APPLICATION OF STWAVE IN NORWEGIAN COASTAL WATERS

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## 1 INTRODUCTION

In connection with design of pipelines for transportation of oil and gas, information regarding significant wave height, wave directions and spectral period is required. In particular, wave information is crucial in the near-shore areas characterized by shallow waters. Wave data are used for stability and fatigue analyses of the pipeline. Usually, wave information from measurements is only available from some few points along the pipe route and very often from deep waters.

During the last years, STWAVE (Steady-State Spectral Wave Model, Smith et al., 2001) has been used in order to provide wave design parameters for pipelines along the Norwegian coast. The coastline of Norway has complex bathymetry with fjords, small islands, large islands and rocks. The water depth is also variable (0 - 600 m) and with large gradients. The environment outside the coast is harsh with significant wave height in the range 14 – 16 m for return period of 100-year. So far, it has not been documented that the STWAVE tool is applicable in such conditions. The objective of this work has been to evaluate the quality of STWAVE simulations in Norwegian Coastal waters.

In order to validate STWAVE in Norwegian waters, model data have been compared to measured wave data along a pipeline route between the Snøhvit Gas Field in the Barents Sea and Hammerfest in the Northern Norway, Figure 1.

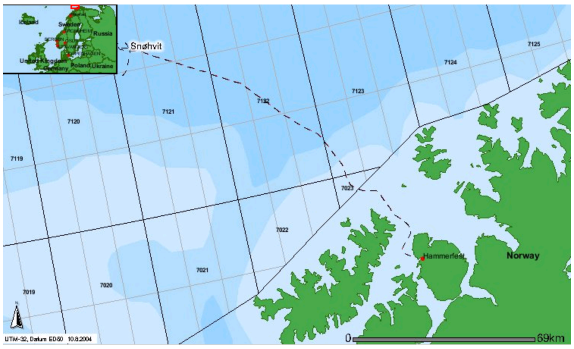

Figure 1. Parts of the Barents Sea between the Snøhvit field and the coast of Finnmark. Also is shown the approximate pipeline route.

## 2 WAVE MEASUREMENTS

Wave measurements have been carried out in 3 locations during the winter/spring 2003 (February – June). Figure 2 shows the locations. All locations are along the planned pipeline route between the Snøhvit Field and Hammerfest. Location W1 is an offshore reference station. W2 is located in an area characterized with relatively shallow water (approximately 60 m depth). Due to shallows and banks in this area, possibility for increase in wave heights caused by deflection of the wave paths could not be excluded. Location W3 is somewhat north of the approach area north of Melkøya. Exact positions and water depths are given in Table 1.

Seawatch Mini directional wave measuring buoys where applied in all three locations. The buoys measure waves in 17 minute long intervals and the wave parameters are sampled every hour. The data recovery was close to 100% for all three buoys.

Some severe storms occurred during the winter 2003 and all wave parameters are recorded and stored from these events. Figure 3 shows time series plots of the periods with highest wave recordings. Significant wave height of nearly 12 m was recorded at the offshore reference station (W1). This corresponds to a return period of nearly 10 years.

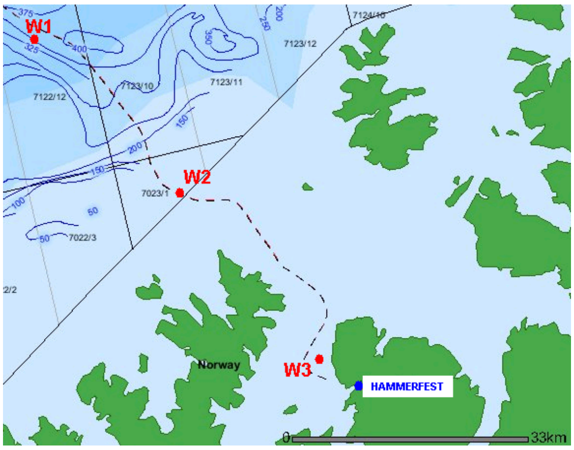

Figure 2. Map showing locations for wave measurements.

