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EXPERIMENTAL STUDY ON TURBULENCE GENERATED BY REGULAR WAVES

Francesca De Serio[1] and Michele Mossa[2]

Abstract: This paper describes the final results of an experimental research carried out in the wave flume of the laboratory of the Water Engineering and Chemistry Department of Bari Technical University, Italy, and based on the analysis of three different regular waves breaking on a sloping bottom. The investigation refers particularly to the surf zone, where a turbulent flow develops consequently to wave breaking. The necessity to study the surf zone dynamics springs from the great influence exercised by turbulence on coastal processes, such as undertow currents, sediment transport and action on maritime structures.

INTRODUCTION AND THEORETICAL BACKGROUND

The vertical flow structure in the surf zone is a subject of great importance in coastal engineering for understanding many correlated processes. The velocity distribution of longshore currents and undertow, the sediment concentration field, the wave set-up and the wave-driven currents in the surf zone are all phenomena which depend on flow field in breaking waves. Moreover the surf zone dynamics holds a pivotal role in the dynamic equilibrium of beaches, because it can be considered as a seaward boundary of the swash zone, that is the region of shoreline erosion and accretion (Elfrink and Baldock, 2002; Longo et al., 2002). The study of turbulent flow mechanisms in breaking waves has represented a difficult task for many researchers, due to the extreme unsteadiness and non uniformities associated with it. In fact wave breaking is characterized by a sudden transition from irrotational to rotational motion, with a violent transformation of wave energy into turbulence and eventually into heat (Feng and Stansby, 2002; Pedersen et al., 1998).

In the horizontal direction of the surf zone, the following zones can be distinguished (Christensen et al., 2002). Initial wave deformation occurs in what has been termed the shoaling zone, where wave profile is characterized by a rapid change in shape. Subsequently, the wave reaches the breaking point in the outer zone, originating an overturning jet, whose strength depends on the type of breaker. In the inner surf zone

1 Technical University of Bari, D.I.A.C., Via E. Orabona 4, 70125 Bari, Italy, f.deserio@poliba.it
2 Technical University of Bari, D.I.A.S.S., Via E. Orabona 4, 70125 Bari, Italy, m.mossa@poliba.it

the wave undergoes a gradual transformation into turbulent bore, until reaching the swash zone. It is the shoaling and outer zones that are of interest to this paper, which focuses on spilling, plunging and spilling/plunging breakers (i.e. the intermediate range between spilling and plunging, taking into account the Irribarren number). Acquired data were used in a previous work (De Serio and Mossa, 2003a) in order to analyse velocity and Reynolds shear stress distributions of the regular wave field and to provide spatial correlations in the vertical direction. Thus it was possible to contribute to the validation of those models which do not neglect the shear stress contribution in the momentum balance equations (Rivero and S.-Arcilla, 1995; Deigaard and Fredsøe, 1989), in contrast with classical theories predictions. In the present paper the same laboratory tests are studied with the aim to explain both the spatial and temporal variations of turbulence in the surf zone (De Serio and Mossa, 2003b) and the correlation between the flow and the turbulence level, in order to qualitatively explain cross-shore sediment transport mechanisms (Ting and Kirby 1994, 1995, 1996).

The problem is governed by the Navier-Stokes equations and for simplicity is confined to a 2D frame, in which the waves propagate along the x direction and the z axis is directed vertically upward from the free surface. Taking into account that any physical quantity can be split into the steady mean flow component (i.e. time-averaged component), the fluctuation component due to the statistical contribution of the wave and the fluctuation component of the turbulence (Ting and Kirby, 1996), the velocity component u_i (i=1,2) can be expressed as follows:

$$u_i(x_i,t) = \langle u_i \rangle(x_i,t) + u_i'(x_i,t) = U_i(x_i) + \tilde{u}_i(x_i,t) + u_i'(x_i,t) \qquad (1)$$

where t is the time quantity, x_1 and x_2 are respectively the x and z Cartesian coordinates, the angular brackets < > are an operator to take an ensemble average, the tilde symbol indicates the oscillating components, the prime symbol indicates the turbulent fluctuations and the capital letters or the over-bar indicate the time-averaged components. Ensemble averaging requires the phenomenon to be highly reproducible, (Longo et al., 2002). In the present study, where regular waves are analysed, the ensemble average method can be adopted (Okaiasu et al., 1986; Feng and Stansby, 2002) by phase-averaging the measured signals over a great number of cycles. Then, these values were averaged to yield the time-averaged velocities. Consequently, turbulent fluctuations were obtained as the difference between the original time series and the ensemble-averaged velocities.

