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**◉ Technical Paper**

# The Development of an Early Production System off the Coast of Korea+

Byung-Kun Yu*, In-Kyu Park**, Youn-Sang Won**, Hyun-Soo Shin**
and Young-Sik Jang**

# 한국형 해저원유 초기생산시스템 개발

우병건 · 박인규 · 원윤상 · 신현수 · 장영식

**Key Words :** Early Production(초기생산), Load-Excursion Curve(하중-주유곡선), Mooring(계선), Conceptual Design(개념설계)

## 초 록

한국형 해저원유 초기생산 시스템은 제주도 남쪽의 한·일 공동개발구역 및 이와 유사한 조건의 지역에서 소규모 유전이 발견되었을 때, 빠른 시간내에 저렴한 초기투자비로 석유를 생산할 수 있도록 개발되었다. 이 시스템은 원유저장용 선박, tower, yoke, gravity base 및 원유처리장치등로 구성되어 있으며 각 구조물들은 pin 또는 universal joint들로 연결되어있다(Fig.1 참조).

본 구조물의 파도중에서의 동적거동은 전산 program을 이용하여 구하여 wave tank에서 수행된 실험의 결과와 비교, 검토하였다. 그리고 이들 결과를 이용하여 구조적 안전성을 검토하였으며, 설계, 해석 및 model test의 결과들은 선급협회의 승인을 받았다.

## 1. Introduction

This paper deals with the conceptual design, analysis and model test of the oil production system off coast of Korea. General figure of the offshore oil production system, composed of fixed jacket and subsea pipeline transportation, requires such a high construction cost and long construction leadtime that sufficent amount of proven throughput is necessary. On the contrary, Early Production System replaces the subsea pipeline by oil transportation with temporary storage and shuttle tanker. A shuttle tanker can off-take the oil and transport it to shorebase oil customer (see Table 1).

This system is especially competent at the marginal oil field, isolated oil field or early stage of the conventional oil field. At articulation part of tower and yoke, flexible pipelines are used. Gravity base with permanent ballast transmitts the total environmental force to the sea bed foundation.

## 2. Conceptual Design

### 2.1 Single Point Mooring

After investigation of all the existing mooring types, we selected 2 or 3 candidates for the conceptual design. Four typical mooring types are compared in Table 2. Although each can be used as a Floating Production Storage and Offloading System,

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* Member, Naval Archi. Dep't., Ulsan University
* Member, Hyundai Maritime Research Inst., Hyundai Heavy Ind. Co., Ltd.

