◉ Technical Paper

An Improved Structural Analysis Method for Ocean Transportation of Marine Structures

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해양구조물의 해상 운송을 위한 개선된 구조 해석에 관한 연구

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Key Words : Sea-Transportation(해상운송), Marine Structures(해상구조물), Inertia Loads(관성력), Stochastic(스토케이틱), Motion Response(운동응답)

초 록

본 논문은 해양구조물 중 특히 자켓이 부선에 설치되어 운송되는 시스템에 대한 개선된 해상 운송 해석에 대한 고찰이다. 해석 방법의 개선은 파력에 의해 발생되는 부선 운동에 따른 관성력의 추계적 처리에 기본을 두어 얻어지고 있다. 이 방법은 소위 말하는 강체 부선 방법과 연체 부선 방법의 중간적이라고 할 수 있으며, 두가지 방법의 단점을 보완하였다. 전형적인 자켓-부선 시스템에 대하여 유한요소법을 이용하여 모델링한 후 본 해석 방법을 적용하여 해상 운송 해석을 수행하였으며, 자켓-부선간 반력을 구하여 기존의 방법과 비교 검토하였다. 본 방법은 현실적이고 효과적임이 증명되었다.

1. Introduction

There are two important items in the transportation analysis of offshore platform. One is whether the platform/barge system can complete the trip to the installation site without the capsizing etc., and the other is whether the platform and the barge suffer any major structural failures during the transportation. From a structural point of view, major efforts have been devoted to the structural safety of the platform and seafastenings. As the sea transportations, however become frequent and the transported objects become various

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in size and sort, it has been recognized, especially in economic sides, that the range of the barge usages should be enlarged over the range which was considered in the initial design level and, consequently, the as-built barge needs to be checked against the more severe design criteria than that which was considered initially. Together with these efforts, more sophisticated analysis techniques are being developed to perform more realistic transportation analysis.

The transportaion analysis by the so-called Rigid Barge Method, which has been used in case of the relatively small jacket, is often criticized as being too conservative. On the other hand, recently, the so-called Flexible Barge Method is used for the transportation analysis of very large jacket. But this method requires a lot of computational procedures and efforts [1].

In this study, a procedure is suggested, which can be considered to be an intermediate method of the Rigid Barge Method and the Flexible Barge Method.

In this procedure, although the barge is assumed to be rigid, the inertia loads due to the barge motion are stochastically treated instead of being treated as semi-deterministic.

In the following sections, the procedures of the Rigid Barge Method and Present Method are described. And, through the case study of San-Miguel jacket transportation, the results by two different methods are compared.

2. Analysis Procedures

In the following, the computational procedures of the two methods are described. Although the procedures are, presently, confined to the calculation of the jacket/barge interaction forces, they can be easily applied to the calculation of the jacket stresses during transportation.

2. 1 Rigid Barge Method

This method can be classified semi-deterministic because of its similarity to the design wave approach in the inplace analysis of the platform and has been widely used in the transportation analysis, especially for the relatively small sized platform.

This procedure consists of the following steps.

STEP 1 Define a sea state corresponding to the maximum expected storm for a given return period.

STEP 2 Predict the maximum motion responses of the platform/barge system in all 6 degree-freedom for the design sea state.

The maximum responses can be predicted from the significant responses by application of the following relationship[2].

$$R_{max} = R_{sig}\sqrt{2 \ln N} \quad \cdots\cdots (1)$$

where,

R_{max} : the desired maximum expected value

R_{sig} : the significant value of the motion response

N : number of cycle which is derived from the defined duration

STEP 3 Compute the distribution of inertia forces induced by motion and the eccentric gravitational forces due to roll and pitch motion on the basis of the predicted maximum motions.

