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The Dry Transport of the Green Canyon Tension Leg Wellhead Platform by a Semisubmersible Heavy-Lift Ship

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ABSTRACT

A Tension Leg Platform poses unique challenges with respect to its dry transportability. The engineering that is required before such a transport can be effected is given step by step. The development of a new type of cribbing block is described. The predicted extreme design environmental conditions and resulting extreme motions are compared with the actual monitored weather conditions and motions. From the correlation, conclusions are drawn.

INTRODUCTION

On May 26, 1989, the first TLWP (Tension Leg Wellhead Platform) was delivered in the U.S. Gulf by a self-propelled semi-submersible heavy-lift ship. This ship departed Singapore only 41 days earlier after loading the TLWP by means of the float-on method, see figure 1. The dry transport of this platform broke new ground in various areas. The unique nature of the TLWP required various unorthodox solutions. Conventional design methods were revised and new materials were developed.

The Green Canyon block 184 TLWP was built by a shipyard in Singapore, Republic of Singapore, which contracted with a Heavy-Lift Transporter for the dry transport of the TLWP to Pascagoula, Mississippi, where it was to be final outfitted before installation in the U.S. Gulf.

References and illustrations at end of paper

Dry transport by a self-propelled heavy-lift vessel offers the highest degree of safety in combination with a minimum of environmental loads on the cargo.

A wet tow was not a realistic option given the distance of over 12,000 miles and an anticipated tow speed of 2 - 3 knots. Transportation by tug/barge was considered, but the increased safety of the self-propelled option proved to be the most attractive.

The TLWP is constructed from stiffened cylindrical shells. The truss deck is carried by four columns of 12.2 meters in diameter, 46.2 meters in height, spaced 42.67 meters apart (center to center). Pontoons, 7 meters in diameter, connect the four columns near the base

At the moment of load-out, the TLWP's displacement was 8,400 T with its center of gravity at 31.8 meters above its base. The draft measured 8.3 meters, leaving a freeboard on the pontoons of 1.2 meters. These pontoons were outfitted with bollards to facilitate the connection of tugboats and winch wires during on- and off-loading.

Given the relatively small footprints of the columns, in combination with the fact that these would mostly overhang the carrier's 40 meter wide deck, four sponsons were required to increase the support area. Much attention was paid to the footprint loads in order to obtain the optimum support configuration.

TRANSPORT ENGINEERING

The engineering done before the actual transport took place consisted of:

A. determination of design environmental criteria
B. calculation of intact/damaged stability during transport
C. calculation of stability during on-loading/off-loading
D. calculation of motion responses during the design storm
E. calculation of consequential extreme footprint loads
F. design of the optimum sponsons/ internal strengthening
G. design of a cribbing arrangement
H. calculation of the extreme transport forces
I. design of the seafastening arrangement

Apart from the sponson design/internal strengthening, the above is standard engineering which has been performed using the Transport Company's own inhouse developed suite of computer programs. All methods/results were carefully checked and approved by all parties involved.

Due to the many uncertainties (TLWP particulars, carrier, route and departure date) at the start of the above mentioned preparations, the engineering took on an iterative character.

A. DESIGN ENVIRONMENTAL CRITERIA

At the time of the contract award, the departure date was not fixed. Furthermore it was decided to study both the route via Suez as well as the route via the Cape of Good Hope in order to assure the greatest flexibility.

The long term prediction of the design sea state is based on the 'Global Wave Statistics' as compiled and edited by British Maritime Technology Ltd.

The data are presented in terms of probability distributions of wave heights, periods and directions for the global selection of 104 sea areas. The data has been derived by a quality enhancing analysis of a massive number of visual observations of both waves and winds reported from ships in normal service all over the world, using a computer program called NMIMET /1/.

From these available wave statistics, short term design sea states are derived with a maximum significant wave height which has a probability of exceedance of 5%. This probability is valid for the most severe area of the route.

Parameters which influence the design sea state are:
- design probability of exceedance (fixed at 5%);
- route;
- weather routing;
- season;
- vessel speed (exposure time).

Theory
The transportation route was divided into straight sections crossing the 'Global Wave Statistics' areas. Since the wave data is presented in terms of probability distributions, bias of areas containing large numbers 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 is retrieved by means of a scatter diagram.

The scatter diagram presents the number of 'observed' wave period combinations for the most severe area. Combining all of the period classes results in the total distribution of 'observed' wave height. Given this distribution a cumulative probability distribution can be determined, using Gumbel formula /2/:

$$P_i = \sqrt{\{m_i \, . \, (m_i + k_i - 1)\}} \; / \; (n + 1)$$

where: n = total number of observations
m_i = number of the first observation within class number i, i.e. sum of number of observations in the preceding classes, plus one.
k_i = number of observations within class number i.

Given the cumulative probability distribution, the design wave height can be calculated after establishing the proper probability of exceedance for each 6 hours stay in a specific area, which is given as follows:

$$P(H_{sig}, 6 \text{ hours}) = \sqrt[N]{\{1 - P(H_{sig}, \text{area})\}}$$

where N = number of 6 hours transit periods through the most severe area, corrected for the calm periods ($H_{sig} \leq 4$ m)
$P(H_{sig}, \text{area})$ = 5%

Given the design wave height and the scatter diagram, 4 short term design sea states were selected, consisting of a combination of design significant wave height and 4 of the most probable wave periods.

The zero up-crossing periods T_z from the 'Global Wave Statistics' are converted to mean periods T_{mean} by:

$$T_{mean} = 1.087\ T_z \quad \text{s}$$

With the significant wave heights and the mean wave periods the shapes of the Pierson-Moskowitz spectra are defined.

The extreme wave height that can be expected during a stationary storm of 6 hours can be calculated from the significant wave height using:

$$H_{extreme} = H_{sig} \times \sqrt{\{(\ln m) / 2\}} \quad \text{m}$$

where m = number of waves encountered during a 6 hours period $= 6 \times 3600 / T_z$

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.

Detailed global analyses of long-term monthly climatological means and standard deviations were performed for the wind speed /3/. For each of the 104 'Global Wave Statistics' area, the monthly mean and standard deviations were extracted from the maps.

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

$$V_{wind\ 10\text{-}min} = \text{mean} + 3.5 \times \text{standard deviation} \quad \text{kn}$$

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

For design purposes, the 1-minute sustained wind speed is used, calculated from the 10-minute mean wind speed by multiplying this with a gust factor of 1.21 in accordance with A.P.I. guidelines /4/:

$$V_{wind\ 1\text{-}min} = 1.21 \times V_{wind\ 10\text{-}min} \quad \text{kn}$$

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

Reliability

The above presented method is based on the present state of the art and on one of the latest and most comprehensive wave data bases. Every method of determining a design sea state and each data base have their own specific drawbacks. After all, the world oceans are not divided into clearly separated squares. However, based on past experience, combined with the fact that the heavy-lift ships are fully self-propelled, with a skilful master and crew on board, (utilizing modern communication equipment to obtain weather information from several sources), it can be said that the presented method generates satisfactory design data.

Design criteria

It is clear that design wave heights/wind speeds are strongly dependent on the actual departure date. The initial selection of the design criteria was based on:

- transport via Suez must be possible all year round;
- unrestricted transport via the Cape of Good Hope must be possible with departure before May. After May, strict weather routing is to be applied.

Based on the above requirements, the following design environmental conditions were selected and approved, see figure 2:

- sign. wave height H_{sig} = 8.51 m
- mean wave period T_{mean} = 9.2 - 12.5 s
- mean wind speed = 78 kn
- 1-min sust. wind speed = 93 kn

These criteria were used throughout the engineering phase, including the design of the sponsons and the cribbing arrangement. The final loading condition and seafastening arrangement was based on the environmental conditions for the actual route (via Suez) and departure date (April 15, 1989):

- sign. wave height H_{sig} = 6.33 m
- mean wave period T_{mean} = 8.2 - 11.4 s
- mean wind speed = 47 kn
- 1-min sust. wind speed = 57 kn

B. CALCULATION OF INTACT/DAMAGED STABILITY DURING TRANSPORT

INTACT STATIC STABILITY

Both the initial stability and the dynamic stability are calculated. The initial stability can be judged from the metacentric height (GM), corrected for free surface effects. The International Maritime Organization (IMO) requires a minimum GM-fluid value of .15 m.

