CHAPTER 184

Wave Forces on Armor Blocks

by

M.A. Losada*, R. Medina* and M. Alejo**

ABSTRACT

Experimental measurements of hydrodynamic forces on a cubic block near the bottom under solitary waves were carried out. Horizontal and vertical forces were recorded and instantaneous and averaged values of hydrodynamic coefficients C_D, C_M and C_L for different boundary conditions, gap between block and bottom, e, and two or three-dimensional flow, were obtained. Horizontal and vertical forces were found to depend strongly on e/D, where D is the block side . Instantaneous values of hydrodynamic coefficients vary considerably during the wave passage and differ appreciably from the averaged coefficients.

* Universidad de Cantabria. Spain.

** Universidad Politécnica de Las Palmas. Spain.

INTRODUCTION

In the last decades great efforts have been done to understand the causes of failure of sloped breakwaters with special attention to the "lift-out" of armor units from the slope by the uprush-downrush flow. Most of the research work has been oriented to evaluate the flow conditions on the slope. Minor contributions have been made in the analysis of pressure distribution around the block or resultant forces on the block. Recently Kobayashi et al., 1985, studied the stability conditions against sliding and lifting of rip-rap, expressing drag, inertia and lift forces in function of drag, C_D, inertia, C_M and lift, C_L, coefficients. This analysis similar to others presented in the past is a force equilibrium, based on Morison's equation.

The lift-out of armors (particularly in the case of cubes) generally starts with a rotation around a point or axle as experimentally may be checked. The moment equilibrium equation for an armor unit neglecting reactions by friction or interlocking and considering the flow forces applied in the gravity center of the block, can be expressed as follows:

$$W_s = \frac{1}{2} \rho_w C_D D^2 u^2 \, [(1 + 2 \frac{C_M}{C_D} D \frac{du/dt}{u^2} + \frac{C_L}{C_D}) \qquad (1)$$

where W_s is the armor weight and u and du/dt the flow velocity and flow acceleration respectively.

Thus, if the flow characteristics (u and du/dt) and the hydrodynamic coefficients, C_D, C_M and C_L are known, the behavior of an isolated block under waves may be predicted. Kobayashi et al., 1985, used a similar equation in their rip-rap stability prediction, and adopted constant values of the hydrodynamic coefficients for all the wave cycle.

To study the evolution of the forces and the values of the hydrodynamic coefficients under a wave cycle a set of experiments in a wave flume were run. In the following, a general description of the experimental work and of the test results is given. It is clearly shown that boundary conditions strongly affect the evolution of forces on the block and that the values of the hydrodynamic coefficients vary considerably during the wave cycle.

EXPERIMENTAL WORK

The hydrodynamic behavior of isolated cubic units under wave action was analyzed. Smooth cubic blocks with side length, D = 5 cm, were subjected to the action of

