11. On Some Problems of the Basic Design Experienced through Construction and Operation of Semi-Submersible Offshore Drilling Units

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Summary

In general, it may be said that semi-submersible offshore drilling units are designed under some conditions, such as design conditions and design criteria. The former include conditions of operation site and the latter consist of requirements for operation and restriction by regulatory bodies, both of which can be largely considered as necessary conditions for initial designing of a semi-submersible.

However, it is necessary to elaborate some sufficient conditions for creating an economical and reliable semisubmersible. In this paper the author explains the above necessary and sufficient conditions obtained through fabrication and operation of the HAKURYU series of semi-submersibles as presenting some problems which must be considered in the initial design stage for creating a new type of semi-submersible.

1. Introduction

Semi-submersible offshore drilling units (hereinafter called "S/S rig") have been widely used for drilling acrivities of undersea oil exploration in rough seas, and their superiority of working probability in high seas has been proven, as a rationalized wave-free form, during their operation in the North Sea.

The realization of the basic design of the S/S rig requires some fundamental conditions which are generally indicated in terms of design conditions and evaluation criteria. The former include those of the operating area, related environment, etc. The latter are the specific conditions required by the regulatory bodies and drilling operators, which will be used as basis for evaluation of the functions of drilling units. Therefore, the above design conditions and evaluation criteria can be said to be the "necessary conditions" for realization of the basic design of an S/S rig. In comparison with ships that transport passengers and cargoes between ports, S/S rigs stay in an uncertain area for operation unless they must be moved to other operating areas. Therefore, the necessary conditions for ships and S/S rigs can be specified from the following different points of view:

Ship	S/S rig
Sea lane	Operating sea area
Dead weight (D/W)	Variable deck load (V.D.L.)
Speed	Positioning performance

Since early S/S rigs built in the 1960s were equipped with drilling rigs designed for land use, many offshore drillers paid special attention to their positioning performance in high seas. As many later S/S rigs being built and operated, great changes have been made in their configuration, as shown in Fig. 1, which signifies that the different conditions had been required by both builders and users, to their satisfaction for realization of the basic design. These might be some kinds of suffici-

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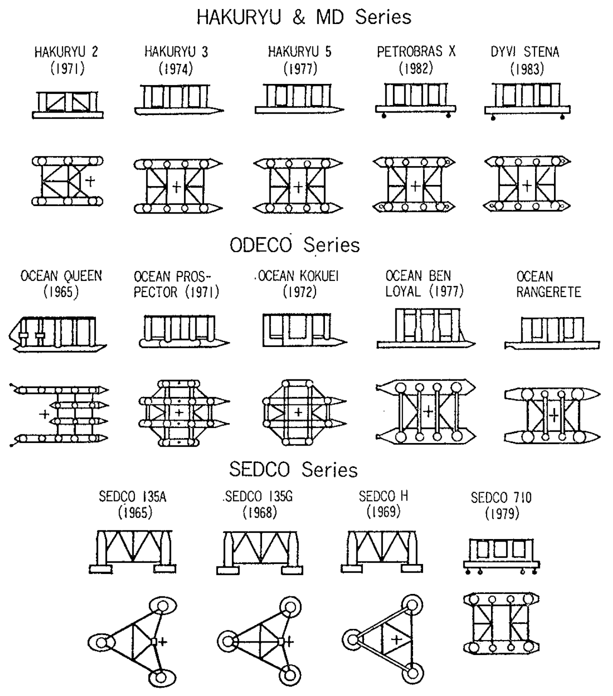


Fig. 1 Historical change of typical semi-sub-drilling units

ent conditions, and the author has come to consider them to be summarized to the following three categories:

(1) To have more workability in a wide sense.
(2) To secure structural integrity of a floating body.
(3) To be of a type of structure for easy construction.

For ships, in general, the necessary and sufficient conditions have been empirically verified. On the other hand, it can be said that the S/S rig has too short a history yet to completely clarify either the necessary or the sufficient conditions. In this respect, the author makes an attempt in this paper to bring to light the problems involved in such conditions for realization of the basic design and to obtain suggestions for the future design by reviewing the records and data of construction and/or operation of S/S rigs including 3 HAKURYUs (original series) and 3 Modified HAKURYUs (MD series) designed by Mitsubishi Heavy Industries, Ltd., and 8 others designed by foreign consultants or companies.

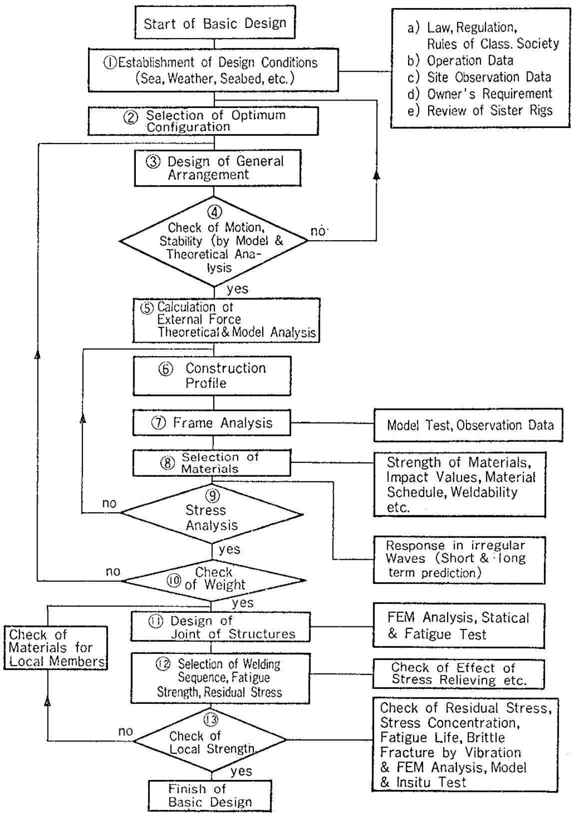
In the meantime, the meaning of the "realization of the basic design" used herein is an engineering to create an ideal S/S rig that would satisfy the above two conditions based on the new concept of "semi-submersible," and not simply the so-called "basic design."

2. Necessary Condition for Realization of Basic Design

2.1 *Design Condition*

Table 1 shows a typical structural design procedure for an S/S rig. Prior to anything else, the design condition should be given, as ①, considering the owener's requirements, the data of full-scale measurements, etc., as shown at top, right. ② is a process to determine an optimal type of structure in a given operating area based on the concept of "semi-submersible." It can incorporate the details of the operation and test data. In ④, the motion modes in waves of the structure determined in

Table 1 Typical structural design procedure for semi-submersible offshore structure



② will be verified by solving the equation of motion of the S/S rig in waves, assumed as a rigid body, under exciting force by small amplitude waves. The motion modes thus obtained will be used as basis for various reviews of the said S/S rig. Items ⑤ and below show a general structural planning. Of the design conditions in ①, those of the operating area, waves and wind are the most important factors which have effects on the final configuration of the S/S rig to be determined. This paper describes these three conditions that seem to greatly affect the determination of the final configuration, although other conditions, such as sea current, temperature, seabed soil, etc., cannot be ignored in relation to the structural and fitting planning.

(1) Operating Area

Most S/S rigs in the early 1970s were of the type for operation in restricted areas, as shown in Table 2, for example, while the recent ones are of the worldwide-operation type except in icy waters. Such a trend of S/S rigs to operate in unrestricted areas is considered entirely natural from the viewpoint of their undersea oil drilling, as understood from the operation records of HAKURYUs II-V, as shown in Fig. 2a and b. Moreover, their inherent nature of operation to be positioned stationary would force them to encounter much severer sea and weather conditions than those for ships.[1),2)] That is, ships navigating through regular sea lanes permit the various initial design items including deck wetness, slamming, stress variations, etc., to be reviewed by means of the statistical probability in general consideration. On the other hand, for S/S rigs to operate in world-

Table 2 Operation area & water depth of HAKURYU series

name of rigs	year of built	expected operation area	water depth	remarks
HAKURYU II	1971	Japan Sea, South east Asia,	m 6~200	
HAKURYU III	1974	beyond continental shelf to cont. slope	40~300	
HAKURYU V	1977	beyond cont. slope to ocean basin	500	off Sakhalin, East China Sea
MD602	1980	all over the world ex. icy area	450	for STENA
MD502	1980	do.	450	PETROBRAS X, XV
MD202	(1980)	do.	450	

