Model testing and comparison to analysis of the closed steel aquaculture unit Aquatraz G4

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ABSTRACT: This paper presents model testing compared to analysis for Aquatraz G4, a steel structure utilized for aquaculture. Aquatraz G4 is a steel cage, mostly impermeable at the sides leading to a mass dominated response that will be introduced to a grid mooring system together with classic drag dominated aquaculture cages. Comparison of results for several tests are presented and compare well. The paper makes a proposal on how to analyse full scale grid systems with a combination of mass dominated cages and drag dominated cages.

1 INTRODUCTION

Figure 1

Aquatraz is a fish cage system, as shown in Figure 1. The 4th generation of this concept has been designed and exposed to testing in tank basin (Marintek 2020). Aquatraz G4 has significantly more added mass than previous versions (e.g. Berstad & Aarnes 2018) meaning even longer perioded for slow drift response which have a strong impact for analysis for design verification.

Figure 2 Aquatraz half cage model. Marintek (2020)

2 TANK TEST ARRANGEMENT

The tank test arrangement with mooring lines is shown in Figure 3 (CeFront 2020). The tested system consists of cage, net and moorings. Half of the cage is shown in Figure 2.

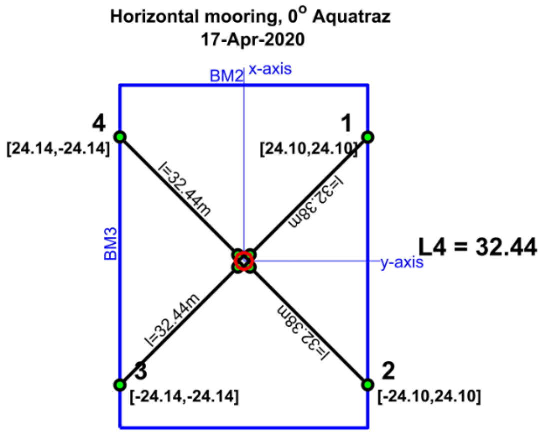

Figure 3 Test arrangement

As seen in Figure 3, an axis system is defined where the mooring lines are 45 degrees to the *x*- and *y*- axis and the origin is placed in the centre of the tank. The *z*- axis points vertically with 0 at the water line.

2.1 *The Aquatraz cage*

Aquatraz is a steel cage with a tube in the water line giving waterplane stiffness and a tube in the lower par giving buoyancy. Table 1 shows the main properties of Aquatraz 4 used as basis for both testing and analysis.

Table 1 Main properties

Property	Value test/ analysis
Total weight steel [Tonnes]	1350
Total buoyancy [Tonnes]	1848
Centre of gravity, x and y [m]	0.00
Centre of gravity, z [m]	-13.36
Radius gyration, x and y [m]	1.80E+01
Radius gyration, z [m]	1.27E+01
Keel	-33.058
COG from keel [m]	19.70

2.2 *Net*

There is a conical net in the bottom of Aquatraz as seen in Figure 4. This net has 23% solidity and with a weight of 1000 kg downwards in the bottom. The lower 5 meters of the tank consist of a permeable net with 25% solidity

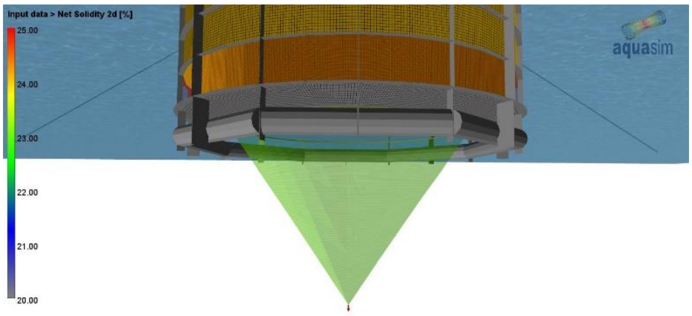

Figure 4 Analysis model 1 lower part

2.3 *Mooring*

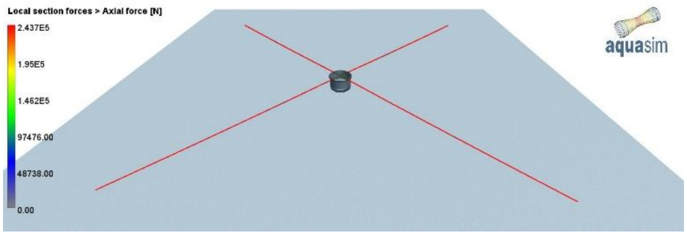

Figure 5 Test arrangement in analysis model 1

The mooring pretension is 243 kN which is included in the analysis model as seen in Figure 5. The mooring stiffness is 27 kN/m per line.

3 ANALYSIS COMPARED TO TANK TEST RESULTS

3.1 *Analysis program*

Analysis has been carried out by the analysis program AquaSim which is the leading analysis program applied in aquaculture for verification of cages, barges, nets, tarps, moorings and coupled systems (Aquastructures 2021b). AquaSim is based on Finite Element Method and is developed for structural analysis of marine- and land-based structures. Calculations of response from environmental loads such as winds, current, waves and interaction in coupled systems makes AquaSim a viable tool for design verification. Time domain simulations are carried out calculating displacements, deformations, forces, and stresses acting onto- and within flexible and rigid structures.