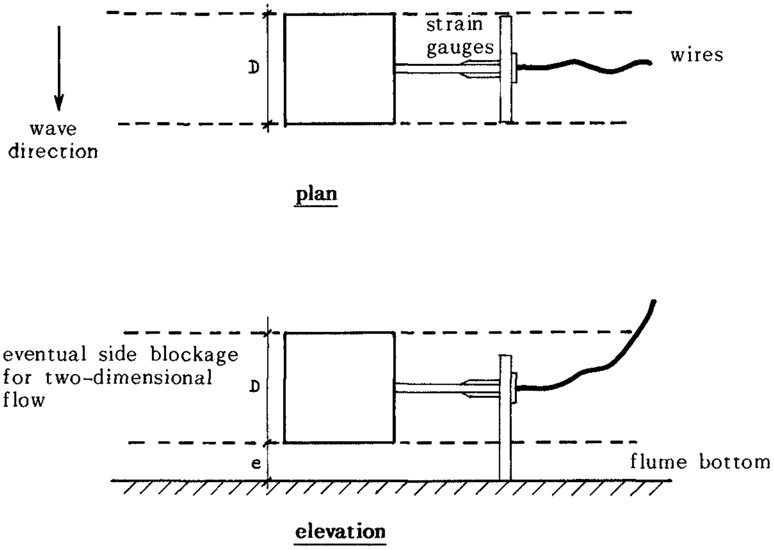

Fig. 1.- FORCE MEASURING DEVICE

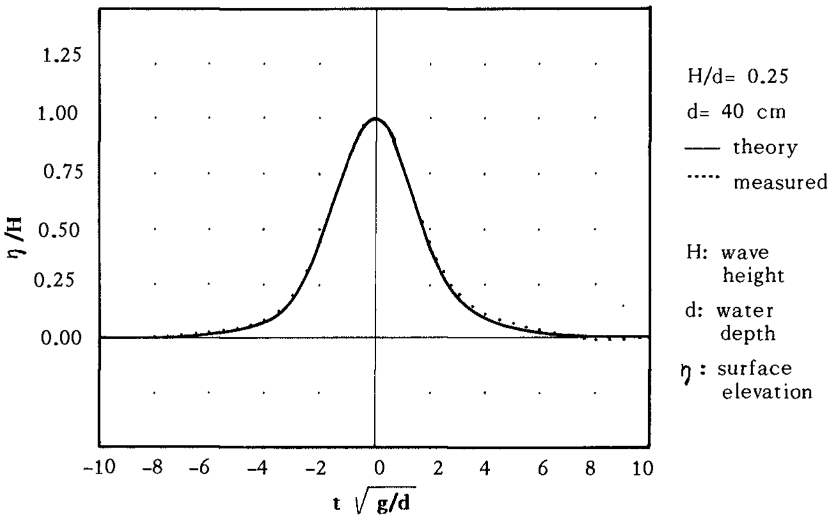

Fig. 2.- SOLITARY WAVE

solitary waves for the following conditions

e/D = approx. 0.0, 0.02, 0.1, 0.2 and 0.4

where e = gap between cube and bottom (see fig. 1). Due to the force measuring technique the case of block resting on the flume bottom was not sealed. Some pressure transmission under the block might had occur, "therefore" the indication approx. 0.0.

The type of waves considered were solitary waves (fig. 2). The distance of the test section to the paddle was approximately 45 m and the wave height varied in the range 2 < H(cm) < 20, thus $10^3 < Re < 10^5$, where $Re = uD\rho/\mu$ is a Reynolds number, μ = dynamic viscosity. The flow velocity was not recorded during the tests.

The cubes were placed horizontally and parallel to the main axes of the flume (fig. 1). Different test conditions were used, varying e, and establishing two or three-dimensional flow by incorporating the cubic block as a section of a square prism or not.

In all cases, cube size and gap were small when compared with water depth, in order to neglect the influence of the free water surface, and to allow the consideration of horizontal flow velocity.

Measurements of horizontal and vertical forces were made with pairs of strain gauges (see fig. 1). Maximum deviation expected in vertical and in horizontal force measurements is about seven per cent.

THREE-DIMENSIONAL FLOW UNDER SOLITARY WAVES

Figures 3, 4 and 5 show horizontal and vertical measured forces under a solitary wave for three cases: $e/D \approx 0$, 0.1 and 0.4 respectively. The most relevant characteristics are:

(1) The horizontal forces attain their maxima under the wave crest and take negative values (opposite to that of wave motion) associated to flow deceleration.

(2) Vertical forces are negative first (down to the bottom) and then positive for $e/D \neq 0$.

(3) For $e/D \approx 0$ vertical forces are always positive, showing two or more peaks. The first one is commonly much higher.

(4) For $e/D \geq 0.4$ the influence of the gap (indicated by the vertical force variation and magnitude) may be neglected.

