A METHOD BASED ON ELECTRICAL CONDUCTIVITY MEASUREMENT TO MONITOR LOCAL DEPTH CHANGES IN THE SURF ZONE AND IN DEPTH SOIL RESPONSE TO THE WAVE ACTION

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This paper presents the development of a novel instrument aimed primarily at measuring the local bathymetry in the surf zone. The technique of electrical conductivity was used with a number of sensors placed on a vertical supporting pole. A number of technical difficulties had to be solved before obtaining reliable results. The instrument was tested during field experiments. Then we investigated the possibility of extending the field of application of the instrument to the assessment of soil porosity using Archie's law. Using this law and the cementation factor, defined through laboratory experiments, we processed the data from an in-situ experiment. Changes in porosity within the sediment have been observed. However, these results have to be taken cautiously because of the novelty of the instrument.

1. Introduction

The aim of this paper is to present a new technology being currently at the development stage and aiming at monitoring real time depth changes in the surf zone. This work has been performed as part of a collaboration between a company specialized in electronic technologies (Imartec) and the University of Pau (Laboratory of Applied Sciences in Civil and Coastal Engineering).

The idea was to develop a simple and economic apparatus based on a soil electrical parameter measurement to survey autonomously the seabed local depth changes in the surf zone. The potential applications of such a technology are various and numerous. It could be used as a complementary information to the classic bathymetry survey. Indeed, if the latter gives access to the spatial dimension of the seabed (although the word "spatial" is not really correct since time does not stop during the survey operation), an automatic local depth measurement covers the temporal domain which is generally almost never investigated. This temporal dimension of seabed depth evolution is of course of primary importance when considering storm events. An automatic device makes possible and safer the survey during these very energetic events. In this context, measurements, even local, would be valuable to better understand morphodynamical processes as well as to test numerical models against more accurate in situ data. In a more practical way, such a technology could provide an efficient solution to undertake a long term survey of a coastal area or to control in real time the water depth in harbor access channel or tidal inlets.

2. Other technologies used in this field

Measuring seabed level in the surf zone is a great technological challenge considering the extreme dynamics of this area. Its physical characteristics are complex and drastically reduce the technologies usable to achieve this objective. Sonic altimeter measurements can be employed to carry out automatic survey of the seabed level in the surf zone (Gallagher et al., 1996). The acoustic signal must be filtered to extract the noise generated by air bubbles. This technique is efficient in terms of resolution but could be difficult to apply on a whole surf zone profile and especially in the swash zone. Indeed, altimeters have to be always submerged into water in order to record the depth signal. In a more global environmental context (estuary, river, sea (intertidal and underwater areas)), Thomas and Ridd (2004) gave a comprehensive review of the methods used to measure sediment accumulation and bed level changes. In the case of level change measurement, only three technologies have been reported to be automatic. The photo-electronic erosion pin (PEEP) of Lawler (1991) uses a set of vertically distributed photosensitive sensors to detect the interface between sediment and water (using daylight). Its potential application in the surf zone appears difficult as this technique is based on daylight and thus limited to the day time and to bright environment. A better solution has been proposed with the sedimeter of Erlingsson (1991). This instrument is composed of a vertical array of infra-red transmitters and backscatter detectors. This optical device could be applied to the surf and swash zones but no trials have been reported until now. Finally, Ridd (1992) developed a field instrument based on electrical conductivity measurement to record the water/sediment interface level.

In all three previous cases, probes were vertical rods half buried into the sediment layer. Both optical devices used a discrete distribution of sensors whereas a more global measurement was made in Ridd (1992). This latter point is a disadvantage as a variation in salinity or an inhomogeneous sediment layer is interpreted as a level change.

