

## NEAR-BED CURRENT VELOCITY PROFILES IN THE EASTERN IRISH SEA: IMPLICATIONS FOR RADIOACTIVE WASTE DISPOSAL

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### ABSTRACT

*Near-bed current velocity data have been recorded at six different stations in the eastern Irish Sea using a vertical array of five electromagnetic current meters in the boundary layer. The data suggests that circulation in the Irish Sea is dominated by tidal streams modulating at semi-diurnal frequency and circulating in counter-clockwise direction. Values of friction velocity and roughness height determined from the current velocity suggest that (1) for slow currents the flow is "smooth turbulent" in most part, (2) at higher velocities the flow becomes "rough turbulent" and the seabed becomes rippled. It appears that form drag increases resistance to flow instead of skin friction (grain size).*

*Wave parameters recorded at one of the stations indicate that during calm weather wave height varied between 11.4 cm to 1.11 m, wave period between 8-20 S, and wavelength from 103 to 346 m in 35 m deep water. It has also been observed that even in the presence of small waves, wave orbital currents are produced in the boundary layer which add to the shear stress caused by tidal currents and increase the potential for resuspension of bed sediments. Since the Irish Sea generally becomes storm dominated during winters, resuspension of bed sediments and attached radionuclides may increase during this season.*

### INTRODUCTION

The Irish Sea is a shallow, funnel-shaped body of the Atlantic Ocean (Fig. 1). The southern and western parts of the sea are relatively deeper than the north-eastern part where mean depth between the English coast and Isle of Man is about 30 m (Bowden, 1980). Circulation of water in the sea is predominantly controlled by semi-diurnal tides having a typical surface magnitude of 1 m/s (Robinson, 1979). Tidal streams enter simultaneously from south and north, and meet at about 54° N. The tidal range is 9 m

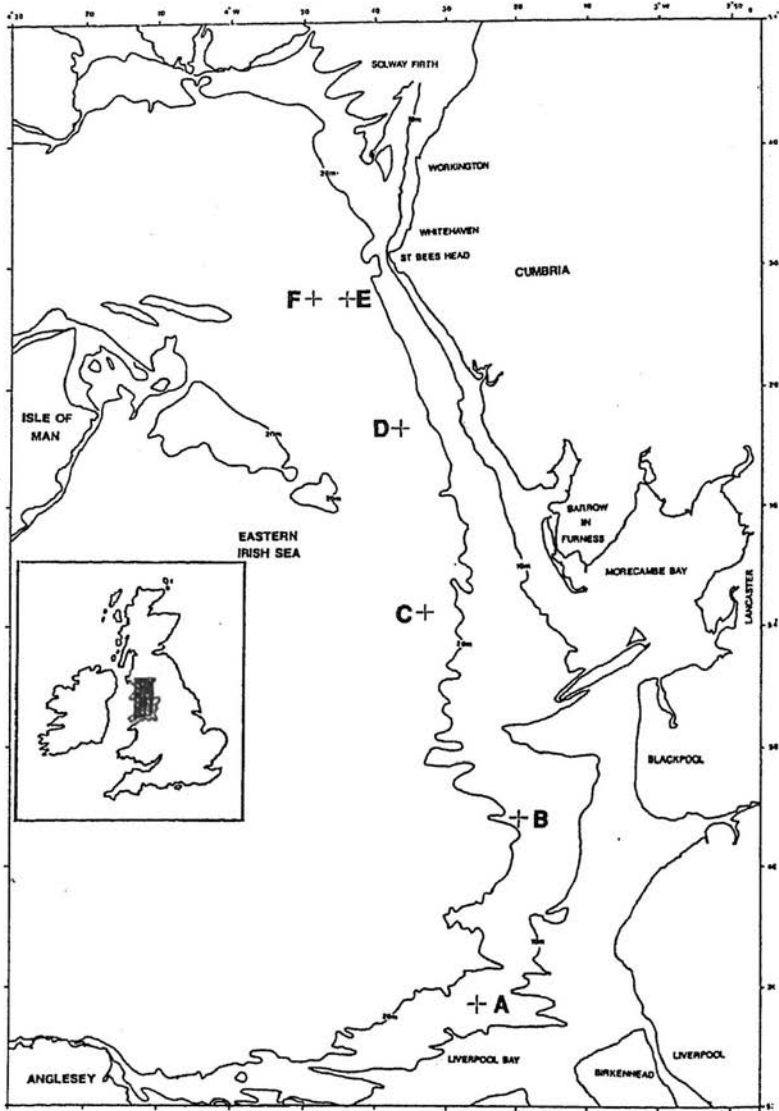


Fig. 1. Location map of the eastern Irish Sea showing positions of the current-meter stations.

on the shallow English coast and 1.3 m near the deep Irish coast (Bowden, 1983).  $M_2$  (lunar semi-diurnal) is the most predominant tidal constituent and  $S_2$  (solar semi-diurnal), with one third the amplitude of  $M_2$ , is the next significant constituent (Hughes, 1969). Current velocity varies harmonically with the phase of the major tidal constituents and a decrease from surface to bottom in the phase and amplitude of the tide have been recognized (Ahmad, 1979). Mean spring amplitudes are twice the mean neap

amplitudes in the eastern Irish Sea. Tidal currents are slowest near the Isle of Man but have a greater amplitude (0.9 m/s) to north and south of the island (Howarth, 1984).

