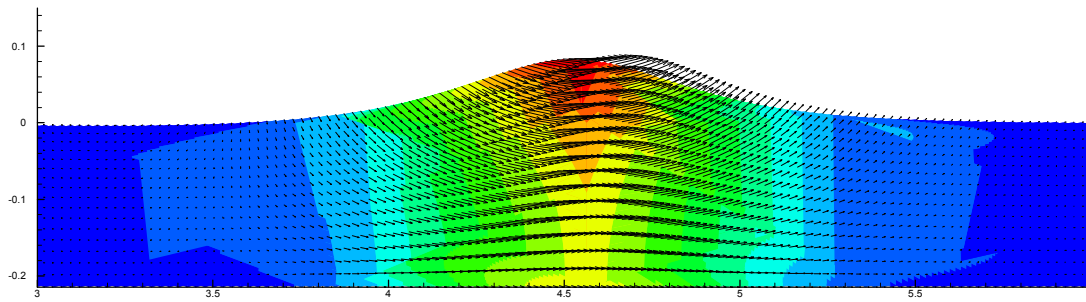


Solitary Waves and PIV measurements at IGAW Wave Flume



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Research Topic and Motivation:

The simulation of nonlinear waves can be carried out by using the conventional methods like Finite Element Method (FEM) and Boundary Element Method (BEM) based on Mixed Eulerian and Lagrangian (MEL) formulation. The simulations based on FEM have the advantages of extending the code easily to viscous flow and to 3Dimensional tank with complex geometry. In the context of FEM, the derivatives are usually found by differentiating the shape function, which is the direct differentiation of the velocity potential resulting in the velocity field lower than the approximation of potential, if one considers the linear element. In time-dependent problems this plays an important role. Thus, researchers have been focusing on obtaining the derivatives through different methods such as Global Projection, Local Finite difference, mapped FD, least square method. The present research topic is to investigate the need for smoothing/regridding and to overcome this at least for small steepwaves. The application of the developed code is used to carry out the extensive investigation on the Sloshing waves under random excitation, Solitary wave interaction with continental shelf and with vertical wall, interaction of steep nonlinear waves with submerged bar. The code is also extended to unstructured mesh with suitable velocity estimation technique and to 3D tank.

Research and Studies planned at Germany:

In our investigation, the proposed methodology based on cubic spline leads to phase shift in the results for steep nonlinear waves, but it works well for small steep waves. So, in order to have a clear understanding the experimental velocity measurement is required. Hence, it is planned to measure the velocity information using the wave flume in IGAW, Germany and compare it with our numerical code using two different velocity techniques (Cubic spline and Least square). We have planned to carry out the PIV measurements for regular, bichromatic and wave packets, which are already available at this flume. More importantly, we would like to generate the Solitary waves which are not so far investigated in this flume. It should be mentioned that the investigation on solitary waves is limited when compared to other kind of waves, due to the difficulties in generating this kind of long waves in the flume owing to the paddle

limitations, which are preliminary not intended to generate these extreme nonlinear waves and also the application is very limited in practical situation. Even though, the experimental paddle laws are well established in literature.

Difficulties faced in IGAW

If one could see that the research studies planned at IGAW is simple to look at the first instance apart from solitary waves, but as per the author's experience this is also easy to simulate in any flume within the limitation of the paddle. *In general research, if one thinks about some problem which is more important that leads to simple, but nature will show other kind of problem, which are practical and difficult to overcome.* The research stay at IGAW for 6 months gave me an excellent and wonderful experience in experiments and the difficulties that one faces while carrying out the experiments since, I have been involved in numerical work all these years.

The Wave flume at IGAW is moved from the main lab to the new lab. After it was moved, this is the first time to test the system once again. At first glance by visual observation, it seems that the system is alright but when it is tested, one observes that the paddle motion is large than the given signal. This is the first problem we have faced, it has been thought that this could be problem with the (Analog to Digital) AD card. The data acquisition hardware is from Computer Boards CIO-DAS 1601/12. This is a 12 bit card with 16 analog inputs and 2 digital output. The existing software code was written by Dr.Koola under AvH program taking +/-10 volts as the signal range, i.e., ranging from 0 to 4096, whereas the wave maker hardware is +/-1.5 volts which has lead to the usage of the external amplifier. Initially, we are not aware of the settings they have used in this external amplifier before it moved to the new place. Hence, we have tried to reduce the input signal by some constant factor (say 90%) to get the required output. Then we have measured the surface elevation at some location using the Wave gauges from Hannover, but we found that there are lots of noises in the signal. This is certainly due to the AD card problem. Now our intention has been slightly changed to check the complete system. So, we start from the scratch, by using the WaveTech signal generator, which could generate regular waves of various amplitude and frequency and to measure the signal

using Ultrasonic sensors (range of 350mm). At the same time, we would like to measure the paddle displacement, because when we checked the output using the AD card (there is a feedback signal exist) it shows lot of noise. Hence, above the paddle a plate has been fixed and the motion is measured using Ultrasonic probe as shown in Fig. 1. The test has been carried out for input frequency of 0.5, 1 and 1.5 Hz with constant amplitude. The measurement of the paddle displacement is shown in Fig.2.



Fig.1. Ultrasonic sensor for measuring paddle signal.

From the figure, one can clearly understand that there are lot of noises, which could be a problem with the electric induction by the wires or due to the wave Generator machine of IGAW or due to the motor signal or due to the mechanical vibration by the paddle. The first and last one based on induction of the high electric wire and mechanical vibration, respectively, has been checked as far as we have concerned and it could not be the problem. Hence the problem is either with the wave machine or with the motor. To know the difference with the target signal, the AD card was once again used and tested for Solitary wave. Since its easy to investigate the deviation as it is a single motion not a cyclic one.

