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Model tests on overall forces on the SSG pilot plant

by

Lucia Margheritini
Alex Morris

October 2007

Preface

This report presents the results on overall forces acting on the SSG structure in 3D wave conditions. This study was done according to the Co-operation agreement between WEVEnergy AS (Norway) and Aalborg University, Department of Civil Engineering of which the present report is part of Phase 5.

The tests have been realized at the Department of civil Engineering, AAU, in the 3D deep water tank with a scale model 1:60 to prototype and a reproduced bathymetry of the selected location at the time of the experiments. Overall forces and moments have been measured during the tests.

The results are given in terms of maximum forces in the three different directions and respective application points on the structure. Also results in terms of overturning moments are presented.

The tests have been performed by Lucia Margheritini, Alex Morris (guest student) with the supervision of Jens Peter Kofoed, AAU. The testing took place during June and July 2007. The report has been prepared by Lucia Margheritini (e-mail: lm@civil.aau.dk).

Revision History

Version	***Date***	***Author***	***Comment***
0.0	20.10.2007	Lucia Margheritini	

Introduction

This report presents results from laboratory tests on overall forces and overturning moments acting on the SSG structure under design wave conditions. The tests have been carried out in the 3D deep water tank at the Hydraulic and Coastal Engineering Laboratory at Aalborg University. One hundred years return period waves have been used, according to the survivability standards decided for the SSG Pilot plant. Different tests have been done changing the water depth, the spreading and the wave's attack angle.

The motivation behind this study was the request from the constructors of the SSG pilot to have additional information on overall forces acting on the structure. Previous results on pressures (Vicinanza et all.), which by integration could be easily modified into forces, were too conservative in the constructors' opinion and there was not clear indication of which pressure was acting at the same time of others. Moreover no application point of the maximum forces was given. Thus, the purpose of this report is to clarify, where possible, all these aspects. In addition, two overturning moments on the structure have been calculated by measurements of moments in specific points of the structure. Additionally, a comparison between these results on forces and the ones calculated by the integration of the pressures on the surface of the SSG will be showed; the expected differences will be excuse for discussing the setup and the measurement methodology.

Objectives of the tests

The specific objectives of the tests were:

1. to measure time series of forces acting on the model in the three different directions under design wave condition and different water depth, spreading and angle of attack.
2. To measure time series of moments under design wave condition and different water depth, spreading and angle of attack.
3. To find the maximum forces (F1/250) acting on the three main directions and the overturning moments.

Moreover, overturning moments on the structure have also been calculated. The purpose of this report is to give information on the overall forces and overturning moments acting on the SSG pilot plant's structure under design wave conditions or critical condition for one or more parts of the structure. Also, the application points of the maximum forces have been calculated from pressures data files recorded during previous tests in the same setup (Vicinanza et all.) with pressure transducers (5,000 DKR each); these and are considered to be representative of the application points of the present set of tests.

Tests setup

The testing was conducted in the deep water wave tank at Aalborg University. The model of the SSG wave energy converter is in scale 1:60 to prototype and it has been realized by adapting the old model used by Vicinanza (in March 2006) to the latest drawing available. The Plexiglas model is 530mm long, 157mm high and 130mm wide. The lengths of the ramps are 67mm, 71mm and 76mm from bottom to top.

It must be noticed that the present structure results about 3 meters higher and 2 meters narrower (prototype scale) then the one tested by Vicinanza one year and a half ago. The model is representing it as good as it is possible.

Measuring equipment

In order to measure the forces and moments acting on the structure, two transducers were used (Figure 1). One is a 'bone' transducer (7,500 DKR) using pairs of strain gauges in a Wheatstone Bridge to measure the moments at two points and one was a tri-axial load cell (30,000 DKR) which measures the forces in all three axes. These were placed on top of each other. This setup, even if has the disadvantage to obstruct part of the waves to the upper part of model, has been tuned in order to simulate the static response of the structure. Both the instruments were recording at 50Hz. The structure behaviour simulates the prototype one, a part from the natural frequency of our model has been measured and can be filtered. Note that the axes used for these tests are shown positively in Figure 1 and all references to the x, y and z directions in this report refer to this. The 'bone' transducer measures moments in 2 planes so some tests were repeated with the moment transducer turned 90 degrees to measure the sideways moments (Figure 2). It had been thought that the sideways overturning moments might be quite large because the surface is not inclined, unlike the front. The SSG model is suspended a few millimetres above an artificial landscape reproducing the bathymetry of location 1 (first choice for installation of the SSG pilot) by rigid connection to the bridge over the wave tank. Generated wave are monitored by 7 wave gauges between the wave paddles and the model, enabling 3D measurements. The setup of the wave tank is showed in Figure 3.

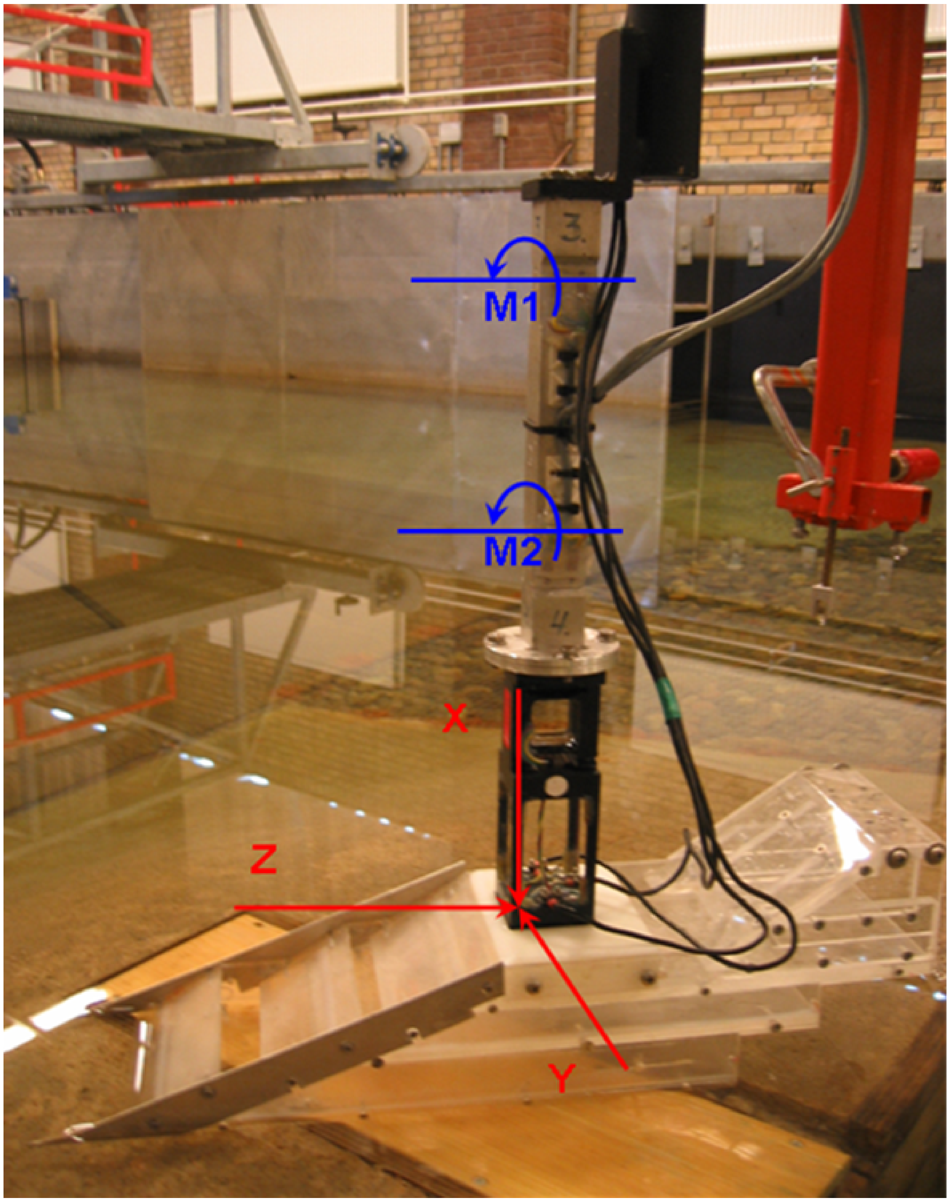

Figure 1 - Photograph of the SSG 1:60 model with the positive directions of forces and moments measurements.