Introduction of loads from waves and current to membrane element representing (parts of) nets in AquaSim is shown in Berstad et al (2012). The closed part of the main tank is modelled as a shell. Load introduction from waves and current to panels on shell is described in Aquastructures (2019).

3.2 *Analysis models*

Two analysis models have been established.

3.2.1 *Model 1*

Model 1 is a model where the cage has been modelled with shell elements and the bottom net is modelled with membrane elements for nets. The analysis models are modelled in full scale. Due to the refinement of model 1, it will have local elasticity. It is not the aim of this elasticity to be realistic for this comparison although the dimensions used in for the model are meant to represent values in the vicinity of the real full-scale parameters or stiffer. Further data on the model can be seen in Aquastructures (2021).

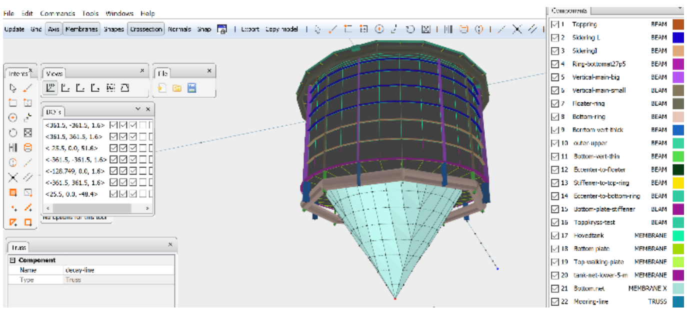

Figure 6 Analysis model 1

Pressure to the outer shell surface is based either on MacCamy Fuchs (1954) or numerical diffraction (e.g., Barbarit 2015). The two methods are analysed for selected wave periods. Comparison of the results, show small deviations. This paper is based on results from the MacCamy-Fuchs method Wave drift forces is calculated by direct pressure integration by including pressure integration to the instantaneous water line and including the velocity squared term of Bernoulli’s Equation when calculating wave pressure. The dynamic pressure and fluid velocity including diffraction is kept track of. If the total pressure including static pressure is lower than 0, it is assumed that the structural element is out of water. If the dynamic pressure at the water line is positive the corresponding wave heigh is found by the relation $p=\rho g(h-z)$ for $z>0$. Pressure is applied as loads to the cage in the area from $z=0$ to $z=h$. Viscous drag forces are also integrated to the instantaneous water line, but in this case only to the waterline caused by the incident wave.

3.2.2 *Model 2*

Model 2 is a simplified model, where viscous forces are distributed along a center beam. Mass-, diffraction- and drift properties are assigned as node-properties to the center-node of the beam, as shown in Figure 7. The model was restrained from vertical motion and rotations about the horizontal axis. Mass, including added mass, wave generated damping, drift coefficients (Figure 8) and RAO for linear loads at the wave period is placed to the node as indicated in Figure 7.

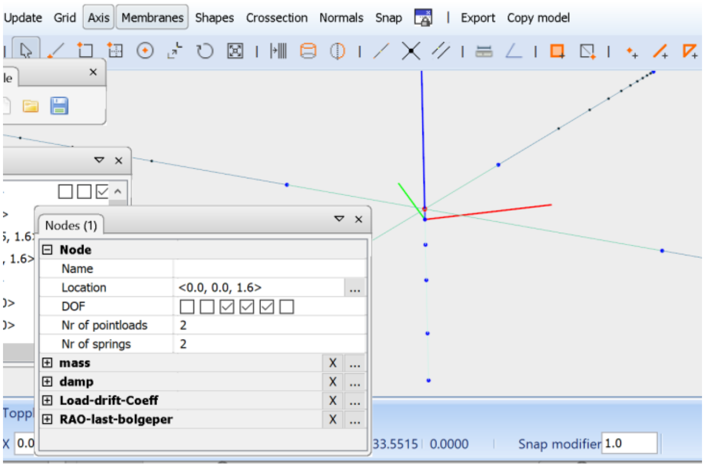

Figure 7 Excerpt analysis model 2

Loads from the drag-term in the Morison (1950) equation is introduced from a drag-coefficient to the 30 meter deep vertical beam seen in Figure 7. A drag diameter of 50 m and a drag coefficient of 0.833 give the results in current as seen in Figure 9. The stiff rod has a length of 1.6 meters above the water line. In waves, drag is calculated for the wetted surface to the actual incident waterline. This originates a drift-term in waves in addition to wave drift forces calculated based on the coefficient in Figure 8.

The wave drift coefficients are modified in case of combined current and waves (see e.g., Faltinen 1990 pp 146).

