

# DESIGN CRITERIA FOR SELF-PROPELLED HEAVY-LIFT TRANSPORTS - AND HOW THEORY CORRELATES WITH REALITY -

BY

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## ABSTRACT

Since the beginning of dry transports of large drilling rigs, floating plants, drydocks, etc. by self-propelled heavy-lift ships, design criteria have evolved from existing dry tow criteria. Starting from the simple rule of thumb that for design purposes it is assumed that ship plus cargo will roll 20 degrees in 10 seconds and pitch 12.5 degrees in 10 seconds, the criteria have developed to what they are today. The state of the art design criteria for self-propelled heavy-lift transports are outlined in this paper.

In order to validate these, a large number of voyages have been monitored over the past years and the observed environmental data and resulting motions are compared with the engineering predictions for each specific transport. The collected wave data correlates well with the inhouse wave data. The observed extreme wave heights are generally less than half of the predicted design significant wave heights, clearly indicating the effects of routing the vessels around stormy areas. The experienced motions are also well within the design limits.

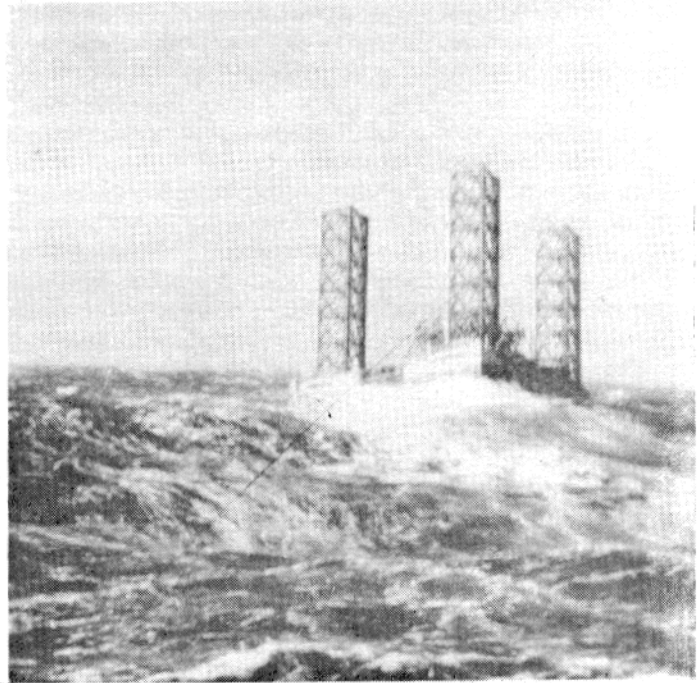
From a direct correlation between predicted and monitored motions it follows that the roll motion prediction is slightly conservative. The predicted pitch motions however are much too conservative; over three times the actual monitored pitch motions. This does require further study, especially since pitch motions can be the limiting criteria in case of dry transports of large jack-up drilling rigs.

## 1. INTRODUCTION

One of several Dutch-based shipping firms that specialize in transporting extremely heavy and voluminous equipment, the author's company has developed various innovative solutions to ocean

transportation of drilling rigs, offshore production platforms, dredging equipment, floating plants, (un)damaged vessels, large cranes, drydocks as well as various other kinds of sizable installations.

At first, floating cargoes were transported simply by being towed across the oceans (see figure 1) while non-floating equipment was loaded onto barges which in turn were towed by oceangoing tugs.



*Fig. 1 Traditional wet tow of a jack-up drilling rig*

Then, semi-submersible barges allowed for the dry towage of floating cargoes as well. The safety of the tow largely depended on the link between the towed object and the tug. Parting of this towline frequently ended in significant accidents [1].



Improving the concept of the bottom reaction barge, Wijmuller introduced in the late seventies the fully horizontally semi-submersible barge with auxiliary propulsion. This, in turn, provided the impetus for the following step: the fully self-propelled heavy-lift ships with full horizontal semi-submersion capability. Of this type of vessel, the company at present operates five units of the so-called Super Servant class and three larger Mighty Servant type ships, while it also has a management contract for a similar type Russian owned vessel, the Transshelf. To date, over 400 dry transports have been performed worldwide by these vessels. Figure 2 shows the dry transport of the world's largest jack-up drilling rig "Maersk Giant" by Mighty Servant 3 from Bass Strait, Australia, to Rotterdam, the Netherlands.