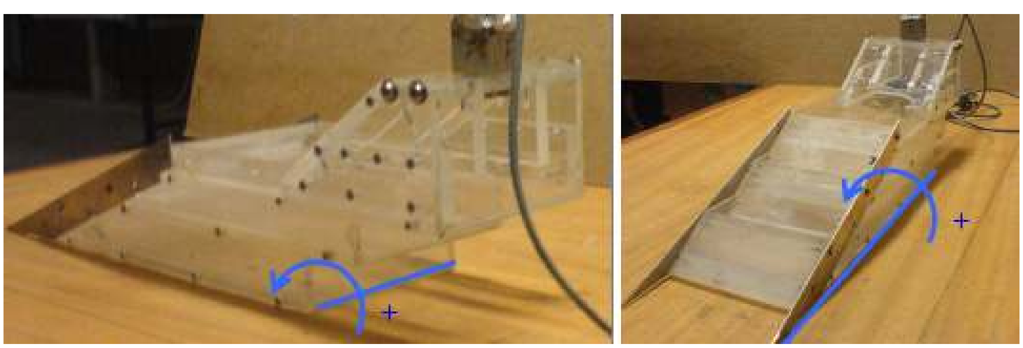

Figure 2. Two corners of calculation of the overturning moments.

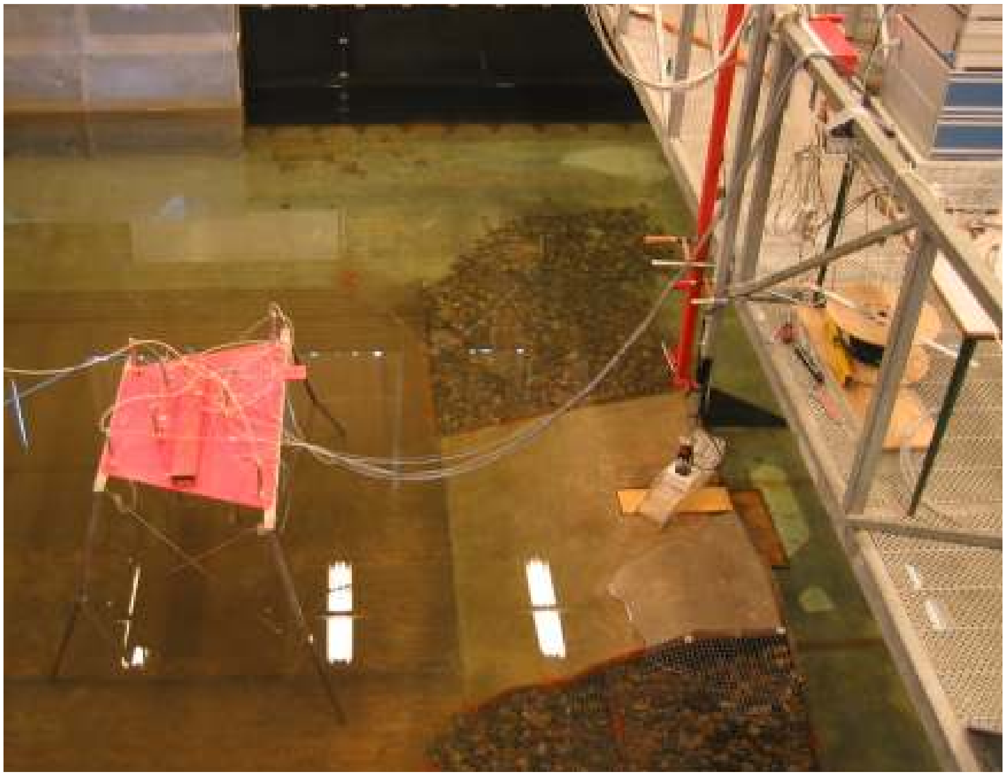

Figure 3. Tests setup. The 1:60 model is placed on an artificial cliff and turned of 45° in order to simulate the 45° wave's attack angle.

Description of Tests

All of the tests were run for the 30 minutes and the initial tests were all 3D with a spreading of 10 and a water depth of 0.66m (2.5cm free space on the lowest crest, model scale). Further tests were then done in order for comparisons to be made; firstly with 2D waves and then with 3D waves at a higher water depth (increased by 3cm). The wave conditions for the tests correspond to values around the design criteria of a 100 years event (0.208m Significant Wave Height, 1.94s Peak Period for head on waves, model scale) , as well as some with more and less extreme conditions. In particular the 45° attack angle on the structure has been tested as it represents the most demanding condition for the lateral vertical wall. The forces and moments were recorded in WaveLab and the wave data in Catman. The equation for the spreading is below, where 'n' is the spreading coefficient taken as 10.

$$\cos^{2n}|(\beta - \beta_0)/2|$$

To achieve the 15 degree angle of attack, the wave generating paddles angled the waves. With the 45 degree angle of attack however, the model itself was turned because narrowness of the tank means that it is impossible to achieve such an angle with the wave paddles due to reflection from the side walls (Figure 3).

The bathymetry was not moved because it does not directly relate to the sites currently being considered for the SSG and has little influence (error smaller compared to other assumptions for the measuring equipment, for example).

Table 1. Realized parameters during the tests, model scale.

Significant Wave Height (m)	Peak Period (s)	Angle of Attack (degrees)	Moment Transducer Direction	Type of Waves	Water Depth (m)
0.1058	1.546	0.9	z axis	3D	0.66
0.1541	1.781	2.9	z axis	3D	0.66
0.1854	1.743	0.9	z axis	3D	0.66
0.2093	1.862	1	z axis	3D	0.66
0.1052	1.575	1.5	y axis	3D	0.66
0.1488	1.781	2.1	y axis	3D	0.66
0.2001	1.707	2.5	y axis	3D	0.66
0.2142	1.95	1.5	y axis	3D	0.66
0.1155	1.546	-5.2	z axis	3D	0.66
0.1606	1.743	-5.2	z axis	3D	0.66
0.1773	1.862	-4.2	z axis	3D	0.66
0.2001	1.82	-3.6	z axis	3D	0.66
0.1158	1.575	-5	y axis	3D	0.66
1.552	1.82	-3.5	y axis	3D	0.66
0.1987	1.905	-4.9	y axis	3D	0.66
0.2045	1.781	-4.1	y axis	3D	0.66
0.04358	1.078	-43.2	y axis	3D	0.66
0.08013	4.8618	-43.2	y axis	3D	0.66
0.107	1.321	-42.4	y axis	3D	0.66
0.1256	1.517	-43.9	y axis	3D	0.66
0.1619	1.781	-44.7	y axis	3D	0.66
0.2159	1.781	0.5	z axis	2D	0.66
0.2165	1.95	0.5	z axis	2D	0.66
0.2153	1.95	0.4	y axis	2D	0.66
0.1734	1.781	-15.7	z axis	2D	0.66
0.2035	1.781	-15.7	z axis	2D	0.66
0.2021	1.781	-15.7	y axis	2D	0.66
0.1265	1.517	-42.2	y axis	2D	0.66
0.1259	1.575	2.5	z axis	3D	0.69
0.1975	1.905	2.8	z axis	3D	0.69
0.1292	1.517	1.4	y axis	3D	0.69
0.2096	1.781	0.9	y axis	3D	0.69
0.1197	1.575	-4.9	z axis	3D	0.69
0.1884	1.82	-4.9	z axis	3D	0.69
0.1186	1.388	-4.3	y axis	3D	0.69
0.1904	1.743	-3.4	y axis	3D	0.69
0.04483	1.064	-42	y axis	3D	0.69
0.1272	1.437	-42	y axis	3D	0.69

