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# SEISMIC ASSESSMENT OF AN EXISTING EQUIPMENT STRUCTURE IN REFINERIES

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## SUMMARY

Reflecting the maturing of industries in Japan, assessment of existing plant facilities, from the viewpoints of both seismic resistance and deterioration during the period in service, has been become important these days. The authors introduce their methodology of the seismic and deterioration assessment in Japan, by taking an example of seismic assessment of an existing equipment structure supporting two vertical vessels on the top floor.
In the assessments, by means of comparison with response values calculated by two different analysis methods and revision of loading data to reflect the current conditions, it is possible to perform effective seismic evaluation and propose economical countermeasures for upgrading and modification of the existing structures.

## INTRODUCTION

Hyogo South Area earthquake, taken place in 1995, caused heavy damages to high-pressured gas facilities. The lessons learnt from such experience resulted in revision of the Seismic Design Code of High-pressure Gas Facilities in Japan, which will be called “the Seismic design notice” hereafter. As the result, a new seismic design method was established against Level 2 earthquake (Safety Shutdown Earthquake) considering non-elastic deformation behavior. This design philosophy was adopted widely for all the plant facilities, which include hydrocarbon, chemical, power, and gas plants, etc., and afterward all related seismic design codes and regulations were revised accordingly.

Although these codes and regulations are prepared for design of newly-constructed plant facilities, the demands to make seismic assessment for the existing plant facilities in accordance with these codes are increasing. The reasons to increase the demands are as follows.
1) Enforcement of a new notice establishing the new seismic design method against Level 2 earthquake
2) Eliminating seismic risk caused by imbalance of seismic performance between new facilities and old ones

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3) Long-term services for existing facilities due to economical reasons

In this paper, technical contents on seismic and deterioration assessments are investigated as a tool for maintenance of the plant facilities. And the relationship between these assessments and risk management is also discussed. Based on the above considerations, the classification of seismic performance levels to be used in these assessments is proposed. Then a case of seismic assessment of the existing equipment structure supporting a reactor and a regenerator on the top floor in a refinery is introduced.

## CORRELATION BETWEEN SEISMIC AND DETERIORATION ASSESSMENTS

### Relationship between seismic and deterioration assessments

When evaluating the present seismic performance of existing structures, it is required to investigate how much the structural strength has been decreased compared with the original at the time of their completion of construction. Therefore investigating actual deterioration of the structures is essential for accurate evaluation of seismic performance.

From other standpoint of deterioration assessment, in case an existing structure is planning to be maintained by upgrading and modification based on the result of deterioration investigation, it is necessary to include making the countermeasures by means of seismic evaluation and re-design, because most of the sectional dimensions of the structures are governed by seismic load cases in Japan.

The purpose of seismic assessment aims to improve seismic performance. On the other hand, deterioration assessment aims to upgrade and modify the deteriorated parts of structures. Accordingly both assessments are required to evaluate their seismic performance and to provide their countermeasures based on their evaluations.

### Deterioration and Seismic Performance

The conceptual relationship between deterioration and seismic performance of structures can be schematically shown in Figure 1.
The vertical and horizontal axes show the seismic performance level and elapsed time, respectively. The solid line shows the seismic performance level as a functional of time at each time.