3.3 *Comparison analysis to model test*

Comparison has been carried out in the following conditions:

- Current
- Decay test
- Regular waves
- Irregular waves
- Irregular waves and current

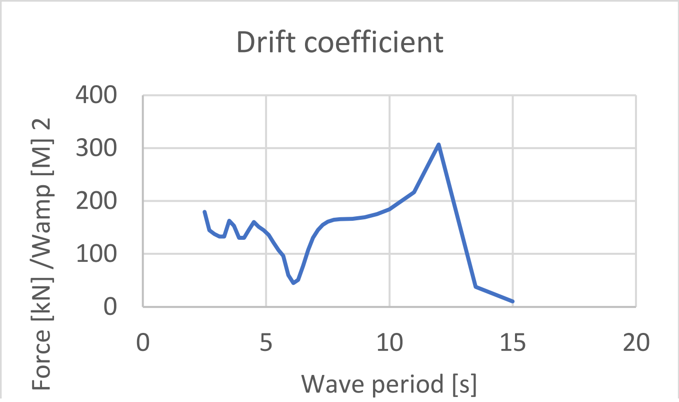

Figure 8 Drift coefficients, Model 2

3.3.1 *Current*

Figure 9 shows test data and analysis in current. As seen from this figure, current has been applied for 5800 seconds, and as seen from the figure, the displacement varies strongly. The eigenperiod of the system is approximately 200 second. The motions roughly follow that period. For the analysis, the response in (static) current is static and determined by the drag coefficient. For both analysis models, the drag coefficients were chosen to the high side of the average, but lower than max response in the tank as seen in Figure 9. The chosen displacement from current in the analysis compared well with the displacement in the testing in waves and current before the waves were introduced.

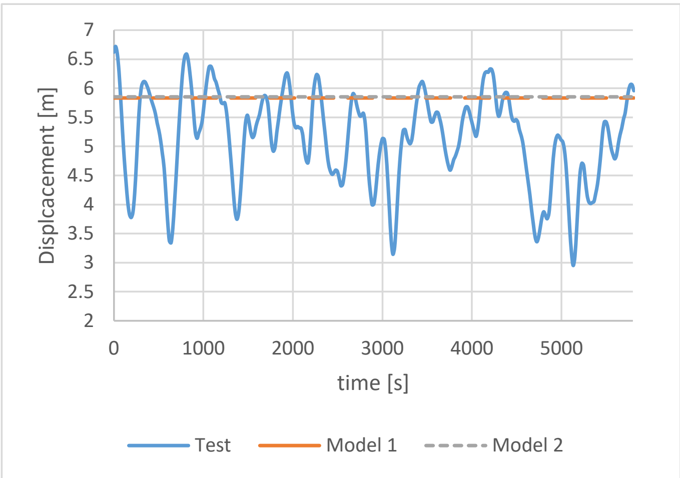

Figure 9 Comparison current

3.3.2 *Decay test*

Two steps were carried out comparing analysis to the decay testing in the tank. First there were no wave generated damping added to the properties of the analysis models. Figure 10 shows comparison of analysed decay compared with the tank data. As seen from this figure, the analysis dampens out slower than the test whereas choosing the added mass corresponding almost exactly to the water within the tank. The model damping seen in Figure 10 is caused by drag in Morisons equation.

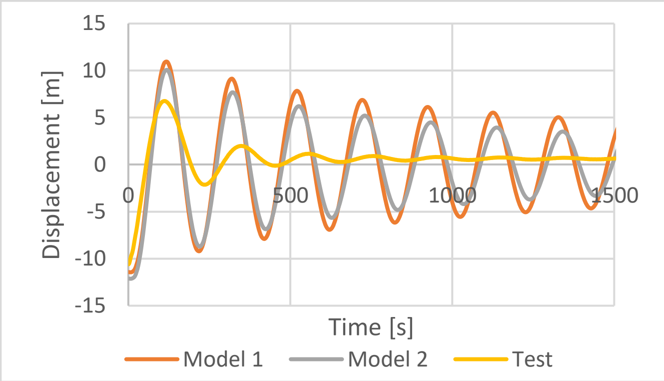

Figure 10 Comparison decay test

Introducing damping of 1% of mass to both analysis gives the results seen in Figure 11. As seen from this figure, results compare well in this case.

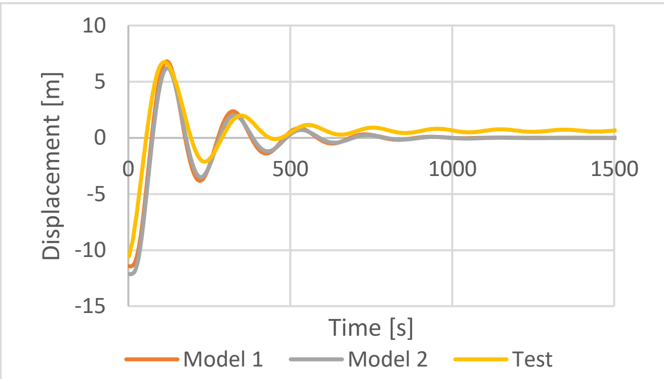

Figure 11 Comparison decay test

Wave generated damping of 1% is included in the succeeding analysis.

3.3.3 *Regular waves*

Table 2 shows the analysed regular wave conditions.

Table 2 Test cases regular waves

Test #	H [m]	T [s]
2021	1	5.1
2040	1	7
2050	2	5.1
2060	2	7
2072	3	7

Results from load case 2021 is shown in Figure 12. The analysis and test last for approximately 10 minutes. In the analysis 100 seconds was used to increment to the given wave height. As the eigenperiod of the system is approximately 200 seconds, the drift will be of large importance. Both analysis and testing leads to a response where there is a transient response, then the response will fluctuate about the mean drift displacement. By seeing how fast the transient fades out one may compare damping.

