Design Loads on Platforms on Offshore wind Turbine Foundations with Respect to Vertical Wave Run-up

Damsgaard, Mathilde L.; Gravesen, Helge; Andersen, Thomas Lykke

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Design loads on platforms on offshore wind turbine foundations with respect to vertical wave run-up

Mathilde L. Damsgaard
DONG Energy
matda@dongenergy.dk

Helge Gravesen
DONG Energy
hgx@dongenergy.dk

Thomas L. Andersen
Aalborg University
tla@civil.aau.dk

Abstract:

Experiences have shown that the vertical run-up generated by waves meeting the offshore wind turbine foundations, can result in rather vigorous loads on appurtenances and platform structures. This study aims to provide a qualitative method of determining run-up height and the following loads depending on the wave parameters in the area in question. This is approached by a three step calculation routine supported by model tests. Supplementary tests have been made to determine the reduction in loads, when grated platforms are used in preference to a closed surface. This leads to an appreciable reduction in the loads by up to 75%.
Furthermore it is indicated, that the fact that offshore wind turbines often are placed on limited water depths thereby increasing the amount of (nearly) breaking waves, seems to increase the run-up height and thereby the pressures on the structure.

Keywords: design loads, waves, secondary structures.

1 Experiences with wave run-up

In offshore wind farms the effects of vertical wave run-up has appeared evident as little or no attention has been paid to this phenomenon during the traditional design process. This has resulted in extensive damages to platform structures and appurtenances, as seen at the Horns Reef offshore wind farm. An illustration of the phenomenon is shown in figure 1.

Figure 1: Example of wave run-up; Horns Reef

2 Model tests

As the run-up is governed by complex hydrodynamics the initial step is to investigate the phenomenon through a model test program. This is initiated in cooperation with Aalborg University (AAU), and the test runs are carried out in the wave flume in Aalborg. The aim of the model test runs are partly to investigate the nature of vertical wave run-up and to detect the governing influences, partly to set up a calculation model in preparation for design purposes. The model tests at AAU are supported by the PSO project with participants from DONG Energy, Danish Hydraulic Institute (DHI) and Vestas.
The PSO project only examines the run-up height, but do so through more complicated wave patterns in a 3D wave basin at DHI. The two independent test series are compared for verification of results.

2.1 Calculation model approach

As the main goal is the ability to include the loads from wave run-up in the design process, a calculation model is suggested and then attempted calibrated through the test results.

A three step calculation routine is suggested:

1) Determine run-up height based on wave parameters and water depth

2) Determine vertical velocity at the level of the structure in question

3) Determine the pressure induced by the water masses impact on the structure

The run-up height is expected to be described as a sum of the elevation and a factor, m, times the velocity head

$$R_u = \eta + m\frac{u^2}{2g} \qquad (1)$$

The vertical velocity at the level, z, above SWL is then suggested calculated by the expression

$$v(z) = \sqrt{2g(R_u - z)} \qquad (2)$$

Finally the load is calculated as a slamming force

$$\frac{F}{A} = ½\, C_S\ \rho\ (v(z))^2 \qquad (3)$$

The factors m and C_S are then investigated based on the test results from AAU. Furthermore the expression for v(z) is checked against the measurements. The wave parameters η, crest elevation, and u, maximum horizontal particle velocity, are calculated using stream function theory.

2.2 Test series in wave flume

A number of parameters are investigated as variables in the test program. Both wave steepness, s_{op}, normalized depth, h/D, and normalized wave height, H_{m0}/h, are included in the study. Table 1 lists the cases, each case is run with s_{op} = 0.020 and s_{op} = 0.035, hence 24 different wave series are run.

H_{m0}/h	h/D = 2	h/D = 3	h/D = 4
0.35	H_{m0}=0.070 m	H_{m0}=0.105 m	H_{m0}=0.140 m
0.40	H_{m0}=0.080 m	H_{m0}=0.120 m	H_{m0}=0.160 m
0.43	H_{m0}=0.086 m	H_{m0}=0.129 m	H_{m0}=0.172 m
0.46	H_{m0}=0.092 m	H_{m0}=0.138 m	H_{m0}=0.184 m

Table 1: Test conditions for irregular wave trains

The geometry of the wave flume is shown in figure 2.