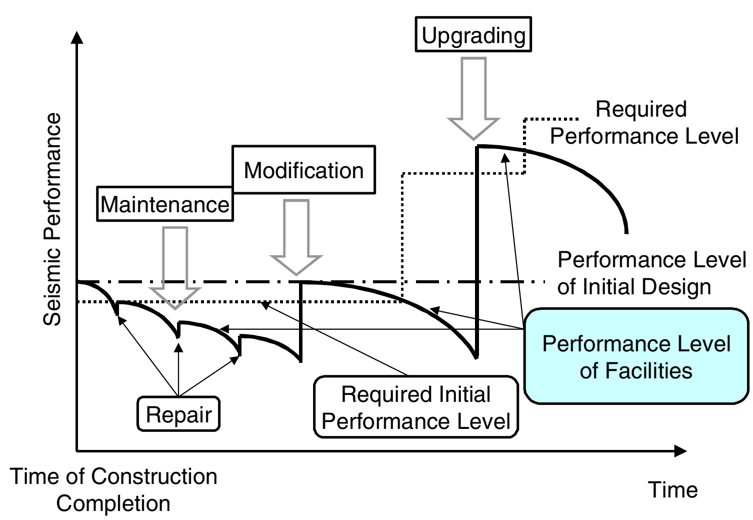


**Figure 1: Relationship between deterioration and seismic performance**

Even if seismic performance of existing plant structures is retained enough, its performance is gradually decreased regardless of maintenance. As the seismic codes and regulations are revised, and the levels of required seismic performance become higher, major upgrading will be required in case the present codes and regulations are applied to the existing structures.

Because plant structures are often located on the seaside and usually served in harsh weather conditions, the aged deterioration of the structure caused by corrosion under such environment is of foremost concern. Hence, when seismic and deterioration assessments are performed, the target of seismic performance level should be determined considering the extent and degree of deterioration at present.

**Importance factors of facilities**
In order to determine a target of seismic performance level of an existing facility, an importance factor has to be determined for each facility. Figure 2 describes the relationship between seismic design level and the seismic performance level for an example.

Their required seismic performance levels depend mainly on their levels of the importance factors. Intensity of design earthquake motions is going to be determined by the both the levels of the importance factor and those of the evaluation methods of the seismic performance. The importance factor should be presumed on the basis of the results of comprehensive evaluation from the standpoint of risk, which is composed of direct influences of leakage of hazardous materials against environment and human beings, and indirect influences concerning impact on the society and potential financial damage by plant shutdown, etc.

In case of the Seismic design notice, the importance factor for each facility is set by means of matrices comprising the storage capacity of designated materials and the distance from protective facilities.

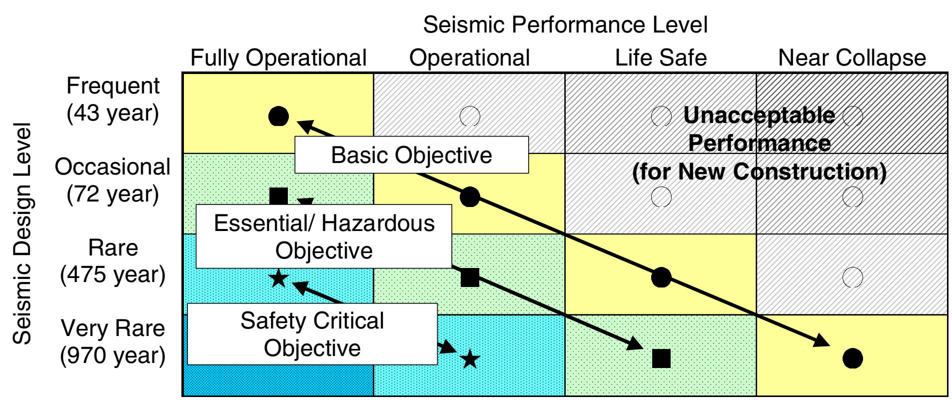


**Figure 2: Recommended seismic performance objectives for buildings (risk assessment matrix)**

**Seismic risk management**
Figure 3 presents a framework for seismic risk management. Seismic risk assessment provides information for decision making when setting levels of importance factors of the intended facilities, which are not specified in any codes and regulations, and reducing their total numbers to be evaluated.

Seismic risk assessments for the facilities start from comprehensive quantification of the risk, based on grasping their risk, and analyzing frequency of the seismic events, their modes of damage, and the degrees of their damage at the time.

The measures against seismic risk include risk transfer by earthquake insurance or securitization, and risk mitigation by seismic upgrading or decentralization of facilities. Eventually appropriate measures will be proposed by employing both these two measures.

However at this time it is difficult to quantify risk as regards the degrees of damage in a certain specific plant facility, since databases based on probabilistic and statistic approach concerning the frequency and the degree of their damage are not available in general. Practically the level of required seismic performance is determined by means of applying importance factors to each facility according to the Seismic design notice.