Low level effluent nuclear waste has been discharged into the Irish Sea from the Sellafield reprocessing plant at Cumbria, since 1952. These effluents contain both soluble ( $^{90}\text{Sr}$ ,  $^{137}\text{Cs}$ ) and insoluble ( $^{106}\text{Ru}$ ,  $^{144}\text{Ce}$ ,  $^{240}\text{Pu}$ ,  $^{241}\text{Am}$ ) radionuclides of which the latter are ~95% (Hetherington, 1976; Hain, 1986; Kershaw et al., 1986). The soluble component stays in solution and either moves with currents or becomes trapped in the interstitial waters, but the insoluble component descends to the sea-floor as colloids of particles (Howarth, 1984). These insoluble pollutants have been abundantly found in the vicinity of the outfall and intertidal sediments of the Esk estuary and Cumbrian coast (Aston et al., 1985; Hamilton, 1985). A positive correlation between Pu activity and fine fraction of the mud have also been identified in the area (Aston et al., 1985; Kershaw et al., 1986).

This paper presents the current-meter data recorded at 6 different stations in the northeastern Irish Sea. The data were collected during 1988 and 1989. A special bottom-mounted autonomous system, equipped with a vertical array of five electromagnetic current meters and a pressure sensor was used for this purpose (Rehman & Vincent, 1988; Vincent et al., 1990). Current and wave data were recorded on a battery operated Seadata logger, mounted on a platform 2 m above the base of the tetrapod.

## THEORY

Flowing water experiences friction at the fluid solid interface due to current shear. Correspondingly water exerts an equal and opposite tangential drag on the boundary, called shear stress ( $\tau$ ) which is proportional to the square of the flow speed. As a result the flow speed gradually decreases from surface to bottom in a logarithmic layer whereby layers with different velocities shear past each other. If current velocities ( $U_z$ ) are recorded at different levels above the bed and plotted against logarithm of distance from the bed, then shear or friction velocity ( $U_*$ ) can be determined from the gradient of the line by following relationship (Open University, 1989):

$$U_* = \frac{k (U_2 - U_1)}{(\log z_2 - \log z_1)} \quad (1)$$

where  $U_1$  and  $U_2$  are the current velocities at two reference levels,  $\log z_1$  and  $\log z_2$  are the log of the distance between the seabed and the respective measurement level,  $k$  is von Karman's constant having a value of 0.4.

The shear velocity is effectively related to the drag on the sea bed,  $\tau_0$ , as well as the density of water  $\rho$  and is, therefore, responsible for the sediment transport by:

$$\tau_0 = U_*^2 \rho \dots\dots\dots (II)$$

The effect of bed on the flow is expressed as  $C_D$ , the drag coefficient which accounts for the roughness of the bed or the particle size making the bed. Mathematically, it can be expressed as :

$$C_D = (U_*/U_z)^2 \dots\dots\dots (III)$$

where  $U_z$  is current velocity usually measured 1m above the bed.

At slow currents flowing over a bed composed of fine grained sediments, a viscous sublayer ( $\delta$ ) can form beneath the logarithmic layer. The thickness of this sublayer is normally of the order of a few mm which is inversely proportional to  $U_z$  (and thus  $U_*$ ). In this region the flow is quasi-laminar because viscosity dominates it and the current flow only sees a smooth bed. At this stage the sediment diameter ( $d$ ) is not significant and roughness height of the bed ( $z_0$ ) is a function of flow speed.

A flow is regarded as "smooth turbulent" if the grain diameter of the bottom is less than one third of the thickness of viscous sublayer ( $d < \delta/3$ ). A flow will be "rough turbulent" if the grain diameter is seven times the thickness of  $\delta$ , and "transitional" between these two maxima. The thickness of  $\delta$  is determined as:

$$\delta \sim 10 \nu / U_* \dots\dots\dots (IV)$$

where  $\nu$  is the kinematic viscosity (molecular viscosity divided by density = 0.014 cm/s for seawater).