Figure 12 shows the response in case 2021. As seen from this figure, the mean response after some time compares well for model 2 whereas model 1 leads to a higher mean drift. Both model 1 and model 2 damp out faster than the test indicating that wave generated damping may be less than 1% in this case.

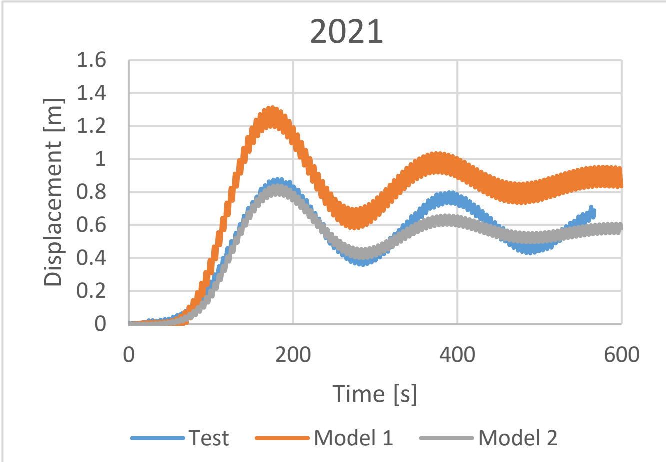

Figure 12 Comparison regular waves

Figure 13 shows comparison for case 2040. In this case model 2 lays out lower than the test data and model 1 is in the vicinity but also slightly lower. Note that the 2nd peak of the test data response is higher than the first peak. This is inconsistent with the other test data so it might be a measurement issue.

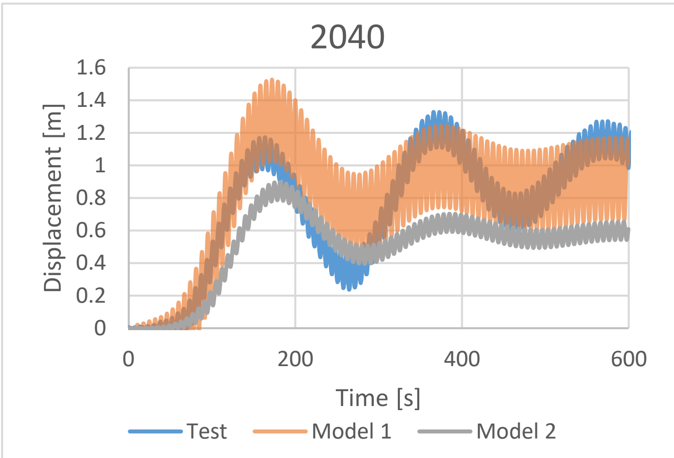

Figure 13 Comparison regular waves

As seen from Figure 13 model 1 has a larger wave induced response. Model 1 includes elasticity of the system as well as vertical motions and rotation so there might be several causes for this larger response at wave period. This is of interest for further studies.

Figure 14 shows results for case 2050. In this case results compare well with model 1 slightly above.

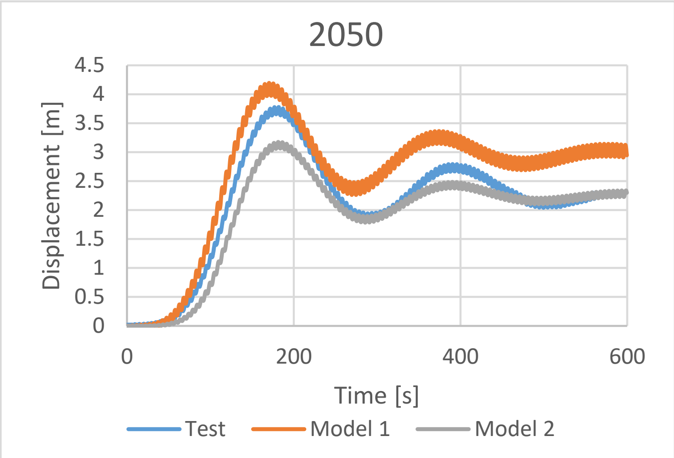

Figure 14 Comparison regular waves

Figure 16 shows results for load case 2060. It is seen that also in this case the test falls in between model 1 and model 2 results, closer to the former.

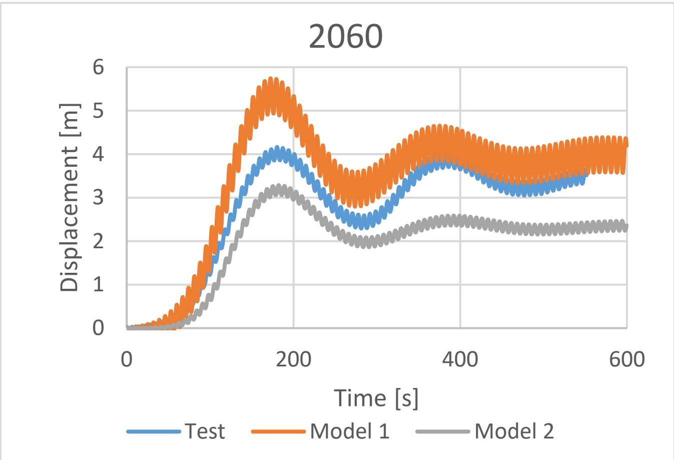

Figure 15 Comparison regular waves

Figure 16 shows results for case 2072. Also, in this case the analysis models compare well. In this case both models are slightly to the lower side compared to test results.