3. Presentation of the method

3.1 Principle of operation

The instrument developed is based on the measure of the electrical conductivity. It was chosen to use this technique because the sea water has a high electrical conductivity whereas the dry sediment has a low electrical conductivity. Sediment saturated with sea water will have an electrical conductivity that will be function of the ratio sea water to sediment. Also the air has a very low electrical conductivity that would be much lower than that of the saturated sediment. This gives us three distinct ranges of electrical conductivity for the three elements present in the field (air, sea water and saturate sediment). The ranges of the electrical conductivity for the air, sea water and saturated sediment is given in Table 1.

Table 1. Usual ranges of electrical conductivity for air, sea water and saturated sediment.

	Conductivity min (mS/cm)	Conductivity max (mS/cm)
Air		Tends towards 0
Sea water	40	60
Saturated sediment	10	35

It is important to note that although in Table 1, the minimum conductivity of the sea water is close to the maximum conductivity of the saturated sediment, it is always possible to differentiate between the sea water and the saturated sediment because the conductivity of the saturated sediment is function of the conductivity of the sea water. This means that if the sea water conductivity is in the lower part of its range, then the saturated sediment conductivity will also be in the lower part of its range.

The conductivity of the air is almost 0 which means that the air is a bad conductor for electric current. This conductivity can be affected by the hygrometry, but in our case these changes would be insignificant.

The conductivity of the sea water is mostly function of its salt content and the temperature. Depending on where the instrument is planned to be used, it is important to define its measuring range in order to match the expected range of conductivity. By example, if the instrument was to be use in a tidal inlet or a river mouth, the changes in salinity due to the tides would need to be accounted for.

The conductivity of the saturated sediment is function of the conductivity of the sea water saturating the sediment, the conductivity of the sediment itself (low in general) and the ratio of sea water to sediment. Loose soils will contain more sea water than hard packed soils, therefore the conductivity of loose soils will be higher that that of hard packed soils, for the same type of sediment. The grain size of the sediment will also influence the conductivity of the saturated sediment, but again due to the difference between the ratios of sea water to sediment that would be different with fine or coarse grain sizes.

We have shown that it is possible to reliably differentiate between air, sea water and saturated sediment measuring their electrical conductivity. Therefore, by using a number of conductivity sensors placed along a vertical pole, it is possible to define the height of the saturated sediment and the height of the water in a reliable manner.

3.2 Description of the instrument

The instrument can be divided into two parts, the sensors and the data logger (see figure 1).

The sensors are mounted on a supporting pole and are regularly spaced. The space between the sensors is what is going to define the vertical resolution of the instrument. A spacing of 10cm between the sensors was chosen to give us a large range (320cm with 32 sensors) while retaining sufficient resolution. Also the scour generated by the supporting pole means that there is little to be gained in having a very fine resolution.

The data logger contains the electronic circuitry for generating the measuring signals, the circuits for amplifying and filtering the signals from the sensors, a large Flash memory, a USB connection for the data download and a micro-controller. All of this fits into a waterproof enclosure and is attached to the supporting pole. The data logger can record the signals from 32 sensors at a rate of 10Hz per sensor for more than a day. The memory capacity can vary from 32Mbytes to 1 Gbytes. 32Mbytes is enough to record the 32 sensors at 10Hz for 13 hours, enough for a complete tide cycle. Larger memory capacity will allow to record at full speed longer periods of time. Different recording schemes such as burst recording are being studied and will be implemented to allow recording for a few months. The current consumption of the data logger was also reduced to allow for a longer autonomy of the instrument.

