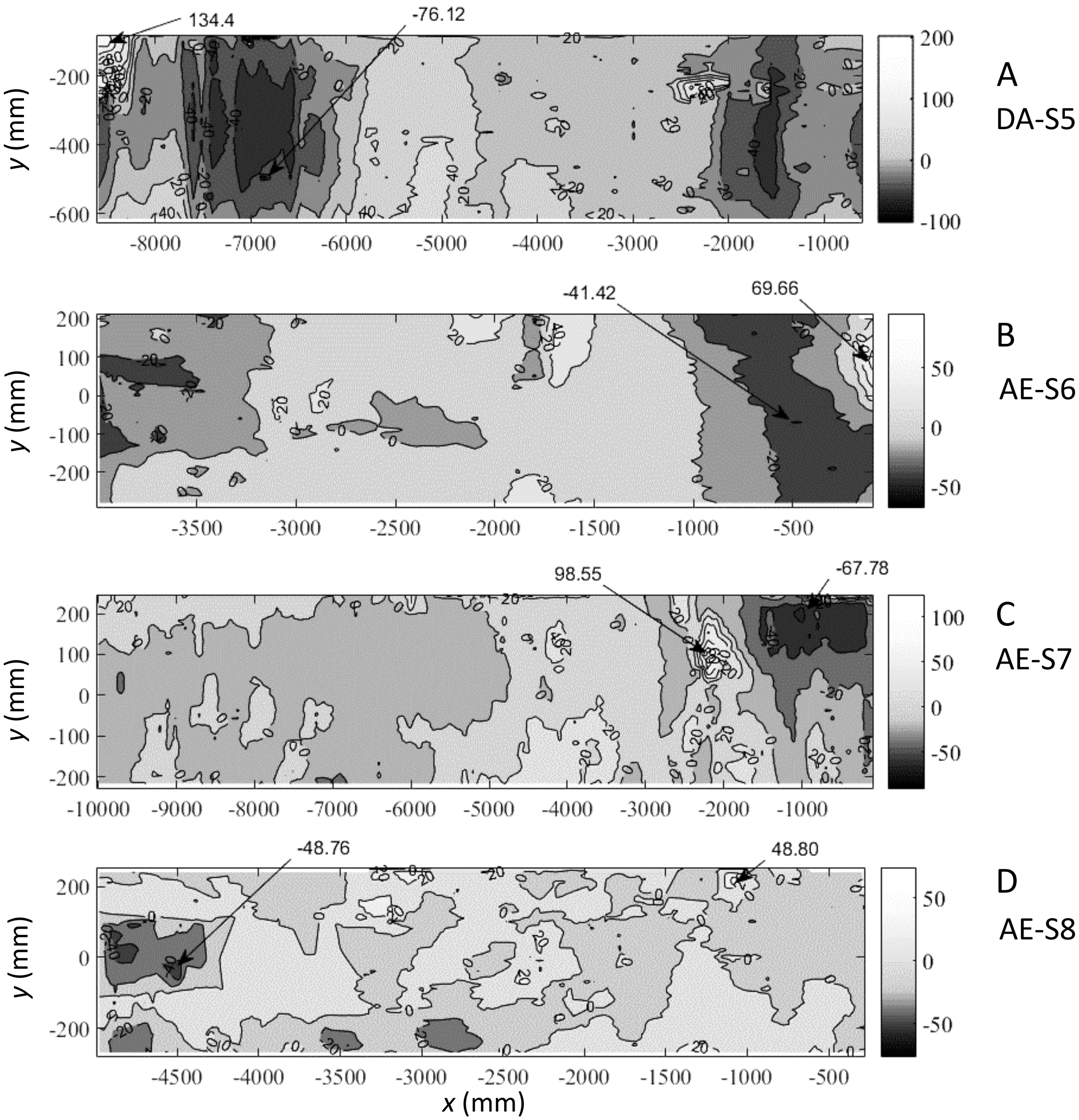
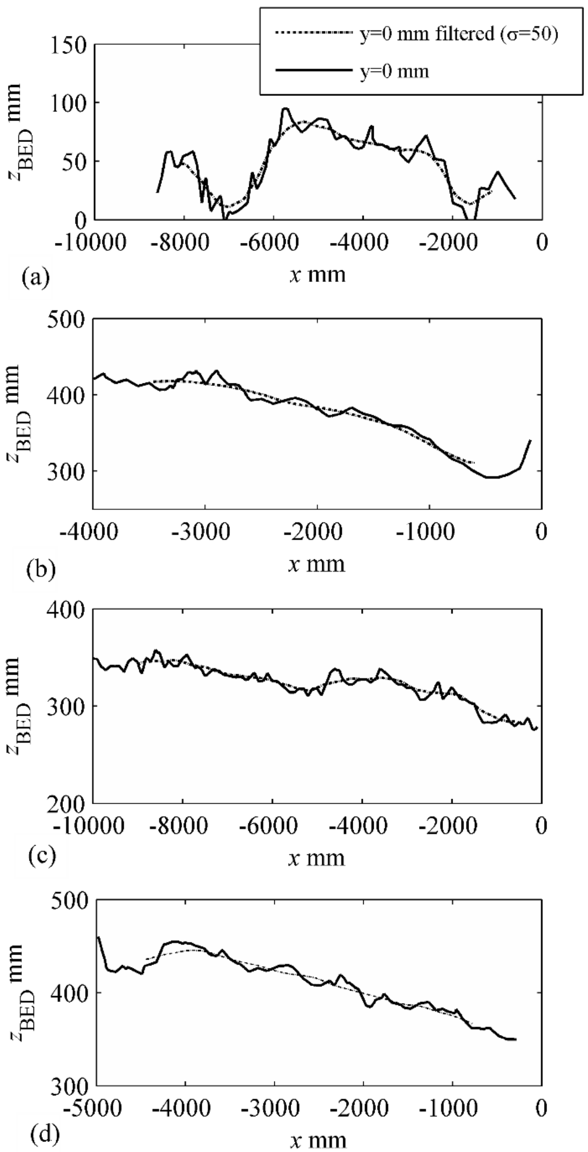

134.4
-76.12
A
DA-S5
-41.42
69.66
B
AE-S6
98.55
-67.78
C
AE-S7
-48.76
48.80
D
AE-S8
y (mm)
x (mm)

Figure_7



y=0 mm filtered (σ=50)
y=0 mm
150
100
50
0
z_{BED} mm
-10000
-8000
-6000
-4000
-2000
0
(a)
x mm
500
400
300
-4000
-3000
-2000
-1000
(b)
400
200
(c)
-5000
(d)

Figure_8