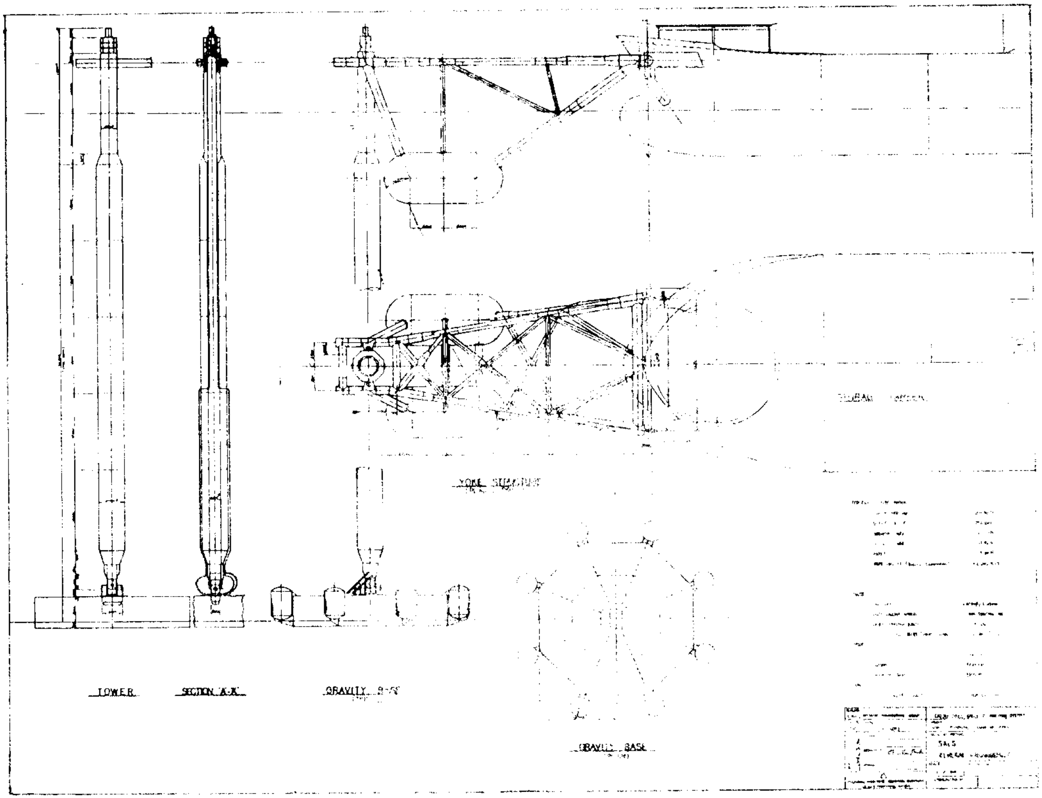

Fig. 1 Conceptual general arrangement of proposed FPSO

Table 1 Early production syslem vs. conventional system

| System / Function | Fixed production system<br>Conventional system<br>Pipeline transportation | Floating production system<br>Early production system<br>Tanker transportation |
|---|---|---|
| Platform type<br>(mooring type) | • jacket<br>• gravity platform | • articulated tower<br>• CALM buoy<br>• semi-submersibles<br>• tension leg platform |
| Processing facility | • on the platform | • on the tanker |
| Storage facility |  | • converted tanker<br>• purpose built barge |
| Oil transportation<br>Offloading facility | • subsea pipeline | • shuttle tanker<br>• on the storage tanker |

the selection depends generally upon the particular field environmental conditions. There are various kinds of Single Point Mooring concept. We may classify them as two categories; rigid yoke type and hawser type. Table 3 shows the merits and demerits of these rigid yoke and hawser type.

We investigated the current concept of yoke type single point moorings which can be classified by the following four concepts ; SBS (Single Buoy Storage), SALMRA (Single Anchor Leg Mooring Rigid Arm), Yoke Tower and SALS (Single Anchor Leg Storage). All the previously proven site is investigated with the type and environmental condition for the yoke type Single Point Mooring System to get the basis of SPM type selection. From these investigations, we can classify that SBS

**Table 2** Comparison of various mooring system as a FPSO

| Characteristics \ Mooring | Multi point catenary mooring | Multi point catenary mooring + Swivel | Single point mooring + Swivel | Dynamic positioning |
|---|---|---|---|---|
| Applications | semi-submersibles<br>crane-barges<br>fixed multi mooring | drill ship<br>CALM, SPAR<br>turret | SALM, ALP<br>SALS, yoke<br>tower | semi-submersibles<br>drill ship<br>SWOPS<br>OLS, SOLS |
| Reliability | ○ | △ | ○ | ○ |
| Initial investment | △ | ○ | ○ | △ |
| Operation cost | ○ | ○ | ○ | △ |
| Weather vane | × | ○ | ○ | ○ |
| Mobility | △ | △ | △ | ○ |

**Table 3** Rigid yoke v.s. hawser types

| | Rigid yoke | Mooring hawser |
|---|---|---|
| Loading hose | ordinary steel pipe | floating flexible hose |
| Routine maintenance | easy | difficult |
| Auxilliary piping (installation & maintenance) | easy | difficult |
| Motion characteristics | reasonably stable | peak load if the motion phase are opposite |
| Collision with tanker & buoy | no collision | possible |
| Fish tailing | no | possible (additional power is required) |
| Emergency mobility of storage tanker | possible if required | good |

type is suitable for shallow water and mild environmental area while SALS and Yoke Tower type is feasible in relatively harsh environmental area. By considering our design requirements as shown in Table 4, SALS type is selected to proceed with a more detailed design, analysis, and model test.

**Table 4** Design environmental criteria

| | |
|---|---|
| Water depth | [illegible]00m |
| Soil condition | sand 70% silty mud 25% |
| 100 year wave | Hmax = 26*m* |
| | Hsig = [illegible]*m* |
| Windspeed(1 *min*, mean) | 100 *knots* |
| Current speed | 3 *knots* |
| Tide | 1*m* |
| Oil production rate | 10,000 *bbl/day* |
| No. of wells | 2 |

The design parameters of the SALS type single point mooring system can be determined by establishing the quasi-static force-excursion relationship. The stiffness of the mooring system should be determined by the maximum applied horizontal mooring force and corresponding allowable excursion. As a normal practice for shallow water, allowable excursion is limited to 30% of water depth ; for deep water, 10% of water depth. In our case, the dimensions are determined by parametric study with the maximum inclining angle of 15° in static and 25° in static and dynamic mooring load. To optimize the mooring system, the restoring force of the system is provided by two longitudinally parallel buoyancy tanks. Due to this configuration, the buoyancy tanks are located close to the tower as possible prior to contact each other so that most of the buoyancy of tanks can contribute to the restoring force.