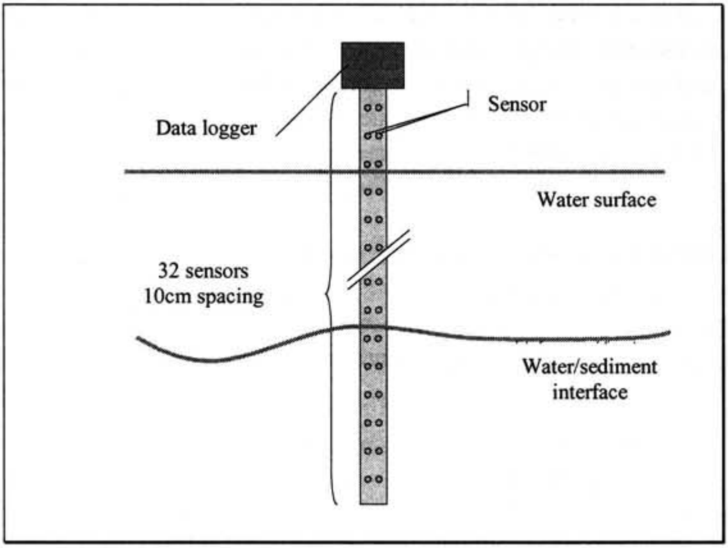

Figure 1. Schematic view of the instrument.

3.3 Technical issues

The very first prototype measured the conductivity using a DC signal. This has proved to cause some problems such as oxidation of the sensors and offset voltages that would make the measurements nearly impossible to interpret. These problems have been solved by measuring the conductivity with an AC signal which limits considerably the oxidation and remove any offset voltages.

A lot of time and effort has been spent on the design of the sensors. Although the first sensors were giving good results individually, they were interacting between each others when placed on the supporting pole. We thought that this would be due to the electrical field of the sensors being too wide and interacting. An electric field distribution calculation for a model of our sensor was done and confirmed that more than 30% of the electrical field extended over a 10cm diameter circle centered on the sensor. A simple solution would have been to reduce the distance between the sensor electrodes, but this would lead to a measuring zone being too small which would not have an homogeneous distribution of sediment with the larger grain sizes. In the light of this, we have redesigned the sensors in order to keep a spacing of 10cm and a sufficiently wide measuring zone, but avoid interaction between the sensors.

Power consumption has also been an issue because we wanted to have an autonomous instrument which would therefore be battery powered. Work was done to reduce the power consumption of the electronics to less than 1mA/h per sensor. There is a trade off between the power consumption and the accuracy of the measurements, but we have reached a good compromise that allows us to record continuously for more than a tide cycle with a good accuracy. Recordings of a few months can also be done when the data logger is going into sleep mode between bursts of recordings.

4. In situ measurement of local bathymetry

In order to test the instrument we have performed a number of recordings on the beach in Biscarrosse (Atlantic coast, south west of France). We will detail here the results from one of these experiments.

The beach in Biscarrosse is composed of fine non cohesive sand, and the instrument was placed on a steep part of the beach that is uncovered at low tide. The instrument is modular and we can use between 8 to 32 sensors. Only 8 sensors were used for this experiment.

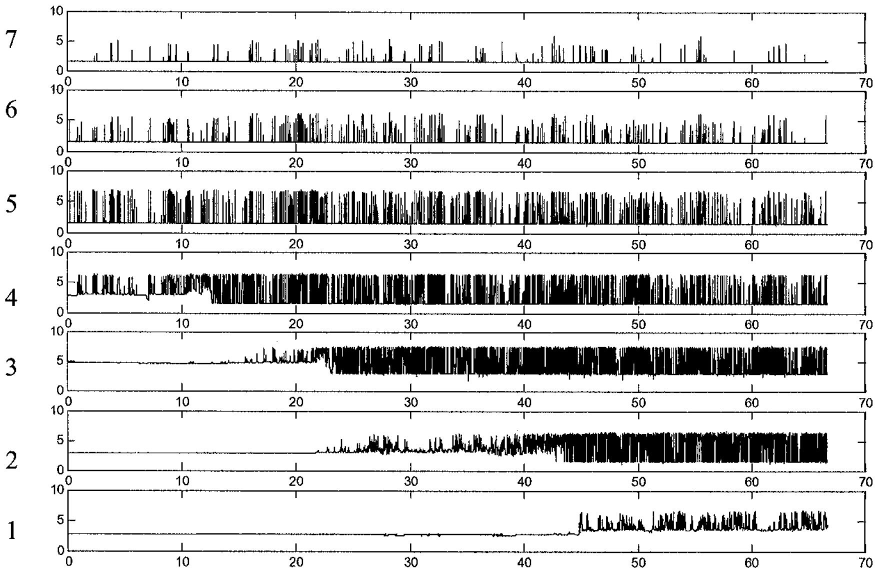

Figure 2. Recorded signals with sensor 1 being the lowest sensor and sensor 7 being the highest sensor. X-axis = time in min., Y axis = conductivity in S/m

