Experimental investigation of the wave-induced currents above rippled beds

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Abstract

Wave-induced currents measurements have been carried out using laser Doppler velocimetry in a wave channel above an artificial rippled bed. The tests were carried out in rough turbulent and transitional regimes. A one-dimensional approach of the flow, horizontally-averaged over a ripple length and similar to the classical approach for rough flat beds is used to describe the flow. In the case of rough turbulent regime and close to this regime, the drift at the edge of the boundary layer is found to be lower than the classical value of Longuet-Higgins (1958) for smooth flat beds ($U_\infty c / U_0^2$ =0.75). A simple modelling allowing to estimate the Eulerian drift above rippled and very rough beds at the edge of the boundary layer as a function of a/k_s is proposed. In the case of transitional regime, the drift at the edge of the boundary layer decreases in a logarithmic way with increasing Reynolds number. Vertical profiles of drift velocity are compared with the results of Davies and Villaret's (1999) model. The model's coefficients representing the variation amplitude of the eddy viscosity during a wave cycle are found to be overestimated.

Introduction

Waves over a flat bed of sand often distort the bed into a ripple pattern if the critical bed shear stress for the initial motion of sediments is exceeded. These ripples significantly affect near-bed currents. The drift currents induced by waves are of great importance for coastal protection. Although this steady drift is weak compared with the oscillatory component of velocity, it has a significant effect on the transport of sediment and pollutant in the sea. Such currents affect the vertical profile of the residual current in the water column as a whole since the near-bed drift provides the bottom boundary condition for this profile. Longuet-Higgins (1953) has developed a theory for the mass transport produced by waves over a smooth bed in laminar flow. The solution of this model is characterised by a forward mass transport near the bottom. Laboratory tests have shown good agreement between theory and experiment in this case. Longuet-Higgins (1958) suggested that the mass transport velocity just outside the boundary layer above a smooth bed would be the same in turbulent flow as for laminar flow. Despite its engineering importance, rather little is known about wave-induced currents above rippled and very rough beds. Davies and Villaret (1999) have developed an analytical model of the wave-induced drift above rippled and very rough beds. However, the lack of experimental data does not allow to accurately know the range of validity of this model and the reliability of the model coefficients. The aim of this work is to bring new experimental data to improve the modelling of wave-induced currents above rippled beds.

1-Experimental set up

The experiments were carried out in a 9 m long and 0.80 m wide wave flume at the University of Le Havre. Surface gravity waves are generated by a piston at one end of the flume and absorbed by a beach at the other end. This device leads to a reflection coefficient less than 5% for present tests. The mean water depth was d=27 cm and the wave period T=1.08 s. In the test section, approximately 5 m far from the wave generator, artificial ripples were set. The porous feature of the bottom and the sediments in the flow are not taken into account in this study. The ripple profile, similar to that of natural ripples, is described by the parametric relationships (Sleath, 1984):

$$\begin{cases} x = \xi - \dfrac{h}{2}\sin(\dfrac{2\pi\xi}{L}) \\ y = \dfrac{h}{2}\cos(\dfrac{2\pi\xi}{L}) \end{cases} \tag{1}$$

where h is the ripple height (h=3 mm), L the wave length of the ripples (L=18 mm), ξ a dummy variable and (x,y) an orthogonal system with the x-axis lying on the average bottom along the direction of wave propagation. The y-axis is directed upwards and has an origin midway between crest and trough.

The test conditions are shown in table 1. In this table, H is the wave height, U_∞ the amplitude of the horizontal component of velocity just outside the boundary layer at the bed, a the orbital amplitude of fluid at the same place, k_s the Nikuradse roughness length, R the Reynolds number based on U_∞ and a: R= $U_\infty a/\nu$ where ν is the kinematic viscosity, and B the waves asymmetry parameter: $B=0.75ka/\sinh^2(kd)$ where k is the surface wavenumber. The mean water depth was d=27 cm and the wave period T=1.08 s for all of the tests. The values of U_∞ and a were calculated from the first order waves theory. The Nikuradse roughness length k_s of ripples was estimated with Swart (1976) formula:

$$k_s = 25\frac{h^2}{L}\ ; \tag{1}$$

this leads to k_s=12.5 mm for present tests. The fluid velocities were measured with a 4 W Argon laser Doppler anemometer in forward scatter mode. The measurement volume was 0.14 mm^3. For tests N°1 & 2, these measurements were carried out within a ripple wavelength, from the rippled bed up to outside the boundary layer, that is approximately up to one ripple wavelength above the mean bed level. For these two tests, the grid spacing was 1 mm in the horizontal direction, 0.25 mm in the ripple trough and 0.5 mm above in the vertical direction. For tests N°3 to 14, the velocity measurements were carried out at one point at the edge of the wave boundary layer.
The flow regime depends on the parameters R and a/k_s. The regime limits according to Davies (1980) are shown on figure 1. This figure allows to compare the experimental conditions of this study with those of previous studies concerning wave-induced currents above rough flat beds or rippled beds. Two-dimensional artificial ripples were used for the tests of Van Doorn and Godefroy (1978), Marin and Sleath (1994) and Mathisen and Madsen (1996). The tests of Villaret and Perrier (1992) were carried out with a mobile rippled bed and the tests of Brebner *et al*. (1966) and Klopman (1994) with a rough flat bed. Marin's (1999) study shows that for experimental conditions similar to present ones, the turbulence intensity varies like 1/y at sufficient distances from the bed for the tests with a Reynolds number greater than 1700, that is for test N°2 and tests N°7 to 14. In the following, we will study the relationship between the drift currents and a/k_s for these tests which will be considered in the rough turbulent regime (tests N°12 to 14) and close to the rough turbulent regime (tests N°1,2 and 7 to 11). The corresponding physical parameter for tests N° 3 to 6 (transitional regime) is the Reynolds number R.

2-The drift at the edge of the boundary layer

The figure 2 shows the results in the case of rough turbulent regime and close to the rough turbulent regime. The theoretical value obtained by Longuet-Higgins (1953) for smooth flat beds is also shown on this figure. For all the tests series, the drift at the edge of the boundary layer is lower than the one predicted by Longuet-Higgins ($\overline{U_\infty} c / {U_0}^2 = 0.75$ where c is the wave phase speed). Present tests show that this value of 0.75 is a peak value which is reached for $a/k_s \approx 2$. For $a/k_s \leq 2$, the momentum transfer is dominated by the eddy-shedding process. As a/k_s increases, the role of coherent vortex structures decreases while the importance of random turbulent fluctuations increases. Despite the dispersion of the results on figure 2, the evolution of $\overline{U_\infty} c / {U_0}^2$ with a/k_s can be modelled by two logarithmic laws. The equations of the corresponding straight lines on figure 2 are:

$$\frac{\overline{U_\infty} c}{{U_0}^2} = 1.58 \mathrm{Ln}\left(\frac{a}{k_s}\right) - 0.30 \qquad (\text{for } a/k_s < 2) \tag{2}$$

$$\frac{\overline{U_\infty} c}{{U_0}^2} = -1.75 \mathrm{Ln}\left(\frac{a}{k_s}\right) + 2.07 \qquad (\text{for } a/k_s > 2). \tag{3}$$

The figure 3 shows the results of the theoretical model of Davies and Villaret (1999) for the tests considered on figure 2. The drift at the edge of the boundary layer according to this model is given by:

$$\frac{\overline{U_\infty} c}{{U_0}^2} = \frac{3}{4}\left[1 + \frac{1}{2}\left(1 - \frac{1}{\sinh^2(kd)}\right)|\varepsilon_2| \cos\varphi_2\right] - \frac{1}{2}\frac{c}{U_0}|\varepsilon_1|\cos\varphi_1 \tag{4}$$

where $|\varepsilon_1|$, $|\varepsilon_2|$, φ_1 and φ_2 are coefficients which are linked to the formulation of the eddy viscosity K near the bed proposed by Davies and Villaret:

$$K = \frac{1}{2} K_0 \left[1 + \varepsilon_1 e^{i\theta} + \varepsilon_2 e^{2i\theta}\right]. \tag{5}$$

In this equation, θ is the wave phase function, $1/2K_0$ the constant term of K, ε_1 and ε_2 the complex coefficients: $\varepsilon_1 = |\varepsilon_1| \exp(i\varphi_1)$ and $\varepsilon_2 = |\varepsilon_2| \exp(i\varphi_2)$. The dominant peak of K within a wave period occurs for the following phase angle φ_1 :

$$\varphi_1 = -\arccos(B - \frac{\overline{U_\infty}}{U_0}) + \Delta\varphi \qquad (6)$$

with

$$\varphi_2 = 2\pi + 2\varphi_1 . \qquad (7)$$

The recommended value for $\Delta\varphi$ in equation (6) is: $\Delta\varphi$ =4°. The determination of φ_1 (equation (6)) requires the knowledge of $\overline{U_\infty}$. This significantly restricts the possibilities of use of the analytical model when the equations (2) and (3) allow a direct estimation of the drift at the edge of the boundary layer.