For this type of vessel, a much larger GM value is required to withstand the wind loads, wave loads, etc. A large GM value however, will result in a stiff ship with regard to roll motions.

The loading condition needs to be optimized taking both the stability requirements and the motion responses into account.

The dynamic stability at a certain angle of heel is equal to the area under the curve of righting levers up to that angle, multiplied by the displacement.

Classification societies, Surveyors and Statutory Authorities each have their own set of requirements to be met by the stability curve. The Author's Heavy-Lift Transport company has adopted the generally accepted American Bureau of Shipping (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 /5/.

The dynamic stability of the heavy-lift vessel is calculated including the buoyancy contribution of the TLWP which are combined to form one hydrostatic body for intact static stability calculations.

Rotating this combined body over a range of heeling angles results in the corresponding KN-values. From these, the righting levers GZ are calculated, using:

$$GZ = KN - KG' * \sin \phi$$

in which KG' = center of gravity of ship plus cargo above keel, corrected for free surface effects
ϕ = angle to which the hydrostatic body has been rotated

See also figure 3.

Wind loads/moments
The wind loads/moments are calculated in accordance with the ABS rules for Mobile Offshore Drilling Units /5/, based on the design mean/1-min wind speeds.

Wind load
The wind load is calculated for the ship/cargo using the following equation:

$$F_{wind} = .0623 * V_w^2 * A * C_s * C_h/1000 \qquad T$$

in which V_w = wind speed at 50 feet above sea level
A = projected area of all exposed surfaced at inclined condition
C_s = shape coefficient
C_h = height coefficient, as per ABS table /5/

Wind speed used is absolute wind speed i.e. influences of drift, ship's speed, etc. are not taken into account.

No shielding of the major components is taken into account.

Windoverturning moment
The windoverturning moment of the ship/cargo combination is calculated using:

$$\text{Windoverturning moment} = F_{wtotal} * H_t \qquad Tm$$

in which F_{wtotal} = total transverse wind load on ship/cargo combination
H_t = vertical distance from center of effort to center of hydrodynamic pressure

Wind lever
The total wind lever is calculated by dividing the windoverturning moment by the displacement of the cargo/ship combination. The wind lever curve grows substantially with increasing heel angles due to the increasing effect of the large underdeck area. The 1-min sustained beam wind of 57 knots resulted in a wind lever in upright condition of .26 meter. At an angle of inclination of 40 degrees, the wind lever has reached its maximum of .47 meter, after which it slowly decreases with increasing heel angles.

Results
The resulting dynamic stability calculation, based on the actual departure date, is summarized in figure 4. The maximum righting lever amounts to 1.61 meters at 35 degrees. At 50 degrees, which is the downflooding angle of the heavy lift vessel, the righting lever is still 1.27 meters. The first intercept with the wind lever is at 2.4 degrees. The area ratio is 3.10, well in excess of the ABS criterion.

DAMAGED STABILITY
The damaged stability of the heavy-lift vessel loaded with the TLWP was checked for one-compartment damage in combination with a 50 knots wind. Flooding of the largest wing tank would result in an equilibrium list of 5.3 degrees. A 50 knots wind would increase this list to 7.7 degrees. The area ratio is still 1.57, thus meeting the ABS criterion.

C. CALCULATION OF STABILITY DURING ON-LOADING/OFF-LOADING

The stability during the loading of the TLWP was calculated in order to determine the most optimum deballast sequence. Over a large range of displacements, the metacenter KM was calculated for trim of 0, 2, 4 and 6 meters by the stern.

Plotting these in combination with the vertical center of gravity KG indicates the critical area where the stability (GM) is negative, see figure 5. In this critical displacement range of 60,000 to 58,000 T (just before the main deck breaks the water), the trim was to be at least 6 meters in order to guarantee a positive stability of .5 meter. The deballast sequence was designed to slowly increase the trim from zero (moment of picking up load from the TLWP) to 6 meters during the critical range, reducing to zero when reaching the departure draft.

The dynamic stability was checked for the critical range and this was found to be satisfactory i.e. steadily increasing GZ-values with increasing heeling angles.

The off-loading operation was the reverse of the loading operation.

D. CALCULATION OF MOTION RESPONSES DURING THE DESIGN STORM

The behavior of the vessel is calculated by MARIN with the aid of their SHIPMO computer program based on linear seakeeping theory. Within the scope of such a theory the problem of determining the wave induced motions can be separated into the problems of determining the wave induced forces in waves (vessel fixed in space) and determining the unit motion response reaction forces (in calm water).

The wave induced forces, together with the reaction forces and the inertia and geometric characteristics of the vessel, result, when applying Newton's law, in the motion response. The computer program used for determining the induced wave and reaction forces is based on two dimensional strip theory. In order to 'tune' the calculations, model tests were performed by MARIN, Wageningen, the Netherlands. Much attention has been paid to the non-linearity of the roll motion at larger angles. The motions responses are calculated for beam, bow quartering and head seas.

Theory
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, for the various modes of freedom.

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

Single significant amplitudes
Given the response spectra and the broadness parameters, the single significant amplitudes (mean value of highest one-third) are calculated using /6/:

$$\text{single sign. response} = 2\sqrt{\{m_0\}}\,CF$$

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

$$= \sqrt{(1-\varepsilon^2)}$$

m_0 = area under response spectrum

Single extreme amplitudes
The extreme values of a random process are dependent on the number of oscillations or, more meaningful, dependent on the duration of the process being stationary. This stationary period is taken as 6 hours, analogous to the design sea state calculations.

Given the response spectra, the most probable single extreme amplitudes are calculated using /6/:

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

in which T = stationary storm period = 6 hours

m_n = n-th moment of response spectra

Point accelerations
For specific points of interest (TLWP center of gravity, points on TLWP main deck level), linear accelerations are 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.

Results
The motion response results for the all year departure as well as the actual departure date are summarized in table 1.

Note that the reduced design wind speed for the actual departure date made it possible to reduce the stability in favor of the motion responses, as a result, the natural roll period increased from 17.5 to 20.1 seconds.

The predicted extreme lateral acceleration values on TLWP deck level are well within the process equipment's design limit of .4 g.

E. CALCULATION OF CONSEQUENTIAL EXTREME FOOTPRINT LOADS

Given the design accelerations/loads, the extreme footprint loads were predicted. The following assumptions were made:
- the TLWP behaves as a rigid body;
- loads which have no phase relationship are treated as being statistically independent, analogous to the design transport forces.

The TLWP columns footprint loads are composed of the following components:

+	static weight	(1)
+/-	heave acceleration	
+/-	transverse acceleration	(3)
+/-	angular roll acceleration	(3)
+/-	longitudinal acceleration	(4)
+/-	angular pitch acceleration	(4)
+/-	mean wind loading	(1)
+/-	extreme wind loading	(2)
+/-	mean wind loll	(1)
+/-	extreme wind loll	(2)

The numbers between brackets indicate the phase relationship between the various components i.e. extreme wind loll (2) is in phase with extreme wind loading (2).

Results
The static footprint load was 2,170 T. The total footprint loads, including all the dynamic components, were calculated for the three wave headings, see table 2. The highest total load was found for the bow quartering heading. This all year departure load of 3,822 T, plus 5% for contingencies, was used for the design of the support arrangement.

F. DESIGN OF THE OPTIMUM SPONSONS/INTERNAL STRENGTHENING

Although it was initially intended to support the footprints for the full 100%, indepth studies revealed that the consequence of having large sponsons would be some significant negative side effects, which were in conflict with the advantages of self-propelled dry transportation, of which the most important one was the effect on transit speed. It was estimated that four full depth sponsons would reduce the carrier's average transit speed from 12 knots to a slow 8 knots, thus increasing the exposure time by almost 50%.

Small sponsons, which would remain above the waterline, would however not effect the known hydrodynamic properties of the carrier. The small sponsons proposed were 16 meters in length, 3.65 meters in width and 3 meters in height.

