A COMPARISON OF TIME AND SPECTRAL ANALYSES ON NUMERICAL AND FLUME SIMULATIONS OF WAVE RECORDS

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The analysis of wave records originated by physical simulation experiments in wave flumes or tanks may be done considering suitable wave parameters, either using spectral or time analysis methods. The first type of analysis was made available in the SAM application, Capitão (2002), an integrated software package that has been in use at LNEC for some years now. However, a time analysis method was lacking in this software package. This paper describes the implementation of this time analysis method (direct method) into the existing SAM software, and the testing procedures to verify that it performs as intended. In order to test this type of analysis and to compare it with the spectral analysis, a number of numerical and physical tests were performed using SAM and a wave flume. A comparison between time-domain and frequency-domain methods was the main result obtained with this work. The comparisons made use of the parameters wave height, mean wave period and significant wave period, obtained with both methods.

Keywords: time and spectral analyses; wave records; flume simulation.

1. Introduction

The analysis of wave records originated by either numerically simulated wave records, nature wave records or physical simulation experiments in wave flumes or tanks is a common task in coastal engineering studies and in hydraulic laboratories. The wave records may be numerically simulated to feed some wave model, measured in nature in measurement campaigns or from a physical experiment, like a wave flume or tank (Figure 1).

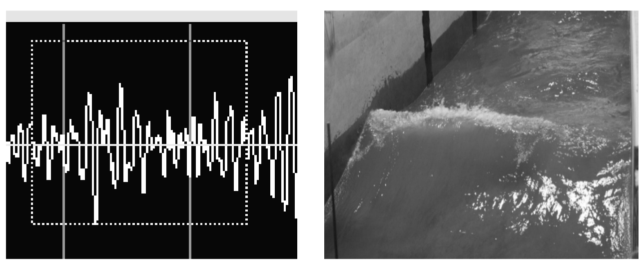


Figure 1. Numerically simulated and physically measured wave records

Several wave parameters may be calculated from a wave record, i.e., a time series of the water surface elevation. These parameters may be calculated using time-domain methods (so-called time analysis methods) or frequency-domain methods (so-called spectral analysis methods).

The aim of this paper is not describing or detailing any of these methods since these are very well known for a long time (see Carvalho, 1973). However, it must be pointed out that the time analysis method starts by firstly defining individual waves, using a certain wave definition criterion, and then calculating a number of statistics on the total number of waves existing in the record. On the other hand, a completely different approach can be performed on the wave record by doing a frequency analysis of the time series. For that, the so-called spectrum of the record, which, broadly speaking, represents the way the energy of the waves are distributed along a range of frequency components, is computed. Once the spectrum of the record is found, several parameters may be determined from it (See Goda, 1985).

Some important wave parameters normally calculated on the wave records are identified for wave heights and for wave periods, in particular the significant wave height, H_S for the time analysis, or H_{m0} for the spectral analysis, the mean wave period, T_Z for the time analysis, or T_{02} for the spectral analysis, and the significant wave period, $T_{1/3}$ for the time analysis, or the peak period, T_p for the spectral analysis (IAHR, 1989).

In order to validate the different methods considering a number of wave records, the probability density function of its wave heights was analysed. According to Goda, 1985, the histogram of wave heights of a wave record containing a small number of waves usually exhibits a rather jagged shape because of the relatively small sample size. However, we can obtain a smoother distribution of wave heights by assembling many wave records with the wave heights normalized by the mean wave height and by counting the relative frequencies of the normalized wave heights in the respective class-intervals. The ordinate of the plot is the relative frequency, n/N (n is the number of waves in each class-interval and N is the total number of waves in the assembled wave record), divided by the class-interval of the normalized wave height, so that the area under the histogram is equal to unity. In most cases the Rayleigh distribution, given by Eq. [1] provides a good approximation to the distribution of individual wave heights defined by the zero up-crossing method.

$$p\left(\frac{H}{\overline{H}}\right) = \frac{\pi}{2}\frac{H}{\overline{H}}\exp\left[-\frac{\pi}{4}\left(\frac{H}{\overline{H}}\right)^2\right] \quad [1]$$

In this paper, the comparison between the histogram of the analysed signal and the Rayleigh function was quantified by computing the so-called "deviation", given by Eq. [2], an average of squared deviations between the relative values, taking as reference the Rayleigh distribution values.

$$\text{deviation} = average\left[\left(\frac{s-R}{R}\right)^2\right] \quad [2]$$

where,

p = probability density function of;

$\left(H/\overline{H}\right)$ = dimensionless wave height;

$\overline{H}$ = mean wave height;

s = histogram value for each $\left(H/\overline{H}\right)$ class; and

R = Rayleigh distribution value for each $\left(H/\overline{H}\right)$ class.