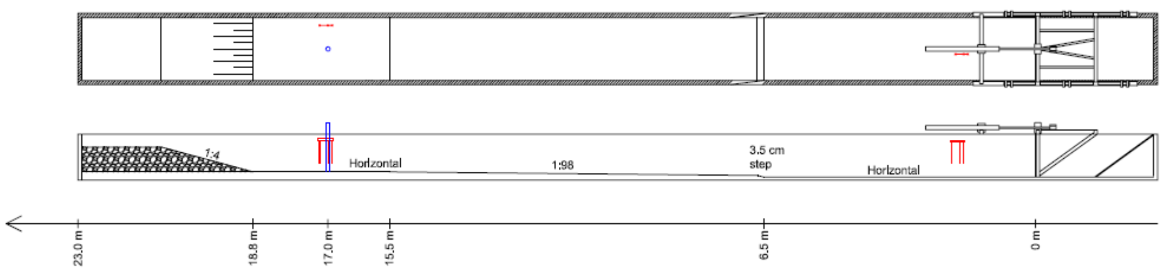

Figure 2: Layout in flume. Wave gauges are shown in red, run-up model in blue

The modeled structure to generate the run-up is a monopile with the diameter, D = 10 cm. The cylinder is equipped with surface wave gauges per 22.5° asymmetrically. 0.0° indicates the impact point for the wave front.

An air gap of approximately 2 mm between the wires and the cylinder wall minimize the risk of water standing between the surfaces and thereby inducing errors on the measurements.

Figure 3 show pictures of the model set-up, whereas figure 4 presents a principle sketch of the wave gauge layout.

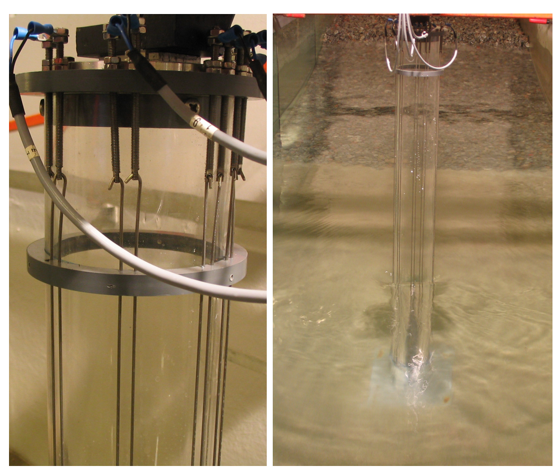

Figure 3: Pictures of the run-up model

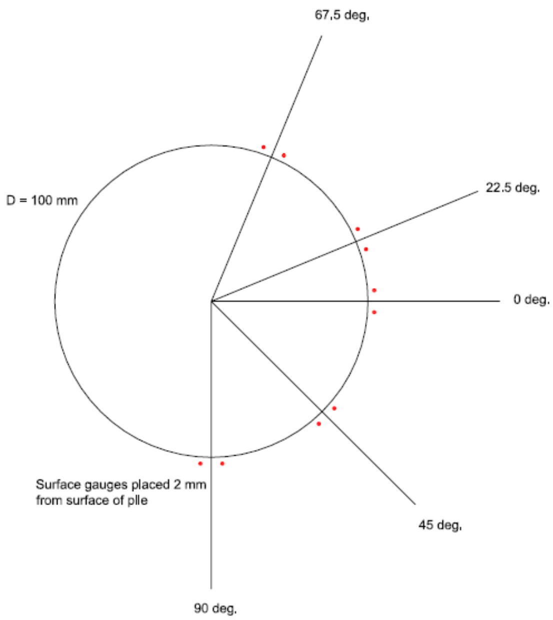

Figure 4: Run-up model with orientation of surface gauges indicated; waves are approaching from the right.

After completing the tests measuring the run-up heights the model monopile is equipped with a horizontal and then a cone shaped platform before running the same wave series once again. The platform models are mounted with a number of pressure cells logging at 1000 Hz. The models are illustrated in figure 5 and 6.