Observing that surf zone turbulence originates from instabilities of surface waves, the fundamental source of energy for turbulence is the kinetic energy, released by breaking, whose ensemble average is defined as:

$$k = 1/2 \langle u'_i \, u'_i \rangle . \qquad (2)$$

The distribution of k may be determined by solving the equation of conservation of the turbulent kinetic energy (Damani and Mossa, 1999), which states that the local time rate change of turbulent kinetic energy is due to convection by mean flow, diffusive transport by pressure and turbulent fluctuations, turbulent energy production and viscous dissipation:

$$\frac{\partial k}{\partial t}+\frac{\partial\langle u_j\rangle k}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\frac{1}{\rho}\langle u'_j\,p'\rangle+\langle u'_j\,k'\rangle-2\upsilon\langle u'_j\,s'_{ij}\rangle\right)-\langle u'_i\,u'_j\rangle S_{ij}-2\upsilon\langle s'_{ij}\,s'_{ij}\rangle \quad (3)$$

being *k'* the oscillating component of *k*, *p* the hydrodynamic pressure, ρ the water density,

$$S_{ij}=1/2\left(\partial\langle u_i\rangle/\partial x_j+\partial\langle u_j\rangle/\partial x_i\right) \quad (4)$$

and

$$s_{ij}=1/2\left(\partial u'_i/\partial x_j+\partial u'_j/\partial x_i\right) \quad (5).$$

The determination of *k* is fundamental to evaluate the turbulent diffusion coefficient and consequently the turbulent mass transport (assumed to be related to the gradient of the transported quantity, on the analogy of turbulent momentum transport).

EXPERIMENTAL EQUIPMENT AND PROCEDURE

The 45 m long and 1 m wide wave channel used to carry out the tests is located in the laboratory of the Water Engineering and Chemistry Department of Bari Technical University (Italy), largely described in De Serio and Mossa (2003a). Also a detailed description of the main characteristics of the tested regular waves can be found in De Serio and Mossa (2003a). Taking into account the Irribarren breaking number, the wave fields of the present study are characterized, respectively, by a spilling/plunging breaker in test 1, a spilling breaker in test 2 and a plunging breaker in test 3.

Like most of the recent experimental investigations (Okaiasu, 1986; Feng and Stansby, 2002), the Laser Doppler Anemometry, a modern nonintrusive measurement technique, was used to measure the instantaneous Eulerian velocity. In particular a backscatter, two-component, four beam LDA system and a Dantec LDA signal processor based on the covariance technique (Damiani and Mossa, 1999) was adopted. The wave elevations were measured with a resistance probe. Moreover velocity and wave elevation measurements were assessed simultaneously, allowing us to perform the phase-averaging analysis. A consideration must be pointed out. In the experiments by Ting and Kirby (1996) the horizontal and vertical components of water particle velocity were not measured at the same time, but by conducting the same experiment twice. On the contrary in the present research, where horizontal and vertical velocities were assessed simultaneously, it was possible to examine directly fluxes and correlation coefficients. The velocity components measured in the present study are *u* in the *x* direction, established as positive if oriented onshore and *w* in the vertical direction, established as positive if oriented upward.

ANALYSIS OF TURBULENCE AND TURBULENT TRANSPORT

Ting and Kirby (1994, 1995, 1996) studied in detail turbulence transport in the surf-zone, by determining each term of eq. (3) and, from simple reasoning, they derived that the sediment transport had to be offshore directed under spilling breakers and onshore directed under plunging breakers. The present experimental results show a general agreement with these conclusions.