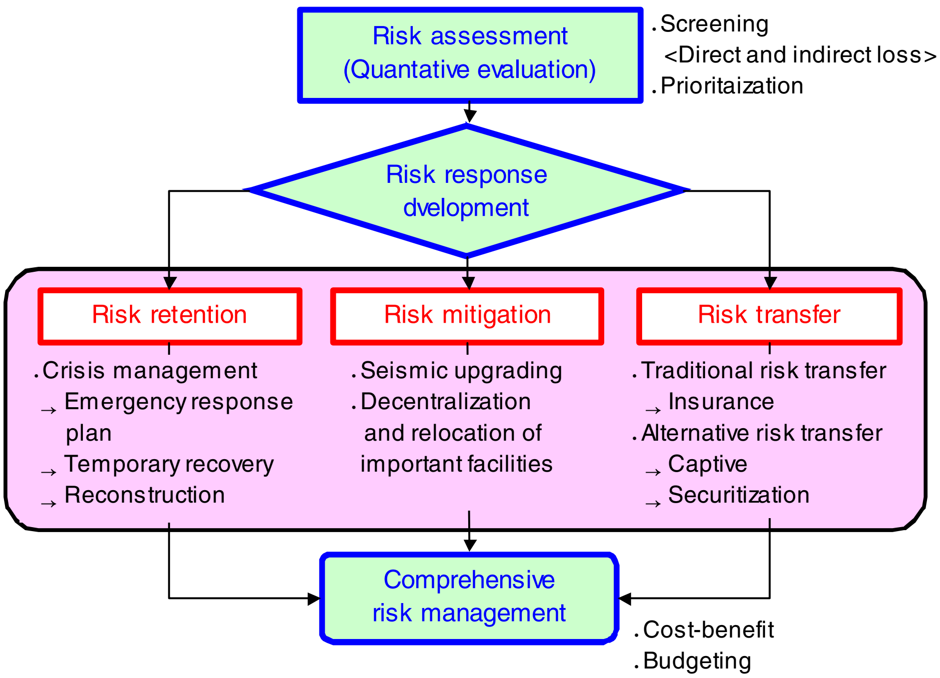


**Figure 3: A framework for seismic risk management**

## CLASSIFICATION OF REQUIREMENTS AND ASSESSMENTS

In order to respond practical requirements of assessments, classification of the evaluation levels on seismic and deterioration assessments and grading on these assessments are proposed in this section.

**Target levels of seismic performance**

In seismic assessment, there are various requirements by owners, for examples, an obscure request to evaluate how strong some equipment is against earthquake, or a practical request to propose an evaluation method in order to hold down the modification costs for an existing facility. So these requirements shall be set in order, and classified according to required seismic performance levels in the seismic and deterioration assessments, as follows.

0: Improvement of defects: The parts, which are presumed as structural defects judging from the experience of past earthquake damage, are improved. (Improvement of only the defects in seismic performance)

1: Modification up to a level of the original codes: The parts of aged deterioration are modified up to the level of required seismic performance of codes and regulations at their construction. (Modification just up to required performance level of the original codes)
2: Modification up to a level of the original performance: The parts of aged deterioration are modified up to the level of the original seismic performance. (Return to original performance level)
3: Upgrading to a level of current code requirements: Upgraded in conformity with the current seismic design codes and regulations. (Upgrade to current codes level)
4: Retrofitting to a level of voluntary seismic upgrading: After analyzing the site-specific ground motions, upgraded in conformity with the specific ground motions. (Retrofit up to seismic hazard analysis level)

**Classification on seismic and deterioration assessments**

In case that seismic performance evaluation is performed based on investigation of deterioration conditions, and that pre-earthquake upgrading and modification is intended, the following grades of assessments shown in Table 1 are proposed. This grading of assessment levels is prepared on the assumption that the grading are set on the basis of each code and regulation to be applied.