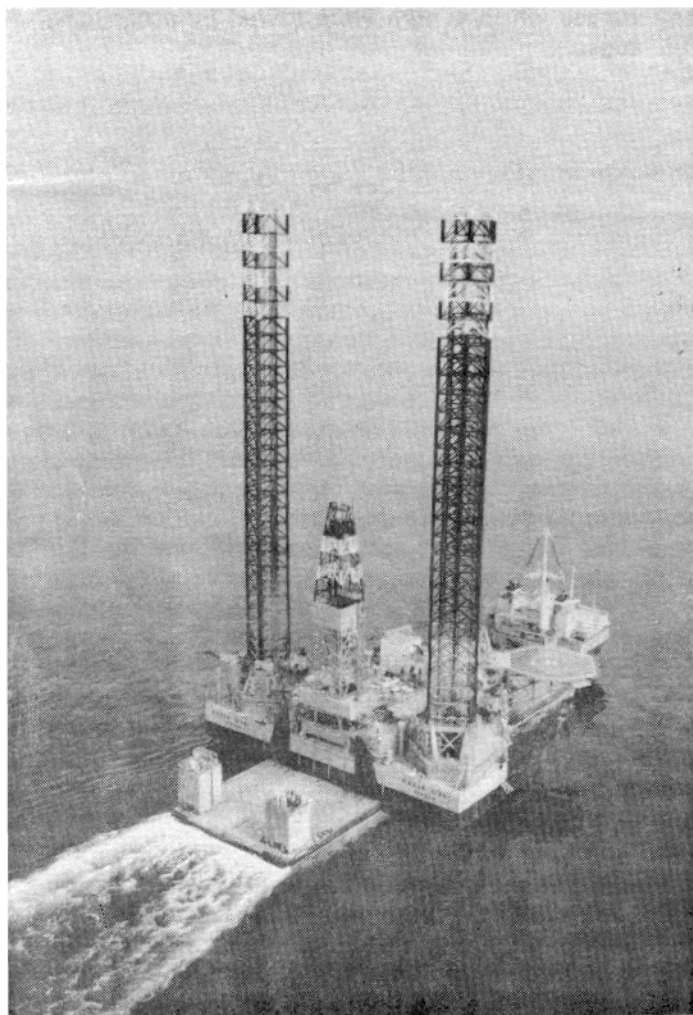


Fig. 2 Dry transport of "Maersk Giant" jack-up drilling rig

Transportation by self-propelled heavy-lift vessels means:

- reduced transit/exposure time;
- improved time scheduling;
- reduced motion responses, hence reduced inertia forces on the cargo;
- maneuverability in all circumstances;
- maximum safety and reliability, reduced cargo insurance premiums.

Each of these items potentially results in cost savings.

The design criteria used for judging the feasibility of dry transports originated in the days of tug/barge transports. With the introduction of self-propelled heavy-lift vessels, these criteria have been adapted to take the specific advantages of a self-propelled vessel over a tug/barge into account.

Since heavy-lift transportation by self-propelled heavy-lift vessels is a relatively young industry, these design criteria are still in a developing stage.

## 2. RULE OF THUMB CRITERIA

In the early days of dry transportation of heavy cargoes, the physical understanding and the analytical capabilities were lagging behind the actual practice. For judging the stability of a dry transport, surveyors adopted the rule as stated by the American Bureau of Shipping, i.e. the area under the righting moment curve at or before the second intercept or downflooding angle, whichever is less, is not to be less than 40 percent in excess of the area under the wind heeling moment curve to the same limiting angle [2]. For the design wind speed, 100 knots was taken, independent of route and season.

For judging the strength of the cargo and the adequacy of the proposed seafastening arrangement, surveyors adopted the 20 in 10 rule of thumb, i.e. the barge/cargo combination was assumed to roll 20 degrees (single amplitude) in 10 seconds (full cycle period) and pitch 12.5 degrees in 10 seconds. The point of rotation was arbitrarily taken on the waterline of the carrier. These motions and resulting design accelerations were independent of barge dimensions, cargo, route, season, exposure time, etc.

The above rule of thumb has the advantage of being simple to apply. The design accelerations are generally conservative. The disadvantage of this rule however is that it has no relationship with reality. Given this lack of rationalism, more realistic

methods for determining design accelerations were developed.

Over the last decade, motion response prediction programs for mini and micro computers were developed with increasing speed. Nowadays, after years of experience with these programs, combined with numerous model tests, the motion response of a vessel/cargo combination in a specific sea state can be predicted reasonably accurate. The discrepancies in results generated by the various available motion response programs are generally small [3].

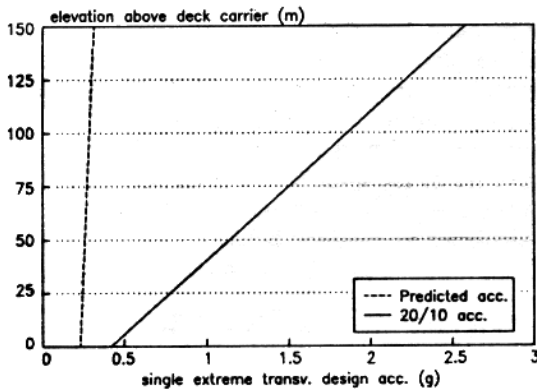


Fig. 3 Comparison 20/10 versus predicted accelerations

Figure 3 clearly illustrates the differences in design accelerations between the 20 in 10 rule of thumb and those based on the actual predicted motion responses for the dry transport of the "Maersk Giant" from Australia to the North Sea with a February departure. Such a dry transport, with jack-up legs over 150 meters in height, could never have been approved basis the 20 in 10 rule of thumb without extensive strengthening of the legs, jack houses and adjacent hull structure. This is clearly indicated by the design extreme leg bending moments at the upper guides, see following table:

L.B.M.(Tm)	Beam seas	Head seas
20/10 12.5/10	190,000	120,000
Prediction	23,000	65,000

Based on the predicted motions, the design extreme leg bending moments are in the order of

90% (beam seas) to 45% (head seas) less than those based on the 20 in 10 rule of thumb.

Above comparison is an extreme case. With such a large jack-up drilling rig onboard, the heavy-lift vessel has a natural roll period of over 30 seconds and as such is not effected by ocean waves with periods in the range of 5 to 15 seconds. In case of smaller jack-up rigs, jackets, modules, etc., the natural roll period may be shorter and closer to the wave periods of the design sea states resulting in roll excitation by waves coming in from the beam. The design motions and resulting accelerations are a function of the design wave heights and periods, carrier, loading condition, mass inertia, etc. and as such no simple rule of thumb can be given which covers all variables.

The 20 in 10 rule of thumb is a practical method for quick generation of design accelerations which are generally on the conservative side. For detailed engineering of the transport of large and complex structures, a complete motion response analysis is essential.

### 3. PRESENT CRITERIA

#### 3.1 INTRODUCTION

Based on over 400 heavy-lift voyages, executed with its fleet of semi-submersible heavy-lift vessels, the author's company has developed its own set of criteria for self-propelled dry transports. These criteria are based on the state of the art and are updated whenever applicable. The seafastening calculation is based on the permissible stress method.

#### 3.2 LOADING/OFF-LOADING

In case of a critical float-on operation, stability during the (de)ballasting operations shall be calculated. During the phase of minimum stability, the calculated maximum vessel list is to be within 4 degrees.