2. Time analysis

The time analysis of a wave record depends mainly on the used criterion for defining what a "wave" is in the "oscillations" observed in the sea surface record, $\eta(t)$. The zero up-crossing, or down-crossing criteria, consists in identifying a wave based on consecutive up or down-crossings of the mean level (zero) of the sea surface elevation record. Each wave is thus limited by any two of these zeros (Figure 2).

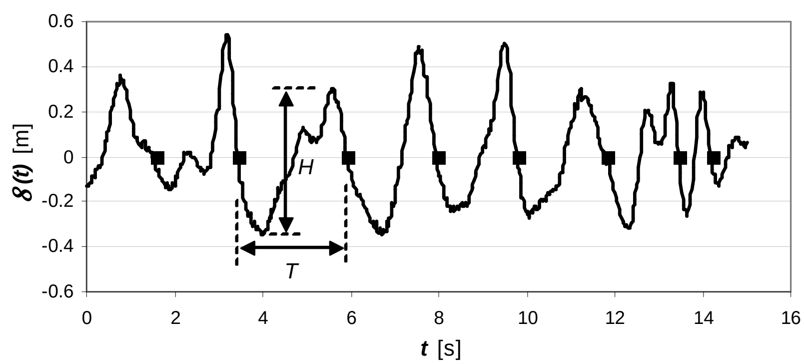


Figure 2. Time analysis of a wave record

Here, the wave period T is the time interval between successive crossing zeros, whereas the wave height H is the vertical distance from trough to crest, i.e., the difference between the heights of wave crests and troughs.

3. Spectral analysis

The short term stationary irregular sea states may be described by a wave spectrum; that is, the power spectral density function of the vertical sea surface displacement, $S(f)$ the Fourier transform of the autocorrelation function of $Z(t)$, the random process from which $\eta(t)$ is one of its many realizations. Broadly speaking, one can say that the spectral analysis is a technique to transform a given function from the time-domain to frequency domain and vice-versa, using the Fourier transform. Spectral parameters are calculated based on the moments of the spectrum, m_n given by Eq. [3], (Bendat and Piersol, 1986):

$$m_n = \int_0^{+\infty} f^n\, S(f)\, df \cong \sum_{k=1}^{N} f_k^{\,n}\, S(f_k)\,\Delta f \quad [3]$$

The sea surface is assumed to be stationary for a duration of 20 minutes to 3 hours, so that a set of environmental parameters such as the significant wave height H_{m0}, the mean period T_{02} and the spectral peak period T_p may be computed according to Eqs. [4], [5] and [6]. Here, f_p is the frequency at which the wave energy spectrum has its maximum value.

$$H_{m0} = 4\sqrt{m_0} \quad [4]$$

$$T_{02} = \sqrt{\frac{m_0}{m_2}} \quad [5]$$

$$T_p = \frac{1}{f_p} \quad [6]$$

4. SAM Software

SAM application is an integrated software package coded in National Instruments' LabView©, which has been in use at LNEC for some years now (Capitão, 2002). This package contains several routines designed to deal with numerical and physical aspects in a laboratory environment.

However, a time analysis method was lacking in this software package, which eventually was made possible in the framework of a cooperation project between Portugal and Brazil (Figure 3).

The objective was then to embed into the existing SAM package a new time analysis module, MOD 6, along with another new module (MOD 8) for directional analysis of wave records (not shown in this paper). The time analysis panel, shown in figure 3(b), is the main output of this work. Similarly as in the spectral analysis, figure 3(a), one can see the wave record on the top and, at the bottom, some wave parameters calculated from the defined waves on that wave record, according to some wave criterion. In the time analysis module, one has to consider several variables that might modify the wave parameters, such as i) the criterion used for the definition of zeros (up-crossing, down-crossing) and the number of points defining those zeros, below and above the mean level (2 points or 4 points in this work); ii) the way the mean level is calculated (averaged or by applying a polynomial function) and iii) the method used to calculate other minor parameters such as $T_{1/n}$.