Firstly, the horizontal and vertical transport of turbulent kinetic energy by mean flow, $\langle u\rangle k$ and $\langle w\rangle k$ respectively, were investigated. Referring to a section in the breaking region (section 46) for the sake of brevity, results are shown in Figure 1.a, for spilling/plunging breaker, in Figure 1.b, for spilling breaker, and in Figure 1.c, for plunging breaker. The analysis of Figure 1.b highlights that, in the spilling case, the energy flux by advection, $\langle u \rangle k$, is shoreward, under the wave front, and backward, under the trough, whereas the vertical energy flux, $\langle w \rangle k$, is upward under the crest. Moreover, at all depths, during the larger part of the wave period, $\langle u \rangle k$ is negative and for the most depths the negative area of the diagram (i.e. the integral of the negative part of the function) prevails with respect to the positive one, thus stating that the horizontal turbulent transport is essentially offshore directed. These observations confirm the previous results by Ting and Kirby (1996) and Damiani and Mossa (1999). About spilling/plunging breaking, Figure 1.a shows, similarly to Figure 1.b, that $\langle u \rangle k$ is positive under the crest and negative under the back face of the wave, whereas $\langle w \rangle k$ is still positive under the crest. Considering the positive and negative areas of the $\langle u \rangle k$ diagrams, they are quite balanced with the positive one which prevails in the upper part of the section. This behaviour indicates that in the spilling/plunging case a shoreward transport of turbulent energy is present in the surface roller. In good agreement with Ting and Kirby (1995), Figure 1.c highlights that, under the crest of the plunging breaker, horizontal advection carries turbulent energy shoreward and vertical advection carries turbulent energy upward. In this case, analysing the diagrams of $\langle u \rangle k$ at the different depths, the area under the positive curve results greater than the negative one. This observation enables us to conclude that the in the plunging breaking the net turbulent transport is onshore directed. Consequently, taking into account that suspended sediment transport resembles turbulence transport $\langle u \rangle k$, it is possible to conclude that in the spilling breaker the net sediment transport is offshore, while, in the plunging breaker, it is directed onshore.

Also the transport of *k* by turbulent velocity fluctuations was examined. In the case of spilling and spilling/plunging breaking it seems essentially directed shoreward and downward, while it is directed seaward and downward in the case of plunging breaking. Moreover, in spilling breaking, turbulence spreads slowly towards the bottom, whereas the vertical mixing is faster in the plunging breaking, due to the presence of eddies of larger scale.

In the following, the trends of the phase averaged horizontal $\langle u'^2 \rangle^{1/2}$ and vertical $\langle w'^2 \rangle^{1/2}$ turbulent intensities in the surf zone are plotted, both for spilling (Figures 2 and 3, respectively) and plunging case (Figures 4 and 5, respectively). Each contour map shows the spatial distribution of the turbulent intensities at the same wave phase. Therefore starting with spilling results (test 2), the analysis of Figure 2 highlights that in all the investigated sections the horizontal turbulent intensities present maximum values when the elevation becomes positive (t/T=0), before the crest passes, and that significant values are visible only onshore the breaking point. Moreover higher turbulence is localized near the surface rather than near the bottom. Under the crest (t/T=0.2) the horizontal turbulent intensities decrease and they still persist in the most inner sections. These values becomes much more small in the successive phases, starting to increase again at t/T=0.8, after the trough passes. These results are expected, as in spilling breaking the surface roller is confined in a superficial region and precedes the crest. Figure 3 shows the distribution of $\langle w'^2 \rangle^{1/2}$. It can be underlined that the vertical turbulent intensities are small in the spilling case if compared with the horizontal ones and that they are quite negligible when the elevation is negative. It is clear that both $\langle u'^2 \rangle^{1/2}$ and $\langle w'^2 \rangle^{1/2}$ are higher in plunging breaking, with respect to the spilling breaking. From Figure 4 it is possible to observe that in the passage trough-crest (t/T=0) the horizontal turbulent intensities show significant values, starting from the breaking section, and they reach the maximum under the crest and immediately after the wave breaking (t/T=0.05). Moreover these highest values concern a region onshore the breaking section, spreading towards the bottom. Therefore, this distribution seems to be in accordance with the existence of the splashing jet. After the wave crest passes, $<u'^2>^{1/2}$ values rapidly decrease, as can be observed at t/T=0.2 where it is confined near the bottom, and they reach the minimum when approaching the trough (t/T=0.8). Consequently turbulence dies out between two consecutive breakers. This trend confirms Ting and Kirby's observations (1995). An analogous behaviour can be deduced in the distribution of the vertical turbulent intensities (Figure 5).

