Bedload quantification by passive acoustic measurement: case of an isolated dune

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ABSTRACT: A preliminary study is performed in a non-tiltable current flume to evaluate bedload transport quantification by passive acoustic measurement with an hydrophone. Tests are conducted with a medium sandand a pre-formed isolated dune as bedform and for different current forcing. Bedload transport is evaluated by two methods: dune-tracking and passive acoustic measurement. Promising results are obtained comparing the root-mean-square pressure from acoustic signals and bedload transport based on excess bottom shear stress. Results from dune tracking method also highlights the sediment supply limitation induced by the isolated dune.

1 INTRODUCTION

Passive acoustics measurements using hydrophones can assess bedload transport quantification during long periods with high temporal resolution as well as during high turbid eventswhich is not possible with optical methods. Research on bedload quantification with hydrophone have been mainly conductedon natural streams and used to quantifygravel bedload (Geay et al. 2017, 2020,Krein et al. 2016). In-situ preliminary studies to estimate bedload transport using passive acoustics measurements were performed by Blanpain et al. 2015 over sands and by Homrani et al. 2019 over coarse shelly sediment of median diameter 1.25mm. The need of laboratory experiments was pointed out in the last study to go further in the analysis.

Thorne 1985 and 1986, based on laboratory experiments in a rotative drum proposed an empirical law to link the number of grain collisions to the root-mean-square pressure. This approach is widely used in the literature. According to Wenz 1962, bedload transport acoustics signal is higher than 20 kHz for sand. Belleudy et al. 2010 have shown that the frequency of bedload transport acoustic signal is increasing when the sediment diameter is decreasing.

Although the difficulties to separate the different components of acoustic signals, in particular to isolate the component related to sediment transport, the hydrophone measurements are simple to implement. Furthermore, in-situ bedload transport quantification is a challenge. Monitoring thebedload transport when submarine dunes migrate is particularly important. It was shown that bedload transport can be correlated to dune migration velocity under unlimited sediment supply as well as under limited sediment supply (Vah et al. 2020). An isolated dune is a particular case of a dune field under sediment supply limitation considering only one dune.

This study is based on experimental tests carried out in a flume under unidirectional current. The case of an isolated dune isstudied. A comparison between results obtained with acoustic and dune tracking methods is performed. The main objective of this preliminary work is to evaluate acoustic measurement possibilities to quantify sand bedload transport in a flume experiment.

2 EXPERIMENTAL SETUP AND TESTS CONDITIONS

Experiments are conducted under unidirectional flow in a non-tilting current flume. The flume is 10.7 m long and 0.49 m wide (Fig. 1). A honeycomb-shaped screen isinstalled in the upstream part of the flume (Fig. 1) to ensure uniform flow conditions.

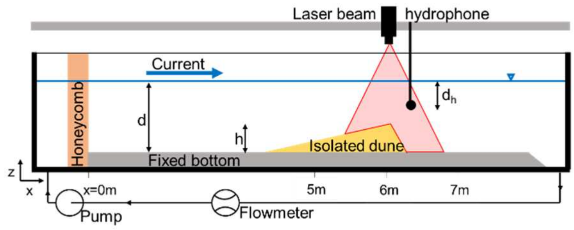

Figure 1. Schematic side view of the current flume

The laser beam is placed above the free surface, laterally centered to the flume at x=6m, where x is the distance from the honeycomb measured in the horizontal direction.A high-resolution digital camera (Basler acA2500-60um, 2048 × 2592 pixels) with a 16 mm focal length is used. It is fixed on a tripod and positioned on the side of the flume at x=6m, inclined from vertical with an angle equal to 50° to visualize the laser plane on a distance of 70 cm. The image resolution was 0.27 mm per pixel. Images are acquiredat a frequency of 0.5Hz with an exposure time of 80,000µs.

A spherical omnidirectional hydrophone (Brüel&Kjær® Type 8105) is placed vertically at x=6.2 m, at a distance d_h below the free surface and at 10 cm from the flume median vertical plane in order to limit perturbation of the free surface near the laser beam.At the beginning of test, the hydrophone is situated above the end of the lee side.It is coupled to a conditioning amplifier (Nexus Type 2692) with 10 mV/Pa calibration on a frequency range extended from 10 Hz to 100 kHz.Data were acquired using an oscilloscope (Teledyne Lecroy Waverunner HRO 66ZI) with a sampling of 2M/sec. Acquisition duration is fixed to 10 s.

Water level far from the isolated dune is set to d=0.25m for present tests. Dune height at equilibrium is noted h. Dune length is equal to approximately 1.2m.

Post-processing for dune tracking method is performed using images acquired with a high-resolution camera. Dune position is extracted after calibration from the position of the laser beam on the images. Migration of the isolated dune is estimated from the crest displacement. Dune height h at equilibrium is also measured. These two parameters allow to calculate the bedload transport rate.