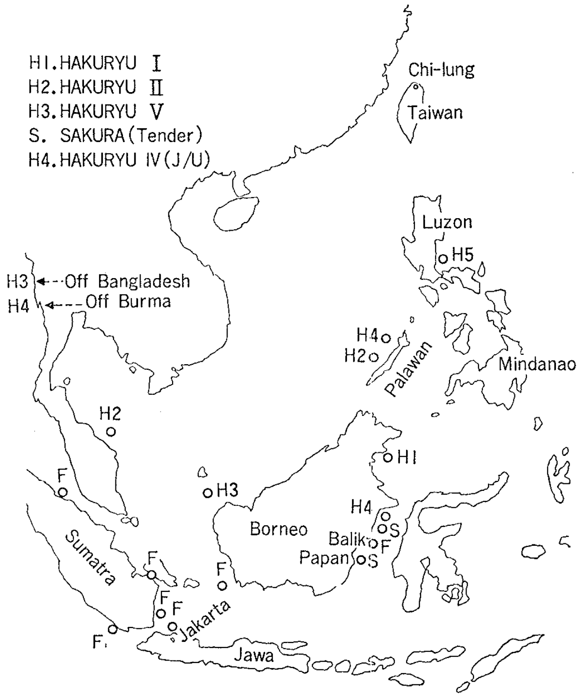


Fig. 2a Locus of operation of HAKURYU series

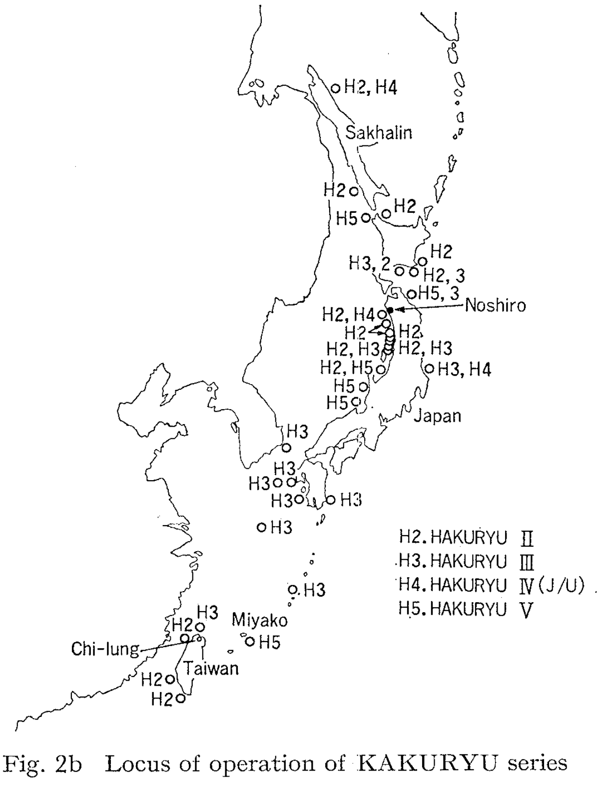


Fig. 2b Locus of operation of KAKURYU series

Table 3 Environmental condition of HAKURYU series

design condition		HAKURYU II	HAKURYU III	HAKURYU V	MD202	MD502	MD602
transit	wind speed max. m/sec.	15/60*3	15/60*3	15/60*3	36	36	36
	wave height max. m	5/18.5*3	5/18.5*3	5/18.5*3	10	10	10
	wave period*1 sec.	6∼20	6∼20	6∼20			
operation	wind speed max. m/sec.	15	15	15	36	36	36
	wave height max. m	6	6/10	6/10	12	12	12
	wave period*1 sec.	6.5∼15	9∼20	9∼20			
very severe sea	wind speed max. m/sec.	60	60	60	51.5	51.5	51.5
	wave height max. m	18.5*2	24*2	36.6	30.5	33.5	33.5
	wave period*1 sec.	11−20	18−25	20−25			

remarks

*1. actual wave period corresponding to wave height

*2. denote the values at the construction, and were altered into 27m (HAKURYU II), 36.6m (HAKURYU III) after statistical review

*3. up/lower=afloat condition/semisub condition

wide unrestricted areas for a long time, the difficulties that lie in easy determination of the design conditions affecting their functions and in analysis of their overall system under the concept of a long term statistical probability have led to the present reliance on the deterministic means.

However, since the operating sea condition even for the worldwide-operation type of S/S rig can be sufficiently understood as its operation records being accumulated, it will make sense to review the entire basic design by means of the statistical probability. In such a concept, the maximum wave height in very severe sea condition for HAKURYUs II and III were reexamined and the condition of the basic design, modified (see Table 3).

(2) Waves and Air Gap ($\bar{\delta}$)

Waves determine the nature of the S/S rig. The classification societies of various countries have provided the method of defining waves by means of statistical probability only in terms of recommendation. Takahashi et al.[3] give their concept of extending such a recommendation. However, waves acting on an S/S rig are governed by the deterministic concept. Table 3 shows typical environmental conditions deterministically given to the HAKURYU and MD series. As the operating area of S/S rigs is gradually extended toward rough seas, consideration of even $H_{\max}=120$ ft (36.6 m) is given to HAKURYU V, as shown, which is generally judged as overestimate of the field record. The DNV rules, 1981, show that no waves exceeding 30 m corresponding to those in 100-year storm should be taken into account. Hammet shows an empirical value of $H_{\max}=98$ ft (29.8 m) in 180 rig years,[2] which are obtained as aggregation by multiplying the number of operating years of each SEDCO rig up to the given time. At present, with all values integrated, $H_{\max}=110$ ft (33.5 m) has been specified for waves to act on the S/S rigs of MD series operating all over the world (see Table 3). Thus, given waves deterministically, the motion characteristics of the designed configuration can be uniformly obtained by solvthe equation of motion in regular waves. In irregular waves, however, such motion characteristics will become unreasonable for proper understanding of the safety condition of the S/S rigs. Especially, to make full use of the features of the S/S rig having its operating deck above the wave surface, as in Fig. 3, it will be considered more reasonable to review the air gap $\bar{\delta}$ from the response of the rig in irregular waves. The classification rules specify the standard value of $\bar{\delta}\geqq 1.5$ m as the design criteria. Such a value depends on the column height of the S/S rig under consideration and constitutes an important factor affecting its stability and building cost. If the probability technique is not used, $\bar{\delta}$ will be reviewed by applying a tentative value of clearance higher than 1.5 m from the crest line ($H_{\max}$) of regular waves at the position of the mean value of heaving (Z_{mean}). For such a problem, however, it will be more appropriate and

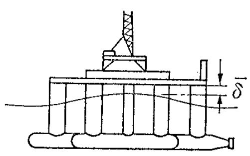


Fig. 3 Definition of air gap

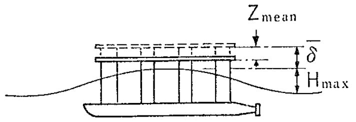


Fig. 4 Air gap of semi-sub in regular wave

rational to review in a response analysis of the S/S rig in irregular waves at its relative motion to waves by obtaining the response spectrum $\Phi(\omega)$ of the S/S rig in irregular waves from Eq. (1) using the response function $H(\omega)$ and the wave spectrum $S(\omega)$.

$$\Phi(\omega)=|H(\omega)|^2\cdot S(\omega) \qquad (1)$$

The recent increasing recognition of the importance of wave spectrum also in the field of offshore structure has led S/S rigs to be provided with observation instruments necessary for analyzing waves and their response spectrum directly in the operating areas. The results of such analyses would be useful for future exploration and production activities for undersea oil. To design an S/S rig available for global operation, one of several sea spectrum giving the most severe response (for example, the North Atlantic Ocean wave spectrum that are being used in calculations of ships) should be taken into consideration rather than the wave spectrum of a particular sea which would provide little meaning. Fig. 5 shows an example of the wave spectrum obtained by HAKURYU V at a water depth of 286 m off Miyako Island.