CONCLUSION

This experimental research deals with spilling, spilling/plunging and plunging breakers generated by three different regular waves, focusing on the spreading of turbulence in the breaking region. The analysis of horizontal and vertical fluxes of turbulent kinetic energy driven by advection in the surf zone at various depth highlights that in the spilling breaker the net sediment transport is offshore, while in the plunging breaker it is onshore. Also the turbulent kinetic energy transport by turbulent velocity fluctuations was examined, confirming literature results. Finally the spatial distribution of the turbulent intensities was analysed, highlighting generally greater values for the plunging breaker with respect to the spilling one and maximum values near the surface for the spilling case and, on the contrary, near the bottom for the plunging case.

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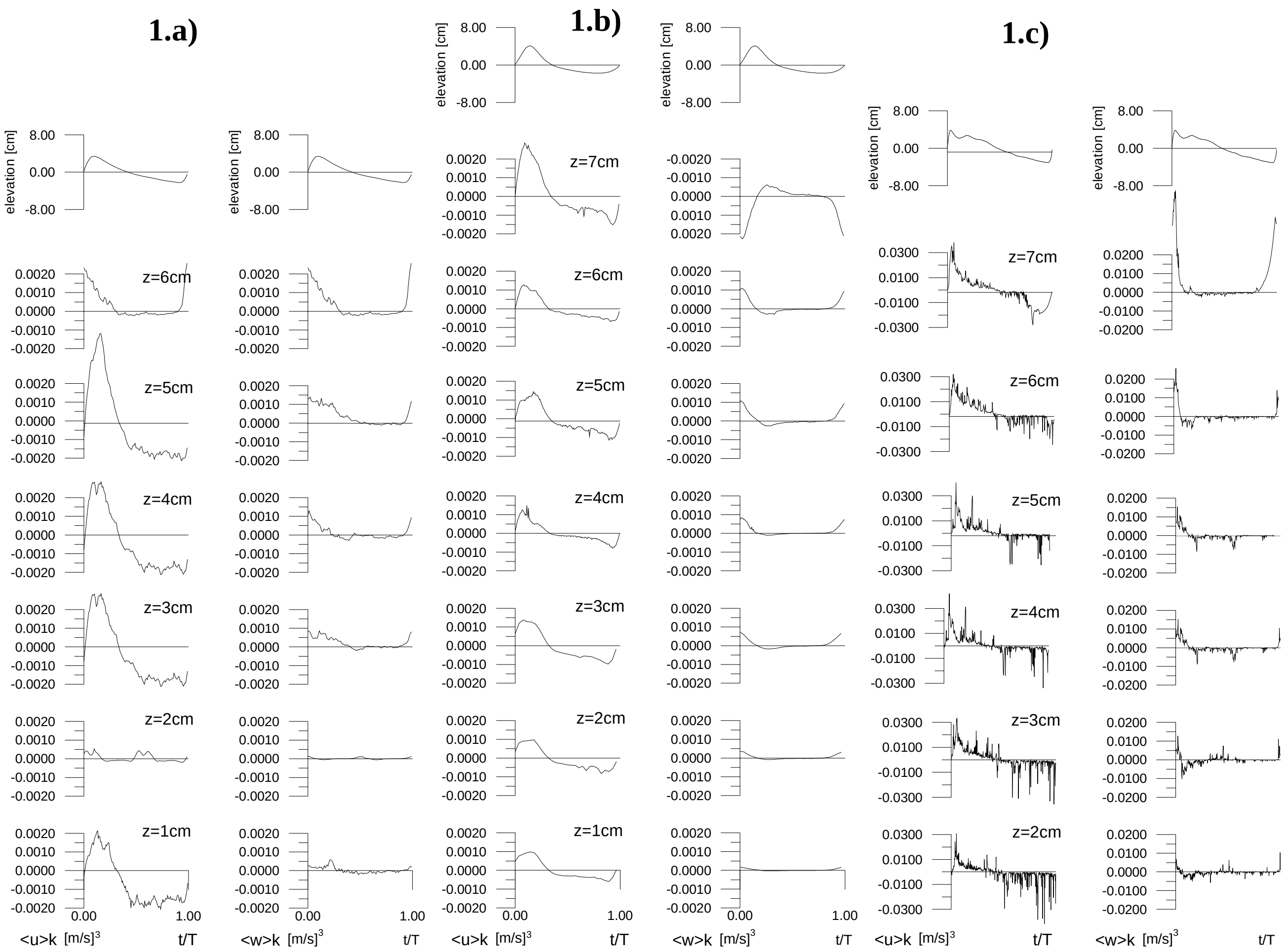

