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Technical note: X-ray computed tomography to measure bed density in sand transport

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Abstract:	This paper reports a new experimental method applying medical X-rays computed tomography (CT) to estimate the bedload in sand transport. A set of current-generated sand ripple experiments were conducted in a small hydraulic flume inserted in the CT scanner. The methodology is based on the measurements of height, velocity and density of bedforms to estimate bedload. A temporal series of bed topography is first extracted from the CT scan images. The velocity is estimated by tracking the displacement of bedforms from two successive bed topography. The sand bed density (ρ sb) is estimated from the CT-scan measurements using a calibration technique. The method measuring ρ sb to calculate bedload is validated comparing measurements made with sand traps. The advantages and limitations of the CT method applied to bedload transport are discussed.
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Technical note: X-ray computed tomography to measure bed density in sand transport

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Abstract

This paper reports a new experimental method applying medical X-ray computed tomography (CT) to estimate the bedload in sand transport. A set of current-generated sand ripple experiments were conducted in a small hydraulic flume inserted in the CT scanner. The methodology is based on the measurements of height, velocity and density of bedforms to estimate bedload. A temporal series of bed topography is first extracted from the CT scan images. The velocity is estimated by tracking the displacement of bedforms from two successive bed topography. The sand bed density (ρ_{sb}) is estimated from the CT-scan measurements using a calibration technique. The method measuring ρ_{sb} to calculate bedload is validated comparing measurements made with sand traps. The advantages and limitations of the CT method applied to bedload transport are discussed.

Practical Applications

Sediment transport is a fundamental physical process in Earth Sciences. It refers to the movement of sediment grains moved by water currents and deposited where or when water flow ends. This cycle seems at first inoffensive but could impact millions of human lives all around the world. River floods, sea-level rise and storms are likely to modify the landscape of many populated areas located nearby in the next decades. Our understanding of sediment transport processes would greatly benefit our capacity to determine the impact of those extreme events on river and coastal morphology. To achieve this, physical models are used in laboratories to simulate sediment dynamics at a smaller scale. These results help researchers developing numerical models of sediment transport to better predict river dynamics as well as the movement of coastlines. This study is an insight on the application of new laboratory techniques using advanced 3D imaging technique as an effort to contribute in the development of our knowledge in the field of sediment dynamics.

Introduction

Bedload transport, the transport rate of unsuspended grain by flowing water, of fine sediments is often observed through bedform migration. It remains, however, difficult to measure and quantify using laboratory and field techniques. Sediment traps are generally used (Roberts et al. 2003, Holmes 2010, Mrokowska et al. 2018, Khosravi et al. 2019) but they only provide a local section-averaged and temporally averaged estimation of bedload transport. Yet, most of the classical equations (Khorram and Ergil 2011) for bedload transport are derived from this averaged trap method. Acoustic tools such as Acoustic Doppler Velocity Profiler (ADVP) (Blanckaert et al. 2017) or acoustic concentration and velocity profiler (ACVP) (Hurther et al. 2011) can be used to evaluate bedload characteristics, but for a single point only. Bedload transport can also be estimated using the mass conservation equation, known as the Exner equation, by calculating the bed form velocity (McElroy and Mohrig 2009); this method is commonly known as the dune-tracking method. It can be non-intrusively established by acquiring a temporal series of bed topography and tracking the displacement of the bed forms with time (Muste et al. 2016, Tsubaki et al. 2018). However, there is still one parameter of the Exner equation that is roughly approximated, which is the dry sand bed density (ρ_{sb}). The density of a sand layer including voids is indeed difficult to measure in real time without disturbing the experiments or the bed structures. Recent studies attempted estimating sediment matter density in water flows in a non-intrusive way for multiphase flows using Synchrotron X-ray (Kastengren and Powell 2014) and gamma-Ray attenuation. However, these approaches are restricted to very small volumes (Mayar et al. 2020).

This study explores the use of medical X-ray computed tomography (CT) to estimate ρ_{sb} in the bedload layer. The CT is a non-destructive technique applied in numerous fields of geosciences calculating a 3-dimensional attenuation coefficient matrix of the scanned object scaled in Hounsfield units (HU), which is physically related to matter density (Ketcham and Carlson 2001, Otani and Obara 2004, Ketcham and Iturrino 2005). The large opening of medical CT scanners allows for a small hydraulic flume to be installed within the scanner's gantry. Previous studies shown promising results in quantifying sediment transport processes using this kind of setting (Yamada et al. 2013, Tilston et al. 2015, Brunelle 2019). However, it has not been demonstrated how precise and accurate is the medical CT scanner to derive the bedload transport especially for moving sand grain with particle size (D) smaller or close to the CT image resolution (0.56 mm). In this case, any segmentation technique that classifies CT image pixels to differentiate the volume of sand and void (Griffin et al. 2012) is not applicable. CT also suffers from numerous image artefacts (Hsieh 2009) that might compromise its application when using large and squared objects such as a uniform and rectangular hydraulic flume filled with a movable sand bed.

To estimate the potential of medical CT scanner for the study of fine and non-cohesive sediment bedload transport in the laboratory, a series of flume experiments over mobile sand bed with increasing unidirectional flow velocities is performed. First, the data analysis procedure is detailed in order to extract the parameters of bedload transport equation (*i.e.*, bed shear stress, bed elevation, bedforms velocity and bed density) from measurements (*i.e.*, water velocity and HU). Secondly, the resulting bedload rates are compared to sand trap measurements carried out at the downstream end of the flume. Based on the experimental results, the manuscript discusses potentialities and limitations of the method.