## 2.2 Storage Tanker and Processing Facility

Storage tanker can be either a purpose built barge or a used crude oil carrier. Modifications to existing vessels involve installation of a thwartship beam at either bow or stern with appropriate internal structural strengthening as required. Besides furnishing buffer storage capacity and shuttle tanker loading facilities, the floating unit also provides space for the installation of processing and power generation equipment, crew accomodations and helideck. Shuttle tankers can berth alongside the storage vessel or in tandem. If specially demanded, cargo may be transferred via separate tanker loading terminals. The process facilities are designed to process 10,000 *bbls* per day of well effluent consisting of waxy, high pour point crude oil and water with a maximum gas rate of 10 million cubic feet per day. Two stages of gas compressor will compress up to 750,000 STD *ft* of gas for artificial lift during the late stages of production life. The separating and treating equipment are designed to reduce the effect of storage tanker motion on the fluid interfaces in the vessels.

## 3. Theoretical Analysis

In the previous section SALS system was selected as the most feasible among the various kinds of FPSO systems for the assumed environmental conditions. To determine the appropriate dimensions and scantlings of SALS system, we established the equations of motion and investigated the motion behaviours and corresponding loads on the structure. First, the static equilibrium was calculated, which would be used as the initial condition for dynamic analysis and would provide the load-excursion relationship. Then, the motion behaviours of SALS system were found in frequency domain on the assumption that the motion of SALS system is governed by that of storage tanker. In the dynamic analysis the hydrodynamic forces including the motion-induced forces were calculated to perform the structural analysis. The calculation results were verified by comparisons with model test results.

### 3.1 Equation of Motion

Since the SALS system, a weather-vane type, rotates to the most favorable weather direction, the maximum loads may occur when wind, current and wave travel from the same direction. Then, it becomes two dimensional problem which has three degrees of freedom, two translations and one rotation.

Each component of the SALS system-base, tower, yoke and storage tanker-gives three equations of motion. The base has fixed boundary conditions and the tower is allowed only rotational movement. Yoke and storage tanker have three degrees of freedom, respectively. In addition to the equations of motion, the geometric relations are required to solve the motion of SALS system. They describe the geometric restriction that each component of SALS system is connected with another by hinge point.

### 3.2 Static Equilibrium

The first step to solve the dynamic problem was to calculate the static equilibrium which would provide the initial condition for dynamic analysis. By eliminating the time-variant terms and simplifying the equations, the problem can be reduced to the following four coupled equations.

$$P_{CY}=f(\phi_T)=a1+a2\tan\phi_T+a3/\sin^2\phi_T$$
$$+a4/\cos\phi_T\sin^2\phi_T \tag{1}$$
$$P_{CY}+b1\tan\phi_B+b2=0 \tag{2}$$
$$P_{CY}\phi_S+c1\,P_{CY}+c2\,\phi_S+c3=0 \tag{3}$$
$$P_{CY}+d1\,\phi_S+d2\sin\phi_T+d3\sin\phi_B+d4=0 \tag{4}$$

where $P_{CY}$ : vertical component of pin load between yoke and storage tanker
$\phi_T, \phi_B, \phi_S$ : inclining angles for tower, yoke and storage tanker respectively
a, b, c, d : constants determined from geometric properties

These simultaneous equations can be solved by the half interval method, one of the iteration methods. That is, for the assumed value of $\phi_T$, calculate the values of $P_{CY}$, $\phi_B$ and $\phi_S$ according to the equations (1), (2), (3). Then, check whether these values satisfy the other equation (4) within the allowable error bound. If not, assume new value of $\phi_T$ by the half interval method and