**Table 1: Target levels of Seismic Performance and Grades of Assessment**

| Grade | Target level of Seismic Performance | Seismic Countermeasure | Countermeasure of Deterioration | Type of Investigation | Evaluation items | | Remarks |
|---|---|---|---|---|---|---|---|
| | | | | | Seismic Performance | Deteriorated Condition | |
| 0 | Improvement of Defects | Improvement of deficient parts | (Repair or replacement of deficient parts) | Visual inspection | Execution, if necessary | Execution, if necessary | 1), 2) |
| 1 | The Original Code Requirements | Modification, if necessary | Repair | Deterioration investigation | Execution | Execution | 2), 3) |
| 2 | The Original Performance | Modification, if necessary | Replacement or modification | Deterioration investigation | Execution, if necessary | Execution | 3) |
| 3 | Current Code Requirements | Upgrading or retrofitting | Repair or replacement, if necessary | Deterioration investigation, if necessary | Execution | Execution, if necessary | 4), 5) |
| 4 | Voluntary Seismic Upgrading | Upgrading or retrofitting | Repair or replacement, if necessary | Deterioration investigation, if necessary | Execution | Execution, if necessary | 6) |

For reference, the following requirement levels of implemented assessments, which are derived according to the classification of Table-1, are shown in the remarks column in the table.

1) The parts that reduce the original seismic performance of the existing facilities due to defects are selected and improved. (Improvement based on lessons learnt from past earthquake damage after the completion of construction)
2) The load-carrying capacities of the existing facilities are examined, and a structural system is modified to increase its ductility to be resistant to big earthquake.
3) The deterioration of existing facilities is investigated, and the facilities of which seismic performance levels are reduced by deterioration are modified.

4) Old facilities are upgraded to match new facilities regarding seismic performance by rectifying the difference of seismic performance of old and new facilities.
5) Because of alteration, the existing facilities are upgraded to comply with the current codes and regulations.
6) Seismic hazard analysis is carried out, and seismic performance of existing facilities is evaluated based on the calculated site-specific ground motions.

It could be generally accepted that the grade 1 and 2 of the assessment are regarded as deterioration assessment, and the grade 0, 3, and 4 are regarded as seismic assessment.

## A CASE OF SEISMIC ASSESSMENT

Seismic assessment considering an interaction between equipment structure and two vertical vessels on the top floor is presented in this section.
Outline drawing of the facility is shown in Figure 4.
In this case a target level of the seismic performance is ranked as the 3rd grade that is the level of "Current code requirements".

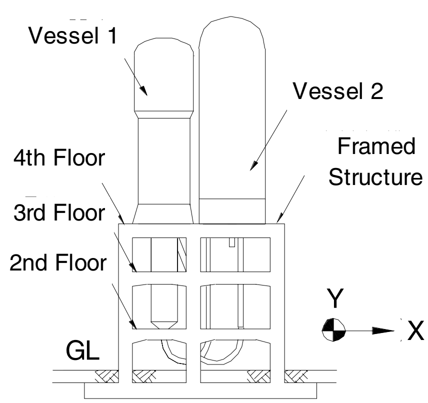


**Figure 4: Schematic view of two vessels and their supporting equipment structure**

Outlines of the structure

Dimensions: 16 m in height (4 stories), 10m×16m (1span×2spans)
Major use: Equipment structure for two vessels
Type of structures: Moment-resistant space frame in both horizontal directions, and steel reinforced concrete structure in main members

**Objectives of assessment**
In principle, this facility is not governed by the Seismic design notice, but this is a component of the whole plant system, which includes a lot of components governed by the notice. So the requirement in this assessment by the owner is to propose how this facility should be modified to hold the same level of seismic performance as the other ones conformed to the notice. Accordingly this facility was evaluated in terms of seismic performance and its countermeasures for the parts not retaining the required performance level were proposed.

The intended facility of this assessment is an equipment structure supporting two vessels. Main requirement of the client was to devise means of applying calculation methods in order to reduce the extent of seismic upgrading and retrofitting and to propose effective and economical countermeasures finally. In addition aged deterioration was not studied in the assessment, because the materials composed of the structure was considered to be sound by a tentative investigation.

