

Experimental dam-break waves profile analysis: Horizontal mobile bed

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ABSTRACT

An experimental study aiming the evaluation of the influence of mobile bed on dam-break wave propagation is presented. The experimental results were obtained in a horizontal prismatic flume, using two types of bed: fixed and mobile. In the mobile bed tests, two types of sediment were used: sand and pumice. Initial conditions also comprised dry and wet bed downstream the lift-gate (dam). The experimental data include bed and free-surface profiles, free-surface time evolution, wave maxima levels and wave maxima arrival times. The results obtained for different initial conditions are compared and analyzed. For small relative downstream initial water depths, the increase of bed mobility induces significant changes on the bed profile with consequences on the free-surface, originating a hydraulic jump. These changes also induce higher wave maxima levels. The existence of a relatively high initial water level downstream makes the sediment mobility less important. The wave maxima levels and their arrival time become dependent, mostly, on the inertia needed to initiate the motion of the still water downstream.

Keywords: Dam-break, mobile bed, wave profile, wave maxima levels

1 INTRODUCTION

Dam-break flows (DBF) are among the most feared natural hazards. During the 20th century some catastrophic dam accidents occurred (among others, Vajont, Malpasset, Teton and Machhu II). Those accidents increased societies awareness for the risk associated to DBF.

Starting from Ritter's (1892) initial study, DBF have been studied by many authors. Until few years ago, the majority of those authors considered fixed bottom. For this particular setting, DBF could be treated as a classic problem of free-surface unsteady flow. In this context, the experimental study by Lauber & Hager (1998) allowed the characterization of some of the most important features of DBF, namely the wave maxima levels and its arrival time along the downstream channel.

When DBF occur in alluvial streams, it has been reported that the flow can interact strongly with the bed, causing major impacts in bed morphology. One well documented example of that is related with

the rupture of a dyke in the Lake Ha! Ha! reservoir (Lapointe et al. 1998). Observations showed major morphologic impacts in the downstream valley, including strong bed erosion, in the upstream steeped regions, and generalized deposition in the downstream mild regions.

Capart & Young (1998), using an experimental installation composed of a straight flume with horizontal bed and a lightweight granular material (mean diameter, d_s , equal to 6.1 mm and specific gravity, s , equal to 1.05), verified that, just after opening the dam simulating gate, the wave excavates a scour hole that increases with time in the upstream direction. Due to this scour hole a hydraulic jump is formed which also propagates upstream with time (cf. Ferreira et al. 2006). Therefore, DBF over highly mobile bed are expected to be strongly influenced by flow-bed interaction.

Spinewine & Zech (2002) repeated the tests carried out by Capart & Young (1998), using PVC cylinders ($d_s = 3.5$ mm and $s = 1.54$) which are heavier and smaller than the bed material used by the later

authors. The preliminary results of these tests were discussed by Fraccarollo & Capart (2002) based on a theoretical solution for the problem. They concluded that bed mobility affects both the bed morphology and the free-surface profile. The scour hole and the hydraulic jump observed by Capart & Young (1998) are significantly attenuated for a less mobile bed composed of heavier particles (tests from Spinewine & Zech 2002).

Ferreira et al. (2006) derived a theoretical solution for geomorphic DBF and compared the results with experimental evidence, concluding that the hydraulic jump is associated to the scour hole and both migrate upstream. They point out a combination of friction effects, non-equilibrium sediment transport and two-dimensional effects as a possible explanation to the formation of the hydraulic jump.

Leal et al. (2006) referred that the presence of intense sediment transport in DBF, as well as its interaction with the bed, can affect the flow dynamics, usually contributing for an increase of the free-surface levels and for a decrease in the wave-front celerity. Fraccarollo & Capart (2002) pointed out that this interaction between bed morphology and DBF requires a morphodynamic approach to reproduce the time and space scales of the involved phenomena.