5. Tests

In order to test the methods, a number of numerical and physical tests were performed using SAM and a wave flume. The tests included different types of target waves, both regular waves and irregular waves. Therefore, different combinations of *H* and *T* were used for both the numerical simulations and flume simulations. A total of 36 wave records were numerically simulated (18 regular and 18 irregular), 15 regular wave records were simulated in the flume (not shown in this paper) and a more 27 irregular wave records were simulated in another flume. For the numerical simulations, prototype values were used, whereas for flume simulations model values were considered.

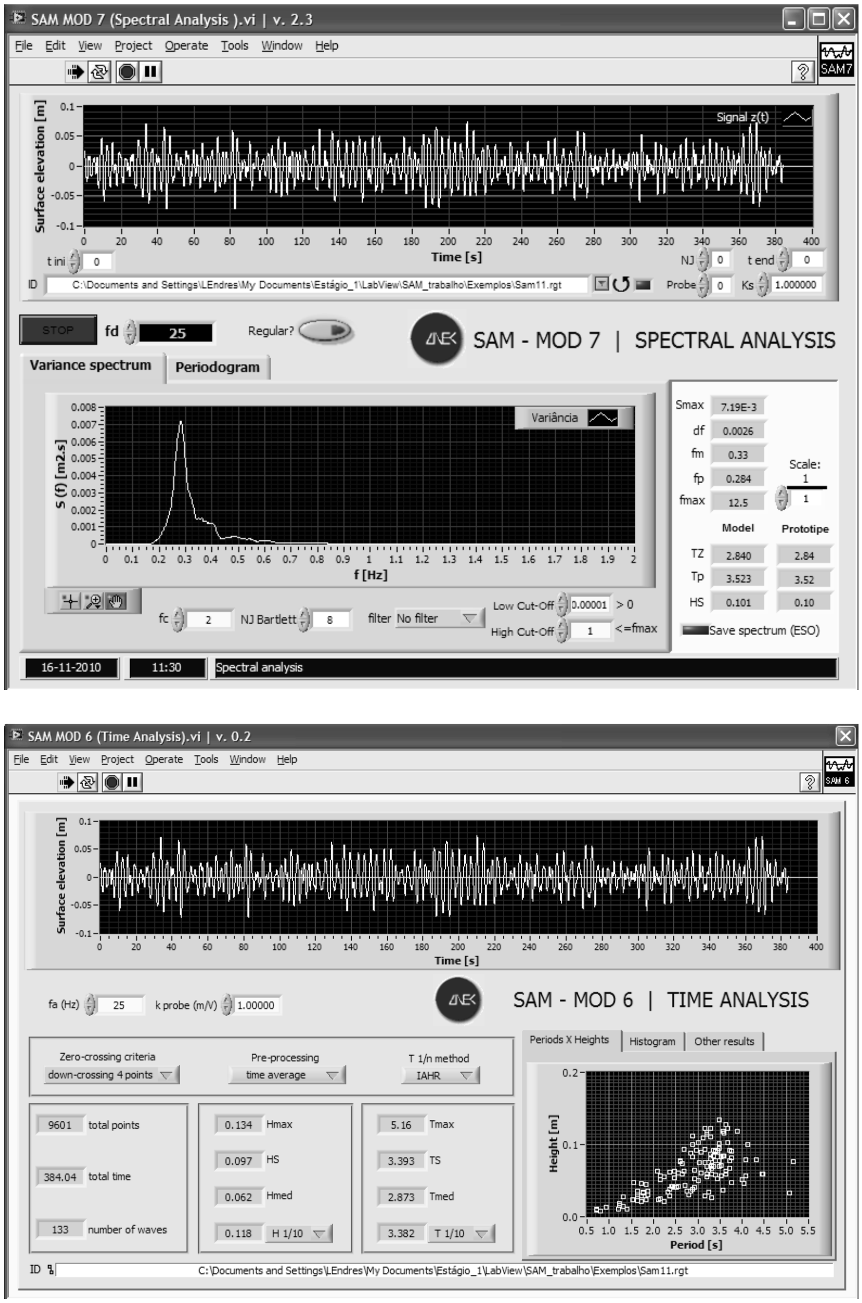
Table 1 shows the parameters used in the comparison between target values (labeled "Target") and obtained time and spectral values (labeled "Time" and "Spectral", respectively).