After the total angular and translational accelerations at the center of gravity of the jacket/barge system are obtained, the translational accelerations at any arbitrary position of the system can be calculated as follows. (Here, the total translational accelerations are the sum of the translational acceleration induced by motion and the eccentric gravitational acceleration.)

$$T_r = T_{CG} + \dot{\omega} \times R \quad \cdots\cdots (2)$$

where,

- T_r : the translational accelerations at arbitrary position
- T_{CG} : the translational accelerations at C.G. of jacket/barge system
- $\dot{\omega}$: the angular accelerations about C.G. of jacket/barge system
- R : The vectorial distance between the C.G. and the arbitrary point

It should be noted that all the properties described above are to be represented in local or body-fixed coordinate system.

The total applied forces on an arbitrary member are computed by multiplying the mass properties of the member by the translational accelerations described above.

Because of the manner in which these responses–maximum angular displacement and accelerations–were derived, the values will always be found to be positive. For this reason, various sign combination of maximum responses should be investigated to cover a wide range of realistic possibilities.

These maximum motion combinations are obtained for each wave heading of interest, resulting in a series of inertia load conditions to be used in the structural analysis.

STEP 4 Perform a structural analysis of the platform for the prescribed inertia forces.

The structural analysis will provide the maximum support reactions, which can be interpreted as the interaction forces between the jacket and the barge.

2. 2 Present Method

This method requires more computational procedures than Rigid Barge Method. However, it takes far less computational procedures and endeavors to prepare the analysis model than the so-called Flexible Barge Method. This procedure consists of the following steps.

STEP 1 Define a design sea state corresponding to the maximum expected storm for a given period.

STEP 2 Compute 6 degree-of-freedom motions and accelerations of the jacket/barge system on a unit amplitude regular wave basis. Each of the response quantities, i.e. the amplitudes and phases of 6-degree-of-freedom motions computed on the unit amplitude regular wave basis are converted into the form of complex variables. Additionally predict only the maximum angular displacements for the design sea state.

STEM 3 Compute the distribution of the motion-induced inertia accelerations on the jacket caused by the unit amplitude regular waves. Finally, member inertia forces induced by the motions are computed in the forms of complex variables for each wave frequency for three heading angles.

The translational accelerations at any arbitrary position of the jacket/barge system can be calculated as follows[2].

$$X_L = X_G + \dot{\omega} \times R + \omega \times (\omega \times R) \quad \cdots\cdots (3)$$

where,

- X_L : the translational acceleration at arbitrary position
- X_G : the translational acceleration at C.G. of jacket/barge system
- $\dot{\omega}$: the angular acceleration about the C.G. of jacket/barge system
- ω : the angular velocity about the C.G. of jacket/barge system
- R : the vectorial distance between the C.G. and arbitrary point

STEP 4 Compute the motion induced reaction force RAOs (Response Amplitude Operators) by performing the structural analysis for the prescribed inertia forces. The reaction force RAOs are computed in the forms of complex variables by applying the inertia forces obtained previously to the jacket. The reaction force RAOs can now be found for the given wave frequencies and wave headings by the following equation.

$$RAO(RF(\omega,\mu)) = [(Re(RF(\omega,\mu)))^2 + (Im(CRF(\omega,\mu)))^2]^{1/2} \quad \cdots\cdots (4)$$

where,

ω : wave frequency
μ : wave heading
RF : reaction force

STEP 5 Predict the maximum motion induced reaction forces for the design sea state using the spectral analysis technique.

STEP 6 Perform the additional structural analysis : For the maximum-rotated conditions by roll or pitch motion, the reaction forces due to the eccentric gravitational forces are computed.

STEP 7 By combining the reaction forces computed in step 5 and 6, the maximum interaction forces between the jacket and the barge are obtained.

3. Application to San-Miguel Jacket Transportation

Differences between the two transportation analysis procedures are shown by comparing the results from San-Miguel Jacket application. A comparison of jacket/barge interaction forces is presented for a prescribed design sea state of the significant wave height of 38 feet and 13.8 second mean period. The results from both methods are in the form of maximum predicted values using the procedures outlined in previous sections.