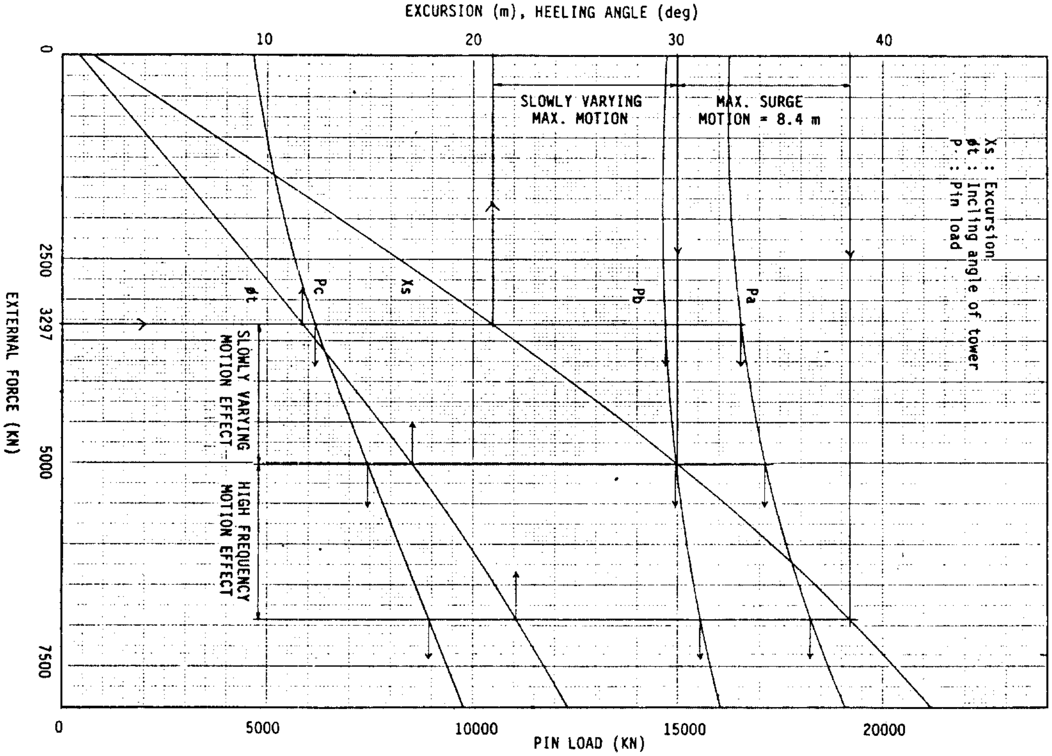

**Fig. 2** Load-Excursion curve from static equilibrium

repeat the above procedures until the equation (4) is satisfied. Once these equations are solved, the other variables can be easily derived by elementary calculations.

From the static equilibrium, the load-excursion curve can be obtained which presents the excursion, tower heeling angle and pin loads, along the varying external forces on storage tanker. It can be used to decide the design parameters and to estimate the dynamic loads according to the quasi-static method as shown in Fig.2. However, the quasi-static method seems inappropriate for this problem because it does not take into account the dynamic forces on tower and yoke.

### 3.3 Dynamic Analysis

The dynamic responses of SALS system can be found by solving the equations of motion and the geometric restrictions. However, much consumed time and labor are required to solve these equations simultaneously. If we make the following assumption, this problem becomes a conventional problem of a moored ship. That is, the behaviour of storage tanker is so dominant as to govern that of SALS system. This assumption can be justified because the storage tanker has a much larger mass inertia than the other components of SALS system. Effects of tower and yoke on the behaviour of SALS system can be replaced by the longitudinal spring on the storage tanker. The spring coefficient is determined from the slope of load-excursion curve at the static equilibrium position.

The motion responses of moored storage tanker in regular waves were found by the computer program based on three dimensional sink-source distribution method. The storage tanker was modeled into 198 sink-source elements and motion responses were calculated for 10 frequencies. Once the motion responses of storage tanker were found, those of tower and yoke can be determined by using the geometric relations. Fig.3 shows the calculation results of motion RAO of SALS system.

In irregular waves the motion behaviors can be

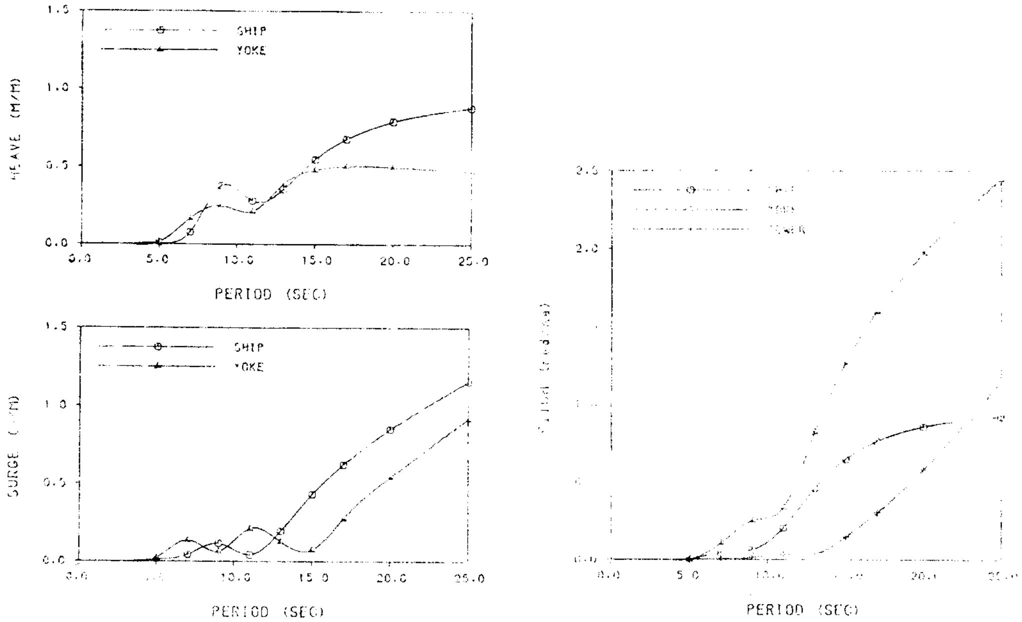

**Fig. 3** Motion RAO's of SALS system

divided into two groups ; one in high frequency range due to the first order oscillating force and the other in low frequency range due to the slowly varying drift force. The former can easily be found by spectral analysis method, whereas the latter is so cumbersome to find that the model test results were used. The dynamic loads on the elements of tower and yoke were calculated in frequency domain by Morison's formula when they oscillated in predescribed mode around the maximum excursion due to quasi-static force and slowly varying drift force.

