

REDUCTION IN DENSITY OF SUSPENDED - SEDIMENT - LADEN NATURAL WATERS

Antony Joseph¹, Ehrlich Desa¹, Elgar Desa¹, David Smith²

Vani B. Peshwe¹, Vijaykumar¹ and J.A. Erwin Desa³

¹ National Institute of Oceanography, Goa, India.

² Proudman Oceanographic Laboratory, U.K.

³ Department of Physics, Goa University, Goa, India

ABSTRACT

Pressure measurements made in various turbid natural waters have led to the inference that the effective depth-mean in-situ density values $\bar{\rho}_{eff}$ of these waters are less than ($\approx 2.70\%$) their static bulk densities and also ($\approx 0.4\% - 4.5\%$) that of the density of the same water without suspended sediment. The values of $\bar{\rho}_{eff}$ in a given site differed from one tidal cycle to another ($\approx 1.9\%$). These values varied slightly ($< 0.8\%$) from mid-tide to slack water of the same tidal cycle, with $\bar{\rho}_{eff}$ being lower at mid-tide. It was found that the use of bulk density to estimate tidal height gave an under-estimation of tidal range (upto 7%). The under-estimation has been corrected (to within $\pm 1.5\%$) with the use of $\bar{\rho}_{eff}$ parameter. For clear waters there was no observable under-estimation in tidal range. The observations strongly suggest that suspended sediments play a hitherto unknown role in the apparent in-situ density reduction effect seen in turbid natural waters.

INTRODUCTION

Sea level measuring devices are typically deployed in coastal and estuarine waters. While the water in some such regions are free from suspended sediment concentration (SSC) for most of the year, there are estuaries where turbidity is high throughout the year (namely; Hugli estuary, India; Humber estuary, U.K.). Pressure transducers, as a result of this portability are popularly used for water level measurements from remote locations. In this paper we evaluate the performance of pressure transducers in turbid natural waters, and examine the role of suspended sediments in contributing to inaccuracies in the measurement of tide in these waters; an issue that has not received adequate attention thus far.

TIDE MEASUREMENT FROM TURBID WATERS OF HUGLI ESTUARY

Hugli estuary is exceptional in terms of the high turbidity throughout the year. A differential quartz pressure transducer was installed at Hugli Point station, where there was no wave activity. The transducer was rigidly mounted inside a water proof stainless steel (s.s) housing. The positive port of the transducer was exposed to water via an oil filled capillary tube. A flow retarding perforated cap over the positive port minimised Bernoulli effects. This

perforated cap was somewhat similar to some types of static pressure probes used in meteorology. Effects of atmospheric pressure variations were compensated by venting the negative port to atmospheric pressure via a flexible plastic hose which terminated in a dry air atmospheric static pressure chamber. Each value of water level recorded in the logger was an average over 30 seconds.

The discrete water samples at the measurement site were collected and the mean density of these samples were found to be 1.062 g.wt/cm^3 . This density value together with differential pressure measurement was used to estimate water height above the transducer port. Readings from a tide staff located at the measurement site were used to reference the pressure transducer-derived water level to the Chart Datum (C.D). This referencing was done at the time of slack water during which the water level was steady and, therefore, tide staff readings would be made with greater precision. Initial offset adjustment of the pressure gauge was made at high tide so that the pressure-derived water level matched with the tide staff readings within observational accuracy ($\pm 1\%$).

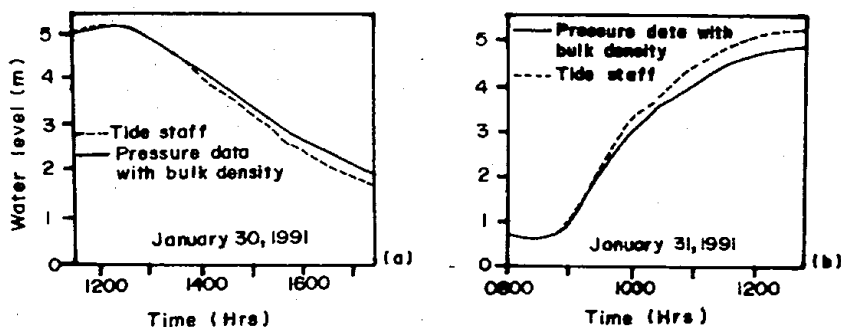


Fig.1. Tidal range under-estimation in Hugli estuary when average bulk density was used. (a) offset adjusted at high water. (b) offset adjusted at low water.

