PASSIVE ACOUSTIC MEASUREMENT OF BEDLOAD DISCHARGE FEATURES ON A SANDY SEAFLOOR

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1 INTRODUCTION

Bedload transport monitoring at sea still remains a challenge for sedimentologists and coastal engineers. Although such measurements are required to validate sediment transport models, data and instrumental techniques that establish a detailed link between boundary layer turbulence and sediment mixture dynamics are still scarce. Passive acoustic devices can offer this possibility when associated with high frequency velocity measurements in the nearbed. The method is based on the use of hydrophones recording self-generated noise due to inter-particle collisions during bedload transport. It presents numerous advantages: it is not disruptive to the flow field or the seabed, light, easy to handle and cost effective.
The literature mainly describes developments made in controlled conditions[1, 2] (flume or even drum) with coarse particles. Few experiments took place in rivers[3, 4] or marine environment[2]. It has been shown that the amplitude and the frequencies spectrum of the monitored signals are linked to bedload fluxes and grain size distribution. The use of a passive acoustic technique has been tested to (i) measure the threshold of gravel movement, (ii) provide continuous high temporal resolution records of sediment transport, and (iii) supply information on the size distribution of mobile particles. From laboratory studies, it has been shown that the observations could be explained in terms of rigid body radiation, which arises from the sudden velocity change of the impacting particles. A theoretical analysis using the Hertz law of contact to describe the acceleration time history of the grains during impact, allow predicting the pressure wave that propagates out into the fluid[5].
The present paper describes further developments in the prediction of the global self-generated noise level emitted by natural sand grains subject to tidal currents. Measurements on a sandy dune in the Iroise Sea are first briefly described and then an empirical model is proposed to generate a simulated signal as a summation of individual shock signals. Its intensity is mainly affected by the number of moving particles and their sizes. Thus, by minimizing the error between acoustic levels simulated and measured, the optimized grain size or the sediment fluxes can be calculated.

2 METHODOLOGY

2.1 In-situ measurements

The study area is located in the Four Channel (Iroise Sea) by 60 meters depth (Figure 1). The sea floor is covered by sandy dunes and influenced by strong tidal currents varying from 0 to 1 m/s. An instrumented frame was deployed on the sea bottom during 3 days. Only data acquired during 20 hours are exploited here. During this measurement campaign, tidal range was about 4.5 m, sea state was smooth to moderate with significant wave height ranging between 0.3 and 2 m and wind speed never exceeded 15 knots.
Passive acoustic data have been acquired with the use of one HTI - 99 hydrophone (Sh = -190 dB/V, F = 312 kHz) located 40 cm above the bottom. Current velocity has been recorded with an upward-looking ADCP (RDI Sentinel 600 KHz) within the first ten meters above the bottom: the lower part of the water column was divided into 42 bins of 0.20 m height.

No grab sediment sample has been done during the deployment. But data acquired during previous surveys on the area allow the specification of the sedimentary characteristics: the median diameter is ranging between 0.4 mm and 1 mm.

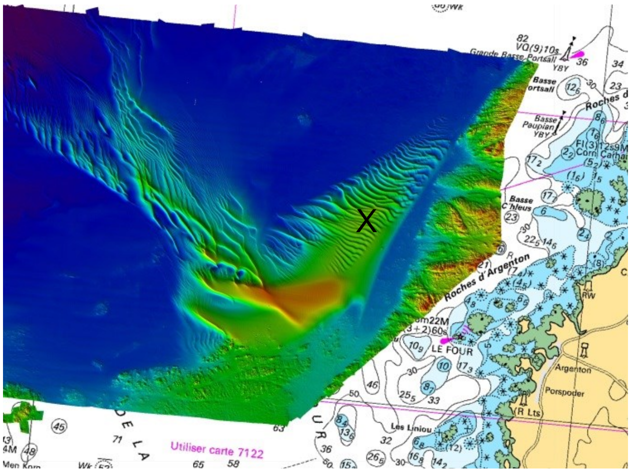

Figure 1: Deployment site bathymetry and location.