Table 1. Parameters used in the comparison

COMPARISON	Target	Time	Spectral
Significant wave height	H_{S-t}	H_S	H_{m0}
Mean wave period	T_{Z-t}	T_Z	T_{02}
Significant/peak wave period	$T_{1/3-t}$	$T_{1/3}$	T_p

The comparisons were made between target wave heights or wave periods (subscript *t*) and corresponding (comparable) parameters as obtained from spectral analysis (H_{m0}, T_{02} and T_P) and time analysis (H_S, T_Z and $T_{1/3}$). Results on time analysis are calculated for the down-crossing-4 pt criterion.

One should note that the last parameters (T_p for spectral analysis and $T_{1/3}$ for time analysis) are not comparable, but they were the best approximation for this type of comparison one achieved. However a comparison of these parameters may give an indication of the general agreement between them.



(a)

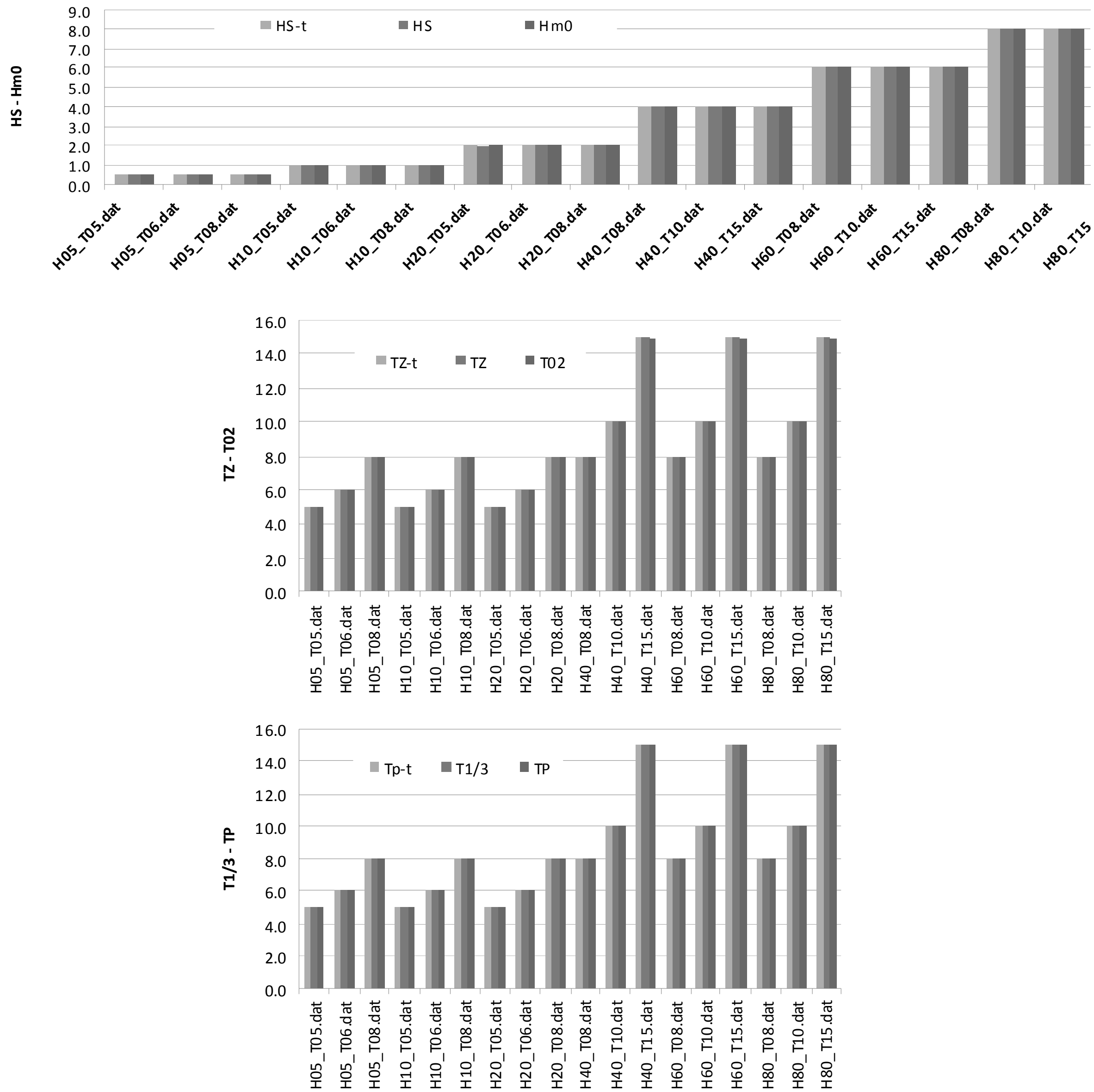
(b)