The present study aims the evaluation of the bed mobility in DBF, namely in what concerns the wave profiles, wave maxima levels and their arrival time. For that purpose, the experimental results of Leal et al. (2002) are used.

2 EXPERIMENTAL TESTS

The experimental data used in this study refer only to horizontal bed. The experimental tests were carried out in a 19.2 m long, 0.5 m wide and 0.7 m high rectangular horizontal flume. A vertical lift-gate, installed in the flume middle cross-section, was opened rapidly, simulating an instantaneous dam-break. A sketch of the initial conditions is presented in Fig. 1. They comprised constant upstream initial water depth ($h_u = 0.40$ m), constant initial bed elevation, both up- and downstream ($z_u = z_d = 0.07$ m), and several initial water depths downstream (h_d ranging from 0.000 m to 0.210 m). Concerning the bed type, three groups of tests were carried out: fixed, sand and pumice bed. Both sediments are approximately uniform (gradation coefficient less than 2). The main features of the tests used in the present study are presented in Table 1 (for details see Leal et al. 2002). In the table, $\alpha = h_d/h_u$ is relative downstream initial water depth and $d_s^* = d_s/h_u$ is the relative sediment diameter.

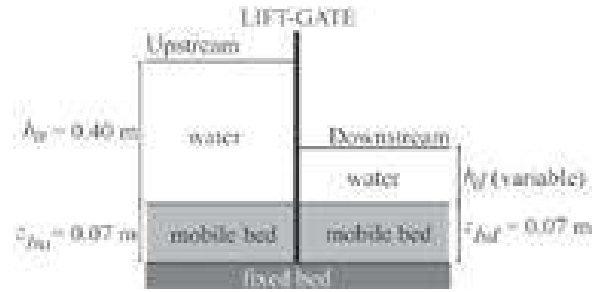


Figure 1. Sketch of initial conditions.

Assuming hydrostatic pressure distribution, the free-surface levels were measured by seven pressure transducers installed downstream the gate on the flume side-wall. They were located at $X = 0.5, 2.5, 5.0, 7.5, 12.5, 17.5$ and 22.5 from the gate section, being $X = x/h_u$ the downstream dimensionless coordinate. Five digital video cameras were used to record free-surface and bed level profiles. Actual measurements were obtained by direct video inspection.

3 DISCUSSION

3.1 Flow description

Comparing the results for fixed, sand and pumice bed, Leal et al. (2002, 2003) concluded that the increase of bed mobility (being the pumice bed the most mobile) induces the increase of the free-surface elevation near the gate (dam) cross-section and the decrease of the wave-front celerity (cf. Leal et al. 2006).

Table 1. Initial conditions of experimental tests.

Test	Type of bed	h_d (m)	$\alpha = h_d/h_u$ (-)	$s = \rho^{(s)}/\rho^{(w)}$ (-)	$d_s^* = d_s/h_u$ (-)	
T.1		0.000	0.00			
T.2		0.023	0.06			
T.3		0.049	0.12			
T.4		0.056	0.14			
T.5	fixed bed	0.071	0.18	-	-	
T.6		0.082	0.20			
T.7		0.094	0.23			
T.8		0.114	0.28			
T.9		0.142	0.35			
T.10		0.212	0.52			
Ts.1		0.000	0.00			
Ts.2	Sand	0.009	0.02	2.65	0.002	
Ts.3		$d_s =$	0.040			0.10
Ts.4		0.8	0.075			0.19
Ts.5		mm	0.106			0.27
Ts.6			0.203			0.51

Tp.1		0.000	0.00		
Tp.2	Pumice	0.009	0.02		
Tp.3	$d_s =$	0.040	0.10	1.40	0.003
Tp.4	1.2	0.075	0.19		
Tp.5	mm	0.106	0.27		
Tp.6		0.203	0.51		

For quasi dry bed conditions, Leal et al. (2002, 2006) attribute the wave-front deceleration to the added inertia associated with the entrainment of sediments in the flow and to the increase of flow resistance due to bulking with bed material of zero momentum but finite inertia (cf. Capart & Young 1998; Ferreira et al. 2006).