**Assessment methods**

The methods for this seismic performance evaluation were as follows:

1) Actual operational weight of the vessels and the equipment structure were re-evaluated to review structural design.
2) Seismic performance of the structure was evaluated for Level 1 ground motion as per Importance factor "I" in compliance with the Seismic design notice.
3) Two types of calculation methods in accordance with the Seismic design notice were applied as follows:

- Case 1: The seismic loads acting on two vessels were individually calculated by the modified seismic coefficient method. In this procedure, the seismic loads for the two vessels included increase of response considering amplification caused by interaction between the structure and two vessels in compliance with the notice. The SRSS (Square Root of Sum of Squares) method was applied to sum up two seismic loads of the vessels to determine loading data for the structure.
- Case 2: Two vessels and the structures were modeled as three lumped masses and springs, and analyzed by modal analysis using response spectrum method.

Here fundamentally the loading data of Case 1 was applied for seismic evaluation, after the load values in Case 1 were confirmed to exceed that of Case 2.

4) Seismic performance of top floor slab should be checked in case that the two seismic loads of vessels are acting under the unfavorable combination in their directions on the slab.

**Result of assessment**

*Review of loading data*

A comparison between load values of its initial design, which are called "old values", and those of the reviewed ones in the assessment, which are called "new values", is made in Table 2. The new values for the total vertical loads of the two vessels and the equipment structure are 9 % lower than those old values. As far as horizontal design seismic loads concerned, the new values are approximately 35% smaller than the old ones. Because their seismic responses have resulted in being decreased on ground that SRSS methods are adopted considering phase difference in vibration between two vessels with the consequence that the fundamental periods of two vessels were fairly different.

Concerning horizontal seismic load acting on the structure, the new values on the 4th floor and 2nd, 3rd floor are 2.3 times and 1.5 times larger than the old ones respectively, because of the following two reasons. First, basically the new seismic coefficient of the structure according to the notice is approximately 1.5 times larger than its old one. Second, coefficient at the 4th floor results in 1.5 times larger than those of the other floors, because seismic coefficient increases in proportion to height of floors in conformity with the Seismic design notice. Consequently the new seismic coefficient at the 4th floor becomes 2.3 times lager than its old one.

The new seismic force acting on the 4th floor, by which seismic performance for the structure was mainly evaluated, is 10-12% larger than the old one. This seismic force is the sum of the seismic force transmitted from the vessels to the floor and the seismic force acting on self-weight of the floor.

Regarding the overturning moments of the vessels acting on the supporting floor slab, the new values of vessel 1 and vessel 2 become 1.9 times, and 1.4 times larger than the old ones, respectively.

**Table 2: Comparison of the calculation sheets**

| Items | | | Old values (A)[a] | New values (B)[b] | (A) / (B) |
|---|---|---|---|---|---|
| Permanent Load (ton) | | | | | |
| Vertical Force of vessel weight | | | 1108.0 | 877.0 | 0.79 |
| Vertical Force of Framed Structure | | | 1909.9 | 1858.3 | 0.97 |
| The Sum of Vertical Forces | | | 3017.9 | 2735.3 | 0.91 |
| Horizontal Load caused by substances in vessels | | | 28.5 | 18.5 | 0.65 |
| Horizontal Seismic Load (ton) | | | | | |
| Vessel 1,2 | X Direction[c] | 4th Floor | 480.2 | 318.9 | 0.66 |
| Framed Structure | X Direction[c] | 4th Floor | 180.3 | 421.0 | 2.33 |
| Framed Structure | X Direction[c] | 3rd Floor | 79.6 | 120.7 | 1.52 |
| Framed Structure | X Direction[c] | 2nd Floor | 76.0 | 113.8 | 1.50 |
| Vessel 1,2 | Y Direction[c] | 4th Floor | 480.2 | 307.0 | 0.64 |
| Framed Structure | Y Direction[c] | 4th Floor | 180.3 | 421.0 | 2.33 |
| Framed Structure | Y Direction[c] | 3rd Floor | 79.6 | 120.7 | 1.52 |
| Framed Structure | Y Direction[c] | 2nd Floor | 76.0 | 113.8 | 1.50 |
| Overturning Moment acting on the parts supporting vessels (ton·m) | | | | | |
| Vessel 1 | X, Y Direction | | 1330.0 | 2485.5 | 1.87 |
| Vessel 2 | X, Y Direction | | 1770.0 | 2471.3 | 1.40 |

a. Values in existing calculation sheets of initial design
b. Reviewed values in this assessment
c. X and Y directions are shown in Figure 4