### 3.4 Structural Analysis

To evaluate structural safety, several analysis methods were proposed. If the dynamic force is comparatively important, dynamic analysis is preferred and one can work in the frequency domain which concentrates on steady state solution. This method assumes a linear system. The design wave height, wind speed and current speed used for structural analysis are those corresponding to a 100-year storm. Spectral analysis procedure was chosen to obtain maximum dynamic stress using stress RAO's and wave spectrum. The procedure of structural analysis is as follows ;

—Prepare hydrodynamic model and structural model of the tower and yoke at the maximum drift condition. The maximum drift excursion is obtained from the model test at the irregular sea of the storm condition. Self-weight is also included in the hydrodynamic model.

—Apply a series of unit amplitude regular waves coming from head and ship motion RAO's obtained from computer analysis and verified by model test.

—Calculate static load due to buoyancy and self-weight and wave load RAO's (see Fig.4).

—Calculate wind and current load and include them in the static load under the assumption that wave, wind and current are collinear.

—Obtain static stress and dynamic stress RAO's (Fig.5). To obtain a dynamic stress, a full dynamic structural analysis is too complicated to be practical in the early design stages. So all dynamic actions are assumed in the fundamental mode and stress having no dynamic effect is multiplied by the steady state dynamic amplification

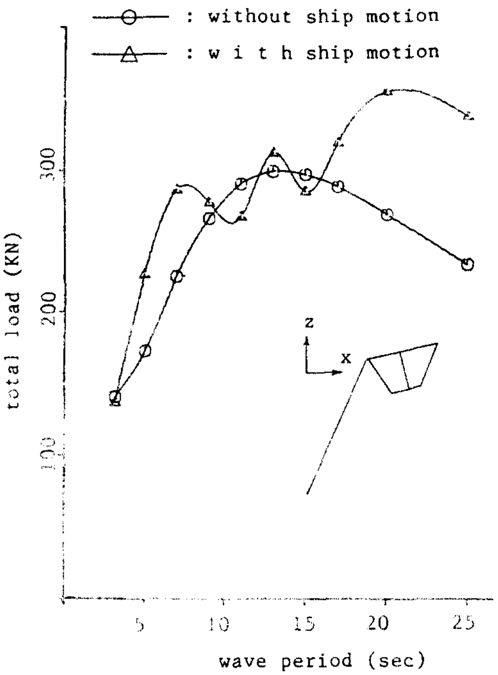

**Fig. 4** Total X-force RAO acting on tower

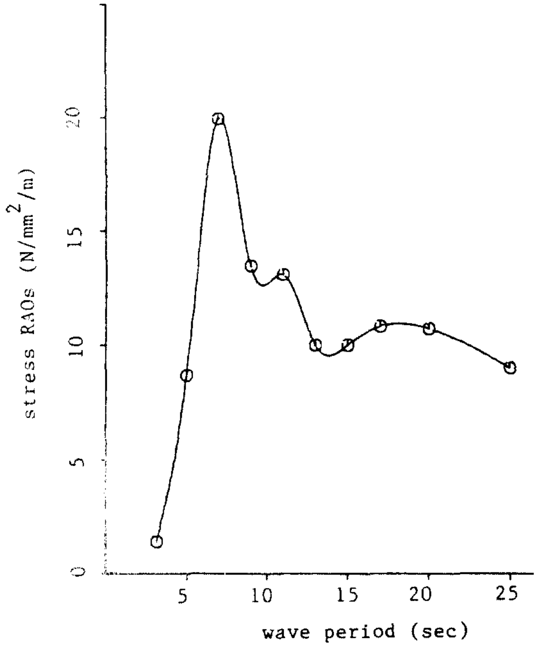

Fig. 5 Stress RAO of tower element at midspan

factors to get a dynamic stress.

- —Perform spectral analysis for the elements showing relatively high stress levels to obtain maximum dynamic stress.
- —Perform code checks according to API RP2A.

The analysis showed high stresses at the members on the tower which is about 60 meters above the lower universal joint and on the yoke around the buoyancy tank.

The member forces are used to design connecting members such as lower universal joint, gimbal joint, pinns, etc.