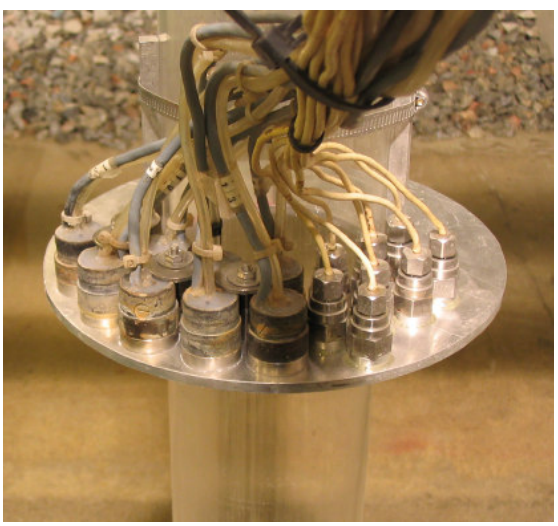

Figure 5: Model of horizontal platform with pressure cells

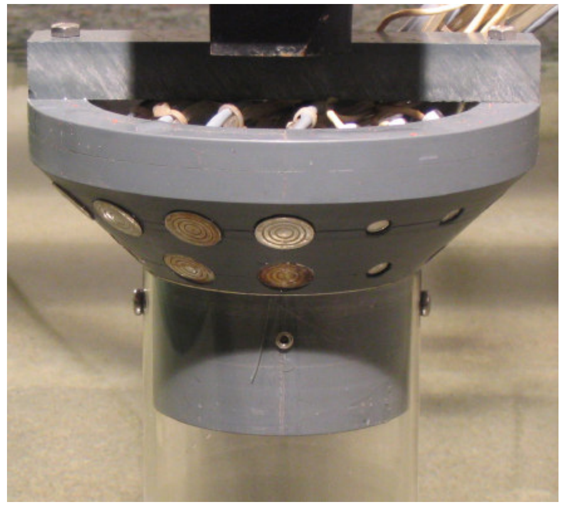

Figure 6: Model of cone platform

The run-up tests serve to describe the m-factor on the velocity head in expression (1), whereas the test series with the platform models should lead to the estimation of the introduced slamming coefficient, C_S, in expression (3).

2.3 Test series in 3D wave basin

The wave tests at AAU are carried out in a 2D wave flume. To elaborate further on this subject DONG Energy entered into a Public Service Obligation project in cooperation with Vestas and Danish Hydraulic Institute (DHI), concerning the run-up height. Those model test series was carried out in a 3D wave basin at DHI, and focus mainly on the influence of 3D-effects on the run-up height.

Looking at figure 7, the wave parameters are illustrated.

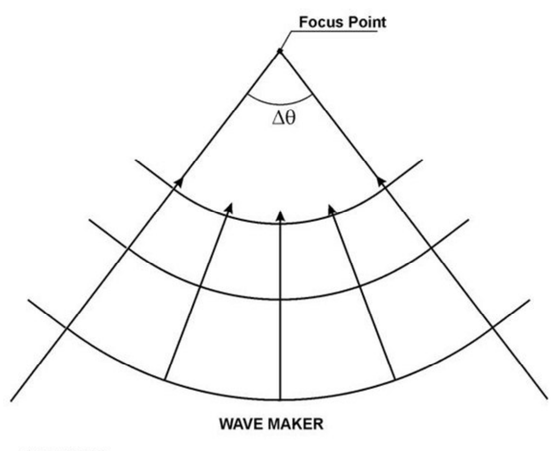

Figure 7: Wave parameters in DHI tests

The variable parameters in this study are:

1) Incoming angle, $\Delta\theta$

2) Location of focus point with regard to pile centre

3) Wave height at focus point

The modeled monopile is shown in figure 8.

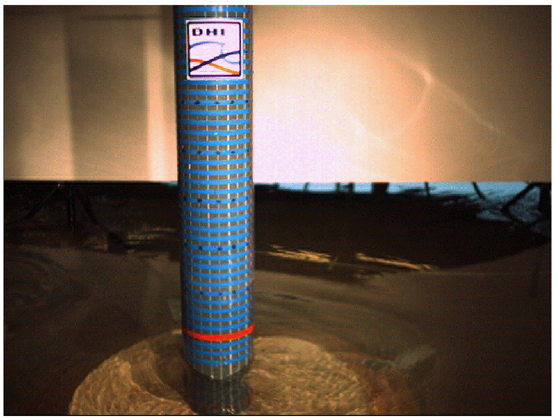

Figure 8: Model set-up for wave run-up tests at DHI

The run-up is registered both by wave gauges and by high speed camera – hence the blue horizontal lines on the pile.