Acoustic data and current velocities were recorded during fifteen minutes every half an hour. In order to reduce the background noise, the raw acoustic signal has been high-pass filtered with a 10 kHz cutoff frequency. The peak frequency having an inverse dependency on particles diameter[1], only signal from colliding grains smaller than 12 mm can be detected.

The filtered signal is composed of short spikes (0,05 ms typical duration, 100 kHz dominant frequency) emerging from the background sound (Figure 2). Thus, the temporal signal can be considered as a combination of successive and numerous shocks due to sediment transport.

A root mean square (rms) pressure has been calculated every minute for the first 5 minutes of each 15 minute period. The average Prms is associated with a velocity measurement at 2.5 m above the bottom at the same time. In order to reduce the background sound (ambient and electric noise), the minimum value of Prms (which is considered to be characteristic of a period without sediment movement) is removed from other values.

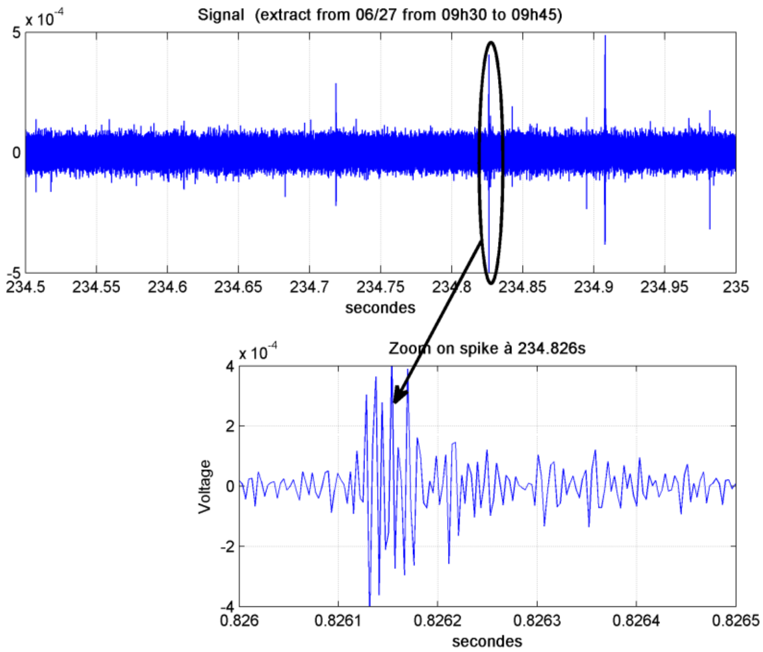

Figure 2: Top, high-pass filtered acoustic signal versus time. Below, zoom on a spike supposed to be the signature of an individual shock.

2.2 Model description

The model aims to estimate the total rms pressure generated by moving sand particles on the sea floor. In accordance with the observations, the temporal simulated signal is considered to be the combination of individual shock signals. Figure 3 presents a diagram of the modeling strategy we used and highlights the different processes we need to quantify.
For each current velocity *u* and grain size *D*, we first calculate the number of moving grains *N* and their velocity during the collision *Uc*. Then, the number of impacts *NbC* and the pressure radiated from a pair of impacting particles *Pp* are quantified. Finally, a total rms pressure level *Prms* is obtained by the summation of each particle impact signal.