In order to ensure the adequacy of the ship's structure (including the proposed internal strengthening) and the sponson design, Lloyd's Register of Shipping was asked to do a structural analysis using their 3-D finite element program. A large section of the vessel was modelled. The lower part of one of the TLWP columns was added to this model as well as the cribbing interface. The finite element model had about 10,400 degrees of freedom. Part of the model is shown in figure 6. Both the static and the dynamic load cases were studied.

From this analysis, the following main conclusions were drawn /7/:

1. The behavior of both the ship structure as well as the TLWP structure was satisfactory, with acceptable stress levels.

2. Because of the flexibility of the TLWP structure, the peak cribbing pressures found were well beyond the crushing limit of ordinary softwood, see figure 7.

The latter conclusion resulted in the development of special rubber cribbing blocks with a spring stiffness similar to that of softwood, but capable of withstanding cribbing pressures well over 200 kg/cm^2.

Rubber cribbing blocks
The blocks were designed such that the stiffness is similar to that of softwood, thus enabling the use of softwood and rubber blocks parallel to each other.

To verify the characteristics of the cribbing blocks, two prototypes (with different hardness) were manufactured and tested, together with two types of softwood.

Each rubber cribbing block measures 1,300 x 200 x 55 mm. Slots are provided for the steel fastening straps to sink in, thus ensuring a flush surface.

A 15 mm steel plate is built in just below the top surface. This plate guarantees the stiffness of the top and thus avoiding digging in of the TLWP hard points.

The prototype blocks were tested in order to:
- establish the stiffness and maximum allowable pressures of the rubber (compression test);
- establish the resistance of rubber in transverse direction (lateral stiffness test).

The first test was performed for both the softwood and the rubber blocks.

The hardness of rubber is measured in 'shore' units. The prototypes were 70 and 80 shore. The wooden prototype blocks consisted of DEAL and OREGON PINE.

The results of the compression tests are plotted in figure 8. The wooden blocks are clearly crushed in the end. The compression continues without further increase of pressure. The DEAL showed a lot of cracking and afterwards returned to only 80 % of its original height. The OREGON PINE however seemed stronger. There was no sign of cracking, even at crushing pressure and it slowly returned to its original height after relieving the pressure.

The rubber blocks behaved well, even at extreme high pressures (up to 300 kg/cm^2, 3 times the design extreme). The steel plate ensured that the top of the blocks were very stiff. This was verified using a simulated hard point of the TLWP. The 'bottom plate' (19 mm) remained straight i.e. the 'bulkhead' did not dig into the rubber block, see figure 9.

Due to the possibility that the TLWP might tend to shift, seafastenings must assure that this movement is restricted. Friction between the soft wooden cribbing blocks and the TLWP also counteract this movement.

In the case of rubber cribbing blocks, the friction coefficient is much higher, but the rubber itself is more flexible and starts to deform in lateral direction. Because of the stiffness of rubber, this will also generate a reaction force.

G. DESIGN OF A CRIBBING ARRANGEMENT

For the cribbing arrangement, OREGON PINE was selected for the areas where the maximum predicted cribbing pressures were in the order of 30 kg/cm^2. For all other areas the hardest 80 shore rubber blocks were selected. The stiffness is very similar to that of the soft wood and the rubber behaves very well, even at extreme high pressures. An additional advantage of the 80 shore rubber is its high stiffness in the lateral direction.

The lateral stiffness of the blocks is of the same order of magnitude as the stiffness of the rubber seafastening fenders and the resulting lateral resistance was incorporated in the design of the seafastening arrangement.

With a compatible behavior of the rubber compared with that of the soft wooden blocks, it was possible to design a hybrid cribbing arrangement with soft wooden blocks in the low pressure areas (up to 30 kg/cm^2) and rubber blocks in the remaining (high pressure) areas (i.e. under the outer shell, pumproom bulkhead and longitudinal bulkheads) thus combining the known behavior of the soft wooden blocks with the pressure resistance of the rubber blocks. The area ratio between wood and rubber was approximately 1, see figure 10.

H. CALCULATION OF THE EXTREME TRANSPORT FORCES

The design extreme forces on the cargo in case the transport vessel meets its design extreme environmental conditions are a combination of:
- transverse/longitudinal inertia forces due to ship motions (F_{acc});
- transverse/longitudinal forces due to mean/1 min sustained wind load (F_{mwind}/F_{ewind});
- transverse gravity forces due to static mean/1 min sustained wind heel (F_{mloll}/F_{eloll}).

The transverse/longitudinal 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 calculated extreme value is based on a single occurrence of this extreme during the stationary 6 hours 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 super-imposed directly, see also figure 11.

The total design extreme force on the cargo are thus calculated as follows:

Transverse:

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

Longitudinal:

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

Results

The analysis, based on the actual departure date resulted in the following design extreme forces:

Transverse: $F_{total} = 2{,}149$ T

Longitudinal: $F_{total} = 1{,}767$ T

To keep the TLWP in place, a seafastening arrangement was designed in such a way that it was able to sustain these design extreme forces.

I. DESIGN OF THE SEAFASTENING ARRANGEMENT

The forces on the seafastenings arranged around the TLWP are determined basis the following assumptions:
- the flexibility of the TLWP is small compared to that of the rubber seafastening fenders;
- the lateral stiffness of only 80% of the rubber cribbing blocks is taken into account, assuming 20% of the blocks do not contribute. For the lateral stiffness of the rubber cribbing blocks, the lowerbound value of 307.2 T/mm as obtained from the tests is used;
- As a combined soft wooden/rubber cribbing is used, no friction reduction of the wood is taken into account.

The local displacement of the TLWP at each seafastening is determined by the two translation components of the cargo in the horizontal plane and one rotation component about the vertical axis. These displacement components can be found by solving the three equilibrium equations for the TLWP in the horizontal plane:
- transverse external force equals the rubber cribbing reaction force plus the summation of transverse components of seafastening reaction forces, see figure 12;
- longitudinal external force equals the rubber cribbing reaction force plus the summation of longitudinal components of seafastening reaction forces;
- summation of moments of seafastening forces with respect to the center of gravity of the TLWP equals zero.

The final seafastening arrangement consisted of 6 seafastenings per column, in a semi-circle around the inside. Each seafastening was positioned against a bulkhead or stiffener.

The total lateral resistance of the rubber cribbing blocks was in the order of 1,150 T. The remaining load was taken by the seafastenings. Per seafastening, this load ranged from 68 to 208 T. In order to transfer the highest loads into the TLWP columns, 2 special seafastenings per column were built which could accommodate 4 rubber fenders. The remaining seafastenings were of the standard type, each accommodating 3 rubber fenders.

MARINE WARRANTY SURVEYOR APPROVAL

Upon appointment as Marine Warranty Surveyor, a meeting was arranged with Conoco, Inc. to obtain pertinent details of the TLWP which would be transported and a discussion was held concerning general recommendations for the dry transport.

In general the role of the Marine Warranty Surveyor in regard to engineering review, for a dry transport on a semi-submersible heavy-lift ship, consists of an evaluation of all engineering listed in items A through I including all aspects of on-loading and off-loading of the dry transport cargo.

As a standard practice Underwriter-approved Marine Surveyors often begin their participation in similar projects with confirmation of the design sea state, which later is utilized as input data for the vessel motion response program, as listed in section A.

In line with the above, both intact and damaged stability are checked for the combination of cargo and dry transport vessel based on a specific departure draft.

One of the first steps in the approval process concerns the stability criteria. The standard Stability Criteria utilized by many Marine Warranty Surveyors is from ABS /5/, as summarized in section B.

Additionally with respect to this transport the Marine Warranty Surveyor conducted an independent vessel motion response for the TLWP as loaded on the transport vessel to validate results from item D. Results from the above mentioned vessel motion response study were utilized to validate results, in item E and H, obtained by the Transport Engineer.

Because of the unique nature of the TLWP as dry transport cargo, items F, G and I required further research. A meeting was convened in London at Lloyds Register of Shipping to further discuss the transport loadings. On site calculations performed by various interested parties validated the feasibility of the dry transport of the TLWP on the transport carrier, outfitted with limited sponsons.

It is noteworthy that this particular transport of the Conoco TLWP on a heavy-lift vessel presented a unique set of problems whose solution was based largely on current dry transport engineering experience. However a number of problems could only be solved utilizing innovative technology. The derivation of forces on the TLWP as predicted by the Transport Engineer required a new design of cribbing material supporting the TLWP's footings.

