# CHAPTER 122

# WAVE INDUCED VELOCITIES AT
# A RUBBLE MOUND BREAKWATER

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## Abstract

An experimental study has been carried out concerning horizontal velocities induced by a regular wave acting on a rough permeable steep slope. Time-histories of vertical distributions of the horizontal component of local velocity observed for all the considered wave conditions have been compared with results from 1st and 2nd order wave theories. Further analysis has concerned water surface elevation, depth-averaged velocity and uniformity level of velocity profiles. For both local and global characteristics of velocity field, results from wave theories expected to apply are not in good agreement with experimental data. 1st order theory appears satisfactory for the shorter waves but departs significantly from data as the Ursell number increases.

## INTRODUCTION

Despite their importance in design of rubble mound breakwaters, kinematics of waves propagating along a steep slope has received little experimental attention (Tørum and Gudmestad 1990). On the contrary, a large amount of experimental data is available for the case of a wave propagating over a horizontal impermeable smooth bottom (e.g. Ragone 1983) or over a gentle slope (e.g. Iwagaki et al. 1974; Stive 1980). Due to the lack of data, no comparison between theoretical and experimental vertical distributions of velocity on a steep slope is available. In the last decade, interest for systematic experimental investigations has grown up due to the

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development of 1-D numerical models simulating the wave induced kinematic field along and inside a rubble mound breakwater (Kobayashi and Wurjanto 1990; van Gent 1993). Comparisons between 1-D model previsions and experimental values have been carried out for the case of regular waves spilling on a rough, impermeable mild (1:35) slope (Cox et al. 1995) while with regard to steep slopes, only not consistent comparisons between computed depth-averaged velocity, $U$, and experimentally observed values of the mean local velocity, $u$, are available (e.g. Tø rum and van Gent 1992). Moreover, 1-D numerical models have been extended to the formulation of a vertically 2-D shallow-water model (Bradley et al. 1996) and even to the reshaping simulation of a berm breakwater (Norton and Holmes 1992; van Gent 1995). The purpose of this paper is to present and discuss results from an experimental investigation concerning regular waves acting on a rough permeable steep slope. Data from this study are discussed from two complementary points of view. The first of them relates vertical distributions of the horizontal component of local velocity; the second one concentrates on the characteristics of some selected global quantities of the wave induced flow field which are provided by 1-D numerical models. In both cases comparisons are provided with wave theories which are expected to apply.

## EXPERIMENTS

Laboratory tests were carried out in a wave flume 35 m long and 0.75 m wide equipped with a piston-type wave maker generating regular waves. The water depth, constant along the flume, was equal to 0.50 m. The breakwater, with a 1:2 uniform slope, was composed of an armour layer $2D'_{n50}$ thick, with nominal diameter $D'_{n50} = 0.027$ m, a filter layer $6D''_{n50}$ thick, with $D''_{n50} = 0.015$ m, and an impermeable core (Fig. 1).

Wave conditions were selected in order to produce no damage or overtopping of the structure and breaking waves of surging type. Table I shows the considered wave conditions at the structure toe with $T$ and $H'$ being the wave period and the wave height (incident + reflected), respectively.

Water surface elevation, $\eta$, was contemporary measured by standard conductivity-type gauges at the structure toe and at the section where velocity measurements were taken. Time-histories of the vertical distribution of the horizontal component of the mean local velocity, $u$, at four sections along the slope ($x = 0.0$, 0.3, 0.4 and 0.5 m) were obtained placing a single micro-propeller at different depths.
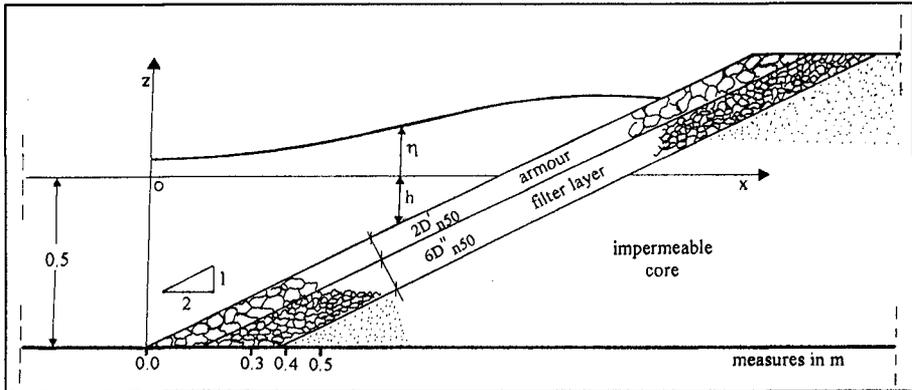
Figure 1 - Geometry of the tested structure and co-ordinate system.