According to Leal et al. (2002), in the case of the most mobile bed (pumice bed) the morphological impacts are neater and consist in the excavation of a scour hole near the gate (dam) cross-section. The scour hole that is carved in the lighter material bed (pumice) induces the formation of a hydraulic jump that moves upstream for higher times. This hydraulic jump was first mentioned by Capart & Young (1998) using a bed material with very low specific gravity ($s = 1.05$) and its relation with the scour hole was discussed by Ferreira et al. (2006).

3.2 Free-surface time evolution

The free-surface time evolution observed in fixed bed tests is presented in Fig. 2 for several α values. The free-surface was measured at seven cross-sections located downstream the gate (dam). The wave maxima levels are also identified.

It should be noted that the dimensionless free-surface elevation, Z_s^* , is measured starting from the initial downstream bed elevation and discounting the initial water level downstream, *i.e.*, $Z_s^* = Z_s - \alpha$. The dimensionless time is given by $T = t/(h_u/g)^{0.5}$.

For the lower values of α (Figs. 2a and 2b), the free-surface level rises abruptly, in each section, immediately after the wave-front arrival; afterwards, it increases slowly until reaching the maximum. After the maximum, the free-surface level decreases slowly as the upstream reservoir empties. This free-surface behaviour is similar to the one referred to by Lauber & Hager (1998) for fixed smooth dry bed conditions.

For higher values of α (Figs. 2c to 2f), the free-surface levels start to be influenced by the downstream weir used to impose the initial water level downstream. The maxima levels due to this effect will be

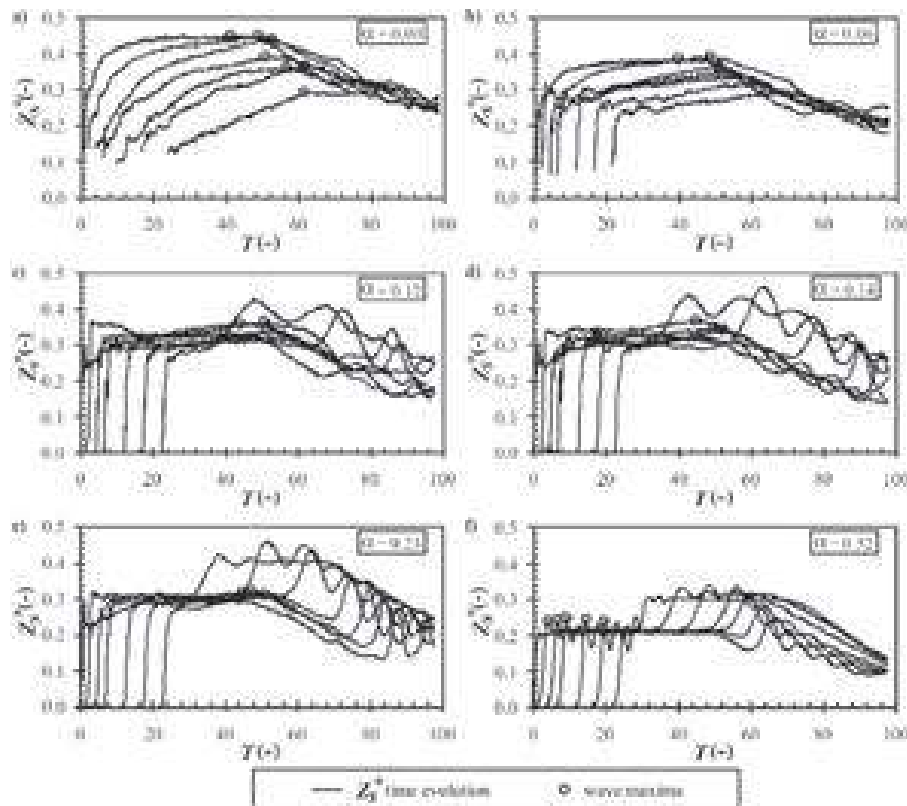


Figure 2. Z_s^* time evolution at positions $X = 0.5, 2.5, 5.0, 7.5, 12.5, 17.5$ and 22.5 (presented from right to left) and wave maxima levels for fixed bed tests: a) $\alpha = 0.00$; b) $\alpha = 0.06$; c) $\alpha = 0.12$; d) $\alpha = 0.14$; e) $\alpha = 0.23$; f) $\alpha = 0.52$.