In summary, the Marine Warranty Surveyor approval was based on review of all engineering listed in items A through I, included innovative technology used to safely transport the TLWP on a dry transport vessel over a distance of 12,000 nautical miles and including the on-loading and off-loading of the TLWP

We believe the derivation of environmental forces and reactions on the TLWP to be a very accurate estimation of the true sea loading the TLWP could have experienced if the transport had en-countered its design sea state. Future transportation of unique cargoes if modelled and analyzed consistent with those methods utilized on the above mentioned transport are likely to have similar results.

THE ACTUAL TRANSPORT

LOADING

Before the TLWP load-out, the following preparations were made onboard the heavy-lift vessel:
- installation of local internal strengthening;
- installation of the four sponsons;
- laying out of the cribbing arrangement;
- installation of the positioning guides.

These preparations, executed by the yard which built the TLWP, took 10 days. In the meantime, the TLWP was prepared for its voyage i.e. all loose items onboard the TLWP were secured. All securing was carefully checked by the Transportation Engineer and the Marine Warranty Surveyor.

The afternoon before the load-out, the ship moved to the West Jurong anchorage for loading of the TLWP. The weather forecast indicated favorable conditions for the following day.

Load-out started at daybreak on April 14, 1989. While the heavy-lift ship submerged to its loading draft of 21 meters (i.e. 9 meters of water over the main deck), the TLWP was unmoored from the yard and towed to the loading location. In order to facilitate the connection of tug boats and winch wires, each pontoon was outfitted with two sets of double bollards.

Around noon, the TLWP arrived and was slowly manoeuvered over the main deck of the submerged heavy-lift vessel and positioned by winches against the guides. The heavy-lift vessel commenced deballasting until the TLWP started to rest on its cribbing.

A diving survey indicated that the TLWP was exact in position and deballasting continued in accordance with the prepared deballasting schedule. During this deballasting, a small list to starboard was maintained to limit any free surface effect. The minimum stability range was crossed without a moment of instability.

At 18:00, the main deck emerged and the 24 seafastenings were positioned. Welding started around midnight, after reaching the departure condition, and finished before dawn the next morning.

That same day, at 10:00 a.m., while the weather conditions started to rapidly deteriorate, the heavy-lift ship departed Singapore, R.O.S. to deliver the TLWP to Pascacoula, Mississippi, see figure 13.

TRANSPORT

During the transport, the experienced weather was in general favorable with a maximum wind speed of 35 knots (Red Sea, head on) which slowed the ship down to 9.4 knots. The average transit speed was in the order of 12 knots, with a maximum recorded speed of 15.2 knots.

A Marine Warranty Surveyor attended onboard the transport vessel in the capacity of an independent observer for the full duration of the voyage.

Observations from the Surveyor indicated that the transport never encountered the design sea state as predicted for the transport and the TLWP motions and accelerations were well within the design limits. The rubber cribbing blocks and rubber seafastening fenders were reported to show some dynamic compression due to the motions and deflections of the carrier.

Correlation predicted - actual
The actual sailed route, plotted in the 'Global Wave Statistics' map, is given in figure 14. For each area crossed, the maximum observed 6-hours mean wave height and extreme wind speed are compared with the for that same area predicted significant wave height and 1-minute sustained wind speed, see figure 15. Given these predicted wave heights, the resulting extreme roll and pitch motions are calculated (assuming beam respectively head seas) and compared with the in the corresponding areas maximum observed 6-hours extreme roll and pitch motions, see figure 16.

In general, the correlation is good, with the monitored values showing the same trends as the predicted values.

The design extreme roll amplitude was 4.3 degrees and the design extreme pitch amplitude was 5.3 degrees. The observed extreme motions were all well within these design limits, leaving a safety margin in the order of 60%.

The presentation of only the observed maximum conditions and motions per area creates the impression that the transport did not meet any calm periods. The contrary however was true, as is clearly shown in figure 17 where the frequency distributions of the observed wave heights and resulting motions are plotted. Over 75% of the voyage, the TLWP was subjected to negligible dynamic loads.

It must be noted that the wave heights were visually observed and were subject to inaccuracies due to darkness, distance from the bridge to the water surface, etc. This clearly shows in the observation of the most severe mean wave of 3.0 meters in the Red Sea (area 37), in combination with negligible motions.

OFF-LOADING

The discharge site was selected after consultation between the Port of Pascagoula, the Transport Company, the Marine Warranty Surveyor, and other interested parties. The site was located off Ingalls Shipyard in the Port of Pascagoula. The water depth was approximately 70 feet and a maximum current of 1.0 knot was estimated during the off-loading operation.

The off-loading of the TLWP from the transport vessel was conducted on May 28, 1989 at the indicated site. The transport vessel was submerged to off-loading depth. By 10:38 a.m. the TLWP was afloat and utilizing the transport vessel mooring winches manoeuvred off the transport vessel. Under tow of three harbour tugs, the TLWP was cleared from the heavy-lift vessel at 10:53 hours.

From this point the TLWP was towed to Hamm Industries Shipyard in Pascagoula, Mississippi and moored at their berth with a spacer barge placed between the TLWP and the dock.

CONCLUSIONS

The unique nature of the TLWP required various unorthodox solutions. Conventional design methods were revised and new materials were developed.

Sound engineering proved the feasibility of supporting only 70% of the TLWP's footprints, see figure 18, thus safeguarding the advantages of these self-propelled ships.

Much emphasis was paid to avoidance of unnecessary conservatism. The design criteria/motions/loads were to be realistic extremes. The correlation between design motions and actual observed motions confirm the reasonability of the design parameters.

The design environmental conditions were not met during the voyage. The high transit speed of the vessel in combination with anticipating actions of the master enabled avoidance of stormy areas.

The observed motions show a good correlation with the predicted motions. The extreme observed motions were well within the design extremes.

The TLWP was delivered to its owner within schedule. The average transit speed over the 12,000 miles voyage was in the order of 12 knots.

The dry transport of the Conoco TLWP has again proven that transport by a self-propelled semi-submersible heavy-lift ship is a reliable and safe option for sensitive and valuable cargoes with strict installation windows.

In general, it is important to involve the Transportation Engineer in an early stage of the (conceptual) design of a novel structure in order to jointly establish the specific transport requirements.

ACKNOWLEDGEMENT

The Authors wish to acknowledge their gratitude to Conoco Inc., operator of the Jolliet TLWP, and its partners, OXY U.S.A, Inc., a subsidiary of Occidental Petroleum Corporation, and Four Star Oil and Gas Company, a subsidiary of Texaco, Inc., for their cooperation in the successful completion of this work.

The Authors would also like to express their sincere gratitude to all of the people who where involved from, Far East Levingston Shipbuilding Ltd., Lloyds Register of Shipping, Earl & Wright and Rubber Industrie Soest NV for their support, valuable input and good co-operation during the preparations and execution of this unique dry transport.

Managements of Wijsmuller Transport B.V. and Matthews-Daniel Company are acknowledged for providing the time and means, necessary for writing and presenting this paper.