The deepest point for velocity measurement was at 3.5 cm from the surface of the mound. Due to the use of a single micro-propeller, velocity measurements along the vertical were synchronised by superimposing measurements of free surface elevation at the considered section; synchronisation of velocity measurements at different sections was reached by superimposing measurements of $\eta$ at the structure toe. Velocity signals presented noise which was removed by a Butterworth lowpass digital filter. Finally, according to observations by Tørum and van Gent (1992) and Cox et al. (1994), a phase averaging was made in order to reduce the remaining small irregularities in the velocity time series.

TABLE I. Wave characteristics

| wave condition | symbol | $T$ (s) | $H'$ (cm) |
|:---:|:---:|:---:|:---:|
| 1 | o | 0.80 | 3.51 |
| 2 | ● | 1.50 | 4.91 |
| 3 | ☐ | 1.50 | 5.48 |
| 4 | × | 1.70 | 7.59 |
| 5 | ▲ | 1.25 | 3.10 |

## EXPERIMENTAL OBSERVATIONS AND THEORETICAL RESULTS

### Local Characteristics of the Velocity Field

Time-histories of the vertical distributions of the horizontal component of local velocity were obtained for all the five wave conditions at the four considered sections. All velocity distributions present values of $u$ with the same sign along the vertical. A time shift can be observed between the extreme values of the free surface elevation $\eta$ and those of $u$. Absolute values of $u$ at the passage of the wave through result systematically larger than the corresponding ones at the wave crest. Finally, the non-uniformity of the velocity profile depends on the wave characteristics; in particular, non uniformity increases for decreasing wave period.

Before introducing comparisons between experimental and theoretical velocity distributions, a selection of wave theories to consider was made, even if in a somewhat arbitrary and merely qualitative way, by evaluating the following dimensionless parameters (Le Méhauté 1976): relative water depth, $h / gT^2$, and relative wave height, $H / gT^2$, where $H$ = wave height, $h$ = water depth, and $g$ = acceleration due to gravity. Ursell number, $U_R = HL^2 / h^3$, with $L$ = wave length, related to the ratio of the convective inertia term to the local inertia one, was also considered. Table II reports the values of the three above mentioned dimensionless parameters for the considered experimental conditions.

TABLE II. Wave dimensionless parameters

| wave condition no. | | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| $h/gT^2$ | $x = 0.0$ m | 0.0796 | 0.0226 | 0.0226 | 0.0176 | 0.0326 |
| | $x = 0.3$ m | 0.0557 | 0.0158 | 0.0158 | 0.0123 | 0.0228 |
| | $x = 0.4$ m | 0.0478 | 0.0136 | 0.0136 | 0.0105 | 0.0195 |
| | $x = 0.5$ m | 0.0398 | 0.0113 | 0.0113 | 0.0088 | 0.0163 |
| $H/gT^2$ | $x = 0.0$ m | 0.0056 | 0.0023 | 0.0025 | 0.0026 | 0.0020 |
| | $x = 0.3$ m | 0.0072 | 0.0023 | 0.0018 | 0.0020 | 0.0032 |
| | $x = 0.4$ m | 0.0059 | 0.0021 | 0.0015 | 0.0017 | 0.0033 |
| | $x = 0.5$ m | 0.0057 | 0.0016 | 0.0013 | 0.0013 | 0.0031 |
| $U_R$ | $x = 0.0$ m | 0.2823 | 4.3470 | 4.8407 | 8.5617 | 1.4858 |
| | $x = 0.3$ m | 1.0551 | 9.4812 | 7.2463 | 13.6100 | 6.1511 |
| | $x = 0.4$ m | 1.3674 | 11.294 | 8.3772 | 15.3138 | 8.5275 |
| | $x = 0.5$ m | 2.2798 | 13.0164 | 10.3179 | 17.1729 | 11.5205 |

The range of experimental conditions include relative depths, $h / gT^2$, from 0.0398 to 0.0796 for wave condition no. 1 and from 0.0088 to 0.0326 for wave