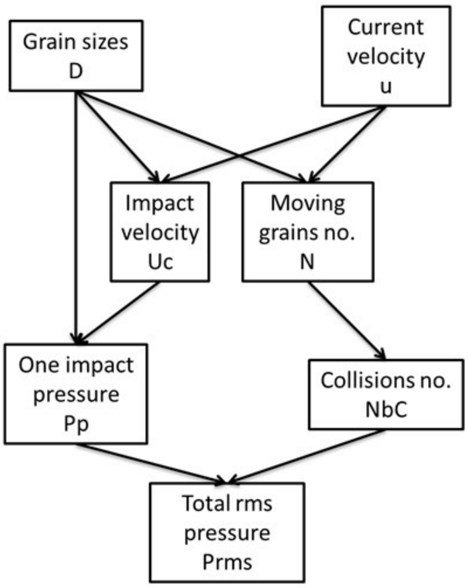

Figure 3: Diagram of the modeling strategy.

2.2.1 Collision number estimation

The Shields diagram[6] is widely used to specify the critical thresholds θ_{cr} for initiation of sand grain motion. It was calibrated and validated with regards to many flume tests. Soulsby[7] proposed a parameterization of the curve:

$$\theta_{cr} = \frac{0.3}{1 + 1.2 \cdot D_*} + 0.055 \cdot [1 - exp(-0.02 \cdot D_*)]$$

With D_*, the dimensionless grain size :

$$D_* = D \cdot \left[\frac{(s-1) \cdot g}{\nu^2}\right]^{1/3}$$

With ν the cinematic viscosity of water and *s* the ratio between sediment density and water density.

For each current velocity and grain size values, the Shields mobility parameter θ can be calculated and compared to the critical threshold for initiation of motion θ_{cr} to determine if particles are moving:

$$\theta = \frac{u_*^2}{(s-1) \cdot g \cdot D}$$

According to Karman-Prandtl equation, the friction velocity u_* can be expressed from the current velocity u_z at height *z* above the seabed:

$$u_* = \frac{\kappa \cdot u_z}{ln(z/z_0)}$$

with κ = 0,4 the von Karman's constant and z_0 the roughness length:

$$z_0 = {}^{D}/_{10}$$

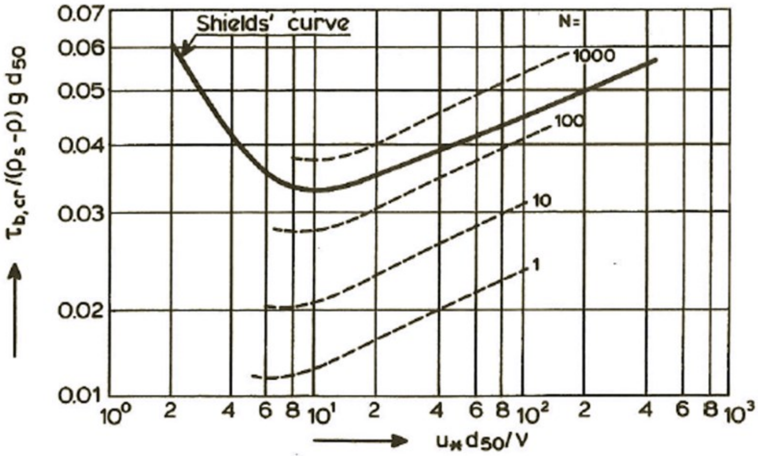

Figure 4: Number of particle moving per unit area (m²).

Van Rijn[8] plotted the Shields curve on a diagram with the aim of quantifying the number of sand grain moving per unit area (Figure 4). It is noticeable that Shield's curve is included between the 100 and the 1000 moving particle curves. It seems to indicate that Shield criterion correspond to a global initiation of motion or to a permanent particle movement and not a single grain movement at one location. This agreement is confirmed by Bufington and Montgomery[9]. They pointed out that Shields' criterion of incipient motion is derived from an extrapolation of bed load transport rates to a low reference value. This method employs shear stress and bed load transport data collected after attainment of equilibrium conditions prior to which considerable reworking of the bed surface may occur.

