Evaluation of Pressure Transducers under Turbid Natural Waters*

ANTONY JOSEPH, EHRLICH DESA, AND ELGAR DESA

National Institute of Oceanography, Goa, India

DAVID SMITH

Proudman Oceanographic Laboratory, Birkenhead, United Kingdom

VANI B. PESHWE AND VIJAYKUMAR

National Institute of Oceanography, Goa, India

J. A. ERWIN DESA

Department of Physics, Goa University, Goa, India

11 December 1996 and 2 September 1998

ABSTRACT

Pressure measurements made in two turbid natural waters have led to the inference that the effective depth-mean in situ density values, ρ_{eff}, of these waters are less than ($\approx$2.70%–6.5%) their bulk densities (i.e., densities of water–sediment mixture), and also less than ($\approx$0.4%–4.5%) that of the density of the same water after removal of suspended sediment. The values of ρ_{eff} in a given site differed from one tidal cycle to another ($\approx$1.9%). These values varied slightly (<0.8%) from midtide to slack water period of the same tidal cycle, with ρ_{eff} being lower at midtide. It was found that the use of bulk density to estimate tidal elevation yielded an underestimation of tidal range (up to 7%). The underestimation has been corrected (to within $\pm$1.5%) with the use of ρ_{eff} parameter. For clear waters there was no measurable underestimation in tidal range. The observations indicate an apparent in situ density reduction for turbid natural waters. With the use of two pressure transducers at a known vertical separation, the value of ρ_{eff} over this vertical column of water may be determined during each sampling of pressure values. The present studies indicate that when pressure transducers are used for water level measurements in turbid natural waters, the use of ρ_{eff}, in contrast to the bulk density, significantly improves the measurement accuracy. For clear waters, precision density measurements made on discrete water samples agreed with ρ_{eff} values derived from pressure measurements to better than $\pm$0.4%. Thus, use of ρ_{eff} is expected to improve the accuracy of water level measurements also from clear water estuaries where depth-mean water density undergoes marginal changes with differing phases of tide and significant changes with seasons.

1. Introduction

Sea level measuring devices are typically deployed in coastal and estuarine waters. While the water in such regions is usually free from suspended sediments for most of the year, there are some estuaries where turbidity is high throughout the year (e.g., Hugli estuary, India; Humber estuary, United Kingdom). Pressure transducers, as a result of their 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 water levels in these waters, an issue that has not received adequate attention thus far.

2. Tide measurement from turbid waters of the Hugli estuary

A differential quartz (Paroscientific) pressure transducer with an FM output, whose negative port was vented to the atmosphere, was installed at Hugli Point station, which is free from wave activity. Venting of the negative port was to compensate for the inverted barometer effect. The transducer, having a metallic casing, was rigidly mounted inside a waterproof stainless steel housing. The positive port of the transducer was exposed

* NIO Contribution Number 2582.

Corresponding author address: Dr. Antony Joseph, National Institute of Oceanography, Dona Paula, Goa 403 004, India.
E-mail: ocean@bcgoa.ernet.in

to water via an oil-filled capillary tube. A flow retarding perforated cap over the positive port minimized Bernoulli effect. This ability of a perforated cap was verified in a later experiment conducted by us in a flow flume, in which the improvement was found to be in close agreement with that obtained from a parallel-plate geometry at the sensor's pressure inlet (Joseph et al. 1995a). Lebreton et al. (1991) have reported that a similar cap, attached to the orifice of an air-acoustic gauge's protective well significantly reduced Bernoulli dynamic pressure effects in the measurement of tide. Each value of water level recorded in the logger was on average over 30 s. Time-averaging, over periods ranging from 30 s to a few minutes, is a common practice to filter out short-period fluctuations in tidal records arising from wind waves (e.g., Paroscientific intelligent pressure transmitter). Also, Joseph and Desa (1984) and Lamy (1988) have successfully used this method to limit the interference of long-period waves (swell).