Table 1. Location and water depth for measurement stations.

| Buoy | Water depth | Latitude | Longitude |
|---|---|---|---|
| W1 | 357 m | 71° 14' 00" N | 22° 20' 00" E |
| W2 | 78 m | 70° 57' 14" N | 23° 11' 10" E |
| W3 | 126 m | 70° 42' 30" N | 23° 35' 00" E |

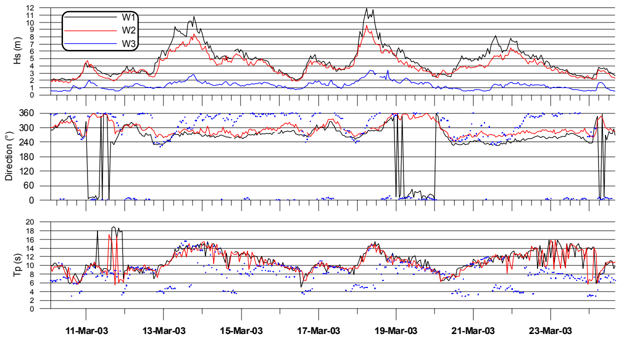

Figure 3. Time series plot of the periods with highest recorded waves.

## 2.1 *Wave spectra*

Visual inspections of all measured wave spectra from the most severe seastates have been carried out. In general, the JONSWAP wave spectrum with peak enhancement factor, γ, equal to 2 is in good agreement with the measured spectra. This is also consistent with findings from Whalen and Ochi (1978), Donelan et al. (1985) and Haver (1983). Figures 4 -6 show the measured and parameterised wave spectra from all 3 stations during the most severe storm in 2003. From Figure 6, it can however, be seen that a 2-peaked wave spectrum is more appropriate in the fjord since wind induced waves are building up simultaneously to the incoming swells. Figure 7 show that the Torsethaugen wave spectrum, (Torsethaugen, 2004) seems adequate conditional that correct significant wave height, $H_s$, and spectral peak period, $T_p$, is used as input. For pipelines however, only the swell is of importance since the wind induced waves rarely cause movements at the seabed along the pipeline route. The TMA wave spectrum, Buows et al. (1985), are identical with the JONSWAP spectrum except for a term taking into account reduction in energy due to the limited water depth. Since the JONSWAP spectrum is found adequate at site W1 and W2 it is reasonable to believe that the TMA spectrum will be most appropriate in the STWAVE simulations. As for the JONSWAP spectrum, a peak enhancement factor about 2 should be appropriate for the offshore wave conditions. Evaluation of directional wave spectra based on the measurements has not been carried out.

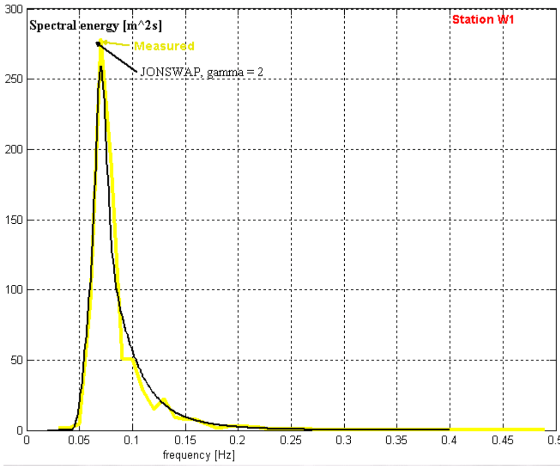

Figure 4. Measured and parameterised wave spectra for the most severe sea state measured at the offshore location, W1. Date 18.03.2003, $H_s$ =11.9 m, $T_p$ =13.1 s, HsDir=280°.

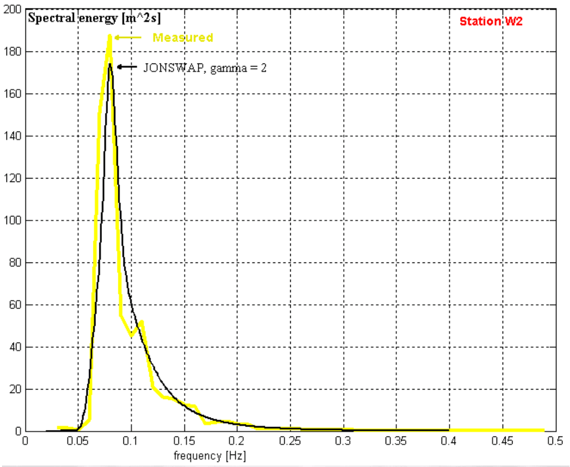


Figure 5. Measured and parameterised wave spectra for the most severe sea state measured at the shallow water location, W2. Date 18.03.2003, $H_s$ =9.6 m, $T_p$ =13.1 s, HsDir=281°.