Two different isolated dunes are created in the flume: a mobile one and a fixed one. The mobile dune is composed of medium sediment from a quarry with a medium diameter D_{50} equals to 617µm. This sediment is well-sorted, based on Soulsby 1997 criterion with a density of s=2.65. The fixed dune is composed oflarge pebbles (diameter between 2 to 6 cm) covered with small pebbles with a diameter from 4 to 6 mm to obtain the smallest possible bottom rugosity for a fixed dune under present hydrodynamic forcing.During all the tests on the fixed dune, no pebbles movement are observed.
The same experimental procedure is used for the two series of tests, with a mobile anda fixed dune:

- The dune is manually pre-formed
- Current is turned on with an acceleration phase of 1 minute to reach to desired flow value.
- Acquisition of images for dune tracking measurement is started. Acoustics acquisitions of 10s are triggeredwith a one-minute period.
- After 10 to 15 min the current is turned off.

No image acquisition is performed for tests with the fixed dune.

Conditions of the tests with the mobile isolated dune are given in table 1. The same

Table 1: Tests conditions with the mobile isolated dune. Parameters are given at equilibrium.

test	U (m/s)	h (m)	d_h (m)
1	0.3	0.08	0.075
2	0.32	0.074	0.075
3	0.34	0.075	0.075
4	0.36	0.073	0.075
5	0.38	0.074	0.1
6	0.4	0.08	0.1

tests are conducted with the fixed dune for the same flow velocities. Fixed dune height is equal to 0.085m for all the tests. An additional test was performed without flow to obtain the ambient noise.

For the mobile isolated dune, the angle of the lee side is 32° at equilibrium for all the tests, which corresponds to the avalanche angle and the angle of the stoss side near the crest is 1.5°.

For all the tests the flow regime is turbulent with a Reynolds number larger than 5000. The shear Reynolds number is defined in Equation 1.

$$R_* = \frac{u'_* k_s}{\nu} \quad (1)$$

where u'_* is the bed shear velocity calculated from Equation 2 given below, k_s is the roughness height with $k_s=2.5D_{50}$ (Nielsen 2009) and ν the fluid kinematic viscosity;

$$\frac{u(z)}{u'_*} = \frac{1}{\kappa}\ln\left(\frac{z}{z_0}\right) \quad (2)$$

where z is the distance from the bed in the vertical direction, u(z) is the flow velocity at a distance z from the bed, κ=0.4 is the von Karman constant and z_0 is a length scale.

For all the tests, the shear Reynolds number R_* is higher than 70 at dune crest which correspond to a rough turbulent flow regime (Sleath 1984). The length scale z_0 may be estimated using Equation 3.

$$z_0 = \frac{k_s}{30} \quad (3)$$

The effective Shields parameter θ' is obtained with Equation 4:

$$\theta' = \frac{{u'_*}^2}{(s-1)gD_{50}} \quad (4)$$

where g is the acceleration due to the gravity.

The effective Shields parameter is calculated at equilibrium state and at the dune crest.

The critical Shields number $\theta_c$corresponding to the Shields number at the sediment motion threshold is obtained for the D_{50}=617µm sedimentfrom Vah et al. 2022 and $\theta_c = 0.0373$.

Dimensionless bedload sediment transport is calculated from Equation 5.

$$\Phi = \frac{Q_s}{\sqrt{(s-1)g\, D_{50}^3}} \quad (5)$$

where Q_s is the dimensional bedload transport [m²/s].

Charru 2006 showed theoretically that Φ is proportional to $\theta'^{3/2}$, based on a conservation equation and an erosion-deposition model. Bedload transport is compared with a formulation based on the excess of shear stress (Eq. 6), with m a dimensionless parameter. This equation is based on the one proposed by Meyer-Peter and Müller 1948.

$$\Phi = m(\theta' - \theta_c)^{3/2} \quad (6)$$

3 BEDLOAD TRANSPORT USING DUNE TRACKING METHOD

Results obtained for dimensionless bedload transport from tests with the mobile isolated dune are shown in Figure 2 and in Table 2.

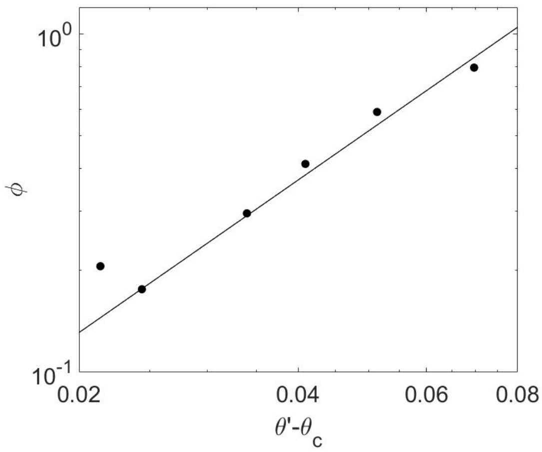

Figure 2. Dimensionless bedload transport. The black line represents the best fit obtained.

Equation 6 has been fitted to the present data and the best value for the parameter m is m=46.3 with a correlation coefficient R^2=0.96.