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TABLE 1 - Motion response output

Departure date	all year	April 15	
extr. single roll ampl. extr. single pitch ampl.	9.8 7.3	4.3 5.3	deg deg
C.O.G. TLWP			
extr. single transv. acc. extr. single longit. acc.	.32 .27	.21 .20	g g
TLWP main deck level (design limit = .4 g)			
extr. single transv. acc. extr. single longit. acc.	.37 .39	.24 .29	g g

TABLE 2 - Predicted footprint loads

Departure date	all year	April 15	
Head seas	3,488	3,105	T
Bow quartering	3,822	3,279	T
Beam seas	3,648	3,075	T

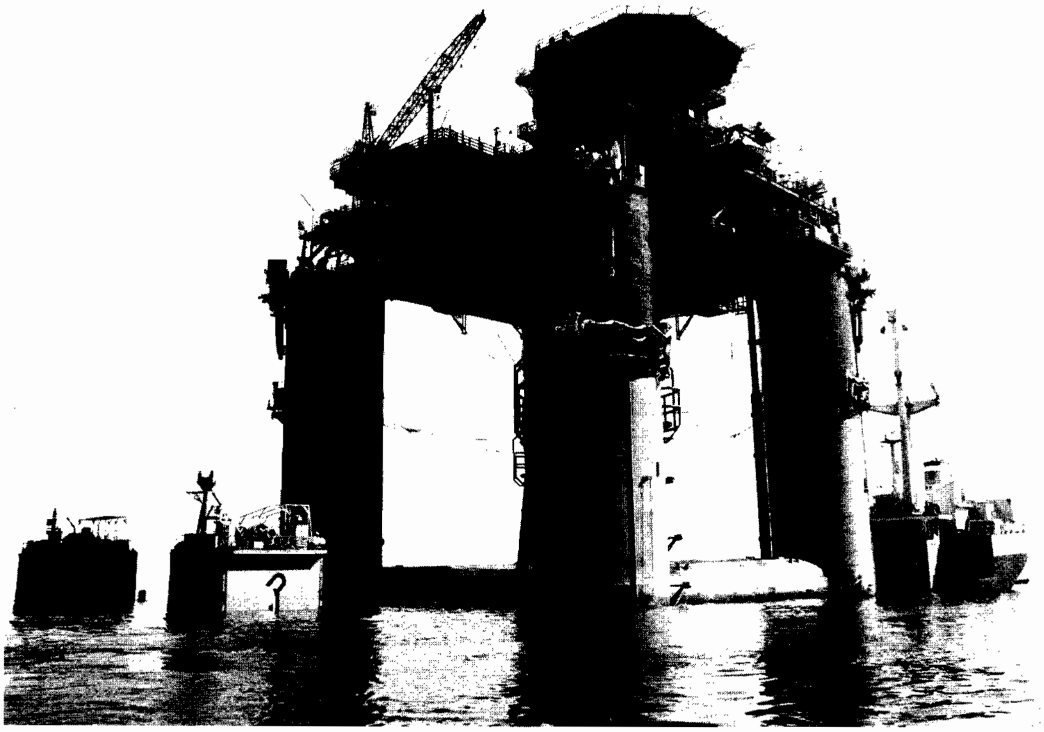

Fig. 1 - Float-on operation of TLWP.

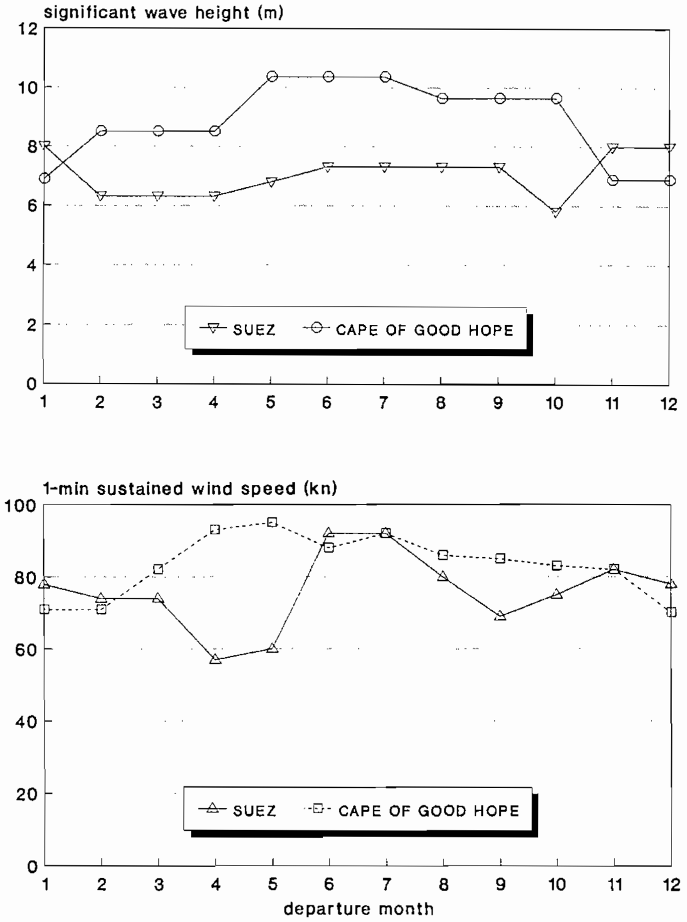

Fig. 2 - Design environmental conditions versus departure date.

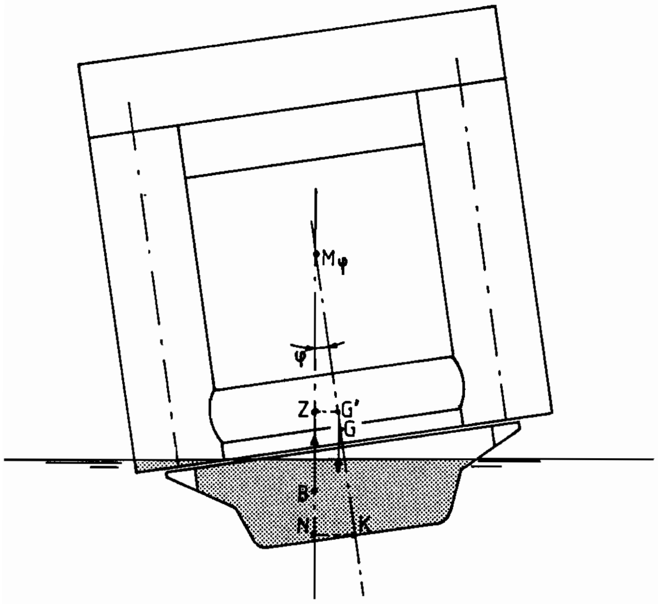

Fig. 3 - Nomenclature dynamic stability.

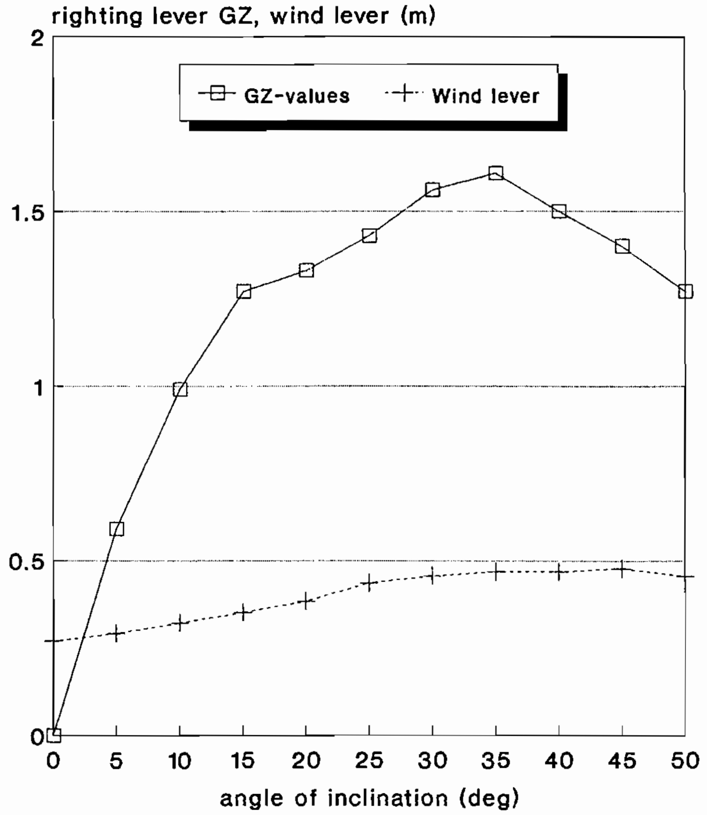

Fig. 4 - Dynamic stability curve/wind lever.

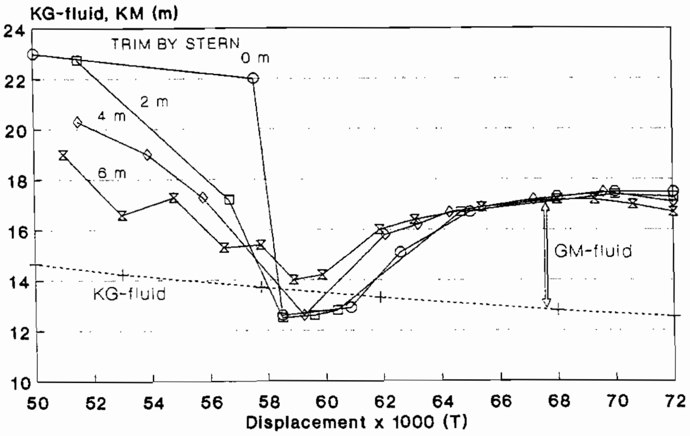

Fig. 5 - Stability during deballasting.