In case of loading/off-loading by lifting, skidding, rolling or jacking, specific problem areas need to be studied and feasibility shall be demonstrated.

#### 3.3 LOADING CONDITION AND STABILITY

The optimum loading condition shall be determined, taking all operational criteria into account. The loadline of the vessels are not to be exceeded. The still water bending moment in departure condition

needs to be checked to ensure that the strength requirements of the Classification Societies are met.

Both the initial stability and the dynamic stability need to be checked. The initial stability can be judged from the GM-value (corrected for free surface effects). Minimum GM-value is to be .15 m in accordance with the IMO requirement.

The buoyancy of the cargo is to be included in the stability calculations. The intact statical stability about the roll axis shall not be less than 36 deg. The dynamic stability has to be in accordance with the ABS stability criterion under wind force, i.e. that the area under the righting moment curve at or before the second intercept or downflooding angle, whichever is less, is not to be less than 40% in excess of the area under the wind heeling moment curve to the same limiting angle [2]. The design 1-minute sustained wind speed used is to be determined based on the route and season.

Damage stability requirements are not applicable, unless the transport is considered to be marginal with respect to the stability.

### 3.4 DESIGN ENVIRONMENTAL CONDITIONS

Unlike a stationary structure, the heavy-lift ships are mobile and controlled by a master who receives weather information on a daily basis. With this information he is able to plot the optimum route, avoiding stormy areas where possible. This effect is difficult to incorporate in a statistical method. The author's company has developed an engineering approach to take this effect into account.

#### Design Sea State

The long term prediction of the design sea state is based on the "Global Wave Statistics" (GWS) as compiled and edited by British Maritime Technology Ltd. [4]. From these available wave statistics, short term design sea states are derived with a maximum significant wave height which has a design probability of exceedance of 5% for the most severe area of the route.

The transportation route is divided into sections crossing the GWS areas. Since the wave data is presented in terms of probability distributions, bias of areas containing large number of observations is eliminated. For each area, the total transit time is

calculated, given the average speed of the vessel. Also the appropriate season is selected, given the departure date and the time passed until a certain area is entered. After selecting the most severe area, the corresponding wave data scatter diagram is retrieved. This diagram presents the number of "observed" wave period combinations for this area. Combining all the period classes results in the total distribution of "observed" wave heights. Given this distribution a cumulative probability distribution is determined, using the Gumbel formula [5]. The total probability of exceeding the design significant wave height within the most severe area is set at 5%. Given the transit time through this area, the probability of exceedance of the individual "3 hour stationary storm" design wave height is calculated. An engineering approach is used to take the vessel's capability to avoid bad weather into account by reducing the number of 3 hour steps per area, with a factor which depends on the severity of the area. The probability of exceedance of the 3 hour design significant wave height is thus calculated as follows:

$$P(H > H_{sig\ 3hours}) = \sqrt[N]{1 - P(H > H_{sig\ area})}$$

where N = number of 3 hour transit periods through the most severe area, multiplied by the number of observations of waves  $\geq 4$  m, divided by the total number of observations.

$$P(H > H_{sig\ area}) = 5\%$$

Given the cumulative probability distribution of the area, the design significant wave height can be obtained. From the scatter diagram, a set of four most probable wave periods is selected. With the significant wave height and the four mean wave periods, the Pierson-Moskowitz wave spectra are defined.

#### Design wind speed

The long term prediction of the design wind speed is based on the "U.S. Navy Marine Climatic Atlas of the World" as prepared by the Naval Oceanography Command Detachment [6]. The means and standard deviations are presented by isopleths (lines connecting points of equal magnitude). For

each GWS area, the monthly means and standard deviations have been extracted from the maps.

Given the route and departure date, the 10-minute average wind speed is calculated for each area using:

$$v_{\text{wind } 10\text{-min}} = \text{mean} + 3.5 (\text{std. dev.})$$

The resulting wind speed has a probability of exceedance of less than 1%.

For the design wind speed, the 1-minute sustained wind speed shall be used, calculated from the 10-minute average wind speed by multiplying it with a gust factor of 1.21 in accordance with API guidelines [7]:

$$v_{\text{wind } 1\text{-min}} = 1.21 v_{\text{wind } 10\text{-min}}$$

From all areas crossed, the most severe area determines the design wind speed.

### 3.5 MOTION RESPONSES

The motion response calculation is based on the two dimensional strip theory. In order to fine-tune the calculations, model tests were performed by MARIN, Wageningen, the Netherlands. In line with reality, the forward speed has been made depended on the design wave height. For significant wave heights smaller than 4 m, the forward speed is set at 6 kn for head and bow quartering seas and 12 kn for beam seas. For waves over 4 m, the forward speed reduces to zero kn for head and bow quartering seas and to 6 kn for beam seas. For waves over 8 m, the forward speed reduces also for beam seas to zero knots.

The motion responses in irregular waves are calculated by multiplying the squared response functions with a uni-directional (long-crested seas) Pierson-Moskowitz wave spectrum, given by the following formula [8]:

$$S_{\zeta}(\omega) = \frac{A}{\omega^5} e^{-\frac{B}{\omega^4}}$$

where  $A = 172.8 (H_{\text{sig}})^2 (T_{\text{mean}})^{-4}$

$$B = 691 (T_{\text{mean}})^{-4}$$

The areas under the resulting response spectra and their second and fourth moments are calculated by:

$$m_n = \int_0^{\infty} \omega^n S_{\text{response}}(\omega) d\omega \quad \text{for } n = 0, 2, 4$$