conditions no. 2 to 5; relative wave height, $H/gT^2$, from 0.0056 to 0.0072 for wave condition no. 1 and from 0.0013 to 0.0033 for wave conditions no. 2 to 5; Ursell number, $U_R$, from 0.2823 to 2.2798 for wave condition no. 1 and from 1.4858 to 17.1729 for wave conditions no. 2 to 5. Thus, values of the three dimensionless parameters for wave condition no. 1 are significantly different from those attained in conditions no. 2 to 5. Specifically, wave motion no. 1 appears to be characterised by quasi-deep water conditions and by very small values of the Ursell number with respect to the other cases. On the basis of Fig. 2 (Le Méhauté 1976), for wave condition no.1, 2nd order and only marginally 3rd order theories apply; for the case of wave conditions no. 2 to 5, 2nd order theory should be taken into account. As a term of reference, also 1st order theory was considered in calculations.
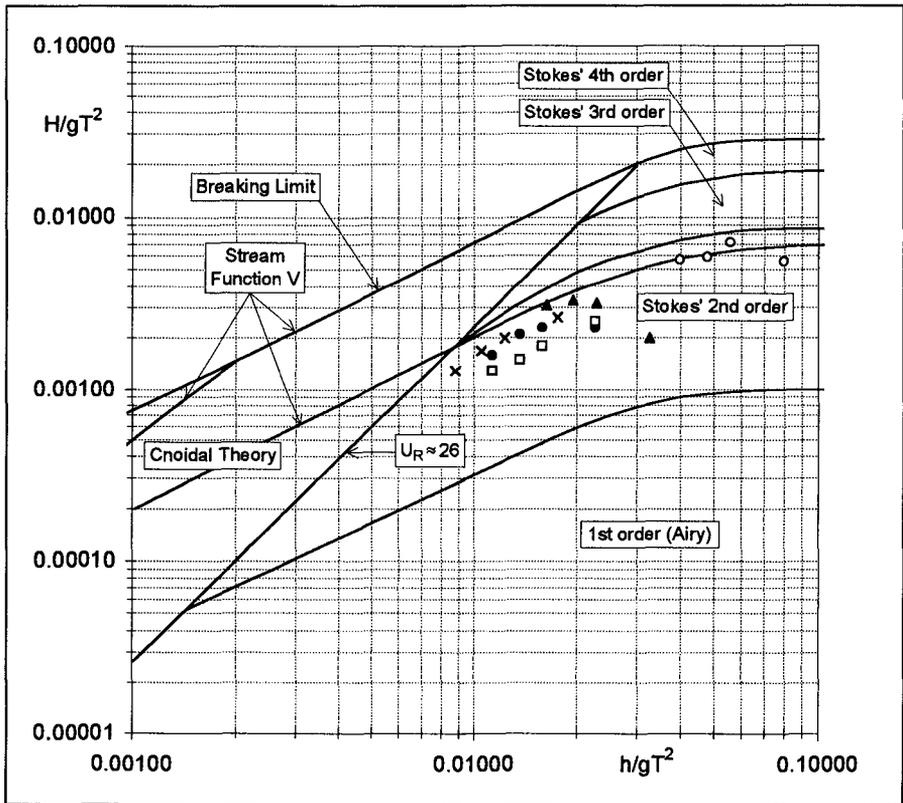


Figure 2 - Regions of validity for various wave theories and experimental conditions from the present study (modified from Le Méhauté 1976).

Comparisons have been carried out between observed and calculated velocity

distributions at some selected times counted in terms of $t^* = t/T$, with $t^* = 0$ corresponding to $\eta = \eta_{max}$ at the considered section. Figs. 3a and 3b refer to section $x = 0.3$ m and to wave conditions no. 2 to 5; in plots, $z$ is the vertical co-ordinate, positive upward with $z = 0$ at the armour surface. Fig. 3a shows the comparison between experimental and 2nd order theory velocity profiles, while in Fig. 3b 1st order theory results are considered. It is noted from these figures that nor the 2nd nor the 1st order theory is valid and that only small differences between them arise. Analogous results (not shown) are found at the other sections for wave conditions no. 2 to 5. On the contrary, with regard to wave condition no. 1, values from the 2nd and 1st order theories are practically indistinguishable and therefore in Fig. 4 only results from the 1st order theory are reported. A rather good agreement is found at section $x = 0.0$ m; further landward it gets slightly worse but it can be noticed that the 1st order theory well approximates the velocity profiles of wave condition no. 1.

As a preliminary result, it can be stated that the 1st order theory well simulates experimental velocity profiles characterised by a noticeable disuniformity and corresponding to a short period wave. Moreover, in accordance with the results of Le Méhauté et al. (1968) for a horizontal bottom, also for the case of a steep slope, the selection of the appropriate wave theory to describe the velocity field on the basis of relative water depth, $h / gT^2$, and relative wave height, $H / gT^2$, appears to be not completely reliable.

With regard to the wave kinematics field on a steep slope, more precise indications on the wave theory selection can be obtained by evaluating the influence of different terms like local inertia, convective inertia, wave reflection, energy dissipation due to surface roughness and flow in the mound. For wave condition no. 1, where $U_R$ ranges from 0.2823 to 2.2798, accordance between the 1st order theory and the experimental velocity profiles suggests the predominance of the local inertia term with respect to the others. This is probably due to the small wave period which determines a so rapid change in the kinematic characteristics in one section that the effect of different conditions in the adjacent sections can be considered negligible. For the case of wave conditions no. 2 to 5, where $U_R$ ranges from 1.4858 to 17.1729, other terms become more important than the local inertia one and there is no agreement with 1st and 2nd order theories. In other words, when in a given section the wave field characteristics vary very rapidly due to the small wave period, there is a minor influence of the contemporary changes in the adjacent sections.