Method

In the following sections, spatial averages are indicated with the angle bracket symbol (< >) with averaged dimensions in subscript and time averages with overbar symbol (¯). The indices *x*, *y* and *z* indicate the averaged dimensions along the *x*, *y*, *z* directions. The *x*, *y*, *z* axes are oriented streamwise, transversely and vertically, respectively. The sand bedload (q_{sb}) in terms of mass flow rate per unit width (kg m^{-1} s^{-1}) is computed as:

$$q_{sb} = \rho_{sb}\, V\, \eta\ , \tag{1a}$$

where ρ_{sb} is the dry sand bed density, *V* is the mass flow velocity, here estimated from bedform velocity, and η is the sand bed elevation. The error (ε) on bedload is estimated by using the propagation of error method from the right-hand side of Eq. 1a as described by Bevington and Robinson (2003) for multiplicative terms:

$$\varepsilon_{q_{sb}} = q_{sb} \sqrt{\left(\frac{\varepsilon_{\rho_{sb}}}{\rho_{sb}}\right)^2 + \left(\frac{\varepsilon_V}{V}\right)^2 + \left(\frac{\varepsilon_\eta}{\eta}\right)^2} \tag{1b}$$

The dry sand bed density ρ_{sb} is computed using the CT scanner measured values in Hounsfield units (HU). The HU values vary from -1024 to +3071 providing 4096 levels relative to matter density. A voxel of the CT scan image contains a percentage of water and sand. The CT measurement of wet sand bed (HU_{sb}) is therefore converted into dry sand bed density by testing the following expression:

$$\rho_{sb} = \rho_s \frac{(HU_{sb} - HU_w)}{(HU_q - HU_w)}\ , \tag{2}$$

where ρ_{sb} is a function of the CT scan measurement of water (HU_w), quartz (HU_q) and the density of the sand grain (ρ_s), which is uniform and equal to pure quartz ($\rho_s = \rho_{quartz}$). A 2 cm^3 piece of pure quartz mineral is buried in the sand bed to determine the reference value of HU_q. The sand bed density ρ_{sb} is not considered to be time- or space-dependent and the precision of using the three-dimensional spatial average of dry sand bed density ($<\rho_{sb}(x,y,z)>_{xyz}$) as an input for Eq.1 is evaluated.

The bedform velocity and bed elevation are time- and space-dependent. Consequently, these parameters are both estimated in space (*xy*) but for a period or an instantaneous time, respectively. The cross-correlation algorithm by Scarano (2012), using LaVision software, calculates the temporal average of bedforms velocity vector field ($\overline{V}$) from two successive 2D bed elevation maps separated by a time interval T (Table 1). The calculation creates a 2D vector grid (x,y) of bedform velocities. Only the temporal average of bedform velocity in the streamwise direction ($\overline{V}_x$) is kept for Eq. 1 representing the solid transport in the flow direction. The missing velocity values, where the cross-correlation algorithm failed to calculate velocity, were estimated by calculating the average to closest neighbours.

The bed elevation η is extracted from the 3D HU matrix measured by CT scan to obtain the sand bed topography. In this study, the level $\eta = 0$ is chosen as the minimum of the bed topography. A threshold value HU = 400 is used to distinguish water and sand considering that water and sand HU values are significantly different (where HU > 400 corresponds to sand); HU_w values are around 0. Only the second measurement of bed topography is used in Eq. 1 to specify η, neglecting the change in shape of bedforms with time during measurements as a result of technical limitations.

The velocity ($\bar{V}_x(x,y)$) and height ($\eta(x,y)$) of bedforms are discretised on the bed topography xy-grid. The Eq. 1 returns the time-averaged bedload in the xy-plane ($\bar{q}_{sb}(x,y)$). The bedload is expressed as a function of fluid bed shear stress τ_0. The bed shear stress is estimated by the quadratic stress law:

$$\bar{\tau_0} = \rho C_d \bar{U}^2 \ , \tag{3}$$

where $\bar{U}$ is the mean flow velocity and ρ is the water density. The mean flow velocity $\bar{U}$ is expressed as a function of the time-averaged water discharge ($\bar{Q}$), the width of the flume (W) and the initial water depth over flat bed (d); $\bar{U} = \bar{Q}/Wd$, where $W = 0.30$ m. The empirical non-dimensional drag coefficient C_d depends on the vertical flow velocity profile and is evaluated assuming a logarithmic profile (Soulsby 1983):

$$C_d = \left(\frac{\kappa}{1+ln\left(\frac{z_0}{d}\right)}\right)^2 \ , \tag{4}$$

where κ is the von Karman's constant ($\kappa = 0.41$), z_0 is the hydraulic roughness length. The hydraulic roughness length z_0 is associated with apparent bed roughness (k_s), commonly called equivalent sand roughness, quantified as $k_s = 30\ z_0$ (Nikuradse, 1933). The bed roughness is expressed as a function of grain size $k_s = 2\ D_{90}$ (Yalin 1972), where D_{90} is the ninety percentile of grain size distribution. The bed shear stress is described in terms of a non-dimensional bed shear stress commonly named the Shields' parameter (θ) after Shields (1936):

$$\bar{\theta} = \frac{\overline{\tau_0}}{(\rho_s - \rho) g D_{50}}, \quad (5)$$

where D_{50} is the fifty percentile of grain size distribution and g is the acceleration of gravity (9.81 m s^{-2}). The results are compared to the bedload formulas of Camenen and Larson (2005) to ensure repeatability of the experiments. The equation proposes a transport equation for non-cohesive sediments in steady flows from a wide range of data:

$$\langle\overline{q_{sb}}\rangle = \rho_s \sqrt{\left(\frac{\rho_s}{\rho} - 1\right) g {D_{50}}^3}\, \alpha \bar{\theta}^{\beta} e^{\left(-\gamma \frac{\theta_c}{\bar{\theta}}\right)}, \quad (6)$$

where the critical value of shear stress for grain motion θ_c is set here to 0.02 (based on preliminary experiments), the freshwater density ρ is 1000 kg m^{-3} and the empirical coefficients are $\alpha = 12$, $\beta = 1.5$, $\gamma = 4.5$. Eq. 6 is compared to the estimated bedload to determine the accuracy of the CT scan method. The coefficient of determination (R^2) is estimated for CT and sand trap methods by using:

$$R^2 = 1 - \frac{\sum(\langle\overline{q_{sb}}\rangle_i - f_i)^2}{\sum(\langle\overline{q_{sb}}\rangle_i - \langle\overline{q_{sb}}\rangle_{mean})^2}, \quad (7)$$

where f is the function of Eq. 6 fitted to the data. The summation of Eq. 7 is calculated over the number of elements i that corresponds to the number of measurements. The coefficient R^2 is used to determine the precision of measurements where a value close to 1 indicates a great precision.

Experimental Setup

An acrylic flume 0.30 m × 0.30 m × 7.0 m with 0.025 m thick walls is inserted longitudinally and horizontally (no slope) into the medical CT scanner of the Multidisciplinary Laboratory for Non-Medical Use at the Institut National de la Recherche Scientifique (INRS, Québec, Canada) (Fig. 1a). This scanner (Siemens, Somatom Definition AS+ 128) moves on 2.6-m rails along the flume in the longitudinal *x*-axis. A series of four experiments (EXP1 to EXP4) is performed at different initial water depth over flat bed (*d*), which is measured by the CT scanner, with increasing flow speed. Yet, transitional to turbulent flows are induced by a water pump (Fig. 1d) joining two large water tanks (4 m^3) placed at each extremity of the flume (Fig. 1b, c). The water level into the tanks is a continuity of the flume surface waters. A honeycomb diff user reduces the turbulence at the water inlet (Fig. 1b). The unidirectional flow is maintained for approximately 30 minutes until the mean ripple height becomes constant prior to CT scan measurements. Based on the model by Soulsby et al. (2012), we verified that bedforms reached their equilibrium properties before 30 minutes.

The horizontal sand bed consists in pure (99%) quartz (SiO_2) sand grain with a density of ρ_s = 2650 kg m^{-3}, a median grain diameter D_{50} of 216 µm and a ninety percentile D_{90} of 355 µm. The sand bed is flattened manually before each experiment to obtain an initial bed thickness of 0.05 m. Table 1 summarizes the experimental conditions. A plexiglass box is placed at the downstream end of the flume where the sand in the bedload layer can fall in. The bedload rate per unit width (kg m^{-2}) is computed by weighting the dried sediments of the trap for a similar series of discharges (Camenen et al. 2017).

CT scan data acquisition

The initial measurements are 360 degrees 1D X-ray projections through the cross section of the flume. The 3D matrix is reconstructed with a weighted filtered back projection (Stierstorfer et al. 2004). For the experiments, the X-ray beam collimation is 1.2 mm, and the X-ray tube current intensity was 287 m with a tube voltage of 140 kV. The pitch factor, determining the gantry velocity during measurements in spiral mode (see below), is set to 0.35. The convolution kernel used to remove noise in the image reconstruction is a soft image smoothing Siemens filter (B30s). The CT measurement results in a three-dimensional (3D) HU matrix of 512 × 512 pixels with a resolution of 0.6 mm in the cross-section (*zy*) and 2.0 mm in the longitudinal axis (*x*). Each scan is acquired within seconds. Two consecutive CT scans of a given length (*L*), separated by a time interval (*T*), are used to detect the 2D movement of sand ripples in the plane *xy*. As the bedform velocity increases, the length of the scan (*L*) needs to be shortened to reduce the time *T* between two consecutive scans (see Table 1). The time *T* between two scans is directly limited by the cooling time required by the CT scanner. For EXP1, EXP2 and EXP3, the scans are acquired in the spiral mode where the CT scanner moves on the rails allowing long scan and sufficiently long time *T* to track the displacement of bedforms. For EXP4, where the bedform velocity is the highest, the scan is performed in the static mode and the scanner does not move. This allows shorter time *T* than the spiral mode but shorter length *L*. Nevertheless, *L* remains long enough to allow measurements covering at least the equivalent of one bed forms wavelength (i.e., crest-to-crest of bed structures), as the bed migrates within the flume.

CT image post-processing

One of the main CT artefacts affecting this study is beam hardening (Ketcham and Hanna 2014). It refers to the preferential attenuation of the low-energy photons of the X-ray source, which tends to underestimate the HU values at the centre of objects (Brooks and Di Chiro 1976). In this study, an empirical correction is applied to CT scan cross-section images of the flume to reduce the beam hardening artefacts, as proposed by Brunelle et al. (2015). In short, HU values given by a correction matrix (M_{cor}) calculated following Eq. 8a – 8c is subtracted from the original CT scan image as shown on Fig. 2.

$$\varphi(y,z) = atan\left(\frac{Y(y,z)}{Z(y,z)}\right) \tag{8a}$$

$$r(y,z) = \sqrt{Y^2(y,z) + Z^2(y,z)} \tag{8b}$$

$$M_{cor}\,(y,z) = (0.08\, r^2(y,z)\, |\cos(2\varphi(y,z))|^2\,) - 100, \tag{8c}$$

where $Y(y,z)$ and $Z(y,z)$ are the matrix of position index for each pixel centred in the middle of CT scan image.