The power coefficient proposed by Charru 2006 is still available for present data for bedload transport of an isolated dune.

Based on experiments under infinite sediment supply conditions and bedforms naturally formed with the current conditions in the flume from a flat bottom, Meyer-Peter and Müller 1948 and Vah et al. 2020 found, respectively, m=8 and m=6.

The present study is in limited supply sediment conditions. Conclusions for this supply condition found by Vah et al. 2020 in a flume for the same sediment are the following ones: bedforms formed in supply limited sediment condition are smaller and their migration velocities are higher than ones under infinite supply condition for the same hydrodynamics conditions. Here the isolated dune is largely bigger than the one that would havenaturally been formedin the flume. Due to mass conservation, sediment bedload transport is higher in this case than expected for this sediment and this range of excess shear stress under infinite supply conditions. This explains the larger value found for the coefficient m than the one predicted by Meyer-Peter and Müller 1948 or Vah et al. 2020

4 BEDLOAD TRANSPORT USING PASSIVE ACOUSTIC METHOD

For acoustic measurements, a high pass filter is applied on acoustic signal with a 10 kHz cut off frequency (Blanpain et al. 2015). Signal below 10 kHz is assumed to be due toturbulence, free surface, electric noise as well as bedload for particles larger than 1 cm (Thorne 1985, 1986, Geay 2013). Then, the root-mean-square pressure (P_{rms}) is calculated on each acoustic acquisition.

The empirical formulation proposed by Thorne 1985, 1986 to link frequency peak (F_{peak})of the acoustic signal to bedload particle size, for uniform grain size distributions is given in Equation 7.

$$F_{peak} = \frac{224}{D_{50}^{0.9}} \qquad (7)$$

For the sediment size considered in this study, Equation 7 gives F_{peak}=173 kHz. As the acoustics signal is sampled at a lower frequency (100 kHz), the validation of this empirical law for this set of experiments in a flume is not possible.

Despite the weakerfrequency sampling compared to the one forsome similar works (frequency sampling of 314 kHz for Blanpain et al. 2015 and Homrani et al. 2019 and of 600 kHz for Thorne 1985, 1986), the objective is to questionif correlation between bedload and acoustic signal can however be detected. Indeed, if the acoustic signal is maximum at F_{peak}=173 kHz, the frequency content of the acoustic signal associated to the sand transport is extended on a wide range.

The mean P_{rms} value estimated for each testisplotted as a function of the excess of shear stress (Fig. 3).

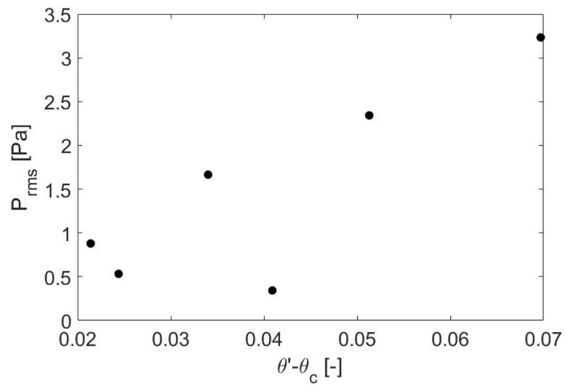

Figure 3. Mean P_{rms} values as a function of the excess shear stress.

Table 2: Dimensionless bedload transport for experimental tests

test	u'* [m/s]	θ' [-]	Φ [-]
1	0.0242	0.0587	0.206
2	0.0248	0.0617	0.176
3	0.0267	0.0713	0.295
4	0.0280	0.0782	0.413
5	0.0297	0.0886	0.588
6	0.0327	0.107	0.796

To fit present values, tests 2 and 4 are removed due to the low P_{rms}value found for these two tests. These outliersmay result from a problem during acquisition such as the presence of air bubbles on the hydrophone. Data are fitting with Equation 8 with a good regression coefficient.

$$P_{rms} = a\,(\theta' - \theta_c)^{3/2} + b \qquad (8)$$

where a=148 Pa and b=0.6 Pa (R^2=0.98).

P_{rms} is also evaluated for the test without flow (only ambient and electric noise), this value is equal to coefficient b in Equation 8. To reduce background noise on data, the P_{rms} value without flow is removed from the P_{rms}values with flow. In spite of the few amounts of testing, it is shown that P_{rms}tends to be proportional to bedload transport.

The same post-processing is applied on acoustic data acquired with the fixed dune and no correlation with the excess bed shear stress was found.

5 CONCLUSIONS

Conclusions on this preliminary work can be resumed as:

- Sediment bedload transport quantification using dune tracking method is consistent with formulations from the literature. The sediment supply limitation which is the consequence of the isolated dune induces larger values for bedload transport than expected using Meyer-Peter and Müller 1948 formulation.
- Even if the acoustic signature of grain collision may be partial due to the weak frequency sampling, mean rms pressure is globally a relevant indicator of bedload transport.

New laboratory tests are necessary to confirm these preliminary results in controlled conditions with various sediments or other bed configurations and a higher sampling frequency.

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