Since the response spectra are generally not Rayleigh distributed, a broadness parameter is calculated for each spectrum using :

$$\epsilon^2 = \frac{m_0 m_4 - m_2^2}{m_0 m_4}$$

Given the response spectra and the broadness parameters, the single significant amplitudes (mean value of highest one-third) are calculated using [9]:

$$\text{sign. resp.} = 2\sqrt{m_0} \text{ CF}$$

in which CF = correction factor to take the broadness into account or:

$$\text{CF} = \sqrt{1 - \epsilon^2}$$

The extreme values of a random process are depending on the number of observations or, more meaningful, depending on the duration of the process being stationary. This stationary period is taken as 3 hours, in line with the design sea state calculations. Given the response spectra, the most probable single extreme amplitudes are calculated using [9]:

$$\text{extr. resp.} = \sqrt{2 \ln \left[ \frac{(60)^2 T}{2\pi} \sqrt{\frac{m_2}{m_0}} \right]} \sqrt{m_0}$$

in which T = stationary storm period  
= 3 hours

For specific points, fixed to the vessel, linear accelerations can be calculated in the three directions of the ship's axis. The linear point accelerations are composed from the linear ship accelerations, the angular ship accelerations and the earth-bound gravity acceleration, taking all relevant phase relationships into account.

The linear motion theory assumes small motion amplitudes and an irrotational ideal fluid medium.

This means that a number of phenomena, e.g. large motion amplitudes and viscous effects such as vortex shedding at bilge keels and bilges are not accounted for. When considering oscillation frequencies corresponding with the natural periods of the structure the linear approach may lead to unrealistic results. Here the resonant motions are limited only by the relatively small damping contribution in the reaction forces, since the much larger inertia and restoring forces cancel out. Because the potential damping for roll is extremely small, the motion amplitude near the natural period of roll will be influenced by additional damping due to other mechanisms, which may be non-linearly depending on the roll angle.

In case of extreme overhang of the cargo, which is anticipated to have a large impact on the motions, model testing is recommended.

With the resulting design accelerations, the inertia forces on the cargo can be calculated.

### 3.6 DESIGN FORCES ON THE CARGO

The extreme design forces on the cargo in case the transport vessel meets its design sea state are a combination of:

- inertia forces due to ship motions ( $F_{acc}$ );
- forces due to mean/1-minute sustained wind load ( $F_{mwind}/F_{ewind}$ );
- gravity forces due to static mean/1-minute sustained wind heel ( $F_{mroll}/F_{elroll}$ ).

The lateral inertia forces are calculated using the worst motion response cases for beam/head seas. Since the transverse/longitudinal accelerations are composed from their individual components (including static part due to roll/pitch), taking all their phase angles into account, the resulting extreme inertia forces are the most realistic extreme values.

The motion response extreme factor used is based on a single occurrence of the extreme during the stationary 3 hour storm period. Since the likelihood that this extreme occurs at the very instant the wind is at its peak (the 1-minute sustained wind) is very small, the inertia forces and peak wind forces are assumed to be statistically independent. Of course, the wind force and the gravity force due to wind heel are in phase, and as such are superimposed directly. The total extreme design force on the cargo are thus calculated as follows:

Transverse:

$$F_{total} = F_{mwind} + F_{mroll} + \sqrt{(F_{acc})^2 + ((F_{ewind} - F_{mwind}) + (F_{elroll} - F_{mroll}))^2}$$

Longitudinal:

$$F_{total} = F_{mwind} + \sqrt{(F_{acc})^2 + (F_{ewind} - F_{mwind})^2}$$

To keep the cargo in place, a seafastening arrangement will be designed in such a way that it is able to sustain the extreme design forces.

### 3.7 SEAFASTENING

Seafastenings are placed around the cargo to restrain the lateral movement. In order to allow for some relative motion in seaway due to differences in stiffness between the ship structure and the cargo structure, rubber fenders are placed between the seafastening and the cargo. The seafastenings are to be placed against strongpoints, i.e. bulkheads, frames, tanktops, etc.

The local displacement of the cargo at each seafastening is determined by the two translation components of the cargo in the horizontal plane and one rotation component around a vertical axis. These displacement components can be found by solving the three equilibrium equations for the cargo in the horizontal plane:

- summation of longitudinal components of seafastening forces plus friction forces equals longitudinal extreme design force;
- summation of transverse components of seafastening forces plus friction forces equals transverse extreme design force;
- summation of moments of seafastening forces, with respect to the center of gravity of the cargo, in excess of the friction moment, equals zero.

The local displacement of the cargo at each seafastening generates a reaction force, depending on the spring characteristic of the seafastening fender.

## Friction

It is standard practice to support the cargo strongpoints (sideshells, bulkheads, etc.) by a softwooden cribbing arrangement. In such case, the friction between the softwood and the steel bottom of the cargo assures a reduction of the forces on the seafastenings. The Swedish Shipowners Association recommends a friction coefficient of .30 between oakwood and steel [10]. Other sources indicate values in the order of .20 to .60 [11][12]. Rust, barnacles, tar, etc. will increase the friction even more.

In the past, the friction has been ignored, in order to create an extra safety margin. Nowadays, a friction of 15% of the cargo weight is taken into account, unless the transport shows an exceptional large overhang, which may result in additional loads not accounted for.

## Weld size

In general the standard Wijsmuller Transport B.V. seafastenings are welded to the deck in accordance with normal shipbuilding practice. The deck needs to be clean and dry at the seafastening positions. The minimum required weld throat follows from the requirement that the combined stress, calculated using Hubert and Hencky formula, is less or equal to 95 % of yield. Experiments have shown that weld material is stronger than the original material, hence the combined stress can be multiplied by a  $\beta$  factor which has been empirically determined to be .7 for base material of mild steel, in accordance with the Euronorm 25-27 [13].

The minimum required weld throat follows from the requirement that the equivalent stress equals the allowable stress.

## Allowable stress levels

The allowable stress levels are defined as follows, including the AISC one-third increase for environmental loading [14]:

- tensile stress  $\leq$  80% of yield stress
- shear stress  $\leq$  60% of yield stress

## Weld inspection

In case of standard seafastenings welded onto the deck, no specific weld specifications or testing

procedures are required as both the deck as well as the seafastenings are constructed from mild steel. All welding is to be 100% visual inspected. Throat heights are to be randomly checked.