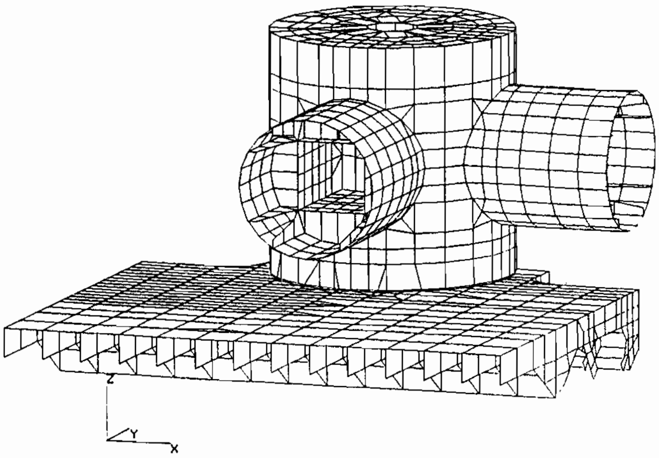

Fig. 6 - 3-D Finite Element model /7/.

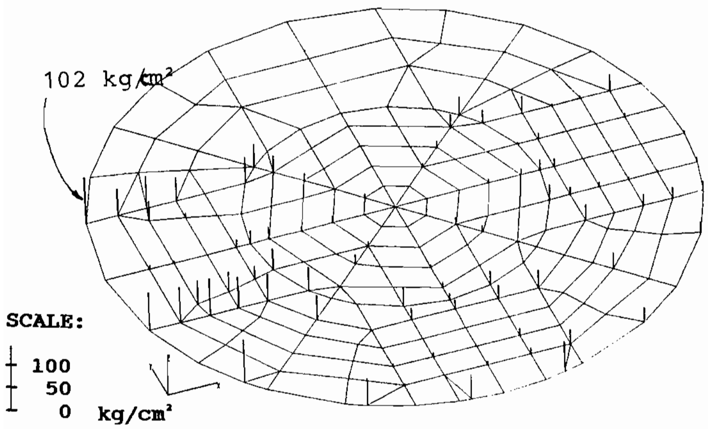

Fig. 7 - Cribbing pressure distribution /7/.

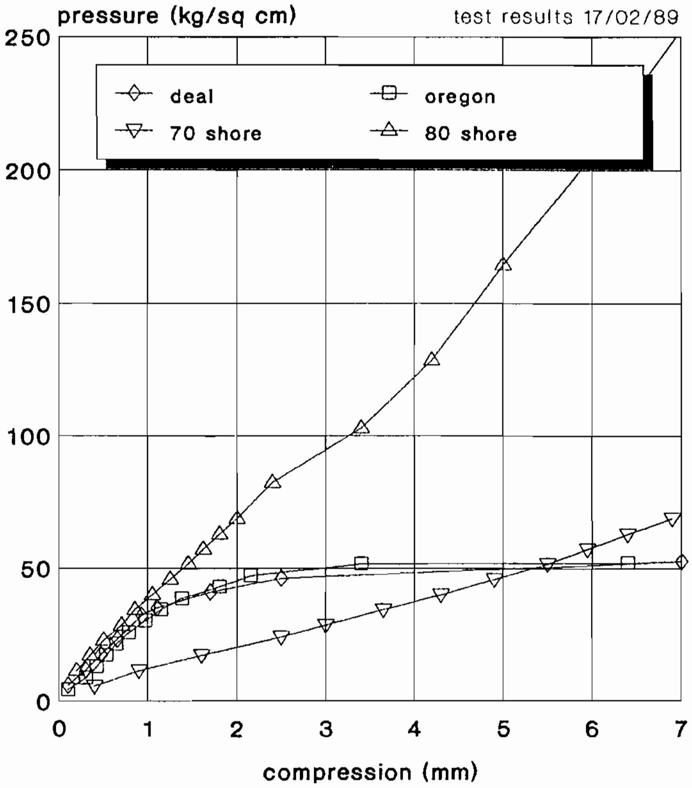

Fig. 8 - Results compression tests rubber/softwood.

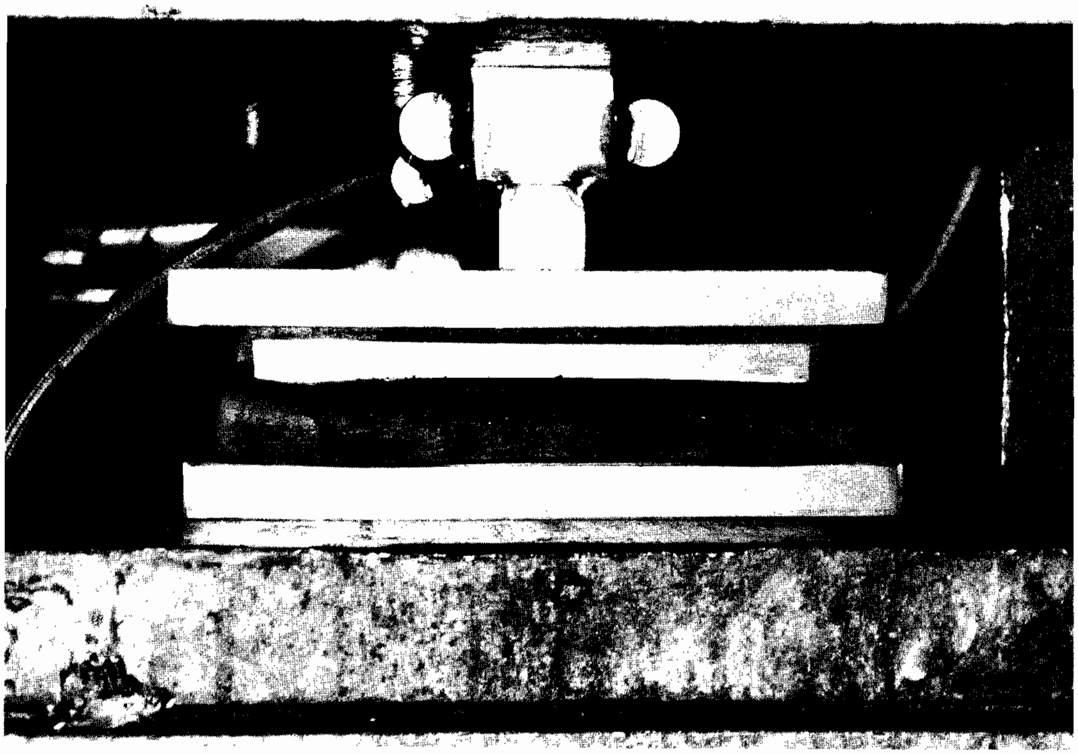

Fig. 9 - Pressure test '80 shore' prototype at 100 kg/cm^2.

Fig. 10 - Cribbing arrangement for forward starboard column.

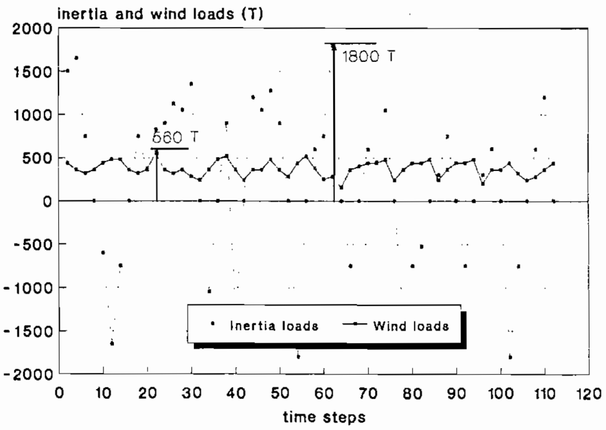

Fig. 11 - Simulated time traces inertia/wind loads.