The bulk density of water samples at the measurement site (1.062 g cm^{-3}), together with differential pressure data 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. This referencing was done at the time of slack water during which the tidal current was negligible and, therefore, tide-staff readings could be made with minimal disturbances arising from current-induced piling effects. 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%).

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. 1a). 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 measurement, 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 the match. As the tide level increased, ΔH was negative and became increasingly negative (Fig. 1b), reaching a value of 39 cm at high tide. The results indicated in Figs. 1a,b essentially revealed an underestimation of tidal range (this being the difference between successive low and high water heights).

Temperature sensitivity of the sensor and the time base in the data logger can give rise to errors in water level measurements. However, based on long-term experiments with a similar Paroscientific pressure transducer by Erdman (1983), the uncertainty in tidal range due to temperature variations in the measurement site was expected to be within 1 cm. An analysis by Joseph et al. (1993) revealed that the uncertainty in tidal range, arising from temperature sensitivity of the time base in the data logger, was also expected to be within 1 cm.

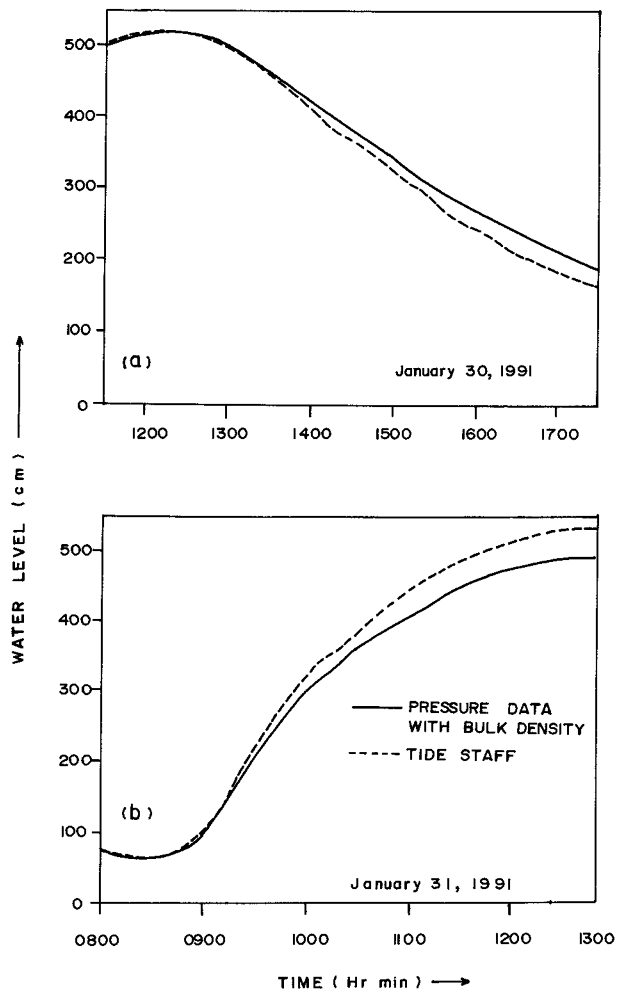

FIG. 1. Tidal range under estimation in the Hugli estuary when average bulk density was used. (a) Offset adjusted at high water and (b) offset adjusted at low water.

Thus, the above two probable factors could not account for the observed large underestimation in tidal range in the Hugli measurements. In any case, water level measurements made by us using the same sensor in the clear waters of the Zuari estuary did not reveal any detectable error in tidal range.

A simple calculation (see appendix) revealed that tidal records, obtained from a pressure sensing tide gauge, can suffer from tidal range underestimation. This occurs if the effective fluid density, ρ_{eff}, which actually contributed to the pressure sensed by the sensor, is less than the bulk density, ρ_b, of the water column above the sensor's pressure inlet (ρ_b being used for estimation of tidal elevation). Figures 2a,b and 3a,b indicate that use of ρ_{eff} in place of ρ_b significantly reduced the error in the measurement of turbid water level. The observed smaller errors in the corrected water levels using ρ_{eff} may be due to errors in tide-staff readings and pressure measurements due to tidal flow. Short period variations in the in situ effective density of turbid water, during