3. 1 Rigid Barge Method

3. 1. 1 Modeling

The structural model of San-Miguel jacket as transported configuration which was prepared by Basic Design & Engineering Dep't of Offshore & Engineering Division of HHI is used for the analysis. The jacket structural model consists of 836 tubular beams and 384 joints. Total weight of the jacket is 32341 kips. The mass distribution of the jacket is determined by multiplying the volume of each member by the density. Appurtenances effects on the total weight of the jacket are considered by applying nodal weights or the distributed weights along some members.

In the case, where the barge is considered to be rigid, the jacket is supported at the main bracing elevations by constraining all translational displacements, which represents the presence of tiedowns and skidbeams and the additional supports are inserted between tow adjacent main bracing elevations to represent the presence of the skidbeams. The reaction forces will be computed at these support points. The loads transferred between jacket and barge can be interpreted as these forces. Figures 1, 2 show the structural model of San-Miguel jacket and its support conditions.

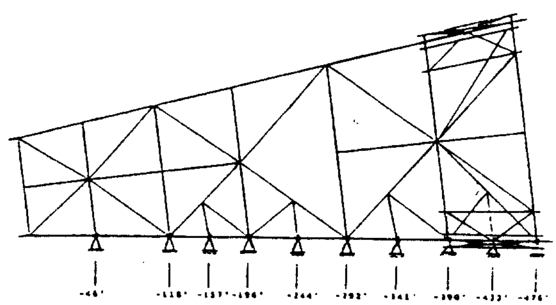

Fig. 1 San miguel jacket structural model and support conditions

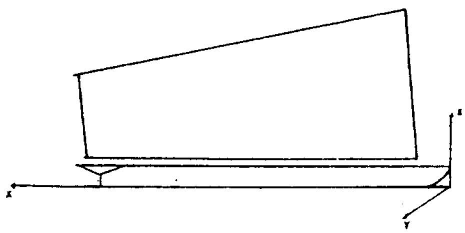

Fig. 2 Vessel coordinate

3. 1. 2 Motion Responses

After the jacket's mass properties such as the center of gravity and mass moment of inertia are determined, they are combined with those of the barge including the ballast water to give the mass properties of the jacket/barge system. Table 1 shows the mass properties of the jacket/barge system[3]. The jacket/barge system is trimmed by 0.14 degree to the forward and heeled by 0.88 degree to the portside at the equilibrium position.

Motion and acceleration RAOs for three heading angles-head sea, bow quartering sea, beam sea are then computed with the mass properties of the jacket/barge system and the barge hull form using the well-established strip theory.

Spectral analysis technique is applied to determine motion responses—motion, accelerations, etc.—in irregular waves. Once the significant motion responses are determined for the design sea states, maximum motion responses, which represents an average of the highest one thousand response, can be predicted by assuming that the motion and acceleration responses follow the Rayleigh distribution[4,5].

$$R_{max} = 1.86 \times R_{sig} \quad \cdots\cdots (5)$$

where,

R_{max} : the maximum motion responses

R_{sig} : the significant motion responses

Ocean System Computer Analysis Routine, OSCAR, was used for the computation of mass properties of the jacket/barge system, the prediction of equilibrium position, and the subsequent motion analysis[7].

Figure 3 through Figure 8 show the motion RAOs for three heading angles, respectively. Statistics of motions and accelerations are shown in Table 2.