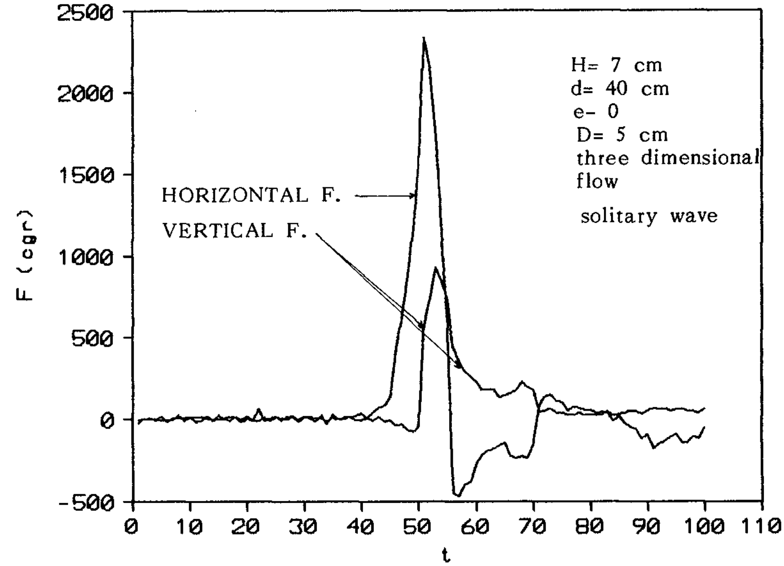

Fig. 3.- HORIZONTAL AND VERTICAL FORCES e/D- 0 . Free cube.

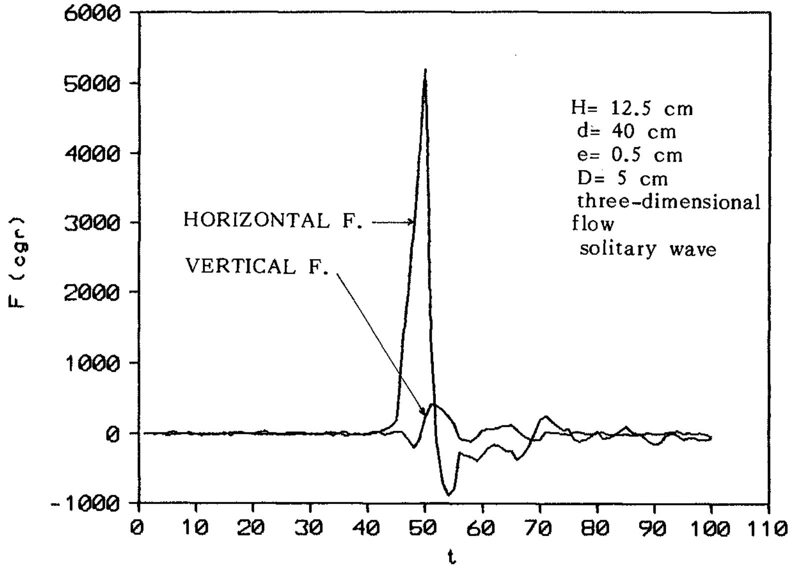

Fig. 4.- HORIZONTAL AND VERTICAL FORCES e/D = 0.1 . Free cube.

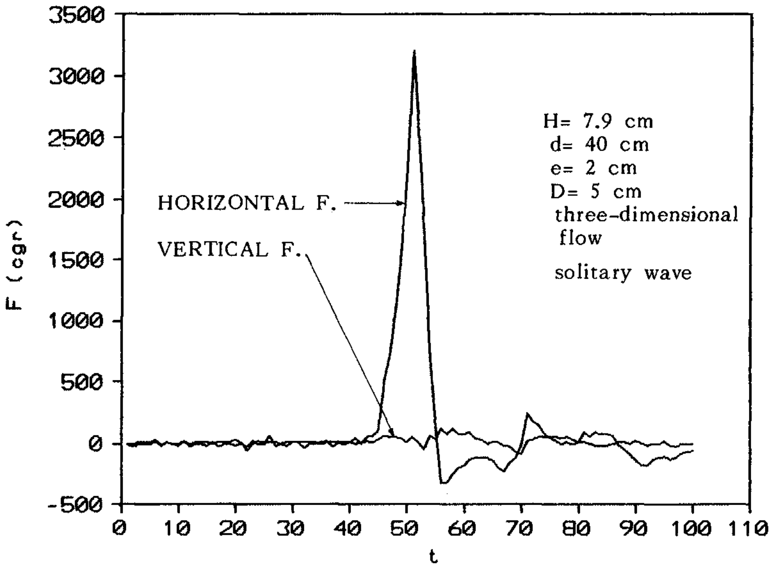

Fig. 5.- HORIZONTAL AND VERTICAL FORCES
e/D= 0.4 . Free cube.

TWO-DIMENSIONAL FLOW UNDER SOLITARY WAVES

Figures 6 and 7 show horizontal and vertical measured forces under a solitary wave for e/D = 0.1 and 0.4 respectively. The most relevant characteristics are:

(1) Maximum vertical and horizontal forces are almost in phase.