neglected throughout the analysis performed in this study. Adopting this procedure, it can be concluded that for higher values of α the free-surface behaves similarly as for lower α values, i.e., in accordance with Lauber & Hager (1998) observations for dry bed. For the highest value of α ($\alpha = 0.52$, Fig. 2f), the free-surface behaves differently from the one mentioned before. In fact, neglecting the weir effect, the wave maxima levels are attained just after the arrival of the wave-front. This is due to the fact that, for high α values, the wave does not break, propagating downstream as a solitary wave or a group of waves (cf. Leal et al. 2002).

The measured free-surface time evolution for sand and pumice bed tests with low, intermediate and high α values is presented in Fig. 3. It can be concluded that the free-surface behavior is similar to the one described for fixed bed tests.

The main discrepancies are observed at the gate nearest cross-section, for the higher mobility bed (pumice bed) and low/intermediate α values (Figs. 3b and 3d), where the free-surface level does not rise slowly until reaching a maximum; instead it exhibits an oscillatory pattern probably due to the previously mentioned morphological bed changes. As a consequence, the maximum level is attained much sooner than for other sections.

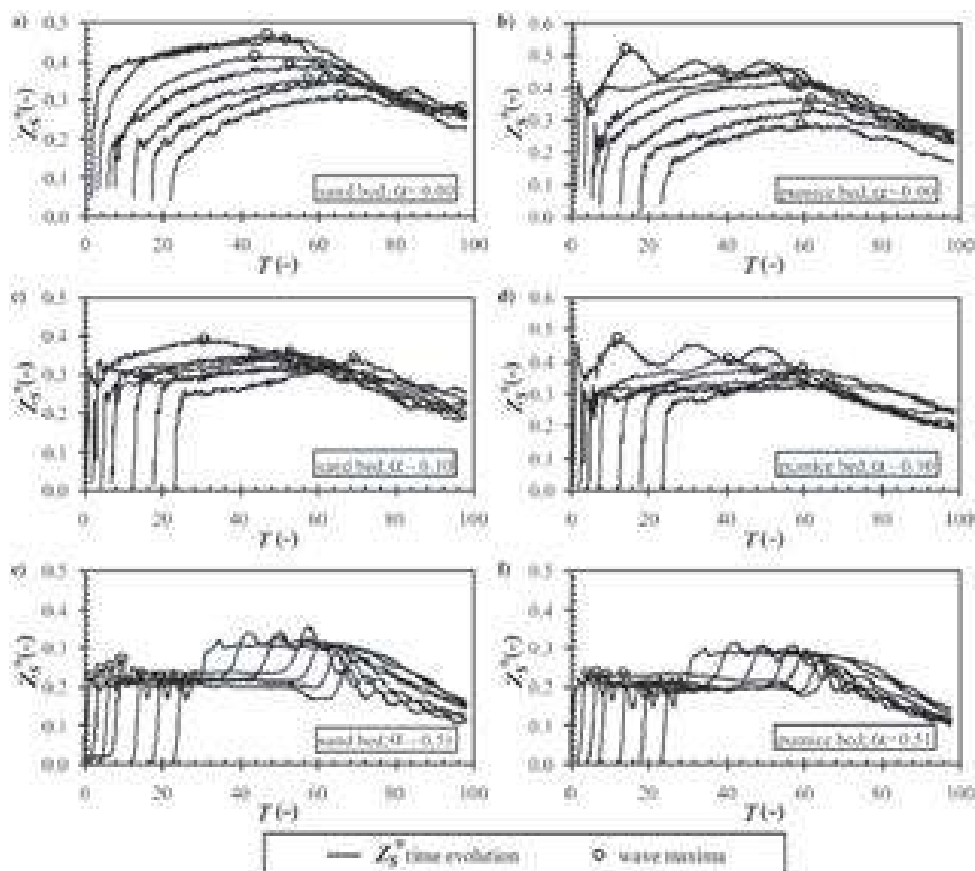


Figure 3. Z_s^* time evolution at positions $X = 0.5, 2.5, 5.0, 7.5, 12.5, 17.5$ and 22.5 (presented from right to left) and wave maxima levels for sand bed tests: a) $\alpha = 0.00$, c) $\alpha = 0.10$ and e) $\alpha = 0.51$ and for pumice bed tests: b) $\alpha = 0.00$, d) $\alpha = 0.10$ and f) $\alpha = 0.51$.

3.3 Wave maxima levels

The measured wave maximum level is found to be related with the α value through the following linear equation

$$1/(Z_s^*)_{\max} = a_1\alpha + a_2 \quad (1)$$