3 Results from model tests

The test results are analyzed with respect to the suggested calculation model, and the results from the AAU test series and the DHI test series are also compared to each other in order to get some verification of the results.

3.1 Run-up tests at AAU

The conclusion is, that the water depth to pile diameter ratio and the wave height to water depth ratio is of little significance to the wave run-up height. The wave steepness however seems to have quite an influence, as the m-factor on the velocity head seems to decrease with increasing wave steepness.

Figure 9 and 10 show the comparison of the result found by the calculation model using the apparent m-factors, and the measured results.

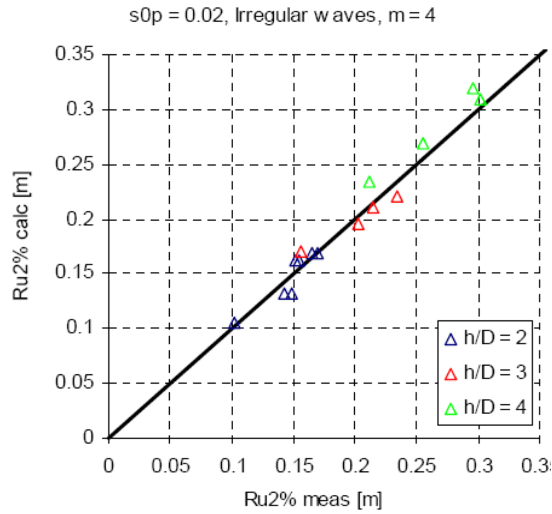

Figure 9: Measured versus predicted values of run-up height using m = 4 for s_{0P} = 0.020; wave kinematics calculated by stream function theory

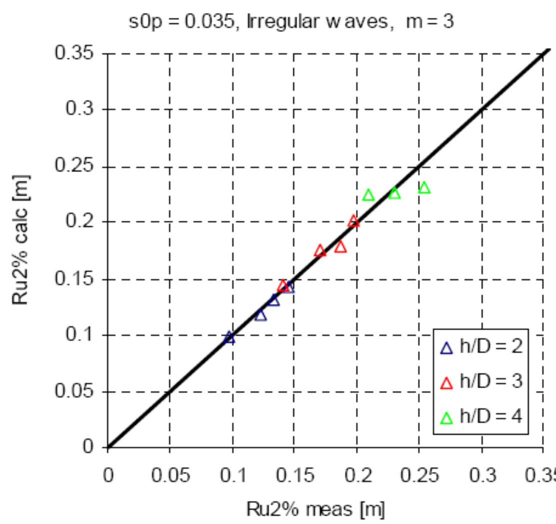

Figure 10: Measured versus predicted values of run-up height using m = 3 for s_{0P} = 0.035; wave kinematics calculated by stream function theory

The run-up tests are also used to verify the suggested expression for the vertical velocity of the water at a given level, z, as presented in expression (2).

There is found a reasonable agreement between the velocities found based on the measurements, through differentiation, and the velocities calculated accordingly using expression (2). The result is shown in figure 11.

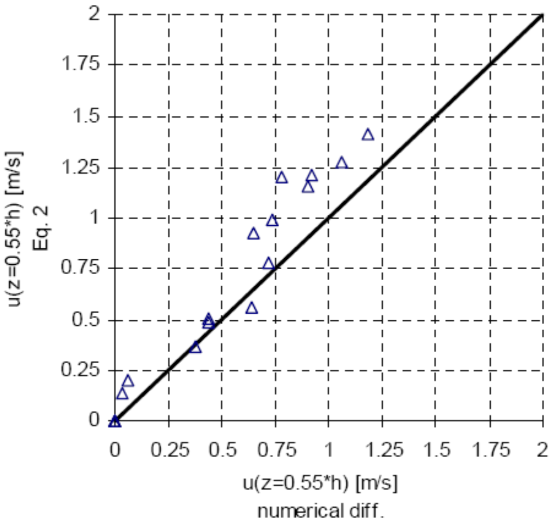

Figure 11: Comparison of vertical velocities of run-up water found based on measurements and based on the calculation model

3.2 Impact pressure tests at AAU

The slamming coefficient is calculated based on comparing the run-up tests with the pressure measurements on the platform models.