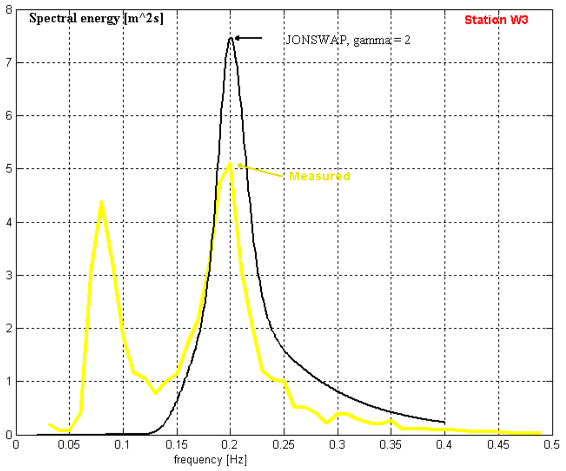


Figure 6. Measured and parameterised wave spectra for the most severe sea state measured at the inshore location, W3. Date 18.03.2003, $H_s$ =3.5 m, $T_p$ =10.2 s, HsDir=6°.

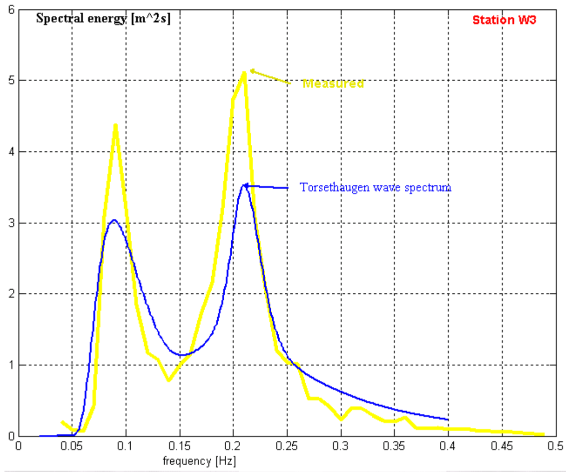


Figure 7. Measured and parameterised 2-peaked wave spectra for the most severe sea state measured at the inshore location, W3. Date 18.03.2003, $H_s$ =3.5 m, $T_p$ =10.2 s, HsDir=6°.

## 2.2 *Directional variations*

The directional wave distributions at the 3 measuring locations, Figure 8, shows that there are only minor differences from the offshore station, W1, to the “shallow water” location, W2, while the waves at the inshore location are significantly modified by the topography in the fjord.

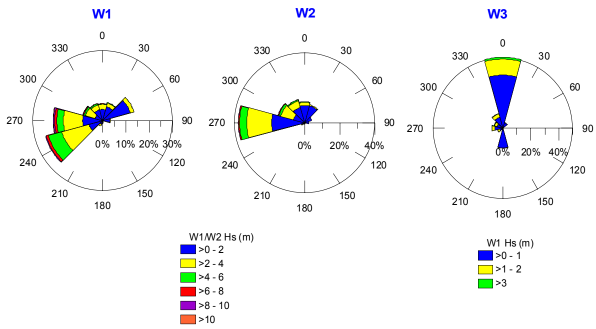


Figure 8. Directional distribution of $H_s$ at location W1, W2 and W3 from February – June 2003.

## 2.3 *Reduction in wave heights due to refraction effects*

Depending on the offshore wave direction, wave energy is lost as the waves propagate towards land and the fjords. Appendix A shows scatter plots of simultaneous recordings of Hs and Tp from the various stations. The scatter plots are divided into classes for different directional intervals. By least squares method, simple linear functions are fitted to the data. Based on this, reduction factors for the wave energy are estimated and shown in Table 2.

Table 2. Relative significant wave height at positions W2 and W3 in percent of offshore significant wave height (W1).

| Sector (°) | Total Sea | | Swell | |
|---|---|---|---|---|
| | **W2** | **W3** | **W2** | **W3** |
| 195 – 225 | 73 | 20 | 60 | 14 |
| 225 – 255 | 82 | 21 | 85 | 24 |
| 255 – 285 | 89 | 28 | 92 | 37 |
| 285 – 315 | 92 | 36 | 91 | 43 |
| 315 – 345 | **97** | **46** | **97** | **52** |
| 345 – 15 | 93 | 45 | 96 | 48 |
| 15 - 45 | 81 | 37 | 82 | 39 |
| 45 - 75 | 69 | 25 | 64 | 23 |

## 3 STWAVE ANALYSES

Wave analyses have been carried out with the STWAVE model, Smith et al. (2001). STWAVE is a steady-state finite difference model based on the wave action balance equation. STWAVE simulates depth-induced wave refraction and shoaling, current-induced refraction and shoaling, depth- and steepness-induced wave breaking, diffraction, wave growth caused by wind input, and wave-wave interaction and white capping that redistribute and dissipate energy in a growing wave field. The effect of reflection of waves from shore is not included.