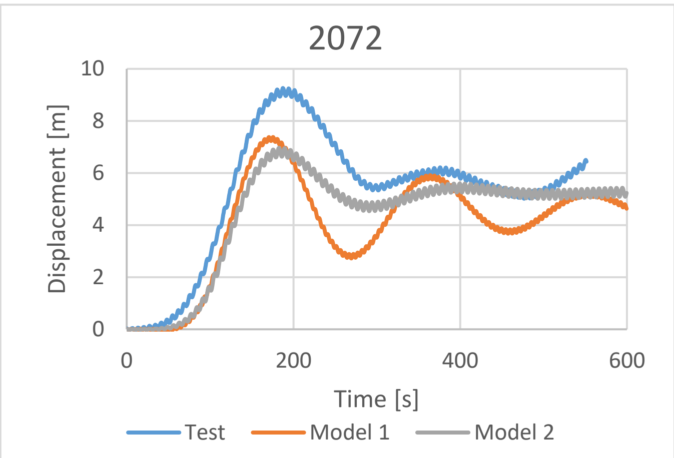

Figure 16 Comparison regular waves

As seen from the results in Figure 16 the strong response in in the wave period more or less "vanish" for this case. This paper does not investigate this further. One plausible cause is that results are sensitive with respect to the element discretization of model 1. This is included as a point for sensitivity and conservative choses in the concluding section.

Irregular waves

Comparison between measurements and analysis has been carried out for the two cases shown in Table 3.

Table 3

Test #	Hs [m]	Tp [s]	Current [m/s]	Gamma
3030	1.7	5.2	0	3.2
3050	2.4	6.1	0	3.2

Figure 17 shows results for case 3030 and Table 4 shows the corresponding main statistics.

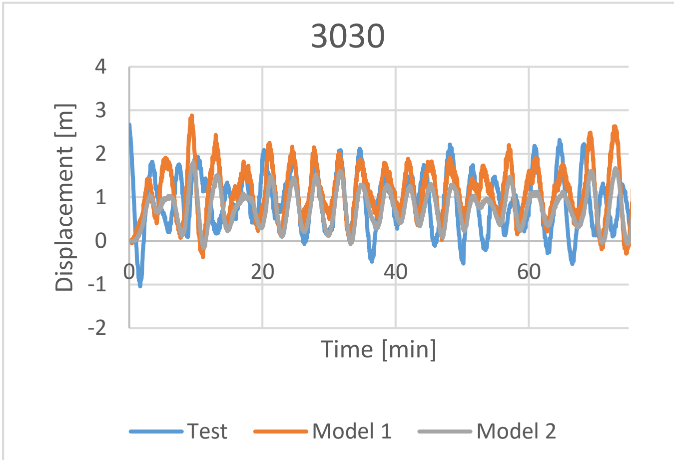

Figure 17 Comparison irregular waves

The results in Figure 15 and Table 4 shows the statistics for the realization seen in Figure 15:

- Test: Test excerpt seen in figure
- Test full: The full 3 hour test
- Model 1: Analysis model 1.
- Model 2: Analysis model 2.

The analysis results are for realizations where a wave train generated from the spectral energy distribution is applied. Statistics will vary from realizations. As seen from the results model 1 is in line with test results while model 2 is on the lower side.

Table 4 Statistics displacement [m]. 3030

	Test	Test full	Model 1	Model 2
Max	2.67	3.00	2.88	1.81
Mean	0.90	0.90	1.14	0.78
Stdev	0.64	0.73	0.62	0.41
Min	-1.05	-1.19	-0.38	-0.17

Figure 18 and Table 5 shows results for case 3050. Also, in this case model 2 is more to the lower side in the shown realization both with respect to peak value and to standard deviation. By analysis of the test arrangement is that one can find relations like this and if needed do modification to analysis parameters to ensure one are on the conservative side for the full design verification analysis.

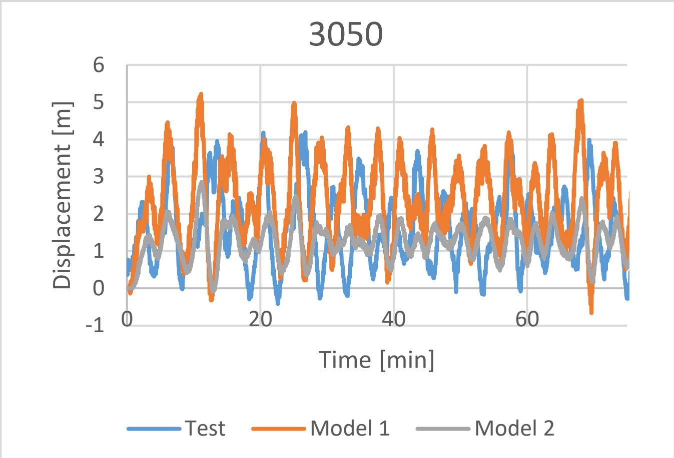

Figure 18 Comparison irregular waves

Table 5 Statistics displacement [m]. 3050

	Test	Test full	Model 1	Model 2
Max	4.19	4.40	5.23	2.86
Mean	1.57	1.54	2.33	1.26
Stdev	1.01	0.95	1.09	0.49
Min	-0.42	-1.44	-0.67	-0.09

3.3.4 *Irregular waves and current*

Table 6 shows the two conditions analysed with waves and current.