The not large number of the examined experimental conditions and the lack of velocity measurements at the surface and close to the bottom give no possibility to
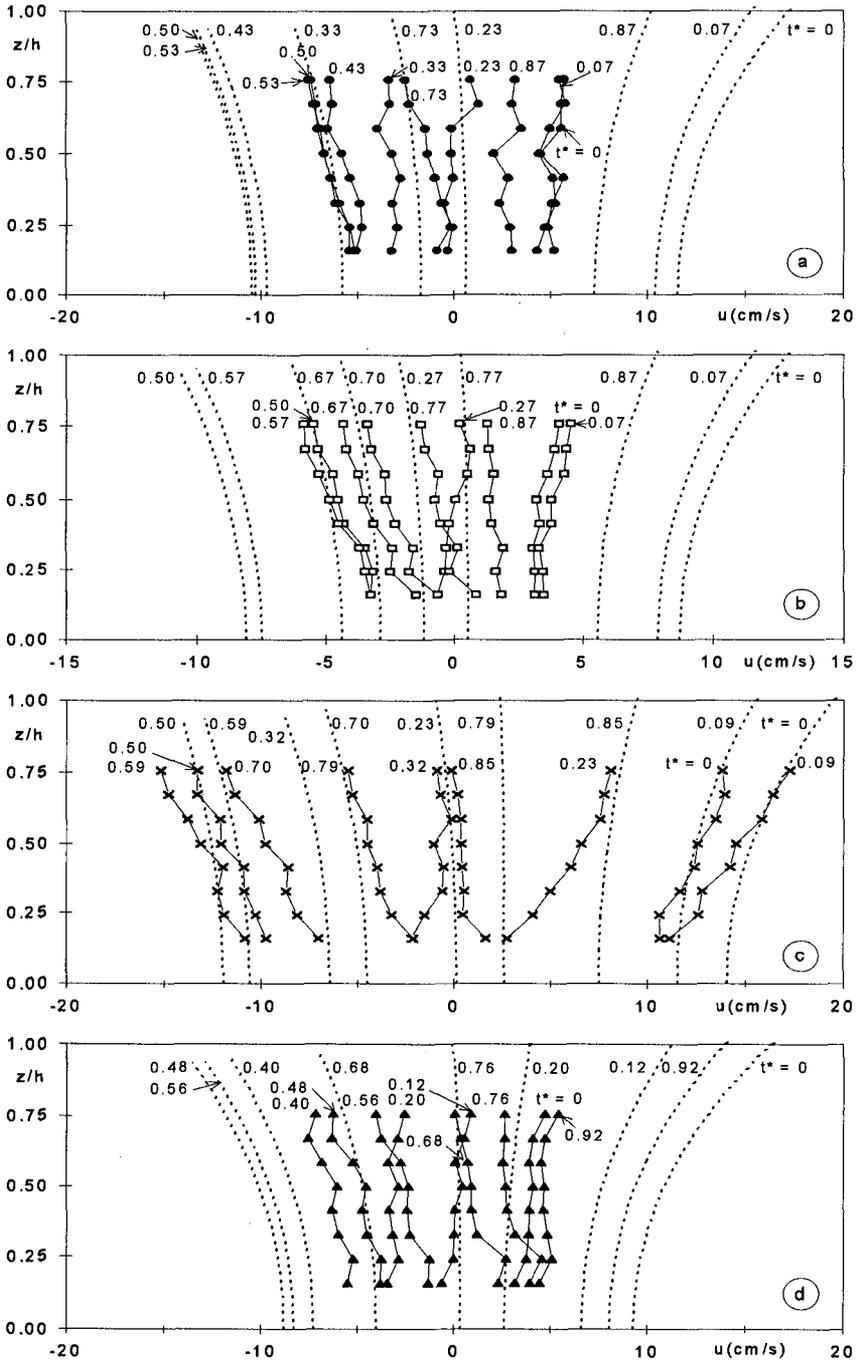
Figure 3a - Vertical distributions of the horizontal component of mean local velocity at section $x = 0.3$ m for wave condition: a) no. 2, b) no. 3, c) no. 4, d) no. 5 (dotted lines: 2nd order theory).
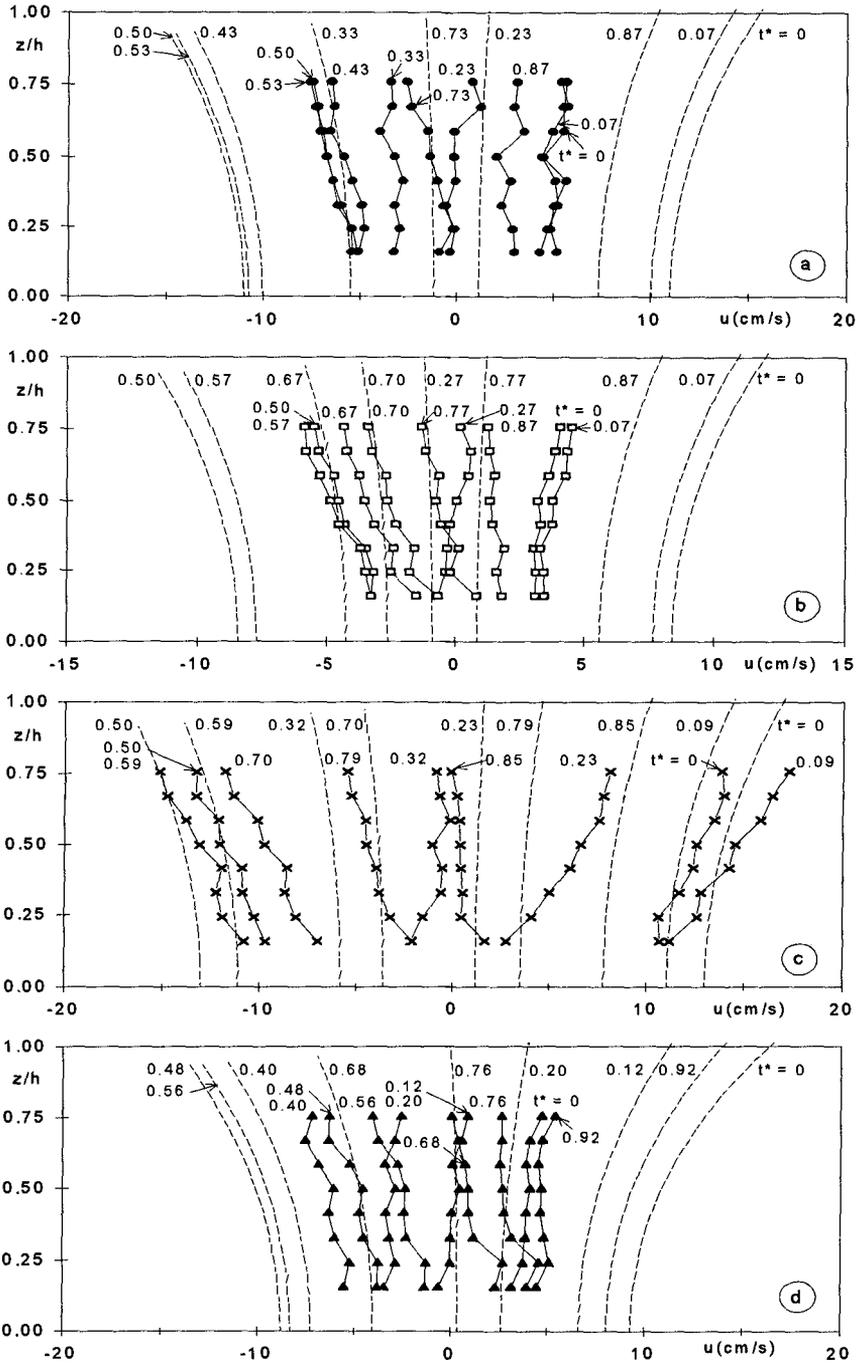