Fatigue analysis followed spectral analysis procedure as structural analysis. But hydrodynamic model and structural model are made at the mean drift excursion in the operating sea condition. Wave spreading was considered because wave, wind and current are not collinear as the sea state becomes moderate.

Stress RAO's were combined with wave spectra of each sea state in the condensed wave scatter diagram (Fig.6) to produce mean zero-crossing period and stress range distribution. The results were summed over all sea states and fatigue damage ratio was calculated using appropriate *S-N* curves and Palmgren-Miner rule.

| Significant wave height, *Hs(m)* | 4.0 | 6.0 | | 8.0 | | 10.0 |
|---|---|---|---|---|---|---|
| 7.0 | 0.0 | 4.4 | | 8.8 | | 2.8 |
| 5.0 | 1.0 | 31.4 | | 39.4 | | 8.3 |
| 3.0 | 15.6 | 20.3<br>58.3 | 39.9<br>85.3 | 34.6<br>59.7 | 16.9<br>22.2 | 15.0 |
| 1.0 | 110.6 | 347.1 | | 80.0 | | 4.0 |

Mean period, *Tz(sec)*

**Fig. 6** Condensed wave scatter diagram

## 4. Model Test

### 4.1 Test Description

Extensive model tests have been performed with the scale ratio of 1/70 at HMRI towing tank which measures 210*m* × 14*m* × 6*m* and has a flap type wave generator. One of the aims of model testing is to provide direct or indirect information about the statistical behaviour of the investigated quantities.

**Table** 5 Model test conditiod

| Condition | Load condition | | Wave | Wind | Current |
|---|---|---|---|---|---|
| | Storage TK | Shuttle TK | | | |
| Operating | ballast | × | regular:<br>H=2, 5*m*<br>T=7~25*sec*<br>irregular:<br>Hs=5*m*<br>Tz=8*sec* | 50*kts*<br>〃 | 1*kts*<br>〃 |
| | full-load | × | 〃 | 〃 | 〃 |
| Offloading | full-load | ballast | 〃 | 〃 | 〃 |
| Survival | full-load | × | regular:<br>H=26*m*<br>T=15*sec*<br>irregular:<br>Hs=14*m*<br>Tz=13*sec* | 100*kts*<br>〃 | 3*kts*<br>〃 |

Tests were performed in regular and irregular waves in 3 conditions ; operating condition, survival condition and offloading condition. The purpose of the operating condition test is to study the behaviour of the FPSO system without shuttle tanker in one sea state at the installation site. Tests were performed for both the full load condition and ballast condition of the storage tanker.

The survival condition test (see Photo) was carried out to study the feasibility of new SALS concept for the maximum sea state of 100 years return period. The storage tanker was in full load condition for the survival condition test.

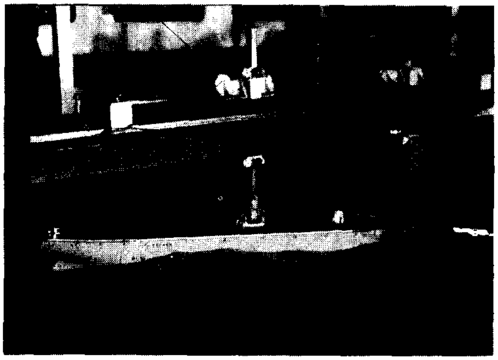

Photo. 1 Test for survival condition

The offloading condition test was carried out to study the behaviours of the FPSO and shuttle tanker in the maximum offloading sea state. In this condition, the storage tanker is in full load condition and the shuttle tanker is in ballast condition, respectively. Test condition is summarized in Table 5.

The directions of wind and current are collinear with the wave direction.

Measurements were carried out for the motions of the storage tanker and the shuttle tanker in 3 degrees of freedom, inclining angle of the riser tower, axial tensions at hinge points, bending moment at the riser tower and tension at hawser.

Froude's scaling law was adopted as the similitude relationships between the model and prototype. The scale relationships were used to extrapolate quantitatively the motion, force and time measurements from model to prototype. The water depth of test tank, however, was actually deeper comparing to the depth of similitude. Hence the generated waves of long length might be affected by the water depth. The depth of sea bottom was achieved by the false bottom secured to the towing carriage.

Current forces were determined from the still water resistance test of the system with or without shuttle tanker. Wind forces were calculated using the API recommending formula. The current and wind forces were simulated in the test by pulling the model system in the wave propagating direction with weights and a thin rope attached to the model system. The weights are equivalent to the wind and current forces. These forces are summarized in the Table 6. The regular waves were generated with 2*m* or 5*m* wave height and 7~25 *sec* wave period. The irregular waves were generated using the 2 parameter Pierson-Moskowitz spectrum.