Apart from current velocity, other factors responsible for initiation of sediment transport include size and shape of the particles making the bed, relative sediment density, nature of bed forms, cohesion between sediments (yield strength), and viscosity of water. When the shear velocity exceeds the threshold limit and overcomes the inter-particle cohesion, sediments along the bed start to move. Depending on the ratio between grain size of the substrate and the thickness of  $\delta$ , particles can be transported as bed load (rolling, sliding or saltation) or as suspended load.

Boundary layer flow in most marine environments is turbulent and characterized by random movements of small eddies within the water column. The initiation of suspended load, however, requires greater turbulence with high eddy viscosity to cause a vigorous erosion of the substrate and lift particles into suspension. Non-cohesive sediments can be resuspended if the upward lifting force exceeds the grain weight. These particles are passively carried by horizontal currents till their velocity is checked and the deposition starts (for details see Ch. 7, Allen, 1985).

## INSTRUMENTATION

### Currents

Current measurements for the present study were recorded by a vertical array of five Marsh-McBirney type electromagnetic current meters with a 2.5 cm diameter sensor head. The current meters were attached to a tetrapod and positioned at 15, 30, 60, 100, and 135 cm heights from its base to measure the Eulerian current velocity at above heights from the sea bed. One of the current meters ( $Z = 30$  cm) was aligned at  $90^\circ$  to the others. Each current meter measured flow velocity along the two horizontally orthogonal axes - a north component and an east component. The sampling was done in bursts consisting of 500 measurements per burst for each current meter. The burst interval was 30 minutes and sampling frequency of 1.2 s, taking 10 minutes to complete a burst. Data from 500 measurements were averaged and recorded as a mean and standard deviation.

### Waves

A common method available for obtaining information on wave parameters is to use a fixed pressure sensor mounted on a stand and deployed near the bed. The sensor measures hydrostatic pressure which varies periodically as the depth of water between surface and the sensor varies with waves of different heights passing over it. This method is useful for shallow waters because the pressure variation is rapid depending upon the wavelength of the waves (Pond & Pickard, 1983). For this study pressure values were recorded by a sensor mounted on the tetrapod 2 m above the seabed. It was also sampling in burst mode consisting of 500 measurements taken at a frequency of 1.2 s. The pressure sensor and current meters were synchronized to start the bursts simultaneously.

## METHOD

Before calculating  $U_*$  (friction velocity) and  $z_0$  (roughness height) for these stations, it was important to check how logarithmic the flow was at the time of measurements. This was necessary because at slow velocity the determination of above parameters becomes inaccurate. The coefficient of regression ( $r^2$ ) was determined for each burst by using linear regression between  $U_z$  and  $\log z$ . Bursts with a critical value of  $r^2 < 0.95$  were ignored for further analysis. Since current meter at level 2 ( $z = 30$  cm) was not aligned with the rest and some of its data were contaminated and hence not included in the calculation of  $r^2$ ,  $U_*$  and  $z_0$ .

## RESULTS

### Stations A, B, C and D

The first set of near-bed current velocity data were recorded from stations A, B, C and D (see Fig. 1) having mean depths of 23, 23, 26 and 31m respectively. The system was deployed for four relatively short periods (16-25 h) in January 1988, when the tidal range was very close to mean neap ( $\sim 5$  m). Profiles of current velocity at 15, 60 and 135 cm from the bed for these stations indicate that mean flow is tidally dominated with a semi-diurnal frequency and tidal streams flow counter-clockwise (Fig. 2). Peak mean velocity at  $U_{135}$  is  $\sim 40$  cm/s and the profiles are logarithmic only when flow speed is  $> 20$  cm/s.

