Evaluation of Shear Stress Computation at a Tidal Inlet Using Different Methods

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ABSTRACT


This paper compares several methodologies used to compute skin-friction shear stresses and drag coefficients using different methods and equipments: a set of pressure transducers, an acoustic Doppler transducer (ADV) and an acoustic Doppler profiler (ADP). The study area is the Ancão Inlet (Ria Formosa, Southern Portugal), an inlet with a mixed wave-tide behaviour. Data presented was collected along an entire tidal cycle. Although results should be analysed on a local perspective, it demonstrate the wide range of shear stress values and velocities, enhancing the difficulties inherent to the estimation of skin-friction and form drag when waves and bedforms are present. The various methodologies used to obtain average values of skin-friction current-only shear velocity, stress and drag coefficient gave results that differ by a maximum factor of 4. This factor must be taken into account when computing the threshold of motion required for estimation of both bedload and suspended sediment transport. The present study indicates that the Reynolds Stress method gives the best estimates of current-only skin friction shear velocity using free-stream current data, and is suggested to be used as the most appropriate method to parameterise the sediment transport based on free-stream profiles for the analysed data.

ADITIONAL INDEX WORDS: Tidal inlet processes, drag coefficient, hydrodynamic

INTRODUCTION

Tidal inlets are located along barrier island systems and are found throughout the world in a variety of geological and oceanographic settings. An inlet is subject to two main forces: (i) waves that normally transport sediment into the inlet and; (ii) tidal currents which normally transport sediment either offshore or into the bay or lagoon behind the inlet (ESCOFFIER, 1940). The size of the inlet, and its survival, are determined by the relative strength of these two transport mechanisms.

The effects of the hydrodynamic forcing agents (currents and waves) on the sediment dynamics take place primarily through the friction they exert on the sea bed. On non-flat sandy beds the total bed shear stress \( \tau_0 \) is composed by three contributions: the skin-friction component (or effective shear-stress) \( \tau_{0s} \) due to the drag on individual sand grains, the form drag component \( \tau_{0f} \) due to the pressure field acting on ripples or larger bed forms, and finally a sediment transport contribution \( \tau_{0t} \) caused by a momentum transfer to mobilise the grains (SOULSBY, 1997),

\[
\tau_0 = \tau_{0s} + \tau_{0f} + \tau_{0t} \quad (1)
\]

Only \( \tau_{0s} \) is effective in moving the sand grains and therefore this component must be accurately measured in order to compute the threshold of motion, the bedload transport, or sediment entrainment in the presence of bedforms (SOULSBY, 1997). On the other hand, it is the total bed-shear stress that corresponds to the overall resistance of the flow and determines the turbulence intensities which influence diffusion of suspended sediments to higher levels of the water column (WILLIAMS et al., 2003). Bedforms increase the form drag and reduces the sediment transport capacity of the fluid. However, in some cases the acceleration and separation of flow over bedform crests can enhance the suspended sediment flux. As a consequence, the total sediment load in a given flow field may be greater over a rippled bed than over a flat one (WILLIAMS et al., 2003).

There are several methods used to compute the shear stress and fluid velocity. The method of EINSTEIN (1950 in SOULSBY, 1997) developed for rivers involve the simultaneous solution of two equations:

\[
\frac{\bar{U}}{u_*} = 6 + 2.5 \ln \left( \frac{d_1}{h} \right) \quad (2)
\]

\[
I = \frac{\tau_{0s}}{\rho g h} \quad (3)
\]

where \( \bar{U} \) is the depth-averaged velocity, \( g \) is the acceleration of gravity, \( I \) is the water surface slope (or hydraulic gradient); \( h \approx 2.5d_{50} \), where \( d_{50} \) is the mean grain size, \( \delta_i \) is the thickness of the internal boundary layer and \( \rho \) is the fluid density. In very shallow waters (\( h \leq 5m \)), the flow is friction-controlled, and the water surface slope can be used to obtain the skin-friction bed shear stress \( \tau_{0s} \) from the relationship (SOULSBY, 1997),