A typical result of measurements at this location is shown in Fig. 1. It is seen that as the water level decreased from high tide stage, the difference ΔH between the pressure-derived water level and the tide-staff readings increased [Fig. (1)]. In this case the value of ΔH was positive and gradually increased with time, reaching a value of 23 cm at low tide. In a subsequent measurements, offset adjustment was carried out to obtain a match between the gauge outputs and the tide-staff readings at a low tide. In this case a different offset was required to obtain a match. As the tide level increased, ΔH was negative and became increasingly negative [Fig. 1(2)], reaching a value of 39 cm at high tide. The results indicated in Figs. 1 (1,2) essentially revealed an under-estimation of tidal range (this being the difference between successive low and high water heights).

REDUCTION IN THE EFFECTIVE DENSITY OF TURBID NATURAL WATERS

It can be shown that an error in tidal range, R_{error} will occur if the value of fluid density ρ_c used for the estimation of water level is different from the depth-mean density ρ_t that actually contributes to the pressure sensed by the transducer. It can be shown that,

$$R_{error} = (P_h - P_l) (\rho_c - \rho_t) / (\rho_c \times \rho_t) \tag{1}$$

Where P_h and P_l are the pressures measured by the transducers at the high and low slack waters respectively. Eqn. (1) shows that if $\rho_t < \rho_c$ the pressure sensing tide gauge will underestimate the tidal range. However from eqn. (1) the unknown quantity ρ_t can be obtained

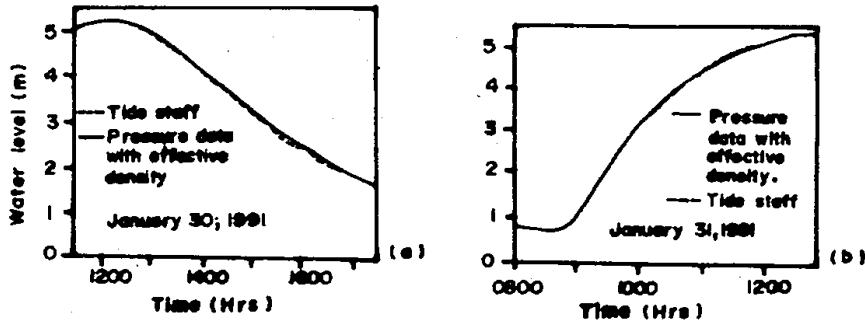


Fig. 2 Correction of tidal range under-estimation of Fig.1 by the use of effective density. (a) ebb tide phase, (b) flood tide phase.

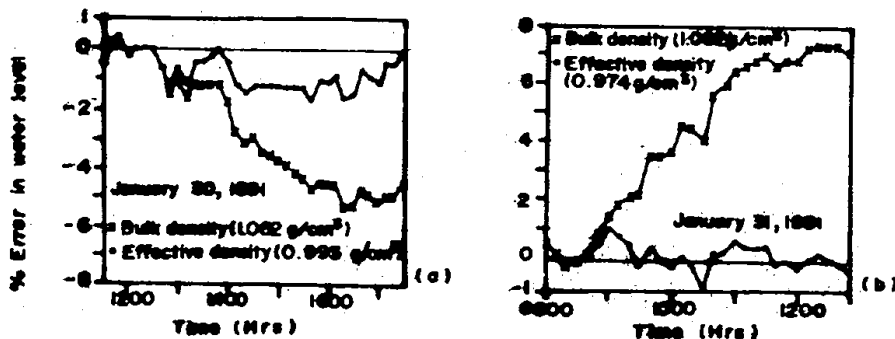


Fig. 3 Percent difference in water level of Fig.1 when bulk density and effective density of turbid water were used.

from the known quantities, Thus,

$$\rho_t = (P_h - P_l) \rho_c / [(P_h - P_l) + \rho_c R_{\text{error}}] \quad (2)$$

Figs. 2 (a,b) and 3(a,b) indicate that use of ρ_t in place of measured density ρ_c significantly reduces the errors in the measurement of turbid water level. The observed smaller errors in the corrected water levels using ρ_t may be due to errors in tide-staff reading and pressure measurements due to tidal flow (Joseph et al. 1997). Short-period variations in the in-situ effective density of turbid water during the period between the slack waters may also have contributed in part to the observed errors in the corrected tide levels using ρ_t . However, after due consideration of these factors, an unexpected result indicated from these pressure measurements in the turbid waters of the Hugli estuary is that the in-situ density of natural turbid water turns out to be less than its bulk density (i.e., density of water-sediment mixture obtained from discrete samples).