It should be noted that due to the spreading, the 15 degree attack angle was not achieved in the 3D tests. The actual attack angle generated was actually between 3.5 and 5.5 degrees. Due to this angle being so small, it may be that there is little difference between these results and those from the head on waves.

It is assumed that there is no friction between the model and the water and therefore the force due to the water acts normally to the surface of the model. This means that the waves striking the side wall of the model have only a horizontal component and this contributes positively to the overturning moment. Wave forces acting on the front of the structure have vertical and horizontal components and the downward vertical force (which would be acting when the waves strike the front of the model) contributes negatively to the overturning moment.

Results

Results are in terms of maximum forces, application points and overturning moments (F1/250). In the following paragraphs, the results from the physical model tests will be presented scaled up to prototype.

Forces

After the force and moments had been recorded, time series analysis was done on the data to find the average of the 1/250th highest forces and moments. The data was also scaled up to prototype scale by Froude scaling. The graphs below compare the significant wave height to the average of the 1/250th highest forces. Each graph looks at the forces in a different direction for all the 3D tests in a water level 30 m (Figure 4).

It can be noticed that to the 45° attack angle, the vertical forces (x positive) are higher than the other cases. This could be because there is no absorption on the side lateral wall compared to the case when waves are coming from head on direction and they are absorbed by the reservoirs of the device. The missed absorption could be responsible of a higher overall overtopping over the structure and then a higher vertical force. Instead it is quite clear that for the y negative direction the forces are bigger with 45° attack angle as the impact occurs on the lateral vertical wall, while on the y positive forces are very close to zero.

With regard to the 15° attack angle it can be said that this condition do not generate higher forces on the z direction than the head on attack and on the x and y directions than the 45° attack angle.

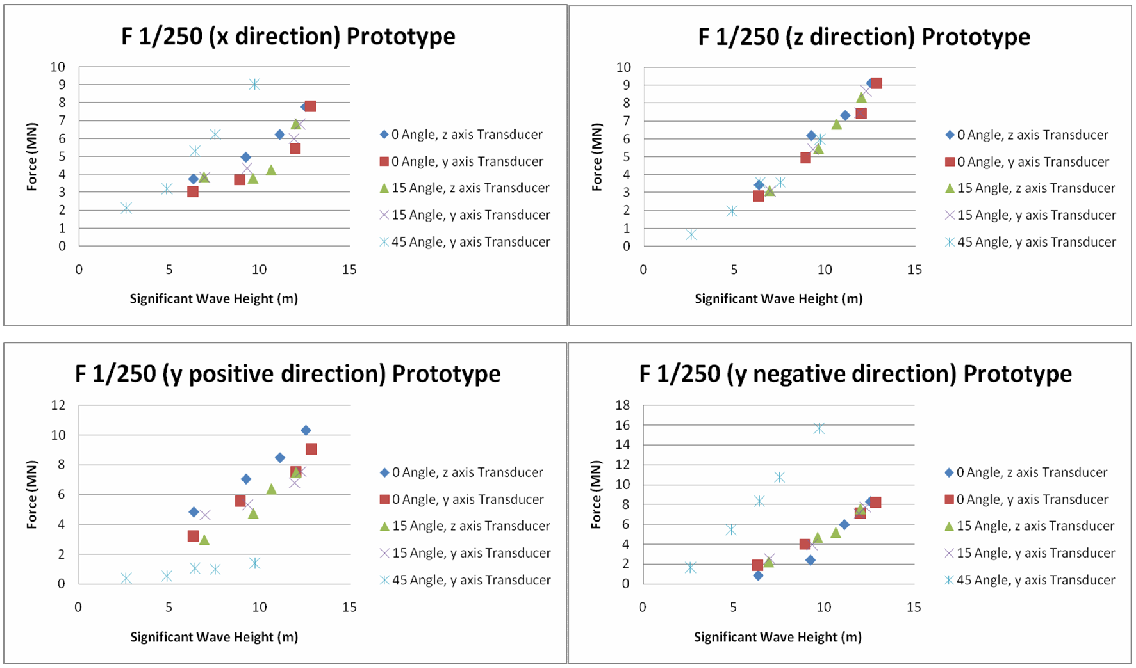

Figure 4. Forces in the relevant directions in prototype scale for different wave conditions.

The influence of the water depth is considered in the graphs below (Figures 5-8). It is shown that the force and 2 different significant wave height, for situations with different angles of attack and different water depths. These plots are explicating the changes on the force components when increasing the water depth. While the general trend is that the forces are increasing when increasing the water depth, it can be noticed that the force acting according to the positive y direction for head on waves is not increasing but decreasing. This could be an error or the influence of bathymetry: having only this tests to think about it is difficult to say. For forces acting on z direction, no significant difference it is noticed when raising the water level.

The difference between the three dimensional and two dimensional cases are also considered. The graphs (Figure9) compare the force and significant wave height for 3D and 2D cases. The angle of attack is not indicated in the graphs.
The graphics show a trend of higher forces for 3D conditions. This must be interpretated as higher spreading = higher energy and so higher overall forces on the structure. This trend is particulary clear for the forces on the y positive direction while is not clear for forces on y negative direction and z positive direction. Nevertheless, it can be said that 3D conditions don´t generate lower forces on the structure.

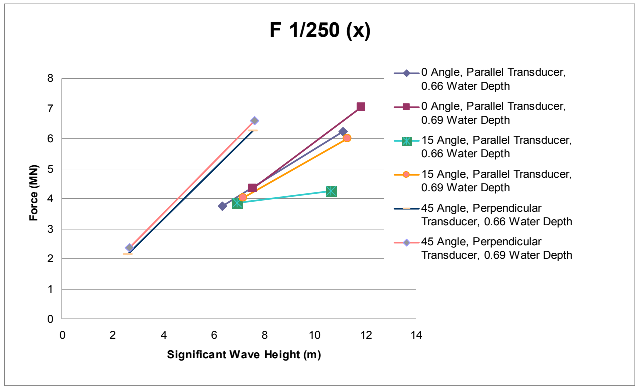

Figure 5. Influence of water depth on V max.