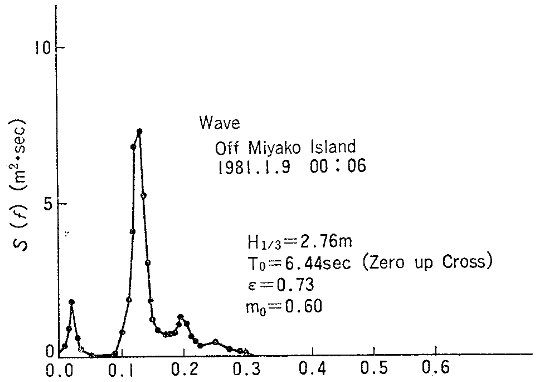


Fig. 5 Wave spectrum obtained by HAKURYU 5 off MIYAKO Island

(3) Wind

The established wind velocity condition provides the basis for calculation of overturning moment in reviewing the dynamical stability of an S/S rig. The regulatory bodies of various countries specify wind velocities for S/S rigs for all normal drilling and in transit or severe storm condition, as shown in Table 3. A wind velocity of 60 m/sec (120 kn.) was specified in the 1970s with the intention of improving the dynamical stability, but it was reduced to 51.5 m/sec (100 kn.), at present. HAKURYU II has encountered with Typhoon Vera off Taiwan and recorded a wind velocity of higher than 68 m/sec beyond the originally designed figures given in Table 3, suggesting the need for providing some redundant dynamical stability. Fig. 6 shows the data recorded by an anemograph on HAKURYU II. When the typhoon passed through, the crew had taken refuge in Taipei leaving the rig unmanned. From the typhoon condition, it is judged that the maximum wave height might have been well over 15 m.

For S/S rigs, having an upper structure with an air gap beneath, a lift force caused by wind effect and rolling due to wind breathing

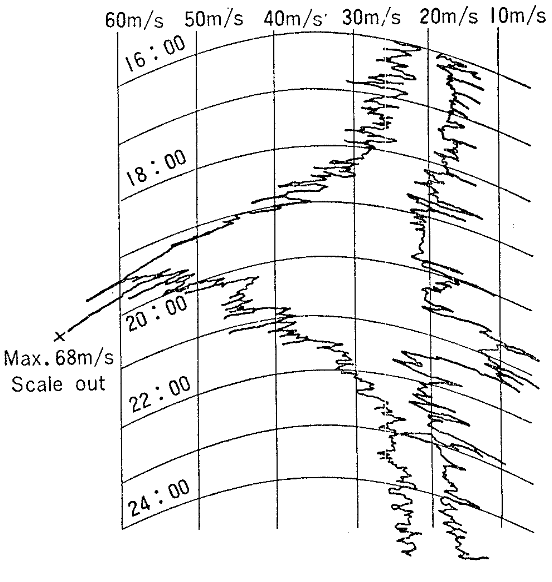


Fig. 6 Histogram of wind velocity of Typhoon VERA experienced by HAKUYU 2, off CHI-LUNG

of a storm must be taken into consideration. The lift force has been studied by Bjerregaard et al.,[4] who pointed out the cause of the unrealistic inclination due to wind heeling moment obtained from the rule and proposed calculation formulas and charts by experimentally reviewing 12 S/S rigs. On the other hand, the study on the lift force has not yet been conducted sufficiently in Japan. Meanwhile, wind in storm actually breathes, as shown in Fig. 6. Its period is close to the natural rolling period of an S/S rig. The values of the energy spectrum of wind are greater also in the vicinity of its period, which will cause a problem.

The result of the spectral analysis of 1,024 waves taken from the rolling histogram of HAKURYU V shows the peaks of spectrum at the periods of 47.6 sec. and and 44.5 sec., respectively, as shown in Fig. 7a and b. These peaks may be considered to have been caused by rolling motion during wind breathing. Meanwhile, the field wind observations on super-high stacks, large cranes, etc., have indicated that the wind breath at a period of about 50 sec. contains an intense energy.[5],[6] It will be understood that the data showing such cause and effect relations, the longer rolling period of S/S rigs that have a small water plane area and a relatively small absolute value of righting lever, etc., all taken into consideration, would lead to a great possibility of synchronized rolling. (refer to Table 4) Under conditions during drilling, this type of rolling has not been positively taken up as considered a transient phenomenon because of small rolling angles and the defined cause of rolling.

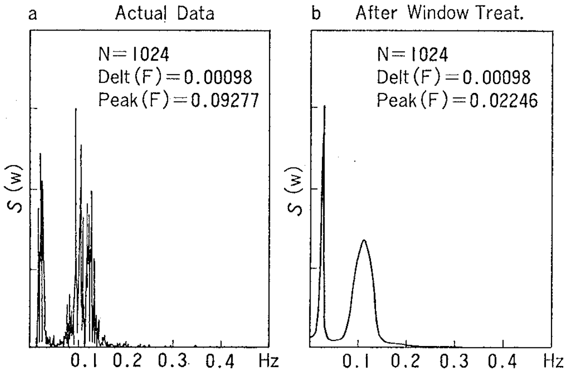


Fig. 7a, b Rolling angle spectrum obtained by HAKURYU 5, off MIYAKO Island

Table 4 Natural frequency of HAKURYU 2, 3, 5

(free floating condition)

items \ name of rigs		HAKURYU II	HAKURYU III	HAKURYU V
$L \times B \times D$		84×61×31m	101×67×35m	104.5×67 ×35m
d		20m	20m	20m
lower hull L1×B1×D1		2× 84×11×5.8m	2× 101×12×7m	2×104.5× 12.6×7m
natural frequency	T_h sec	18.7	20.1	20.2
	T_p sec	30.0	50.1	54.0
	T_y sec	32.3	49.0	57.0

However, in storm condition the effect of waves will be also added, requiring a careful review of the synchronized rolling.

2.2 *Evaluation Criteria*

The evaluation criteria provide a measure for judging the proper performance of a completed S/S rig as designed. For the user, on the other hand, it will form an important item demonstrating the capability of his rig. Although the air gap $\bar{\delta}$ is included in the evaluation criteria, as previously described, the author will discuss in this section V.D.L. and the positioning performance by which the S/S rig is characterized.

(1) Variable Deck Load (V.D.L.)

The demand for operation of S/S rigs has gradually led them toward deeper seas, as shown in Table 2, subjecting them to severer sea environment and to too far a distance from their supply base of consumables necessary for drilling, which are beyond the capacity of a small supply boat. As a result, provision has been made by taking a greater V.D.L. to be loaded on deck, as shown in Fig. 8.

With S/S rigs being built for global operation, the trend is to provide increasingly higher V.D.L. While, the spacing and diameter of the legs supporting V.D.L. greatly depend on the degree of V.D.L. and have a direct effect on the motion characteristics of an S/S rig. Moreover, V.D.L. corresponds to D/W of

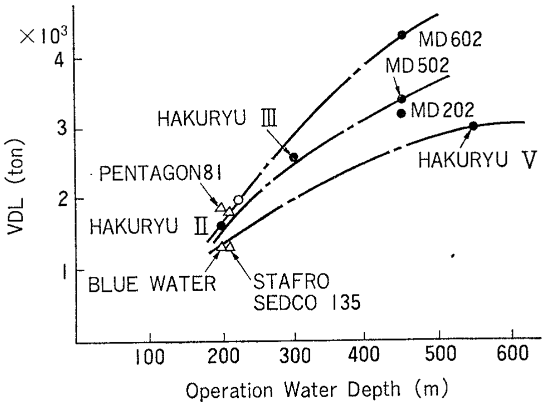


Fig. 8 Variable deck load of HAKURYU series

a ship and its variation has a great effect on the dynamic stability of an S/S rig. Therefore, at the time of realization of the basic design, not to mention, and also during operation, the draft and $\overline{KG_0}$ in response to the variation of V.D.L. in various conditions, as shown in Table 3, should be maintained within the limits specified by the classification rules. Table 5 shows an example of V.D.L., in which the difference in V.D.L. between the drilling and severe storm conditions has been deribed from the estimated amount of consumption up to that time. Since no severe storm can always be encountered with in this condition, V.D.L. can be determined only empirically, leaving a problem for further accumulation of field data.

(2) Positioning Performance

Restrictive condition required for stabilized operation of an S/S rig should comprise every allowable displacement in various operations such as loading, lifting and lowering of pipes, etc., during drilling. Table 6 shows the evaluation criteria for HAKURYU III during etc., during drilling. Table 6 shows the evaluation criteria for HAKURYU III during operation, which are being gradually relieved recently by the improved motion compensator. The horizontal displacement of an S/S rig including sway and surge due to waves is mainly caused by drifting due to constant wind, current and waves. Generally, the displacement S is called "barge offset" (see Fig. 9).

