CHAPTER 38

A COMPARISON BETWEEN MODEL AND PROTOTYPE WAVES IN HARBOURS

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INTRODUCTION

A common method of estimating the sheltering effects of different breakwater locations and layouts is to carry out physical model wave disturbance tests. Such tests have been carried out in different laboratories throughout the world for many years. But to our knowledge no reports are available in the literature showing comparison between model measurements and field measurements.

The trend is that we know more and more on the wave climate along our coasts. Hence we have a better basis to make our economical calculations on breakwaters. We therefore also want to operate our models on a more absolute basis rather than on a comparative basis. The trend in recent years has also been to study breakwater locations and layouts in order to minimize mooring forces and ship movements.

On this background VHL found a comparison between model test results and field measurements necessary. Full scale measurements of waves were carried out in two harbours by VHL during the winter 1976/77. This paper will present the results of the comparison of the model and the full scale measurements in Berlevåg and Vardø fishing harbours on the open coast of Finnmark in the northern part of Norway (Fig. 1). The model tests, as well as the full scale measurements, have been sponsored by the Norwegian State Harbour Authorities.

BERLEVÅG FISHING HARBOUR

Model tests

In 1960-61 VHL carried out model tests on the breakwater layouts for Berlevåg fishing harbour, and in 1976 the construction of the chosen breakwater layout was completed (Fig. 2). The model tests were carried out in scale 1:110 and regular waves were used, as was usual in every laboratory at that time. Due to the use of regular waves, wave spectra could not be compared from model and field measurements. The input waves during the model tests were based on hindcast and refraction analysis, and the sheltering effects of the breakwaters against waves from N and ENE (deep water) were tested with periods corresponding to T = 9 sec and 13 sec. The height of the incoming waves were mostly 5 m but in some tests they were 3 m at the wave generator. The water level during the model tests were +2.5 m.

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FIGURE 2,

Fig. 3 shows some of the refraction analysis carried out for waves from directions E and ENE. It is seen that although differences in direction in deep water are large, the differences in direction in front of the breakaters are only some few degrees.

Fig. 2 shows the model plan for Berlevåg harbour. The waves were mainly measured in the grid points, the distance between each point was approximately 100 m. Detailed measurements were carried out at lines A and B, which are in front of a proposed quay site. These measurements showed that the wave heights varied significantly within short distance and also with time in the model.

During the full scale measurements (see later) the position of the wave meters would vary depending on wave and wind conditions. Hence for the basis of comparisons of model tests and field measurements an average wave height of the grid points closest to the wave meter was used. The three field measurement points are shown in Fig. 2. Since the measurements were carried out in more detail in position 3 than in position 2, we consider the model values more accurate for position 3 than for position 2.

In Table 1 is shown the average wave heights for the different measuring points.

Wave direction deep water	Wave period sec.	Water level m	Wave height position l m	Wave height position 2 m	Wave height position 3 m
ENE	9 9 13 13	+ 2.5 + 2.5 + 2.5 + 2.5 + 2.5	5 3 5 3	1.86	1.21 0.88 1.48 0.83
Ν	9 9 13 13	+ 2.5 + 2.5 + 2.5 + 2.5 + 2.5	5 3 5 3	1.03	1.96 1.04 2.44 0.99

TABLE I. Average wave heights in meters outside and inside Berlevåg harbour based on model tests.

Field measurements

The wave measurements in Berlevåg harbour was carried out during the time period 20 October - 26 November 1976. Three wave gauges of the Datawell Waverider Buoy type were placed in the positions shown in Fig. 2. The wave meters have some freedom to move, and this is to



FIGURE 3. Refraction analysis. Wave period T = 13 s. Depth contours in meters.



FIGURE 4. Wave spectra at Berlevåg 21 October 1976 at 1000.

some extent considered when comparing the field and model data. The wave gauge outside the harbour was placed as close as possible to the reference point for wave measurements in the model and with due considerations to the navigation in the area.

The weather conditions during the measuring period was, however, good with very little waves for that time of the year.

The waves recorded on 21 October, 25-26 October and 24-25 November 1976 had maximum heights of approximately 4 m, and the waves from these days have been used in our comparison.

The waves were recorded on magnetic tape and the wave recordings were analysed by a computer program.