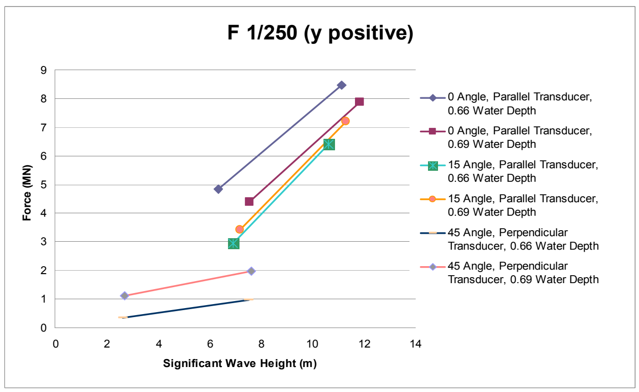

Figure 6. Influence of water depth on H max.

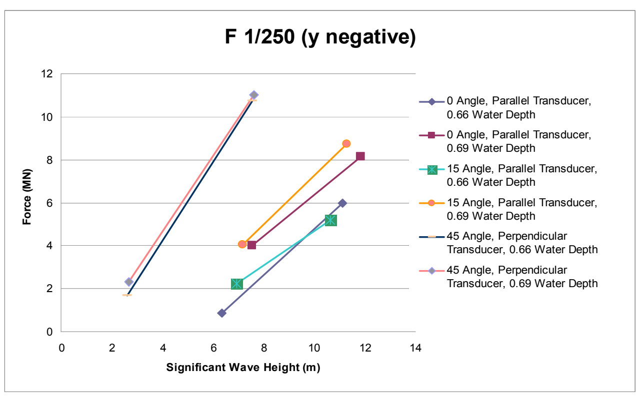

Figure 7. Influence of water depth on L negative max.

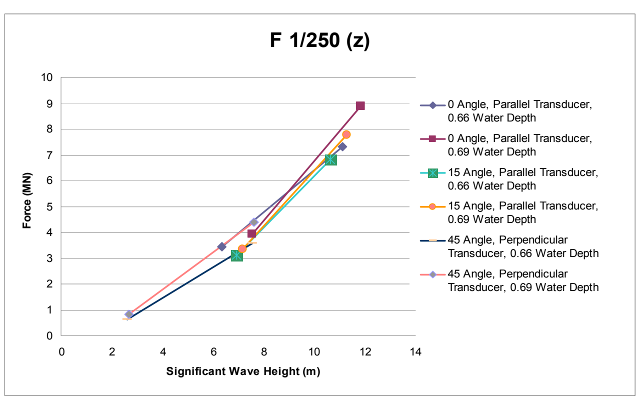

Figure 8. Influence of water depth on L positive max.

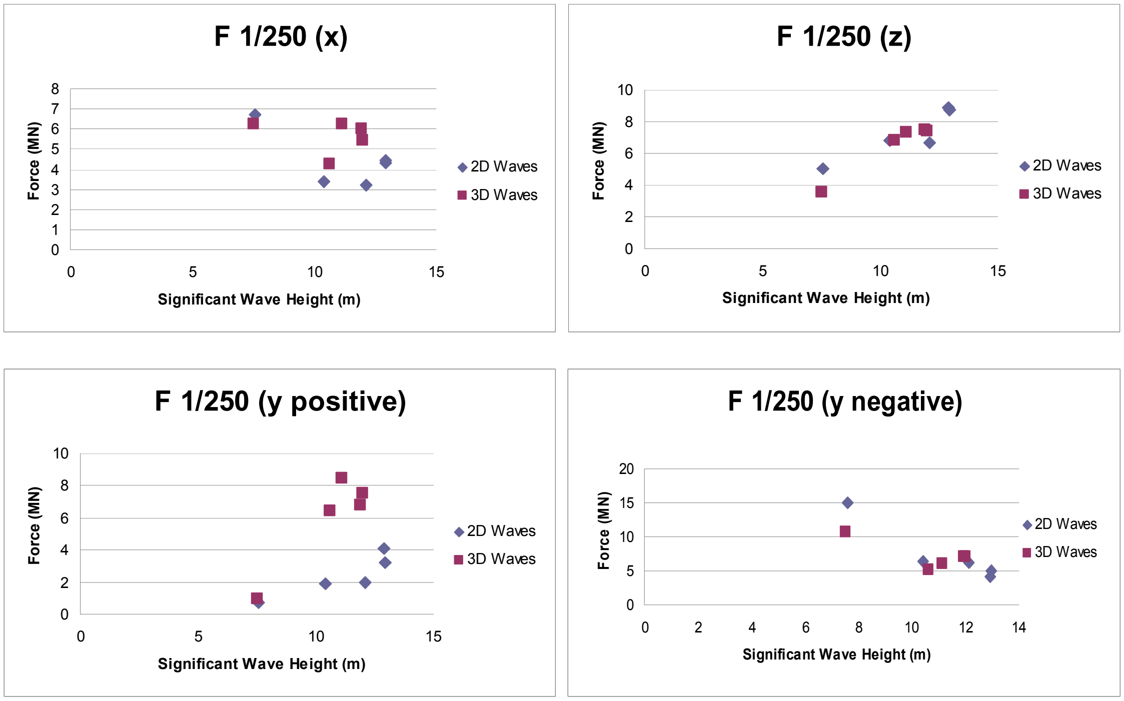

Figure 9. Effect of 3D spreading on the forces in the relevant directions.

On Table 2 the significant results are summarized.

It can be noticed that the force on the lateral vertical wall under 45° attack angle condition, for which the H_s is 1.7 times smaller then the design conditions, is bigger (8.48 MN) then the force acting on thre frontal plates under 100 years extreme event (7.31 MN). This is because the frontal plates have an inclination that improves run-up performances and decreases loads on the structure, while the side walls allow impact and so higher forces on them. Very high forces has also been recorded in the y positive direction under extreme wave conditions (8.41 MN).

Table 2. Summary of the most demanding overall forces on the structure in prototype scale.

Test description	Force in x positive direction	Force in z positive direction	Force in y negative direction	Force in y positive direction
design wave state, head on attack (Hs=12.5 m, Tp=15 s)	6.24 MN	7.31 MN	5.95 MN	8.41 MN
design wave state, 15° attack angle (Hs=12.5 m, Tp=15 s)	4.25 MN	6.83 MN	5.20 MN	6.39 MN
45° attack angle (Hs=7.5 m, Tp=12 s)	5.35 MN	3.55 MN	8.48 MN	-

Overturning moments

The moments measured are the moments acting at two specific points in the transducer. Since the forces have also been measured, it is possible to find the moment acting at any point on the structure. The overturning moments are calculated about the rear of the structure and the side of the structure (See Figure 1 and 2 on the paragraph about the measuring equipment). The equation for calculating the overturning moments about the rear of the model in the laboratory is:

$$M_R = M_1 - H(0.475) + V(0.106)$$

The equation for calculating the overturning moment about the side of the structure is:

$$M_S = M_1 - L(0.475) + V(0.065)$$

Where $M_{R,S}$ are the overturning moment about the selected corners,
M_1 is the moment measured in the upper part of the transducer,
H is the force positive in the z direction,
V is the force positive in the x direction,
L is the force positive in the y direction.
The distance 0.475 m is the vertical distance from between where the overturning moment is being considered to the point where the moment is measured. The distance 0.106 m is the horizontal distance between where the overturning moment is being considered and the point where the moment is measured. The distance 0.065 m is similarly so, but in the lateral (y) direction.
The following plots show the measured moments for different water depths and waves attack angles and in 2D and 3D conditions (Figure 10). The moment is not particularly sensitive to the water depth or 3D conditions.