Table 1 Principal characteristics of jacket/barge system

	Jacket	Dry barge	Ballasted barge	Ballasted Barge /Jacket system
Weight(*kips*)	32320	28351	36025	68345
C.G.(ft) X :	311.25	302.51	295.94	303.18
(vessel— Y :	−2.47	0.0	0.0	−1.17
coordinate) Z :	120.175	16.14	16.02	65.27
Radii of Rx :	116.96	49.3	44.8	102.8
Gyration(*ft*) Ry :	176.05	160.1	142.8	169.3
for each CG Rz :	186.92	160.1	142.8	165.3
Trans.GM(*ft*)				77.022
Longi.GM(*ft*)				1551.04

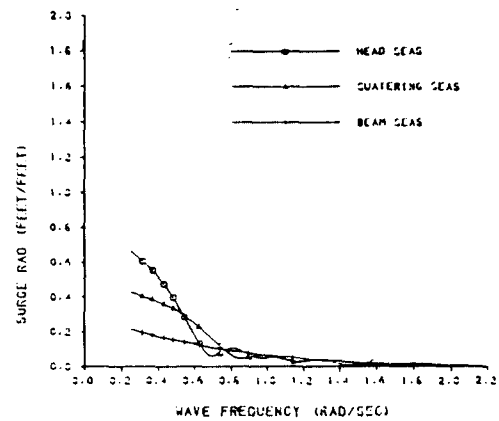

Fig. 3 Surge motion RAO of jacket/barge system

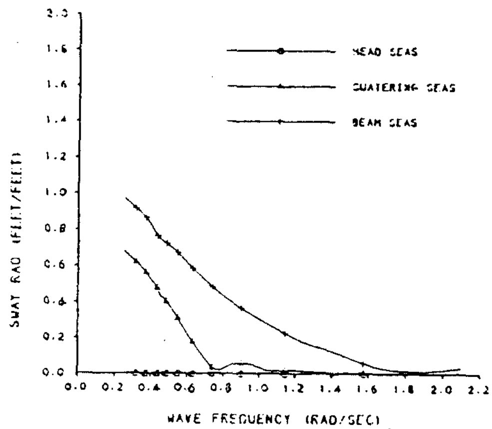

Fig. 4 Sway motion RAO of jacket/barge system

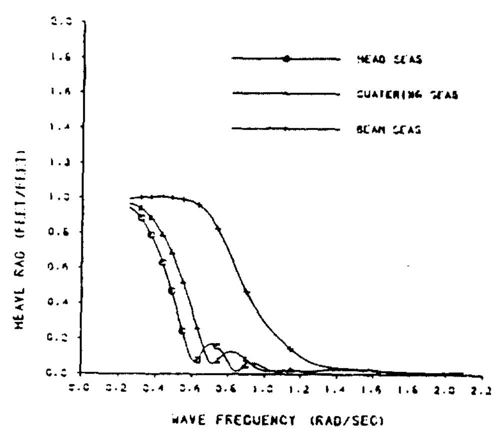

Fig. 5 Heave motion RAO of jacket/barge system

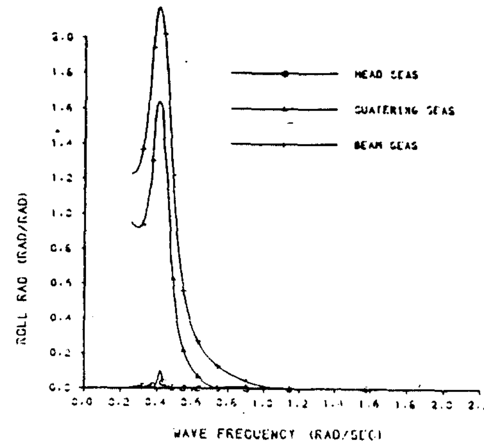

Fig. 6 Roll motion RAO of jacket/barge system

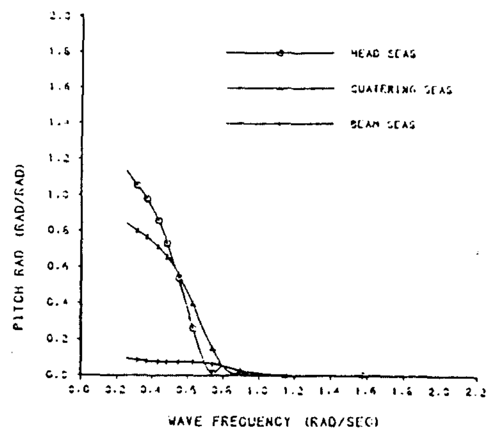

Fig. 7 Pitch motion RAO of jacket/barge system

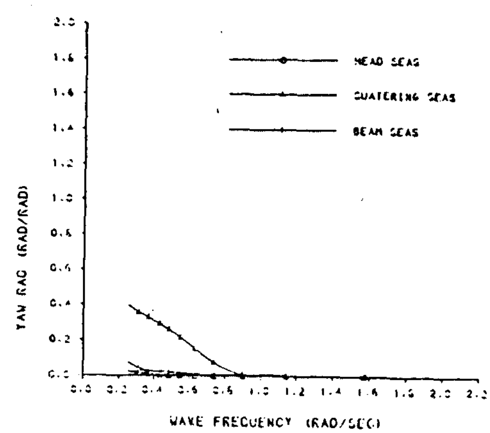

Fig. 8 Yaw motion RAO of jacket/barge system

Table 2 Statistics of motion and acceleration

Heading angles			Head	Bow Quatering	Beam
Surge	Ampl.	*ft.* sig.	8.71	6.46	
		ft. max.	16.21	12.01	
	Accel.	*ft/sec* * *2 sig.	1.44	1.24	
		ft/sec * *2 max.	2.68	2.30	
Sway	Ampl.	*ft.* sig.		8.83	14.57
		ft. max.		16.42	27.11
	Accel.	*ft/sec* * *2 sig.		1.46	3.16
		ft/sec * *2 max.		2.71	5.88
Heave	Ampl.	*ft.* sig.	11.94	14.08	18.41