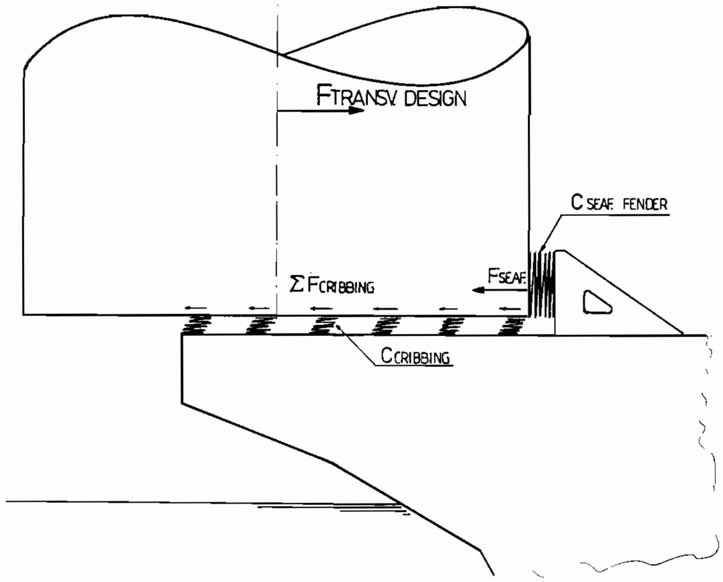

Fig. 12 - Seafastening fender/rubber cribbing reaction forces.

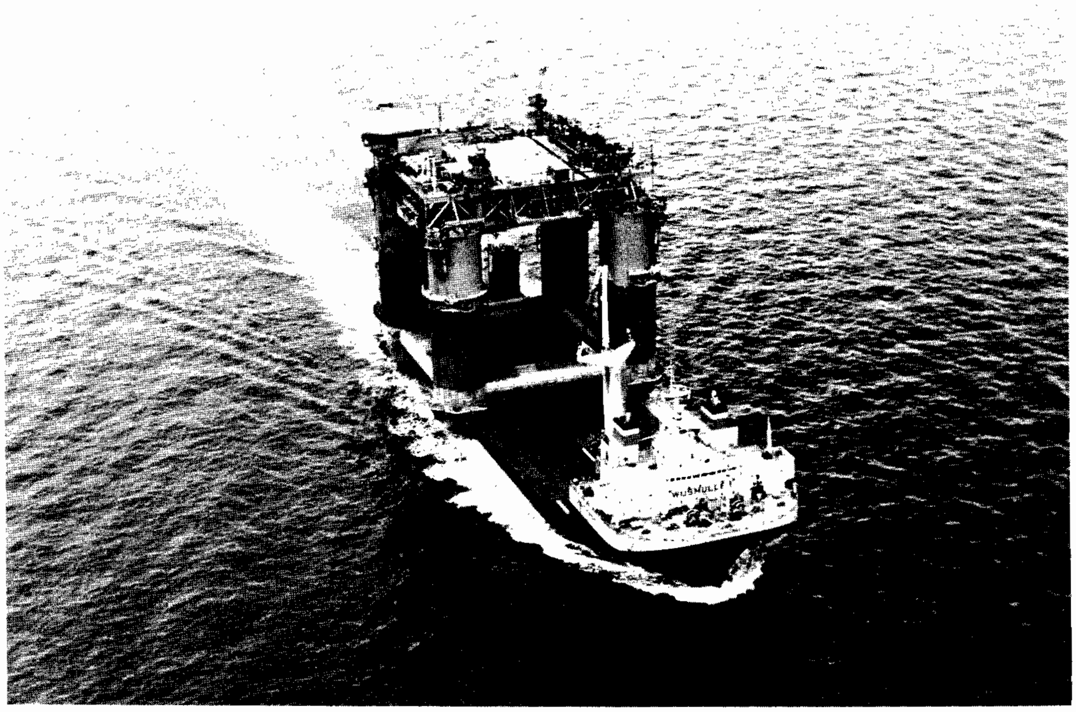

Fig. 13 - TLWP in transit onboard the Heavy-Lift ship.

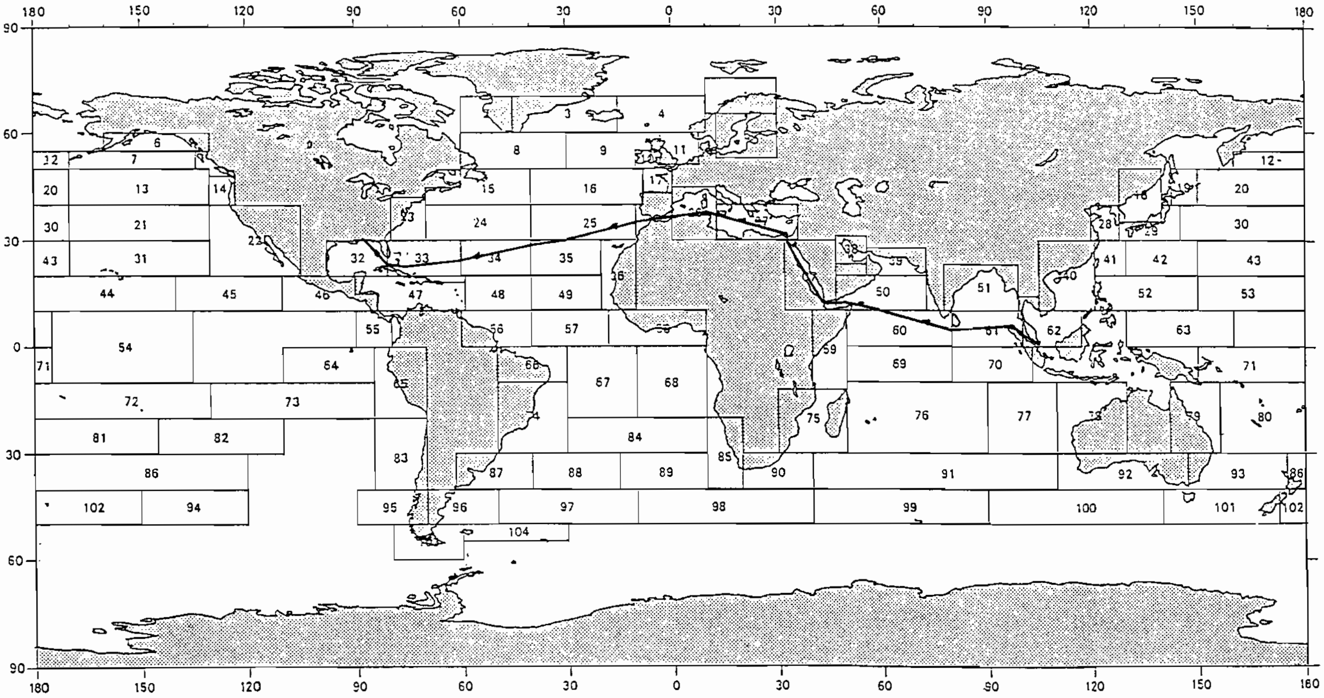

Fig. 14 - Actual route through 'Global Wave Statistics' /1/ areas.

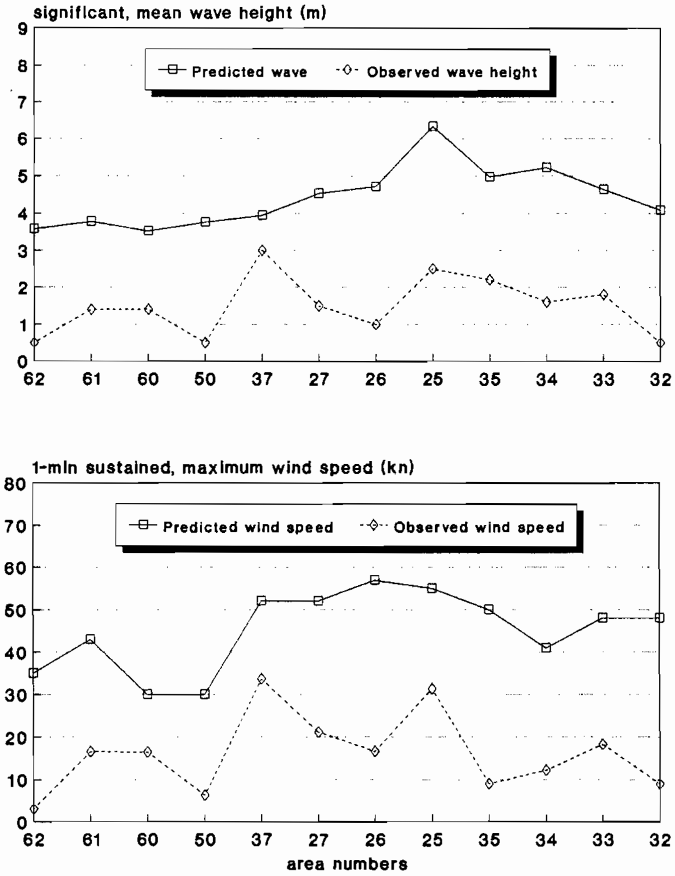

Fig. 15 - Correlation predicted/observed environmental conditions.