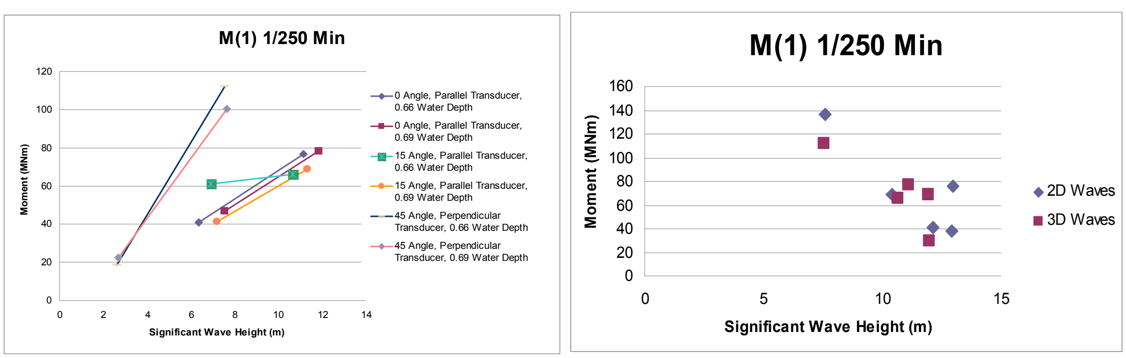

Figure 10. Influence of water depth (left) and spreading (right) on recorded moments.

The calculated overturning moments for the 100 years return period event and for the 45° attack angle wave condition are summarized in Table2. It is obvious that the biggest calculated moment is the one around the side when waves are hitting the lateral wall with 45° attack angle. It was already noticed, indeed, that the force in y negative direction is the largest one.

Table 3. Overturning moments in prototype scale.

Test description	Overall turning moment around rear corner	Overall turning moment around side corner
design wave state, head on attack (Hs=12.5 m, Tp=15 s)	-76.67 MNm	
design wave state, 15° attack angle (Hs=12.5 m, Tp=15 s)	-66.10 MNm	-54.20 MNm
45° attck angle (Hs=7.5 m, Tp=12 s)		-79.32 MNm

Applicdation points

Application points have been calculated from pressures measurements (Vicinanaza et al.). The calculation has been made only for the 100 years return event with head on attack, 15° attack and for the wave condition corresponding to 45°wave´s attack angle. For details about the calculation, see Appendix A.

If we want to give a measure of how these results worked out from extreme pressures in a different experimental set-up can be valid for the last tests of overall forces, it must be noticed that:

1) there are a number of inaccuracies with this method however. Firstly the design of the SSG has changed slightly since the pressure tests have been done, so the dimensions of the new model are slightly different.
2) Secondly in the final calculation a statistical parameter is divided by another statistical parameter. It may in fact not be the case that these two values occur at the same time.
3) The pressure transducers recorded peaks so the overall forces derived by them are higher then the ones recorded with the present set-up. In this way, also the application point will result different.

Anyway, it should still give a reasonable approximation of the positioning of the force for the present case, however.

The application points corresponding to the forces of Table 2 are plotted on Table 4. vertical and horizontal forces are considered to have the same application point (see Appendix A). Condidering the overall dimensions of the SSG pilot, H and V are acting sligtly lower the half height of the structure.

Table 4. Application points of the maximum forces on the structure.

Test description	Application point of V and H (vertical distance from toe of the structure)	Application point of L (vertical distance from toe of the structure)
design wave state, head on attack (Hs=12.5 m, Tp=15 s)	4.19 m	2.72 m
design wave state, 15° attack angle (Hs=12.5 m, Tp=15 s)	-	-
45° attck angle (Hs=7.5 m, Tp=12 s)	4.13 m	3.30 m

Coparison

It is possible to make a comparison between the results obtained with the two different setups: the present one and the one within the tests on pressures. In Table 5 are reported the significant results of this report side by side with the results in terms of forces calculated from the data files on pressures (Vicinanza et all.).

Table 5. Comparison between maximum forces on the SSG structure from direct model measurements and calculated by integration from pressures data files, prototype scale.

	Front attack. Design wave condition: Hs=12.5 m, Tp= 15 s.			**45° attack angle. Hs=7.5 m, Tp=12s.**		
	Pressure tests	Total forces tests	ratio	Pressure tests	Total forces tests	ratio
V [MN]	20.29	**6.24**	3.3	10.29	**5.35**	1.9
H [MN]	14.21	**7.31**	1.9	7.20	**3.55**	2.0
L [MN]	-11.99	**-5.95**	2.0	-12.21	**-8.48**	1.4

It can be noticed that forces derived by integration from pressures measurements are 2 times higher then forces measured with the 3-axial load cell for the same wave conditions.

In Figure 11 is shown a direct comparison of a time series of forces on the lateral vertical wall from direct measurements (blue) and from calculation (modify signal with WaveLab) from pressures on the mode (red)l. The 2 main reasons for this discrepancy is the measuring technique: first, while with pressure transducers the peak (figure 12, church trend) are recorded so that the maximum force calculation (F1/250) is influenced by them, this do not happens for the measurements with the load cell. Second, the calculation of forces from pressures files didn’t take into account any correlation that instead exists with other pressure measurements all over the structure, so that an actual measured pressure could be decreased by an other under pressure somewhere else. This dealing with many signals and time series measurements it is, anyway, time consuming. It appears anyway reasonable that there is a factor 2 between the different results.

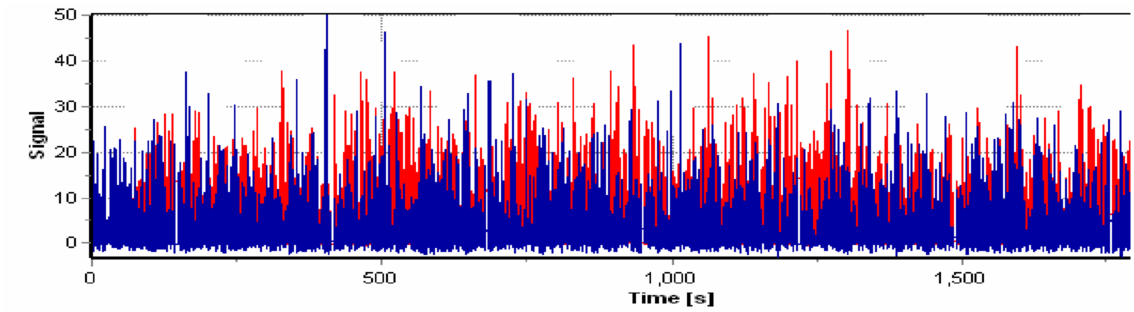

Figure 11. Comparison between lateral forces L (y negative direction) measured with the load cell (blue) and calculated by integration from pressures files (red) for 45° wave´s attack angle.