**Table** 6 Current and wind forces for system (*ton*)

| Condition | Current | | Wind | |
|---|---|---|---|---|
| | 1*kts* | 3*kts* | 50*kts* | 100*kts* |
| Operating ballast | 9.1 | | 53.4 | |
| Full-load | 15.1 | | 45.7 | |
| Unloading | 21.4 | | 74.5 | |
| Survival | | 83.3 | | 183.1 |

### 4.2 Test Results

Some of the motion RAO's analyzed from the regular wave tests are shown in Fig.7~Fig.8 with the theoretical calculation results. They show good agreement with each other. The smaller RAO's of surge motion measurement than predictions seem to be caused by the effects of the mass and the frictional damping of the measuring device.

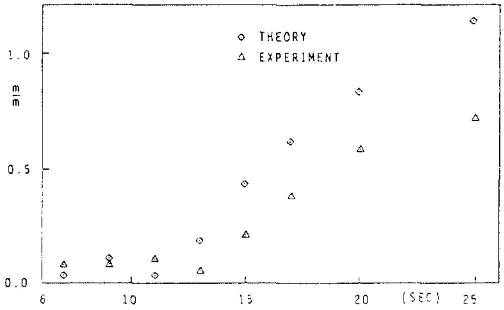

**Fig.** 7 Surge RAO's of storage tanker (operating, full-load)

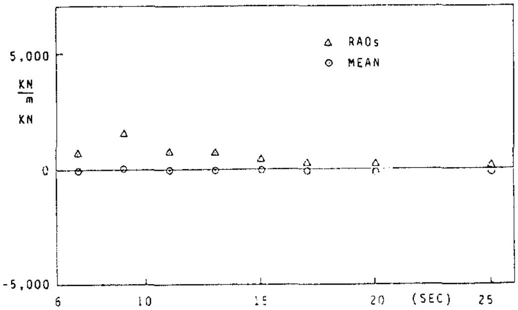

**Fig.** 8 Axial force RAO's at tower bottom(operating, full-load)

The surge motion of the shuttle tanker moored to the storage tanker as tandem in the offloading condition showed the possibility of the collision with storage tanker. During the offloading, the backward thrust will be required for the shuttle tanker.

The inclining angle of the riser tower was analyzed from the acceleration measurement at the top of the riser tower. It was found that the pitch motion of the tower was not harmonic in the case of large motion. It is proved mechanically.

The time history of irregular wave is shown in Fig.9 with its spectrum for the survival condition.

Some time histories of irregular wave motions are shown in Fig.10~Fig.11 with their spectra.