Figure 4 allow us to evaluate the number of moving grains per unit of area as a function of particle diameter and current speed. During the measurement campaign, the parameter $u_* D_{50}/\nu$ is evaluated to be about 40. At this value, the Shields criterion corresponds to *N* = 300 moving particles. By fitting the number of moving particles versus the ratio between the mobility number for *N* particles, and the Shield criterion, we obtain the following expression:

$$N = 10^{5.33 - 2.78 \cdot {u_{*,cr}^2}/{u_{*,N}^2}}$$

The number of collisions *NbC* between a moving particle and grains on the sea floor is estimated as:

$$NbC = N \cdot S \cdot P$$

With *S* the surface of sea floor where impacts contribute to the signal level recorded by the hydrophone (Figure 5) and *P* the probability of collision for each moving grain. According to Thorne[2], *P* = 10%.

The distance *a* corresponds to the radius of the surface *S*. Assuming each impact of a pair of grains is considered as a dipolar source, *a* is estimated as twice the distance *h* between hydrophone and sea floor[10] and thus:

$$S = 4 \cdot \Pi \cdot h^2$$

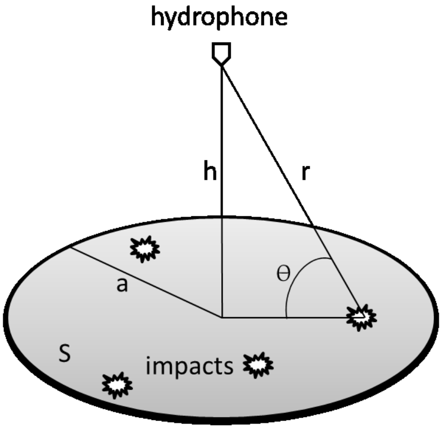

Figure 5: Geometry for the signal generation modeling.

Each particle collision is thus associated with an angle *Θ* and a distance *r* to the hydrophone.

2.2.2 Pressure radiated from a pair of impacting grains

Thorne and Foden[5] described a theoretical framework for the generation of underwater sound by colliding spheres. Rigid body radiation theory has been adopted. The solution proposed considers that each sphere is an independent source which generates a transient that can be described by an impulse solution convolved with the acceleration time history during the collision. The impact process is assumed to be elastic so that a Hertzian acceleration description can be employed. The sound field is then obtained from the sum of the two transients with due allowance for the phase shift due to the path difference from each sphere to the field point.
The total pressure radiated from a pair of impacting grains P_p is formed by the contribution P_s of each particle:

$$P_p(t') = P_s(t', D_1) + P_s(t' - T_d, D_2)$$

With:

$t' = t - \frac{r-D}{2c}$: the retarded time for the impact noise to reach the hydrophone

$T_d = {}^{D\ \cos\theta}/_{c}$: the delayed time between the two pressure radiated to reach the hydrophone

The expression P_s can be simplified if (i) the particles are the same (equivalent diameter and mass), (ii) their density is larger than half the water density and, (iii) the range distance *r* is larger than the particle radius.

$0 \le t' \le t_0$

$$P_s(t') = P_0\{(2\xi^2 - 1)\cos\pi\tau + 2\,\xi\sin\pi\tau - [(2\xi^2 + 1)\sin\pi\xi\tau + (2\xi^2 - 1)\cos\pi\xi\tau\,]e^{-\pi\xi\tau}\}$$

$t' > t_0$

$$P_s(t') = P_0\{[\,(1 - 2\xi^2)\cos\pi\xi(\tau - 1) - (1 + 2\xi^2)\sin\pi\xi(\tau - 1)]e^{-\pi\xi(\tau-1)} - [(2\xi^2 + 1)\sin\pi\xi\tau + (2\xi^2 - 1)\cos\pi\xi\tau]e^{-\pi\xi\tau}\}$$

With:

$P_0 = \rho_w c U_c D\cos\theta/4r(4\xi^4 + 1)$ and $P_0(D_1) = -P_0(D_2)$

$\tau = {}^{t'}/_{t_0}$

$\xi = {}^{2ct_0}/_{\pi D}$: c is the sound velocity in water

$t_0 = 4.53\left(m\frac{1-\sigma^2}{E\,\Pi}\right)^{0.4}\left(\frac{4}{D\,U_c}\right)^{0.2}$: the impact time duration with *E* is the Young's modulus and *σ* the Poisson's ratio

$m = \frac{1}{6}\rho_s\, \Pi D^3$: the grain mass

$U_c = \frac{u_*}{\kappa} \cdot ln(D/z_0)$: the impact velocity

This last one is considered equal to the current velocity at height *D* above the seabed.