The STWAVE analyses have been carried out in accordance to the following procedures:

- The most severe storm peaks (i.e. highest Hs and corresponding Tp) recorded in each directional sector at station W1 have been used as offshore boundary conditions in the wave analyses.

- Swell sea and total sea are treated separately. Influence of wind has not been taken into account in the swell analyses. Reason for this is that it has been assumed that the wind-induced seas not will affect the design of a pipeline. For total sea, an associated wind speed has been applied. The associated wind is the wind recorded at station W1 simultaneously with the recordings of the highest waves.

- The STWAVE is a half-plane model, i.e. energy may only propagate from offshore to onshore. This means that waves from the sector 210° - 300° will not propagate around the northeast corner of Sørøya into Sørøysundet on a grid oriented with west as offshore. In order to account for this a nested grid has been applied (see Figure 9).

- The influence of currents has not been taken into account.

- For all analyses, the TMA wave spectrum, Bouws et al. (1985), has been used with peak enhancement factor equal to 2.0. The directional wave spectrum recommended in the NORSOK standard (NTS, 1999) have been used both with large spreading (n=2) and small spreading (n=10).

The grid for the STWAVE simulations is shown in Figure 9.

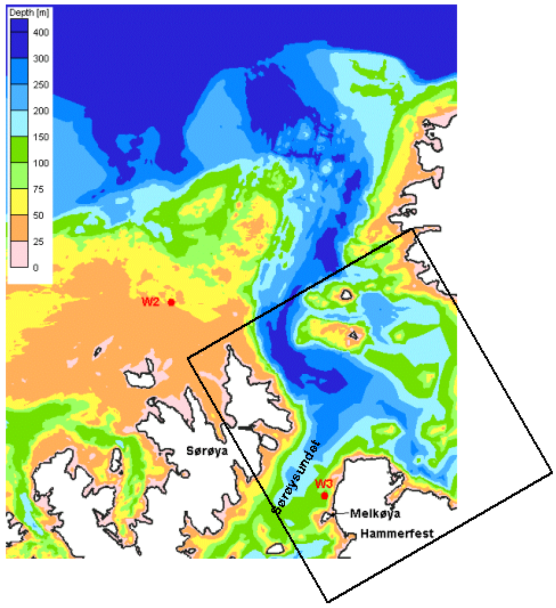


Figure 9. Bottom topography offshore Finnmark in the Northern Norway. Grid resolution is 100 m. Approximate positions for wave measurements are shown. Also is shown the nested grid used for the directions 210 - 300°.

### 3.1 *Results - swell*

Figure 10 shows the results of the STWAVE analyses when the most severe storm was used as input. The waves along the northern border are (found to be) significantly reduced in height as they propagate eastward despite that the water depth is more than 300 m along this intersection. This indicates that energy loss in STWAVE is too large and that new energy needs to be fed into the model in order to get realistic wave heights within the fjord. Comparing the results from stations W2 and W3 with the scaling factors from Table 2 supports this. Table 3 provide relationships between the STWAVE results at the stations W2 and W3 with the input conditions when only swell seas were used.

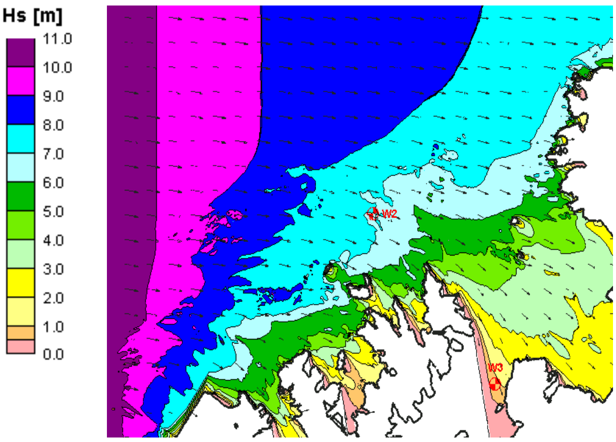


Figure 10. STWAVE output for seastate with Hs=10.9 m, Tp=13.4 s, large spreading (n=2) and no wind.