Figure 3. (a) Spectral and (b) time analysis modules of SAM software

5. 1 Numerically simulated regular waves

One started with regular waves numerically simulated. Regular waves propagate with permanent form, with constant height and period. These characteristics were devised using the numerical simulation module of SAM software.

As expected (see Figure 4), a total agreement between target height and period waves was obtained for a number of different conditions (H_S ranging from 0.5 m to 8.0 m; T_Z ranging from 5 to 15 s). The differences in all cases are negligible.

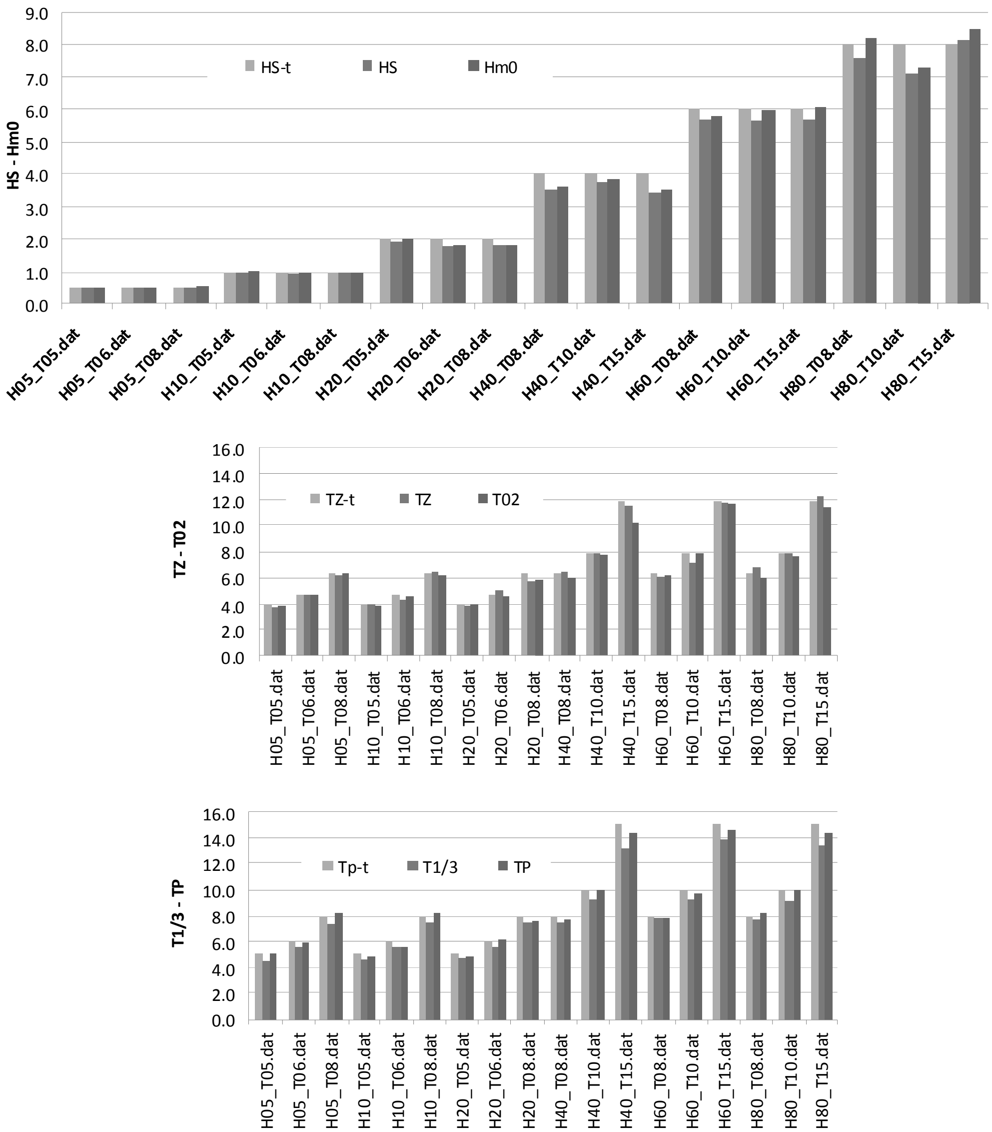


	Time analysis comparison			Spectral analysis comparison		
	HS-t vs HS	TZ-t vs TZ	T1/3-t vs T1/3	HS-t vs Hm0	TZ-t vs T02	Tp-t vs Tp
average diff. (%)	**-0.04**	**0.00**	**0.00**	**0.02**	**-0.13**	**0.02**

Figure 4. Comparisons for numerically simulated regular waves

5.2 Numerically simulated irregular waves

Now the records were numerically simulated as containing irregular waves using the numerical simulation module of SAM software again. A JONSWAP spectrum was used, with $\lambda = 3.3$, using the same values of height and period as in previous section. Here non-negligible differences may be observed, which are higher for higher wave heights and for higher periods (Figure 5).



	Time analysis comparison			Spectral analysis comparison		