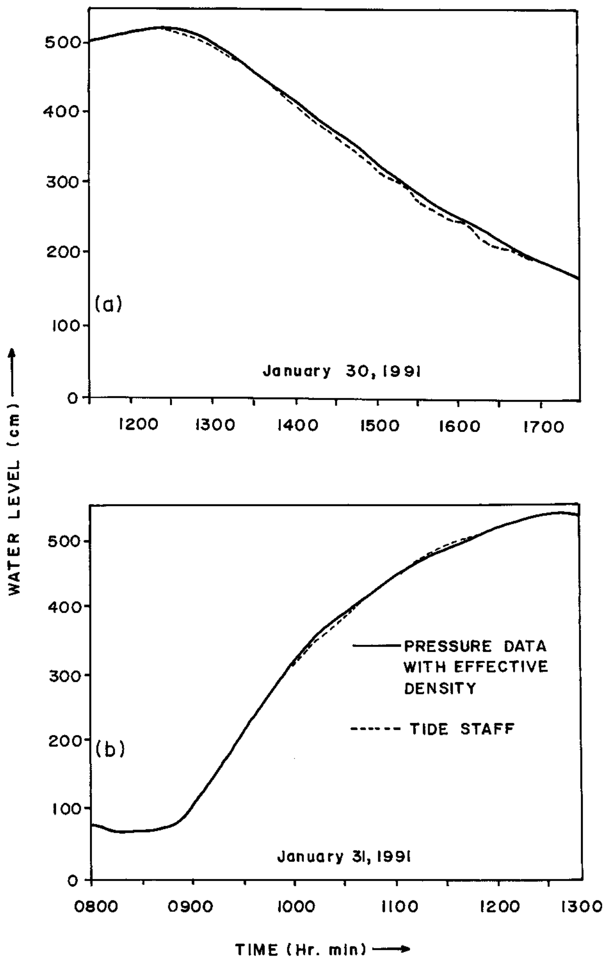

FIG. 2. Correction of tidal range under-estimation of Fig. 1 by the use of effective density. (a) Ebb-tide phase, (b) flood-tide phase.

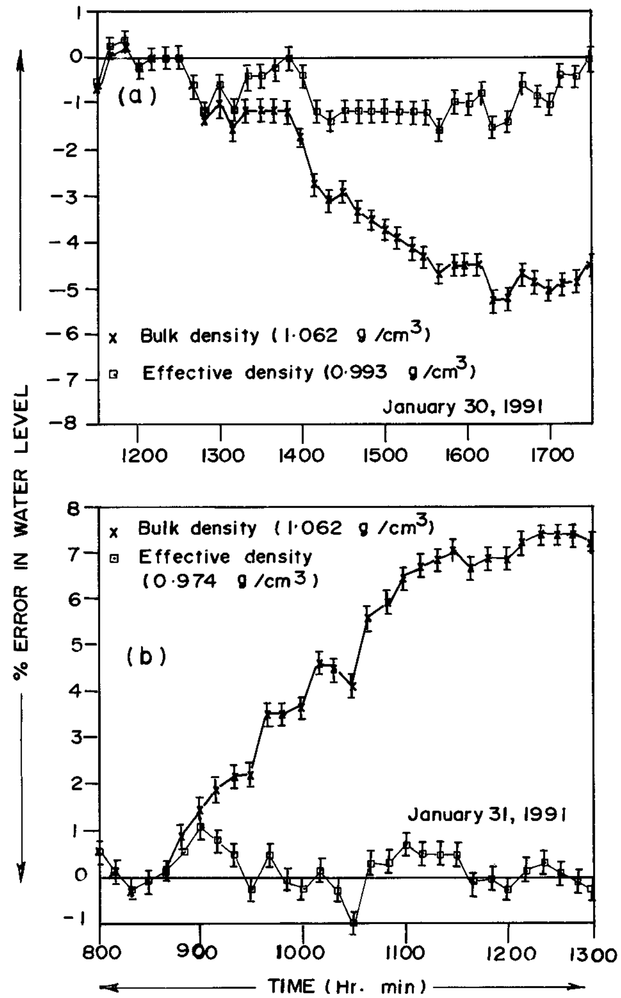

FIG. 3. Percent difference in water level of Fig. 1 when bulk density and effective density of turbid water were used.

the period of generally enhanced turbulence between the slack waters, may also have contributed in part to the observed errors in the corrected tide levels using ρ_{eff}. However, after due consideration of these factors, a paradoxical result indicated from 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.