Fig. 1. Diagram of <*u*>*k* and <*w*>*k* during one wave period in sect. 46: 1.a) test 1; 1.b) test 2; 1.c) test 3.

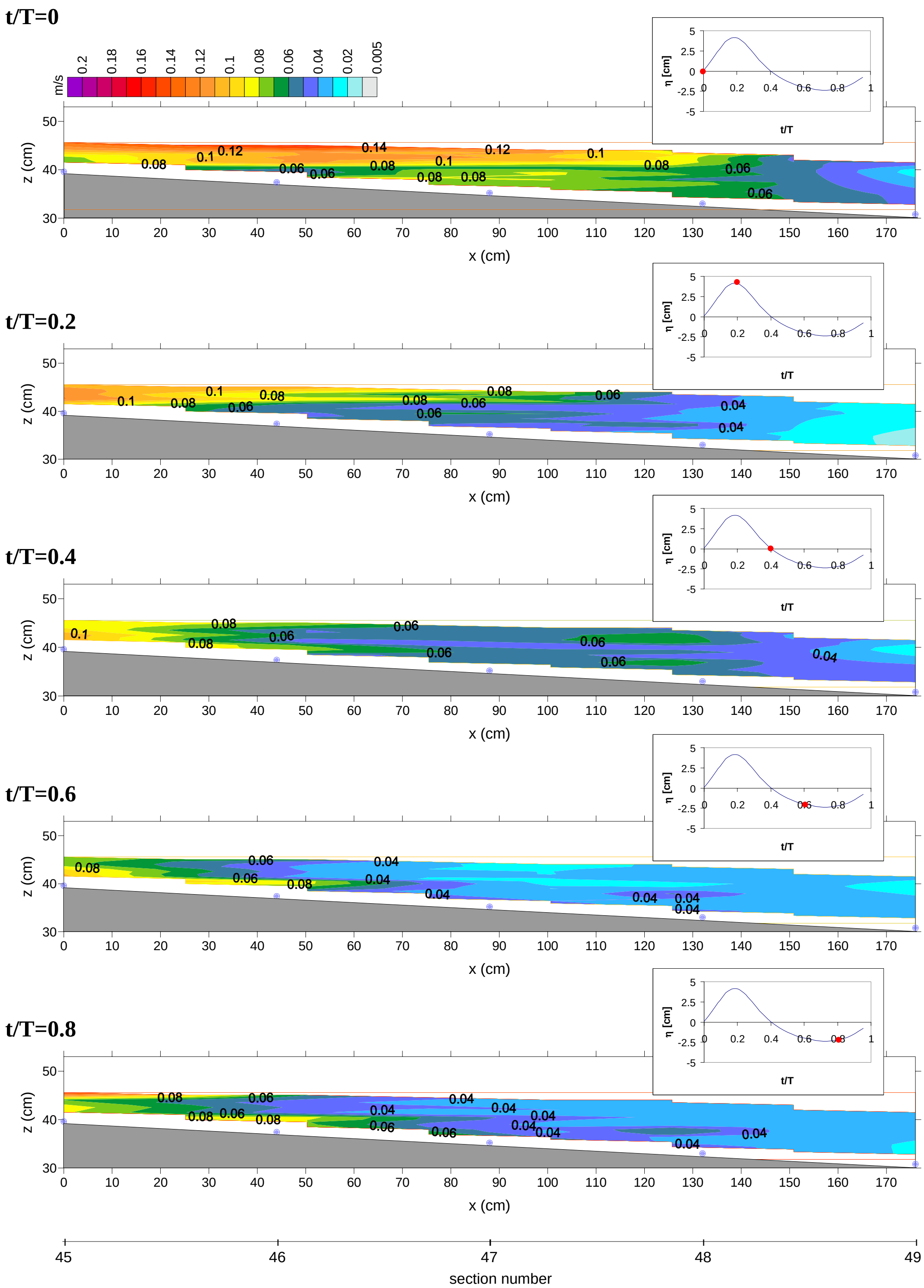

Fig. 2. Test 2. SPILLING breaking: horizontal turbulent intensities.