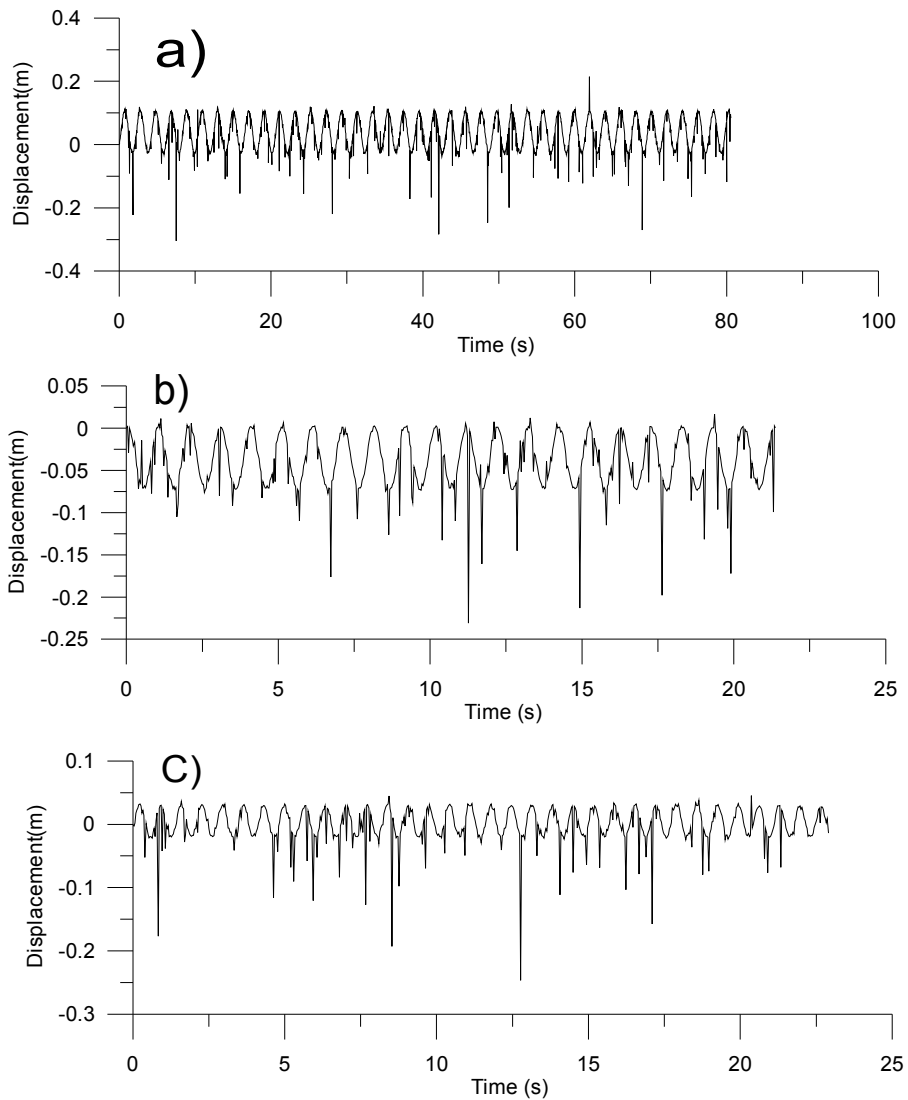


Fig.2. a) $f = 0.5\text{Hz}$, b) $f = 1\text{Hz}$, c) $f = 1.5\text{Hz}$ with constant amplitude of 1.

The Solitary wave has been generated in a water depth of 28.5cm having a target wave height of 3cm. The comparison between the target signal and the actual movement of the wave paddle measured using Ultrasonic probes is depicted in Fig.3. The starting point of the signal and the ending point of the signals are very important to simulate these waves, which highly depends on the accuracy of the wave machine. Solitary wave have infinite wave length, thus in the generation it has to be truncated where the initial acceleration is nearly zero, and at the starting point of the signal lot of high frequency component will merge. The zoomed in view of the fig. 3 (represented as A) at the starting point of the

signal is shown in Figure 4. The figure shows a sudden startup of the wave paddle instead of smooth startup of the target signal. The time histories of the generated wave at two different locations were depicted in Figure 5. The generated wave near the paddle shows a number of high frequency oscillations before the main wave generated and also the wave height generated is only 2.5cm which is far below the target wave height of 3 cm. The reason for the high frequency oscillation is due to the problem in AD Card, where as the reason for the later is due to the difference in the target signal and the generated one. The second and third waves in Figure 5 are the reflected waves from the beach, which is not designed for these waves. It should be mentioned here, the generated wave steepness (wave height/water depth) is 0.1, which is the minimum wave steepness. The maximum wave steepness for solitary wave is 0.7. Hence, there could be some major problem in the wave machine. The wave paddle motion of the Briggs *et al.* (1997) is shown in Figure 6 showing a smooth signal at the start up. These experiments were carried out in U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. Experiments are again carried out by reducing the water depth to 22cm and target wave height of 4cm. The paddle displacement is shown in figure 7 along with the target signal. The wave time histories at two different locations are shown in figure 8. The generated wave height is only 2.8cm, and a large disturbances before the main wave is seen.

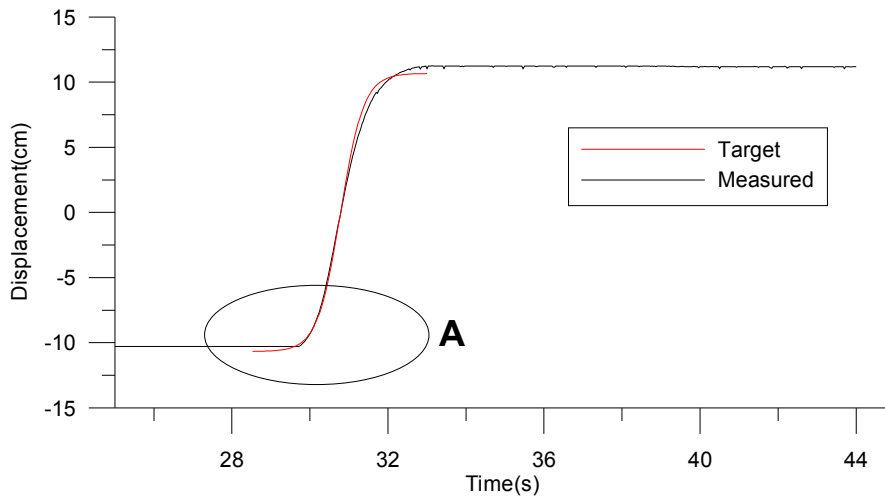


Figure.3.Target Paddle displacement and the measured Paddle displacement.

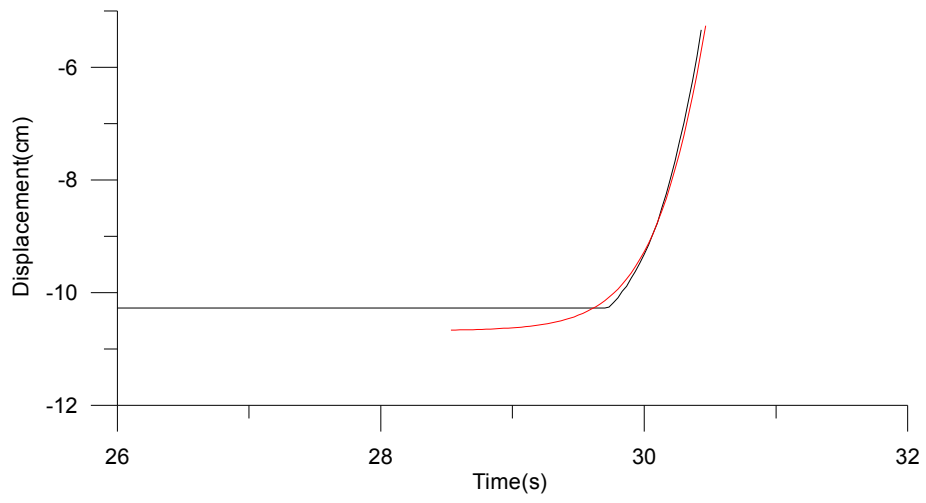


Figure.4. Zoomed in view of A shown in Fig.3.

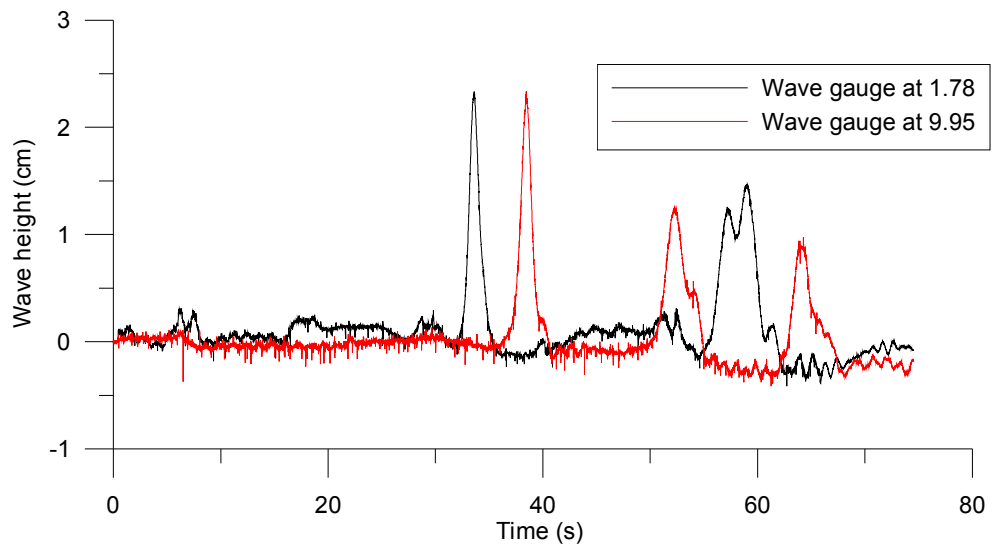


Figure.5. Time histories near and far away from the Paddle.