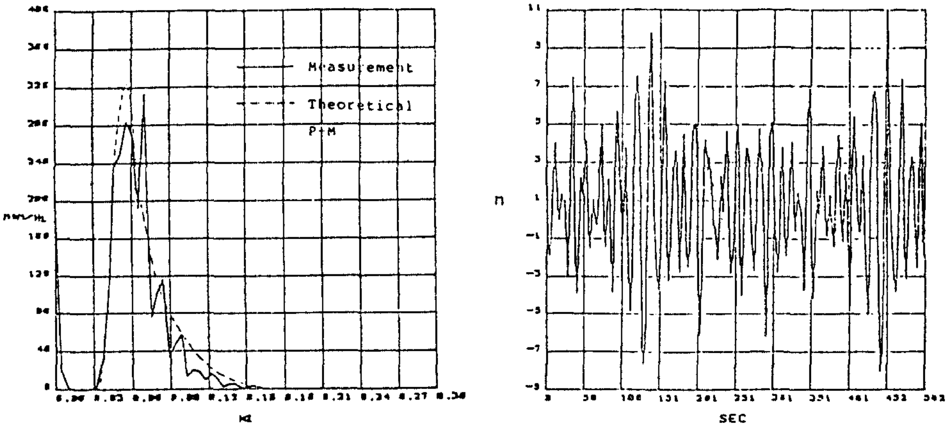

**Fig.** 9 Wave spectrum(Hs = 14*m*, Tz = 13*sec*)

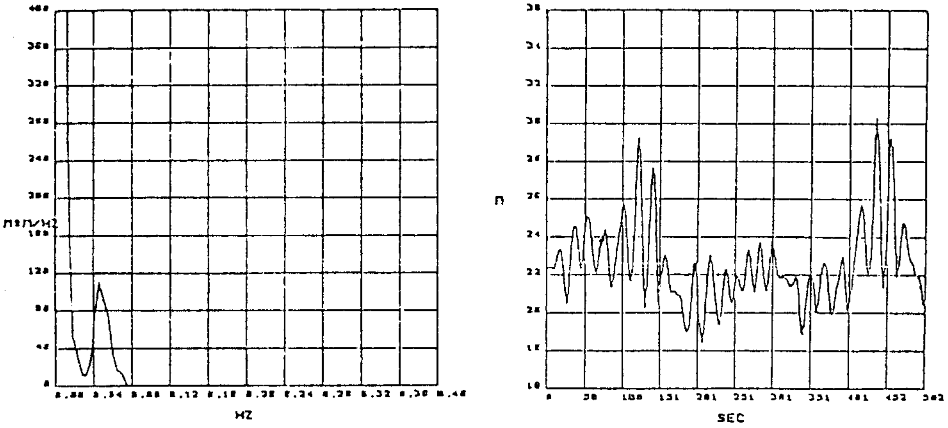

**Fig. 10** Surge motion of storage tanker (operating, full-load)

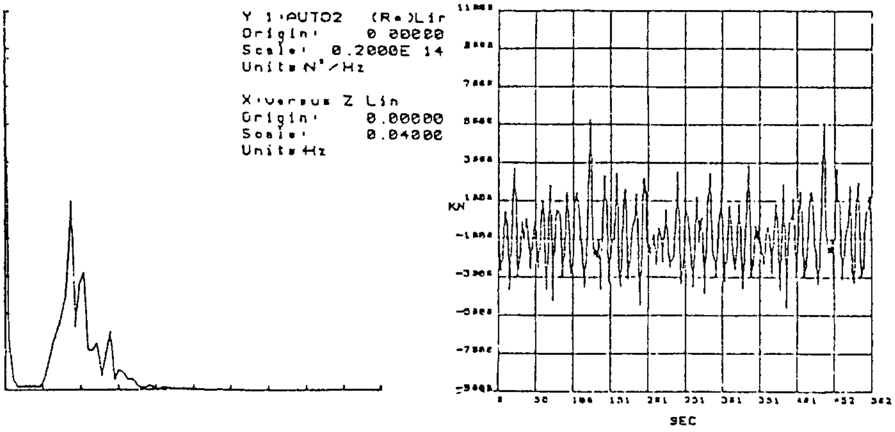

**Fig. 11** Axial force at tower bottom (operating, full-load)

The surge motion has large energy at lower frequency region as shown in its spectrum due to the slowly varying drift forces on the system. The slowly varying motion should be considered in the system design since its magnitude is very large compared to the high frequency motion. The RAO's of reaction forces at hinge points showed peaks at the wave period of 9 or 11 seconds. The maximum forces at each force measuring point in survival condition are as followings;

| | |
|---|---|
| Axial force, Port side of yoke | 7,860*kN* |
| Horizontal force, Tower bottom | 6,890*kN* |
| Axial force, Tower top | 11,200*kN* |
| Vertical force, Tower bottom | 5,370*kN* |

The axial and vertical forces of the tower were measured with zero offset at still water and should be corrected afterwards for the detail system design giving the following values ;

| | |
|---|---|
| Axial force, Tower top | 14,840*kN* |
| Vertical force, Tower bottom | 14,000*kN* |

## 5. Conclusion

1) The maximum wave height off the coast of Korea is estimated to be 26*m* for 100 years return period and their prevalent early production system for this environmental condition is selected as Single Anchor Leg Storage (SALS) type.
2) The theoretical calculations and the model tests show satisfactory results and can be used as the

data for system design.

3) The proposed conceptual design was appraised/approved by American Bureau of Shipping (ABS) and further detail development may be performed.
4) The conceptual design of this study can be applied to the other marginal offshore fields having similar environmental conditions.

## Acknowledgements

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## References

1) Roger Maari, "Offshore Mooring Terminals", SBM Inc., 1980
2) Smulders, L.H. and G.F. Remery, "The Mooring of a Tanker to a Single Point Mooring by a Rigid yoke", OTC 3567, 1979
3) API RP2A, "Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms", 16th edition, 1986
4) Jones, D.E., "ABS's Approach to the Classification/Certification of Floating Production Facilities", American Bureau of Shipping, 1986
5) RINA, International Symposium on "Developments in Floating Production Systems", London (Mar. 21-22, 1984), RINA, London Swix 8 BQ
6) ABS approval letter, 1987

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〈案　內〉

## □ 秋季 學術大會 計劃 □

1987年 秋季 學術大會를 아래와 같이 開催할 예정이오니 會員諸位의 많은 發表와 參席을 바랍니다.

日　　時：1987年 11月末頃
場　　所：추후 확정시 통고함
원고마감：1987年 10月 20日까지
제 출 처：본학회 사무국

※ 원고 작성시는 본 학회의 강연논문집원고 투고요령(학회지 게1권 제1호)을 참조하시기 바랍니다.

## □ 韓國海洋工學會誌 第1巻 第2號 원고모집 □

1987年 12月 末에 발간예정인 韓國海洋工學會誌 第2巻 第1號의 원고를 모집하오니 會員諸位의 많은 투고 바랍니다.

원고마감：1987年 9月 20日까지
제 출 처：本學會 事務局