	HS-t vs HS	TZ-t vs TZ	T1/3-t vs T1/3	HS-t vs Hm0	TZ-t vs T02	Tp-t vs Tp
average diff. (%)	**-6.34**	**-1.50**	**-7.81**	**-2.51**	**-3.44**	**-2.34**

Figure 5. Comparisons for numerically simulated irregular waves

Concerning the heights, small discrepancies are of the order of 0.3 to 0.4 m, when the heights are of 8 m (about 5% difference). For target wave heights less than 2.0 m, the agreement is almost total. For higher heights, the spectral method (darker plot) seems to better agree with the target heights (lighter plot).

Concerning the mean wave periods, both methods underestimate the target wave periods and this is worst for higher periods. For the peak/significant wave periods, the agreement is better than for the mean periods, although there is a somewhat uniform underestimation of the time analysis method relative to the target peak wave period. This is due to the fact that $T_{1/3}$ (time analysis) and T_p (spectral analysis) are not completely comparable.

5.3 Physical flume simulations of irregular waves

A number of irregular wave records coming from physical simulations were also considered. Here, the LNEC's COI1 experimental wave flume was used. The wave records coming from wave gage nº 3 (see Figure 6) were used in this study. The results of the comparison are presented in Figure 7, where "m_all" is the complete (concatenated) set of wave records coming from the wave flume.