Table 6

Test	Hs [m]	Tp [s]	Current [m/s]	Gamma
3040	1.7	5.2	0.7	3.2
3060	2.4	6.1	0.7	3.2

Figure 20 shows timeseries for case 3040 and Table 7 shows statistics.

Note from the 3040- case that the standard deviation is lower in the analysis than in the measurements. This can stem either from the difference in current where there is standard deviation of 0.8 m in the testing, or it may be less wave generated damping in this case.

Table 7 Statistics displacement [m]. 3040

	Test	Test full	Model 1	Model 2
Max	9.58	9.61	9.01	8.44
Mean	6.79	6.75	8.11	7.54
Stdev	0.93	1.00	0.49	0.45
Min	4.71	3.46	7.17	6.82

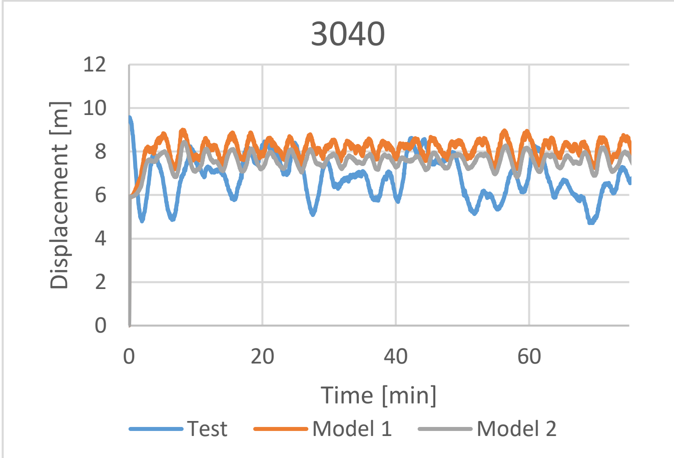

Figure 19 Comparison irregular waves and current

Figure 20 shows timeseries for case 3060 and Table 8 shows statistics. As seen from the cases with current, the mean and max displacements increase significantly while the standard deviations decrease.

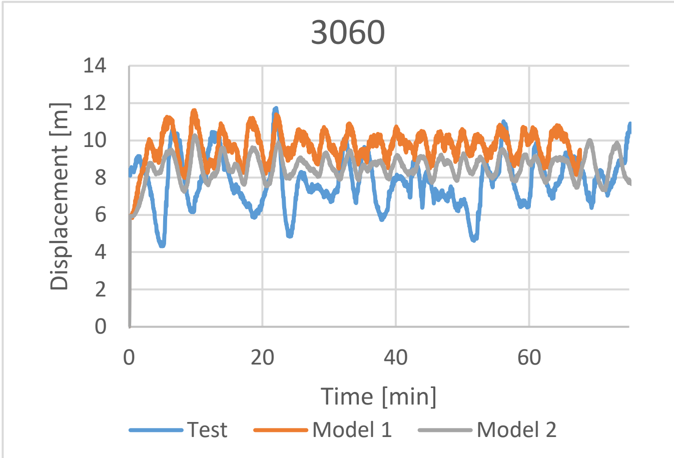

Figure 20 Comparison irregular waves and current

Table 8 Statistics displacement [m]. 3060

	Test	Test full	Model 1	Model 2
Max	11.74	12.61	11.63	10.28
Mean	7.81	8.06	9.66	8.54
Stdev	1.38	1.30	0.87	0.73
Min	4.32	4.29	7.98	7.24

As seen from results in this section both analysis models have higher average values and less standard deviations than the tank results. Probably, this can be traced back to results in current only where both analysis models give a static result while the testing (see Figure 9) gives a standard deviation of 0.8 m. This may lead to increased standard deviations compared to analysis also for cases with combined waves and current.

3.4 *Discussions*

3.4.1 *Damping and sensitivity*

Damping to the system consist of two terms. Viscous effects giving both drag loads and quadratic damping and a linear damping term set to represent wave generated damping. As noted by the results in Figure 10 and Figure 11, introducing 1% damping is of large importance to how fast the system dampens out. From the analysis in regular and irregular waves, and also combined with current, one may assume uncertainty as to how much wave generated damping there is. Figure 21 shows case 3030, but in this case, wave generated damping is not added in the analysis. Table 9 shows the statistics for this case.