Wells et al. (1978), during their measurements in the fluid-mud waters off the coast of Surinam, South America, had also noticed that the ρ_{eff} values of the fluid suspension, estimated using an in situ fluid density sensing device, were different from the mean bulk densities 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. These investigators attributed the discrepancies in density measurements to instrument calibration problems. However, on using calibrated bulk density values of the fluid, they 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.

3. Measurements in turbid waters of the Humber estuary using two pressure probes

A simple experiment to confirm the inferences made earlier, regarding the apparent reduction in in situ density of turbid estuarine waters involved the use of two pressure transducers. Pressures were measured from two different but precisely known levels and the value of ρ_{eff}, of the water column between these two levels, was estimated. Temperature and salinity profiles were also measured to estimate the vertical variability of the density profile of water without its suspended sediments.

TABLE 1. Depth-profile of conductivity, temperature, and density of water in the Humber Estuary, North Sea, United Kingdom. (Presence of sediments not taken into account.)

Depth (m)	Conductivity (m.mho cm^{-1})	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

The measurements reported here were made in the suspended-sediment-laden waters of the Humber estuary, North Sea, United Kingdom.

The measurement location was the harbor entrance of this turbid water estuary, in which a tide station was also located. Two bubblers were used for fluid pressure translation, using pneumatic bubbler gauge principle (Pugh 1972; Ling and Pao 1994), and were rigidly mounted on a vertical pole at a separation of 250 cm. 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 s. The current was found to be less than 3 cm s^{-1}. 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. From these the density profile was obtained. This profile (Table 1) is related to water without its suspended sediment.

In order to estimate the bulk density of the suspension (i.e., fluid inclusive of water and suspended sediment particles), turbid water samples were collected, from approximately the midlevel of the two pressure inlets, using a standard Niskin bottle that could be closed by sending a "messenger." The bulk density was estimated from precise measurements of the weights of equal volumes (1 L) of the thoroughly stirred water–suspended-sediment mixture and the sediment-free water filtered out from the collected fluid sample. The ratio of the densities of the two fluid samples was obtained from the ratio of the respective weights of these two fluid samples. From a knowledge of the density of sediment-free water (estimated from salinometer measurements), the bulk denstiy ρ_b of the fluid suspension was estimated from the ratio of the two density values. Thus, the value of ρ_b was found to be 1.035 g cm^{-3}. Measurements from the Humber estuary, United Kingdom, 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 the Hugli estuary. These measurements suggest that turbid waters in an estuary suffer an apparent reduction in density compared to its bulk density. This effect is more significant during midtide phase for which turbulence and suspended sediment concentration (SSC) values are expected to be larger (Wells 1989). The value of ρ_{eff} was found to gradually increase (from 1.007 g cm^{-3} at midtide) with increasing tide, and reached a maximum value of 1.015 g cm^{-3} 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 (1.035 g cm^{-3}), as well as the density of the local clear water, ρ_w (1.019 g cm^{-3}).

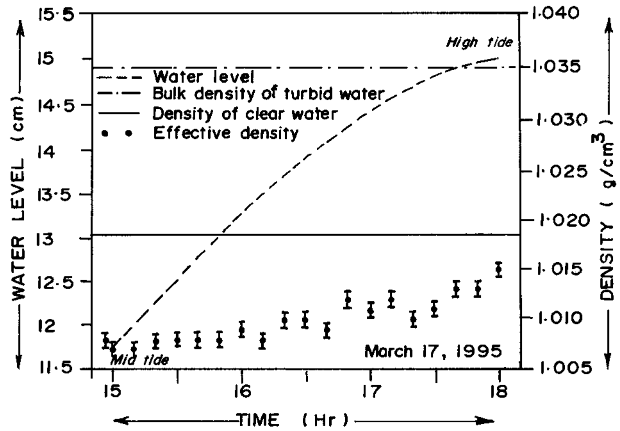

FIG. 4. Comparison of bulk density, clear-water density and effective density of turbid waters of the Humber estuary, North Sea, United Kingdom, as a function of tidal height.