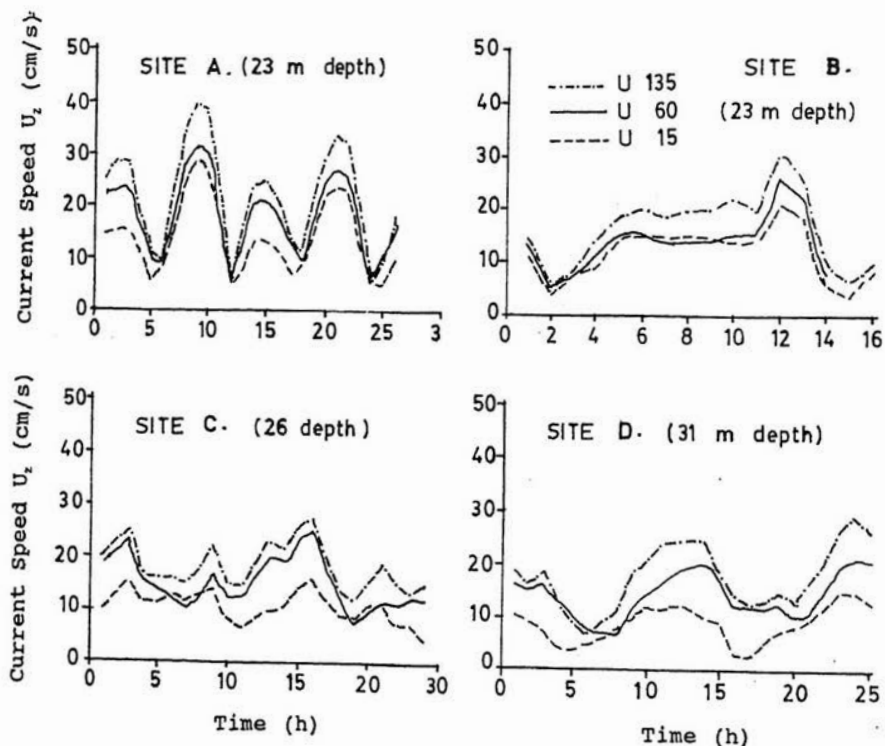


Fig. 2. Current velocity profiles at 15, 60 and 135 cm above the seabed at stations A, B, C and D in the eastern Irish Sea on January 11, 13, 14 and 15, 1988, respectively.

Burst values having  $r^2 > 0.95$  were used to determine the  $U^*$  and  $z_0$  for all four stations (Fig. 3). The relationship between  $U^*$  and  $z_0$  values suggest that for  $U^* < 1.5$  cm/s, the  $z_0$  remains low (0.1 cm), but when the friction velocity exceeds this threshold,

the roughness height also increases accordingly. Thus, it can be inferred that during slow currents at station A ( $< 30$  cm/s),  $\sim 1$  mm thick viscous sublayer ( $\delta$ ) was formed above the bed which rendered the sediment size insignificant and hence  $z_0$  was a function of the flow speed (Fig. 3a). However, as soon as the velocity increased the above value, the thickness of  $\delta$  decreased and the sediment size and the form drag became important. The value of  $z_0$  obtained for this period (1.5 cm) indicate that the bed could be rippled and that the flow was rough turbulent ( $d > 7\delta$ ). Measurements at station B are not logarithmic for the most part and therefore, will not be discussed in detail.

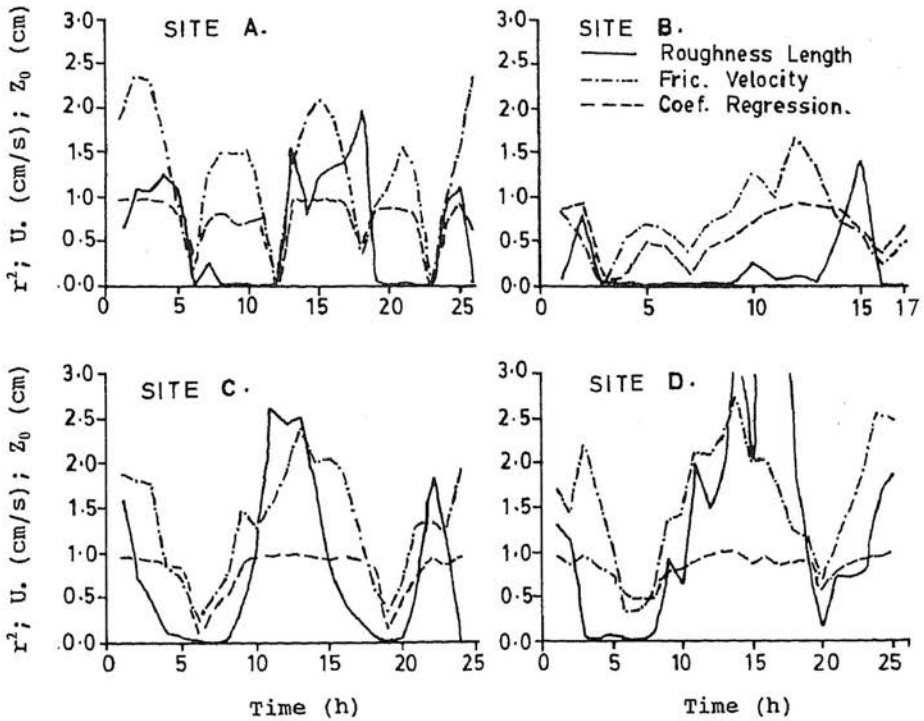


Fig. 3. Plots showing coefficients of regression ( $r^2$ ), friction velocity ( $U^*$ ), and roughness height ( $z_0$ ) for stations A-D.

$U^*$  values for station C show typical values of about 1.5-2.0 cm/s for current velocities  $> 20$  cm/s (Fig. 3c).  $r^2$  is higher than the critical value of 0.95 for most of the bursts. High  $z_0$  values indicate that seabed in this region is rippled and it is the form drag which increases the resistance to flow rather than the skin friction. At station D also (Fig. 3d), high  $U^*$  values ( $> 2$  cm/s) are encountered during very fast flows suggesting a significant friction by the bed forms (high  $z_0$ ).