Table 3. Relative significant wave height at positions W2 and W3 in percent of offshore significant wave height (W1). Based on model results and swell seas only as input.

| **Sector (°)** | **W2** | | **W3** | |
|---|---|---|---|---|
| | *Large spread (n=2)* | *Small spread (n=10)* | *Large spread (n=2)* | *Small spread (n=10)* |
| 195 – 225 | 56 | 38 | 13* | 4* |
| 225 – 255 | 60 | 58 | 15* | 6* |
| 255 – 285 | 62 | 67 | 19* | 13* |
| 285 – 315 | 78 | 81 | 26* | 31* |
| **315 – 345** | 88 | 90 | 42 | 44 |
| 345 – 15 | 87 | 90 | 44 | 54 |
| 15 - 45 | 81 | 87 | 38 | 28 |
| 45 - 75 | 74 | 58 | 23 | 6 |

* Nested grid, see Figure 9.

### 3.2 *Results – total sea*

Figure 11 shows the results of the STWAVE analyses for the same storm as in Figure 10 but for total sea and associated wind speed included. The significant wave height, $H_s$, is now only slightly reduced along the northern border.

Comparing the results in observations points at the stations W2 and W3 with the scaling factors from Table 2 shows that model results and measurements are in relative good agreement. Table 4 provide relationships between the STWAVE results at the stations W2 and W3 for total sea.

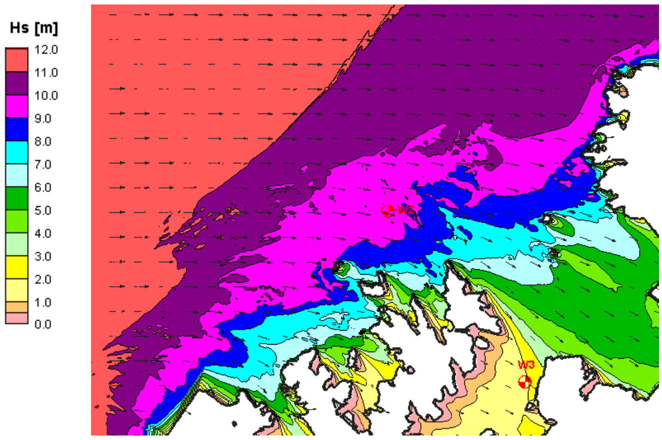


Figure 11. STWAVE output for seastate with Hs=11.9 m, Tp=13.1 s, large spreading (n=2) and 1 hour wind speed 32 m/s.

Table 4. Relative significant wave height at positions W2 and W3 in percent of offshore significant wave height (W1). Based on model results when total sea and associated wind is used as input.

| **Sector (°)** | **W2** | | **W3** | |
|---|---|---|---|---|
| | *Large spread (n=2)* | *Small spread (n=10)* | *Large spread (n=2)* | *Small spread (n=10)* |
| 195 – 225 | 61 | 51 | 24 | 24 |
| 225 – 255 | 80 | 80 | 20 | 20 |
| 255 – 285 | 84 | 84 | 16 | 15 |
| 285 – 315 | 93 | 93 | 21 | 20 |
| **315 – 345** | 90 | 90 | 44 | 44 |
| 345 – 15 | 97 | 97 | 51 | 62 |
| 15 - 45 | 86 | 86 | 41 | 31 |
| 45 - 75 | 76 | 61 | 22 | 15 |

With respect to variations in the spectral peak periods, $T_p$, as the waves propagates towards and over shallow water, the measurements indicate only negligible variations. The STWAVE results indicate that the spectral peak period will increase slightly towards land and into the fjord.

## 4 COMPARISON BETWEEN MODEL RESULTS AND MEASUREMENTS

Figures 12 and 13 show measurements and model results based on swell and total sea respectively. For each 30° sector the reduction factors between offshore seastates and seastates at the location W2 and W3 are plotted. The solutions from the STWAVE analyses with directional spreading that give the highest waves have been selected for the Figures 12 and 13.

Figure 12 shows that STWAVE underestimates the swells approaching from the directions between 225° and 315°. Figure 9 shows that these are waves propagating across an area with hilly topography before reaching station W2.