where a_1 and a_2 are regression coefficients. The determination coefficient, R^2 , is higher than 80% for all tests. For small α values (quasi dry bed) and near the gate cross-section, the increase of bed mobility results in the increase of the free-surface levels (Fig. 4a). This seems to be a consequence of the pronounced morphological changes in the bed profile.

The excavation of a scour hole induces the formation of a hydraulic jump which influences the free-surface time evolution.

The variation of a_1 and a_2 with X can be observed in Fig. 5. For both parameters the variation is well approximated by a linear equation

$$\begin{aligned} a_1 &= a_3 X + a_4 \\ a_2 &= a_5 X + a_6 \end{aligned} \quad (2)$$

where a_3 , a_4 , a_5 and a_6 are regressions coefficients presented in Fig. 5.

Replacing (2) in (1) one obtains

$$\sqrt{(Z_s^*)_{\max}} = (a_3 \alpha + a_4) X + (a_5 \alpha + a_6) \quad (3)$$

Fig. 6 presents the results obtained with Eq. (3) against the experimental data. The equation proposed by Lauber & Hager (1998) for fixed dry bed

$$(Z_s^*)_{\max} = Z_{\max} = \frac{4}{9} \left(1 + \frac{1}{X^*} \right)^{3/4} \quad (4)$$

is also included. Here $X^* = \lambda_r X^{2/3}$, being in the present study $\lambda_r = L_r/h_u \approx 10/0.40 = 25$.

For all types of bed and $\alpha \leq \approx 0.2$ for fixed and sand bed and $\alpha \leq \approx 0.3$ for pumice bed, it can be concluded that $1/(Z_s^*)_{\max}$ increases linearly with the X coordinate, i.e., the maximum free-surface elevation decreases linearly with X .

That increase is due to the finite length of the reservoir and confirms what has been reported for real cases. However, for higher values of α , the wave does not break; instead it propagates as a solitary wave or a group of waves. For those cases, the vertical acceleration is non-negligible, being the kinetic energy transformed into potential energy through the increase of the free-surface elevation. This can explain the increase of the free-surface elevation with X , i.e., the decrease of $1/(Z_s^*)_{\max}$.