Figure 12 and 13 show plots of the maximum measured pressures with lines to indicate a number of slamming coefficients for the horizontal and the cone platform. The slamming coefficient describes the maximum local pressure, affecting an area of 0.5 m^2.

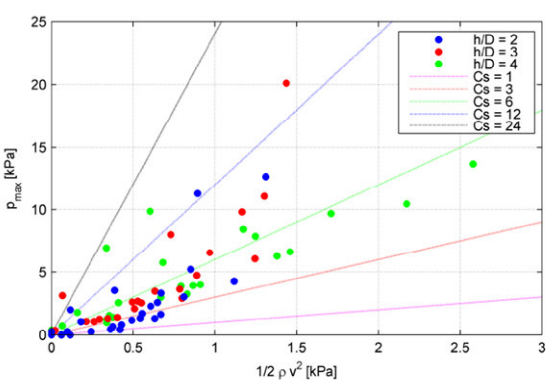

Figure 12: Measured pressures for the horizontal platform indicating the slamming coefficient for the maximum local load according to expression (2)

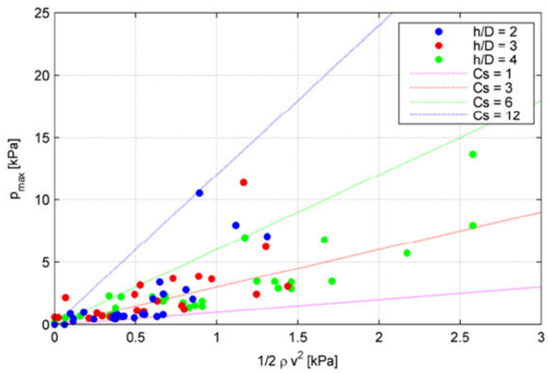

Figure 13: Measured pressures for the cone platform indicating the slamming coefficient for the maximum local load according to expression (2)

As expected it is seen from figure 12 and 13, that the loads on a horizontal platform are significantly larger than those on a cone platform.

The measurements indicate that the loads on a horizontal platform are twice as high as those on a cone platform with the bottom slope of 45°.

3.3 Run-up tests at DHI

Analyzing the results lead to the initial conclusions that both kh and 3D effects are of little influence to the run-up height. Meanwhile the wave steepness are of some influence, as the AAU results also showed, and one of the main results from the test series was that decreasing energy level, i.e. breaking waves, leads to an increase in run-up height. However the tests in the 3D wave basin only showed a very limited influence of the location of the focus point; and thereby the breaking point, relative to the center of the pile.
As an overall result, the maximum run-up height appears to be in the order of

$$Ru_{max} = 1.75\ h \qquad (4)$$

Comparing the run-up height registered by the wave gauges with the high speed camera recordings it is evident, that the wave gauges underestimate the run-up height. This is illustrated in figure 14.

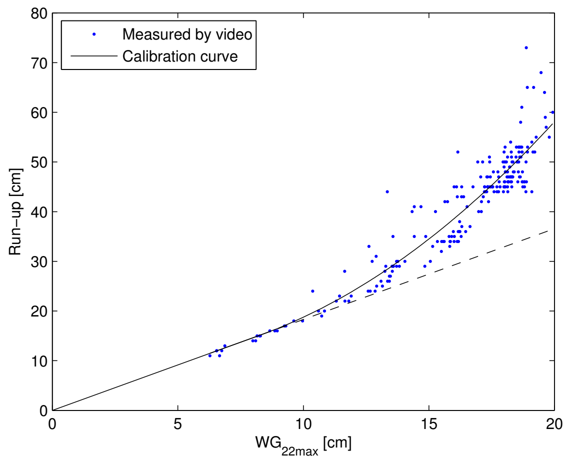

Figure 14: Run-up height measured by video plotted against the run-up measured by the wave gauges

The underestimation is assumed to be caused by air mixed into the water which disturbs the resistance over the wave gauges.