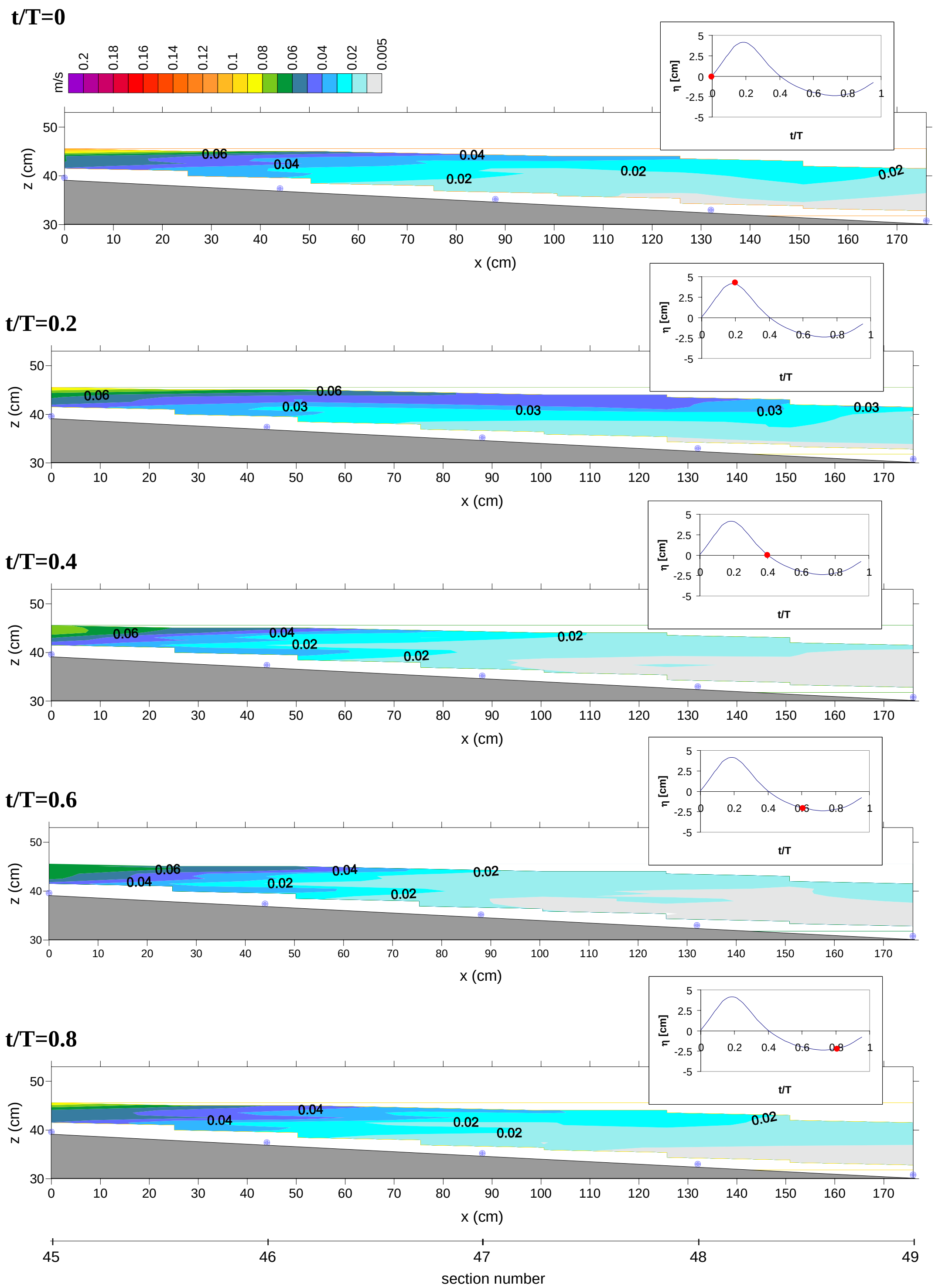

Fig. 3. Test 2. SPILLING breaking: vertical turbulent intensities.