In the case of transitional regime, the figure 4 shows that the drift currents decrease as the Reynolds number R increases. For the low values of R, these currents are greater than the one obtained by Longuet-Higgins and for the high values of R, these currents are in the opposite direction of waves propagation. Tests N°3 to 6 and Brebner *et al.* (1966) tests show that the decrease of $\overline{U_\infty} c / U_0^2$ with R is logarithmic. The best fit with these data using a least-squares technique is given by the equations:

$$\frac{\overline{U_\infty} c}{U_0^2} = -0.60 \mathrm{Ln}(R) + 6.43 \qquad \text{(Brebner } et\ al.\text{)} \qquad (8)$$

$$\frac{\overline{U_\infty} c}{U_0^2} = -0.71 \mathrm{Ln}(R) + 4.82 \qquad \text{(tests N°3 to 6).} \qquad (9)$$

3-Vertical profiles of Eulerian drift

The vertical profiles of drift velocity for tests N°1 and 2 are shown on figures 5 and 6 respectively. These profiles represent a horizontal average over a ripple length of the drift data allowing to have a similar approach to the one used for rough flat beds. The theoretical profiles of Longuet-Higgins and Davies and Villaret are also shown on these figures. The values of Davies and Villaret's coefficients ($|\varepsilon_1|$, $|\varepsilon_2|$, φ_1, φ_2) are based on the experimental results of five laboratory studies which were carried out with rippled beds or rough flat beds. However, none of these studies allows to have vertical profiles of drift velocity representing an appropriately averaged mean velocity, i.e., a horizontal average on at least the scale of the bed roughness elements. This leads to a high uncertainty about the values suggested by Davies and Villaret for these coefficients. The tests N°1 and 2 which are characterised by a very fine spatial resolution of the velocity measurements over a ripple length allowed us to estimate these coefficients. The values obtained for $|\varepsilon_1|$ and $|\varepsilon_2|$ were 0.25 and 0.50 respectively for both tests when Davies and Villaret suggest $|\varepsilon_1|$=0.73 for test N°1, $|\varepsilon_1|$=1.30 for test N°2 and $|\varepsilon_2|$=1.3 for both tests. Present values of $|\varepsilon_1|$ and $|\varepsilon_2|$ are much lower than the ones proposed by Davies and Villaret, which means that the variation of K within a wave cycle is not as significant as these authors suggest. Figure 6 shows that the modification of these coefficients significantly improve the prediction of the drift profile for test N°2 (Davies and Villaret, modified coefficients). The improvement is less significant for test N°1 (figure 5); this is probably due to a particularly low value of the Reynolds number R for this test.

Conclusion

A study of the wave-induced currents above rippled beds has been presented. In the case of rough turbulent regime and close to the rough turbulent regime, present tests have shown that the drift at the edge of the boundary layer is lower or equal to the theoretical value proposed by Longuet-Higgins for smooth flat beds ($U_\infty c / U_0^2$=0.75; 1953). This value corresponds to a maximum which is reached for $a/k_s \approx 2$. A simple modelling allowing to estimate these currents above rippled and very rough beds at the edge of the boundary layer as a function of a/k_s is proposed. In the case of transitional regime, the drift at the edge of the boundary layer decreases in a logarithmic way as the Reynolds number increases.
The estimation of the vertical profiles of Eulerian drift in rough turbulent regime according to Davies and Villaret (1999) can be improved by decreasing the values of the model's coefficients ($|\varepsilon_1|$, $|\varepsilon_2|$) representing the variation amplitude of the eddy viscosity during a wave cycle. However, it would be necessary to carry out other tests to specify the range of validity of this result.

References

Brebner, A., Askew, J.A. and Law, S.W., 1966. The effect of roughness on the mass-transport of progressive gravity waves. *Proceedings of the 10th International Conference on Coastal Engineering, American Society of Civil Engineers*, 175-184.

Davies, A.G., 1980. Field observations of the threshold of sand motion in a transitional wave boundary layer. *Coastal Engineering*, **4**, 23-46.