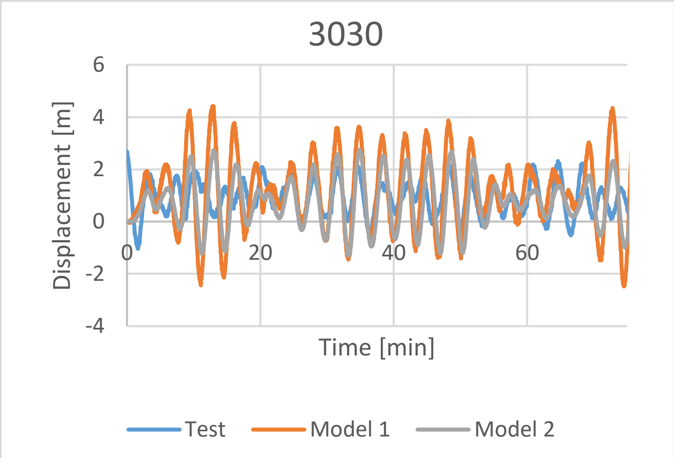

Figure 22 comparison, No wave generated damping in analysis

Table 9 Statistics displacement [m].3030

	Test	Test full	Model 1	Model 2
Max	2.67	3.00	4.87	2.75
Mean	0.90	0.90	1.13	0.76
Stdev	0.64	0.73	1.46	0.96
Min	-1.05	-1.19	-2.48	-1.32

As seen from the results, less damping means a larger standard deviation which is plausible. As seen by comparing analysis model 1 and 2 respectively to the test results, model 1 compares best with results with wave generated damping included, while the opposite is the case for the simple model.

Figure 22 shows results without damping for load case 3060 with statistics given in Table 10.

This shows the important of damping for the results. The standard deviation increases with 0.22 m for both models. The results for refined analysis model showed to be sensitive to refinement in modelling. This, in addition to analysis time, means it is an advantage to a simple model as long as conservative values are set for parameters such as drag, drift coefficients and damping. In addition to tank testing, calibration of a simplified model case be based on a refined model.

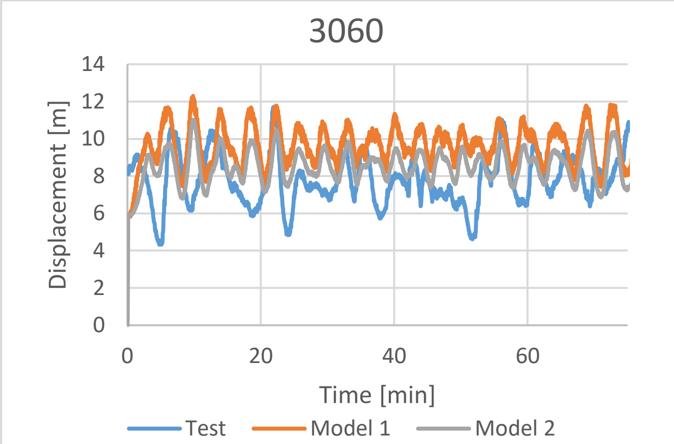

Figure 21 comparison, No wave generated damping in analysis

Table 10 Statistics displacement [m].3060

	Test	Test full	Model 1	Model 2
Max	11.74	12.61	12.31	11.03
Mean	7.81	8.06	9.65	8.55
Stdev	1.38	1.30	1.09	0.92
Min	4.32	4.29	7.42	6.78

3.4.2 *Waves, currents in a full grid*

The waves and current used for the testing are typical values for such parameters in the Aquaculture industry in Norway. As seen from the results, the two most important environmental effects are current and drifting by combined waves and current. By comparing the results for current with the results for waves and the results from waves and current it is seen the combined effect of current and waves is of the same magnitude as wave drifting. This means that all these effects are important to account for in a design approach.

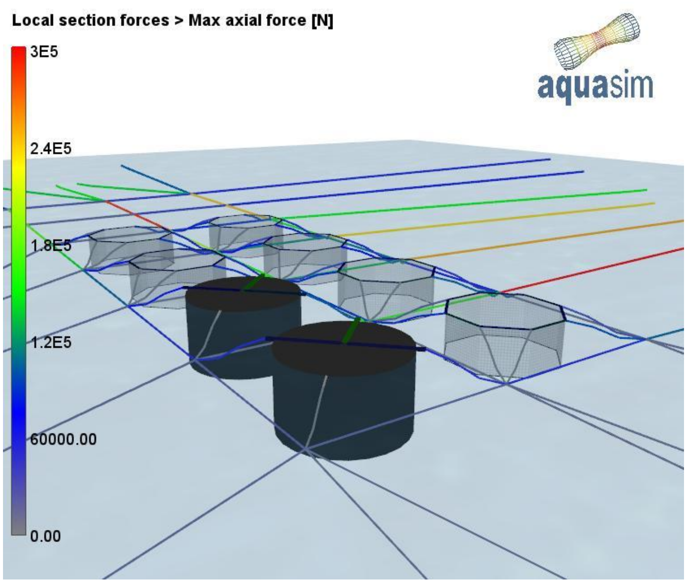

Figure 23 Aquatraz in grid with 6 regular cages

Introduced to a full grid, such as one shown in Figure 23, the natural periods may be higher than in the test setup.

3.4.3 *Analysis model refinement*

Figure 24 shows an excerpt of analysis model 1. In the AquaSim analysis program, the 4-node shell elements used to model the tank. These panels are basis for the accuracy of the analysis. It was noted that results for drift was dependent on the element discretization, particularly in the area close to the water line. This is plausible since the accuracy of force introduction close to the water line is important for drift forces.