The wave analysis was based on 300 consecutive waves. A Fast Fourier Transform was used to calculate the wave spectra. 4096 data points were used. The time interval between each data point $\Delta t = 0.5$ s. 2048 components were calculated in the frequency range 0-1 Hz. The averaging was made over 41 components giving data points at frequency intervals $\Delta f = 0.02$ Hs. The 90% confidence interval for each spectral value is within 0.78-0.55 of the calculated value.

Figs. 4 and 5 show simultaneous wave spectra at the three stations.

The main wave directions were visually judged during the measurements. However, wave directions were also calculated by the Norwegian Meteorological Institute using a numerical hindcast model. The wave directions by this numerical model were caluclated at grid points 150 km apart. The closest grid points to Berlevåg are shown in Fig. 1. The wave hindcast models give the wave direction in deep water. When considering the wave refraction from deep water to the harbour area, the visually observed wave directions corresponded fairly well to the hindcasted wave direction.

Table 2 shows results of the wave measurements in Berlevåg.

It is also interesting to notice the transfer of energy to higher frequencies of the wave spectrum as shown for position 2 in Fig. 4. The spectra of Fig. 4 are for easternly waves, while the ones in Fig. 5 are for more nothernly waves. No significant transfer of energy to higher frequencies is observed for the spectra of Fig. 5.

The reason for the high frequency wave energy or position 2 in Fig. 4 is inferred to be due to waves breaking at the head of the western breakwater. In the breaking process, new short waves are generated. This is a case often observed in model.



FIGURE 5. Wave spectra at Berlevåg 26 October 1976 at 1030. Deep water wave direction N.



FIGURE 6. Berlevåg - Transfer functions. Position 3.

Posi- tion	Date	Time	H _s m	H _{max} m	T _p sec.	Deep water wave direc- tion	Water level m
I	21 Oct. 21 Oct. 25 Oct. 26 Oct. 24 Nov.	1000 1725 2325 1030 2130	2.09 2.09 2.17 2.54 1.56	3.93 3.36 3.68 3.88 2.70	10.0 8.5 10.0 10.0 7.0	ENE E NNE N WNW	+1.0 +1.7 +0.3 +0.7 +1.6
2	21 Oct. 21 Oct. 25 Oct. 26 Oct. 24 Nov.	1000 1725 2325 1030 2130	0.73 0.84 0.45 0.51 0.26	1.13 1.18 0.66 0.75 0.38	4.5 4.0 10.0 10.0 7.0		
3	21 Oct. 21 Oct. 25 Oct. 26 Oct. 24 Nov.	1000 1725 2325 1030 2130	0.33 0.34 0.34 0.39 0.27	0.51 0.52 0.66 0.70 0.45	8.5 8.5 10.0 10.0 7.0		

TABLE 2. Measured waves at Berlevåg harbour. 1976.

 $T_p = I/f_p;$ $f_p = frequency of maximum energy density;$ $H_c = significant wave height.$

<u>Comparison of waves in the field and the model</u>

Since the waves in the model were regular while the waves in the field are irregular and of different heights than in the model, it is not possible to compare directly the waves in the field and in the model. However, to compare we have defined a sheltering coefficient $K_d = H_h/H_i$, where H_h = wave height in the harbour and H_i = wave height outside the harbour. For irregular waves the significant wave height has been used. It should, however, be noted that the sheltering coefficient cient varies for different frequencies of the wave spectrum (see later).

In Table 3 is shown the sheltering coefficients from the field measurements and the model tests.

Generelly speaking the calculated sheltering coefficients are smaller from the field measurements than from the model tests. This is especially the case for position 2. There may be different reasons for this that will be dealt with in the general discussion.

To obtain some feeling for how the sheltering coefficient varies with the frequency, we have calculated a transfer function for the waves defined as:

	Position I		Position 2		Position 3		Water	Calculated	
	H	Т _р	K _d	Тp	Kd	Т _р	level	deep water Wave direction	
	m	sec		sec		sec	m		
Field H=Hs, T=Tp	2.09 2.09 2.17 2.54 1.56	10.0 8.5 10.0 10.0 7.0	0.35 0.40 0.21 0.20 0.167	4.5 4.5 10.0 10.0 7.0	0.16 0.16 0.16 0.15 0.17	8.5 8.5 10.0 10.0 7.0	+ + .7 +0.3 +0.7 + .6	ENE E NNE N WNW	
Model, regular H, T	5 3 5 3 5 3 5 3 5 3 5 3	9.0 9.0 13.0 13.0 9.0 13.0 13.0	0.41		0.24 0.29 0.30 0.28 0.39 0.35 0.49 0.33		+2.5 +2.5 +2.5 +2.5 +2.5 +2.5 +2.5 +2.5	ENE N	

TABLE 3. Berlevåg - sheltering coefficients from field and mode! wave measurements.