During measurements, the temperature profile remained steady at 5.5°C whereas the conductivity marginally increased from 22.7 m.mho cm^{-1} (where m.mho is the reciprocal of water resistance in milliohms) at the surface to 23.7 m.mho cm^{-1} at a depth of 6 m below the surface. The density of the local clear 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.

4. Measurement 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 a single pressure transducer in the Hugli estuary. In an attempt to understand these observations, a similar experiment was conducted in the clear waters of the Zuari estuary, Goa, India, using

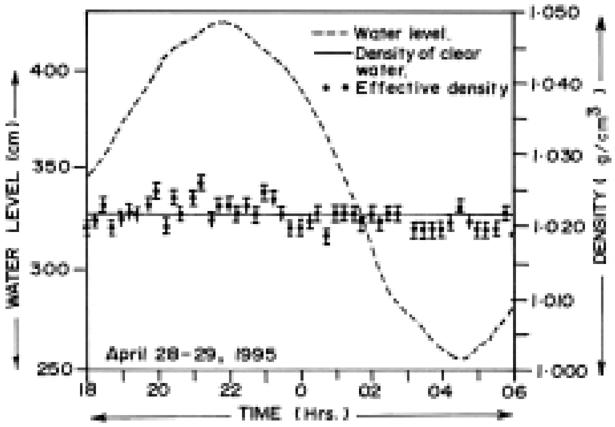

FIG. 5. Comparison of measured and effective densities of the clear waters of the Zuari estuary, Goa, as a function of tidal height.

two precision Digiquartz (Paroscientific) intelligent pressure transmitters, whose negative ports were vented to the atmospheric pressure.

In the present study, these two transducers were mounted with a vertical separation of 100 cm. The inlets were attached to pairs of large horizontal parallel plates to reduce flow effects and also the effects of wind waves (Shih and Baer 1991; Joseph et al. 1995b; Joseph et al. 1996). The effect of this parallel-plate geometry was similar to that of the perforated cap used in the Hugli estuary. The 30-s time-averaged outputs from these two transducers were used to obtain the value of ρ_{eff}. The density of water samples was also measured using a precision density meter that operated on a mechanical resonance principle (Kremling 1972) with an accuracy of ± 0.001 g cm^{-3}. The density of water samples taken during the pressure measurements was 1.022 g cm^{-3}. The values of effective density ρ_{eff}, 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.

5. Discussion of results

The measurements reported above have provided the following insights.

1) There exists an effective reduction in the in situ density of suspended sediment-laden natural waters as observed by pressure measurements in the Hugli and Humber estuaries.
2) A dual pressure transducer system with a suitable vertical separation is capable of correctly measuring the effective fluid density, ρ_{eff}, 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 that may have caused the observed effective reduction in the in situ density of turbid natural waters. Three possible reasons might have been the presence of air bubbles in water, a dynamic uplift force acting on suspended sediment particles in the water column above the pressure inlet, or the presence of a floc framework. As Fig. 5 shows, air bubbles do not appear to have a significant role in reducing the density of clear estuarine 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 might have contributed in part to the observed reduction in the effective in situ density of turbid natural waters. Assuming that the suspension is dilute (i.e., the separation between adjacent suspended particles is much larger than their dimension), Joseph et al. (1997) attempted to provide an explanation for the apparent reduction in the in situ density of suspended-sediment-laden natural waters. However, this assumption is violated if the suspension is in the fluid-mud range, as might have been in the present case, in which the suspension might behave viscoelastically (Dr. G. C. Kineke, 1998, personal communication). The behavior of viscoelastic fluids appears to be poorly understood. Further detailed studies may be required for a deeper understanding of the problem posed here.