2.2.3 Total rms pressure generation

The total pressure generated *Prms* is the summation of pressure signals P_p radiated by each collision for each particle randomly scattered on the sea floor surface *S* during an integration time *T* split in *x* periods.

$$P_{rms} = \sqrt{\frac{1}{x}\sum_{i=1}^{x}\sum_{NbC}\sum_{D} P_p(i)^2}$$

3 RESULTS

Following the modeling strategy (Figure 3), either the particle sizes or the number of moving grains (from which sediment fluxes can be estimated), can be optimized by minimizing the error between acoustic pressure simulated and measured.
Figure 6 presents the pressure time histories of the acoustic transients simulated for particles of equal diameter *D = 1.5 mm*. The pulse depends on the diameter *D*, the location of the impact on the surface *S* and the collision velocity *Uc*. The total signal P_p is the summation of the impactee signal P_{S1} and the impactor signal P_{S2}. This result is in accordance with Thorne experiments[5].

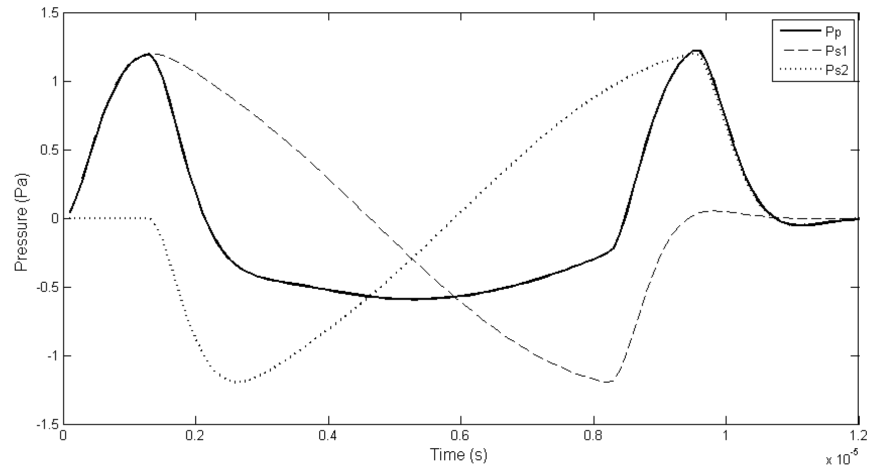

Figure 6: Impact radiation of two colliding particles.

A rms pressure is calculated for particle sizes varying from D = 0.1 mm to D = 2 mm by step of 0.1 mm. The root mean square deviation is minimized for particle size of 0.8 mm. This value is equivalent to the median diameter of sediment samples previously realized near the deployment site.
The match with the measurements is shown on Figure 7. The model tends to underestimate measured Prms and especially fails to reproduce the higher values which are recorded when current velocities are important. Under these strong hydrodynamic conditions, an important spreading of Prms is noticeable for a same current speed value. This observation can be due to (i) the turbulent bursting phenomenon of sediment transport, or (ii) the grains hitting the instrument frame. In either case, model is not set up to simulate these processes.

Another model limitation can explain the underestimation of pressure: only impacts between two particles of the same diameter are taken into account. However, we can consider than the probability for a moving grain to impact a non-moving coarser one is higher, and then the induced pressure is higher.

