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# A Comparative study of Seismic Performances of Plant Facilities Complying with Seismic Design Codes of the Countries of Southeast Asia

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## *Abstract*

On March 11, 2011, several refineries and chemical plants (hereafter referred to as "plant facilities") in eastern Japan suffered serious damages due to the Great East Japan Earthquake and Tsunami. After investigations and studies on the damages inflicted to the plant facilities, design methods for earthquake-resistant plants have been reconfirmed and improved. In addition, seismic diagnosis and reinforcements have been carried out on existing plant facilities that were unaffected by the disaster to be prepared for the potential seismic event of the Nankai Trough mega-earthquake, that is predicted to occur in the near future.

The valuable lessons learnt from these disasters are important for future studies in earthquake-prone countries of southeast Asia. In these regions, as there are old existing plant facilities as well as new ones being built, these countries are expected to make the best use of these experiences from Japan and transfer improved seismic design technology in line with their design codes and practices. Based on the above background, a Japan International Cooperation Agency (JICA) survey project study was carried out in 2012 to investigate whether Japanese seismic technologies could be introduced in Vietnam, Indonesia, and the Philippines appropriately and whether these technologies can improve the safety of earthquake-resistant plants and meet the new requirements

In this study, by summarizing the results of the survey, required seismic performances of the plant facilities in accordance with the seismic design codes of the three countries, and Japan are compared. Moreover, by conducting a trial design, the shell thicknesses of a typical tower designed by adhering to each seismic design code are presented for evaluation. From the outcome of this study, the differences in the required seismic performances of the three countries and Japan are validated, and certain design margins of the actual plant facilities when applying the Japanese code are noted.

Furthermore, two other papers that highlight this design margin are introduced. In one of the papers—"Report of Investigation Study on Evaluation of Seismic Reinforcement for High Pressure Gas Facilities" of 2015—evaluation results of the margins of a tower designed in conformity with Japanese seismic design codes are reported using static elastoplastic analysis of finite element method models. In addition, the authors' paper—"A Study on Optimization of Seismic Strengthening for the Plant Facilities in terms of Plant Management"—examined the sensitivity of development of seismic damage concerning each damage modes of the tower and the foundation in case that seismic loads exceed the (code specified)seismic design load.

The approach referred in the two papers can be applicable to the three countries for which seismic design codes are investigated and evaluated through the trial design in the first part, and it would provide similar results on the design margin and damage modes' sensitivity to large-earthquake.

*Keywords: Trial design of seismic design codes, Margins of seismic design, Sensitivity analysis of damage modes*

# 1. Introduction

Over five years have passed since the Great East Japan Earthquake occurred. Useful lessons learnt have been accumulated with regard to the seismic design and damage of plant facilities in Japan. As investigations and studies proceeded, it was revealed that the degree of ground motion during the earthquake was far greater than the design level in accordance with the existing seismic design codes of Japan, and that the ground motion itself (except the tsunami that followed) did not cause any catastrophic disaster such as a hazardous or flammable gas or liquid leakage and a subsequent fire or explosion in major plant facilities. These facts are considered favorable in Japan, where larger earthquakes such as the Nankai Trough mega-earthquake, are expected to occur in the near future in the southwest regions of the country. Hence, considerable amount of research is required to investigate the effectiveness of the seismic design code with respect to large earthquakes, the extent of allowance and margins for the plant facilities if designed in accordance with the seismic design codes, and identifying parts of the plant facilities most critical when considering large earthquakes.
These concerns are also held in other earthquake-prone countries in southeast Asia. The plant facilities in these countries were built or are being built in accordance with their national seismic design codes and design practices, which have been examined with far less earthquake frequency than that in Japan. Levels of seismic performance of plant facilities are highly affected by the severity of requirements in the seismic design code that is applied, and the Japanese design codes would serve as good references without any doubt. In this context, the JICA project study[1], "Project Study for Seismic Engineering for Chemical and Petrochemical Plant (Final Report)" was carried out in November 2012 with support from the Japanese government, and seismic design codes applied to plant facilities in Vietnam, Indonesia, and the Philippines were investigated. Additionally, in accordance with the seismic design codes of the three counties, the thickness of a typical tower with a supporting skirt considered as the representative equipment of plant facilities is calculated.
In this paper, the following studies for which the author was intensively involved are introduced.

- "Report of Investigation Study on Evaluation of Seismic Reinforcement for High Pressure Gas Facilities," [2]
  Evaluation on the margins of the Japanese-code-based seismic design for plant facilities was conducted.
- "A Study on Optimization of Seismic Strengthening for the Plant Facilities interim of Plant Management" [3]
  Sensitivity analysis of allowable ratios for each damage mode against variations in the design seismic coefficient on ground was conducted.