Figure 3b - Vertical distributions of the horizontal component of mean local velocity at section $x = 0.3$ m for wave condition: a) no. 2, b) no. 3, c) no. 4, d) no. 5 (broken lines: 1st order theory).
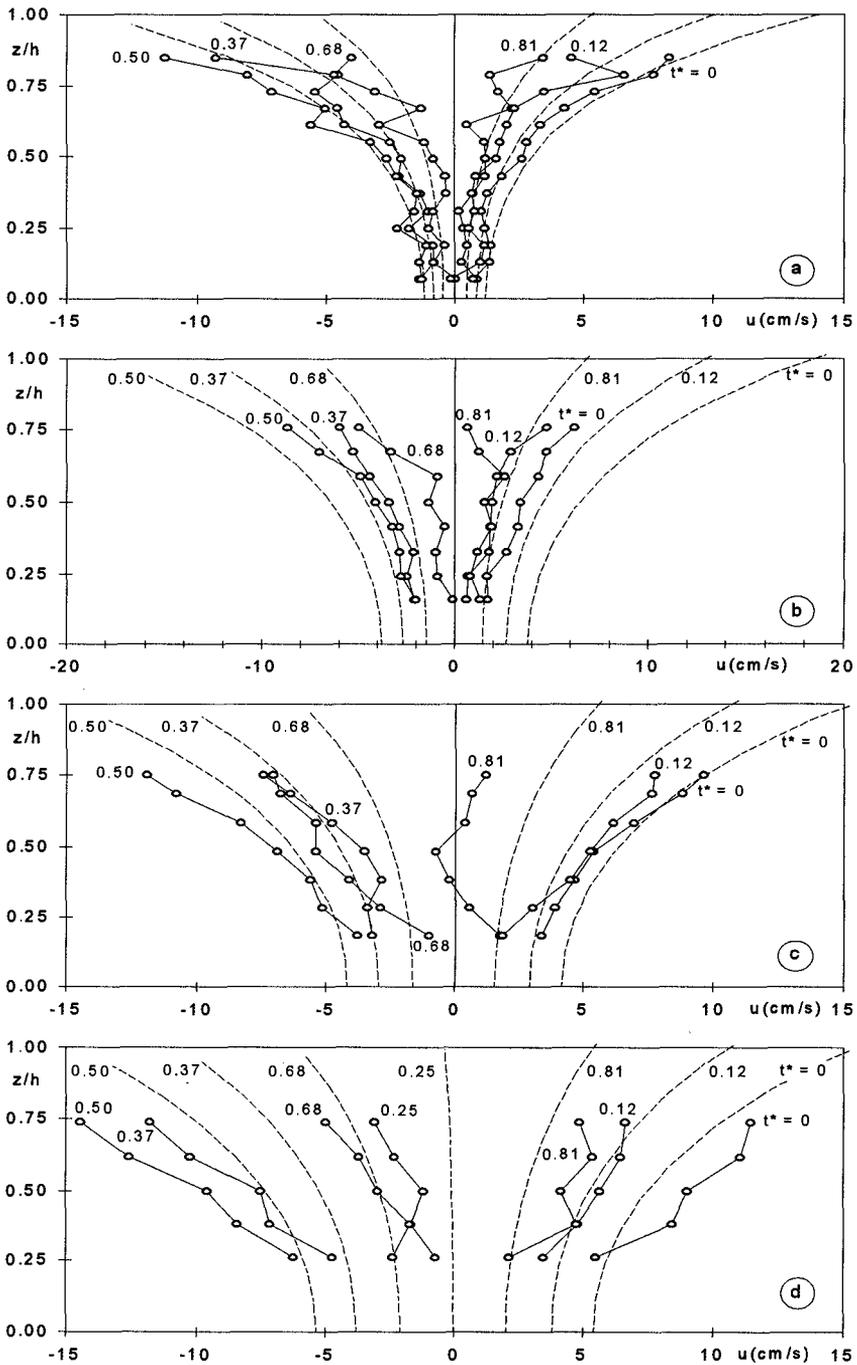
Figure 4 - Vertical distributions of the horizontal component of mean local velocity for wave condition no. 1 at section: a) $x = 0.0$ m, b) $x = 0.3$ m, c) $x = 0.4$ m, d) $x = 0.5$ m (broken lines: 1st order theory).