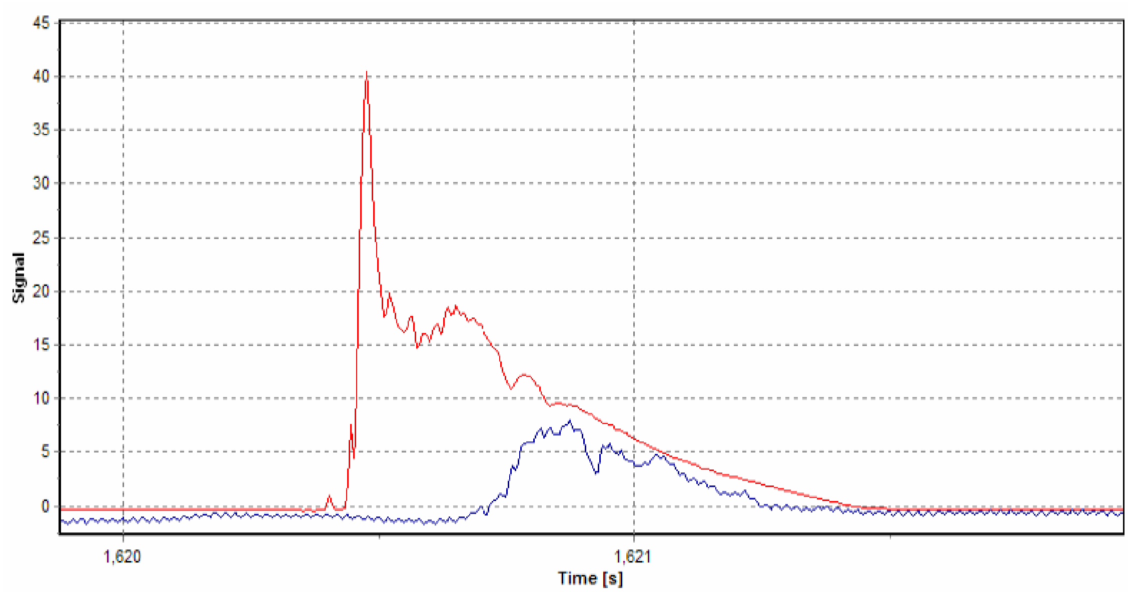

Figure 12. In red: typical church trend recorded during pressures measurements on the SSG model.

Analysis of Results

Figure 13 shows non-dimensional force against the steepness of the waves. Is quite obvious the different behaviour of the forces when the attack angle of the incoming waves is 45° (a part from the z direction). Forces decrease when increasing the wave steepness.

In Figure 14 the the relative wave force is plotted against the relative wave height showing linear relation. Graphs of dimensionless force against angle of attack are plotted in Figure 13.

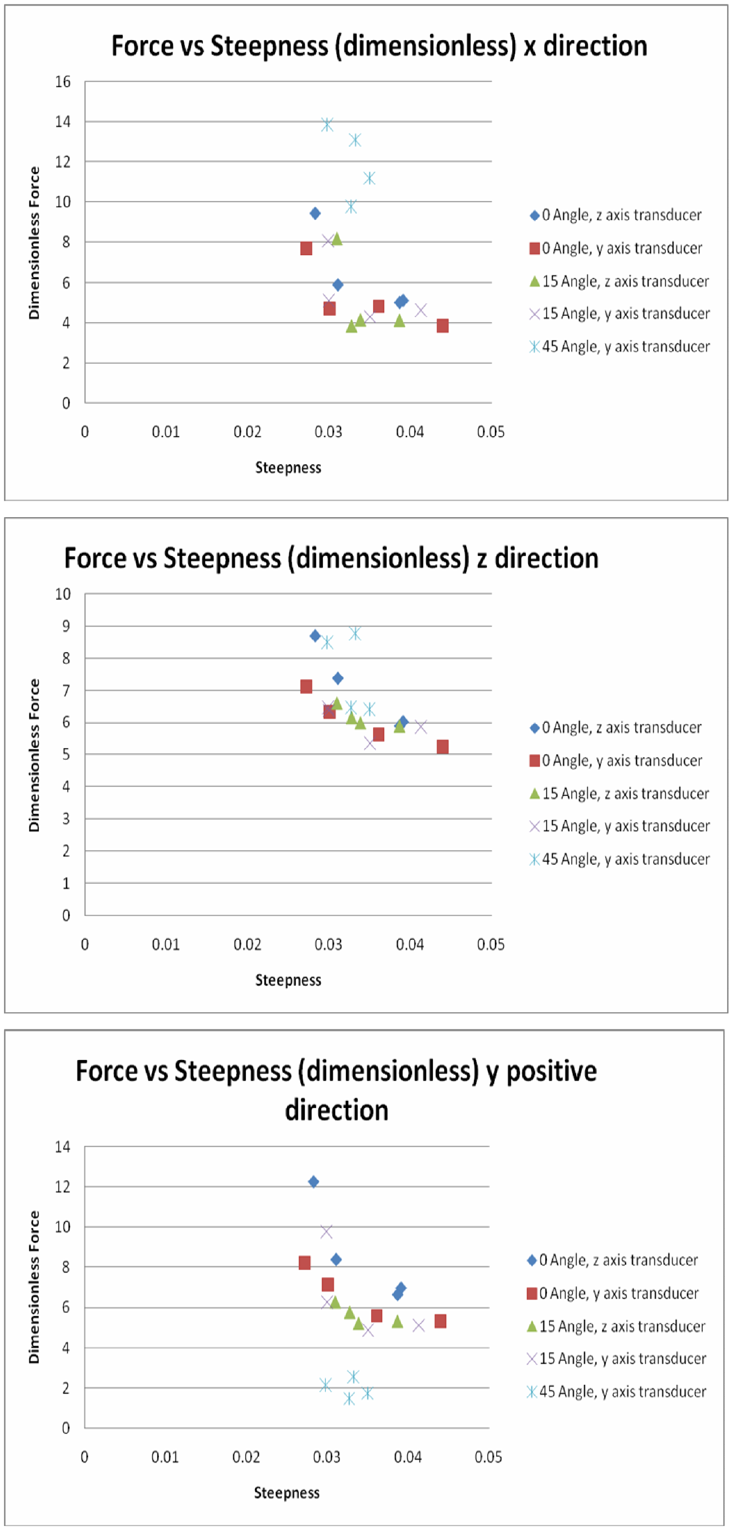

Figure 13. Relative forces against wave's steepness.

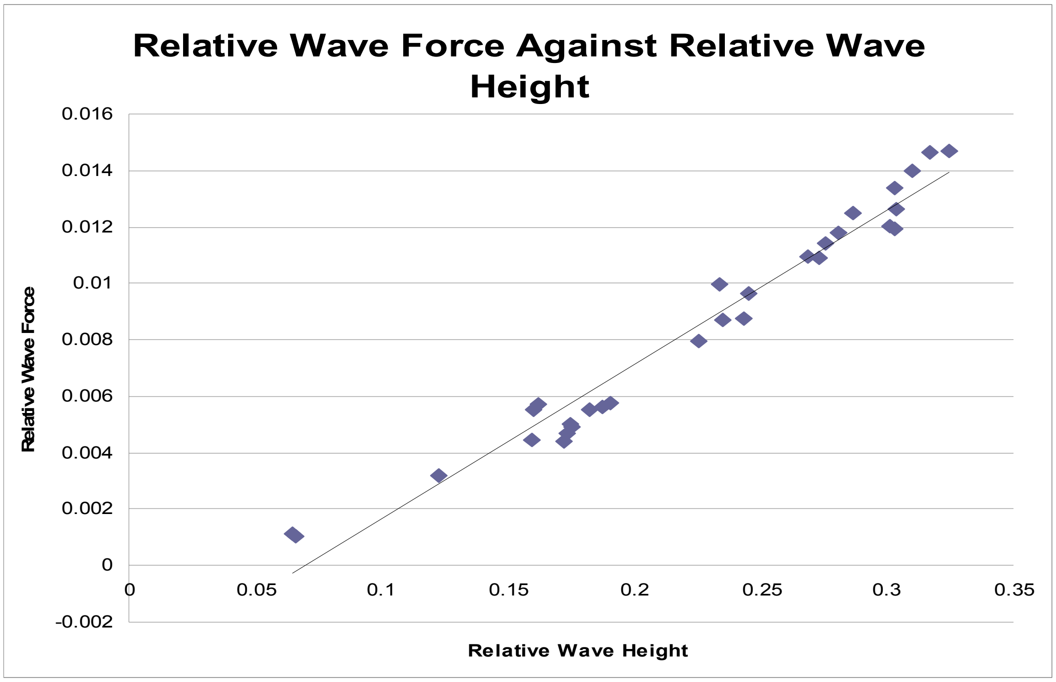

Figure 14. Relative wave force against relative wave height.