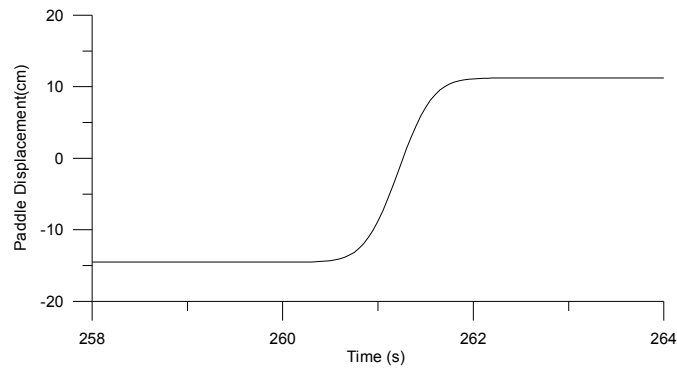


Figure 6. Wave paddle motion of Briggs *et al.*(1997)

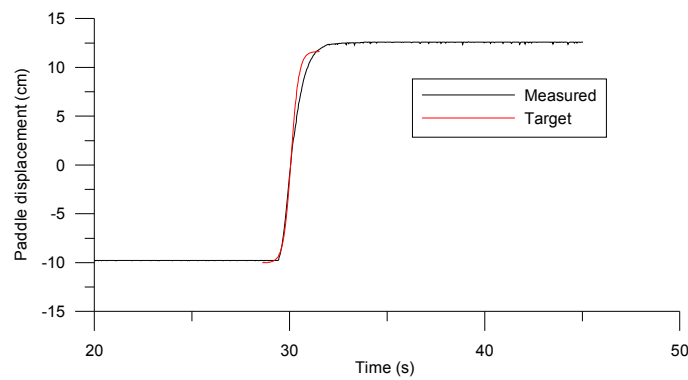


Figure.7.Target Paddle displacement and the measured Paddle displacement for a water depth of 22cm.

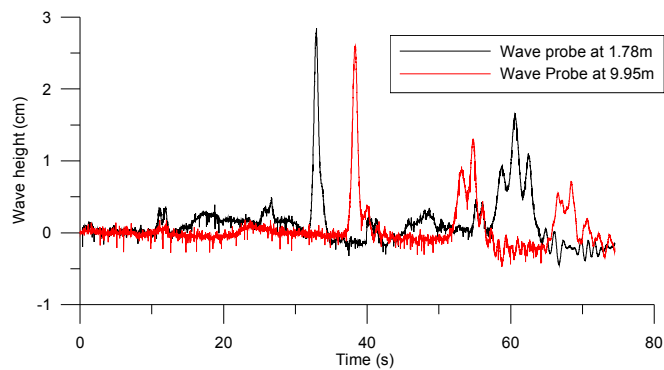


Figure.8.Time histories near and far away from the Paddle.

New Wave Machine at IGAW

To overcome this, the only solution is to replace the complete old system with the new one. Now, the query is *“Whether there is a possibility for the completion of the experiments successfully in the remaining short span of 2.5 months since already*

3.5 months were over?”. We planned to take the risk of ordering a new system which takes a period of 1 month to arrive. The new machine is fully digital one which is mainly used for cutting machine parts with high precision. It has in-built software but not intended for water waves. So, the task now starts again from the scratch to generate regular sine waves. At first glance regarding the new system, the software will support forward motion as one task and for backward motion we have to give another task. Hence in a long run it is questionable to generate random waves, bichromatic waves, whereas, the other kind of waves such as regular, Cnoidal and Rogue waves can be generated but with certain difficulties since the motion task has to be split up and given to the software stating what to do in the subsequent time. Where as, the Solitary wave which is a Single forward motion is the easiest of all the kind of waves (even compared to regular wave) considering the present system.

Results and discussions on the generation of Solitary Waves

Goring(1979) proposed the following formula for generating solitary waves based on extensive experimental measurement,

$$x_p(t) = S_g [\tanh 7.6(t/\tau - 0.5)] \quad (1)$$

Where,

$$S_g = 4\sqrt{\frac{Hd}{3}}, \tau = \frac{4}{\beta C} \left(\tanh^{-1}(0.999) + \frac{H}{d} \right), \beta = \sqrt{\frac{3H}{d^3}}, C = \sqrt{g(d+H)}$$

It has been reported that to reduce the trailing waves during generation, the time τ has to be increased by 10%.

Based on this signal, solitary waves are generated in the lab. Again, as it is a new system, we would like to check the motion of the paddle with respect to the given signal. The paddle motion is again measured using the Ultrasonic sensors and it is shown in Fig. 9 for $H/d = 0.1, 0.2$ and 0.3 . The figure shows that the paddle is reproducing the given signal exactly. We could not able to measure more than this steepness, since the maximum sensor range is 350mm. But, the results are promising than expected. Thus, the transfer

functions need not to be established for the present new system when compared to the systems based on AD cards.