## 3.8 CRIBBING ARRANGEMENT

A softwooden cribbing arrangement will be designed so as to adequately support the cargo strongpoints (bulkheads, frames, sideshells). Cribbing blocks will be secured to the deck by steel clips or brackets. The static plus dynamic cribbing pressures shall be calculated analogous to the design loads, i.e. pressures caused by forces/moments which are considered statistically independent are summed by the square root of the sums of their squares. The maximum allowable cribbing pressure for a softwooden cribbing is 30 kg/cm<sup>2</sup>. In case of higher pressures, alternative cribbing material is to be used [15].

In case of a float-on loading operation, suitable guideposts shall be used to ensure exact positioning of the floating cargo over the submerged cribbing arrangement.

## 4. CORRELATION CRITERIA - REALITY

### 4.1 INTRODUCTION

To validate the above presented criteria, feedback from the executed transports is essential. During each transport the crew monitors daily the vessel speed, wind and wave conditions, roll and pitch motions, etc. By lack of simple, yet reliable monitoring equipment, this is done visually and with use of the inclinometers (attempts in the past to computerize this process have failed due to frequent hardware breakdowns as well as the production of unrealistic results). Since 1984, a large set of monitored data has been collected this way.

An inhouse study was conducted in order to find the correlation between the predicted values (wave height, wind speed, roll and pitch motion) with the actual observed values [16]. A total of 57 voyages have been analyzed. These have been selected on the following grounds:

- the complete voyage was monitored;
- all visual observations were available;
- the recorded data seemed consistent;
- the ship/cargo condition was known.

## 4.2 EXAMPLE TRANSPORT

For each of the 57 transports a comparison between the predicted values and actual observed values is made. The comparison of only one typical transport will be given in this paper as well as the conclusions of the total study. The example transport concerns the dry transportation of a Marathon LeTourneau 84-C jack-up drilling rig by Mighty Servant 2 from the Gulf of Mexico to Exmouth bay in Australia via Cape of Good Hope. The transport departed in August 1987.

### Particulars jack-up drilling rig:

- weight (incl. variables)	: 8200	T
- v.c.g. above base	: 18.8	m
- leg length	: 104.5	m
- protrusion	: .6	m

### Particulars loading condition:

- displacement	: 29250	T
- draft	: 7.9	m
- GM(fluid)	: 8.0	m
- roll gyradius	: 23.6	m
- natural roll period	: 18.3	s

### Design environmental conditions:

- significant wave height	: 11.2	m
- extreme wave height	: 25.2	m
- mean wave period from	: 8.2	s
to	: 12.5	s
- 1-min wind speed	: 70	kn

## 4.3 OBSERVATIONS

During each transport, a log is kept containing relevant data with respect to the cargo and the ship's loading condition. Four times a day i.e. at 0:00, 06:00, 12:00 and 18:00 hours local time, the following observations are made:

- date;
  - time;
  - position (longitude/latitude);
  - heading;
  - speed;
  - wave data (height\*/period/direction);
  - swell data (height\*/period/direction);
  - wind data (speed\*/direction);
  - roll data (amplitude\*/period);
  - pitch data (amplitude\*/period).
- (\* mean and maximum values over previous 6 hour period)

Because of the questionable accuracy of the midnight observations (especially with respect to

the sea and swell conditions) it was decided to exclude these for the analysis. A total of 6200 sets of observations were processed.

## 4.4 COMPARISON WAVE HEIGHTS

The observed wave heights are compared with the GWS statistics [4]. The observed wind wave and swell are combined using:

$$H_{obe} = \sqrt{H_{obe\ wind\ wave}^2 + H_{obe\ swell}^2}$$

The GWS statistics are corrected for the actual exposure times in the areas crossed. The comparison of the frequency distributions between the two sets of data for all areas combined is given in figure 4. Because small waves are often neglected and recorded as zero, these zero wave height observations have not been taken into account.

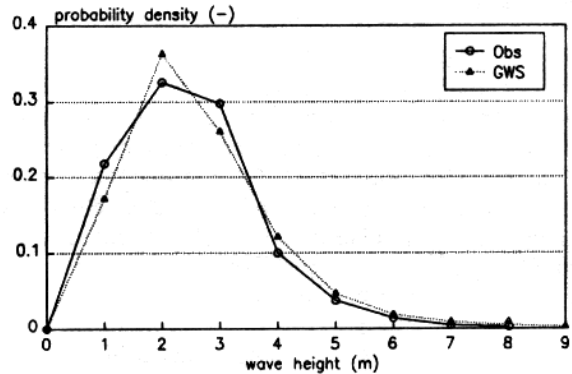
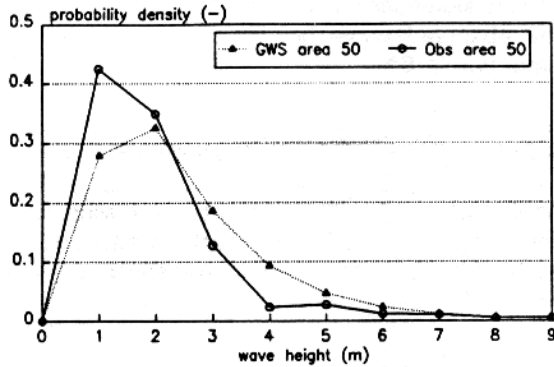


Fig. 4 Comparison between observed wave heights and GWS wave

In case a sufficient number of observations in a certain area is available, such a comparison can be made for an individual area, such as the Arabian Sea (GWS area 50, containing 210 observations from 23 voyages), see figure 5.