Wells et al. (1978), during their measurements in the fluid-mud waters off the coast of Surinam, South America had also noticed that the depth-mean density values of the fluid suspension, estimated using an in-situ fluid density sensing device, were different from those obtained using measurement of fluid samples. The in-situ depth-mean density of the fluid-mud suspension was estimated from the pressure outputs of two transducers and a precisely known vertical distance between their pressure inlets. They attributed the discrepancies in density measurements to instrument calibration problems, and on using calibrated bulk-density values of the fluid, obtained errors in water level measurements, ranging from 0.3% to 5.3%, even though the accuracy of the pressure sensing system inclusive of linearity and hysteresis was better than 0.35% (Wells 1978). It was also observed that the increase in the error of water level measurement from 0.3% to 5.3% was associated with a corresponding increase in suspended sediment concentration of 10^{-2} mg/cm^3 to 10^{-2} g/cm^3 respectively.

MEASUREMENTS IN TURBID WATERS USING TWO PRESSURE PROBES

A simple experiment to confirm the inferences made earlier, regarding the apparent reduction in in-situ density involved the use of two pressure transducers. Pressure was measured at two different but precisely known levels and the in-situ depth-mean density was estimated. In this technique, reference to the tide staff was not required. The water column in an estuary is likely to be stratified due to river and estuarine effects, and to possess a temperature and salinity profile. These profiles were measured in order to exclude their effects and to confirm the findings of a reduced in-situ density. The measurements reported here were made in the suspended sediment-laden waters of the Humber estuary, North Sea, UK.

The measurement location was the harbour entrance of this turbid water estuary, in which a tide station was also located. Two bubblemeters were used for fluid pressure translation, using pneumatic bubbler gauge principle (Pugh 1972), and were mounted on a vertical pole at a separation of 250 cm. Logistic problems did not permit deployment of the bubblemeters below the chart datum. For this reason pressure measurements over the full tidal range were not possible.

The two separate pressure channels were connected to a 'Digiread' quartz crystal based differential pressure indicator which continuously displayed the pressure difference between the two pressure inlets. Water level measurements were made using a conventional float-driven gauge.

As part of the experiments, water current measurements were also made using an impeller type current meter, with each measurement being an average over 30 seconds. The current was found to be less than 3 cm/s. As current and wave effects in the measurement site were negligible, these and piling effects on the pressure inlets were unlikely to have introduced errors in the pressure measurements. Temperature and conductivity profiling was made at 1 m depth intervals when both the pressure inlets were fully submerged in water. From these the density profile was obtained. This profile (Table1) related to water without its suspended sediment.

Table 1. Depth-profile of conductivity, temperature and density of water in the Humber estuary, North Sea, U.K (Presence of sediments not taken into account).

Depth (m)	Conductivity (m.mho/cm)	Temperature (°C)	Density (g/cm ³)
0	22.7	5.5	1.018
1	22.7	5.5	1.018
2	23.0	5.5	1.018
3	23.2	5.5	1.018
4	23.4	5.5	1.018
5	23.6	5.5	1.019
6	23.7	5.5	1.019

In order to estimate the bulk density of the suspension (i.e., fluid inclusive of water and suspended particles) turbid water samples were also collected, from approximately the mid-level of the two pressure inlets. The bulk density, ρ_b , of this fluid suspension was 1.035 g/cm³. Measurements from the Humber estuary, U.K showed (Fig. 4) that the effective depth-mean density ρ_{eff} , of the turbid water column (in the present case, of height 250 cm) was always less than its density under static conditions, supporting the inference made earlier on measurements from Hugli estuary. These measurements clearly indicate that natural turbid waters suffer an apparent reduction in density compared to its bulk density. This effect is more significant during mid-tide phase for which turbulence and Suspended Sediment Concentration (SSC) values are expected to be large (Wells 1989). The effective density was found to gradually increase (from 1.007 g/cm³ at mid-tide) with increasing tide, and reached a maximum value of 1.015 g/cm³ at high tide slack water during which turbulence and SSC values were expected to be minimum. These density values were consistently less than the bulk density, ρ_b , of the fluid suspension as well as the density of the local water, ρ_w .

During the measurements the temperature profile remained steady at 5.5°C whereas the conductivity marginally increased from 22.7 m.mho/cm at the surface to 23.7 m.mho/cm at a depth of 6m below the surface.

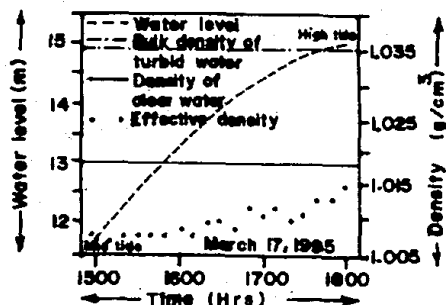


Fig. 4 Comparison of bulk density, clear-water density and effective density of turbid waters of the Humber estuary, North Sea (U.K.) as a function of tidal height.