		ft. max.	22.22	26.19	34.25
	Accel.	*ft/sec* * *2 sig.	1.32	2.38	4.43
		ft/sec * *2 max.	3.38	4.43	8.24
Roll	Ampl.	*deg.* sig.		4.59	8.31
		deg. max.		8.53	15.45
	Accel.	*deg/sec* * *2 sig.		0.81	1.62
		deg/sec * *2 max.		1.50	3.01
Pitch	Ampl.	*deg.* sig.	4.53	4.12	
		deg. max.	8.43	7.66	
	Accel.	*deg/sec* * *2 sig.	0.08	1.06	
		deg/sec * *2 max.	1.82	1.96	
Yaw	Ampl.	*deg.* sig.		1.67	
		deg. max.		3.11	
	Accel.	*deg/sec* * *2 sig.		0.43	
		deg/sec * *2 max.		0.80	

* Pierson−Moskowitz Spectrum : Hs=38*feet*

* max.=1.86×sig.

3. 1. 3 Loads Generation

Once the maximum responses of the system are predicted, various sign combinations of the maximum responses such as angular displacements, linear accelerations and angular accelerations which simulate one load case per each combination are investigated to cover a realistic possibilities.

Table 3 shows the load combinations adopted in this analysis. Although load combinations don't cover all possibilities, the orders of the reaction force quantities will show what heading angle is the most critical. And the load combinations for the critical heading angle are sufficiently investigated.

The wind effect is not included in this analysis. "TOW" inertia load generator of SACS system is used for the generation of member inertia loads relevant to the maximum responses of the jacket/barge system[7].