*Review of load for vessels*

Table 3 shows the comparison between the seismic load values, which are acting on each component, calculated according to the reviewed loading data by modified seismic coefficient method and the calculated ones using modal analysis of three lumped masses system. The both calculation methods complied with the Seismic design notice. For the modal analysis, the normalized response spectrum of the notice was adopted.

**Table 3: Comparison of horizontal shear forces calculated by each method**

| | Members | Lateral Seismic Coefficient on Ground Surface | Response Amplification Factor $\beta 5$[a)] | $\beta 7$[b)] | $\beta 5 \times \beta 7$ | Shear Force (tonf) | |
|---|---|---|---|---|---|---|---|
| Load Values Calculated Using the Reviewed Loading Data | Framed Structure | 0.099 | 2.80 | | | | 974 |
| | Vessel 1 | | 3.30 | 1.26 | 4.15 | 243 | (SRSS) 319 |
| | Vessel 2 | | 3.30 | 1.16 | 3.83 | 206 | |
| Load Values Calculated by Modal Analysis with Three Lumped Masses System | Framed Structure | 0.099 | Vibration mode of Response Magnification Factor: 1st: $2.80 \times 1.18 = 3.30$ 2nd: $2.41 \times 1.18 = 2.85$ 3rd: $2.02 \times 1.18 = 2.38$ | | | | 921 |
| | Vessel 1 and Vessel 2 | | | | | 161 | (Total) 309 |

a): Amplification factor of structures in compliance with the Seismic design code
b): Amplification factor of interaction between structures and vessels in compliance with the Seismic design code

As shown in the table, the maximum shear forces in horizontal directions combined by SRSS method were larger than the maximum ones calculated by modal analysis of three lumped masses system.

*The results of the seismic performance evaluation of the structure*
Using the value of SRSS in Table 3, the result of the seismic performance evaluation of the framed structure is presented in the following Table 4.

**Table 4: The result of analysis (Summary of members in shortage of strength)**

| Members | Types of force | Floor | Positions of insufficient strength / Material | Ratios of stress | Directions of seismic load |
|---|---|---|---|---|---|
| Columns | Shear force | 1 | Bottom / RC | 1.10 | +X |
| | | 1 | Bottom / RC | 1.04 | -X |
| | Bending moment | 3 | Bottom / RC and S | 1.001 | -X |
| Girders and Girders supporting vessels | Shear force | | None | | |
| | Bending moment | | None | | |
| Beams supporting vessels | Shear force | | None | | |
| | Bending moment | 4 | Center / RC | 1.06 | +Y |

1) Columns
The strength of two corner columns out of 6 in the 1st floor carries insufficient strength against shear forces. Here strength against shear forces of the columns in the 1st floor is smaller than those of the 2nd and the 3rd floors, because the length of columns in the 1st floor is short in comparison with ones in the other floors. Regarding short columns their strength is mainly determined by shear failure. Then the calculated bending moment at the top of columns in the third floor has a slight shortage of the required one.

2) Girders and girders supporting vessels
All the girders meet the strength requirement based on the Seismic design notice.

3) Beams supporting vessels
The strength of bending moments of beams supporting vessels in the 4th floor is insufficient in the span direction. Strength against bending moment at the center of these beams is insufficient to the vertical load caused by the overturning moment of vessels, on condition that the permanent loads of the vessels have already acted on the same parts. However, it is considered that the beams have enough strength on the whole, because the beams seem to be combined with the slab, of which thickness is the same as the beams.

**Seismic countermeasures**
Based on the results, countermeasures of pre-earthquake upgrading and retrofitting for the columns, which have shortages of shear strength, are the following.