The density of the local water, ρ_w , also exhibited a marginal increase from 1.018 g/cm^3 at the surface to 1.019 g/cm^3 at this depth. There was thus no indication of any unusual estuarine physics having played a role in the observed apparent reduction in density of the turbid waters of the Humber estuary.

MEASUREMENTS IN CLEAR WATERS USING TWO PRESSURE TRANSDUCERS

It has been noted that measurements of differential pressures from two pressure probes submerged in the turbid waters of the Humber estuary in the North Sea yielded reduced effective density values. This result agreed with measurements using single pressure transducers in the Hugi estuary. In an attempt to understand the observed unique phenomenon, a similar experiment was conducted in the clear waters of the Zuari estuary, Goa using two precision Digiquartz pressure transmitters.

In the present study, these two transducers were mounted at a vertical separation of 100 cm. Both the transducers were positioned below the C.D. so that they were fully submerged during low tide. The inlets were attached to pairs of large horizontal parallel plates to reduce flow effect and also the effects of sea surface oscillations (Joseph et al. 1997). The 30-second time-averaged transducer outputs were used to obtaining the in-situ density. The density of water samples was also measured using a precision density meter which operated on a mechanical resonance principle (Kremling 1972) with a accuracy of $\pm 0.001 \text{ g/cm}^3$. The density of water sample taken during the pressure measurements was 1.022 g/cm^3 . The effective density values, estimated from the measured pressure differences and the known vertical separation between the pressure inlets are plotted in Fig. 5 over one tidal cycle. It is seen that the effective mean density estimated by the dual pressure transducer system deployed in the clear waters of the Zuari estuary was in close agreement with the density of water samples measured using a density meter. The observed minor fluctuations in the density

as a function of time is likely to have arisen from similar fluctuations in the measured pressures due to microturbulence at the pressure inlets.

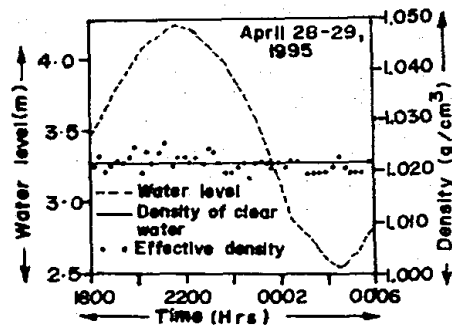


Fig. 5 Comparison of measured and effective densities of the clear waters of the Zuari estuary, Goa as a function of tidal height.

DISCUSSION OF RESULTS

The measurement reported above have provided the following insights:

1. There exists an effective in the in-situ density of suspended sediment-laden natural waters as observed by pressure measurements in Hugli and Humber estuaries.
2. A dual pressure transducer system of a suitable vertical separation is capable of correctly measuring the effective fluid density in-situ. In situations where appreciable density stratification exists this vertical separation would need to be as large as is practical.

There are many factors which may have caused the observed effective reduction in the in-situ density of turbid natural waters. Two possible reasons are presence of air bubbles in water and the lift force acting on suspended sediment particles. As Fig. 5 shows, Air bubbles do not significantly reduce the density in clear waters. Observations by Turner (1961) and Thorpe et al. (1992) have indicated that the presence of particulates in water increases the number of microbubbles. Such enhancement in the concentration of air bubbles in the presence of suspended sediments may have contributed partially to the observed reduction in the effective in-situ density of turbid waters.

INFLUENCE OF SUSPENDED SEDIMENTS

The effect of rotation of a suspended sediment particle, as observed by Muller et al. (1971) and Teleki (1972), is similar to the effect of a local circulation imparted to it so that there is a peripheral velocity on its surface. A dynamic uplift force, known as the Magnus effect, is exerted on a suspended solid particle when a circulatory motion is super-imposed upon the basic translatory motion.

In a turbulent flow regime such as tidal flow where the energy of turbulence is distributed among eddies of various sizes (Ichiye 1966) the turbulent eddies in the flow provide the necessary 'circulation' even for a non-rotating particle such as a sphere. In such cases Kutta-Zhukhovski's lift theorem allows a lift force to act on the suspended particle, where the lift force is given by (Kundu 1990):

$$F_l = \rho U_\infty \Gamma \quad (3)$$

where ρ is the fluid density, U_∞ is the mainstream flow velocity, and Γ is the circulating flux of water particles around the suspended particle. The result that lift force is proportional to Γ is of fundamental importance in the present case because tidal flows are always turbulent, as are turbulence-induced eddies which provide the necessary 'circulation'.