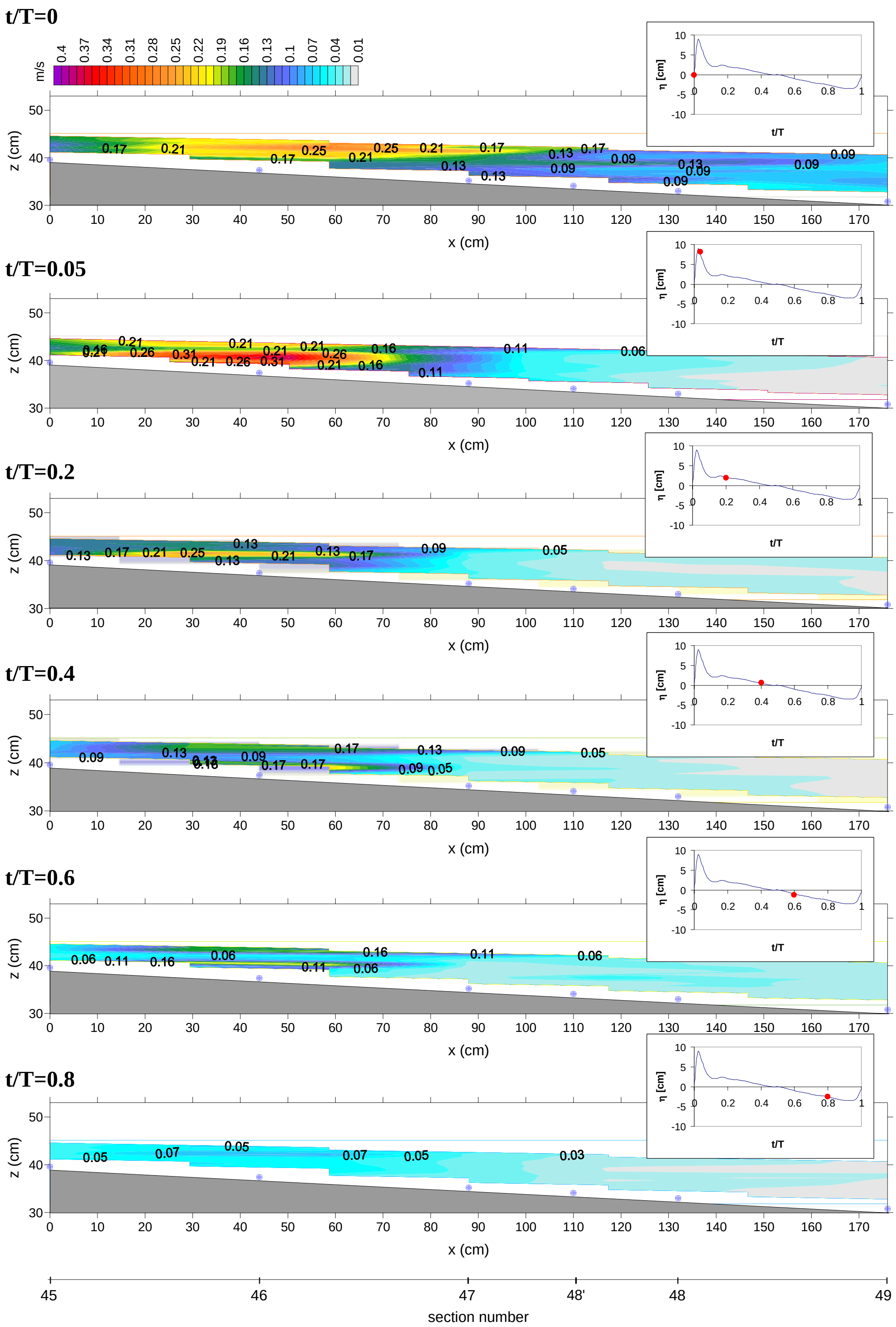

Fig. 4. Test 3. PLUNGING breaking: horizontal turbulent intensities.

