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Effect of a submerged plate on the near-bed dynamics underincoming waves in deep water conditions

V. Rey*, J. Touboul, D. Sous

Mediterranean Institute of Oceanography, CNRS/INSU, UM 110, University of Toulon, Aix-Marseille University, SeaTech, l Av. G. Pompidou, BP 56 F-83162 La Valette du Var Cedex, France

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ABSTRACT

It is well known that wave induced bottom oscillations become more and more negligible when the water depth exceeds half the wavelength of the surface gravity wave. However, it was experimentally demonstrated for regular waves that the bottom pressure oscillations at both first and second wave harmonic frequencies could be significant even for incoming waves propagating in deep water condition in the presence of a submerged plate [16]. For a water depth h of about the wavelength of the wave, measurements under the plate (depth immersion of top of plate h/6, length h/2) have shown bottom pressure variations at the wave frequency, up to thirty times larger than the pressure expected in the absence of the plate. In this paper, not only regular but also irregular wave are studied together with wave following current conditions. This behavior is numerically verified by use of a classical linear theory of waves. The wave bottom effect is explained through the role of evanescent modes and horizontally oscillating water column under the plate which still exist whatever the water depth. Such a model, which allows the calculation of the velocity fields, has shown that not only the bottom pressure but also the near bed fluid velocity are enhanced. Two maxima are observed on both sides of the location of the plate, at a distance of the plate increasing with the water depth. The possible impact of such near bed dynamics is then discussed for field conditions thanks to a scaling based on a Froude similarity. It is demonstrated that these structures may have a significant impact at the sea bed even in very deep water conditions, possibly enhanced in the presence of current.

1. Introduction

Wave induced bottom pressure and velocities have been widely studied for both sediment motion and impact on structures (see e.g [8,15]). Pressure oscillations may have significant impact on the bed of poro-elastic behavior [17] and liquefaction may occur under pressure forcing [4]. Above a critical threshold, near bed velocities may lead to sediment motion and transport. The bed stability is then studied through either the mobility number or the Keulegan–Carpenter number in the presence of structures or bodies. Both numbers depend on the square of the bottom velocity amplitude.

It is well known that progressive wave induced bottom dynamics become more and more negligible when the water depth exceeds half the wavelength of the surface gravity wave. However, for partially standing waves, bottom pressure variations are observed at twice the wave frequency, due to non-linear wave–wave interactions [6]. If this process may explain the occurrence of microseisms, it cannot be at the origin of sediment motion since no near bed fluid velocity is predicted at second order.

For waves propagating in the presence of structures, depth discontinuities are at the origin of local or evanescent modes which are local solutions of the conservation equations. They play a significant role in the dynamics of water waves (wave phase and pressure fields, interference processes). For floating or submerged structures, a fluid oscillation which does not depend on the water depth is a solution of the motion under the structure. Both evanescent modes and this oscillating horizontal mode have to be taken into account in the calculation of the wave behaviour in the presence of such structures (see e.g. [9,11,14]). Unlike the propagating modes, the evanescent modes induced velocities do not vanish for deep water conditions.

If many studies have been carried out on wave–structure interactions, they focused on the wave–structure interactions and did not consider the bottom forcing for deep water conditions. This phenomenon was recently discussed by [16] for regular waves including deep water conditions for the incoming wave. The purpose of this work, which extends the work of [16] to both irregular waves and following current conditions, is twofold. In a first stage, experimental results concerning the bottom pressure distribution

* Corresponding author.
E-mail address: rey@univ-tln.fr (V. Rey).

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Table 1
List of experiments conducted for regular waves.

No.	1	2	3	4	5	6
T (s)	1.4	1.4	1.4	1.4	1.4	1.4
U (m/s)	0	0	0	0.3	0.3	0.3
a_i (mm)	44	54	65	33	42	52
kh	6.16	6.16	6.16	4.89	4.89	4.89
ε	0.09	0.11	0.13	0.054	0.068	0.085

Table 2
List of experiments conducted for irregular waves.

No.	1	2	3	4
T_p (s)	1.4	1.4	1.4	1.4
U (m/s)	0	0	0.3	0.3
H_{Si} (mm)	35	62	28	52

are presented for both regular and irregular incoming waves in deep water conditions with or without current. They are compared to a potential model for linear waves applied to the case without current. In a second stage, water depth influence on bottom pressure and velocity fields are calculated. Discussions on the water depth influence on the near bed dynamics are then carried out for realistic conditions thanks to Froude similarity.

2. Experimental setup and measurements

2.1. The BGO FIRST wave basin

Experiments were carried out in the Ocean Engineering Basin (BGO) FIRST, Toulon, France. It is designed to conduct ocean and coastal engineering model studies. Its useful length is 24 m, its effective width is 16 m. Water waves can be generated by means of a surface wave-maker covering the entire width of the basin. In the present experiments, water depth is $h = 3$ m, both wave alone ($U = 0$ m/s) and wave following current ($U = 0.3$ m/s) conditions are considered. The wave period is $T = 1.4$ s for the regular waves. The studied amplitudes a_i are respectively 44, 54 and 65 mm for $i = 1$, 2, 3 for $U = 0$ m/s, and respectively 33, 42 and 52 mm for $i = 4$, 5, 6 for $U = 0.3$ m/s. The corresponding dimensionless wavenumbers with respect to the water depth kh and wave steepness $\varepsilon = ka_i$ are given in Table 1.