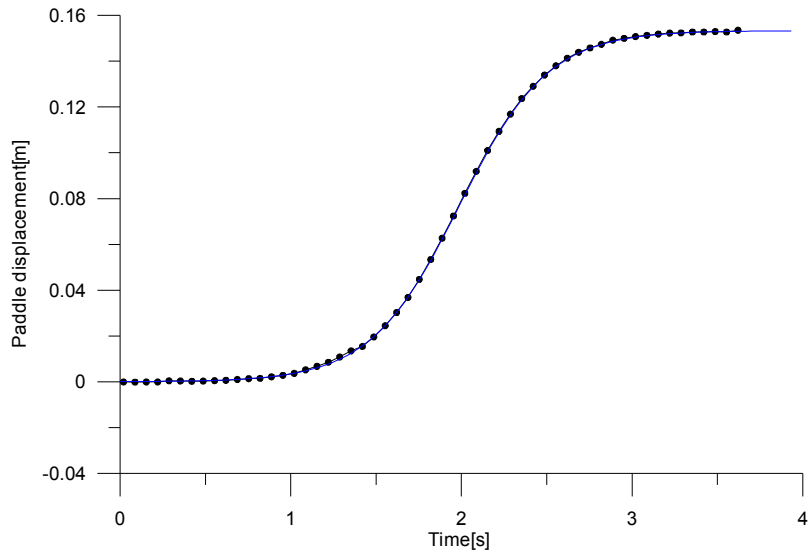


Fig.9a, Measured (dotted) and targeted(line) input signal for $H/d = 0.1$

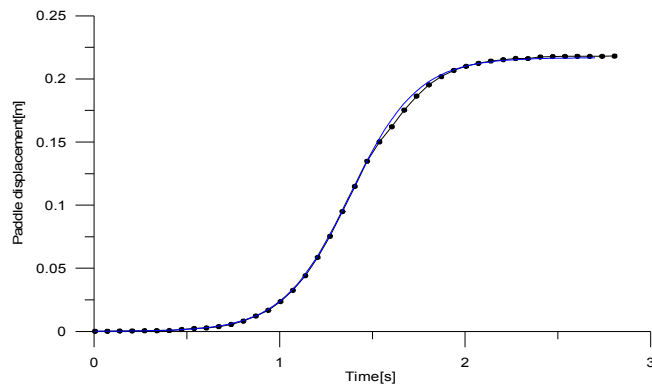


Fig.9b, Measured (dotted) and target (line) input signal for $H/d = 0.2$

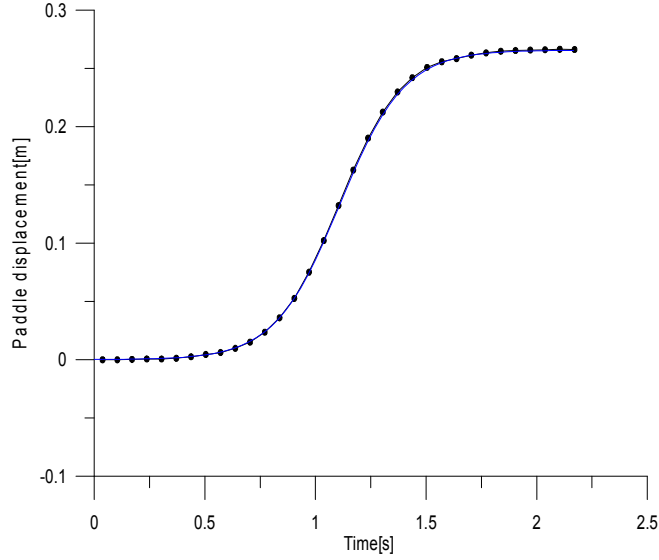


Fig.9c, Measured (dotted) and target (line) input signal for $H/d = 0.3$.

When using this formula for generating Solitary waves, we could not able to generate waves more than $H/d = 0.4$, the reason is the motion is too fast so there is a jerk in the paddle which could be visually seen. This is more mechanical problem than the electric one. Hence, we have used the Goring (1979) theory for generating solitary waves, which is given below.

The simulation of solitary waves by prescribing the ‘piston’ wave maker motion is determined from the first order Boussinesq wave theory used by Goring (1979). The velocity of the wave maker is given by,

$$\dot{x}_p = \frac{cH}{h} \frac{1}{\cosh^2 \chi(t) + \frac{H}{h}} \quad (2)$$

and the paddle displacement is

$$x_p(t) = \frac{H}{k} \left[\tanh \chi(t) + \tanh \frac{k}{h} L \right], \quad (3)$$

$$\text{where, } \chi(t) = \frac{k}{h} (ct - x_p(t) - L) \quad (4)$$

and $k = \sqrt{3H/4h}$, $c = \sqrt{g(h+H)}$. The implicit eqns. (3) and (4) is solved using the Newton –Rapsion method. For the truncation of the initial motion (L in Eqn.(11)) reader can refer Grilli and Svendsen (1990).

The difficulties arising due to this implicit equation is that the trailing waves are more pronounced than the simple formula given in Eq.(1). But in the current flume this is not the case, which will be dealt in the subsequent paragraph.

Using the present equations the generation of solitary waves has been carried out and the surface profile has been measured using ultrasonic probe. The reason for still using the ultrasonic probe for measurements when compared to the wave gauges rented from University of Hannover is the width of the flume is small and the wave gauges are mainly used in larger flumes at Hannover, so we found large disturbance of waves when this gauges are deployed, i.e. diffraction. Hence, we preferred to use ultrasonic probe, which are available only 2 in number with the range of 350mm. Having found that the paddle motions are alright, there is no need to measure it any more. So, the probes are located near by the wave paddle (5m) and at 15m. The water depth is 0.21m and the target is 0.021m the measured wave height as shown in Fig.10. The interesting feature which we have noticed from the figure is that the free surface elevation at the far end is high than the input. When we examined the flumed, it has been noticed that the water depth is not constant and the flume is erected with some inclination. Hence, the flume is rectified for the constant water depth, even then we found that the width of the flume is elongated to 3mm at certain locations on the flume where there is no stiffener provided. This effect is more after 8m. So, the effective length of the flume is reduced to 8m.

Thus, the flume width is reduced herein, the experiments are again carried out with the water depth of 0.2145m for $H/d = 0.1$ to 0.4 and measured wave height is compared with the numerical simulation as shown in Fig.10b-e, from the figure it is clearly noticed that the measured wave height is small and the profile is different when one compares to the numerical simulation for smaller steepness, whereas for steep waves, even though the wave height remains the same but the width of the solitons are small, the reason is the mass of the water that is generating is different, even though the paddle signal is exactly the same.