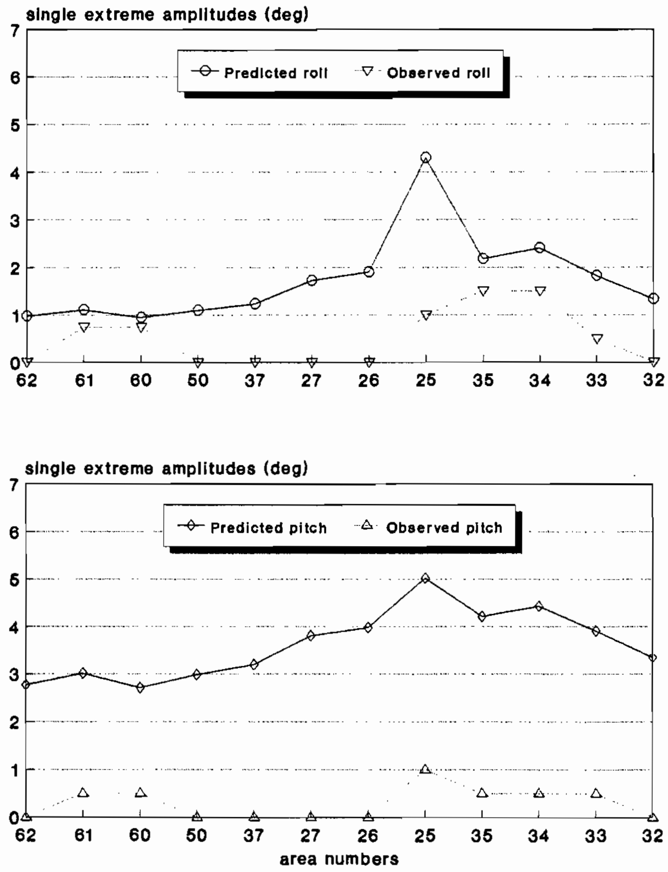

Fig. 16 - Correlation predicted/observed ship motions.

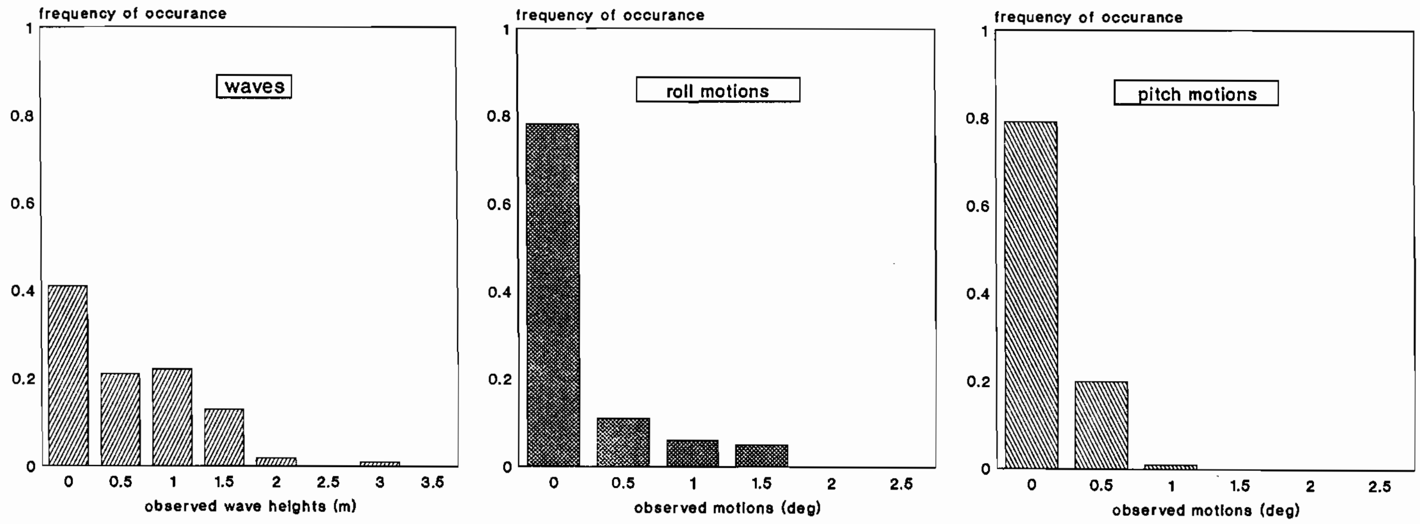

Fig. 17 - Frequency distributions of observed waves and motions.

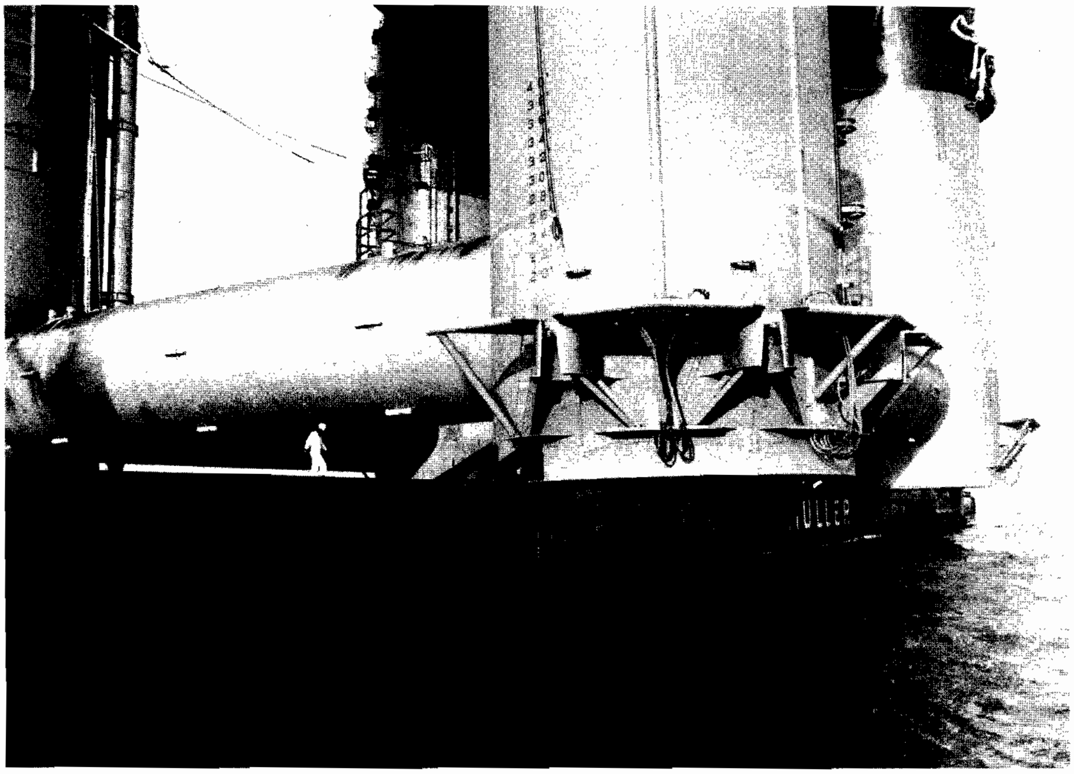

Fig. 18 - Columns partly overhanging deck/sponsons.