Davies, A.G. and Villaret, C., 1999. Eulerian drift induced by progressive waves above rippled and very rough beds. *Journal of Geophysical Research*, **104**, C1, 1465-1488.

Klopman, G., 1994. Vertical structure of the flow due to waves and currents. *Progress Report H 840.30, Part II, Delft Hydraulics, Delft, The Netherlands*.

Longuet-Higgins, M.S., 1953. Mass transport in water waves. *Philos. Trans. R. Soc. London, Ser. A, 245*, **903**, 535-581.

Longuet-Higgins, M.S., 1958. The mechanics of the boundary-layer near the bottom in a progressive wave. *Proceedings of the 6th International Conference on Coastal Engineering, American Society of Civil Engineers*, 184-193.

Marin, F., 1999. Experimental study of the wave boundary layer over rippled beds. *Proceedings of the I.A.H.R. Symposium on River, Coastal and Estuarine Morphodynamics, Genova, Septembre 1999*, Vol. 2, 179-188.

Marin, F. and Sleath, J.F.A., 1994. Mass transport over rippled beds. *Sediment Transport in Coastal Environments and Rivers, Euromech 310, World Scientific*, 246-254.

Mathisen, P.P. and Madsen, O.S., 1996. Waves and currents over a fixed rippled bed, 2, Bottom and apparent roughness experienced by currents in the presence of waves. *Journal of Geophysical Research*, **101**, C7, 16543-16550.

Sleath, J.F.A., 1984. Sea bed mechanics. *Wiley-Interscience, New York*.

Swart, D.H., 1976. Coastal sediment transport. Computation of longshore transport. *Delft Hydraul. Lab. Rep. r968. Part 1*.

Van Doorn, T. and Godefroy, H.W.H.E., 1978. Experimental investigation of the bottom boundary layer under periodic progressive water waves. *Rep. M1362, part I, Delft Hydraul., Delft, Netherlands.*

Villaret, C. and Perrier, G., 1992. Transport of fine sand by combined waves and current: An experimental study. *Rep. HE-42/92.68, Electr. de France, Chatou*, 81 pp.

Test N°	H (mm)	U_∞ (m/s)	B	R	a/k_s
1	48	0.099	0.027	1691	1.36
2	92	0.190	0.052	6213	2.61
3	14	0.029	0.008	144	0.40
4	25	0.052	0.014	459	0.72
5	32	0.066	0.018	752	0.91
6	43	0.089	0.025	1357	1.22
7	52	0.107	0.029	1985	1.47
8	63	0.130	0.036	2913	1.79
9	74	0.153	0.042	4020	2.10
10	82	0.169	0.047	4936	2.32
11	91	0.188	0.052	6079	2.59
12	98	0.203	0.056	7050	2.79
13	107	0.221	0.061	8404	3.04
14	117	0.242	0.067	10049	3.33

Table 1. Test conditions.

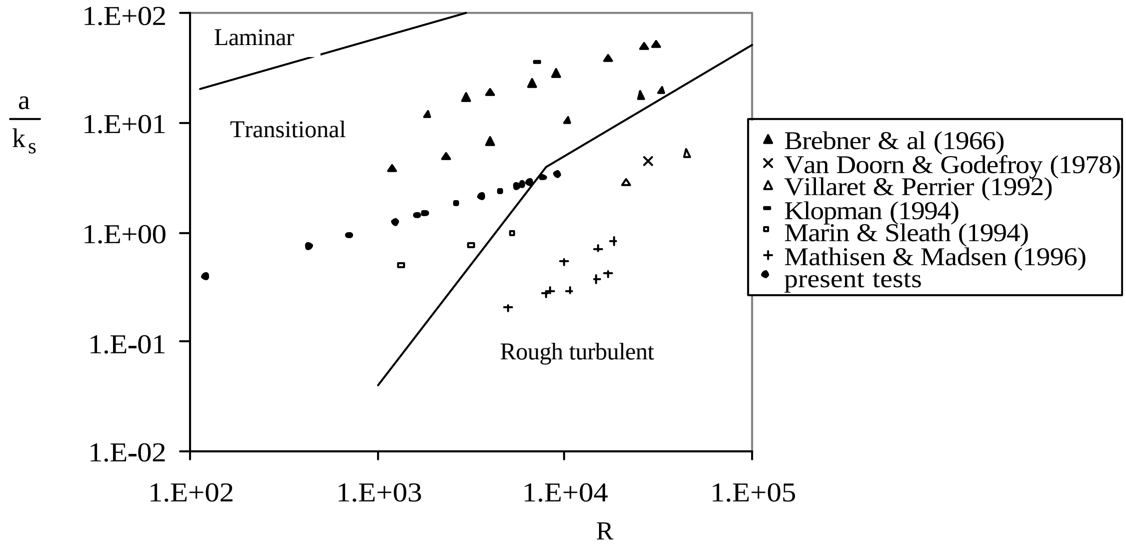

Figure 1. Delineation of flow regimes according to Davies (1980).