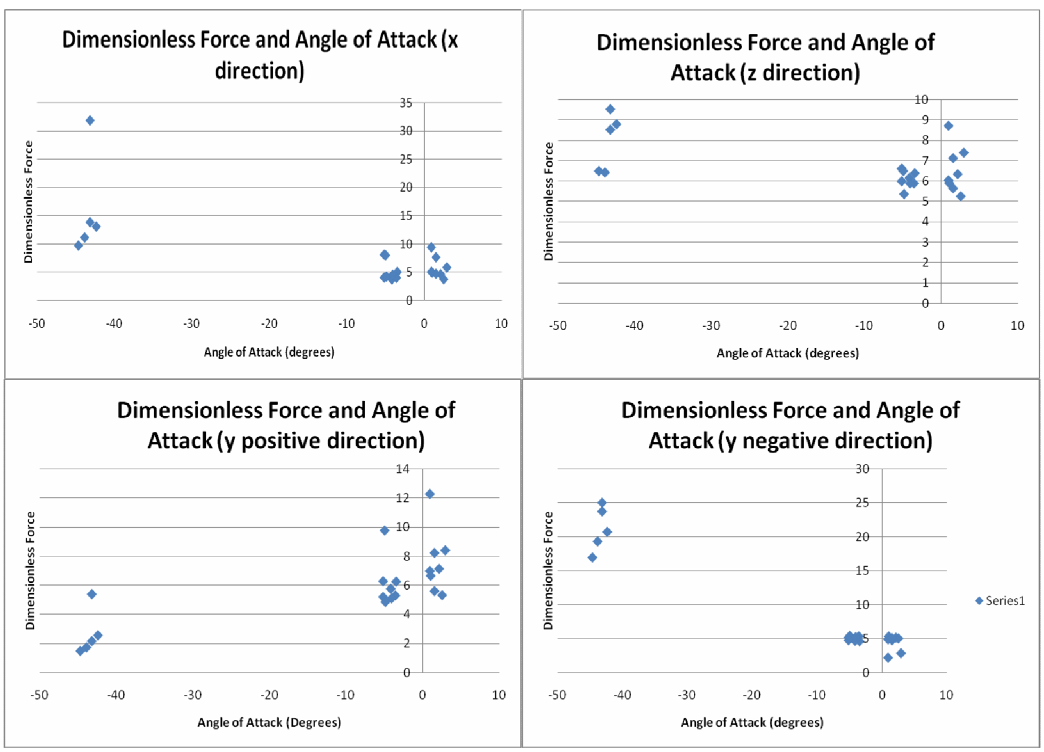

Figure 15. Relative forces against different wave's attack angles.

Conclusions

Measurements of time series of forces and moments have been done for the SSG model is scale 1:60 to prototype. The maximum forces in the main directions have been calculated as well as the structure's overturning moments around two different corners.

Application point of the maximum forces on the structure have been worked out using the pressure measurements from Vicinanza et all. set of tests. This was necessary, as the present set up did not allow such a calculation.

A comparison in between maximum forces measured on the model and calculated by integration from pressure measurements has been done and commented.

The main conclusions of the present report are:

1. The forces and overturning moments are most critical when striking the side of the structure.
2. For 45° wave's attack angle, H_s=7.5 m and T_p=12 s (corresponding to NW wave climate) the maximum Lateral overall force (y negative direction) is 8.48 MN and the Horizontal is 3.55 MNm. The overturning moment around the side is -79.32 MNm.
3. The maximum Horizontal overall force (z positive direction) for head on wave's attack, H_s=12.5 m and T_p=15 s (design wave condition, return period 100 y) is 7.31 MN and Lateral (y positive) is 8.41 MN. The overturning moment around the rear corner is 76.67 MNm.
4. Vertical forces (x positive direction) are stabilizing the structure and no uplifting forces are expected to occur (x negative direction) because of the nature of the foundation/ installation.
5. Vertical and Horizontal force have the same application point on the structure; this is, for design wave conditions on the front plates of the structure at a height of 4.19 m from the toe of the structure (vertical distance) and 0.75 m from the swl (it has been decided that the lowest reservoir will be partially flooded permanently).
6. Comparison between maximum forces calculated from direct measurements on the model and worked out by integration from pressures (also measured on a similar model) showed a discrepancy of a factor 2 in between them. This difference was expected and the reasons are to be found in the different measuring techniques.

Notes

The tests have been done we a certain amount of know uncertainties that need to be listed and should eventually lead to a higher security factor for the constructors.

Those uncertainties are:

- In general for the tests realized on this setup, the dynamic response of the model influences the results. Because of the natural frequency of the model we are filtering the signals from the forces at 8 Hz (prototype scale ≈ 1 Hz). The justification can be seen that the SSG pilot is a heavy structure and we don't expect resonance to occur.
- The exact location for the SSG pilot is uncertain; therefore tests have been run with a model of the bathymetry for the last location. Bathymetry can have great influence on the waves that are reaching the structure and on the forces acting on it.

It is suggested that when the testing phase will be concluded, a meeting is setup with the constructors in order to discuss these and other issues. It is important to make all the details of the testing that led to the results plenty understood.

References

Vicinanza D., Kofoed J.P. and Frigaard P. March 2006: "Wave loadings on Sewave Slot cone Generator (SSG) at Kvitsøy Island (Stavanger, Norway)", Hydraulic and Coastal Engineering No. 35, ISSN: 1603-9874, Dep. Of Civil Eng. , Aalborg University.

Appendix A

Application points

Application points

With the information available from the measurements taken here it is impossible to find the position of action of the total forces. However, since the tests are mirroring those previously done by Vincinanza et al, the application point of the total forces in those tests can be representative for the present set of tests. Using the records from the tests on pressures, then, the signal given for each pressure transducer on the model is assumed to be constant for a certain area so that the total force could be found by integration. The time series of pressures can therefore be converted into a time series of forces. Similarly a time series of moments can be calculated by also multiplying the forces by their respective moment arms ($a_{i,j}$) (Figure).

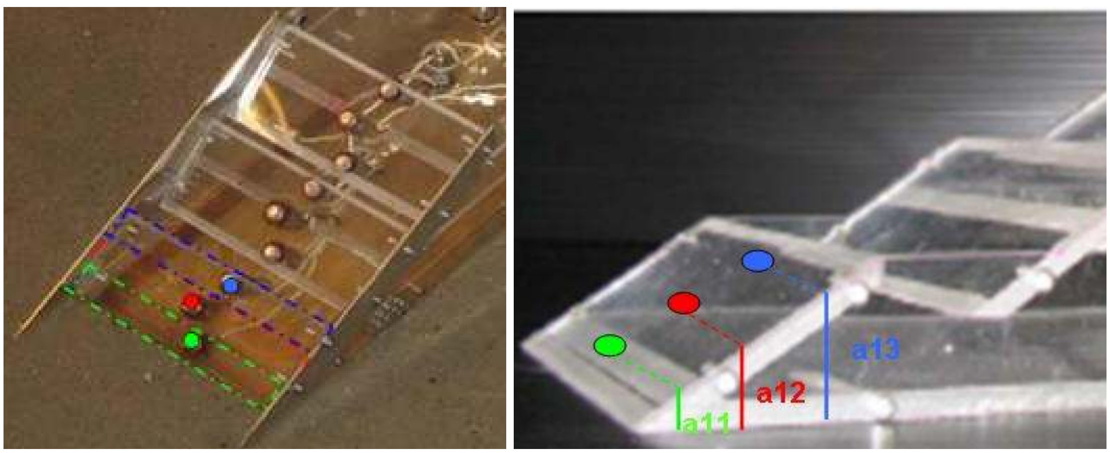

Figure 1. Areas around the pressure transducers in which pressure have been considered to be constant for calculation of H and V forces (left). Arms for calculation of moments (Right).