## Station E

The next set of data were recorded at station E in 24 m deep water. Here the tetrapod was deployed for 23 days during Jan. Feb. 1988. The sampling was controlled by pressure fluctuations which would continue for the next 12 hours if the fluctuation was greater than a certain threshold. Otherwise, the samples were recorded once every 12 h. Thus, during the period of 23 days, there are about half a dozen such occasions when measurements went on for 12 hours or more. Figure 4 represents four such events when the velocity was recorded for 20 hours or more at a stretch, chosen for further analysis.

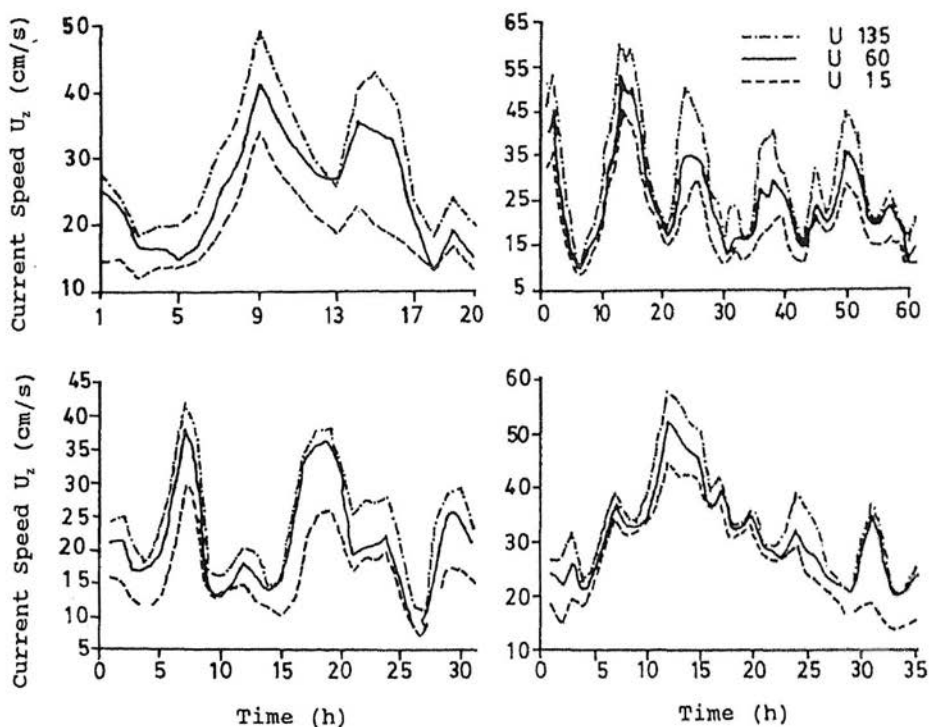


Fig. 4. Current velocity profiles at 15, 60 and 135 cm above the seabed at station E in the eastern Irish Sea. (a) 20 h on 19-1-1988, (b) 60 h on 31-1-1988, (c) 30 h on 7-2-1988, and (d) 35 h on 9-2-1988.

The first event lasted up to 20 hours at a time when the tidal range was  $> 8$  m at Liverpool (Fig. 4a). The second set of data represents current measurements for 60 hours with tidal range of 6 m (Fig. 4b). The third set represents 30 hours of measurements in nearly 7 m tidal range (Fig. 4c) and, and the fourth event lasted 35 hours in 6 m of tidal range (Fig. 4d).



A generalized examination of the mean velocity profiles for station E shows that fastest currents speed at 135cm from the bed reached 61 cm/s which corresponds to 47 cm/s near the bed ( $U_{15}$ ). Records show that these profiles are generally logarithmic and above the critical value of  $r^2 > 0.95$ . Currents show a clear modulation at semi-diurnal frequency and an anticlockwise rotation.