Acknowledgments. The authors gratefully acknowledge the support and encouragement from Captains A. C. Dutta and R. C. Paul of the Calcutta Port Trust, and services extended by V. N. Chodankar, D. Rodrigues, and E. D'Silva of the National Institute of Oceanography (NIO), Goa. The generous support received from the Proudman Oceanographic Laboratory (POL), United Kingdom, was extremely valuable. Antony Joseph is grateful to Joe Rae, John Casson, and others at POL for their active cooperation in the completion of the experiments at the Humber estuary. Finally, we thank the reviewers and the editor (Dr. Albert J. Williams III) of this journal for many useful comments and suggestions that enabled us to improve the quality of this paper.

APPENDIX

Relation between Error in Tidal Range and Bulk Density of Water

Tidal range is the difference in water levels between successive high and low waters. Let us assume that flow- and wave-induced errors in the measurement of pressure have been removed by the use of a suitable hydromechanical front end. Let P_H be the time-averaged pressure measured by a pressure sensor during high tide. Let ρ_{eff}

be the density of the water column that actually contributed to the pressure sensed by a pressure sensor deployed below the low tide level. Then P_H is given by the standard hydrostatic equation:

$$P_H = H\rho_{\mathrm{eff}}g, \qquad (A1)$$

where H is the height of the water column above the pressure inlet at high tide, and g is the acceleration due to gravity (time-averaging over periods ranging from 30 s to a few minutes filters out short-period fluctuations from the tidal record). Similarly, the time-averaged pressure P_L sensed by the pressure sensor at low tide is given by

$$P_L = L\rho_{\mathrm{eff}}g, \qquad (A2)$$

where L is the height of the water column above the pressure inlet at low tide. The true tidal range R_t, given by $(H - L)$, can be expressed as

$$R_t = \frac{(P_H - P_L)}{(g\rho_{\mathrm{eff}})}. \qquad (A3)$$

If depth-mean bulk-density (ρ_b) of the water column above the pressure inlet is used for estimation of water level, the computed tidal range (R_c) is given by

$$R_c = \frac{(P_H - P_L)}{(g\rho_b)}. \qquad (A4)$$

The error in tidal range, R_{error}, given by $(R_t - R_c)$ can be obtained from Eqs. (A3) and (A4) as

$$R_{\mathrm{error}} = (P_H - P_L)\frac{(\rho_b - \rho_{\mathrm{eff}})}{(g\rho_b\rho_{\mathrm{eff}})}. \qquad (A5)$$

Equation (A5) shows that if $\rho_{\mathrm{eff}} < \rho_b$ the pressure sensor will underestimate the tidal range. However, from Eq. (A5) the unknown quantity ρ_{eff} can be obtained from the known quantities, as

$$\rho_{\mathrm{eff}} = \frac{(P_H - P_L)\rho_b}{[g\rho_b R_{\mathrm{error}} + (P_H - P_L)]}. \qquad (A6)$$

We find from Eq. (A5) that $R_{\mathrm{error}} = 0$, if $\rho_{\mathrm{eff}} = \rho_b$. In clear waters the value of ρ_{eff} is very close to that of ρ_b, so that R_{error} is negligibly small. However, in turbid estuarine waters $\rho_{\mathrm{eff}} < \rho_b$, resulting in underestimation of tidal range. Because turbulence and turbidity levels change with time (and space) the correction factors cannot be considered constant. However, if two pressure sensors are deployed with a vertical separation D between their pressure inlets, the value of ρ_{eff} of the water column of height D can be estimated, after each sampling, from the measured pressures P_1 and P_2 using the relation

$$\rho_{\mathrm{eff}} = \frac{(P_1 - P_2)}{(Dg)}, \qquad (A7)$$

where ρ_{eff}, P_1, P_2, D, and g are all expressed in the same system of units. Thus, simultaneous measurement of time-averaged pressures (P_1 and P_2) from two submerged pressure sensors deployed at a precisely known vertical distance D provides a means of estimating the value of ρ_{eff} during each sampling. This would enable measurement of water levels with an enhanced precision even from turbid waters (patent application filed).