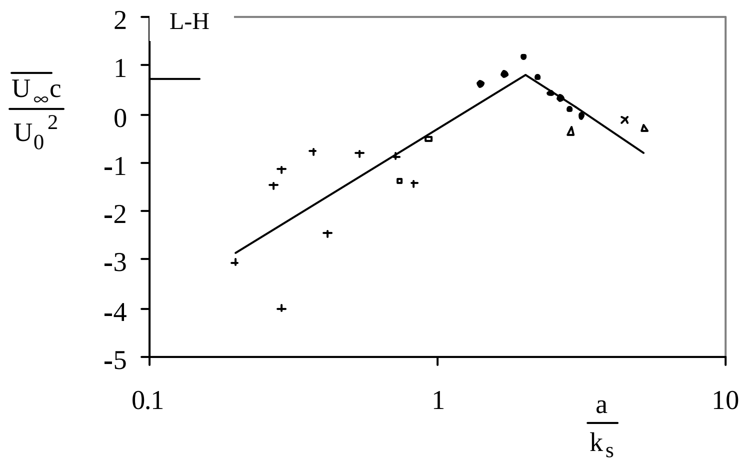

Figure 2. Nondimensional Eulerian drift ($\overline{U_\infty c} / U_0{}^2$) at the edge of the boundary layer in relation to a/k_s for the subset of data in rough turbulent regime and close to the rough turbulent regime. The definitions of the symbols are the same as in Figure 1; L-H=Longuet-Higgins.

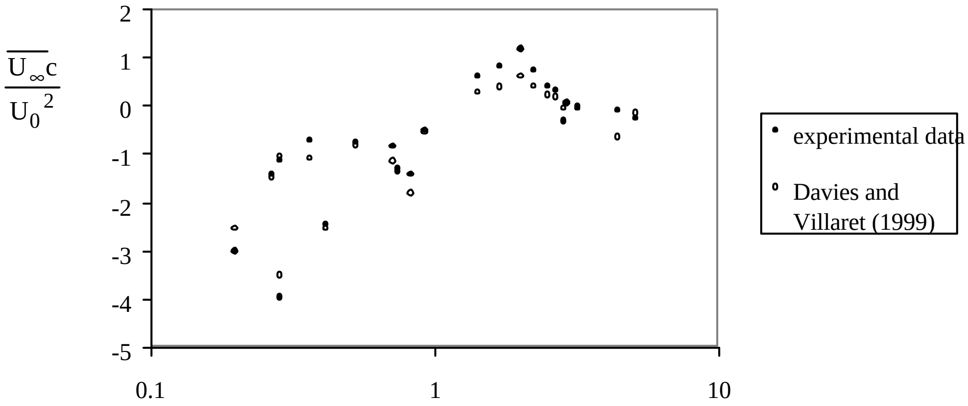

Figure 3. Comparison between measured and predicted (Davies and Villaret's (1999) model) Eulerian drift at the edge of the boundary layer for the subset of data in rough turbulent regime and close to the rough turbulent regime.