In Figure 2, we can see the signal recorded for the first seven sensors. The signal from sensor 8 is not shown as it is always in the air and does not bring any information. Sensor 1 (bottom trace) was the lowest sensor and the sensor vertical spacing was 10cm. At the beginning, sensors 1 to 4 were in the sediment and sensors 5 to 7 were in the air and would get covered by water because of the swash. The instrument was placed at the top of a sloped part of the beach with shorebreaking waves. Because of the slope of the beach, the sand would appear between each swash. The sensor signal is saturated when the sensor is in the air because the conductivity of the air is too low and out of the sensor range. This can be seen on sensors 5 to 7 where the conductivity is flat at about 2 S/m. The conductivity of the air is lower than that, but this is the lower measuring limit of our sensors. The vertical spikes on sensors 5 to 7 are the signals from the waves, the sensors were covered when a swash came and dried after each swash. A detailed view of this is shown in Figure 3.

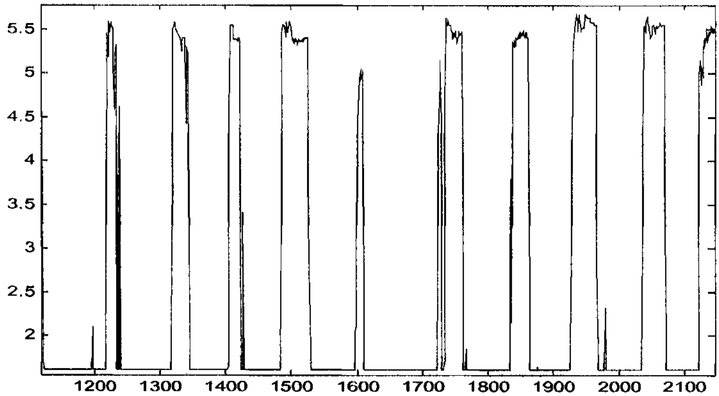

Figure 3: Detailed view of the signal from a sensor alternating between the air and the water. Same axes as in figure 2.

Looking at sensor 4, we can see that although it was in the sediment at the beginning of the experiment, almost immediately we start to see some spikes in the conductivity signal. These large spikes between the conductivity of the sediment and the conductivity of the water show that much more water has gone into the sediment to the point that the conductivity is almost that of the water. This means that there is suspension of the sediment at that time due to the wave action. A more detailed view of this is shown in Figure 4.

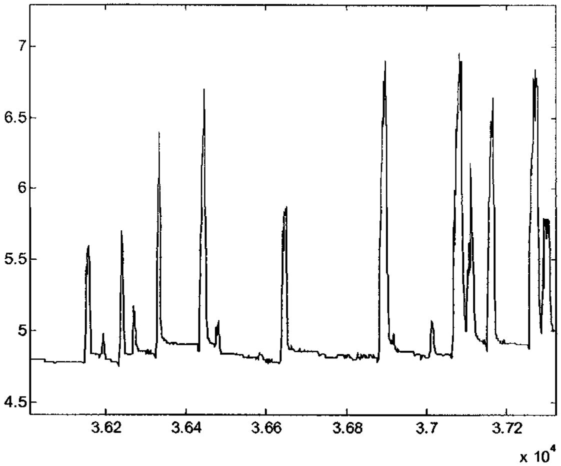

Figure 4. Detailed view from a sensor in the sediment with suspected events of sediment suspension. Same axes as in figure 2.