discuss further in terms of velocity profiles and makes not convenient to consider higher-order wave theories.

### Global Characteristics of the Flow Field

In the present section the discussion refers to global quantities of the flow field, provided by 1-D numerical models, such as water surface elevation, $\eta$, and depth-averaged velocity, $U$, defined as:

$$U = \frac{\sum_{i=1}^{n'} u_i \Delta z_i}{h + \eta} \tag{1}$$

where $n' = n + 2$, with $n$ being the number of the velocity measurement points along the vertical at the considered section. The extension of the experimental velocity profiles to the bottom and to the surface has been obtained by extrapolation. Because the momentum flux correction coefficient, $\beta$, is not defined when $U$ is close to zero, the variance, $\sigma^2$ (Brunone and Tomasicchio 1996) defined as:

$$\sigma^2 = \frac{\sum_{i=1}^{n'} (u_i - U)^2}{n' - 1} \tag{2}$$

must be introduced. It allows to describe the uniformity level of velocity profiles and to evaluate 1-D approximations during the whole wave period.

With regard to $\eta$, for all the considered cases, in agreement with Le Méhauté et al. (1968), also when a steep slope is considered, differences between experiments and theory are not as great as that for local velocities since the most significant feature, the wave height, is imposed by experiments. For wave condition no. 1, Fig. 5 presents the experimental and calculated (1st order theory) time-histories of $\eta$, $U$ and $\sigma^2$ through the wave period at the four different sections. Small differences and a moderate phase shift are observed between the experimental and calculated values of $U$. Maximum and minimum values of $U$ happen at the same time of the corresponding extreme values of $\eta$. In agreement with the experimental observations (Brunone and Tomasicchio 1996), the calculated time-history of variance $\sigma^2$ presents a bimodality with two relative maximum (minimum) values. At section $x = 0.0$ m, calculated variance of velocity profiles simulates rather well the experimental data; further landward, differences increase and approximation is not satisfactory even if the
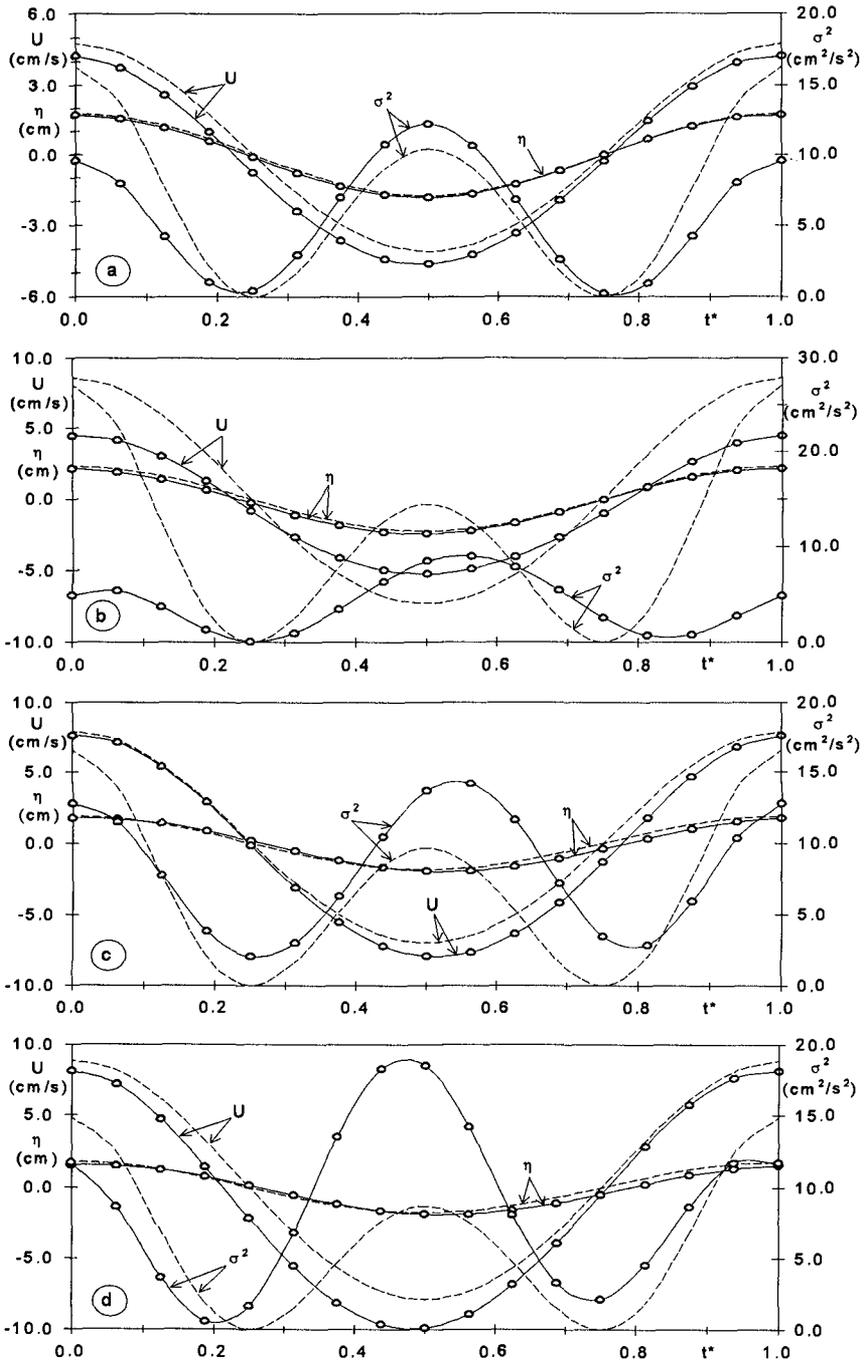
Figure 5 - Time-history of water surface elevation, depth-averaged velocity and variance of velocity profiles for wave condition no. 1 at section: a) $x = 0.0$ m, b) $x = 0.3$ m, c) $x = 0.4$ m, d) $x = 0.5$ m (broken lines: 1st order theory).
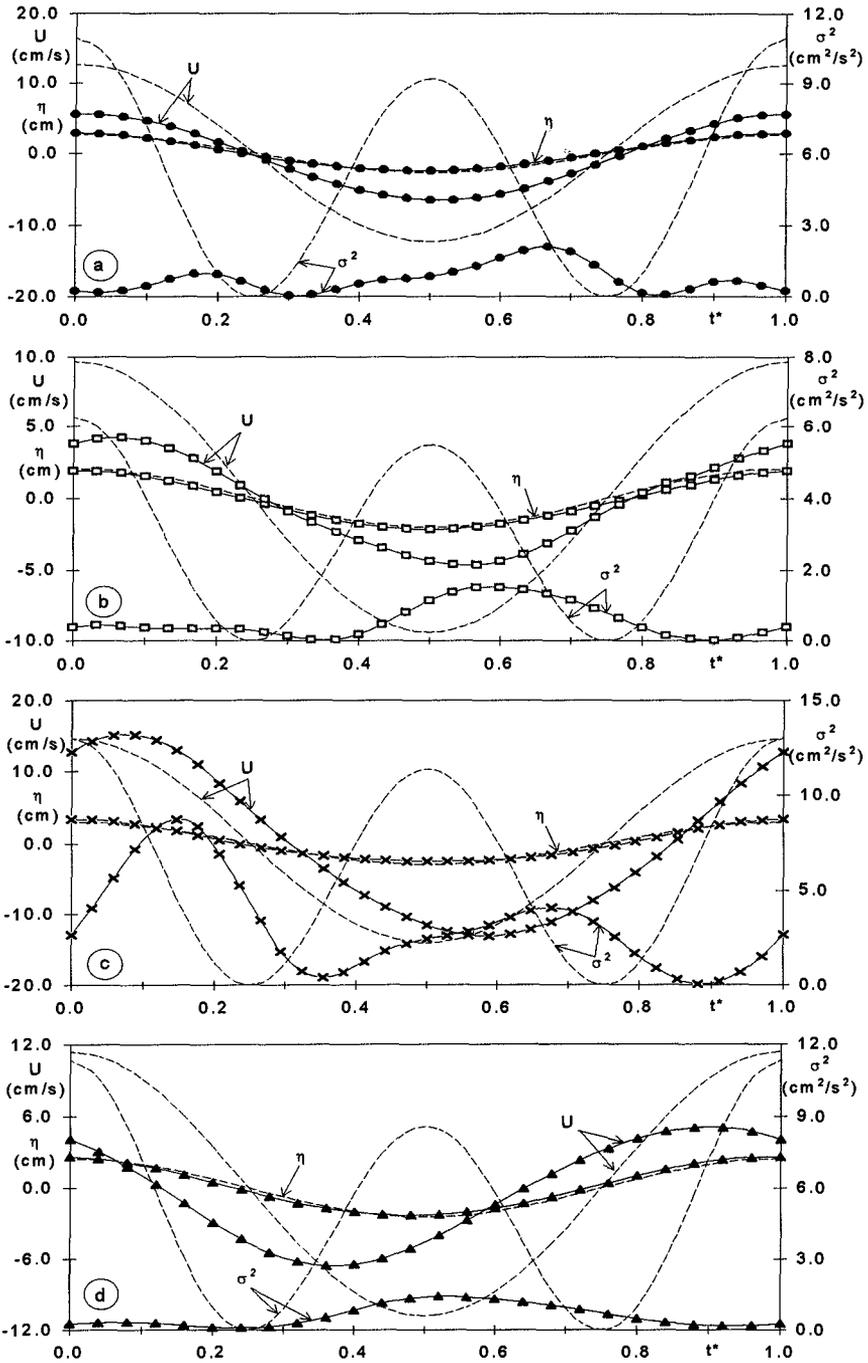
Figure 6 - Time-history of water surface elevation, depth-averaged velocity and variance of velocity profiles at section $x = 0.3$ m for wave condition: a) no. 2, b) no. 3, c) no. 4, d) no. 5 (broken lines: 1st order theory).