REFERENCES

Erdman, M. R., 1983: Bottom pressure observations on the continental shelf. *Sci. Eng,*. **44,** 1–6.

Joseph, A., and E. S. Desa, 1984: A microprocessor-based tide measuring system. *J. Phys. E,* **17,** 1135–1138.

——, E. Desa, and E. S. Desa, 1993: Probable errors of pressure sensing tide gauges: A critical appraisal. National Institute of Oceanography Tech. Rep. NIO/TR-12/93, 68 pp. [Available from Publication and Reprography Division, NIO, Dona Paula, Goa 403 004, India.]

——, P. Foden, and K. Taylor, 1995a: An experimental evaluation of flow-induced errors in a pressure transducer and some design solutions to improve its performance in a flow field. Proudman Oceanographic Laboratory Internal Document 82, 52 pp. [Available from Librarian, Proudman Oceanographic Laboratory, Birkenhead, Merseyside L43 7RA, United Kingdom.]

——, J. A. E. Desa, E. Desa, P. Foden, and K. Taylor, 1995b: Flow effects on a pressure sensor. *Symposium on Ocean Electronics,* Cochin, Kerala, India, Cochin University of Science and Technology, 11–16.

——, ——, ——, J. McKeown, and V. B. Peshwe, 1996: Wave effects on a pressure sensor. *International Conference in Ocean Engineering,* Chenmai, India, National Institute of Ocean Technology, 568–572.

——, E. Desa, E. S. Desa, D. Smith, V. B. Peshwe, Vijaykumar, and J. A. E. Desa, 1997: Reduction in density of suspended-sediment-laden natural waters. *Second Indian National Conference on Harbour and Ocean Engineering,* Thiruvananthpuram, India, Centre for Earth Science Studies, 708–718.

Kremling, K., 1972: Comparison of specific gravity in natural sea water from hydrographical tables and measurements by a new density instrument. *Deep-Sea Res.,* **19** (5), 377–384.

Lamy, A., 1988: Sea level measurements in Indian sector of the Antarctica. IOC Workshop Rep. 54, 79 pp.

Lebreton, B., H. Dolou, C. Batany, and J. C. Kerinec, 1991: Evaluation des maregraphes Suber en presence de courants forts. Suite: Evaluation d'un attenuateur de depression. *Ann. Hydrogr.,* **17,** 37–43.

Ling, S. C., and H. P. Pao, 1994: Precision water level and sediment monitoring systems. *Int. Symp. on Hydraulic Measurements,* 1–33.

Pugh, D. T., 1972: The physics of pneumatic tide gauges. *Int. Hydrogr. Rev.,* **49,** 71–97.

Shih, H. H., and L. Baer, 1991: Some errors in tide measurement caused by dynamic environment. *Tidal Hydrodynamics,* B. B. Parker, Ed., John Wiley and Sons, 641–671.

Thorpe, S. A., P. Bowyer, and D. K. Woolf, 1992: Some factors affecting the size distribution of oceanic bubbles. *J. Phys. Oceanogr.,* **22,** 382–389.

Turner, W. R., 1961: Microbubble persistence in fresh water. *J. Acoust. Soc. Amer.,* **33,** 1223–1232.

Wells, J. T., 1978: Shallow-water waves and fluid-mud dynamics, Coast of Surinam, South America. Coastal Studies Institute, Tech. Rep. 257, 53 pp. [Available from Center for Wetland Resources, Louisiana State University, Baton Rouge, LA 70803.]

——, 1989: In-situ measurements of large aggregates over a fluid-mud bed. *J. Coastal Res.,* **SI** (5), 75–86.

——, J. M. Coleman, and W. J. Wiseman Jr., 1978: Suspension and transportation of fluid-mud by solitary-like waves. *Proc. 16th Coastal Engineering Conf.,* Hamburg, Germany, ASCE, 1932–1952.