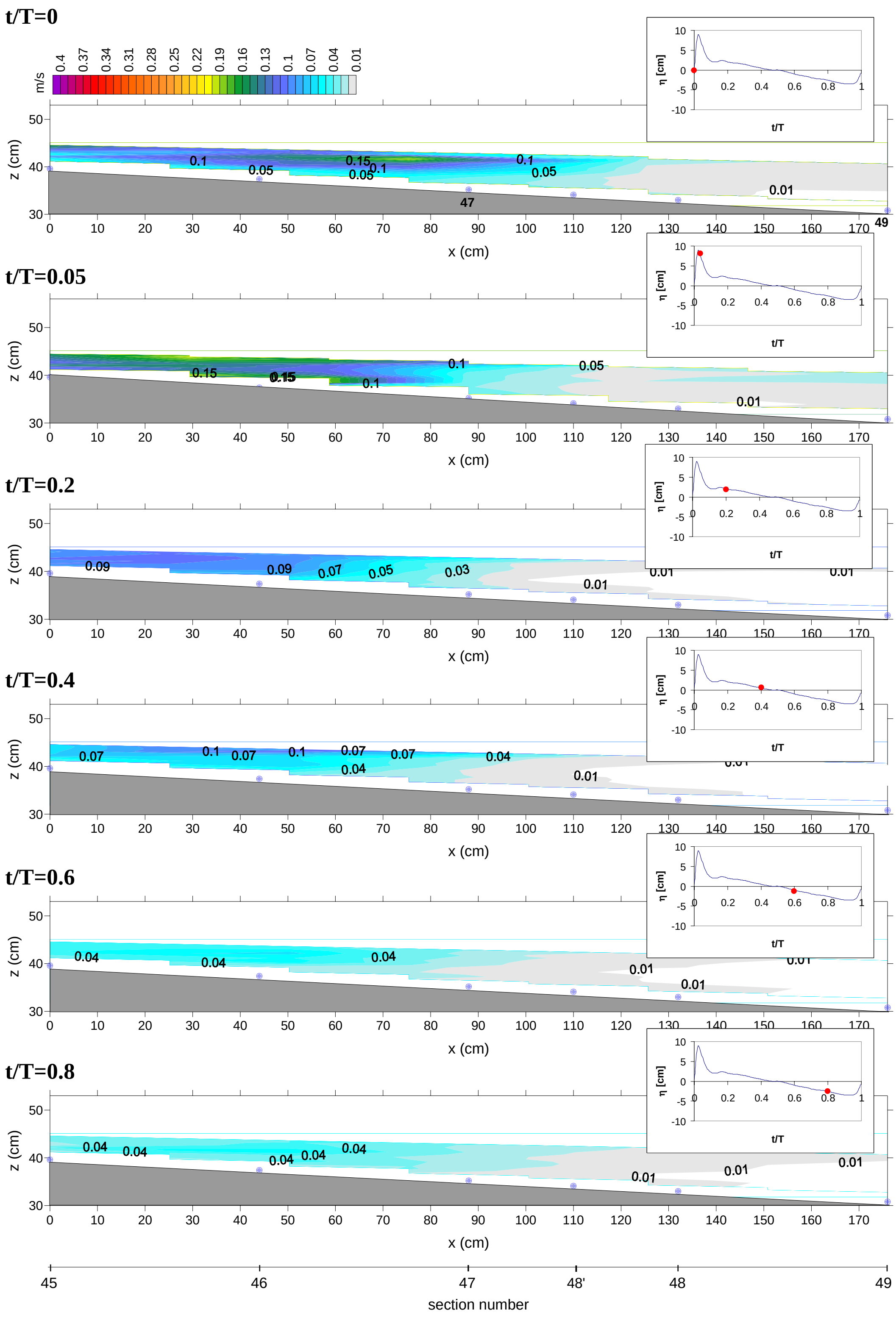

Fig. 5. Test 3. PLUNGING breaking: vertical turbulent intensities.