The expression (3) for lift force is strictly valid for a single two dimensional body. It may also be noted that no colloidal particles were present in these waters as the suspended sediments were found to settle immediately after collection from their natural environment.

The lift force acting on suspended sediment particles might have led to the observed important consequence of reduced in-situ density of suspended sediment-laden natural water. There are also a large number of suspended particles which tend to settle down with a very small settling velocity, usually in the range 0.05-0.09 cm/s. Thus a variable net flux appears to be maintained among the various particles tending to move to the surface as a result of their reduced weight, and those tending to settle down. The resultant effect appears to be a reduction in the weight per unit volume of the suspension. This causes a pressure transducer deployed in such a suspension to experience a reduced pressure compared to that of the same fluid column in the static environment.

INFLUENCE OF LIFT FORCE ON DENSITIES

The condition for the sediment particle to be lifted up and remain in suspension is given by (Modi and Seth 1985):

$$U_\infty^2 > 0.93a(s-1)g \quad (4)$$

where s is the specific gravity of the sediment particle, 'a' is its mean radius, and g is the acceleration due to gravity. The characteristic specific gravity of the sediment is usually assumed to be 2.65. Mean diameters of suspended sand particles in estuaries range from 1 to 600 μm . Thus for these particles the corresponding flow velocities in the range 0.27 to 6.72 cm/s should provide enough uplift force to neutralize their weight. The suspended particles may then move along with the water as weightless bodies even at these relatively small flow velocities.

If the suspension is dilute (i.e. the separation between adjacent suspended sediment particles is much larger than their dimensions), mutual interaction between the particles are absent. In this

case, assuming that the suspended particles experience loss of weight, an expression for the bulk density ρ_b , of the suspension may be derived as (Joseph et al. 1996);

$$\rho_b = \rho_{eff} + [\rho_s (\rho_w - \rho_{eff}) / \rho_w] \quad (5)$$

where ρ_{eff} is effective depth-mean in-situ density of the suspension (obtained from pressure measurements), ρ_w is sediment-free water density and ρ_s is density of the sediment particles.

The bulk density of the turbid waters of the Humber estuary during the measurements reported here was calculated using the following observed values:

$\rho_w = 1.019 \text{ gm.wt/cm}^3$ (Table 1), $\rho_{eff} = 1.011 \text{ gm.wt/cm}^3$ (Fig. 4), $\rho_s = 2.65 \text{ gm.wt/cm}^3$. Thus, $\rho_b = 1.032 \text{ gm.wt/cm}^3$. This value is close to the measured value of ρ_b (1.035 gm.wt/cm^3), derived from the fluid sample. Thus, measurement from two or more pressure transducers mounted on the vertical plane may provide a mechanism to estimate the bulk density of dilute suspension. This measurement scheme also permits error-free estimation of tidal heights from turbid water bodies.

CONCLUSION

Pressure measurements were made in; suspended-sediment-laden turbulent waters of the Hugli estuary and a cove in the turbid waters of the Humber estuary, North Sea. These led to the inference that the effective depth-mean in-situ density ρ_{eff} of turbid natural waters in all these cases was less than their bulk densities and sediment-free water densities. In the case of measurements made in the sediment-free waters of the Zuari estuary, Arabian Sea, ρ_{eff} was found to be close to the density measured by a precision density meter. The expression (5) is based on the premise that suspended particles experience a loss of weight. The close agreement between the computed and observed bulk densities, ρ_b , supports the conjuncture that a parameter such as the 'effective density' serves the useful purpose of explaining the reduced in-situ density effect observed in turbid natural waters.

It has been found that the application of the bulk density or the sediment-free water density for estimation of tidal height using pressure measurements given rise to an under-estimation of tidal range. The under-estimation is more significant with the use of bulk density. Inter-comparison water level measurements showed that the under-estimation can be reduced to negligible values by the use of a new parameter which we introduce as the effective density ρ_{eff} . A simple model based on the assumption that suspended particulates experience loss of weight as a result of lift forces, probably caused by microturbulences in the flowing water body and/or their rotation, has been put forward as a likely explanation for the observed reduced in-situ density of turbid natural waters. The new findings reported here may perhaps enable a better understanding of the unique, yet poorly understood, mud-bank phenomena which occurs on the Kerala Coast during monsoon season.

Acknowledgments

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