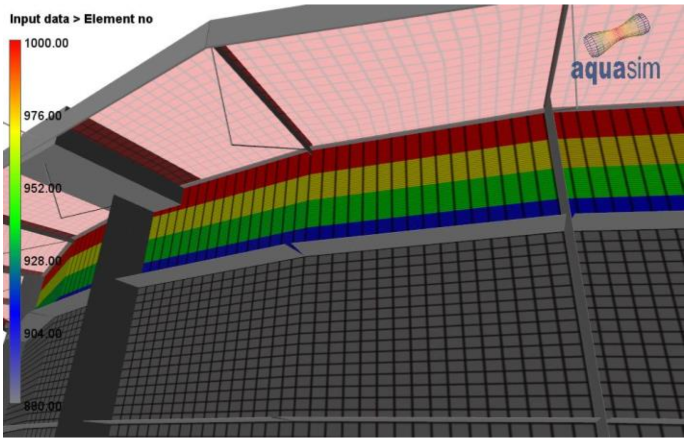

Figure 24 Part of analysis model 1.

4 CONCLUSIONS

Current and slow drift motions caused by combined waves and current are of importance for the Aquatraz G4 cage in a grid mooring typical for Aquaculture systems leading to very long drift periods in realistic cages.

Both analysis models presented in this paper capture the response on the Aquatraz G4 in a manner good enough to capture the important effects in a mooring analysis.

Long analysis with irregular waves needs to be carried out to determine the maximum response in cases where high accuracy is needed for the drift response (see further in Section 4.1.1)

4.1.1 *Analysis for design*

Due to the importance of drifting around the natural period to loads, this means analysis should be carried out to investigate the effect of this. This means time series with length of 1.5 hours and upwards to 3 hours. The refinement of model 1 means this will take too long for such an analysis. Since the results compare well model 1 & 2 and the test data it was decided introduce model 2 to grids such as the one seen in Figure 23 for analysis of sea states up to 3 hour length. The damping, drag and drift coefficients should be made to the safe side, or if it is uncertainty as to which side is the conservative side, sensitivity analysis should be carried out. The results in this paper indicates that wave generated damping should be included with care, and the most conservative approach is to not include it, which is the recommendation. Check also drift coefficients both from analysis and model basin testing and take the highest if different.

In a classic grid, Aquatraz G4 will be combined with classic nets. Using the normal refinement of classic drag dominated grids means a very long analysis time. To speed up the analysis time, also classic grids need to be modelled with fewer elements. The depth and solidity of such simplified net should be matched to a model with normal refinement.

In addition to analysis long time series with simplified models of cages as shown in Figure 23 more refined models can be applied with short time-series and regular waves. In this case, static loads should be applied to the Aquatraz cages to have them placed in a realistic position also including slow drift.

This means expanding vastly the analysis culture for regular drag dominated grids, but for the combination of these units that is a necessity.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

Aquastructures (2019) " Loads on Impermeable Nets and Large Volume Objects in AquaSim." Aquastructures Report no. TR-FOU-2328-revision 05. www.aquasim.no.

Aquastructures (2021) "Analysis compared to testing, Aquatraz 4", TN-30986-6589-4. Rev 1. Aquastructures report, www.aquastructures.no

Aquastructures (2021b) "Aquasim User manual" Document ID: TR-20000-583-1 Date: 3/4/2021 AquaSim version: 2.16.2 Aquastructures. Kjøpmannsgata 21 7013 Trondheim. Norway.

Babarit, A., & G. Delhommeau (2015): Theoretical and numerical aspects of the open source BEM solver NEMOH. In Proc. of the 11th European Wave and Tidal Energy Conference (EWTEC2015), Nantes, France

Berstad, A. J., J Walaunet & L. Heimstad (2012) "Loads From Currents and Waves on Net Structures" Proceedings of the ASME 2012 31st International Conference OMAE2012-83757.

Berstad, A.J and J.V. Aarsnes (2018). "Offshore Structures for Aquaculture. Comparison of Analysis with Model Testing". Proceedings OMAE2018-78542

CeFront (2020) "Model evaluation report; Aquatraz_G4" Date: 14.08.2020. Author Jan Vidar Aarsnes.

Faltinsen (1990) "Sea loads on ships and offshore structures". Cambridge university press 1990. ISBN 0 521 45870 6.

MacCamy,R.C & R.A. Fuchs (1954) "Wave Forceson Piles: A Diffraction Theory." Corps of Engineers, Washington, D. C.

Marintek (2020) "Model tests of Aquatraz G4". Version 2.0. Date: 20.08.2020. Author: Senthuran Ravinthrakumar.

Morison, J. R., M.P. O'Brien, J.W. Johnson & S.A. Schaaf (1950), "The Force Exerted by Surface Waves on Piles," Petroleum Transactions, AIME. Vol. bold 189, 1950, 149-154

Standards Norway (2009) "Norwegian Standard NS 9415:2009. Marine fish farms. Requirements for site survey, risk analysis, design, dimensioning, production, installation and operation." www.standard.no