 $|T(f)| = \sqrt{\frac{E(f)_h}{E(f)_i}}$

where $E(f)_{h}$ = power density spectrum within the harbour

 $E(f)_i$ = power density spectrum outside the harbour.

This transfer function is very much used for linear systems.

The calculated transfer functions are shown in Figs. 6 and 7 for measuring stations postions 2 and 3. Apparently the sheltering effect is less for higher frequencies than for lower frequencies contradictory to linear theory. However, as pointed out during the description of the field measurements, there was apparently a transfer of wave energy to higher wave frequencies due probably to wave breaking around the breakwater head.

Thus the transfer functions rather reflect non-linearity effects than physical contradictions. It should also be noted that there is a larger uncertainty of the values of the transfer functions for the higher frequencies because of the rather small values the power density spectra have for the higher frequencies.

It is interesting to note that the transfer function for position 2 for 21 October shows a somewhat lower sheltering coefficient in the frequency range of the peak frequency (0.1-0.15 H_Z) than obtained from the ratio of the significant wave heights shown in Table 3.







 FIELD MEASURING POINTS, DEPTH CONTOURS IN m.

FIGURE 8. Vardø harbour

The wave sheltering in Berlevåg is apparently better than indicated by the tests with regular waves. How much better is, however, difficult to assess.

VARDØ HARBOUR

Field measurements

The wave measurements at Vardø harbour were carried out prior to the model tests. Fig. 8 shows the area at Vardø harbour and Fig. 9 shows the model plan with depth contours and with the field measuring points.

Waves were measured in Vardø during the time period 1 March - 24 May 1977.

Outside the harbour waves were measured with a Datawell wave rider buoy. At the dock, within the harbour the waves were measured by a pressure type wave gauge. Individual waves are not so easily obtained by pressure wave gauges. However, the wave spectrum is fairly well measured by a pressure gauge, taking into account the wave pressure attenuation with depth.

The waves from the two gauges were recorded on magnetic tape. The wave analysis was based on 300 consecutive waves. The procedure for the spectral analysis was the same as for the waves measured in Berlevåg.

The significant wave heights from the Datawell wave rider buoy was calculated from the wave record, while the significant wave height from the pressure wave gauge was taken as $H_s = 4\sqrt{m_o}$, where $m_o =$ spectral area. Fig. 10 shows wave power spectra for some of the recorded waves.

Table 4 shows some of the results of the measured waves in Vardø. The wave directions in paranthesis are those calculated by the Norwegian Mateorological Institute, in deep water, while the others are those visually observed.

Model tests

The model tests for Vardø harbour were carried out to improve the wave conditions within the harbour. The model scale was 1:100. Fig. 9 shows the model plan for Vardø harbour with the breakwaters as they were built many decades ago and as they were during the field wave measurements.

Most wave energy will enter the harbour from the north. Hence this wave direction was chosen for the model tests.

Irregular waves were used during the tests. The wave generator had one straight flap. Hence the wave crests were straight when they left the wave generator.

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FIGURE 9. Vardø habour model.



FIGURE 10. Vardø harbour. Field and model wave spectra.



FIGURE 11, Vardø harbour - Transfer functions. Position 2,

Position	Date	Time	H _s m	H _{max} m	Τ _ρ sec.	Direction	Water level m
	3 March 5 " 6 " 18 " 24 " 25 " 25" " 20 April 20" "	1700 2115 0915 1415 0600 2136 2315 0905 0905 1445 1445 1445	1.35 1.01 0.83 1.31 1.65 1.03 0.98 1.20 1.08 1.51 1.59	2.8 1.65 1.51 2.12 3.37 1.86 1.62 1.84 1.90 2.33 2.68	6.85 7.1 8.3 8.3 5.6 7.1 6.25 6.75 7.1 7.1 8.3	NW (W) NW NW SE NW NW NW NW NE (ENE) NE (ENE) NW (NNW)	+2.5 +0.8 +1.0 +1.8 +2.4 +2.3 +1.1 +2.8 +2.8 +2.8 +2.4 +1.7 +1.7 -+2.2 +2.8
2	3 March 5 " 6 " 18 " 24 " 24 " 25 " 25 " 20 April 20 " 7 May	1700 2115 0915 1415 0600 2136 2315 0905 0905 1445 1445 0810	0.28 0.15 0.12 0.40 0.25 0.33 0.33 0.37 0.39 0.41 0.42 0.50	0.51 0.27 0.22 0.72 0.47 0.60 0.60 0.68 0.71 0.74 0.75 0.90	6.25 8.3 8.3 7.1 10 5.0 7.1 7.1 6.25 7.1 7.1 8.3		