Still looking at sensor 4, we can see that after 10 minutes, there is an erosion and that after about 13 minutes the sensor is not in the sediment anymore because the conductivity signal does not come back to the value of the sediment but to the value of the air (as for sensors 5 to 7).

Looking at sensor 3, we can see that it is fairly stable until 15 minutes into the recording. Then we get about 5 minutes with episodes of suspension of the sediment, and again an erosion after the 21st minute and the sensor is not anymore into the sediment after about 23 minutes.

The same happens to sensors 2 and 1 with sensor 2 being uncovered after about 44 minutes. The recording does not show here the sensor 1 being uncovered, but we can find again the suspension of the sediment on the signal from sensor which is preceding the erosion.

By looking at the times when the sensors are completely uncovered, we can calculate the erosion rate. Sensor 4 has been completely uncovered after 13 minutes and sensor 2 after 44 minutes. This gives us an erosion of 20 cm in 31 minutes, or an erosion rates of about 40 cm/h for this part of the beach.

5. Assessment of soil porosity

Now, it is intended to investigate the possibility of extending the field of applications of the conductivity system, previously described, to the assessment of soil porosity. Our objective is to provide a device allowing to study the evolution in space and time of the effective stresses produced inside a sandy bed when water gravity waves pass over it. This information is of prime importance to better understand the complex flow in the swash zone, or the occurrence of liquefaction near coastal structures (Mory *et al.*, 2004) for instance.

In various studies, soil resistivity has been related to different hydraulic properties including water content, degree of saturation, salinity and hydraulic conductivity (Kalinski *et al.*, 1993). Thus, the Archie's law (Archie, 1942) proposes a simple relation between the resistivity of a saturated soil R_s and of the brine R_w :

$$R_s = \theta^{-m} R_w \qquad (1)$$

The porosity θ of a sand can then be deduced from conductivity measurements and reads

$$\theta = \left(\frac{\sigma_s}{\sigma_w} \right)^{1/m} \qquad (2)$$

where σ_s and σ_w respectively denote the saturated sand conductivity and the water conductivity. The empirical cementation exponent m depends on sand geometrical characteristics. In the literature, the value of m ranges between 1.2 and 1.5 for non cohesive sands (Taylor-Smith, 1971; Jackson *et al.*, 1978).

Our conductivity apparatus was used in a field experiment to measure the spatial and temporal variations of porosity (based on Eq. 2) induced by gravity waves propagating over a sandy bed. The experiment was carried out at Biscarosse. The apparatus was installed on a gentle slope, in the surf zone. The conductivity was measured by seven sensors, 10 cm spaced and numbered from the bottom to the top of the probe. The sensors 1 to 4 were immerged all the time, and the wave conditions calm (H_s= 50 cm, T = 10s). The sand can reasonably be considered saturated in the vicinity of the probe. This fulfills the requirement of the Archie's law.

During the experiment, the sand never reached the sensors 5, 6 and 7. Thus, in the data analysis, these sensors provide an estimate of the water conductivity σ_w used in Eq. 2. The comparisons between the three sensors highlight an error of 5% on the estimation of σ_w, with an average water conductivity of 6.3 $S.m^{-1}$. In laboratory, sand samples of the beach were used to estimate the cementation factor m in Eq. 2. Several tests carried out for different grain sizes provided an average value of 1.36, which corresponds to what it is commonly used. As a first approximation, a unique m equal to 1.36 is considered in the present study. Nevertheless, it is reminded that it is recommended to take a different m for each type of sand (Jackson, 1975a). The time average porosity obtained from the sensors 1 to 4 are $\theta_1 = 55\%$, $\theta_2 = 52\%$, $\theta_3 = 61\%$, $\theta_4 = 52\%$. Taking into account the uncertainty on the σ_w and σ_s measures, and the assumption of a constant cementation factor m for all the sensors, these values of porosity have to be considered with caution. At the moment, it is preferable to use the apparatus to qualitatively study the evolution of the sand porosity under the influence of the surface waves transformation.