\[
\tau_{0s} = \rho v \frac{h I}{\delta_i} \quad (4)
\]
The measured velocities can be described in terms of a mean and a fluctuating component, i.e., $U = U' + U''$. Time-averaged bed shear stress can be estimated from the first moment (mean) statistics or second moment (turbulence) statistics. The 1st moment method assumes rough turbulent flow and uses the log-profile (LP) to describe the vertical velocity profile. The 2nd method assumes a specific Reynolds stress profile, usually a near-bed constant stress layer. The log profile is defined by the von Karman-Prandtl equation,

$$U(z) = U_0 \frac{z}{\kappa} \ln \left( \frac{z}{z_0} \right)$$

where $U$ is the mean velocity at depth $z$, $\kappa$ is the von Karman constant and $z_0$ is the bed roughness length which is related to the Nikuradse grain roughness, $k$. The bed roughness length can be replaced by the apparent roughness length ($z_a$), where a linear regression of the form $y = mx + c$ performed using $U(z)$ as $y$ and $\ln(z)$ as $x$ can be established to obtain $z_a$ from the logarithmic profile fitting ($z_a = \exp(c/m)$, and $u_* = mk$). The drag coefficient ($C_D$) relates to $z_0$ or to its approximation $z_a$ through the equation,

$$C_D = \left[ \frac{\kappa}{1 + \ln(z_a/h)} \right]^2$$

The boundary layer dynamics is dominated by high-frequency, intermittent phenomena that can only be described in detail using turbulent statistics. The Turbulent Kinematic Energy method (TKE) make use of the 2nd moment of statistics, where the turbulence kinetic energy ($E$) is estimated from the turbulent fluctuations and relates directly with the shear stress,

$$\tau_{ref}(z) = C \rho E(z)$$

where $C$ is a constant ($C$ was found to be 0.19 by Stapleton and Huntley, 1995), and the turbulent kinetic energy $E$, at height $z$, is defined as $E(z) = \frac{1}{2} \sqrt{u'^2 + v'^2 + w'^2}$, where $u', v'$ and $w'$ are the variance of the normal zero-mean orthogonal flow components. The TKE method does not require knowledge of $z_0$ or the exact measuring height and Pope et al. (2006) considered it to be more robust than the LP method (in field situations excluding waves). Another method using the 2nd moment of statistics is based upon calculation of Reynolds stresses (RS), or eddy correlation method (e.g. Soulsby and Humphery, 1990) and assuming a log-profile (Kim et al., 2000),

$$\tau_{ref}(z) = \rho \left[ \overline{u'w'} + \overline{-vw'} \right]$$

where $\overline{u'w'}$ and $\overline{-vw'}$ are the mean Reynolds stresses and $\rho$ the fluid density. The time-averaged bed shear stresses or the equivalent bed shear velocities are frequently used to parameterise the combined forces of lift and drag primarily implicated with the mobilisation and transport of sediments (Williams et al., 2003).

The aim of this study is to present and compare detail measurements of time-averaged bed shear stresses, velocities and drag coefficient, along a tidal cycle at a tidal inlet using data from different equipment including: pressure transducers (PTs) and Acoustic Doppler Velocimeter (ADV). The results obtained are compared with theoretical approaches to determine current-only skin-friction shear stresses and velocities based on current data collected with a boat-mounted Acoustic Doppler Profiler (ADP).

The results are used to analyse the differences between the various methods employed to estimate the bed shear velocities, stresses and drag coefficient. Results also contribute to expand the knowledge on inlet dynamics and provide useful data for numerical modeling of sediment transport in an inlet.

**STUDY AREA**

Anção Inlet is a small migrating inlet located in the Ria Formosa, Southern Portugal (Fig. 1). It is part of a multi-inlet system consisting of five islands and two peninsulas separated by six tidal inlets. The backbarrier is characterised by large salt marshes, sand flats and a complex network of natural and partially dredged channels. Tides in the area are semi-diurnal, with an average range of 2.8 m for spring tides and 1.3 m during neap tides. Predominant wave directions are from the W-SE, approximately 76%, while waves coming from the E-SE only account for 24% of the observations (Costa et al. 2001). Wave climate in the area is moderate to high (annual $H_s \approx 3$ m).