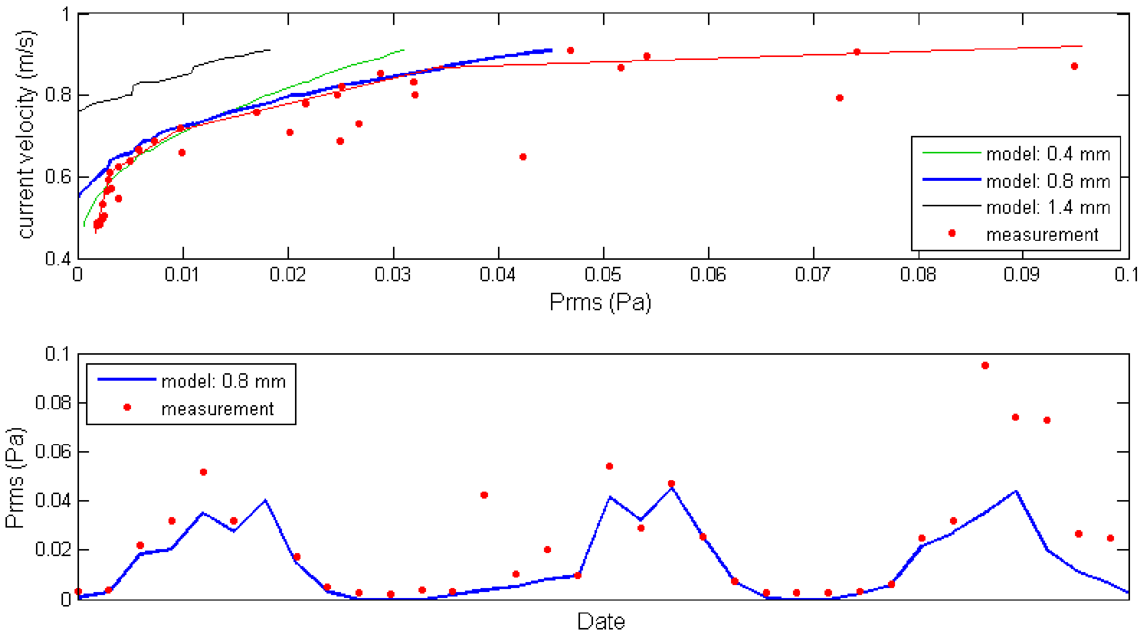

Figure 7: Comparison between model calculation and measurements.

These results are obtained for a single size diameter representative of a well sorted sediment. Although the accordance with measurements is correct, a better error minimization can be reached by taking into account a grain size distribution. The measured curve has been manually fitted by several red straight lines delimiting four sections (Figure 7). That partition can be explained by the contribution of bigger grains set into motion with the increase of current velocity. A preliminary analysis with four different grain sizes (associated with a proportion of presence in the sediment cover), tends to better represent the shape of the curve.

4 CONCLUSIONS

A sea experiment has been undertaken to evaluate the feasibility of using passive acoustic for sand transport characterization. Measurements have shown that the recorded Prms evolves with current velocity fluctuations and, even for grain sizes as small as sand, self-generated noise due to inter-particle collisions can be relevant to identify bedload transport.

An empirical model has been set up in order to simulate the pressure signal due to moving grains. Governing parameters are the number of moving particles and their size. By fitting the pressure measured and calculated, a median grain size involved into the sediment transport has been evaluated. This value is consistent with the medium grain size observed on the area. First attempts made with several grain sizes tend to improve the simulated signal. Once particle sizes are settled on, the number of grains in movement can be optimized with measurements and then a sediment flux could be estimated.

The validity of this inversion process depends on the empirical model precision and the raw data processing. Major limitations can be overtaken by taking into account collision from two particles of different size. Data acquisition can be improved by using an hydrophone with a higher frequency sampling rate and a lower signal to noise ratio. A signal analysis effort can be made on the detection of grain-frame impacts.

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