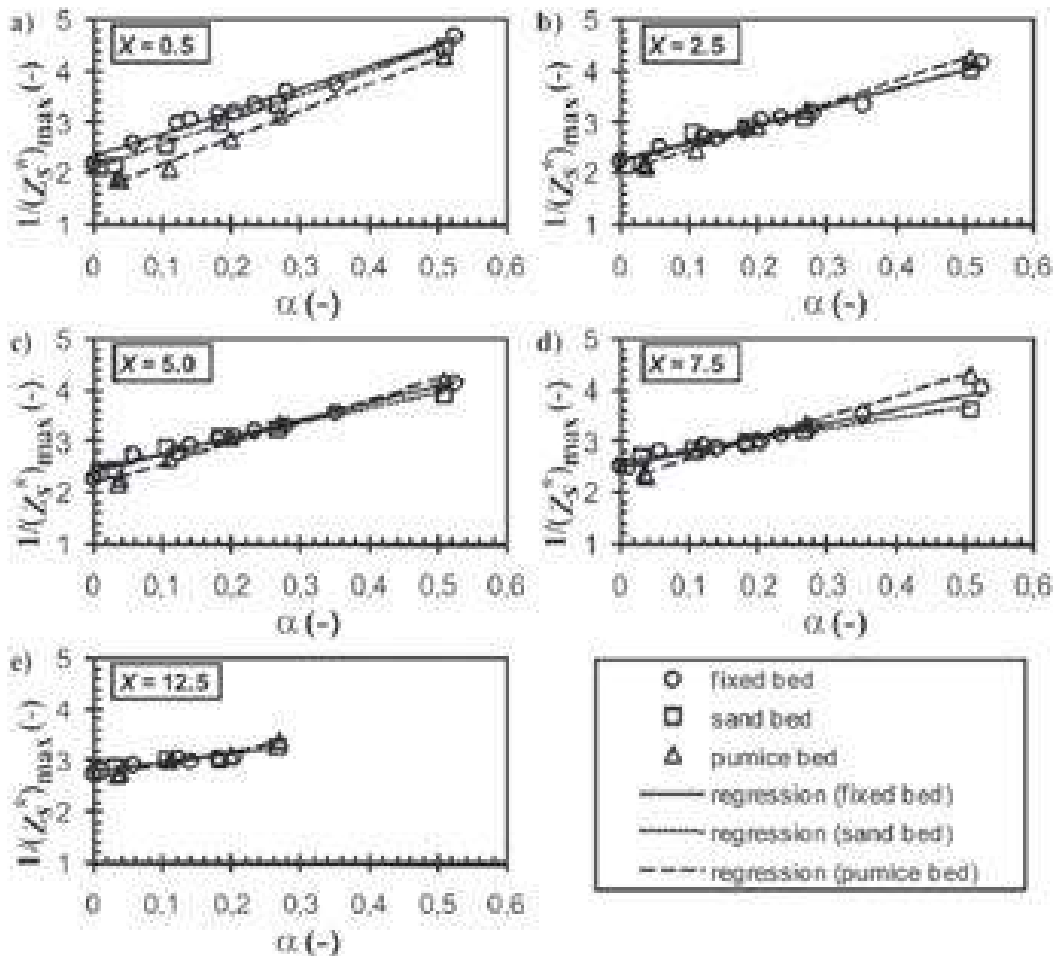


Figure 4. Variation of $1/(Z_s^*)_{\max}$ with α for fixed, sand and pumice bed at: a) $X = 0.5$; b) $X = 2.5$; c) $X = 5.0$; d) $X = 7.5$ and e) $X = 12.5$.

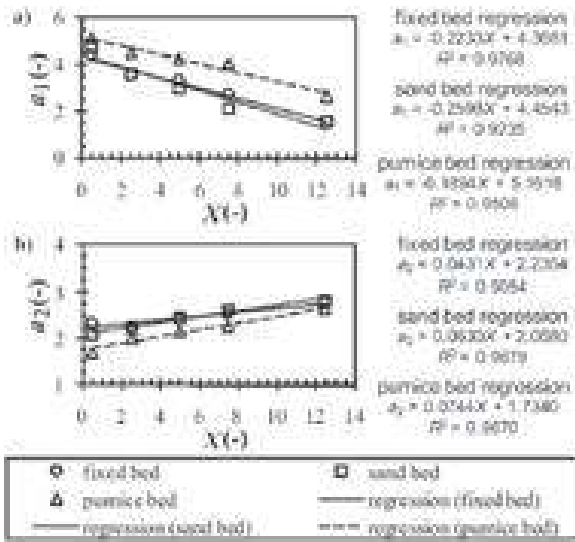


Figure 5. Variation of regression parameters of Eq. (1) with X for fixed, sand and pumice bed: a) a_1 and b) a_2 .