The above two studies provide important findings related to the Japanese seismic design codes for plant facilities in large earthquake-prone areas. These findings would provide precious hints for seismic design in these southeast Asian countries. In combination with the JICA study results, seismic countermeasures to avoid intense damage due to large seismic loads exceeding the design load would be obtained by a similar study approach.

# 2. Comparison of the minimum required thicknesses of tall towers designed in accordance with the national seismic design codes of Indonesia, Vietnam, and the Philippines

## 2.1 Seismic design code of each country

With the help of the JICA's investigation in 2012 on seismic design codes of Indonesia, Vietnam, the Philippines, USA, and Japan, the applicable scope for plant facilities is summarized in Table 1.

Table 1- Applicable scope of seismic design codes

| Facilities | Japan | USA | Vietnam | Indonesia | Philippines |
|---|---|---|---|---|---|
| Building structures | The Building Standard Act | ASCE 7 (or UBC, IBC) | TCXDVN 375 | SNI-03-1726 | NSCP |
| Nonbuilding structures similar to building | High Pressure Gas Safety Act | | | | |
| Nonbuilding structures | | | (None) | (UBC) | |
| -Pressure vessels | | | | | |
| -Heat exchangers | | | | | |
| -Piping | | ASME B31E | | (None) | (None) |
| -Storage tanks | Fire Service Law | API 650 Appendix E | EN 1988-4 | (API 650 Appendix E) | (API 650 Appendix E) |

Note: Code names with parenthesis mean de-facto standards. They are not specified by national codes but are applied in those countries.

(1) Indonesia

In 2012, the Committee of Research Institute for Human Settlement had a plan of introducing the concept of the ASCE 7-2009（American Society of Civil Engineers）into the new seismic design code of SNI 03-1726-2002, which was written based on the UBC -1997 (Uniform Building Code). The new code, SNI 03-1726-2012, was approved by the Ministry of Public Works, and it is currently used in design.

(2) Vietnam

Although “TCXDNV 375: 2006 ‘Design of Structures for Earthquake Resistance’” was provided based on the “EURO CODE (1998-1 BS-EN: 2004)” in 2012, the code has not been widely used.

“TCXDNV375: 2006” was planned to be applied for plant facilities under design at the time, but it was difficult in reality because the EURO CODE itself had not been required for plant equipment (for example, towers, vessels, and spherical tanks) except storage tanks.

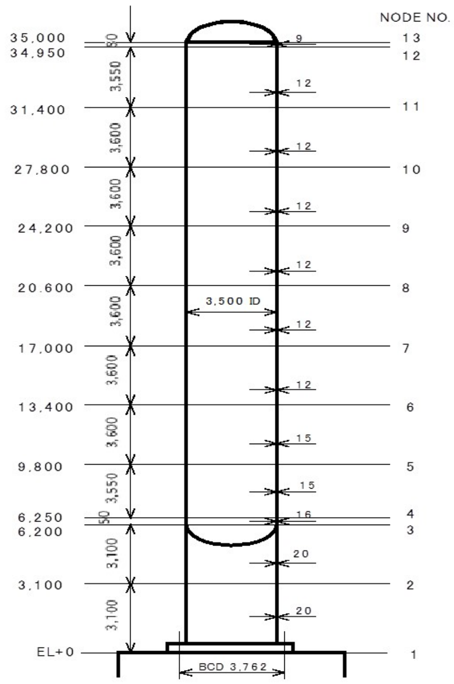
(3) Philippines

NSCP (National Structural Code of the Philippines) 6$^{th}$ Edition-2010 has been organized with reference to UBC, and plant facilities are also recognized as target structures (nonbuilding structure) in the code. Hence, except for piping, the seismic design procedures for plant facilities are developed in the code.

## 2.2 Calculation results

Based on the investigation results of seismic design codes applied to plant facilities, the minimum required thicknesses of a tall tower, which is one of the typical instruments in plant facilities, was calculated as part of a trial. The tall tower is the center of plant systems in various plant facilities, such as process reactors, and it is assumed to suffer significant damage from large seismic loads.

To study the effects of these seismic design codes on the actual thicknesses of shell and supporting skirt, the minimum required thicknesses were calculated on trial for the sample tower shown in Figure 1.




- Design Pressure: 0.35 Mpa
- Design Temperature: 150 °C
- Material
  - Steel: SA516 Gr. 70(CS)
  - Head: SA516 Gr. 70(CS)
  - Skirt: SA516 Gr. 70
- Natural Period: 0.59 s
- Damping Factor: 3 %
- Pressure Vessel Design Code:
  - ASME Section VIII division 1

Figure-1 Calculation model for seismic design of a tall tower

### 2.2.1 Calculation Model

As shown in Table 1, seismic design codes of Vietnam and Indonesia can be applied to building structures, but these cannot be applied to nonbuilding structures, which constitute the majority of plant facilities. Accordingly, as some components cannot be realistically designed if the seismic design codes are strictly applied, certain necessary factors for the trial calculation, such as importance factors, are assumed based on the past actual design results.