In Table 6, the limitation of S to 5% of water depth means to maintain $\theta_0 = \tan^{-1}(5/100) \doteqdot 3°$. Considering elastic deformation of a riser pipe due to tidal current and the effect of drill water inside a pipe, the actual inclination of $\theta°$ will make the limiting angle to be about 4° (see Fig. 8).

In general, the drill pipe inside the riser may hit the inside wall of the riser ball joint at $\theta > 4°$ and damage it at $\theta > 10°$. Although there is no data clearly showing the limits in storm

Table 5 Example of V.D.L. (MD502)

condition / V. D. L.	V. D. L. (t)		
	transit	drilling, stand by	severe storm
drill pipe/collar	380	380	330
set back	0	150	0
riser pipe	120	120	120
casing pipe	300	300	200
liquid mud	0	500	500
bulk mud/cement (in column)	500	750	750
sack	330	330	100
B. O. P.	170	170	0
Misc.	300	700	600
total	2,100	3,400	2,600

Table 6 Restriction of movement in waves (HAKURYU II) (moored condition)

heaving	Z	±1.0m～1.5m
offset	S	5% of water depth (m)
rolling	ϕ	±2°～3°

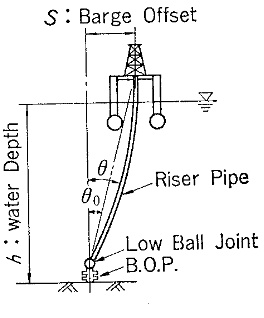
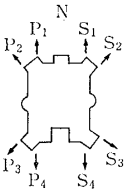


Fig. 9 Barge offset

Table 7 Motion in rough sea of HAKURYU 2 off Noshiro City (moored condition)

date	wind speed	wind directn	atmos. press-ure	wave height	offset	rolling	pitching	heaving
					y' ※	ϕ	θ	Z
12/1 14	m/sec 29	W	mb 997.8	7 m	2 %	1°	1°20′	1.7 m
16	31	W	998	8	2	1°30′	2°30′	2
18	30	W	999.5	9	2	1°30′	2°30′	2.2
20	32	W	1000	9	3.3	1°20′	2°	2.5
22	34	NW	1000	10	3	2°	2°	3.2
23	38	NW	1000	10	3	2°	2°	3.2
24	34	NW	1001.5	11	—	3°	2°10′	4
12/2 1	34	NW	1003.2	8	—	2°10′	2°20′	4
2	32	WNW	1003.8	9	—	2°10′	2°10′	4
3	26	WNW	1004.5	9	—	2°10′	2°20′	3.5
4	31	NW	1004.7	9.5	6.8	2°30′	2°	4
5	31	NW	1005.8	10~13	10	2°50′	1°50′	4.5
6	29	NW	1007.7	13	10	2°40′	2°	5
7	30	NW	1008.8	12	10	2°30′	2°10′	6

※ y' = offset/water depth × 100



corresponding to those in Table 6, some of the S/S rigs built overseas have been specified for θ to be 9% of the water depth as the evaluation criteria in storm.[1] HAKURYU II has encountered with a typhoon of an average wind velocity of 30 m/sec. lasting 15 hours during operation off Noshiro. Table 7 shows the record taken at that time giving the barge offset as about 10% of the water depth. In general, there care less data of field measurements available for displacements in storm. The correlations between the variation in wind velocity and the rolling angle and between the wind velocity and the horizontal motion, etc., in such an offset condition should be observed in detail in future for establishing the proper evaluation criteria in storm.

As described above, the first stage of the realization of the basic design will be completed when the concept of the configuration of an S/S rig has been composed to satisfy V.D.L. for possible operation within its design conditions, the limits of Z, ϕ, (θ) and S as shown in table 6, and the limitation in air gap $\bar{\delta}$ as specified in the classification rules. Nevertheless, it should be recognized that the necessary conditions and criteria for the S/S rig have only been satisfied, which seem to be yet incomplete to cover the drilling operation. Accordingly, it can well be said that the S/S rig has reached a stage for its review by means of statistical probabilism in one way or another.

3. Sufficeint Condition in Realization of Basic Design

As described in "Introduction," the author considers the following three factors to be the sufficient conditions that have been deduced to date from the experience of construction and operation of S/S rigs:

1) High workability in a wide sense.
2) Security of structural integrity of floating body.
3) To be of a type of structure for easy construction.

3.1 *Review of Workability in a Wide Sense*

When reviewing the workability in a wide sense, the S/S rig must be recognized for its superiority in the following two conditions:

(1) Operating Condition
  a) Minimum motion in waves.
  b) Sufficient stability in wind and waves.
  c) Capability of positioning within limits.
(2) Severe Storm Condition
  a) Sufficient air gap.
  b) Not to be overturned in waves.
  c) Capability of positioning to some extent.
  d) No structural failure.

The condition (1) is the operating principle of S/S rigs, while the condition (2) means the operation in a 100-year storm in a wide sense. Both are important subjects for reviewing the workability. Needless to say, the workability depends greatly on the motion characteristics in waves during operation. Also, from the concept of lamp sum operation, other important items to be reviewed include propulsion efficiency in transit condition, dynamic stability in all conditions of S/S rig, quality of the crew, layout and performance of equipment on board. In planning an S/S rig for global operation, points to be noted will be discussed hereunder, deducing from the operating records, with respect to its motion in waves, stability, propulsion efficiency and positioning which can be treated by the shipyard engineers.

3.1.1 Weather Down Time

S/S rigs have sufficiently been studied on their superiority in motion in waves by computer simulation and tank test,[7),8)] but, unexpectedly, little on the agreement of their results with those of the full-scale measurements.[9),10)] This is probably because of too few encounters of S/S rigs with storms in survival condition, for example, to obtain sufficient data therefor. Fig. 10 shows a good agreement between the computed values and the regularly recorded data by HAKURYU V using the MUSE-CDMT system during operation off Miyako Island, in which the dimensionless values corresponding to $T=2\pi\cdot m_2/m_1=3.86\sqrt{H_{1/3}}$ have been plotted. Nearly the same tendency is shown in the recorded data[9)] by HAKURYU II, which suffices to predict the superiority of the S/S rig in workability in waves. Table 8 shows a very little weather down time of HAKURYU V from its operating record. This value may be considered a probability for a long term down time. The practicability of the configuration selected for HAKURYU V has also been verified by Hamett, SEDCO,[2)] that showed its one-year down time of as low as 2% or 8 days due to waves, winds, floes and tidal currents during operation off the west coast of Canada. In this connection, the wave occurrence distribution chart off South Aftica prepared by Hogben and Lumb was used in an assumption that the motion response in waves would follow the Rayleigh distribution to obtain the probability of short term probability distribution of motion beyond $Z_0=1$ m, $\phi_0=2°$ and $\theta_0=2°$ by Eq. (2), as shown in Table 9.

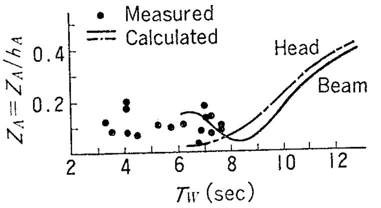


Fig. 10 Heaving (HAKURYU-V)

Table 8 Weather downtime (HAKURYU V)

location	latitude londitude	duration of drilling		operation days	down time	%
		beginning	end			
off SOYA	45° 29′ 31″ N 141° 12′ 34″ E	1979. 7. 1	1979. 9. 19	days 81	days 5/24	0. 3
off FUKUE	33° 18′ 02″ N 128° 20′ 44″ E	1979. 11. 2	1980. 3. 22	142	1	0. 7
mouth of Sinano-river	38° 00′ 36″ N 139° 02′ 44″ E	1980. 3. 28	1980. 10. 7	194	0	0. 0
off Sin-Yoneyama	37° 22′ 27″ N 138° 23′ 50″ E	1980. 10. 8	1980. 12. 4	58	3	5. 2
Off Miyako island	24° 46′ 20″ N 125° 41′ 50″ E	1980. 12. 15	1981. 3. 13	89	3/24	0. 1
Balesin	14° 24′ 10″ N 121° 57′ 15″ E	1981. 3. 18	1981. 4. 22	36	0	0. 0
Off Kita-Yoneyama	37° 20′ 44″ N 138° 25′ 49″ E	1981. 5. 7	1981. 6. 21	46	5/24	0. 5
				days Σ646	days 4-13/24	0.7%