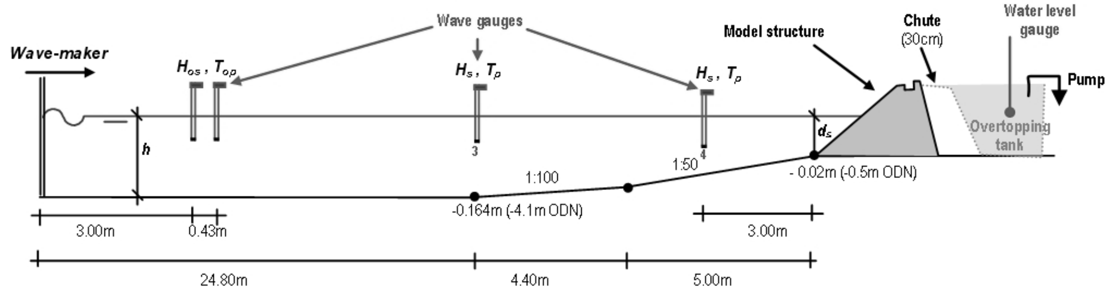
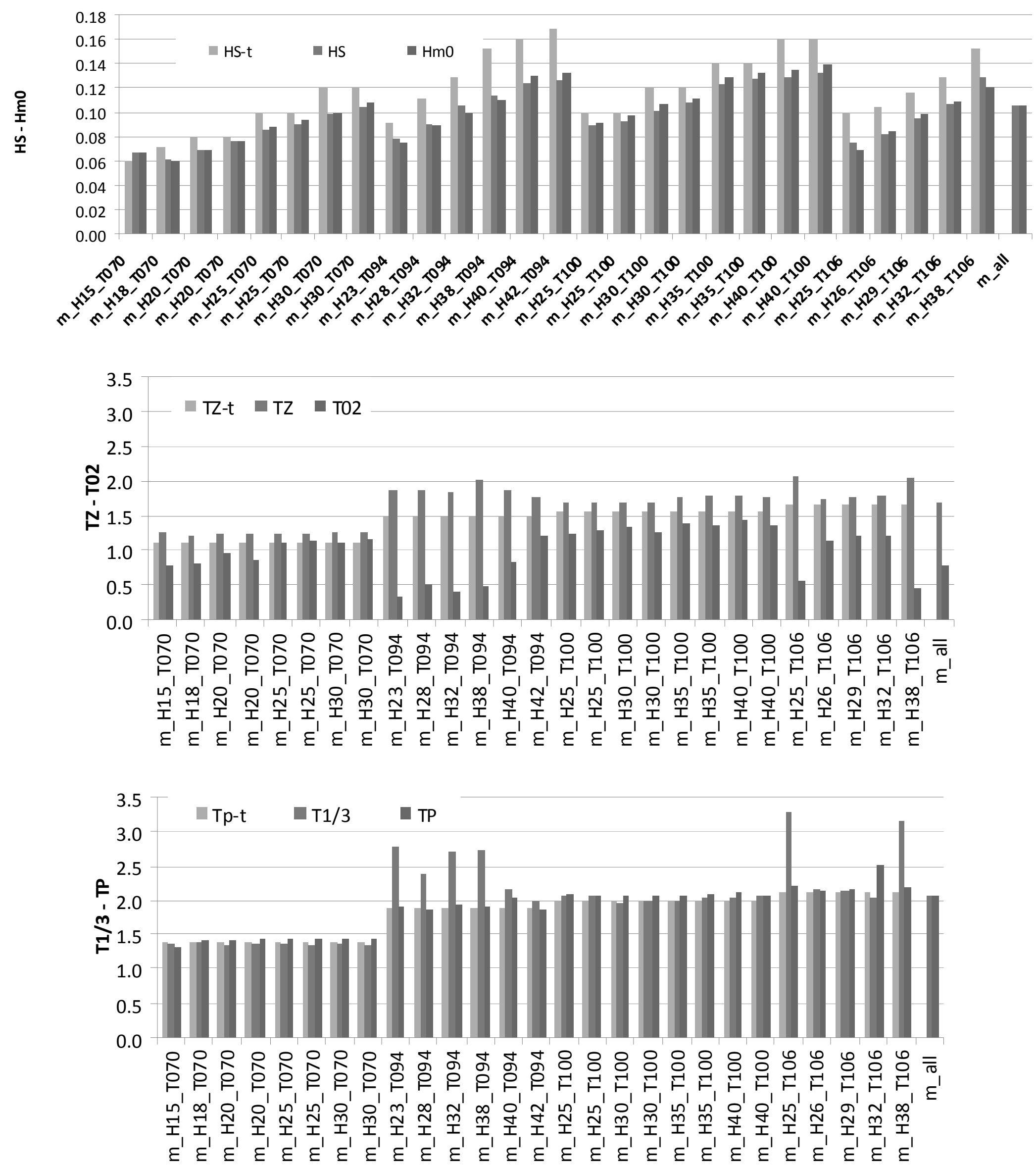


Figure 6. Setup used for the physical model tests of irregular waves



	Time analysis comparison			Spectral analysis comparison		
	HS-t vs HS	TZ-t vs TZ	T1/3-t vs T1/3	HS-t vs Hm0	TZ-t vs T02	Tp-t vs Tp
average diff (%)	**-14.93**	**15.01**	**10.24**	**-13.93**	**-28.50**	**2.83**

Figure 7. Comparisons for irregular waves in a physical flume

One observes in Figure 7 that the target values for both the wave heights and wave periods are generally higher (about 15%) than computed values for both analyses, with the spectral method giving slightly better agreement with target values (about 14%). These differences are mainly explained by the fact that, for such a long flume, there is always some loss of energy in the walls. Also, although an AWASYS active absorption system is used, reflected waves still exist in the flume, which may adversely affect the results.