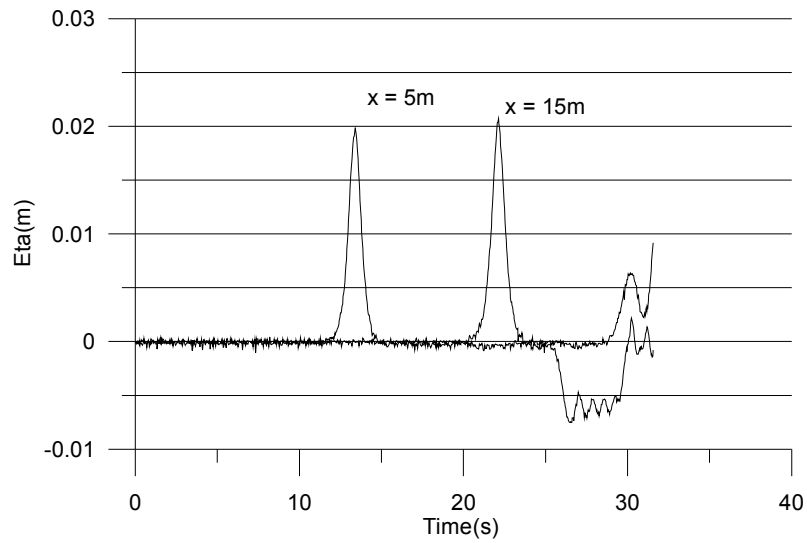


Fig.10a. Time histories for $H/d = 0.1$

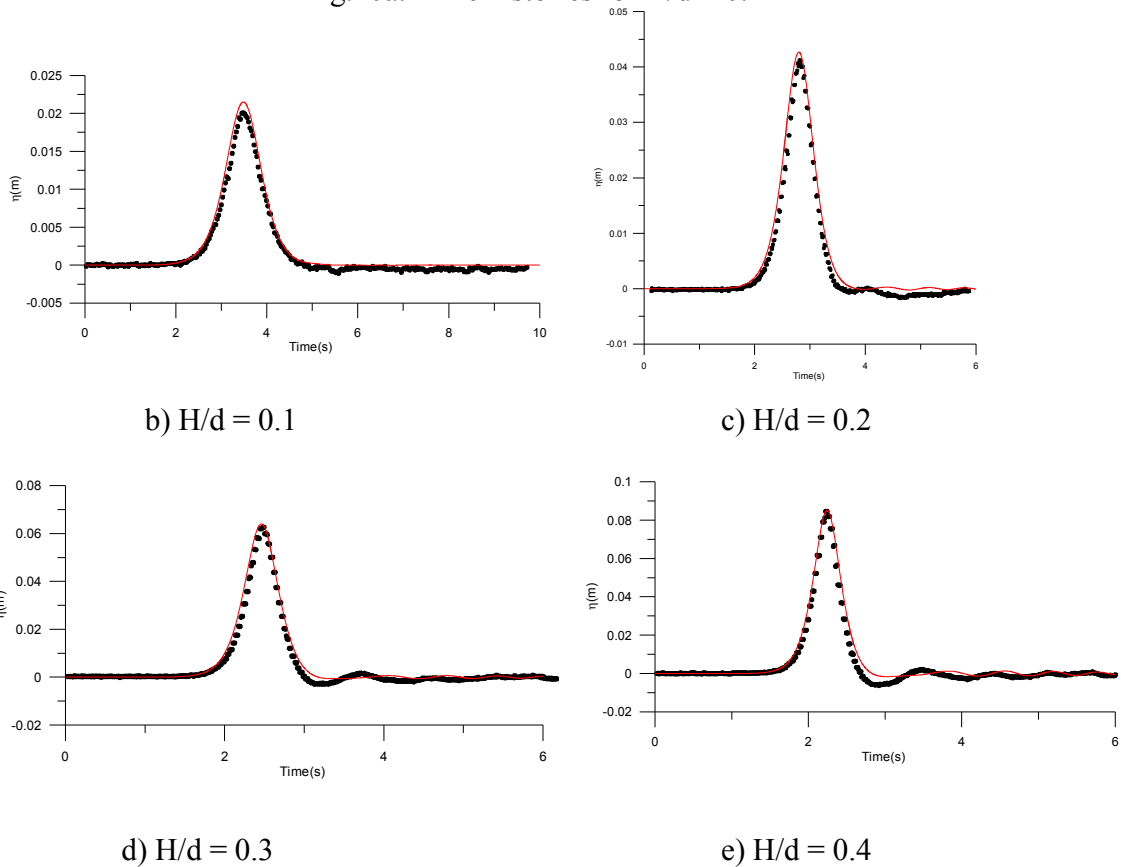
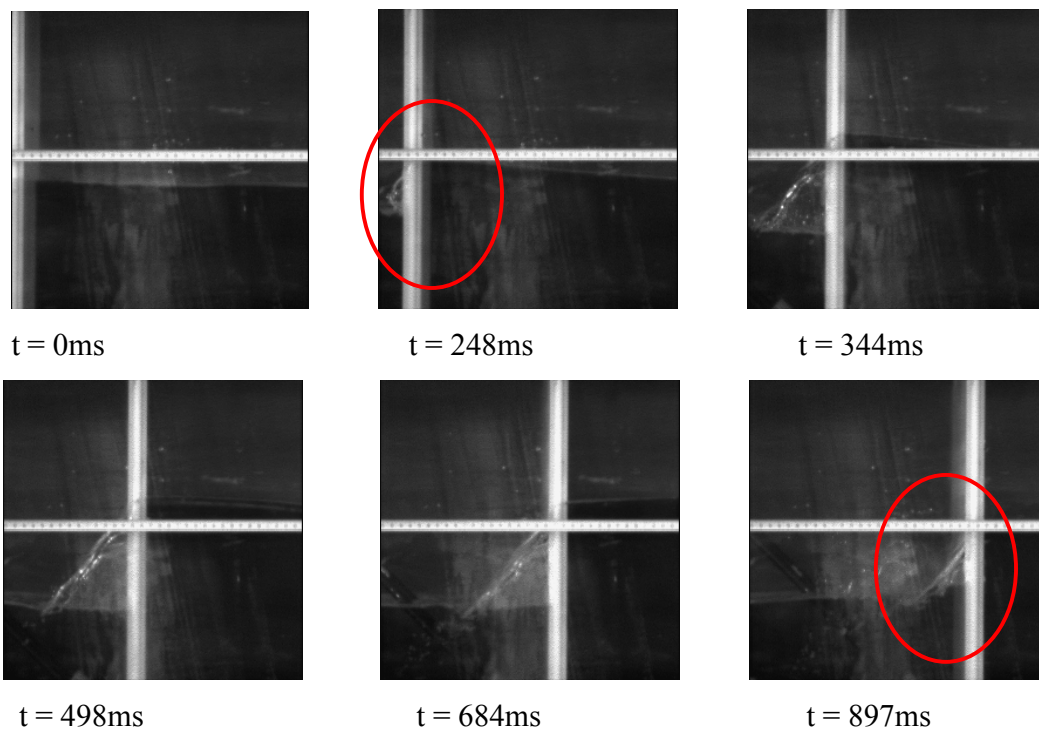


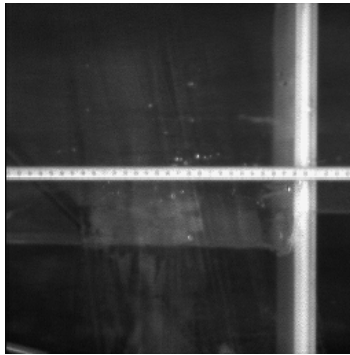
Fig.10, Comparison between numerical (line) and experiments(dotted)

The loss of volume of water is due to the fact that the water is flowing backward of the paddle when it starts generating, through the gap between the wave paddle and the side walls. The width of the flume is very small, so this effect is more pronounced. The reason

for the wave height remains unchanged for the steeper ones are owing to the fact that the time of stroke is very fast, when compared to smaller steepness. Since the width of the profile is small, the waves are become unstable and lead to trough formation (more trailing waves than expected). This feature has been captured using the high speed camera and the various snap shot is shown in Fig.11.

One can minimize this effect by adjusting the input signal to generate the target wave height and profile. This could be done by increasing the stroke and adjusting the upward acceleration and downward acceleration of the signal by trial and error method to generate the required profile and wave height. It should be noted that this has to be done for all the wave steepness and one cannot establish a single transfer functions, since the amount of water flowing backward will be different for different signals. Hence, we have carried out a trial and error method to generate the target profile for different steepness. The fig. 12, shows the input signal for the numerical model (i.e., the real one) and the signal given to the paddle (i.e., based on trial and error) to generate a same wave height at the location 1.743m from the paddle. The target wave height and its comparison have been shown in Fig. 13.





$t = 2348\text{ms}$

Fig.13. Snap shots of the water flowing through the side walls.

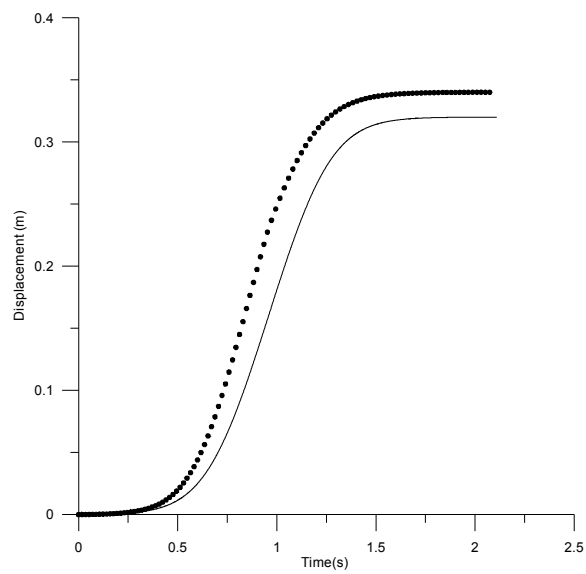


Fig.12. Showing the real signal (Line) and the input signal(dotted) to the paddle to generate same wave height($H/d = 0.1$).