Table 9 Probability of occurrence of weather down time (long term)

(1) heaving

Z_o	$p(Z>Z_o)$
0. 8m	3. 3%
1. 6	0. 9
2. 0	0. 5
3. 0	0. 2

$Z_o=\pm 1$ m

(2) pitching

θ_o	$p(\theta>\theta_o)$
0. 4°	9. 7%
0. 8°	1. 2
1. 2°	0. 2

$\theta_o=\pm 2°$

(3) rolling

ϕ_o	$p(\phi>\phi_o)$
0. 4°	14. 3%
0. 8°	2. 0
1. 2°	0. 4

$\phi_o=\pm 2°$

$$\left.\begin{array}{l}\text{Vertical Motion:}\\ \qquad p[z>z_0]=\exp\left(-z_0^2/2\sigma_z^2\right)\\ \text{Rolling:}\\ \qquad p[\phi>\phi]=\exp\left(-\phi_0^2/2\sigma_\phi^2\right)\\ \text{Pitching:}\\ \qquad p[\theta>\theta_0]=\exp\left(-\theta_0^2/2\sigma_0^2\right)\end{array}\right\}\quad(2)$$

where σ_z, σ_ϕ and σ_θ are the standard deviations from their respective responses, and the wave spectrum are indicated in accordance with ISSC. A comparison between Tables 8 and 9, both of which are shown in nearly the same order, suggests that the introduction of the statistical probabilistic concept to the realization of the basic design as a guidance would be meaningful.

3.1.2 Review of $\bar{k}$ Value on Righting Moment Curve

The IMCO integrated rules on drilling unit specify the area ratio indicating the dynamic righting moment. to the wind heeling moment by Eq. (3) on the righting moment curve shown in Fig. 11.

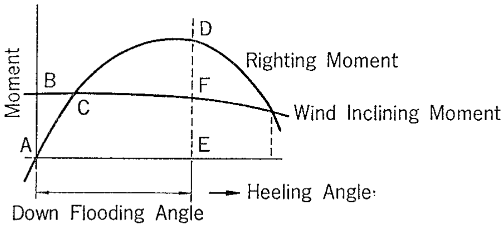


Fig. 11 Righting moment curve

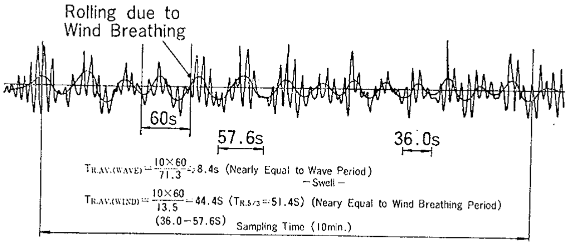


Fig. 12 Rolling histogram of HAKURYU III off NIIGATA City

$$\bar{k}=\frac{\text{Area ACDFE}}{\text{Area ABCFE}}\geqq 1.3 \qquad (3)$$

The reasonableness of $\bar{k}=1.3$ has been discussed by ASME members.[11),12)] The value of $\bar{k}$ can be induced from Eq. (4) of rolling motion under wind pressure to Eq. (5).

$$I\ddot{\varphi}+C\dot{\varphi}+M_r(\varphi)=M_{ext}(t) \qquad (4)$$

where

I: apparent inertia moment of floating body
C: damping moment per unit angular velocity
$M_r(\varphi)$: righting moment at an inclining angle φ
$M_{\mathrm{ext}}(t)$: wind helling moment

Integrating Eq. (4) from $\varphi=0$ to φ_1 and assuming the actual rolling motion as a periodical motion up to $\pm\varphi_1$ with the original point as center,

$$\bar{k}-1=\frac{(1/2)I\dot{\varphi}_0{}^2-a}{A_e} \qquad (5)$$

where $\bar{k}=A_r/A_e$, in which A_r is the area from 0-φ_1 within the righting moment curve; A_r, the area from 0-φ_1 of wind heeling moment; and a, the damping energy. Acting favorably on $\bar{k}$ value, a is ignored in this consideration. HAKURYU III has recorded rolling motion during operation off Niigata (refer to Fig. 12) and obtained Eq. (6) from its wave shape.

$$\varphi=0.013+0.026\sin\frac{2\pi}{51.4}t \quad \text{(rad)} \qquad (6)$$

By substituting I and A_e obtained from the displacement and righting moment curve in Eq. (5), $\bar{k}=1.37$ is obtained. In the same manner, from the record of Typhoon Vera off Taiwan encountered by HAKURYU II, $\bar{k}=1.13$ is obtained by assuming its rolling motion by Eq. (7).

$$\varphi=0.02+0.11\sin\frac{2\pi}{45}t \quad \text{(rad)} \qquad (7)$$

Although these calculated results suggest $\bar{k}\geqq 1$, it is not yet clear whether it is sufficient or not. In particular, since these results have been based on the records of typhoons of about 20 m/sec. of mean wind velocity and 70 m/sec. of instantaneous maximum wind velocity, it is considered necessary to accumulate more full-scale measurement data for further review.

3.1.3 Propulsion Efficiency

The trend of S/S rigs toward global operation has accelerated the need for speedier arrival at site for drilling to cope with the faster navigation of their rival drilling vessels. Thus, emphasis has been placed on the propulsion efficiency of S/S rigs, and an idea of building a mini-S/S rig capable of passing through the Panama Canal was once put into action, but brought to an unsuccessful end due to failure of making full use of the characteristics of the S/S rig. However, the consequence has provided an opportunity for reviewing the configuration of the submerged portion of the S/S rig from the viewpoint of propulsion resistance. Fig. 13 shows the changes of the lower hull configuration of HAKURYU series which aimed at a minimum towing resistance as well as at easy construction and defect-free joints. The towing data in Table 10 suggest the curse of progress made by such engineer-

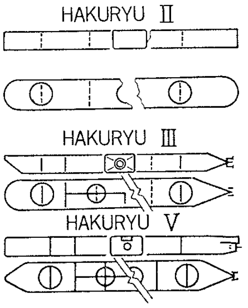


Fig. 13 Historical change of lower hull in HAKURYU series

Table 10 Towing data of semi-sub

	name of rigs	type	fig of transit.			H. P. Needed	data of transit.		
			draft/▽	s	fig		day	distance	speed
1	SEDCO 135E 105.9×103.6 ×50.6	3 caisson tooting型	7.5(0.4) /10,900	m² 412	afloat by footing	9,600 BHP	days 92	Hiroshima s Australia 5,700NM	3.1 (6.3)
2	Ocean Prospecter 104.3×80.3×38.4	4 lower hull	7.2(0.5) /13,900	184	afloat by L.hull	SHP 5,400 + BHP 3,600	6	Hiroshima s Hamada 650NM	4.5
3	Hakuryu Ⅱ 84×61×31	2 lower hull	5.4(0.5) /9,900	118	do.	BHP 3,600 + 4,000 + 4,000	9	Hiroshima s Akita 1,200NM	5.4 (7.3)
4	Ocean KOKUEI 97.5×81.1×31	4 lower hull	8.9(0) /14,460	LH 229 ca 84 313	afloat by L.hull footing	※ 7,000 SHP + 17,000 IHP	Ca 100	Hiroshima s North Sea 15,000NM	6.0
5	Hakuryu Ⅲ 101×67×35	2 lower hull	6.7(0.6) /14,600	150	afloat by L.hull	IHP (4,750 IHP 5,000) (Parallel)	4	Hiroshima s Joban 750NM	8.7 (13.5)
6	Ocean Bounty 107.4×81.1×39	2 lower hull	10 /18,750	420	semi sub	IHP 14,000	60	Hiroshima s Alaska 5,500NM	Ca 4.0
7	Hakuryu Ⅴ 104.5×67×35	2 lower hull	6.8 /15,600	160	afloat by L.hull	13,000	6	Hiroshima s Hachinohe 940NM	Ca 8.0

※ self propulsion

ing efforts. In the table, SEDCO 135E and HAKURYU II were by simple towing and HAKURYUs III and V, by propeller assisted towing.

Future problems to be solved will be focussed on how to reduce resistance of the rectangular section of lower hull that has been specially selected for easy construction in shipyard, as close to that of the circular section as possible, and on how and to what extent the factors causing higher resistance at nodes of members could be eliminated at the time of realization of the basic design. In addition, it is desired to reduce wind pressure to be applied on the upper structure above water line and tendency of causing higher resistance of the leg in waves due to small freeboard of the lowerhull during towing, etc., by improving their respective configurations.