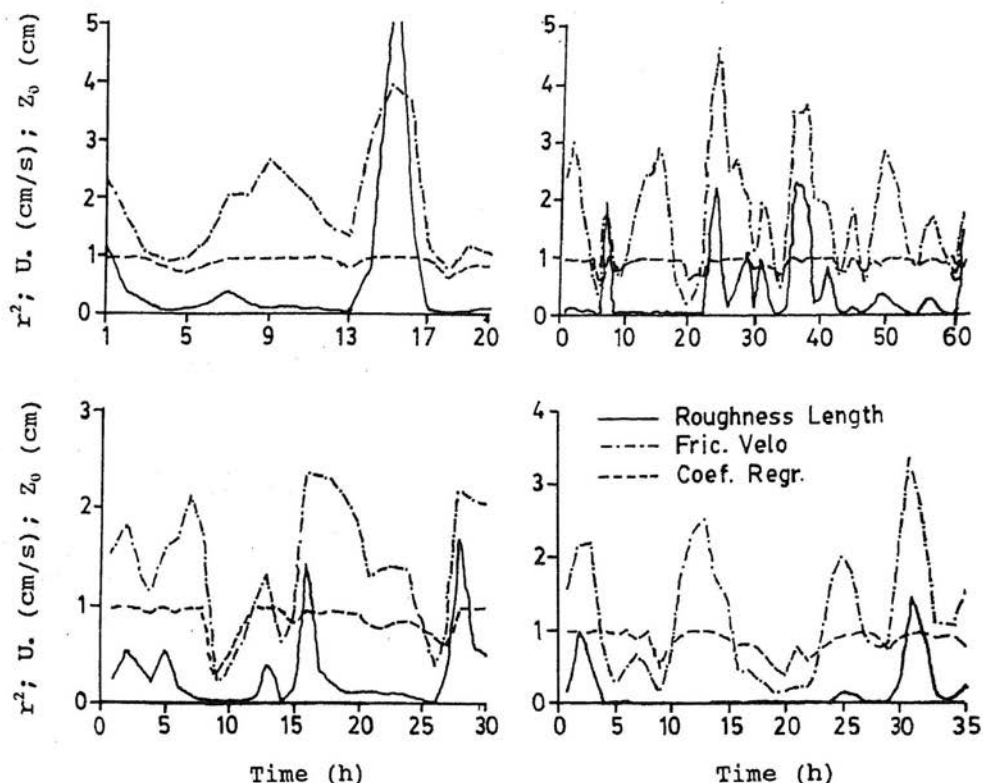


Fig. 5. Plots showing coefficients of regression ( $r^2$ ), friction velocity ( $U_*$ ), and roughness height ( $z_0$ ) from stations E for corresponding periods of figure 4 (a,b,c,d).

The highest  $U_*$  value, determined for this station during a period of 23 days, is about 4.8 cm/s (Fig. 5). Such high  $U_*$  values coupled with high  $z_0$  suggest that the bed at this locality is rippled rather than being made of coarser particles. Water flowing at a speed of 60 cm/s, ~ 1 m above the bed, is capable of initiating transport of non-cohesive sediments of up to 800  $\mu\text{m}$  in diameter. Similarly, a flow with a friction velocity of 4.5 cm/s can transport particles, having 500  $\mu\text{m}$  diameter, in suspension. It is estimated that for  $U_*$  values of < 2.5 cm/s, the thickness of  $\delta$  would be 0.4 mm and the flow would be smooth turbulent if  $d < 0.1$  mm, however, the flow becomes rough turbulent when  $d > 3$  mm. It is because at this stage the bed flow may generate ripples which are responsible for high  $z_0$  values, occasionally encountered during the profiles.

## Station F

Near-bed current velocity data from station F were recorded at a depth of 35 m through a short deployment of 26 hours during March 1989. Calm weather had prevailed before and during the deployment and the tide was at spring ( $> 9$  m). The fastest currents measured simultaneously at 135 and 15 cm above the bed were 55 and 39 cm/s, respectively (Fig. 6a). The tidal frequency is semi-diurnal with a counter-clockwise flow and the major axis of the ellipse oriented towards NW-SE. The  $U^*$  values range from 1-2.7 cm/s, and  $z_0 < 0.1$  cm (Fig. 6b). It has been suggested that a velocity of 55 cm/s ( $\sim 1$  m above the bed) can initiate bed load transport of particles of  $< 600 \mu\text{m}$  diameter, and suspended load transport of up to  $300 \mu\text{m}$ , if the substrate is made of non-cohesive sediments (Open University, 1989).

## Analysis of waves at station F

Pressure profiles were also measured at station F, for the first 22 hours of the deployment. The data were analysed in detail and wavelength ( $L$ ), wave period ( $T$ ), wave height ( $H_{\text{max}}$ ,  $H_{\text{sig}}$ ,  $H_{\text{min}}$ ) and the near-bed wave orbital current velocity ( $U_{\text{max}}$ ,  $U_{\text{sig}}$ ,  $U_{\text{min}}$ ) were calculated for that period. Figure 7 shows the profiles of significant wave height ( $H_{\text{sig}}$ ) and the significant near-bed wave orbital current velocity ( $U_{\text{sig}}$ ). The values of  $H_{\text{sig}}$  range from 0.2 to 0.75 m, and those of  $U_{\text{sig}}$  varies from 10-22 cm/s.