Furthermore there is not established any discrepancy between the DHI and the AAU results, which is serving as an initial verification of the results.

4 Evaluating the calculation model and test results

The test results has provided the factors used in the calculation model and the run-up height is assumed rather well described through the 2D and 3D wave tests. However especially the slamming coefficient is somewhat higher than seen in earlier studies on wave impacts; hence the calculation model leads to rather high values for the loads.

The time series from the pressure cells are studied closer. A typical pressure peak according to one run-up event is shown in figure 15.

There appears to be two indications to the pressure measurements being on the conservative side.

a) The duration of the run-up induced load is very short; in the order of 0.01 s to 0.05 s (prototype scale). This leaves little time for the structure to respond to the full load impact

b) The transient peak drops below zero indicating a sort of dynamic overshoot governed by the dynamics of the pressure cell.

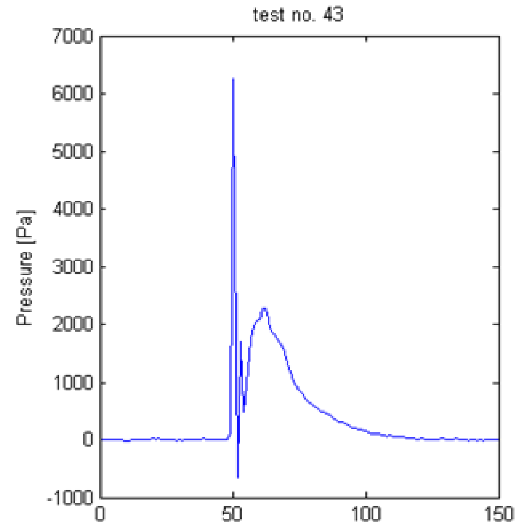

Figure 15: Section of time series during a run-up event

It is assumed that further studies on the loads will give a significant optimization on the design loads, but at this stage it is too early to describe a well defined reduction.

5 Grate platforms

As a way to reduce the loads on the platform structure the effect of using gratings instead of a closed surface is studied by a series of tests at AAU.

The test set-up is illustrated in figure 16.

Figure 16: Test set-up for test with grates

The tests are carried out for four different types of gratings with different porosity, wall geometry and opening sizes, and for a closed surface as reference.
The main result is that the sole governing variable is the porosity, and not the size or shape of the holes or the geometry of the walls. The porosity for the gratings used in the test cases lies from 0.70 to 0.87, and the minimum reduction in load is by approximately 70% compared to the closed surface.

Figure 17 show the forces measured for different angles of attack between 48° to and 90° to the grate of the type Fiberline 40, with the porosity of 0.70.

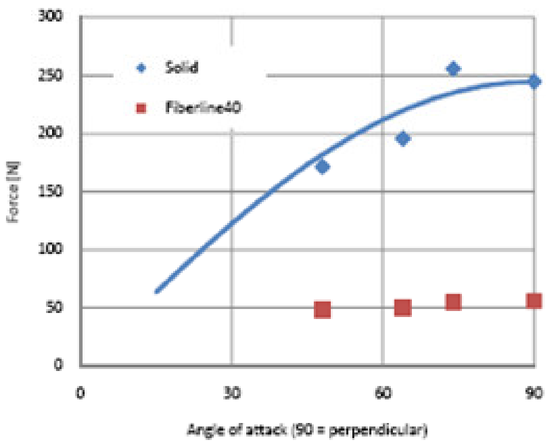

Figure 17: Plot of measured forces at different angles of attack

This indicates that grate platforms could be a way of reducing the design loads due to wave run-up, but previous experiences has shown that there can be some difficulties in the fastening systems, which should be taken into account when choosing the platform design.

6 Conclusion

The calculation model described in section 2.1 provides an initial method for designing with regards to loads induced by vertical wave run-up.
Expression (1) is replaced by expression (5), taking the underestimation of the run-up measured by wave gauges into account. This is only a linear adjustment, and further studies are needed to incorporate the full non-linear underestimation.

$$Ru = 1.2\left(\eta + m\frac{u^2}{2g}\right) \qquad (5)$$

Also the loads can be determined based on the calculation model, however some conservatism is expected at this point, and a more optimized design can be achieved by carrying out elaborating studies on this subject.