Results

The three terms of Eq. 1 and bedload transport have been obtained as follows. The dry sand bed density ρ_{sb} is first estimated using Eq. 2 from the HU values. The CT scan images in the cross-section of the flume (Fig. 2a) shows a range of HU values, indicating some ρ_{sb} variations within the bed. This variation is interpreted as the measurement error of ρ_{sb}. To reduce this error, mainly caused by the beam hardening artefact, a correction (Eq. 8a-c) is applied (Fig. 2b) to CT scan images. The result is illustrated in Fig. 2c showing that most of the beam hardening artefacts within the bed are removed. However, the correction does a poor job in the bedload layer, *i.e.*, at the water sediment interface. The remaining error for ρ_{sb} is estimated by calculating the standard deviation of the three-dimensional spatial distribution of $\rho_{sb}(x,y,z)$. The three-dimensional spatial mean of sand bed density $<\rho_{sb}(x,y,z)>_{xyz}$ and errors are listed in Table 1 for each experiment. The second term of Eq. 1 is estimated from the bedform velocity vector field ($\overline{\boldsymbol{V}}(x,y)$) (Fig. 3b). Only the time-averaged bedform velocity in the streamwise direction $\overline{V}_x(x,y)$ (Fig. 3c) is used to calculate the spatial distribution of bedload (Fig. 3d). The third term of Eq. 1, the bed elevation, is illustrated on Fig. 3a neglecting the change in time of bedforms. The spatial distribution of the time-averaged bedload $\overline{q}_{sb}(x,y)$ is then computed as illustrated on Fig. 3d.

The spatial mean of bedload $<\overline{q}_{sb}(x,y)>_{xy}$ are listed in Table 1 for each experiment. $<\overline{q}_{sb}(x,y)>_{xy}$ is plotted as a function of $\bar{\theta}$ on Fig. 4. The error for bed elevation $\eta(x,y)$ and bedform velocity measurements, estimated to 1% and 10% respectively, are propagated additionally to the error for $<\rho_{sb}(x,y,z)>_{xyz}$ (Eq. 1b) to estimate the error on bedload. The error is on average 17,5 % for the sand bed density according to the standard deviation of $\rho_{sb}(x,y,z)$. The error on bedload is thus estimated on average to 20%. The uncertainty in $\bar{\theta}$ computation (± 10%) mainly comes from the water discharge measurements that are used to estimate $\overline{U}$ (Eq. 3 and Eq. 5).

This indicates that the precision of bedload is low. However, $<\bar{q}_{sb}(x,y)>_{xy}$ values are accurate according to the sand traps. Indeed, the sand trap measurements, equivalent to term $<\bar{q}_{sb}(x,y)>_{xy}$, are in satisfactory agreement with the CT scan measurements (Fig. 4). The accuracy of the new method compared to trap values even improves for higher sediment transport rates. All the CT scan data are also within an acceptable range compared to the bedload equation of Camenen and Larson 2005. Moreover, $<\bar{q}_{sb}(x,y)>_{xy}$ values estimated with the CT method have a higher coefficient of determination (Eq. 7) with $\bar{\theta}$ ($R^2 = 0.94$) when fitting the data using Camenen and Larson (2005) equation (Eq. 6), than the sand traps ($R^2 = 0.11$).

Discussion and conclusions

The experiments showed that the CT scan method calculates accurately the bedload transport by correctly estimating the sand bed density on average. However, the method deals with severe CT scan image artefacts. These CT scan artefacts are the main cause of error for sand bed density measurements and consequently, for bedload transport calculation. Medical CT scanners have not been optimized for thick and dense objects with sharp edges such as a sand bed in a flume, but for the human body with density close to water. These errors are caused by the density, thickness, and sharp edges of the sand bed, which are unusual for a medical CT. While the correction proposed for CT scan image post-processing performed well within the sand bed, it was less efficient for the bedload layer where irregular ripples formed. The weighted filtered back projection image reconstruction algorithm provided by the CT scanner manufacturer produced artefacts on these asymmetrical bedforms in the cross-section. Advanced beam hardening reduction, such as iterative image reconstruction algorithms could help in reducing these kinds of artefacts but are numerically intense and require the knowledge of the scanner geometry (Di Schiavi Trotta et al. 2022), but are viable options to improve image quality.

The experimental setup is also limited to CT scan system capacity. The size, mainly the thickness, of the sand beds is limited, because beds thicker than 0.05 m would attenuate the X-rays to a point this could cause an unmanageable signal-to-noise ratio. The CT scan method is, moreover, limited by the cooling time needed by the X-ray system. This means that the time between two successive scans cannot be shorter than 30 seconds, limiting the length of the topography to 0.1 m. During the experiments, it was also determined that the maximum velocity of bedforms that can be detected using this configuration is around 0.6 mm s^{-1}. Long scans (i.e., up to 2 metres) can be used to detect the movement of ripples if the velocity is not higher than 0.016 mm s^{-1}.

The advantage of the CT scan method over the sand traps is the capacity to provide spatial and temporal variations of bedload transport, including the sand bed density measurements. The correlation between bedload data with the bed shear stress is higher for CT scan than for sand traps. This highlights the benefit of mass flux calculation with bedforms tracking method. The sand trap methods are likely to induce error from sand manipulation. The proposed CT scan method could be applicable to any future bedload transport experiment studying the link between sediment density and bed dynamics within the limitations discussed above. This work can be conducted in parallel with micro-CT scan imaging technique that could determine physical properties of sediments at higher resolution using smaller samples (Mayar et al. 2020, Hodge et al. 2020). It proved to deliver meaningful bedload measurements for migrating ripples and is most promising for the study of symmetric wave ripples that would produce fewer image artefacts, or to the study of the sediment dynamics below the ripple zone, such as the infiltration of fine sediment into a coarse and porous sediment bed (Camenen et al., 2017).