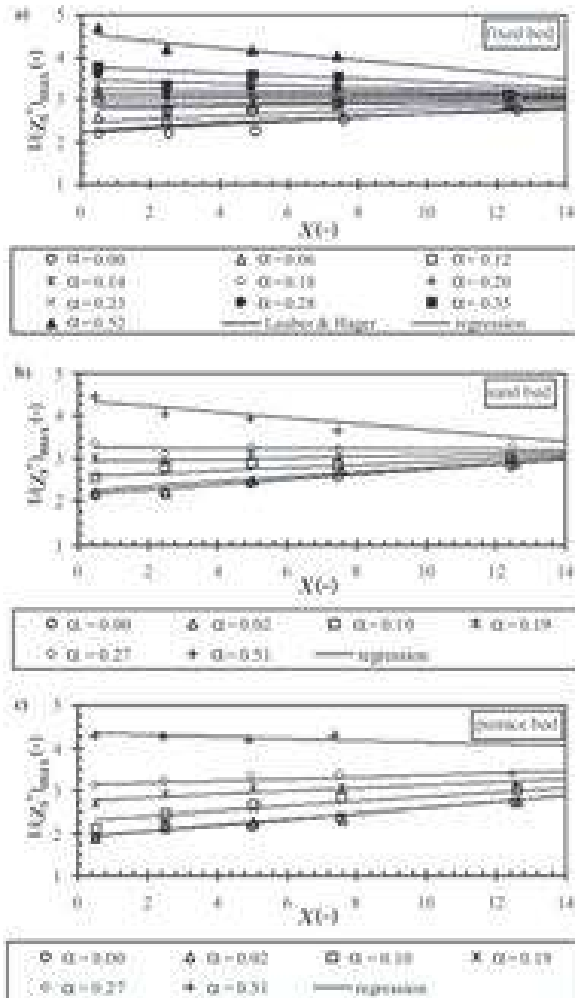


Figure 6. Wave maxima levels, $1/(Z_s^*)_{\max}$, along the X coordinate for several α values: a) fixed bed; b) sand bed and c) pumice bed.

The influence of the initial downstream water level (i.e., α) is less pronounced for higher X values. In fact, for those values, the maximum free-surface level seems to become constant, independently of α value. This should be linked to the finite length of the upstream reservoir. To confirm this conclusion, it would be necessary the use of a longer flume.

The results for fixed and sand bed are very similar (Figs. 6a and 6b), but exhibit some differences when compared with pumice bed results (Fig. 6c).

For small values of α , the free-surface level is higher for the pumice bed, which is in accordance to what was mentioned before, i.e., the bed morphological changes and the flow-bed interaction increase the wave maxima levels, especially near the gate (dam) cross section. Therefore the bed mobility can play an important role in determining the DBF wave profiles and consequently in the definition of inundation maps for risk assessment and management.

3.4 Time to wave maxima levels

The dimensionless time to wave maxima levels, $T^* = T_{\max} X^{-2/3}$, along the X coordinate, for all tests, are presented in Fig. 7, being $T_{\max} = t_{\max}(g/h_u)^{0.5}$, where t_{\max} is the time to wave maxima levels. The equation proposed by Lauber & Hager (1998) for fixed dry bed is also presented

$$T^* = 1.7(1 + X^*) \quad (5)$$

From Fig. 7, it can be concluded that the equation of Lauber & Hager (1998) gives good results for all types of bed, small α ($\alpha < \approx 0.14$) and small X^* values ($X^* < 15$).