(2) Vertical forces are always larger than for three dimensional flow and present two or more peaks.

INSTANTANEOUS AND AVERAGED VALUES OF C_D, C_M AND C_L

Following Sarpkaya and Isaacson, 1981, from the measured horizontal forces the instantaneous values of C_D and C_M were obtained, solving from a set of Morison-type equations at two consecutive instants assuming that C_D and C_M remain constant in the time interval. Figure 8 shows C_D and C_M with the wave passage for e/D = 0.1. Several observations can be made, which agree with those given by Sarpkaya and Isaacson, 1981, for cylinders

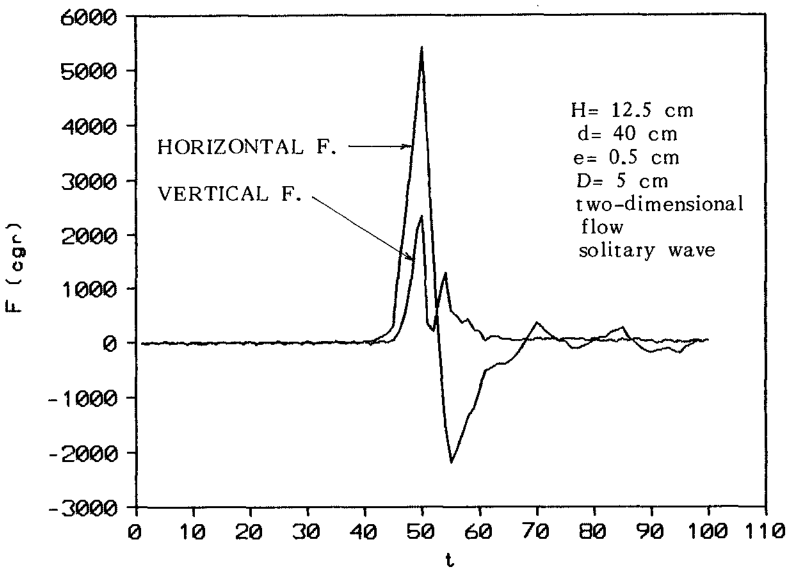

Fig. 6.- FORCES FOR TWO-DIMENSIONAL FLOW e/D= 0.1 . Cube as a part of a prism.

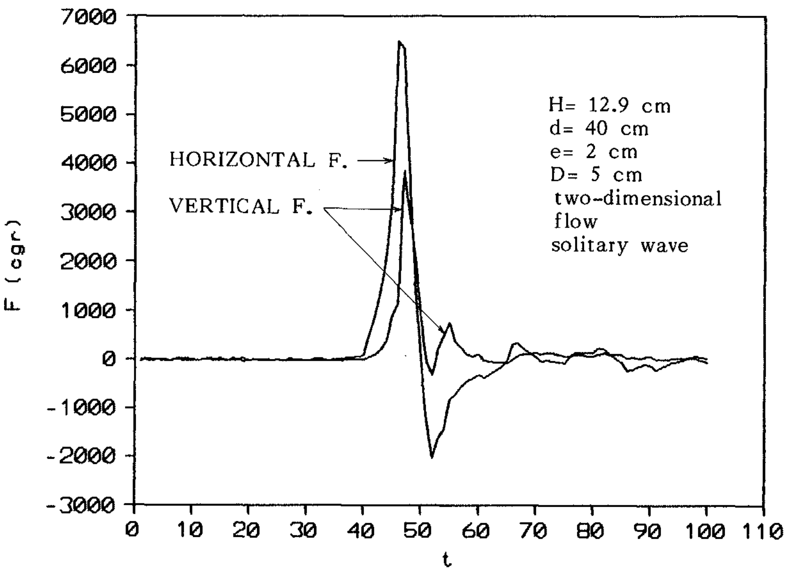

Fig. 7.- FORCES FOR TWO-DIMENSIONAL FLOW e/D= 0.4 . Cube as a part of a prism.