Notation

The following symbols are used in this paper:

HU = Hounsfield unit of CT scan;

q_{sb} = sand bedload rate per unit width (kg m^{-1} s^{-1});

U = water velocity (m s^{-1});

$\boldsymbol{V}$ = bedforms velocity vector (m s^{-1});

V_x = bedform velocity in the x direction (m s^{-1});

η =sand bed elevation (m);

ρ_{sb} = dry sand bed density (kg m^{-3});

ρ_s = sand grain density (kg m^{-3});

ρ = water density (kg m^{-3});

θ = Shields' parameter (-);

$<\ >_{x.y.z}$ = spatial mean in x, y, z dimensions;

$\overline{\ }$ = temporal mean;

Data Availability Statement

All data, models, or code generated or used during the study are available in a repository or online in accordance with funder data retention policies: Brunelle, Corinne, 2021, "X-ray computed tomography to measure real-time porosity in bedload transport experiment", https://dataverse.scholarsportal.info/dataset.xhtml?persistentId=doi:10.5683/SP2/SUNA2L, Scholars Portal Dataverse.

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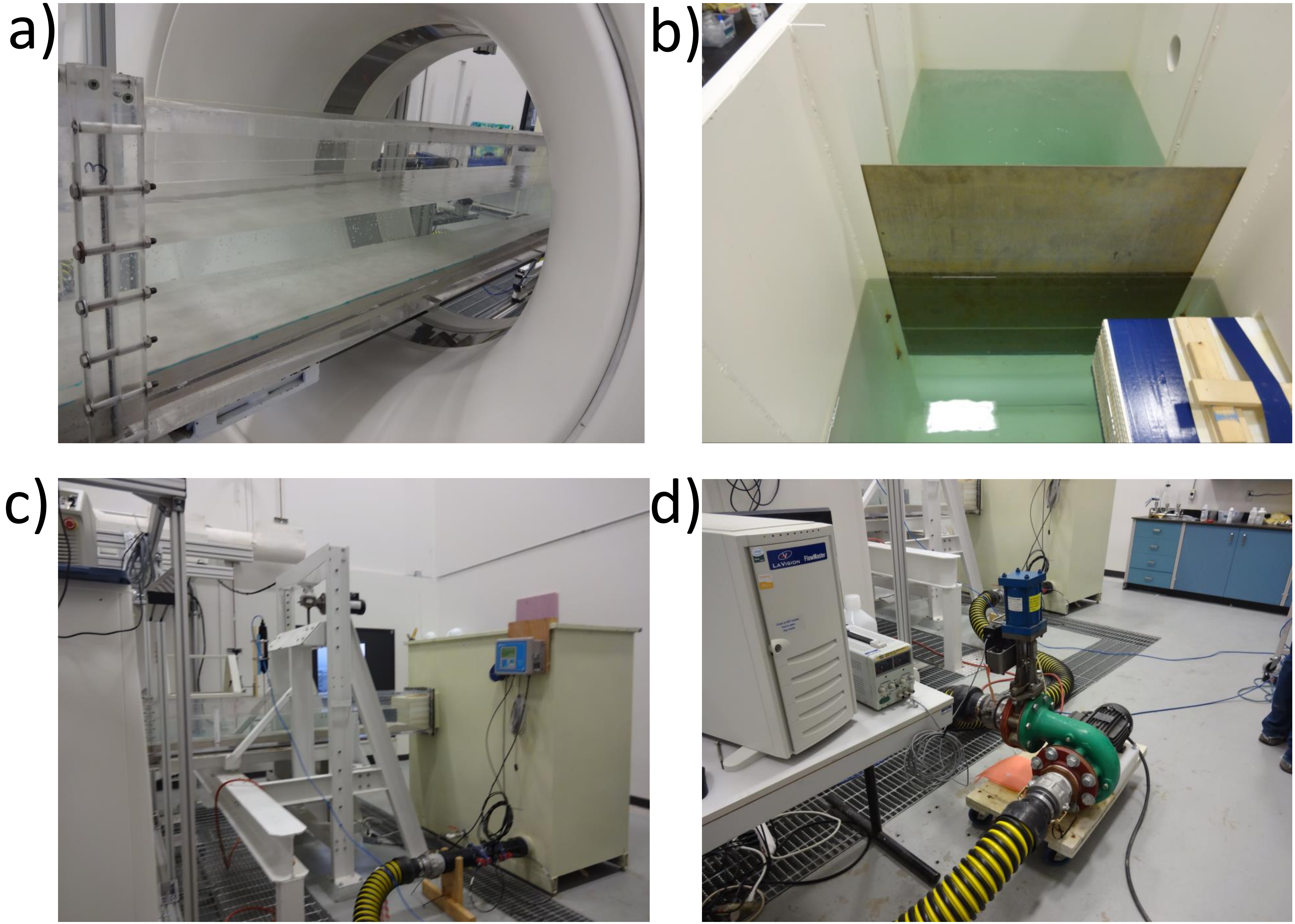
Table 1. Experimental conditions for sand bed experiments (EXP) including water discharge ($\bar{Q}$) initial water depth (d), section and time averaged fluid velocity ($\bar{U}$) estimated using ($\bar{Q}$), Reynolds (Re) and Froude (Fr) numbers using $\bar{U}$, Shields' parameter ($\bar{\theta}$). The standard deviations of mean values are in parentheses. The time- and space-averaged, indicated by overbars and subscripts respectively, bedform velocity in the *x* direction ($<\bar{V}_x>_{xy}$) and bedload transport $<\bar{q}_{sb}>_{xy}$, and space-averaged sand bed density in the bedload layer ($<\rho_{sb}>_{xyz}$) are listed. The length (L) and time between CT scans (T) are indicated.