TABLE 4. Waves measured at Vardø. 1977.

*) Based on 1000 consecutive waves.

Different wave spectra were used for the model tests. Basically the peak frequencies of the model spectra corresponded to the wave periods T_p = 5.7 sec, 7.5 sec, 9.0 sec, 10.5 sec and 12 sec. All spectra were relatively narrow, except the spectrum with T_p = 5.7 sec. which was based on measured waves in Vardø. The significant wave heights close to the wave generator were in most tests 4.0 m, but for the wave spectrum with T_p = 5.7 sec the significant waves at the wave generator were close to the waves measured at Vardø.

In Table 5 is shown some of the wave parameters measured in the ${\tt Vard} {\tt \phi}$ harbour model.

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		Po	sition l		Position 2		
Wave direction	Water level	H _s	H _{max}	Т _р	Hs	H _{max}	Тр
	m	m	m	sec	m	m	sec
N N N N	+2.5 +2.5 +2.5 +2.5	.20 . 9 .49 .37	2.33 2.23 3.01 2.30	6.25 6.25 6.25 6.25	0.20 0.30 0.34 0.38	0.46 0.53 0.56 0.61	5.55 5.55 5.55 5.55

TABLE 5. Significant and maximum measured waves in the Vardø model

Comparison of waves in the field and in the model

Some of the model tests were carried out with waves corresponding to the waves measured in Vardø on 25 March 1977. These waves had rather short periods, and on model scale they were in the order of magnitude 0.5 sec and hence almost on the lower limit of the wave generator.

In Table 6 is shown the sheltering coefficent, K_d = $H_{\rm hs}/H_{\rm is},$ both for the field measurements and from the model tests.

	Positi	on I	Position 2			
	H _{is} m	T _p sec	К _d	T _p sec	Water level m	Calculated deep water wave direction
Model	1.20 1.19 1.49 1.37 2.12	6.25 6.25 6.25 6.25 6.25	0.23 0.25 0.23 0.28 0.33	5.55 5.55 5.55 5.55 5.55 5.55	+2.5 +2.5 +2.5 +2.5 +2.5 +2.5	N N N N
Field	1.20 1.08 1.51 1.31 1.41	6.25 6.25 7.1 8.3 8.3	0.31 0.36 0.27 0.31 0.35	7.1 6.25 7.1 7.1 8.3	+2.8 +2.8 +1.7 +1.8 +2.8	NW NW NE NW NW

TABLE 6. Vardø - Sheltering coefficient in the field and in the model.

Fig. 10 shows the wave spectra from the model and the field for the waves with peak period 6.25 sec.

The sheltering coefficients of Table 6 show that the sheltering is larger in the model than in the field.

WAVES IN HARBOURS

Fig. II shows the transfer function for different wave conditions. The sheltering varies with the frequency, most for the field measurements. In the model the minimum sheltering is obtained for frequencies around the peak frequencies (T = 5-8 s). For higher and lower frequencies the sheltering effect is less. The full scale measurements show the same tendency, except for the highest and lowest frequencies, T < 3 s and T > 10 s. The field measurements within the harbour were carried out with a pressure type wave gauge. There are uncertainties in calculating high frequency waves from such measurements. This could be one reason for the apparent low sheltering at high frequencies. But it has also to be born in mind that transfer of energy from low to high frequencies has been observed due to breaking of waves at the breakwater heads.

The transfer functions show that the sheltering in the model is better than in the field for almost every frequency. Comparison of the sheltering coefficient based on the significant waves and the transfer function show that the sheltering coefficient is lowest for significant waves both in the model and in the field.