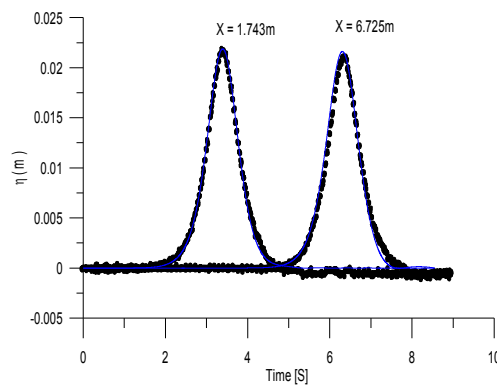
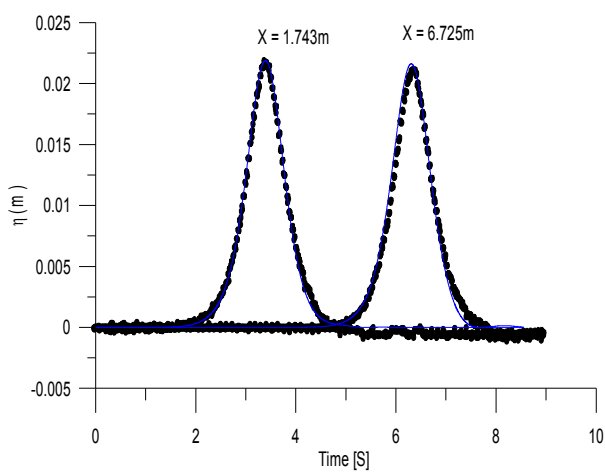


Fig.13. Comparison with the numerical and Experimental measurement for $H/d = 0.1$.

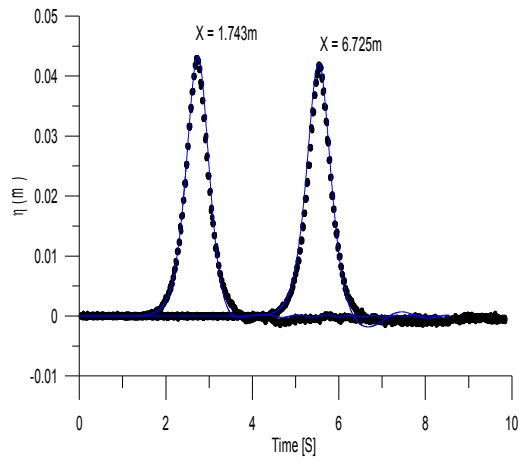
The fine tuning of the profile for different wave height has been depicted in Table 1. It should be noted that these values are established for a water depth of 0.2145m and it should not be generalized. This kind of test should be carried out again for the user's water depth, and one could not establish a generalized transfer function for this problem. Even after this modification, we have seen certain mismatch in the profile, which would be adjusted in the numerical simulation to get the profile exactly at the incident location (1.743m). In Fig.13, we could note another interesting feature that after the main wave passes, the oscillation is below the zero level, which once again proves that the water is flowing back through the side of the wave paddle after reaching the extreme position of the input signal. This will eventually reduce the trailing waves that should be presented in solitary wave, but actually there are lots of researches on this topic of minimization of trailing waves. Thus, in higher wave steepness, one could clearly see that the numerical simulation and experimental measurement have difference in comparison. The comparison between the numerical simulation and experimental measurements for steepness ranging from 0.1 to 0.5 are shown in Fig.14.

Table.1. Actual input and modified input signal details for a water depth of 0.2145m.

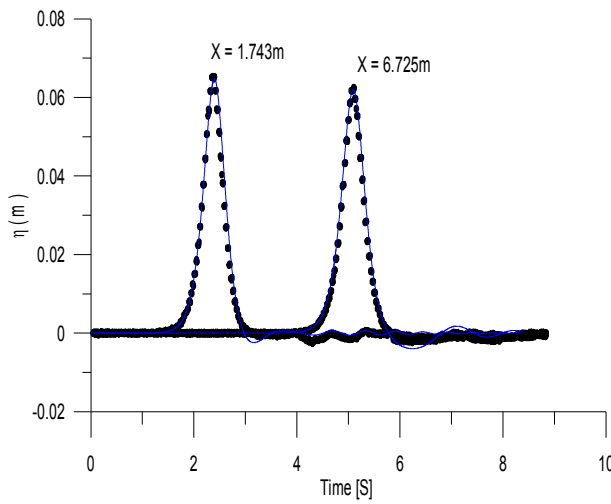
H/d	Actual stroke(mm)	Actual time of acceleration for upward and downward (ms)	Input stroke(mm)	upward time of acceleration(ms)	Downward time of acceleration(ms)
0.1	157	2211	172	2061	2461
0.2	222	1535	242	1305	1850
0.3	272	1235	292	1005	1405
0.4	314	1055	340	855	1255
0.5	351	934	385	734	1134



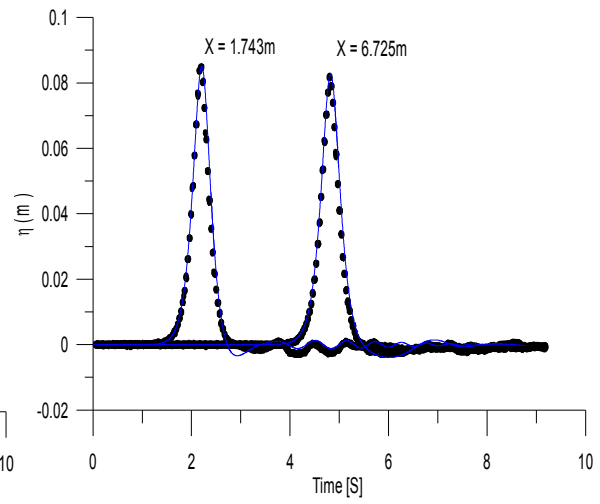
a) $H/d = 0.1$



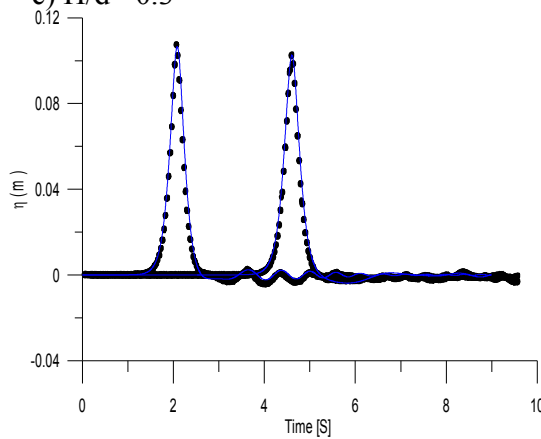
b) $H/d = 0.2$



c) $H/d = 0.3$



d) $H/d = 0.4$



e) $H/d = 0.5$

Fig.14. Comparison between numerical (line) and experimental(dotted) time histories.

In the above figures, apart from the good results for the main wave, one could easily find that the trailing waves are less when compared to the numerical simulation, since the water is flowing through the side of paddle.

Particle Velocity Measurement and its comparison

The particle velocity measurement has been carried out at the location 3.45m from the wave paddle using the high speed camera of IGAW. The light settings are more or less the same as in the old lab, described in Bung report. We have used two 1500 watts from the top on the right and left side and three 150 watts exactly at the top of the measurement location. There are two 150 watts at the bottom of the flume with the spacing of 50cm apart. There are two 1500 watts in front of the flume on the right and left side of the camera. These settings are shown in Photo 1. There should be a black paper at the back of the flume to avoid the visibility of the wall through the glass.