**METHODS**

Pressure transducers (PTs, in Situ Level Troll 300) were deployed in the lagoon and at the entrance of the Anção Inlet (separation distance ca. 200 m, Fig. 1). These instruments were located as close as practicable to the Spring low water line and accurately surveyed to determine their vertical and horizontal coordinates. The PTs were synchronised and recorded the water level at 1 Hz. The simultaneous pressure measurements were used to estimate the water surface slope and mean water depth. Temporal changes in the spatially averaged bed shear stress were obtained using Equation 4.

**M**ean tidal flow and orthogonal flow components were measured with a SonTek/YSI 10MHz ADV. The ADV (with an internal PT) was deployed at a location approximately equidistant between the PTs, also close to the Spring low water line (Fig. 1). The ADV operated in continuous burst mode (burst interval 1800 s and 30000 samples per burst) and collect data at 25 Hz for one complete tidal cycle. The obtained data were de-spiked and smoothed following standard procedures (Goring and Nikora, 2002). Orthogonal turbulent flow components are denoted by $U$, $V$ and $W$ which refer to the flow in the streamwise ($X$), spanwise ($Y$) and vertical ($Z$) directions, respectively. Therefore, the first pre-processing step was to apply an axis rotation algorithm to obtain $U$, $V$ and $W$. Zero-mean flow component time series, $u$, $v$ and $w$, comprising tidally induced turbulence and wave-induced fluid motion were then calculated. In order to perform this step, $U$, $V$ and $W$...
and W time-series were detrended using a least square algorithm to remove the best straight-line fit from the data. The obtained equation was then subtracted from the data: $u = U - U(z)$, $v = V - V(z)$ and $w = W - W(z)$, where the overbar represents the time-average function. The resulting $u$, $v$ and $w$ time-series are composed by a time-varying, semi-random component typical of turbulence and a more regular, semisinusoidal component attributable to the oscillatory flows imposed on the tidal currents by waves (WILLIAMS et al., 2003). Two methods were used to separate the wave induced flows from the tidal currents: (a) a simple moving-average filter (MA) described by WILLIAMS et al. (2003) and (b) the spectral splitting method (SSM) described by SOULSBY and HUMPHERY (1990) and later expanded by VOULGARIS and TROWBRIDGE (1998).

The MA filter was applied to give 1 s average values for $u$, $v$ and $w$ time-series data. The 1 Hz time-series were then resampled to retain the original sampling frequency of a given time-series and subtracted from the original signal to extract the 1st order wave-induced motions. Burst time averaged $u*$ and $v*$ was then computed using the TKE and RS methods (Eq. 7 and 8, respectively). Estimates of the variance due to waves and turbulence obtained for each flow component using the SSM were also used in the TKE method. The total turbulence power spectrum $S_{uu}(n)$, $S_{vv}(n)$, $S_{ww}(n)$ and the co-spectrum $S_{uv}(n)$ was obtained and plotted relative to frequency ($f$) on a logarithmic scale. The area between $10^{-2} < f < 10^{2}$ typifies the region of turbulent energy production in a shear flow (WILLIAMS et al., 2003). This can be graphically identified because the dissipation range follows the $-5/3$ slope, allowing to separate the variance of $u$, $v$ and $w$ time-series into variance due to turbulence (i.e. $u*$, $v*$, $w*$) and to surface gravity wave-induced flow (i.e. $u_{\text{w1}}$, $v_{\text{w1}}$, $w_{\text{w1}}$).

Measurements of current velocity profiles were obtained using the ADP during a spring tide. Measurements were made every hour during a 12.5 hour tidal cycle along the main inlet channel (Fig. 1). The boat location was recorded using a DSNP Scorpio 6001 SK/MK RTK-DGPS connected to a navigational interface using hydrographic survey software Hypach®Max 4.3a Gold. The range cell spacing was set to 0.5 m and the number of cells was set to an appropriate resolution for a given water depth. Blanking distance and ADP transducer draft where both set to 0.5 m. The instrument was run in continuous mode and the ADP profile interval was set to the same value as the averaging interval (5 s). The signal-to-noise ratio (SNR) was set to 5 to remove invalid data below the ambient noise level. Temperature and salinity were adjusted to values measured inside the Ria Formosa system.