There is assumed to be no friction acting on the water from the model, so the force on the front plates is acting normal to them. It can therefore be converted into horizontal and vertical components. For the same reason the force attacking the lateral wall is assuming to have only horizontal component (L) (Figure)

Figure 2. Decomposition of forces on the SSG model.

The calculation of total forces and overall moments from the pressures files has been done within WaveLab program by a function that allows the modification of the acquired signals (pressures → total forces, pressures → moments). Using time series analysis the average of the highest 1/250th moments and forces can be found. The total force (F1/250) and the moment of this force are needed in order to find the application pint of total force (a_{ris}).

Following the "modify signal" functions are reported and the calculations are explained.

Calculation of the application point for H (from pressure files 27 and 31, Diego Vicinanza Data Files).

This has been done simply by dividing the sum of moments by the sum of forces (F1/250) for each plate: $\frac{\sum M_i}{\sum F_i} = a_{ris}$

$\sum F_i$

From the time series of signals (pressures), the time series of total horizontal forces in plate 1 (lower) has been calculated as follow:

F1=((0.021*X15+0.024*X14+0.022*X9)/10)*0.133*cos55°

From the time series of signals (pressures), the time series of total horizontal forces in plate 2 (middle) has been calculated as follow:

F2=((0.022*X11+0.025*X13+0.023*X6)/10)*0.133*cos55°

From the time series of signals (pressures), the time series of total horizontal forces in plate 3 (higher) has been calculated as follow:

F3=((0.023*X12+0.029*X3+0.024*X7)/10)*0.133*cos55°

From the time series of signals in plate 4 (slope added in the new design of the SSG pilot), the time series of horizontal forces has been calculated as follow. It was assumed that the pressures acting on it were the same than the pressures acting on the 3rd slope. This is quite conservative because this slope is actually higher then the 3rd one. This was necessary because in the model from the tests on pressures, the plate 4 was not present so no pressures have been measured on it.

F4=((0.041*X12+0.041*X3+0.041*X7)/10)*0.133*cos55°

X15, X14 and X9 are the acquisition channels of the pressure transducers in lower plate; X11, X13 and X6 in the middle and X12, X3 and X7 are the ones of the third and used also for the higher (fourth plate) at the present configuration. The signal is multiply by the area around the pressure transducers in which the pressure is assumed to be constant. The division by 10 is needed to pass results from mbr to kN/m2 and the multiplication for the cos55 is to have the horizontal component of the applied force that is perpendicular to the plate (that is incline of 35° on the horizontal).

From the time series analysis the F1/250 for each plate is calculated. Summing up the contribution for each plate we have the total force acting on the front of the structure = $\sum F_i$.

$\sum M_i$

Time series of the moment for plate 1 with respect to the distance a_{1i}:

$$M1=((0.021*X15*0.0063+0.024*X14*0.0183+0.022*X9*0.0332)/10)*0.133*\cos 55^\circ$$

Time series of the moment for plate 2 with respect to the distance a_{2i}:

$$M2=((0.022*X11*0.0227+0.025*X13*0.0365+0.023*X6*0.0519)/10)*0.133*\cos 55^\circ$$

Time series of the moment for plate 3 with respect to the distance a_{3i}:

$$M3=((0.023*X12*0.0501+0.029*X3*0.0656+0.024*X7*0.0833)/10)*0.133*\cos 55^\circ$$

Time series of the moment for plate 4 with respect to the distance a_{4i}:

$$M4=((0.041*X12*0.0970+0.041*X3*0.1205+0.041*X7*0.1440)/10)*0.133*\cos 55^\circ$$

The expressions above are obviously the same used for the calculation of the F_i, but each signal is multiplied by the arm $a_{i,j}$ (see Figure).

From the time series analysis the maximum 250^{th} moment for each plate is calculated. Summing up the contribution for each plate we have the total moment = $\sum M_i$.

It is now possible to calculate the a_{ris} of the horizontal force.

Calculation of the application point for V (from pressure files 27 and 31, Diego Vicinanza Data Files). The same procedure that previous case is applied, changing cos55 in a sin 55 in the expressions.

The application point is in the symmetrical plane of the structure and resulted to be the same for H and V (+ - 4 cm in real scale.). This confirms that it is a valid approximation to take them coincident.

Calculation of the application point for L (from pressure files 27 and 31, Diego Vicinanza Data Files).

This has been done simply by dividing the sum of moments for each sub-area by the sum of forces on each sub-area (F1/250): $\frac{\sum M_i}{\sum L_i} = a_{ris}$

From the time series of the pressures on the vertical lateral wall, suitable areas of action have been assumed for each pressure transducer in which the pressure has been considered constant (Figure).

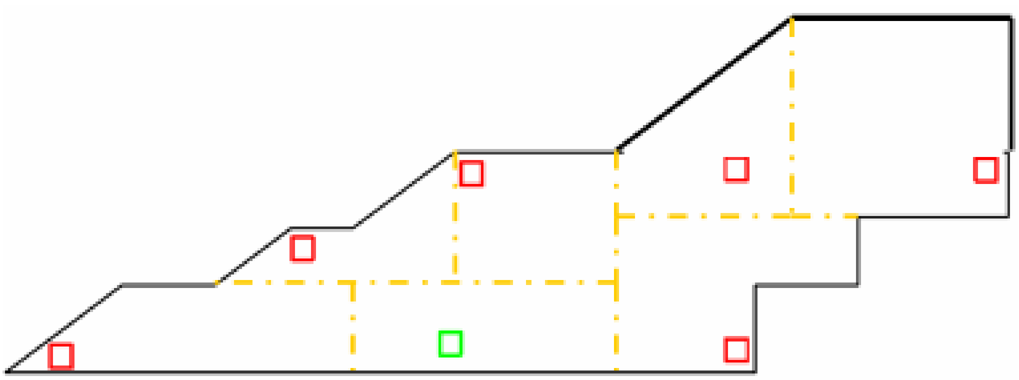

Figure 3. Areas around the pressure transducers in which pressure have been considered to be constant for calculation of lateral force L.

The time series of the Lateral force on the vertical side wall has been then calculated by integration over these areas and sum:

$\sum L_i$=L=(0.00513*X7+0.0068*X13+0.0029*X12+0.0028*X8+0.0076*X9+0.0052*X16+0.0035*X11)/10)

Time series of the moment with respect to the distance a_{1i}:

$\sum M_i$=M=(0.00513*X7*0.018+0.0068*X13*0.019+0.0029*X12*0.038+0.0028*X8*0.054+0.0076*X9*0.067+0.0052*X16*0.102+0.0035*X11*0.112)/10)

From the time series analysis the maximum 250^{th} of the total force L and moment M is calculated. It is now possible to calculate the a_{ris} of the horizontal force.