EXP	$\bar{Q}$	d	$\bar{U}$	Fr	Re	$\bar{\theta}$	L	T	$<\bar{V}_x>_{xy}$	$<\rho_{sb}>_{xyz}$	$<\bar{q}_{sb}>_{xy}$
	$m^3\ s^{-1}$	m	$m\ s^{-1}$	-	-	-	m	s	$mm\ s^{-1}$	$kg\ m^{-3}$	$kg\ m^{-1} s^{-1}$
EXP1	0.008	0.140	0.19	0.16	4433	0.029	1.20	810	0.016 (0.002)	1060 (186)	0.00014 (0.00003)
EXP2	0.010	0.140	0.24	0.20	5600	0.047	0.30	200	0.10 (0.03)	1060 (186)	0.0025 (0.0005)
EXP3	0.012	0.140	0.29	0.25	6766	0.068	0.20	80	0.18 (0.08)	1087 (212)	0.0053 (0.0012)
EXP4	0.012	0.120	0.33	0.30	6600	0.092	0.10	30	0.56 (0.06)	1113 (159)	0.013 (0.002)

Figure 1



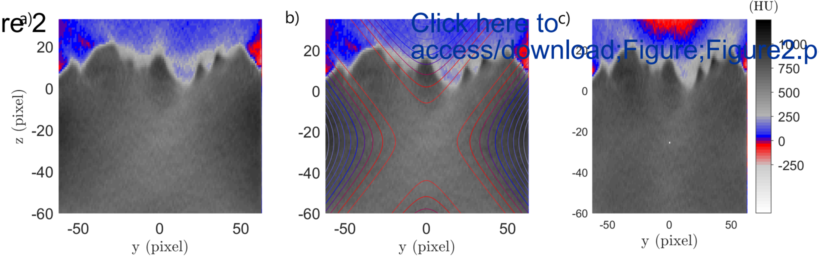


Figure 2

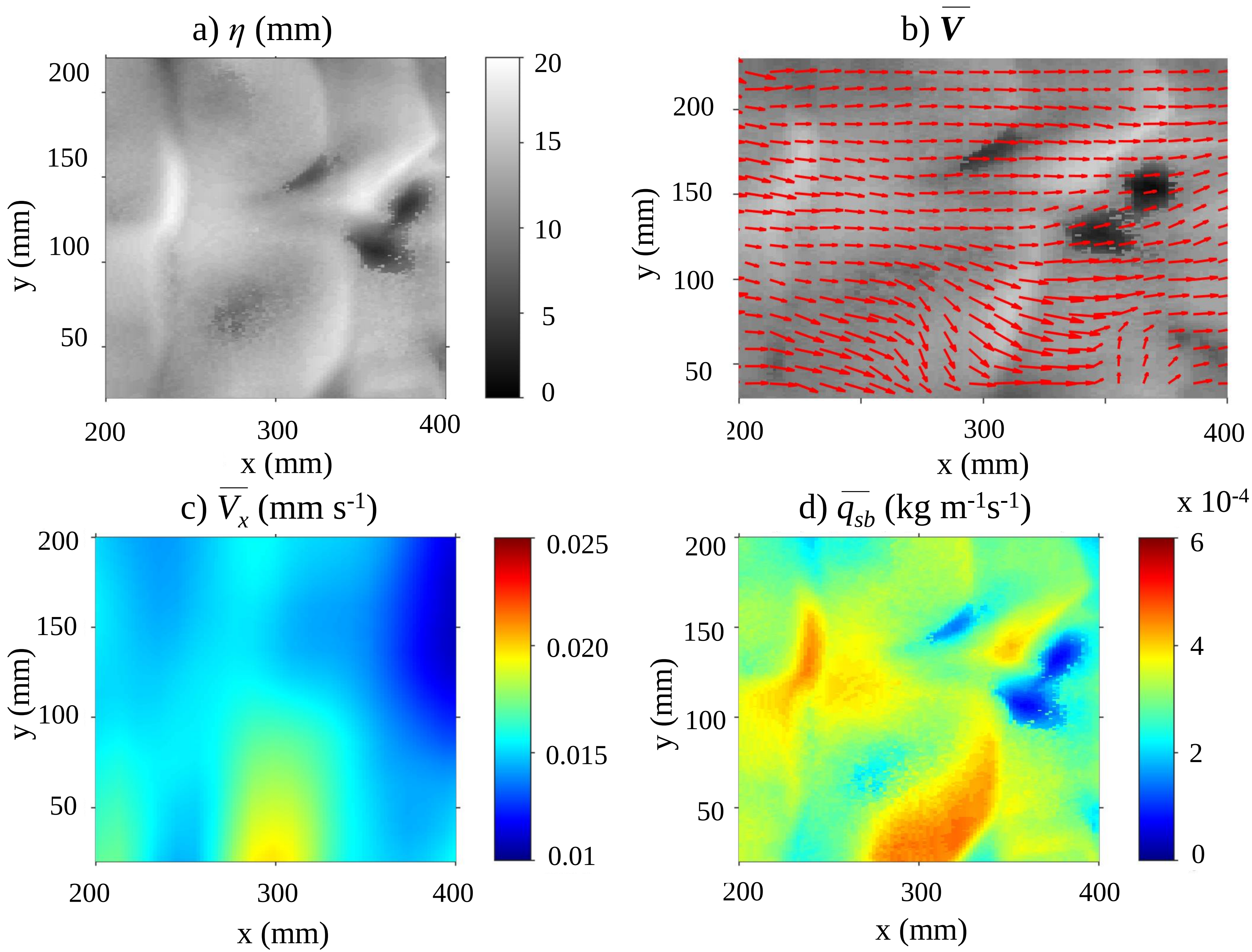
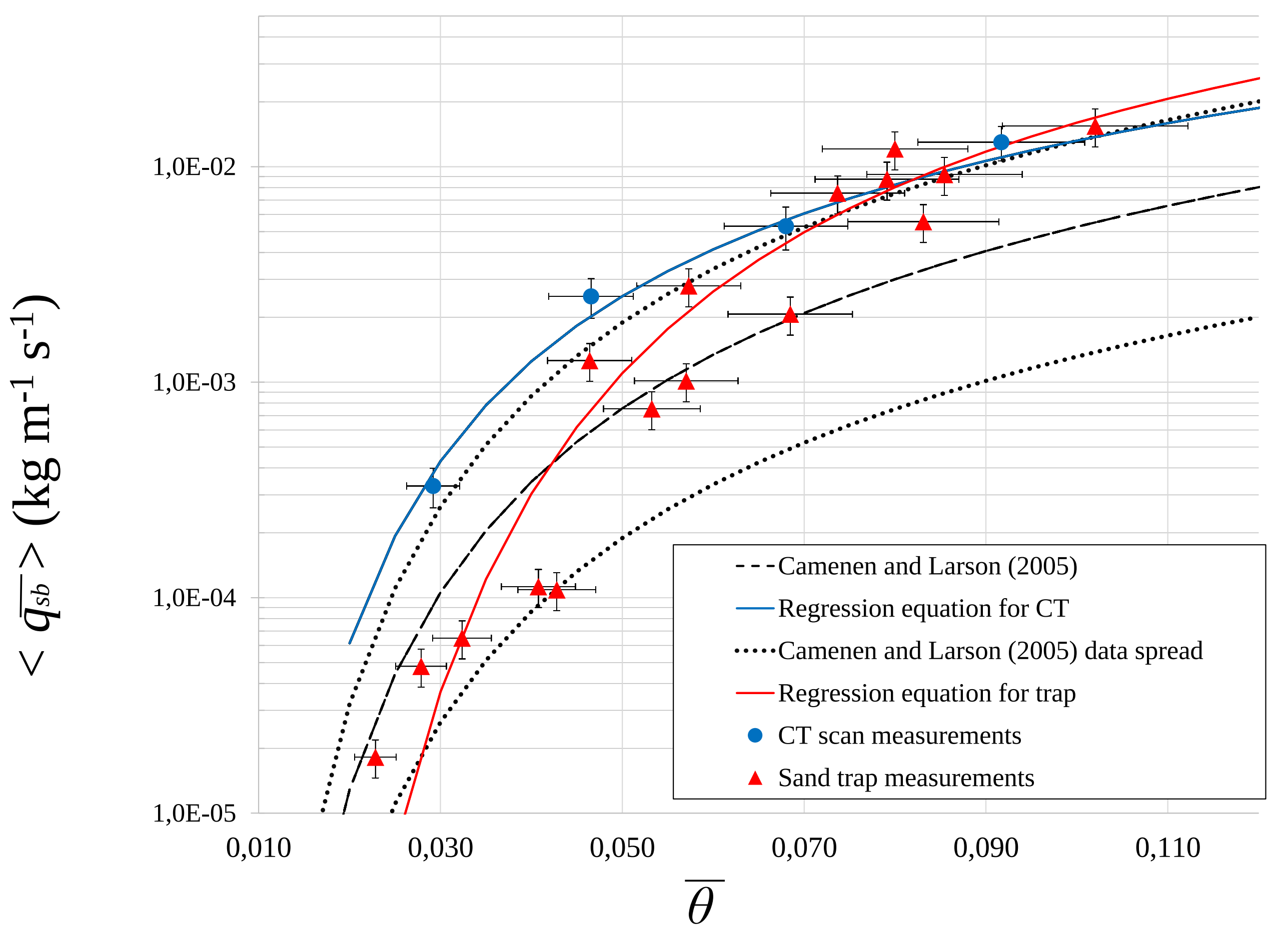

a) η (mm)
200
150
100
50
y (mm)
200
300
400
x (mm)
20
15
10
5
0
b) V
200
150
100
50
y (mm)
200
300
400
x (mm)
c) Vx (mm s-1)
200
150
100
50
y (mm)
200
300
400
x (mm)
0.025
0.020
0.015
0.01
d) qsb (kg m-1s-1)
x 10-4
200
150
100
50
y (mm)
200
300
400
x (mm)
6
4
2
0

Figure 4



1,0E-02
1,0E-03
1,0E-04
1,0E-05
0,010
0,030
0,050
0,070
0,090
0,110
$\overline{\theta}$
$< \overline{q_{sb}} >$ (kg m^{-1} s^{-1})
Camenen and Larson (2005)
Regression equation for CT
Camenen and Larson (2005) data spread
Regression equation for trap
CT scan measurements
Sand trap measurements

Figures

Fig. 1. Experimental setup components: a) the rectangular hydraulic flume inserted into the medical X-ray CT scanner, b) inside view of the water tank, the honeycomb diffuser is on the bottom right, c) the water tank downstream where the flume is inserted at the top left of the tank, the water outcomes at the bottom right, and the flow meter is attached to the top right corner of the tank (in blue), d) the water pump joins the two water tanks, up- and down-stream.