Concerning the comparison of mean periods (T_Z-T_{02}), one observes that some wave records (*_T094 and *_T106) produce very low spectral parameters. The same happens if the time analysis is used although in a lesser extent. These odd values appear mainly in the mean period values, but the peak/significant period values still suffer from this same behaviour, although not so acutely. For this comparison, the spectral method is about 28.5 % off (lower values) the target values, whereas the time analysis method is about 15.0 % off (higher values).

6. Discussion

Numerical comparison tests with regular waves show the exactness of the methods. For irregular waves, the results show some small discrepancies due to the way the waves are defined.

In the flume irregular waves, one observes smaller values than target for both analyses, with the spectral analysis method giving slightly better agreement with target values. These differences are mainly explained by the fact that the real obtained waves in the flume are smaller than the target ones, and therefore the observed differences are not totally justified by the analyses. Actually, for such a long flume, there is always some loss of energy in the walls. Also, although an active absorption system is used, reflected waves still exist in the flume, which may adversely affect the results. Finally, the significant/peak period comparisons give good agreements, with the spectral analysis method giving better values, as some wave records give unexpected values for the time analysis method. Anyway, apart from 6 records, the significant/peak period comparisons give a quite good agreement. The spectral method is clearly more accurate (2.8% diff. only) than the time analysis method (10.2% diff. only).

Observed differences may indicate that some of the assumptions made for the comparison analyses are not correct. In particular, the wave heights may not follow the assumed Rayleigh distribution. In order to investigate it, the complete set of wave records coming from the wave flume (“m_all” in Figure 7) was considered and the Rayleigh distribution was fitted to the set. Figure 8 shows this comparison representing $\left(H/\overline{H}\right)$ from Eq. [1] with the symbol (H/Hmed).

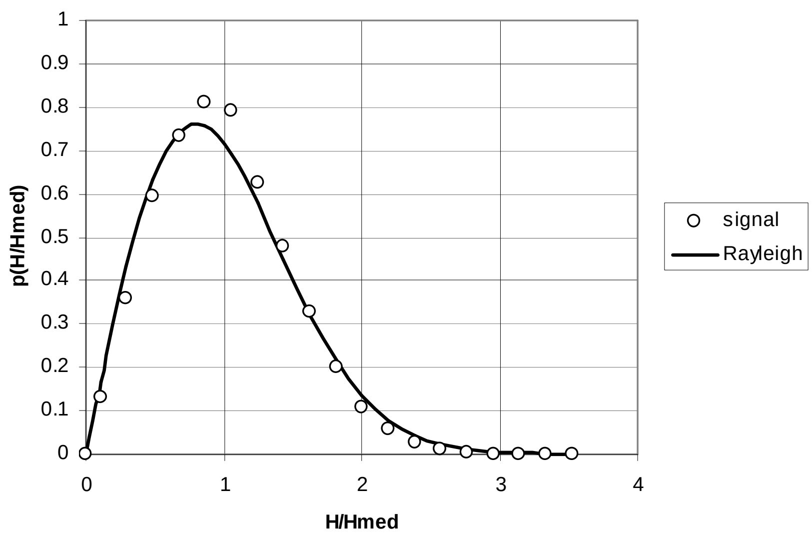


Figure 8. Comparison of the dimensionless histogram of wave heights (signal) with Rayleigh distribution values (Rayleigh).

The computed value for the deviation between sample values and values obtained from Rayleigh distributions (Eq. [2]) is 0.106, which confirms the good agreement observed in Figure 8.

7. Conclusions

Globally, the results show that both methods produce quite similar values for the wave height parameters, although significant differences are likely to occur for the wave periods, mainly if high target values are sought. Also globally, the spectral analysis method is better to estimate H_S (usually a slight underestimation exists) and the time analysis method is better for mean periods. For the peak/significant periods spectral analysis method seems to give better results also. The time analysis method is more sensitive to records where very small oscillations do occur. In these cases, some odd low values are computed. By changing the wave definition criterion, these may change significantly.

Both methods are now available in SAM. This enables one to quickly and effectively produce results one usually deems necessary for the everyday tests of a hydraulics laboratory in an interactive and friendly way.

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