(1) Assumptions for calculation

Seismic design codes of all the three countries can be applied to the steel structure. However, seismic design codes of Indonesia and Vietnam cannot be applied to the tower because the importance and reduction factors (behavior factor in the case of Vietnam) are not specified in their design codes. Therefore, an importance factor of 1.0 is assumed for Indonesia and Vietnam. A reduction factor of 2.9 for the tower is assumed for Indonesia, which is the same value as specified by the UBC—the de-facto standard in Indonesia. For Vietnam, a behavior factor of 2.0, which is the same value as specified for silos by Vietnamese seismic design code, is assumed.

Moreover, it is assumed that the tower and the structure are constructed in the zone where the design horizontal seismic acceleration is the highest and on a soil whose seismic response is the highest with respect to the natural periods of the tower and the structure.

## 2.2.2 Calculation results

(1) Vietnam

The design horizontal elastic response spectra for Vietnam are shown in Figure 2.

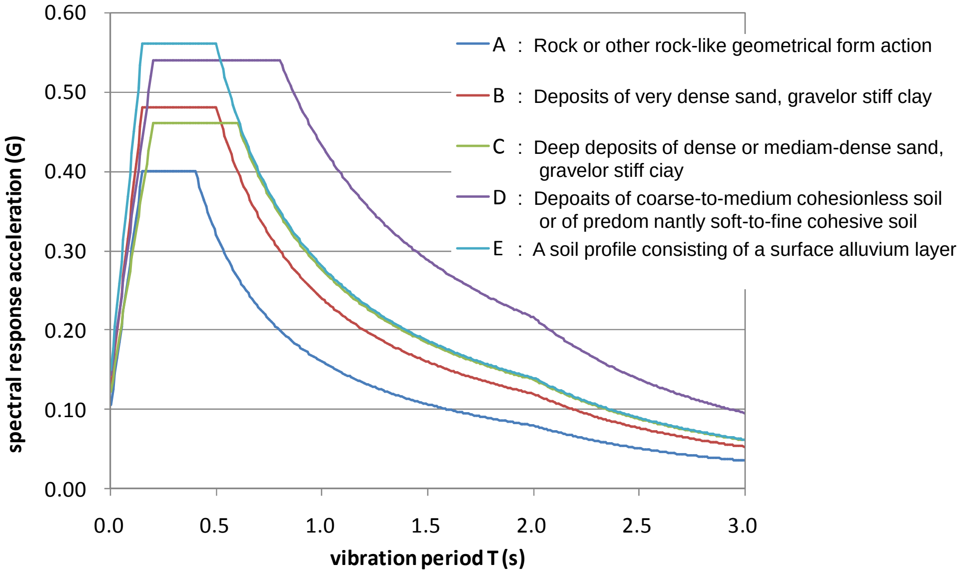



Figure 2. Horizontal elastic response spectra for earthquakes in Vietnam
(Seismic design code of TCXDVN 375-2006, Peak ground acceleration = 0.16G, Importance factor =1.0, Behavior factor =1.0, Damping factor = 5%)

The distribution of the seismic shear forces and bending moments on a sample model of the tower is shown in Figure 3.