The wave parameters recorded at station F show a wide range of scale. During the 22 hours of measurement, the smallest mean waves were 11.4 cm high but the maximum height was 1.11 m. Wave periods range from a minimum of 8 s (corresponding to the highest wave) to a maximum of 20 s. The wavelength of various waves vary between 103 to 346 m. It should be noted here that wave periods measured at this station (depth 35 m) are much longer than expected for a sea such as the Irish Sea (normal  $T = 6-8$  s). However, because wave attenuation increases as  $T$  decreases, the influence of longer waves in the spectrum of surface waves is accentuated at the seabed.

It looks certain from figure 7 that even in the presence of smaller waves, there are wave orbital currents in the boundary layer. These currents add to the total shear stress caused by tidal currents and thus increase the potential for resuspension of the bed sediments. A quantitative estimation of the magnitude of additional stress was obtained through the use of Glenn and Grant's model (1987). This model computes the nearbed kinematic and dynamic parameters for a combined affect of waves and tidal currents on a bed with movable bed roughness.

In order to compute the new values of  $U^*_{\text{cw}}$  (currents and waves) through the above model, it was assumed that the bed was composed of only one size particles (125 mm) having a density of 2.65 g/cm. The angle between the directions of waves and currents was set to  $45^\circ$ . The results showed that wave current interaction does increase

the value of  $U_{*cw}$  between 0.4-1.0 cm/s which in turn affects the bed shear stress  $\tau_0$  and hence the amount of suspended material.

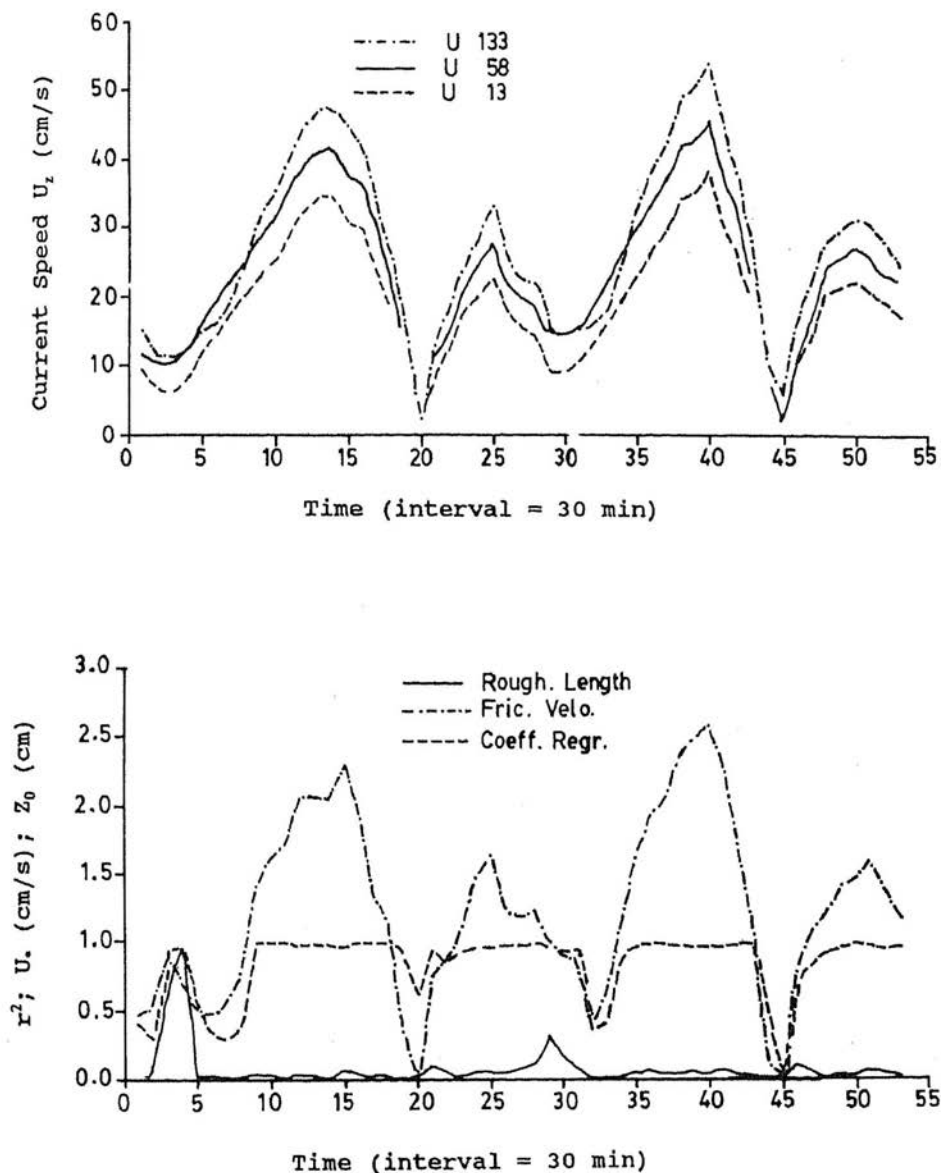


Fig. 6. (a) Current velocity profiles at 13, 58 and 133 cm above the seabed at station F in the eastern Irish Sea during March 1989. (b) Coefficient of regression ( $r^2$ ), friction velocity ( $U_*$ ), and roughness height ( $z_0$ ) from stations F for the corresponding period.