Fig. 2. Illustration for EXP4 of the a) raw HU values in the flume cross-section, b) raw HU value in the background and correction in coloured contour plot, and c) corrected HU values. The coloured contours indicate the HU value subtracted. The minimum value is -100 HU (red) and the maximum value is 250 HU (blue). The distribution of the correction is chosen to preserve the same HU spatial mean before and after the correction.

Fig. 3. Illustration for EXP1 of the a) bed elevation, b) time-averaged velocity vector field of bedforms, c) bedform time-averaged velocity in the flow direction (*x*-axis) and d) spatial distribution of time-averaged bedload transport.

Fig. 4. Comparison of time- and spatial-averaged bedload transport ($<\bar{q}_{sb}(x,y)>_{xy}$) calculated with CT scan and sand trap as a function of the time-averaged Shield parameter $\bar{\theta}$ for each experiment (1 to 4). Previous results of literature are shown. The regression between $<\bar{q}_{sb}(x,y)>_{xy}$ and $\bar{\theta}$ is calculated by fitting the data to Camenen and Larson (2005)'s equation for the sand trap (α = 13, β = 0.4, γ = -12) and CT scan (α = 12, β = 1.1, γ = -4.5).

See authors' answer/comments in blue

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Ref.: Ms. No. HYENG-13187R2
Technical note: X-ray computed tomography to measure bed density in sand transport
Brunelle Corinne; Pierre Francus; Benoît Camenen; Carl L. Amos; Mathieu Des Roches; Emeline Perret; Hachem Kassem; Louis-Frédéric Daigle; Philippe Després

Dear Dr. Corinne Brunelle,

Your Technical Note, listed above, has completed a review for publication in ASCE's Journal of Hydraulic Engineering. The editor has requested that minor revisions be made based on the reviewers' evaluations (shown at the end of this email) and submitted for re-review by 07/18/2022. This revision will only be seen again by the editor and will not undergo the entire review process.

Thank you,

When preparing the revised manuscript in accordance with the reviewers' concerns and suggestions, be sure to address the following additional requirements, if not already completed:

• The editor requests a marked or highlighted copy of the revised manuscript. It should be uploaded as a separate file in the Track Changes version file type, but the Manuscript file type should be used for a clean manuscript.

Done

- In addition, the editor requests a response to the reviewers' comments. This file should be uploaded as a Response to Reviewer file type.

Done

Also, please note in order to clarify math for copyeditors, please ensure that you use boldface for matrices, vectors, and tensors; italics for all variables and lowercase Greek letters; and roman for all numerals, uppercase Greek characters, and mathematical operators.

ASCE is now encouraging authors to add a Practical Applications section to their paper. The Practical Applications section is a concise plain-language summary (150-200 words) of the paper written for non-academic or practitioner audiences to identify the results, relevance, or potential applications the research describes. You can read more about requirements for the Practical Applications section in the Peer Review Process section of the ASCE Author Guide.

Please submit the revised manuscript and a detailed response to the reviewers' criticisms by logging onto the Editorial Management system at https://www.editorialmanager.com/jrnhyeng/ and clicking on the "Submissions Needing Revision" link.

For your convenience, there is a calendar entry item attached that works with electronic calendars in the iCalendar format (e.g. Outlook, iCal, Google). To use, click to open the attachment, and then save it to your calendar.

Be advised that the editor may request further revision or decline your revised version if all of the reviewers' comments have not been adequately addressed.

Comments from the Editor and Reviewers can be found below.

We look forward to receiving your revised manuscript.

Sincerely,

Marwa Fayed
Editorial Coordinator

Reviewers' Questions & Answers:
Reviewer's Responses to Questions

This manuscript was submitted as a Technical Note. Does the reviewer think this is the appropriate article type? To see descriptions of the article types, Click Here.

Reviewer #1:

- Yes. The author is using the correct article type.

Reviewer #2:

- Yes. The author is using the correct article type.

Reviewers' comments:

ASSESSMENT OF THE EDITOR IN CHIEF

Dear Authors:

Thank you very much for submitting the revisions for your article to the Journal of Hydraulic Engineering (JHE), ASCE.

Please implement the remaining suggestions. Please provide a document where changes are highlighted. The paper will be reviewed by the Editor only.

I appreciate the interest to the Journal of Hydraulic Engineering, ASCE, and I look forward to receiving a revised version of your paper.

Sincerely yours,

Prof. Fabian A. Bombardelli
Chief Editor
Journal of Hydraulic Engineering, ASCE
University of California, Davis

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AE:The revised paper has been reviewed by the same Reviewers of for previous round. Both Reviewers are now satisfied with the revision and recommend publication after a last (very minor) revision. I concur with this recommendation.

In addition to considering Reviewer #1 last comments, I would request from the Authors a very cautious reading of the whole text to fix formatting and language issues, such as (non-exhaustive list) on line 112 (punctuation missing), line 145 (space missing) and line 285 (choose between “been” and “not been”).

The formatting and language of the text have been corrected. The corrections can be seen in the track change version.

============================

Reviewer #1: The authors have put a good deal of effort in addressing the previous comments, thanks. Now I have just two suggestions requiring very little work.

Line 272: it could be added that the accuracy of the new method compared to trap values improves for higher sediment transport rate (this is a fully reasonable behavior considering how bed load works).

Correct. This sentence has been added:

Line 273: The accuracy of the new method compared to trap values even improves for higher sediment transport rates.

Line 274: compared to the equation of... (as we are not comparing here with a number of classical equations).

Correct. The sentence has been changed to:

Line 274: All the CT scan data are also within an acceptable range compared to the bedload equation of Camenen and Larson 2005.

Good job; my congratulations.

Thanks!