Figure 13 shows better correspondence between measured data and model results for total sea and associated winds. However, at station W3, it should be expected that the model produced results higher than measured since this area is partly sheltered from the wind. Winds from the sector 225° to 315° are strongly reduced due to the island of Sørøya (Figure 9).

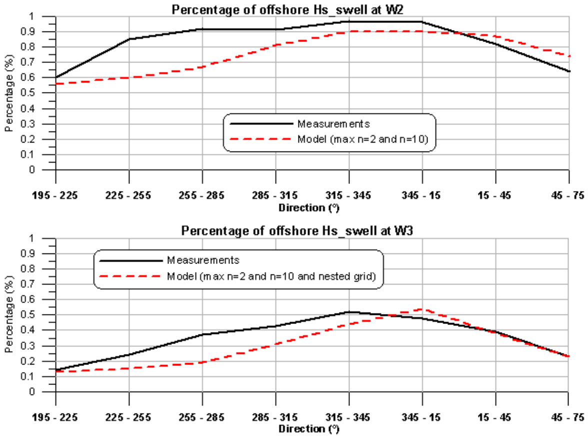


Figure 12. Comparison between measurements and model results for swell seas.

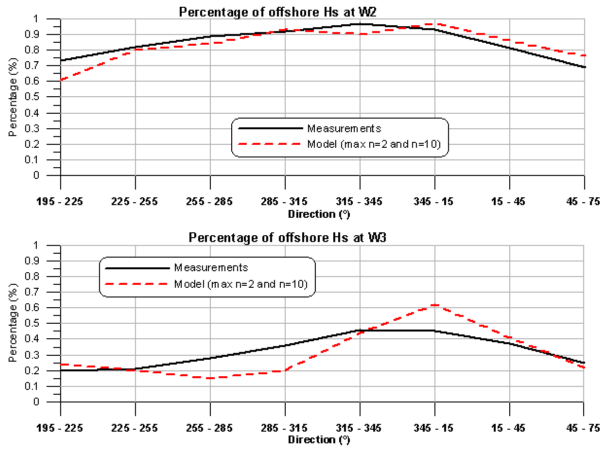


Figure 13. Comparison between measurements and model results for total sea and associated wind speed.

A possible explanation for why the waves are underpredicted is that STWAVE incorporates only linear wave refraction and shoaling, thus not represent wave asymmetry. Due to this, the model may be expected to underestimate the waves with large Ursell numbers. Table 5 lists the seastates used as input in the STWAVE analyses (total sea). It can be seen that the seastates with highest $H_s$ are those corresponding to the directions where model results underestimate the wave heights.

Ursell number: $$U_r = \frac{h}{k^2 \cdot d^3} \qquad (1)$$

where $h$ is the wave height, $k$ is the wave number and $d$ is the water depth.

Table 5. List of seastates (total sea) used as input to STWAVE.

| Direction | $H_s$ | $T_p$ |
|---|---|---|
| 195 – 225 | 3.3 | 7.8 |
| 225 – 255 | 9.8 | 13.8 |
| 255 – 285 | 11.9 | 13.1 |
| 285 – 315 | 11.8 | 14.6 |
| 315 – 345 | 7.1 | 13 |
| 345 – 15 | 6.5 | 11.9 |
| 15 - 45 | 5.9 | 11.6 |
| 45 - 75 | 4.6 | 11.8 |

## 5 CONCLUSIONS

The Steady-State Spectral Wave Model has been applied in Norwegian coastal waters and model results are compared against measurements.

At large water depth, the JONSWAP spectrum with peak enhancement factor equal to 2 describes the distribution of wave energy well. In shallow waters, it is reason to believe that the TMA wave spectrum is more adequate than the JONSWAP spectrum.

Doubly peaked wave spectra may occur in the fjords due to incoming swells and locally generated wind seas. However, only swell is expected to influence a pipeline at the seabed and thus a wave spectrum describing the swell part of the spectrum will be sufficient for design of pipelines.

There are differences in model results for different spreading applied in the directional spectra. It is recommended to apply the least favourable spreading factor of n=2 and 10 when STWAVE is used in design.

In parts of the model domain where the water depth is large, the wave height should not change significantly. However, in STWAVE the wave height seems to be reduced also in deep part of the model domain. To account for this new energy has to be fed into the model as the wave propagates away from the initial border. This is achieved by applying an associated wind speed in the model.