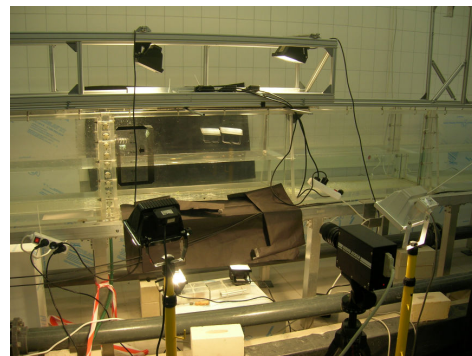
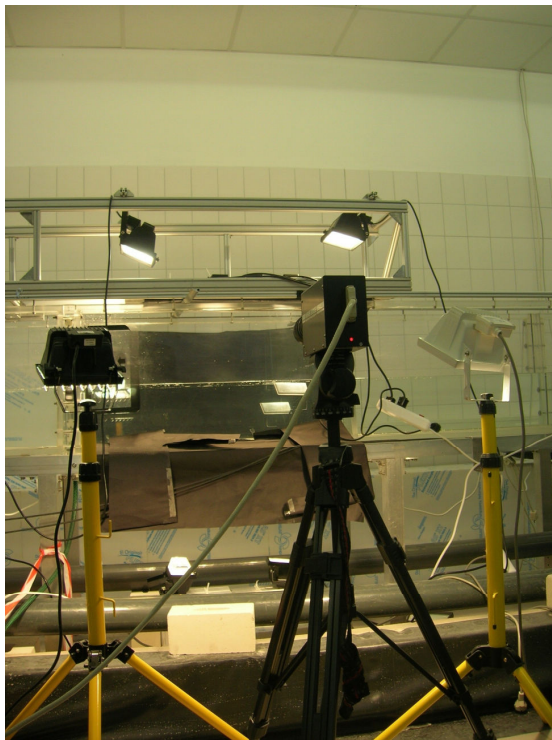
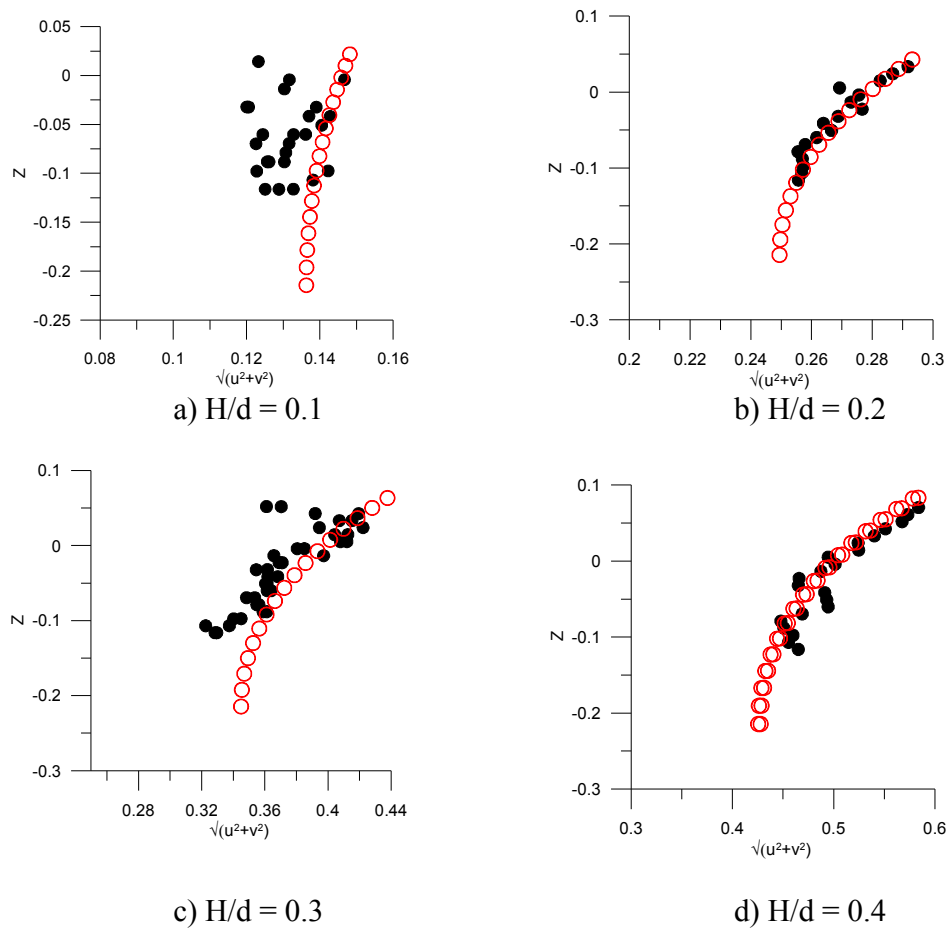
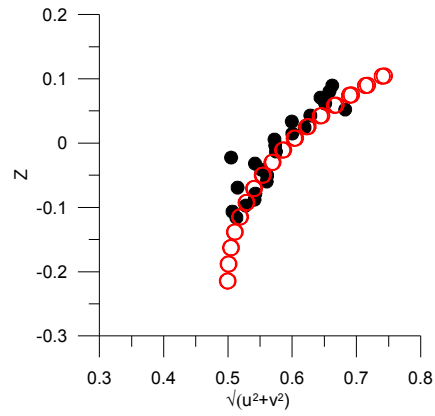


Photo 1. Light settings for PIV measurements.

The camera is placed at 1.45m (focus) from the center of the flume, it should be noted that the minimum focusing distance should be 1m. So, for small steepness waves of 0.1, we have found lots of noise in the data, leading to spurious velocity informations. The field of View (FOV) is 0.26 x 0.26m. The sampling interval is 0.002s and for analysis it is 0.004s, such that the mean of the particle in FOV to move at least one cell distance to avoid spurious velocities. MATPIV developed by Sveen (2003) has been used for the analysis. The comparison between the numerical and experimental measurement for velocity is shown in Fig.15. The figure shows good comparison for velocity magnitudes apart from $H/d = 0.1$, the reason stated above. The spatial velocity information using PIV and numerical simulation is depicted in Fig.16.





e) $H/d = 0.5$

Fig.15. Velocity comparison between experiments (dotted) and numerical simulation (line, Least Square).

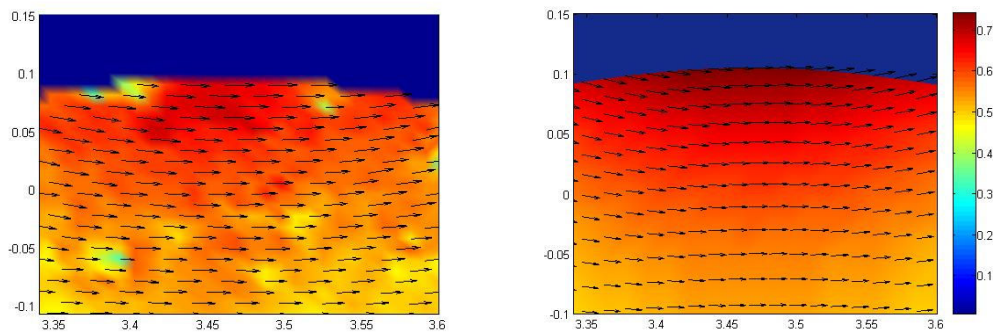
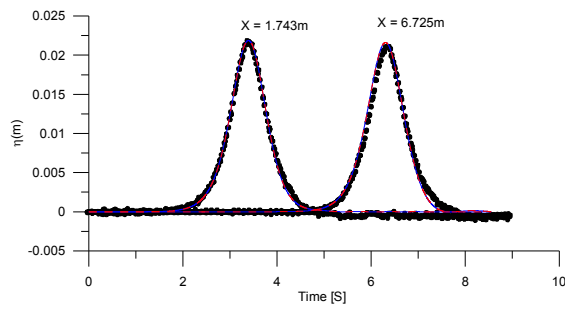
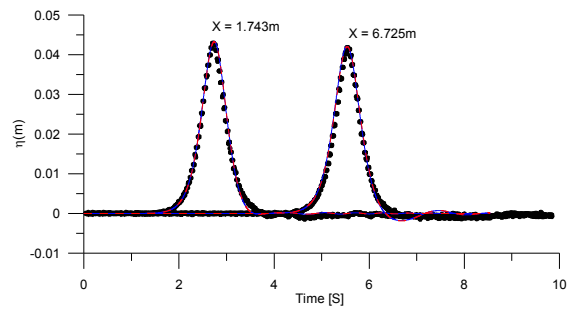