Data was first rotated to streamwise and spanwise direction (Fig. 2) and depth average velocity obtained for each 5 s ensemble. The depth average current velocity ($\bar{U}$) is given by:

$$\bar{U} = \int_{h}^{h+H} U(z) dz$$  \hspace{1cm} (9)

where $h$ is the water depth, $U(z)$ is the current speed at height $z$. A trapezoidal rule can be used to approximate the integral of Eq. 9,

$$\bar{U} = \frac{0.5}{h} \left[ \sum_{i=1}^{n} (u_i + u_{i-1})(z_{i+1} - z_i) + (u_{i-1} + u_i) + 2u_i(h - z_i) \right]$$  \hspace{1cm} (10)

where $u_1,u_2,..,u_n$ are current velocity measurements at heights $z_1,z_2,...,z_n$. The determined $\bar{U}$ was then used to obtain $u_*$ and $C_D$ by the LP method (Eq. 5 and 6).

Sediment samples were collected along the ADP profile by using a small grab sampler (Petit Ponar). Bedforms were also measured in the field with a tape measurement device (height and length) on the intertidal area. Bed sediment samples were separated into particle size fractions (gravel, sand, silt and clay). For the coarse fraction (sand and gravel), particle size analyses were performed by sieving at $\frac{1}{2}$ø intervals. The grain-size parameters were computed according to the methodology described by FOLK and WARD (1957) using the program GRADISTAT (BLOTT and PYE, 2001). These parameters were used to approximate the bed roughness length ($z_0$) using the COLEBROOK and WHITE (1937 in SOULSBY, 1997) approximation to the Nikuradse experimental studies for rough flows.

**RESULTS**

Time-averaged water levels and shear velocities are presented in Fig. 3. In total 15 burst were processed with only the burst record at 13h30 (GMT) unusable. The water levels obtained using the smooth PT values (installed inshore and offshore) and from the PT from the ADV showed close similarity (Fig. 3A). The burst time-averaged shear velocities also agree well, although TKE methods present slight higher values. Results from the RS method show the best correspondence with the gradient slope method results. Difference between burst time-averaged $u_*$ values obtained during flood and ebb tides using TKE and RS methods are most apparent at the beginning stages of the ebb tide.

Maximum values of $u_*$ where obtained using TKE methods: $-0.067$ ms$^{-1}$ and $-0.057$ ms$^{-1}$ applying the MA TKE; and $-0.074$ ms$^{-1}$ and $-0.057$ ms$^{-1}$ for SSM TKE, during flood and ebb peaks, respectively. Maximum values of RS were $-0.048$ ms$^{-1}$ and $-0.051$ ms$^{-1}$ during flood and ebb, respectively, with RS values being always slightly lower to the computed using both TKE methods. Burst time-averaged $u_*$ maxima computed using the
Shear Stress Computation

water slope method where ~0.058 ms\(^{-1}\) and ~0.050 ms\(^{-1}\) during flood and ebb, respectively. All the methods, except the RS, resulted in higher \(u^*\) during flood. The values of burst time-averaged \(\tau_0\) range between 0.4-4.6 Nm\(^{-2}\) for MA TKE; 0.8-5.6 Nm\(^{-2}\) for SSM TKE; 0.2-2.7 Nm\(^{-2}\) for RS and 0.2-4.6 Nm\(^{-2}\) for the gradient slope method. Maximum \(\tau_0\) occurred near the peak flood, except for the RS where maximum was previous to the peak ebb.

Variations of \(u^*\) during each burst were analysed, with Fig. 4 presenting the 5s average burst values of \(\bar{U}\) computed using ADV flow components (A) and \(u^*\) values obtained by TKE (with waves removed by MA) and RS (B). The 5 s burst average \(\bar{U}\) values are approximately the same during flood and ebb, being >1ms\(^{-1}\) at flood and ebb peaks. The 5 s burst time-averaged \(u^*\) values obtained using the TKE show less variation than those obtained using the RS method, resulting in consistently higher values.

The average value of drag coefficient computed using RS and MA TKE methods \((C_D = u^*/\bar{U}^2)\) through the tidal cycle range between 0.0059±0.0054 and 0.0093±0.0072, respectively. Mega-ripples with a wave length (\(\lambda\)) and height (\(\eta\)) of 1.3 m and 0.23 m were measured in the field. These dimensions correspond approximately to predicted dimensions obtained using the \textit{VAN RUN} (1993) method for irregular waves (i.e. \(\lambda=1.7\) and \(\eta=0.16\)).