Table 3 Load combination − Hs = 38 *ft*

Heading	Surge Accel. (G)	Sway Accel. (G)	Gravity+Heave Accel. (G)	Roll Angle (*deg*)	Roll Accel. (*deg/sec*^{2})	Pitch Angle (*deg*)	Pitch Accel. (*deg/sec*^{2})	Yaw Angle (*deg*)	Yaw Accel. (*deg/sec*^{2})
Beam Sea		0.1733	1.2457	17.17	−3.03				
		0.1733	1.2457	−17.17	3.03				
		-0.1733	1.2457	17.17	−3.03				
		-0.1733	1.2457	−17.17	3.03				
Head Sea	0.0770		1.0994			−7.53	1.54		
	0.0770		1.0994			−7.53	−1.54		
Bow Quatering Sea	0.0705	0.0773	1.1342	8.39	−1.54	6.75	−1.44	2.98	−0.71
	0.0705	0.0773	1.1342	8.39	−1.54	−6.75	1.44	2.98	−0.71
	0.0705	0.0773	1.1342	8.39	−1.54	6.75	−1.44	−2.98	0.71
	0.0705	0.0773	1.1342	8.39	−1.54	−6.75	1.44	−2.98	0.71

* Max. roll angle(17.17) = initial heeling(0.88) + max. roll angle from motion analysis(16.29)
* G : gravity acceleration = 32.2 *feet/sec*^{2}

3.1.4 Structural Analysis

The reaction forces at the restraint points of the jacket launch legs are computed by applying the previously generated member loads to the jacket.

SACS system was used for the structural analysis[8]. The maximum reaction forces at 20 points of jacket launch legs are listed in Table 4.

The analysis results revealed that beam sea case is the most critical.

Table 4 Maximum skidbeam reaction forces −rigid barge method. Hs=38 *feet*

Jacket Elev.	Row 2	Row 4
−476 *ft*	8589 *kips*	9003 *kips*
−433 *ft*	689 *kips*	808 *kips*
−390 *ft*	6541 *kips*	5356 *kips*
−341 *ft*	717 *kips*	872 *kips*
−292 *ft*	8167 *kips*	8421 *kips*
−244 *ft*	298 *kips*	501 *kips*
−196 *ft*	5787 *kips*	4639 *kips*
−157 *ft*	657 *kips*	738 *kips*
−118 *ft*	6093 *kips*	5776 *kips*
− 46 *ft*	7516 *kips*	7135 *kips*

3.2 Present Method

This method requires a lot of computational procedures. So, in order to save the computer C.P.U. time and memory space, 6 frequencies for each heading angle are selected to get the motion induced reaction force RAOs. These frequencies are determined in consideration of the motion responses and the wave spectrums − i.e. the frequencies where the peaks of motions and wave spectrums occur − and they are 0.3927, 0.4488, 0.6283, 0.7854, and 1.0472 rad/sec. OTTO program is used in calculating the motion − induced inertia forces[6].

3.2.1 Modeling

Jacket model is same with that used in Rigid Barge Method. For adjustment to the input format of OTTO, fictitious vertical members which connect the jacket and the rigid barge are modelled at selected points along the jacket launch legs. And, then, the loads transferred between jacket and barge in terms of the internal loads of the fictitious vertical members.

3. 2. 2 Motion Responses

The motion analysis is performed using OTTO. To see the variation of the motion statistics due to the difference of number of selected unit amplitude regular waves, additional motion analysis is performed for 30 frequencies using OTTO. Table 5 shows the comparison of motion statistics between the case of 6 frequencies and the case of 30 frequencies. As shown in the Table 5, the differences in the motion statistics may be negligible.

Table 5 Comparison of Motion Statistics According to the Number of Frequency −Beam Sea, Hs=38 *feet*