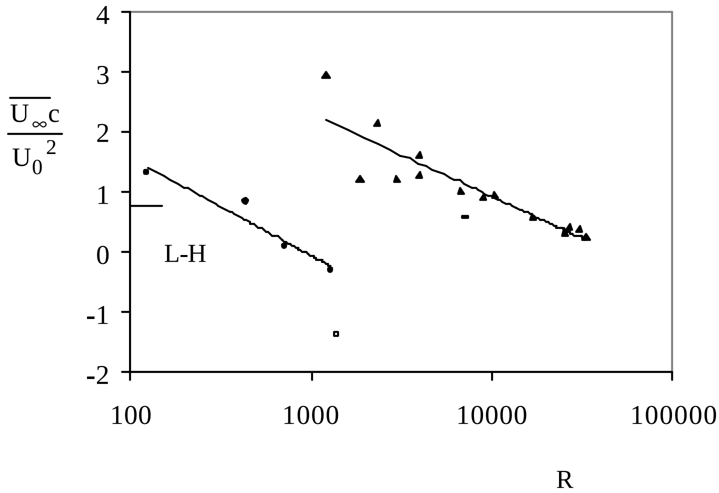

Figure 4. Nondimensional Eulerian drift ($\overline{U_\infty c}/U_0^2$) at the edge of the boundary layer in relation to R for the subset of data in transitional regime. The definitions of the symbols are the same as in Figure 1; L-H=Longuet-Higgins.

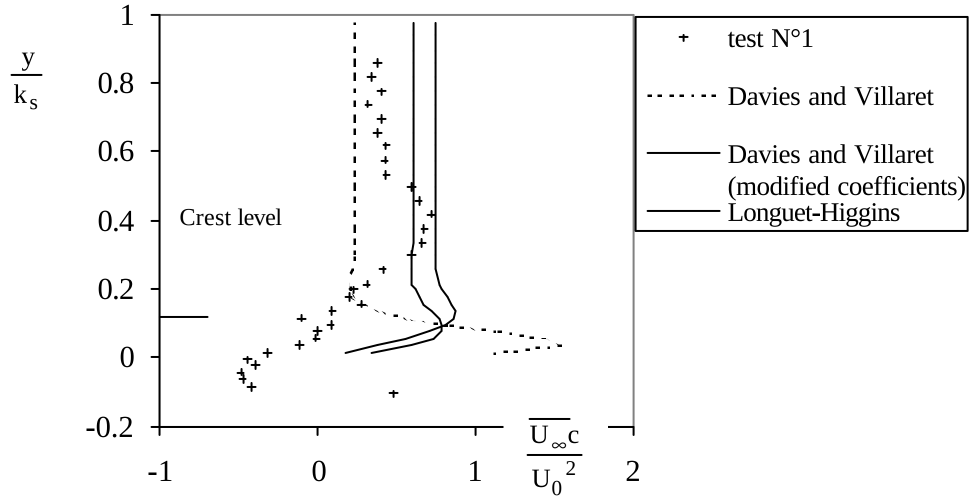

Figure 5. Vertical profiles of the nondimensional Eulerian drift (test N°1).

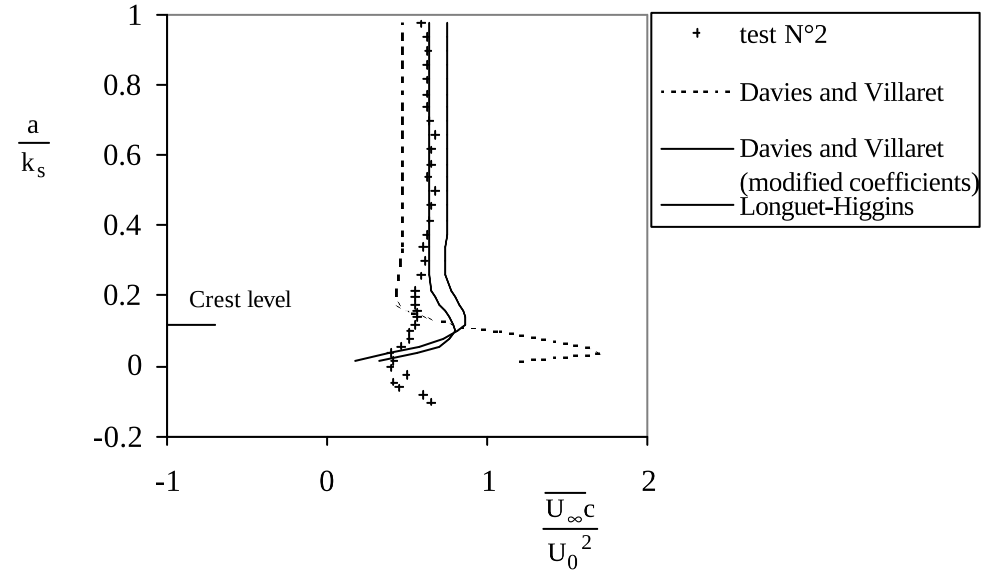

Figure 6. Vertical profiles of the nondimensional Eulerian drift (test N°2).