Figure 5 displays the temporal variation of the porosity obtained from the sensors 1 to 4 for two periods corresponding to different water levels. The left panel represents the sand porosity calculated for each sensor at the beginning of the experiment, at low tide, and the right panel the sand porosity at high tide. The bottom panels give the water conductivity obtained with the sensor 7. This sensor was located at the top of the probe.

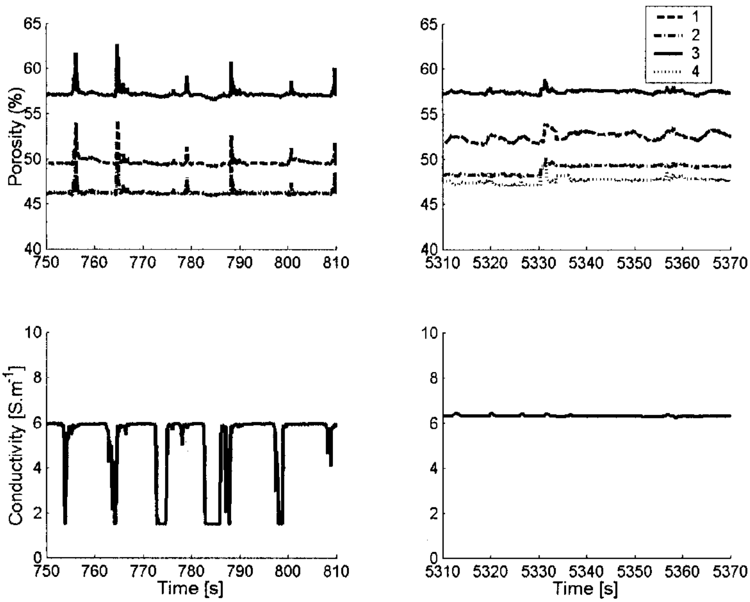

Figure 5. Top panels: temporal evolution of sand porosity obtained from the sensors 1 to 4 at low tide (left) and high tide (right). Bottom panels: corresponding σ_w measured in the water column by the sensor 7.

At the beginning of the experiment, the sensor 7 was periodically submerged by the surface waves as shown by the tooth shape of the conductivity (left bottom panel). When the sensor is in contact with the water $\sigma_w = 6$ S.m^{-1}, otherwise $\sigma_w = 1.5\ S.m^{-1}$. The periodicity is of nearly 10 s, which corresponds to the wave period. The influence of the waves passing over the bed results in a local increase of about 5% of the sand porosity for each sensor (left top panel).

For a higher level of water, σ_w is nearly constant (~6 $S.m^{-1}$) (right bottom panel). At this moment, the sensor 7 is immerged. The sand porosity slightly varies for each sensor (left top panel) compared with the evolution at low tide. For a higher water level, the sand porosity is less influenced by the waves.

6. Conclusion

Starting from the need to measure the bathymetry in the surf zone in a reliable manner and during events such as storms, an instrument as been developed. A number of problems had to be solved before getting reliable results from the instrument, and a number of field experiments have been done to test the instrument. Now the instrument provides good results for measuring the bathymetry in the surf zone. A second aspect of this work was to look at the in-depth soil response due to wave action. We used Archie's law to process the data from field experiments and extract the sediment porosity variations due to wave action. Laboratory experiments were done in order to define the cementation factor for the type of sediment present on the beach used for the in-situ experiments. Although there is still work to be done to validate the results of the measurement of porosity variations within the sediment, the present results show that there are some variations due to wave action and that the instrument developed is able to detect them. However, the absolute value of the porosity have to be taken with caution because of the uncertainties in the measurement of the conductivity for the sediment and the water. Further work is needed to improve the accuracy of the absolute values for the porosity measurements, but prospects of applications for this type of instrument are encouraging.

Acknowledgments

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