1) Upgrading to increase ductility against shear force

This countermeasure is intended to upgrade ductility of the columns to increase shear strength without increase of the bending strength. In general methods of this kind of upgrading columns are wrapping with steel plate, reinforced concrete, or carbon fiber sheet, etc.

2) Retrofitting to distribute shear force
The shear forces acting on the columns are reduced by means of distributing the shear forces to added members. In general steel bracings and anti-earthquake walls are added to retrofit.

In this assessment, some feasible countermeasures are proposed, which include data comparing about constructability, the conditions at the construction, the past performance at work, economical efficiency, and so on. In the near future implementation of the countermeasure is going to be contemplated by the owner.

**Conclusion**
As original design of the equipment structure includes a certain amount of safety factor, few members have shortages of strength, and the degree of the shortages is small despite the fact that design seismic loads used for evaluation increased considerably in comparison with the original ones. Accordingly it is possible to judge that the equipment structure has almost the same seismic performance as ones that are designed in conformity with the Seismic design code because all the members have little shortage of the strength. Therefore whether implementing the countermeasures is going to be the owner's decision.

Examining each member of the structure respectively, the results are considered as follows. First, as for the main frames (i.e., columns and girders), it is considered that the analysis result that the seismic loads transmitted from two vessels were reduced with consideration of the phase difference of the vessels' seismic responses, was of great advantage for the evaluation of seismic performance. Second, the strength of the girders supporting vessels has come little short despite the overturning moments in this calculation became 1.4 to 1.9 times larger than the old values, because the original design of these girders included excessive amount of safety factor. At last, the fact that the permanent loads of vertical direction have decreased approximately 20% based on a review of the current operational weight for vessels had also good advantage to evaluate the equipment structure itself.

In this assessment the seismic load was appropriately evaluated by the modal analysis, considering the review of loading data and the interaction between the structure and the two vessels. As a result, only the minimum extent of upgrading and modification was found to satisfy the required seismic performance by making full use of the original strength and the structural characteristics of each member.

Consequently evaluating appropriate seismic loads by dynamic and/or other detail analysis makes it possible to propose economical and effective countermeasures.

## FOR FUTURE APPLICATION

It is complicated to evaluate seismic performance of the plant facilities, because they are composed from towers and tanks, piping, and their supporting structures, etc., and those components are connected to each other structurally. It is easy to design before construction, if it is possible to adopt safety factors and simplified design methods. However in case of seismic assessment, the sophisticated skills of engineering approaches are required to evaluate their seismic performance in detail in order to make more efficient and more economical countermeasures for the existing facilities. Furthermore required structural details of codes and regulations applied to the existing facilities are different from the latest ones, it is also required to evaluate in consideration of their differences.

In case of plant facilities, all the facilities will be classified into several important levels according to their roles in the plant and risks of their contents, etc. Then it becomes the most important matter that the target facilities to assess seismic performance are chosen and the objectives of their seismic performance levels are presumed, before the seismic assessment is performed.

So it is required to presume each importance level based on the estimation of the seismic risk, since the required level of seismic performance depends on the important levels. At this point, estimation of the seismic risk plays an important role in this decision.

However it is rather difficult to assess quantitatively the extent of damage on highly specialized plants. Consequently in order to improve the precision of assessment of seismic risks, the data gathering under super-corporate control concerning earthquake damage is expected.

In the future it should be required to involve the consideration of the seismic risks, whenever the life-cycle-cost to be required to maintain facilities is examined, because the pre-earthquake upgrading and the repair of deterioration should be considered mutually.

In addition, in the United States, the “Guidelines for Seismic Evaluation of Petrochemical Facilities” and the “Proposed Guidance for PMPP (Risk Management and Prevention Program) seismic assessments” have already published. And these guidelines are prepared for existing facilities. As concerning about significantly wide-spread damage caused by seismic events, there is obvious differences on the level of interest in earthquake disaster between the public and private sector in Japan, it is considered desirable that seismic assessment for pre-earthquake upgrading and modification for the existing plant facilities are discussed and developed in collaboration with the public and private sector.

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