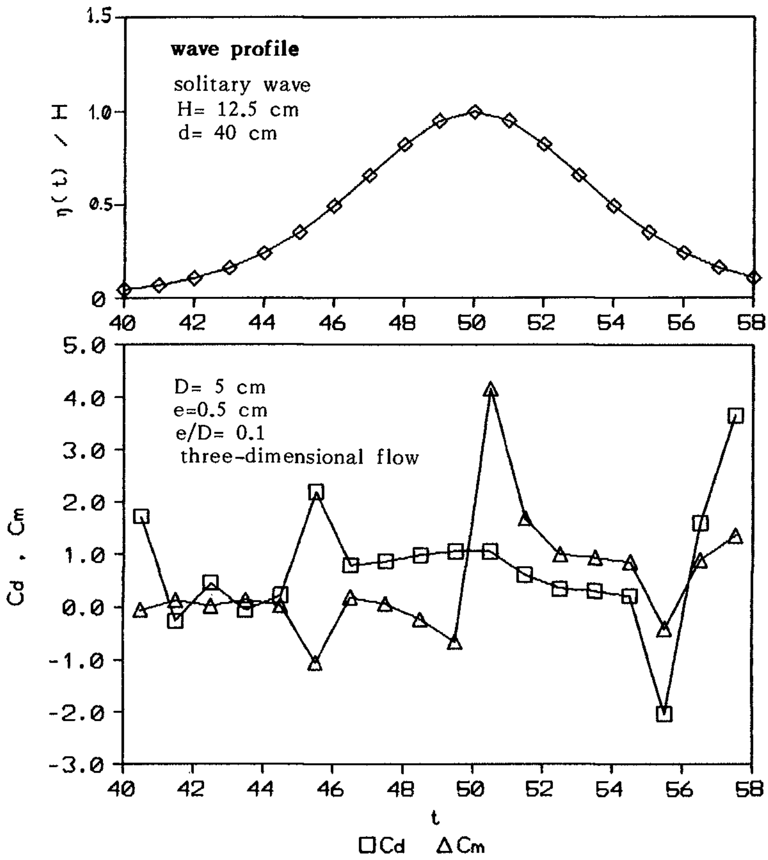

Fig. 8.- INSTANTANEOUS COEFFICIENTS Cd AND Cm

under oscillatory flows.

(1) The averaged C_M is less than unity and the added mass coefficient, C_a, is then negative, as $C_a = C_M - 1$.

(2) Neither C_M, C_D nor C_L are symmetrical with respect to the wave crest, showing a difference between accelerated and decelerated flow.

(3) C_M, C_D and C_L exhibit relative large variations during the wave passage.

From test results average hydrodynamic coefficients C_D, C_M and C_L were obtained. The average values of C_D, C_M and C_L were obtained through the use of the method of least squares by minimizing the square error between the measured and calculated forces. For a solitary wave 12.5 cm high, e/D = 0.5 and three-dimensional flow, the following values were calculated:

$$C_D = 0.65 \qquad C_M = 0.87 \qquad C_L = 4.7 \cdot 10^{-2}$$

When comparing these values with the instantaneous ones shown in fig. 8 it can be concluded that the former differs considerably from the latter.

CONCLUSIONS

In the present study an experimental investigation on wave forces exerted on an isolated armor unit was conducted. The experimental results lead to the following conclusions.

(1) The behavior of the instantaneous horizontal and vertical forces under solitary waves depend on e/D ratio, the relative distance from the block to the bottom. For $e/D \neq 0$ both the horizontal and vertical forces present a positive and a negative peak. For $e/D \approx 0$ the vertical force is always positive.

(2) The maximum positive forces for $e/D \neq 0$ and three-dimensional flow are out of phase. For $e/D \approx 0$ both forces are in phase, as well as for two-dimensional flows.

(3) The instantaneous hydrodynamic coefficients C_D, C_M and C_L vary considerably during the wave passage and differ appreciably from the averaged coefficients.

ACKNOWLEDGEMENTS

This research has been partially supported by the Comisión Asesora Cientifica y Técnica, project nº PA85-0176 and partially by the Dirección General de Puertos y Costas, M.O.P.U.

REFERENCES

Kobayashi, N. and B.K. Jacobs. Rip-rap stability under wave action. The Journal of Waterways, Port, Coastal and Ocean Engrg., ASCE, Vol. 111, No. 3, pp. 552-566.

Sarpkaya, T. and Isaacson, M., 1981. Mechanics of wave forces on offshore structures. Van Nostrand Reinhold Co., pp. 651.