In both cases, the correlation between the observed wave heights and the wave statistics is good. There is some discrepancy in the higher wave height range. This difference can be a result of the fact that the number of high wave heights registrations is relatively low because of the ability (and tendency) of the vessels to deviate in case of extreme weather conditions. The maximum observed wave height is only 8.5 m, recorded in November 1985 in the Bay of Biscay. All other records show lower wave heights.

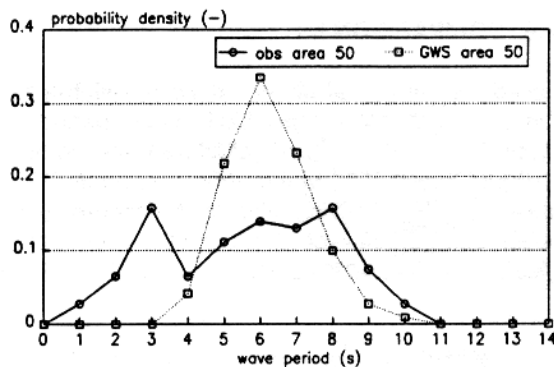




**Fig. 5** Comparison between observed wave heights and GWS wave heights for area 50

#### 4.5 COMPARISON WAVE PERIODS

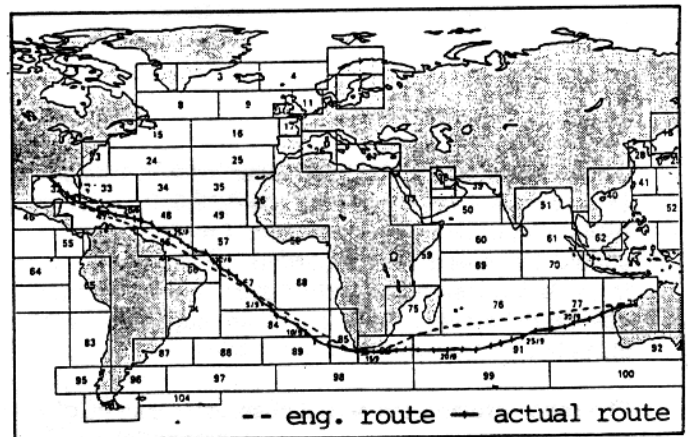
The observed wave periods are compared with those of GWS. In figure 6 the comparison for the Arabian Sea is given. In general it can be concluded that the observed wave periods correlate poorly with those given by GWS. This has also been identified by others [17][18] and for this reason, the wave periods given by GWS have been generated by parametric modelling of the joint probabilistic distribution of wave heights and periods for which the parameters have been derived by regression analysis of measured wave height and period data [4].



**Fig. 6** Comparison between observed wave periods and GWS periods for area 50

#### 4.6 COMPARISON DESIGN WAVE HEIGHTS

In order to correlate the above presented method for obtaining the design wave heights, for all 57 voyages the predicted wave heights have been compared with the actual observed wave heights. During the engineering phase, a certain route is assumed, but circumstances may lead to deviation from this route. To take this into account, the design wave has been re-calculated for the actual sailed route. This deviation is shown in figure 7 for the typical example transport from the Gulf of Mexico, via the Cape of Good Hope to Exmouth, Australia.



**Fig. 7** Comparison between engineering and actual sailed route for the example transport

For the same voyage, the wave height comparison per area crossed is given in figure 8, in which:

- $H_{eng}$  = predicted significant wave height, based on the engineering route;
- $H_{route}$  = predicted significant wave height, based on the actual route;
- $H_{obs}$  = actual maximum observed wave height (combination of wind waves and swell).

The correlation is in general good. In areas where low wave heights are predicted, the actual observed wave heights are also low, while the severe areas (i.e. GWS area 90 - Cape of Good Hope) show higher predicted and observed wave heights. The ratio between the actual observed wave heights and the predicted wave heights ranges from .3 to .8. The design extreme has not

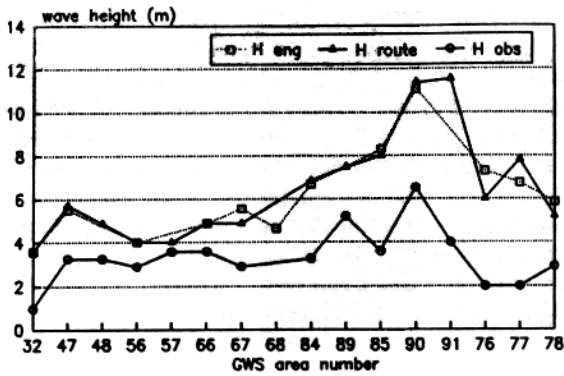


Fig. 8 Comparison between predicted and observed wave heights for the example transport

been exceeded. The highest observed wave height (= 6.3 m) is 44% lower than the design significant wave height for this transport (= 11.2 m). It should be noted that figure 8 only shows the maximum observed wave for each area. All other observations are lower and often negligible, see also [15].

The ratio between the actual observed wave height and the predicted wave height for each area has been calculated for each of the analyzed transports. The result (combined for all transports) is given in figure 9.

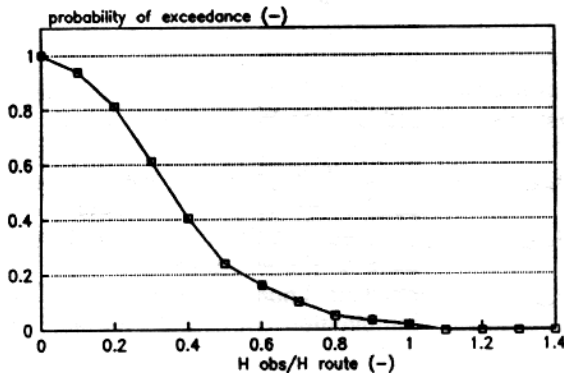


Fig. 9 Ratio between actual observed and predicted wave heights for all transports combined

In 1.3% of the comparisons, the predicted wave height is exceeded by the actual observed wave height. Generally these exceeded predicted waves are smaller than the design waves for the specific

transports. In case of 2 transports, the actual design significant wave heights are exceeded by the observed wave heights. These exceedances were within 6%.