The ADP tidal cycle average cross-section values of \(\bar{U}\) and \(u^*\) computed using Eq. 5 and Eq. 10, respectively, are presented on Fig. 5A and 5B. Fig. 5C presents the ensemble \(u^*_s\) variation along each transect. The tidal range of the spring tide was approximately the same as that pertaining during the ADV/PT deployment and the ADP survey.

The bottom time-averaged bed shear stresses and velocities computed using RS method better agree with the theoretical
current-only \( u^* \) and \( \tau_b \). ADP tidal cycle results, expressing the same behaviour. In all cases TKE-derived values are slightly higher. Maximum standard deviation for \( u_c \) computation between different 2nd moment statistic methods was 0.015 ms\(^{-1}\), which translates to a maximum difference in \( \tau_b \) of about 0.2 Nm\(^{-2}\). In theory RS method should be valid even under waves (SOULSBY and HUMPHERY, 1990), but this requires that the linear wave theory assumption of \( u_w = 0 \) and \( v_w = 0 \) is valid. This might not be the case in shallow waters due to the turbulence generated at the bed by combined action of waves and currents (ANDERSEN et al., 2007). Good agreement was found between bottom time-averaged bed shear stress and velocities obtained with RS method and \( u_c \) and \( \tau_b \) calculated with the LP method (for current only). This agrees well with results presented by VOULGARIS AND TROWBRIDGE (1997), with both methods presenting a similar range of values and behaviour. The RS presents slightly higher values as expected since the measurements relate to a specific point where the form drag component of stress can be more accurately determined, while the LP values depend on the average cross-section values. Also, good agreement was found between RS and the gradient slope method. According to WILLIAMS et al. (2003), partitioning the total shear stress over bed forms between the skin-friction \( (\tau_s) \) and form drag \( (\tau_f) \) can overestimate the form drag. The authors highlighted the importance on carrying field experiments to measure free-stream velocity and the water slope as an additional check on \( \tau_f \) values. Results obtained within this study for the RS and the gradient slope methods presented the better agreement especially during the flood. During the ebb, RS values are slight lower which might be attributable to the position of the ADV and the influence of developing bedforms crests. This happens in all 2nd moment statistic methods. The \( C_D \) values are all within the same order of magnitude. Existing differences can be related to the fact that LP method applied to the ADP velocities is based on an average \( d_{50} \) for the entire cross-section. This assumption is fine when computing the cross-section total sediment transport rate, but it can lead to an underestimation of the form drag and hence the suspended sediment load. In general, average values \( u_c \) \& \( \tau_b \) and \( C_D \) between time-average burst values (PT/ADV) and theoretical current-only skin-friction values (ADP) can differ by a maximum factor of 4. This factor must be taken into account when computing the threshold of motion required for estimation of both bedload and suspended sediment transport.

**CONCLUSION**

Results presented demonstrate the wide range of shear stress values and velocities present in a highly dynamic tidal inlet characterised by a mixed tide-wave dominated behaviour. It has been shown that the estimation of skin-friction and form drag is problematic when waves are present. In such cases it is desirable to estimate time-averaged shear stresses and velocities using different approaches. The study highlighted the importance of accurate determination of the form drag component of total roughness, especially dependent on the formation/destruction of bedforms, as it can significantly influence the suspended sediment capacity. Within the present study the various methodologies used to obtain average values \( u_c \), \( \tau_b \) and \( C_D \) differed by a maximum factor of 4. The present study has indicated that the RS method gives the best estimates of current-only skin-friction shear velocity using free-stream current data. In this respect the RS method is suggested as being the most appropriate method to parameterise the sediment transport based on free-stream profiles measured with the ADP.

**LITERATURE CITED**


**ACKNOWLEDGEMENTS**

This work is a contribution to the IDEM project – Inlet Dynamics Evolution and Management at the Ria Formosa (POCI/MAR/6533/2004). André Pacheco was supported by Fundação para a Ciência e a Tecnologia, grant number SFRH/BD/28257/2006. The authors would like to thank to Sr. Esmeraldo, the boat skipper.