DISCUSSION

The results of the field and model measurements show that there are apparently discrepancies between the field and model measurements. The Berlevåg harbour measurements show that the sheltering is apparently less in the model than in the field, while the opposite is apparently the case in the Vardø harbour measurements. However, there could be different reasons for these apparent discrepancies.

Regular and irregular waves

In the Berlevåg harbour measurements the tests were carried out with regular waves, while in the field measurements the waves were irregular. This makes direct comparisons difficult. Special emphasis is made on the fact that there are some transformation of wave energy from lower to higher frequencies.

In the Vardø harbour tests the waves in both the field and the model were irregular.

Wave direction

The waves were unidirectional in the model at the wave generator flap. In the field the waves were multidirectional at the position of the wave flap. The directional spread at this position was probably, due to refraction effects, not as wide as in the open ocean. The directional spread in the ocean is not fully established yet, but $\cos^n \alpha$ is often used. α is the angular direction from the main direction, n is an exponent, a value of n of 2-4 is often used.

From the refraction analysis shown in Fig. 3 is inferred that atthough the waves may have almost 90[°] difference in direction in deep water, the difference in direction at the wave generator flaps is much less. There are, however, still a multidirectionality at the breakwater flap.

There is an uncertainty in the visually observed and hindcasted wave direction from the field measurements at the Berlevåg harbour. This uncertainty can certainly contribute to the discrepancy between the model and the field measurements.

At the Vardø harbour we assume that the main direction of the waves from deep water northernly direction will be from north at the wave generator flap also. The orientation of the flap is such that maximum wave energy will enter into the harbour from that direction. Although we have no wave directional spectrum at the wave generator, there will be some directionality at this place, in the field. However, we believe that the wave direction in the model and the lack of wave directionality in the model is such that we would have relatively higher waves in the model than in the harbour, while the measurements show the opposite.

Another effect that was observed during the model tests was that there was a tendency of cross waves in front of the flap, generated by the flap. These cross waves had a rather short wave period. To what extent the model results are affected by these crossoscillations are not known. However, it is believed that the effect is small.

Another effect that is present at Vardø is a strong refraction effect due to the rather deep "trench" towards the harbour entrance. This effect was particularly observed in the model tests. Also, the depth contours were not true in the vicinity of the wave generator, where the depth corresponded to approximately 40 m along the whole length of the generator. In front of the ends of the generator, the rate of decrease of water depth was larger in the model than in the field to obtain the true depth. This has an effect on the waves, although it is not possible to quantify this effect.

Reflections

There could certainly be different shore and structural wave reflection effects in the field and in the model causing differences in model and field measurements. Different field boundary and gravel shores were tested in the Vardø model, but no significant effects from the different shores were observed. Hence it is inferred that reflection was probably no major cause for differences in the field and model results.

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Viscous scale effects

Viscous effects on the wave propagation and wave variation is present both in the field and the model. We have calculated the viscous damping effect in the model using the "Stokes shear wave theory". Over a length with constant water depth the wave damping due to viscous effects is [1]:

$$\frac{H}{H_0} = e^{-\alpha x}$$

where

 $\alpha = \frac{a \cdot 4\pi}{\beta L^2(\sinh kd + kd)}$

- a = empirical coefficient
- d = water depth ω^{\perp}

$$\beta = \left(\frac{\omega}{2\nu}\right)^{\frac{2}{2}}; \quad \omega = 2\pi/T$$

- ν = the water kinematic viscousity
- x = wave travel distance

Assuming a water depth of 0.25 m, the average depth in the model from the wave generator to the breakwater, a distance of 9 m, the damping along this distance due to viscous effects is only approximately 2% for a wave with period 0.6 s. If we assume a water depth of 0.05 m, the wave height reduction due to viscous effects is approximately 12% for the same wave period, 0.6 s.

Although there are some effects from viscousity in the model, this effect is almost negligible in our comparisons of field and model wave measurements.

CONCLUSIONS

Although there is a fair agreement between field and model measured waves, it is doubtful if we can use the results from harbour sheltering tests on breakwater layouts on an absolute basis. It is though believed that we will obtain very useful information from such tests on a relative basis.

To improve our model testing technique to obtain information on a more absolute basis, we have to improve our knowledge of field waves, particularly directional wave spectra, especially in shallow water, and general wave climates. We have also to improve our testing equipment. The first basins with directional wave spectra generators have appeared and we need to have a development to use such spectra also for harbour sheltering models.

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