Fig.16. Spatial velocity information using experimental PIV measurement (left) and numerical simulation (right)

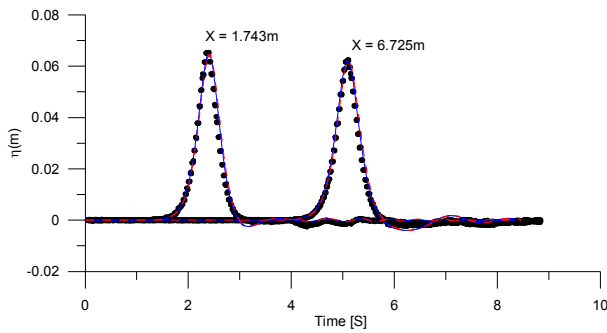
The numerical simulations, which is reported in the previous sections are based on least square approach, as it has been pointed out earlier, the main purpose is also to analyze the other numerical procedure based on cubic spline for estimating the velocities. Hence, the results based on this approach is overlapped and showed in Fig.17 for time histories. The velocity results are depicted in Fig. 18. From the Figures, it is clearly seen, that the cubic spline approach looks same as that of the least square method upto the steepness of 0.3, above that steepness there is a phase shift(Fig.17d,e) and slight reduction in velocities(Fig.18d,e).



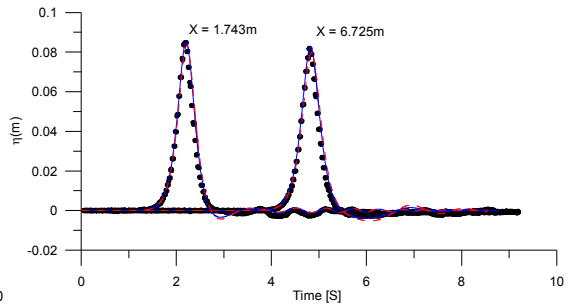
a) $H/d = 0.1$



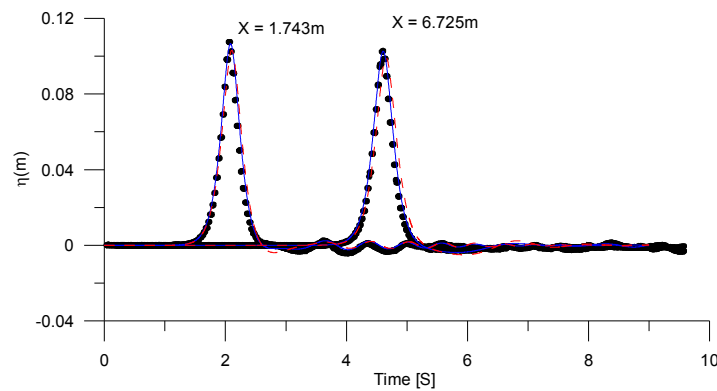
b) $H/d = 0.2$



c) $H/d = 0.3$



d) $H/d = 0.4$



e) $H/d = 0.5$

Fig.17. Comparison of Time histories for Experiments (dotted), Least square (line), and Cubic spline (Dashed line)

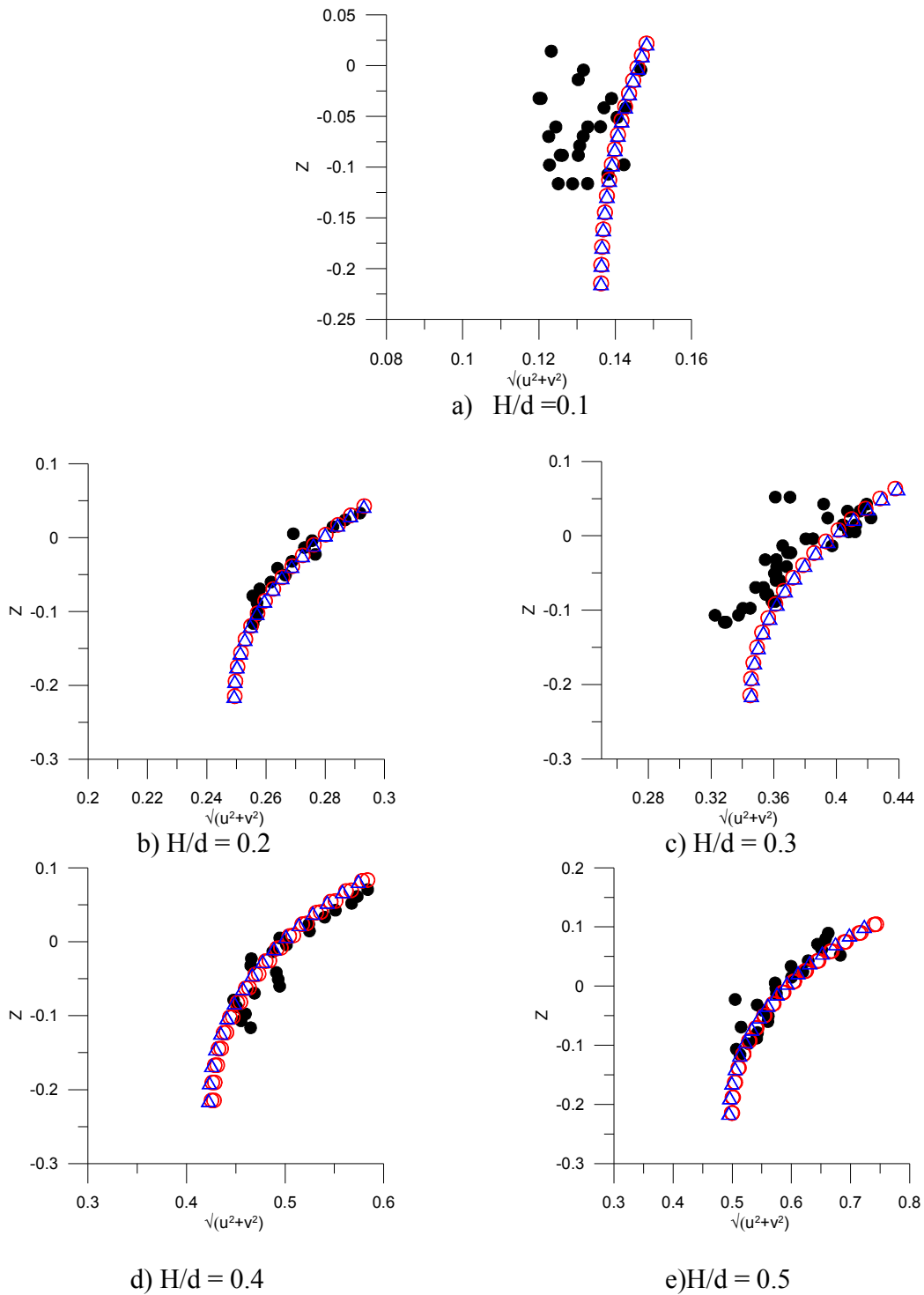


Fig.18. Velocity comparison between experiments(closed circle), least square (open circle) and Cubic spline(triangle)

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