#### 4.7 COMPARISON DESIGN WIND SPEEDS

Analogous to the wave heights, the wind speeds can be compared for each transport. The comparison for the example transport is given in figure 10.

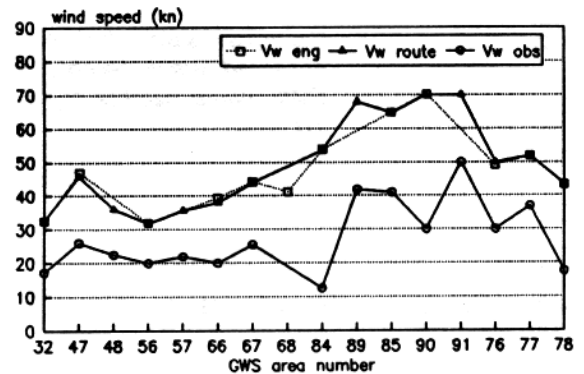


Fig. 10 Comparison between predicted and observed wind speeds for the example transport

The correlation is good with observed wind speeds well below the predicted wind speeds. This is typical for all transports analyzed. In no case has the design extreme wind speed been exceeded. The maximum recorded wind speed of 64 knots was logged near Cape Horn in April 1987.

#### 4.8 COMPARISON MOTION RESPONSES

Based on the actual observed wave heights and a theoretical range of most likely wave periods, the motion responses are re-calculated and compared with the actual observed motion responses. The roll (assuming beam seas) and pitch (assuming head seas) comparison for the example transport are given in figures 11 and 12.

In case of the roll motions, the correlation is poor. There is little resemblance between the two curves, with the exception of the peaks in areas 84 and 90, which coincide. The large discrepancies in the other areas may be caused by waves not coming in from the beam and/or wave spreading.

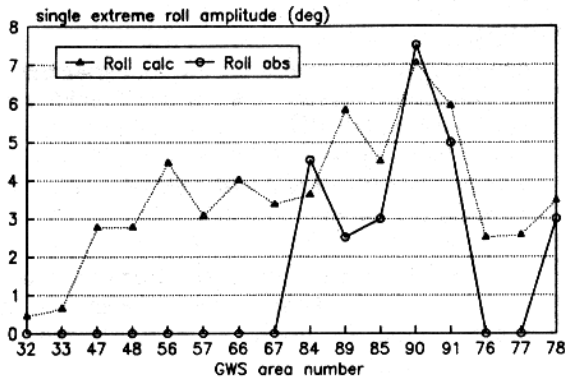


Fig. 11 Comparison between calculated and actual observed roll motions for the example transport

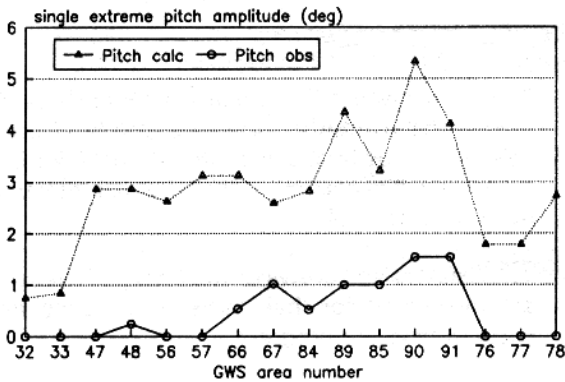


Fig. 12 Comparison between calculated and actual observed pitch motion for the example transport

In case of the pitch motion, the two curves show the same shapes, but the observed values are much smaller. This may partly be explained by the wave heading and wave spreading. However the pitch comparison of all transports show the same trend, see figure 13.

In case of roll motions, 95% of the calculated roll amplitudes are overestimated. The underestimated 5% occurred with transports of jack-up drilling rigs and the increased roll motion may have been caused by wave action on the overhang. Heeling of the vessel due to beam wind may also have effected the roll observation.

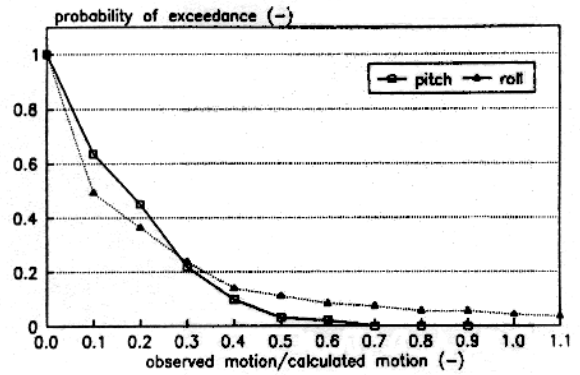


Fig. 13 Frequency distributions of ratios between observed and calculated roll/pitch motions for all transports combined

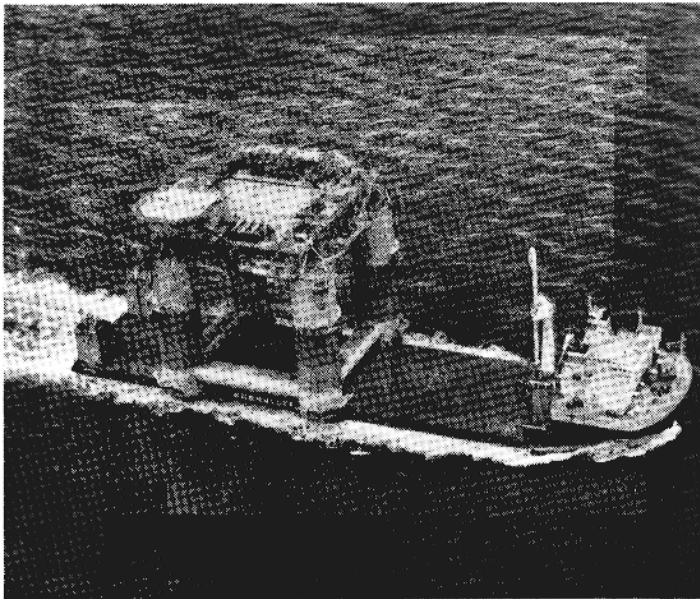
In case of pitch motions, 100% of the calculated pitch amplitudes are overestimated. This overestimation seems consistent to be in the order of 150% - 300%! No explanation has been found for this phenomenon (it should be noted that the correlation between computer calculations and model test results for pitch motion is generally very good [19]).