Number of Frequency			30	6
Surge	Ampl.	*ft.* sig.		
		ft. max.		
	Accel.	*ft/sec*＊＊2 sig.		
		ft/sec＊＊2 max.		
Sway	Ampl.	*ft.* sig.	15.27	14.22
		ft. max.	28.40	26.46
	Accel.	*ft/sec*＊＊2 sig.	2.66	3.01
		ft/sec＊＊2 max.	4.96	5.59
Heave	Ampl.	*ft.* sig.	18.15	18.03
		ft. max.	33.76	33.54
	Accel.	*ft/sec*＊＊2 sig.	3.64	4.14
		ft/sec＊＊2 max.	6.77	7.59
Roll	Ampl.	*deg.* sig.	9.22	12.55
		deg. max.	17.15	23.35
	Accel.	*deg/sec*＊＊2 sig.	1.74	2.26
		deg/sec＊＊2 max.	3.24	4.20
Pitch	Ampl.	deg. sig.		
		deg. max.		
	Accel.	*deg/sec*＊＊2 sig.		
		deg/sec＊＊2 max.		
Yaw	Ampl.	deg. sig.		
		deg. max.		
	Accel.	*deg/sec*＊＊2 sig.		
		deg/sec＊＊2 max.		

＊ ISSC Spectrum : Hs=38 *feet*, Tm=13.8 *sec*
＊ max.=1.86×sig.

3. 2. 3 Loads Generation

Once the motion responses are computed on a unit amplitude regular wave basis, the accelerations at the center of gravity of jacket barge system for each-degree-of-freedom motion can be calculated as follows ;

$$A_a = \omega^2 A_m \qquad (6)$$

$$\phi_a = \phi_m + \pi \qquad (7)$$

where,

A_a : the amplitude of the acceleration
ϕ_a : the phase of the acceleration
A_m : the amplitude of the displacement
ϕ_m : the phase of the displacement
ω : the regular wave frequency

Then, after the translations at all joints of the jacket are calculated by using the equation(3), the motion induced forces acting on all jacket members are calculated by multiplying the mass properties of the each member by the accelerations.

3. 2. 4 Structural Analysis

The interaction force RAOs are computed in the forms of complex variables by applying the inertia forces obtained previously to the jacket. The interaction force RAOs can now be found for the given wave frequencies and wave headings by using the equation(4). Using the spectral analysis technique, then, the maximum motion induced interaction forces are computed.

Additional structural analysis is performed for the maximum-heeled conditions using SACS. Therefore the interaction forces which are caused by the static weight eccentricity due to the roll motion are computed.

The maximum total interaction forces are obtained by adding the maximum motion induced interaction forces to the interaction forces in the maximum-heeled condition. Table 6 shows the maximum total interaction forces.

Table 6 Maximum skidbeam reaction forces —present method Hs=38 *feet*

Jacket elev.		Row 2	Row 3
−476 ft	motion force	2933 *kips*	3469 *kips*
	grav. heel 1	3953 *kips*	601 *kips*
	grav. heel 2	642 *kips*	4082 *kips*
	max. force	6886 *kips*	7551 *kips*
−433 ft	motion force	192 *kips*	309 *kips*
	grav. heel 1	322 *kips*	160 *kips*
	grav. heel 2	215 *kips*	322 *kips*
	max. force	514 *kips*	641 *kips*
−390 ft	motion force	1893 *kips*	1648 *kips*
	grav. heel 1	3455 *kips*	1583 *kips*
	grav. heel 2	1630 *kips*	3025 *kips*
	max. force	5348 *kips*	4673 *kips*
−341 ft	motion force	193 *kips*	322 *kips*
	grav. heel 1	333 *kips*	204 *kips*
	grav. heel 2	232 *kips*	368 *kips*
	max. force	526 *kips*	690 *kips*
−292 ft	motion force	2405 *kips*	2976 *kips*
	grav. heel 1	4273 *kips*	921 *kips*
	grav. heel 2	1841 *kips*	4114 *kips*
	max. force	6678 *kips*	7090 *kips*
−244 ft	motion force	78 *kips*	236 *kips*
	grav. heel 1	176 *kips*	67 *kips*
	grav. heel 2	124 *kips*	211 *kips*
	max. force	254 *kips*	447 *kips*
−196 ft	motion force	1696 *kips*	1408 *kips*
	grav. heel 1	3025 *kips*	1115 *kips*
	grav. heel 2	1303 *kips*	2538 *kips*
	max. force	4721 *kips*	3946 *kips*
−157 ft	motion force	188 *kips*	242 *kips*
	grav. heel 1	309 *kips*	162 *kips*
	grav. heel 2	202 *kips*	323 *kips*
	max. force	497 *kips*	565 *kips*