Since asymmetry in the waves is not taken into account in STWAVE, the highest wave events may be under predicted by the model at shallow water.

STWAVE is found adequate for estimating design values along a pipeline route. However, the model needs to be treated carefully and a safety factor should be added on in order to take all uncertainties into account.

## 6 REFERENCES

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## 7 ACKNOWLEDGEMENTS

Thanks to Martin Mathiesen at Polytec for valuable comments.

## APPENDIX A. SCATTER PLOTS OF SIMULTANEOUS WAVE RECORDINGS AT DIFFERENT LOCATIONS

### A.1 Offshore waves from the sector 45° - 75°

Figure A1 shows waves coming from the sector 45° - 75°. Typical the $H_s$ close to Melkøya is reduced to 25% of the offshore $H_s$.

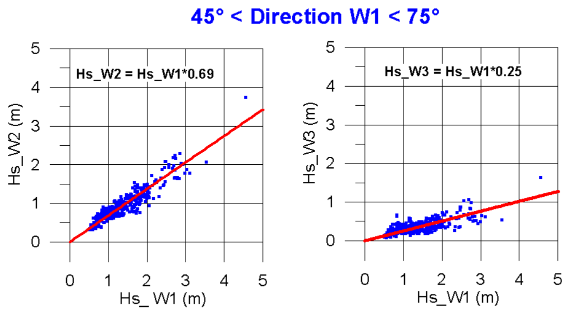


Figure A1. Scatter plots of offshore waves versus waves at W2 and W3. Regressions line is included.

### A.2 Offshore waves from the sector 15° - 45°

Figure A2 shows waves coming from the sector 15° - 45°. Typical the $H_s$ close to Melkøya is reduced to 37% of the offshore $H_s$.

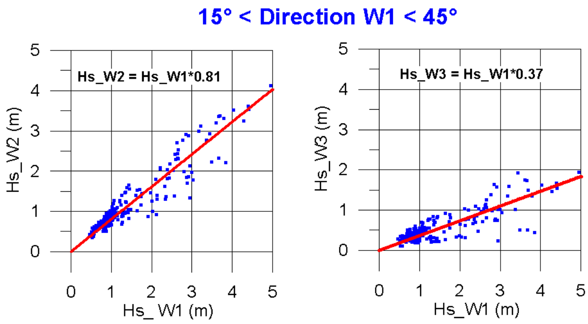


Figure A2. Scatter plots of offshore waves versus waves at W2 and W3. Regressions line is included.

### A.3 Offshore waves from the sector 345° - 15°

Figure A3 shows waves coming from the sector 345° - 15°. Typical the $H_s$ close to Melkøya is reduced to 45 % of the offshore $H_s$. Higher waves seems to be more reduced than lower waves.

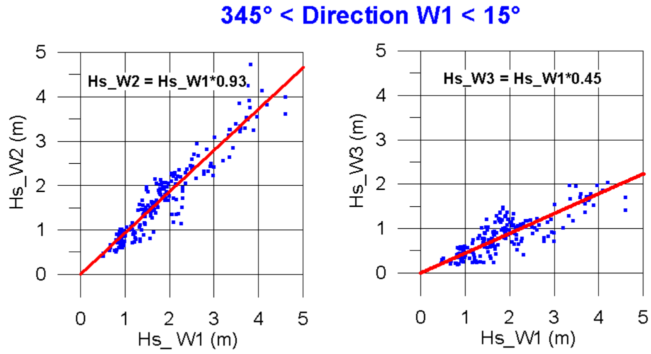


Figure A3. Scatter plots of offshore waves versus waves at W2 and W3. Regressions line is included.

### A.4 Offshore waves from the sector 315° - 345°

Figure A4 shows waves coming from the sector 315° - 345°. Typical the $H_s$ close to Melkøya is reduced to 46 % of the offshore $H_s$.

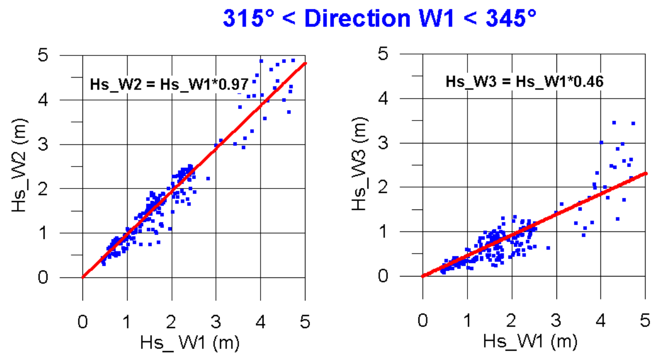


Figure A4. Scatter plots of offshore waves versus waves at W2 and W3. Regressions line is included.