For fixed and sand bed (Figs. 7a and 7b), the dimensionless time to wave maxima levels deviates from Eq. (5) for high values of X^* and α . This means that for sections located near the dam (i.e., with high X^* value) the dimensionless time to wave maxima levels is more dependent on the initial downstream water level.

For the pumice bed (Fig. 7c) the T^* also deviates from Eq. (5) for high to X^* , but this happens independently of the value of α . This should be attributed to the significant morphological changes that occur in the mobile bed, inducing the decrease of T^* .

For all tests and high α values, the wave does not break and therefore the maxima levels are attained shortly after the wave-front arrival.

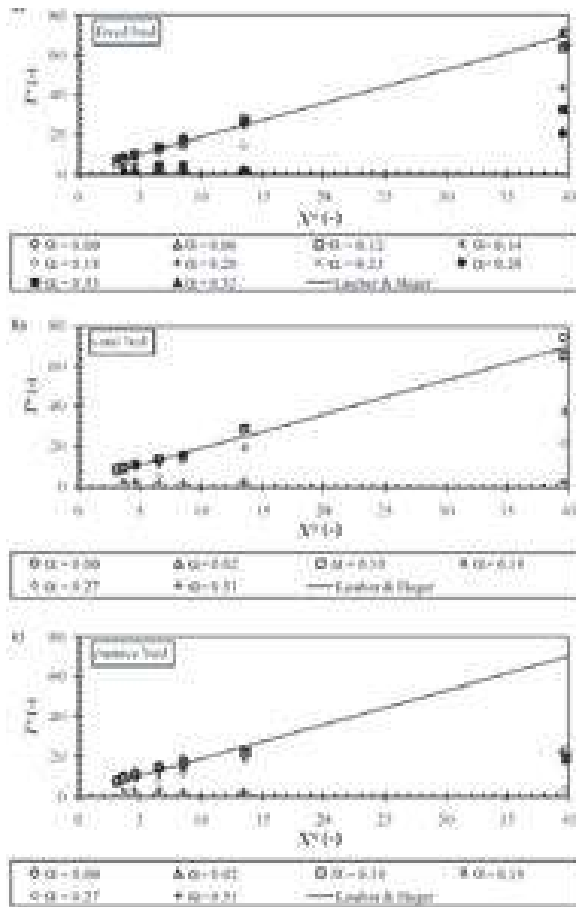


Figure 7. Time of wave maxima levels, T^* , along the X^* coordinate: a) fixed bed; b) sand bed and c) pumice bed.

4 CONCLUSIONS

According to the analysis presented above and within the range of tests carried out, the following conclusions can be drawn:

- The free-surface level exhibits a behaviour similar to the one mentioned by Lauber & Hager (1998), i.e., it increases after the wave-front arrival until reaching a maximum. The exceptions are the cross-sections near the dam on the higher mobility bed (pumice).

- For dry bed conditions and for cross-sections near the dam, the bed mobility can induce significant morphological changes that lead to the increase of the free-surface level, highlighting that bed mobility plays an important role on wave maxima levels and their arrival time.

- For each type of bed, the wave maxima levels are well approximated by a function of α and X . The influence of α decreases with increasing X , since, for high X values, the maximum free-surface elevation seems to tend to a constant value independent of α .

- For all types of bed and $\alpha \leq \approx 0.2$ for fixed and sand bed and $\alpha \leq \approx 0.3$ for pumice bed, the maximum free-surface level decreases linearly with X .

- For high α values, the wave does not break; instead it propagates as a solitary wave or a group of waves, inducing the increase of the free-surface level with X . In those cases, the wave maxima levels are attained shortly after the wave-front arrival.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial support of the Portuguese Foundation for Science and Technology through the project POCTI/36069/ECM/99 and the programme PRODEP, Medida5/Accao5.3, from the Port. Ministry of High Education and Science and Technology, in cooperation with the European Union. The authors also wish to acknowledge the financial support offered by the European Commission through the IMPACT project, fifth framework programme (1998-2002) on Environment and Sustainable Development.

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