3. 3 Comparison of Results

Table 7 and Figures 9,10 show the comparison of the jacket/barge interaction forces. There are considerable differences in the magnitudes of the jacket/barge interaction forces between Present Method and Rigid Barge Method. Rigid Barge Method give about 20% greater values than Present Method. This shows that the loads computed under the assumption of simultaneously occurring maximum motions lead to considerable conservative results.

Table 7 Comparsion of maximum skidbeam reaction forces

Jacket elev.	Method	Row 2	Row 3
−476 ft	Rigid Barge Present	8589 *kips* 6886 *kips*	9003 *kips* 7551 *kips*
−433 ft	Rigid Barge Present	655 *kips* 608 *kips*	754 *kips* 681 *kips*
−390 ft	Rigid Barge Present	6541 *kips* 5348 *kips*	5356 *kips* 4673 *kips*
−341 ft	Rigid Barge Present	690 *kips* 780 *kips*	826 *kips* 379 *kips*
−292 ft	Rigid Barge Present	8167 *kips* 6678 *kips*	3421 *kips* 7000 *kips*
−244 ft	Rigid Barge Present	284 *kips* 322 *kips*	458 *kips* 452 *kips*
−196 ft	Rigid Barge Present	5787 *kips* 4721 *kips*	4630 *kips* 3946 *kips*
−157 ft	Rigid Barge Present	629 *kips* 675 *kips*	696 *kips* 681 *kips*
−118 ft	Rigid Barge Present	6093 *kips* 4957 *kips*	5776 *kips* 4889 *kips*
− 46 ft	Rigid Barge Present	7516 *kips* 5718 *kips*	7135 *kips* 5627 *kips*

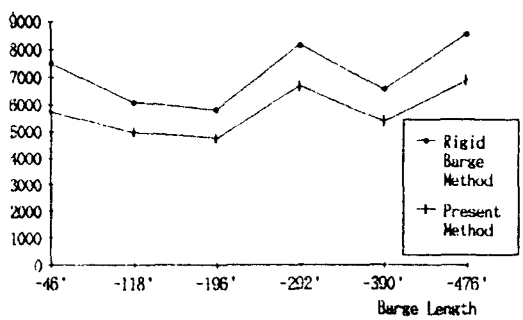

Fig. 9 Comparison of vertical interaction forces (Row 2)

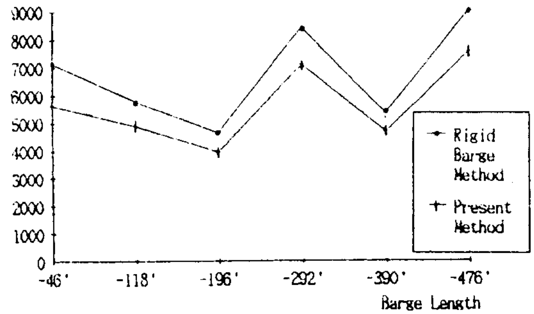

Fig. 10 Comparison of vertical interaction forces (Row 4)

4. Conclusions

According to the results obtained in this analysis, the following conclusions can be drawn.

1) There are considerable differences in the results according to the treatment of loading, either stochastic or semi-deterministic. And the treatment of loading as semi-deterministic may give considerable conservative results. (In the transportation analysis of San-Miguel jacket, the Rigid Barge Method gives about 20% greater values than Present Method.)

2) Beam sea condition provokes the maximum jacket/barge interaction forces during the transpotation of San-Miguel jacket.
3) The Present Method gives more realistic and reasonable results than Rigid Barge Method.

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