3.1.4 Positioning

The vertical displacement of an S/S rig in waves can be solved by selecting a wave-free form. For horizontal displacement due to tidal current, wind and wave drifting force, a chain (wire)-anchor (sinker) combined mooring system or a dynamic positioning system (D.P.S.) must be used to observe the operation criteria given in Table 6. Security of safety of the mooring line will require a correct understanding of the line motion by the dynamic analysis method. For this purpose, it is important to review the items including sea and weather conditions, seabed soil, etc., at the time of realization of the basic design. Tables 11 and 12 show the design condition of the mooring system for MD 602 and an example of seabed soil condition in the operating areas of HAKURYU series. For HAKURYU II that operated in an area of rapid tidal current off Chi-lung, Taiwan, careful measures had been taken by additionally installing pile anchors, etc. Nevertheless, its encounter with Typhoon Vera that exceeded the design condition resulted in only leaving a record of 6

Table 11 Design condition of mooring system (MD602)

condition of rigs	draft m.	wind velocity mean value of one min. m/sec.	current kn	wave height m	wave period sec.
normal operation	20	15.0 (12.8)*	2.0	6.0 (3.0)**	10
operation	20	25.0 (21.3)*	2.0	12.0 (6.0)**	12
stand by	20	36.0 (30.6)*	2.0	18.5 (9.3)**	14
survival	16	51.5 (43.8)*	1.0	33.5 (16.8)**	15

(注) * mean value of 10 minutes observation data
** significant wave height

Table 12 Some example of sea bed cond.

name of rigs	location	water depth m	sea bed condition	density γ (g/cm³)	cohesion C kg/cm²	int. fric. angle ϕ	1-axial comp. st. q_u(kg/cm²)
Hakuryu Ⅲ	off Kashiwa-Zaki 1977, Apr.	134	Clay sand loam	0.713 0.976	0.25 0.33	1° 2°30′	0.32 0.21
do.	JD Z-W-I 1980	81	clay sand	0.83	0.03	2°50′	
Hakuryu Ⅴ	off Tera-domari 1978, Sept.	126	clay silt	0.82	0.24	12.9°	
do.	off Miyako isl. 1980, May	286	coral sand	0.838	0.375	36.67°	

cut chains out of 8 and being drifted away about 2 miles in the direction of 320° from the original direction. Such an accident has revealed the significance of a detailed operation manual to be provided for a mooring system by sufficiently studying the changes of sea and weather conditions and seabed soil, in addition to the careful selection of design condition.

3.2 *Review on Structural Integrity of Floating Body*

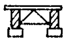
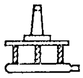
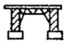
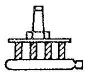
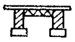
Since the failure of the A. L. Kielland, the structural integrity of a floating body has strongly been taken up as a great problem, which is substantially a fundamental proposition to its frame work not to be collapsed under survival condition. The achievement of this means 100% workability without down time, as discussed in 3.1.1. According to the records of HAKURYU series, the rigs drilled an average depth of 3,305 m/hole in 79.8 days, during which they had to be positioned stationary resisting repeated force of waves. This is considerably a severe condition for a floating structure. Therefore, the security of structural integrity in such environment will give the user a sense of relief for its operation, indirectly guaranteeing its high workability.

Among various items to be materialized for prevention of structural failure, such as types of frame work, external forces, allowable stresses, material, joint configurations, etc., the type of frame work and their application will be discussed in this section as picking up problems in their basic planning.

(1) Evaluation of Type of Frame Work

Table 13 Frame figure of semi-sub

up to 1981 end.

	long.	trans.	typical rigs	no.	remarks.
1	rahmen		HAKURYU V, Ⅲ SEDCO 700	18	double warren
2			AKER H-3 OCEAN ODYSSEY	26	single warren
3			AFORTUNADA BLUE WATER No. 3	5	knee brace
4			MARGIE OCEAN SCOUT	5	truss
5			OCEAN PROSPECTOR SEDCO STATFLO BLUE WATER	12 2	rahmen
6			PENROD 70 MARINER	8	do.
7			C JEAN QUEEM	4	
8	rahmen/brace 		PACESETTER HAKURYU Ⅱ	15	rahmen with brace
9	truss	3 	SEDCO 135~135G (open well)	7	truss
10		3 	SEDCO 135H~ (center well)	4	do.
11		5	PENTAGONE	10	truss
12	vessel		TRANSWORLD RIG 61	1	with sponson
13		mis-cellaneous		2	
14		not clear		10	

The type of frame work of S/S rigs can largely be divided, as shown in Table 13. Fundamentally, they fall into (a) truss structure, (b) Rahmen structure and (c) Rahmen structure with braces. The truss structure contributes to weight reduction, but is liable to cause a total-loss accident originated from damage in a member or a joint. It consists of so many joints that are often difficult to be welded. Thus, the truss structure is not advantageous for the S/S rig that is subject to repeated wave force for a long time. There are two types of Rahmen structure: one comprising both longitudinal and transverse sections with Rahmen structures, and the other with reinforced broces only in the transverse section. Either type of Rahmen structures cause no problem in the longitudinal direction (of an S/S rig) because of its great rigidity of legs and lower hulls which characterize the S/S rig. In the transverse direction, however, reinforced braces are often required as in HAKURYU-III and V due to difficulty in obtaining ample rigidity. In general, the Rahmen structure tends to increase weight in comparison with the truss structure. The trussed Rahmen structure has a so-called high rigidity ratio of brace to leg members with rigid joints at the truss ends which develops sufficient rigidity against rotation. Furthermore, the presence of braces will be able to increase the final plastic strength.[12] Therefore, it has an effect of reducing the possibility of a total loss propagated from a slight damage in a part of a structure of an S/S rig and that with capability of constructing its frame work in sufficient strength using steels weighing

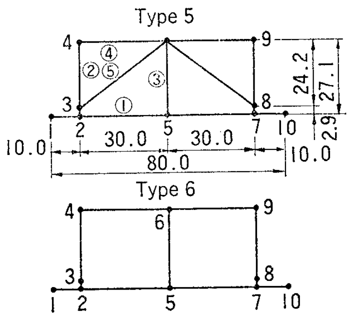


Fig. 14a Longi. section of semi-sub

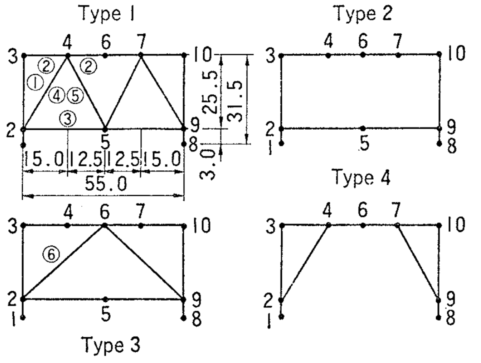


Fig. 14b Trans. section of semi-sub

Table 14 Weight comparison table of various kind of frames (See Fig. 14)

TYPE of FRAME / LOCATION	1	2	3	4	5	6
MAIN DECK	A=1,233㎠ l =25m A=618 ㎠ l =30m W=39t	A=1,261㎠ l =55m W=54t	A=3,690㎠ l =55m W=159t	A=8,748㎠ l =55m W=378t	A=1,261㎠ l =60m W=59t	A=1,310㎠ l =60m W=62t
VERT. BRACE	A=1,028㎠ l =29.6 m ×2 W=48t	A= 827㎠ l =37.5m ×2 W=49t		A=6,161㎠ l =29.6m ×2 W=286t	A=863㎠ l =38.5m ×2 W=52t	
VERT. BRACE (IN)	A=532㎠ l =28.4m ×2 W=24t					
HORI. BRACE	A=1,259㎠ l =55m W=54t	A=1,492㎠ l =55m W=64t	A=3,627㎠ l =55m W=157t (111t)			
CORNER COLUMN	A=4,816㎠ l =31.5m ×2 W=238t	A=4,816㎠ l =31.5m ×2 W=238t	A=6,094㎠ l =31.5m ×2 W=301t	A=6,804㎠ l =31.5m ×2 W=336t	A=4,248㎠ l =27.1m ×2 W=181t	A=4,106㎠ l =27.1m ×2 W=175t
INNER COLUMN					A=3,777㎠ l =27.1m W=80t	A=4,155㎠ l =27.1m W=88t
LOWER HULL					A=7,714㎠ l =80m W=484t	A=9,594㎠ l =80m W=602t
TOTAL	403t	405t	617t (571t)	1,000t	856t	927t

※ ( ) :weight with 2.7mϕ horizontal blac. instead of 1.8mϕ.

almost equal to those for the truss structure. A two dimensional analysis was performed under the same loaded condition on the cross section (Model 1) and the longitudinal section (Model 5) in Fig. 14b and a by giving the changes of Models 2-4 to the former and the change of Model 6 to the latter. The results showed increases in weight for Models 2, 3 and 4 by 1.0, 1.52 and 2.48 times that of Model 1, respectively, and for Model 6, by 1.08 times that of Model 5 (Table 14). From this, the effect of weight reduction of the trussed Rahmen structure is recognized. For integrated evaluation, an accurate comparison will be required including not only weight of steel but also difficulty in assembling joints, manufacturing cost, etc., with L, B and D of an S/S rig, as parameters. The effect of braces in the longitudinal section is very small, as shown in Models 5 and 6. However, since the horizontal force acting on braces is varied depending on the number, spacing, diameter and height of legs, it is considered that the need of braces should be studied according to the type of frame work at the time of realization of the basic design.