behaviour of the experimental values of the variance is certainly captured. Fig. 6 presents time behaviour of $\eta$, $U$ and $\sigma^2$ at section $x = 0.3$ m for wave conditions no. 2 to 5. Still the experimental and calculated values of $\eta$ are almost identical. This is not the case for the values of the depth-averaged velocity, for which differences are large and only a certain similarity in the shape can be found. Calculated time-histories of the variance present values much larger than the experimental ones and a very different shape.

## CONCLUSIONS

Water surface elevation and horizontal velocity profiles at some sections along a rough permeable steep slope were observed for different wave conditions. Two different groups of wave conditions were identified by evaluating relative water depth, relative wave height and Ursell number. For wave condition no.1, 2nd order and only marginally 3rd order theories are expected to apply; for the case of wave conditions no. 2 to 5, 2nd order theory should be considered. As a term of reference, also 1st order theory was taken into account in calculations. Accordance between experimental and calculated values of water surface elevation was found for all the cases. Only for wave condition no. 1, where $U_R$ ranges from 0.2823 to 2.2798, experimental and 2nd order theory velocity profiles show a satisfactory agreement and accordance is noticed also when 1st order theory is considered. Analogous considerations are valid for global characteristics of flow field such as depth-averaged velocity $U$ and variance of velocity profiles $\sigma^2$. For the case of a rough permeable steep slope, as a preliminary result of the study, it can be stated that wave kinematics is not correctly described by wave theories which are expected to apply considering only the values of relative water depth and relative wave height. Phenomena like wave reflection, energy dissipation due to slope roughness and flow in the permeable layer should be necessarily taken into account in description of wave induced kinematics on a steep slope.

**Acknowledgement**

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