A.5 Offshore waves from the sector 285° - 315°

Figure A5 shows waves coming from the sector 285° - 330°. Typical the $H_s$ close to Melkøy is reduced to less than 36% of the offshore $H_s$. Higher waves seems to be more reduced than lower waves.

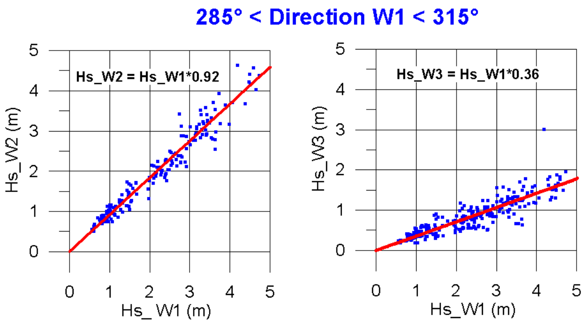


Figure A5. Scatter plots of offshore waves versus waves at W2 and W3. Regressions line is included.

A.6 Offshore waves from the sector 255° - 285°

Figure A6 shows waves coming from the sector 255° - 285°. Typical the $H_s$ close to Melkøy is reduced to 28% of the offshore $H_s$.

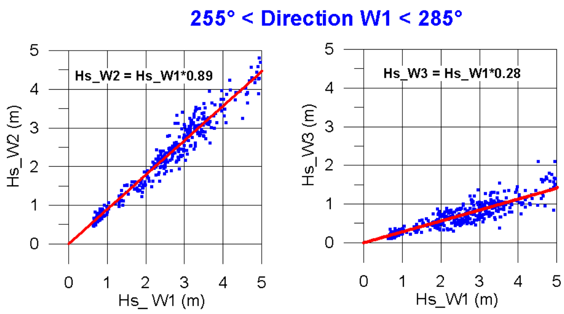


Figure A6. Scatter plots of offshore waves versus waves at W2 and W3. Regressions line is included.

A.7 Offshore waves from the sector 225° - 255°

Figure A7 shows waves coming from the sector 225° -255°. Typical the $H_s$ close to Melkøya is reduced 21% of the offshore $H_s$.

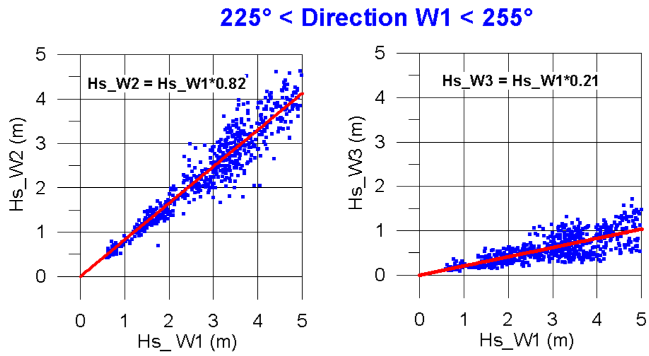


Figure A7. Scatter plots of offshore waves versus waves at W2 and W3. Regressions line is included.

A.8 Offshore waves from the sector 195° - 225°

Figure A8 shows waves coming from the sector 195° -225° (southwest). Typical the $H_s$ close to Melkøy is reduced 20% of the offshore $H_s$.

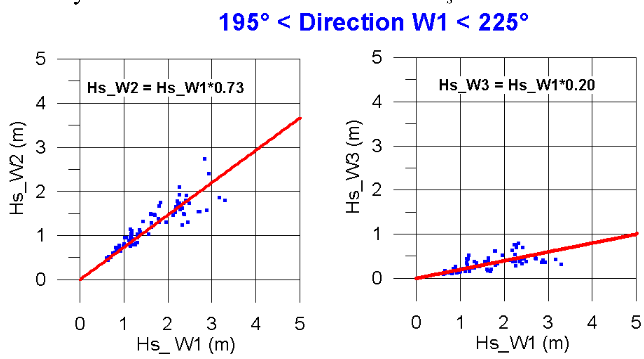


Figure A8. Scatter plots of offshore waves versus waves at W2 and W3. Regressions line is included.