(2) Treatment of Frame Work in Waves

From the observation of member response in waves, the structure was treated as a hyporigid body to analyze the motion response in waves. Further, using the result of that analysis, the member force was obtained by treating the overall structure as an elastic body and the structural response, by the beam theory or the shell theory. An attempt was made to obtain deformation at each nodal point in Fig. 15a and b of of MD-502 under standby condition and the results are shown in Table 15a and b. The nodal points 37–68 and 110 correspond to the points B and A in fig. 15c, respectively. Their small amplitude of deformation by wave force can prove the correct assumption of a hyporigid body in wave response.

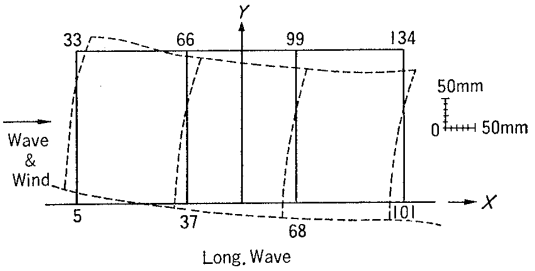


Fig. 15a Deformation of longi. frame under stand by condition

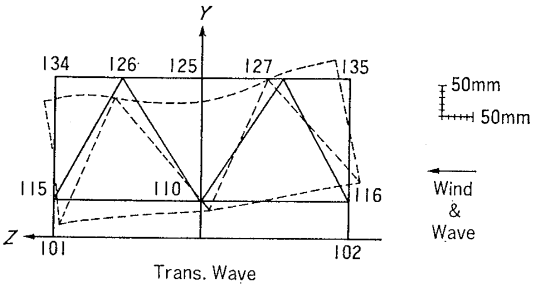


Fig. 15b Deformation of trans. frame under stand by condition

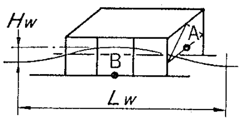


Fig. 15c Modeling of semi-sub

Table 15a Deformation of Longi. frame at stand by cond. (m/m)

$H_W=18.5\text{m}$, $T_W=11\text{sec}$

	no. node \ phase	$\psi=76°$		$\psi=172°$		$\psi=258°$		$\psi=330°$		deformation※	
		X	Y	X	Y	X	Y	X	Y	X	Y
portside frame section	1	−22.1	60.5	−19.0	60.2	−16.8	61.5	−20.6	59.3	2.8	1.1
	5	−21.9	26.2	−19.0	28.0	−16.7	25.3	−20.4	23.5	2.8	−6.8
	33	28.6	23.4	18.3	24.0	18.4	20.7	21.6	19.8	−3.4	−3.7
	37	−21.6	−9.8	−18.8	−4.6	−16.2	−10.1	−19.4	−12.7	2.8	4.7
	66	26.0	−11.6	16.6	−7.3	15.8	−12.5	20.4	−14.5	−3.9	4.2
	68	−21.1	−25.5	−18.5	−23.2	−15.8	−28.5	−18.1	−28.0	2.6	3.1
	99	23.3	−27.9	15.0	−26.3	12.9	−30.7	20.0	−29.6	−4.9	2.3
	101	−20.7	−28.4	−18.3	−29.9	−15.3	−27.6	−17.0	−25.8	2.5	−2.0
	134	21.2	−31.2	13.7	−32.4	10.3	−29.1	20.1	−27.3	−6.1	−2.4
	138	−20.8	−37.3	−18.4	−40.3	−15.2	−33.3	−16.9	−34.3	2.6	3.0

※ small amplitude of deformation by wave force from the mean value of X, Y.

Table 15b Deformation of Trans. frame at stand by cond. (m/m)

$H_W=18.5\text{m}$, $T_W=11\text{sec}$

		$\psi=74°$		$\psi=169°$		$\psi=260°$		$\psi=339°$		deformation※	
		Y	Z	Y	Z	Y	Z	Y	Z	Y	Z
after frame section	101	−37.6	−12.4	−40.5	−20.9	−39.1	−7.2	−36.1	2.7	−2.9	−11.8
	102	35.2	−30.8	37.8	−18.4	36.6	−28.7	34.1	−43.4	2.3	11.0
	110	−16.2	−12.1	−11.1	−12.5	−17.3	−11.5	−22.4	−11.5	5.8	−0.6
	115	−38.1	−7.0	−41.0	−12.5	−39.3	−5.0	−36.2	3.6	−2.4	−7.3
	116	34.8	−18.2	37.0	−12.0	35.8	−17.8	33.5	−27.6	1.8	6.9
	125	−33.7	21.9	−29.0	18.8	−33.5	19.7	−39.8	21.2	5.0	−1.6
	126	−31.1	18.9	−29.3	17.4	−33.4	16.6	−36.0	19.1	−3.2	−1.4
	127	−1.7	23.5	4.6	19.8	−0.9	21.2	−8.0	22.4	6.1	−2.0
	134	−40.2	18.7	−43.2	18.0	−40.7	15.0	−37.5	19.6	−2.8	−2.8
	135	31.6	24.9	32.9	18.2	31.5	21.2	29.6	22.5	1.4	−3.5

※ small amplitude of deformation by wave force from the mean value Y, Z.

The equation of motion of a floating structure under wave exciting force can generally be expressed by Eq. (8). In calculating the workability in irregular waves and the air gap, as described in 3.1, by Eq. (8)′ of linearized Eq. (8), a frequency response function obtained by giving very small amplitude waves to its right side will be used. While, in a structural calculation, finite amplitude waves will be introduced to meet the most severe survival condition.

$$\overbrace{\sum_{k=1}^{6}[(M_{jk}+A_{jk})]\ddot{X}_k}^{\text{Inertia force term}} + \overbrace{B'_{jk}\dot{X}_k}^{\text{Wave making damping force term}}$$

$$\overbrace{+B''_{jk}(\dot{X}_k-\tilde{u}_k)|\dot{X}_k-\tilde{u}_k|}^{\text{Viscosity damping force term}} \overbrace{+C_j(X_1,X_2,\cdots,X_3)}^{\text{Restoring force term}}$$

$$\overbrace{+G_j(X_1,X_2,\cdots,X_6)}^{\text{Mooring system reaction term}} = \overbrace{F_{ej}}^{\text{Wave exciting force}} \qquad (8)$$

Noting that the heaving motion of an S/S rig is less related with other components of motion, Eq. (8) is simplified and linearized, as jollows:

$$(M+m)\ddot{z}+(N+D)\dot{z}+kz$$
$$=F^{FK}+(m\ddot{\xi}_\omega+N\dot{\xi}_\omega) \qquad (8)'$$

where

M_{jk}, A_{jk}, (M, m): mass of floating body and added mass in wide (narrow) sense.

B'_{jk}, B''_{jk}, (N, D): general form of wave making and visious damping coefficients (in narrow sense).

C_j, G_j, (k): general form of restoring force and mooring system reaction coefficients (in narrow sense).

$X_{i(1-6)}$: displacement of the center of gravity of floating body.

Z: vertical displacement.

$\bar{u}_k$: mean value of wave particle velocity component.

ξ: orbital radius of wave particle.