For the irregular wave tests, Jonswap spectra are generated, of peak period $T_p = 1.4$ s with an enhancement factor $\gamma = 3.3$. The significant wave heights and amplitudes are respectively $H_{S1} = 2a_{S1} = 35$ mm and $H_{S2} = 2a_{S2} = 62$ mm for $U = 0$ m/s, $H_{S3} = 2a_{S3} = 28$ mm and $H_{S4} = 2a_{S4} = 52$ mm for $U = 0.3$ m/s. The list of experiments carried out is given in Table 2. In the presence of current, the wave generation was initiated 120 s after the current. The structure considered was constituted by a 1.53 m long plate (located between abscissa $X_1 = 0$ and $X_2 = 1.53$), of thickness 0.1 m (top-side immersion below the still water line $h_t = 0.5$ m, bottom-side immersion depth $h_b = 0.6$ m). To minimize three dimensional effects, the plate extended over the complete width of the basin. This structure was used in this configuration in a former work [14] for the study of the hydrodynamic interaction with gravity waves.

2.2. Instrumentation

The synchronous instrumentation is composed of 18 wave probes (WG_n), $n = 1, \ldots, 18$ and 16 pressure sensors (PS_n), $n = 3, \ldots, 18$, indices n correspond to increasing values of X. Locations of the plate and of the sensors are presented in Fig. 1. The wave probes are resistive sensors, manufactured by HR Wallingford. They deliver a 10 V signal, allowing a precision of 10^{-3} m. The pressure sensors are piezo-resistive sensors, manufactured by STS. The full scale of measurement ranges from 0 to 400 mbar. Resolution of the pressure sensors is 0.2 mbar. The positions of WG 1–18 and PS 3–18 are given in Table 3. As mentioned above, $X = 0$ corresponds to the upstream end of the plate.

2.3. Measurement techniques

The instruments are synchronized at a 32 Hz sampling rate. Data analysis was achieved through Fourier analysis for both mean field and wave induced dynamics. Irregular waves are considered as a linear superposition of Airy waves of amplitude a_i and frequency f_i. The discrete energy density spectra (EDS) for the waves can be defined by $E(f_i) = \frac{1}{2}a_i^2(f_i)$ (in m^2/Hz). The smooth estimate of the spectral density function $W(f_i)$ is then

$$W(f_i) = \frac{1}{2m+1}\sum_{j=-m}^{j=+m} E(f_{i+j}) \tag{1}$$

where $m = 10$ for the present study.

On the basis of synchronized measurements in the presence of current [2,12], either a two-wave gauge or a three-wave gauge method can be used to calculate the rate of standing wave. In the absence of current, the algorithms reduce to those of Goda and Suzuki [3] for the method of two probes and to those of Mansard and Funke [7] for the method of three probes. For the cases considered in the present study, the wave reflection from the beach was found negligible, under 3% in terms of energy, small enough to be neglected in the numerical calculations. Indeed, in the case of regular waves, the reflection coefficient from the beach in the absence of current is of about 1% and the total reflection coefficent upwave the plate, calculated from WG 1 to 3, was 13% for $T = 1.4$ s (see [16]). For the irregular wave cases, the overall beach reflection was also found to be weak. In the presence of current, the beach reflection is smaller.

3. Analytical model

Calculations are carried out for regular waves alone without any current in the vertical plane xOz, z vertical upwards. For irregular wave cases, a linear superimposition of the frequency components is assumed for the wave spectrum. The fluid domain is divided in four sub-domains, two of them corresponding to $X < 0$ and $X > 1.53$ m (respectively up-wave and down-wave the plate), the two others to $0 < X < 1.53$ m (respectively above and under the plate). The solution is obtained by use of the classical integral matching method of both pressure and fluid velocities at vertical boundaries between sub-domains (see e.g [10]).

3.1. Velocity potential

In the linear problem, a general expression of the velocity potential is defined for each sub-domain. In the presence of a free surface at $z = 0$, general expressions of the velocity potential are the sum of two propagating modes in the X-axis direction, of wavenumber k, and an infinity of evanescent modes, of "wavenumber" k_n:

$$\Phi(x, z, t) = \phi(x, z)e^{i\omega t} \tag{2}$$

$$= \left[A^{\pm}e^{\pm ikx}\chi(z) + \sum_{n=1}^{\infty} B_n^{\pm}e^{\pm k_n x}\psi_n(z)\right]e^{i\omega t} \tag{3}$$

The z-dependence of velocity potential is of the form $\chi(z) = \cosh(k(z+h))$ for the propagating modes and