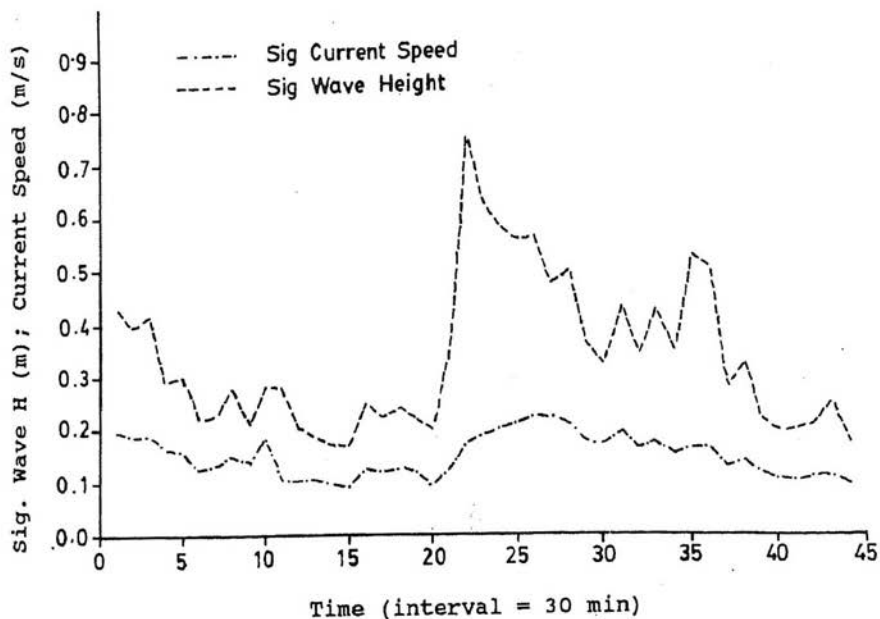


Fig. 7. Plot of significant wave height ( $H_{sig}$ ) at station F and the resulting increase in current velocity due to wave orbital currents.

## DISCUSSION AND CONCLUSION

A generalized analysis of the current velocity data from various points in the shallow eastern Irish Sea suggests that water circulation is controlled by tidal streams at a semi-diurnal frequency. The two incoming tidal streams meet at almost the centre of the Irish Sea basin from where they circulate in a counter-clockwise direction. The longest axis of the tidal ellipse is oriented in NW-SE direction. Typical surface currents in this area flow at  $\sim 1$  m/s which corresponds well with the measured data as the fastest currents measured anywhere in the eastern part of the Irish Sea basin at a height of 135 cm from the bed never exceed 65 cm/s. Because of the significant difference in the depth of the basin from west to east, the tidal range is maximum near Liverpool and minimum near the Irish coast.

Seabed in this part of the basin is composed of sand and sandy mud (Dickson, 1987) with a significant degree of cohesion in the extreme northeastern part. These sediments are eroded and resuspended only when the shear velocity of the currents cross a certain threshold. It follows that at slow currents ( $< 30$  cm/s) the flow is smooth turbulent in boundary layer. When current velocity is higher during spring tides, the flow becomes rough turbulent and coarser particles along the bed form ripples which increases the resistance (form drag). Higher values of roughness height on certain

occasions indicate the above and show that the substrate may be rippled in this part of the sea.

Wave parameters measured during calm weather also indicate that wave orbital currents are certainly very important in terms of adding to the friction velocity of tidal currents, increases their potential for erosion of the substrate and resuspension of particles (Fig. 7). Winter storms (with gale force winds) are common in the north Atlantic and western European coastal regions. These storms (though fetch limited in the Irish Sea region) are likely to generate large waves which interact with the tidal and wind-driven currents. Hence, friction velocity may exponentially increase if such storm coincide with spring tides and erosion/resuspension of the bed particles may ensue. The present study does not support the argument of Sills & Edge (1987) that seabed in this area may be receiving recent sediments as opposed to erosion (cf. Fig. 6; Rehman & Vincent, 1988).

The most important implication of this analysis is that bed sediments in a large part of the northeastern Irish Sea are contaminated/polluted due to the insoluble component of the nuclear waste, a majority of them can be eroded and resuspended during winter storms and the potential health hazard in the area may also increase.

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