The pitch motion is often governing with respect to the leg strength of jack-up rigs. In the past this has occasionally led to decisions to reduce leg length or substitute the proposed carrier by a larger carrier with better pitch behavior. Given the results of the pitch comparison, this may have been unnecessary actions.

## 5. CONCLUSIONS

Based on past experience, design criteria for dry transport by self-propelled heavy-lift vessels have been developed and consequently successfully applied for numerous dry transports, such as the one shown in figure 14 [15].

In order to validate these design criteria, the crews onboard the heavy-lift vessels have monitored the encountered environmental conditions and resulting motion responses over a period of 6 years. This was mostly done by visual observations as an experiment with a fully automated monitoring system has failed.



*Fig. 14 Dry transport of the "Joliet" TLWP from Singapore to the Gulf of Mexico*

An inhouse study was performed to correlate the design environmental conditions and calculated ship motions with the actual observed conditions and motions. From this study, the following conclusions are drawn:

- the database of observed wave heights corresponds well with the "Global Wave Statistics";
- the proposed method for obtaining design significant wave heights results in realistic design extremes. The design probability of exceedance is set at 5%, while the actual experienced probability of exceedance turns out to be less than 2%. This may be the effect of the vessel's ability to limit the exposure to bad weather;
- the observed wave periods correlate poorly with the theoretical wave periods;
- the proposed method for obtaining the design wind speed generates conservative results;
- the observed roll motions are generally well within the calculated roll motions. Occasionally, the calculated roll motions are exceeded;
- the observed pitch motions are in the order of one-third of the calculated pitch motions. The calculations are much too conservative and this requires further study. In case a marginal transports is governed by the pitch motions, this effect has to be taken into account.

The conclusion that the observations for both roll and pitch are generally smaller than the calculations can partly be explained by the fact that the actual encountered waves are seldom unidirectional. Furthermore, the ability of the master to control the ship's heading relative to the wave heading, thus avoiding beam or head seas, ensures that extreme motions are limited.

As a result of the correlation study, the author's company has gained more confidence in the present design criteria. The generated design environmental criteria and resulting ship motions are considered to be conservative design extremes. No additional safety factors need to be added.

The full scale monitoring continues to investigate the pitch behavior of these vessels in more detail. This may eventually result in a significant reduction of the pitch predictions.

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#### REFERENCES

1. Veritec: "Offshore Accident Review", Vol. 2, No. 2, Oct. 1984.
2. American Bureau of Shipping: "Rules for building and classing Mobile Offshore Drilling Units", New York, 1984.
3. Noble Denton and Associates Ltd.: "Barge motion research project, summary report". Report no. L 12140/ NDA/JBW, London, 1984.
4. N. Hogben et al.: "Global Wave Statistics", British Maritime Technology Ltd., Feltham, 1986.
5. E.J. Gumbel: "Statistics of Extremes", Columbia University Press, New York, 1958.
6. Naval Oceanography Command Detachment: "U.S. Navy Marine Atlas of the World",

- Volume IX, world-wide means and standard deviations, U.S. Government Printing Office, Washington, 1981.
7. American Petroleum Institute: "Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms", RP 2A, seventeenth edition, 1987.
  8. W.J. Pierson and L. Moskowitz: "A proposed spectral form for a fully developed wind seas based on the similarity theory of S.A. Kitaigorodsku", Tech. Rept. U.S. Naval Oceanographic Office Contract No. 62306-1042, 1963.
  9. R. Bhattacharyya: "Dynamics of Marine Vehicles", John Wiley & Sons, Inc., Toronto, 1978.
  10. Swedish Shipowners Association: "Safe stowage and securing of cargo on board ships", Research report, MariTerm AB, 1982.
  11. Bowden and Tabor,: "The Friction and Lubrication of Solids", Volume I, Clarendon Press, Oxford, 1950.
  12. Steger, Sieghart and Glauning,: "Statik, Reibung, Festigkeits-lehre", B.G. Teubner, Stuttgart, 1979.
  13. Eurocode No. 3, "Design of Steel Structures, Part 1 - General Rules and Rules for Buildings", Vol. 2: Annexes A to Y, 1989.
  14. American Institute of Steel Construction, Inc.: "Manual of Steel Construction", Eighth Edition, Chicago, 1980.
  15. F. van Hoorn and S.D. Devoy: "The Dry Transport of the Green Canyon Tension Leg Wellhead Platform by a Semi-Submersible Heavy-Lift Ship", OTC paper No. 6471, Houston, 1990.
  16. R. de Boer: "Omgevingscondities en bewegingen tijdens zeereizen", Graduation Thesis, Delft University of Technology, Faculty of Mechanical Engineering and Marine Technology, Delft, December 1990.
  17. Z.S. Fang and N. Hogben: "Analysis and Prediction of Long Term Probability Distribution of Wave Heights and Periods", NMI Report No. R 146, London, October 1982.
  18. K.S. Andrews, N.M.C. Dacunha and N. Hogben: "Wave Climatic Synthesis", NMI Report No. R 149, London, January 1983.
  19. F. van Hoorn and R.P. Dallinga: "Dry Transportation of Large Semi-Submersible Units", Developments in Marine Technology Vol. 4: Floating Structures and Offshore Operations, Amsterdam, November 1987.