F_{ej}: general form of wave exciting force

F^{FK}: Froude-Krillof's force.

Since there is no directly effective solution of the motion in non-linearized waves, the linearized solution of Eq. (8)′ is taken as the first order approximation, in which the motion is converged in the time domain, to study the structural response. Using this method, a comparison is made between the calculated values of stress at the lower flanges of the main girder on the underside of the deck of HAKURYU V (Positions ST_1 and ST_2 in Fig. 16a) and the discrete observation data by MUSE-CDMT corrected by the regular visual observation data and the irregular observation data for spectrum analysis by MEM (maximum entropy method) during its operation off Miyako Island. In the former, the stress per maximum wave height H_w is given by Eq. (9).

$$\sigma/H_w=45\ \mathrm{kg/cm^3}/4.0\mathrm{m} = 11.25\ \mathrm{kg/cm^3/m} \qquad (9)$$

In the latter, 10.1 kg/cm²/m and 13.5 kg/cm²/m have been obtained, which may be considered to prove the reasonableness of the hypo-rigid body as previously assumed. The waves treated in these observation data are still too small, as shown in Fig. 16b. The author is of the opinion that efforts should be made to verify that the assumption of the hypo-rigid body is reasonable by observation data in very high waves in the future.

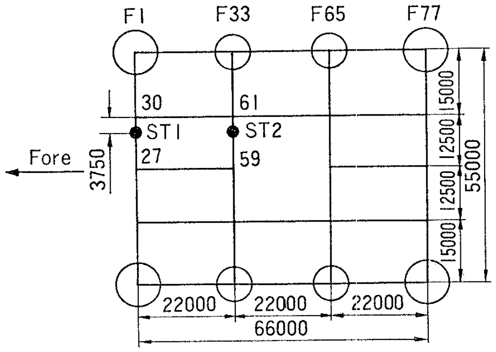


Fig. 16a Schema of plan of HAKURYU V (in mm)

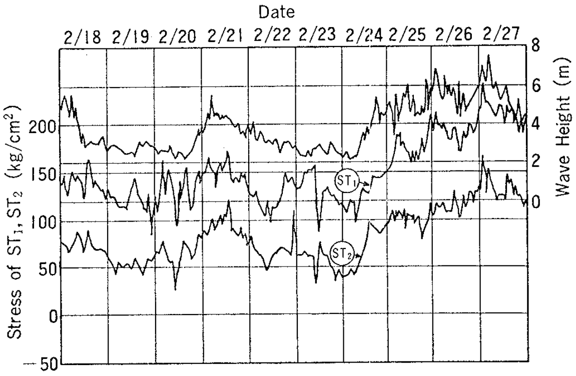


Fig. 16b Histogram of stress obtained by MUSE system at ST1/ST2

3.3 *Review of Type of Structure for Easy Construction*

Mutually satisfying condition for both users and builders of S/S rigs has been deduced from repeated experience of failure during construction of S/S rigs in the 1960s and early 1970s and from the concept of cost reduction. The Accident Investigation Committee of the A.L. Kielland has proposed in its report[14] that the entire frame work should have redundant strength, pointing out the following three problems leading to a possible total loss:

(1) Improper frame work.
(2) Stress concentration at joints.
(3) Hair cracks occurring during operation or construction.

These items may also be said as if referring to rational measures to be taken for a type of structure easy to be constructed. The problem (1) is derived from the difficulties in positioning components of a space frame structure to be assembled and in holding the correct shape. Special consideration should be given at the time of basic designing to a single diagonal member to be incorporated in one plane block or the other three-dimensional block to avoid its inherent inconvenience in fabrication and to higher reliability of joints of members concentrating at one node which should be reduced to a minimum. Therefore, the term "simple construction" is appropriate for the fundamental concept of the frame work to be required from the construction point of view at the time of basic designing. The change from the three-dimensional truss structure to the Rahmen structure (from SEDCO 135A to SEDCO 710) and the change from the open well structure to the center well structure are good examples of simplification.

The Problem of stress concentration in Joints in (2) occurs in column-column fillet welded joints or full penetration welded joints. It also includes decrease in fatigue strength due to misalignment caused by difficulty in construction and stress concentration due to extreme discontinuity which should be eliminated at the time of basic designing for safer operation. Selection of proper types of joint and material will be effective to avoid such a problem. Rational measures having been taken for this purpose are the box-type joint[9] applied to HAKURYU II, the use of rectangular section for the lower hull, as shown in Fig. 13, and the insertion of lamellar-tear resistant steel, etc.

In general, the damage factor of the Minor's law of accumulative damage is given by

$$\eta=\sum_{i=1}^{S}\left(\frac{n_i}{N_i}\right) \tag{10}$$

where

S: number of block divisions of long term stress distribution.
σ_i: stress corresponding to each block
n_i: number of cycles of actual stress σ_i
N_i: number of cycles of causing fracture at σ_i

In 1981, D.N.V. suggested its concept of fatigue strength by specifying $\eta=0.1$ for 20-year stress accumulation. If the stress distribution is assumed to follow the 2-parameter Weibull distribution,

$$\eta=n\cdot\frac{(2\sigma_{\max})^{k'}}{a}\cdot\frac{\Gamma(k'/h+1)}{(\ln n)^{k'}/h} \tag{11}$$

where

n, h: Weibull's parameters.
a, k': values obtained from S-N curve of AWS.

Assuming that the S-N curve complies with the modified X-curve of AWS with special consideration given to the wave direction, the spreading factor α' of actual waves coming from all directions at the same probability will be considered for η in Eq. (11). Thus, the final damage factor η' will be expressed by $\eta'=\alpha'\cdot\eta$. The value of α' will be given 1/2–1/4 depending on the position of the S/S rig with respect to its heading angle to waves. In calculating η, the stress concentration coefficients to be used depending on the type of joint are 2.0 for the box-type joint and 2.5 for simple joints of brace to brace and main-deck to brace. The values for joints of HAKURYU V and MD series obtained according to such a process show approximately in agreement with those required by D.N.V. Whether or not $\eta=0.1$ falls into the sufficient condition will remain to be further studies. From the fact that 16-year-old SEDCO 135A and 10-year-old Ocean Prospector and HAKURYU II, as shown in Fig. 1, are still in satisfactory operation, it may be concluded that attention given at the time of realization of the basic design would be able to greatly prevent fatigue failure.

The problem of inspection for hair cracks in (3) has suddenly been brought to light since the total-loss accident of the A. L. Kielland. A number of circular columns constructing an S/S rig prevent the inspectors from easily entering into the column and performing nondestructive inspection of the joints. The selection of location and configuration of each joint clearly contributes to easy performance of such inspections. In this respect, the box-type joint of simple configuration applied to the HAKURYU series is connected with the other components through their stiffeners to provide ideal flows of stresses. In future, a more simplified and highly reliable joint that would make possible its regular inside inspection should be developed as a means to prevent hair cracks.$^{15)}$

4. Conclusions

The theme given to this paper is the creation of an offshore drilling unit of the concept of a "semi-submersible" floating structure that would be capable of operating even in waves as well as a land structure should be on land. For the purpose of its basic design, the main items of both necessary and sufficient conditions have been described with their backgrounds and the various problems presented by reviewing the data of construction and operation of S/S rigs planned, designed and/or constructed by Mitsubishi Heavy Industries, Ltd. As a result, it has been made clear that both necessary and sufficient conditions still require a great deal of further studies due to lack of data in a short history of S/S rigs. The sufficient condition, in particular, has been obtained in this present stage and possible changes in the items to be emphasized in future will be well anticipated. However, the fact that the excellent operation records of the HAKURYU series that had been carefully planned under such necessary and sufficient conditions are being presented at least suggetss the reasonableness of the author's concept.

In connection with the techniques to be used in the course of realization of the basic design of an S/S rig, the following concepts are being developed:

* From static analysis to dynamic analysis.
* From the use of the idea of deterministic theory to statistic probability theory.
* From linear analysis to non-linear analysis.
* From consideration for safety to redundant strength of the structure.

Therefore, more operation data observed on site must be collected until the completion of a rational S/S rig. The feedback of its results will contribute to the progress of the realization of the basic design of an S/S rig.

This paper is an excerpt of the conditions to be considered at the time of the study of realization of the basic design of an S/S rig from the thesis for a degree, "Study on Realization of Basic Design of Semi-submersible Offshore Drilling Unit," presented to the University of Tokyo.

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