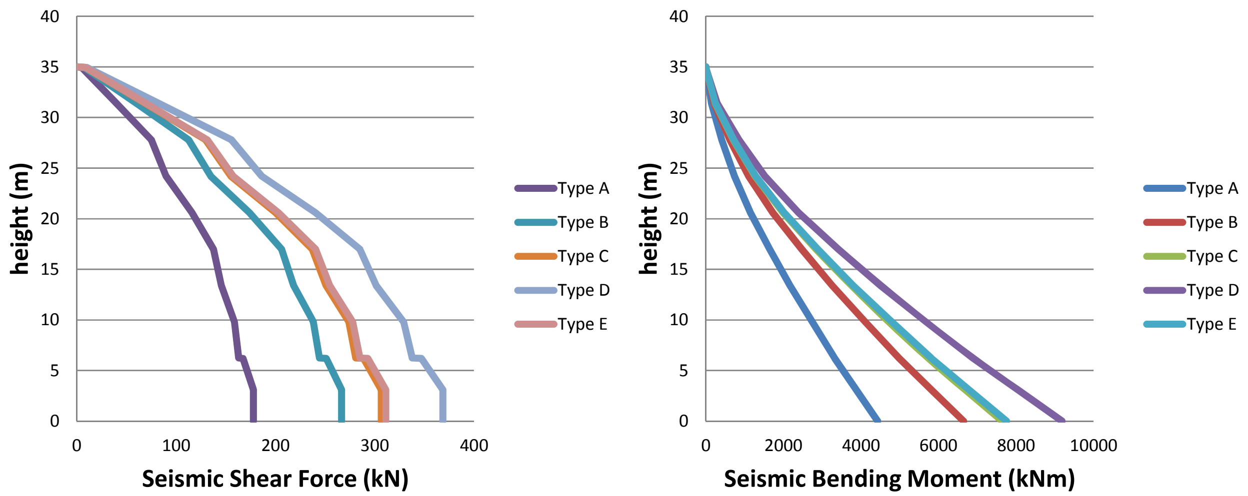



Figure 3. Distribution of seismic shear forces and bending moments for the tall tower in Vietnam
(Seismic design code of TCXDVN 375-2006, agR=0.16, Importance factor = 1.0, Behavior factor (q) =2.0)

(2) Indonesia

The design horizontal elastic response spectra for Indonesia are shown in Figure 4.

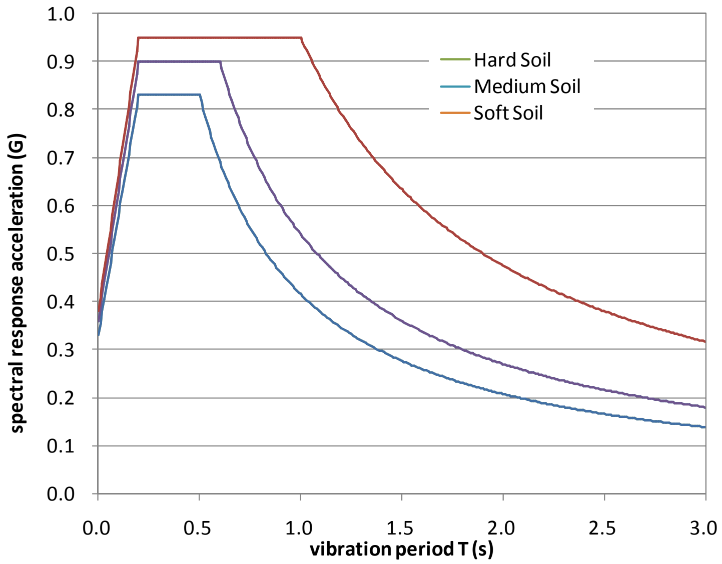



Figure 4. Horizontal elastic response spectra for earthquakes in Indonesia
(Seismic design code of SNI-02-01726-2002, Seismic zone 6, Damping factor =5%)

The distributions of seismic shear forces and bending moments on a sample model of the tower are shown in Figure 5.

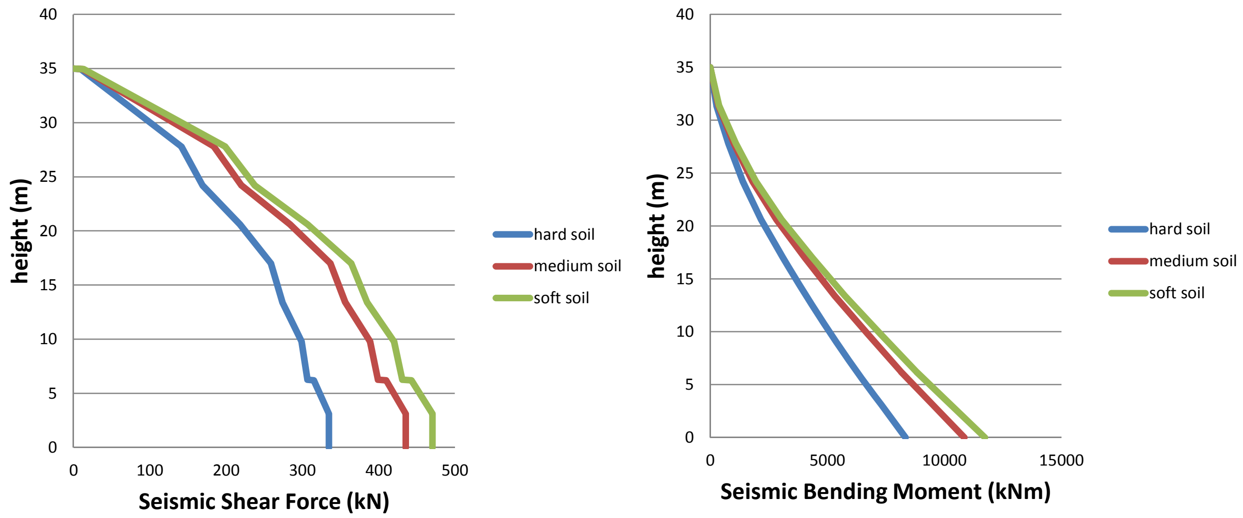



Figure 5. Distributions of seismic shear forces and bending moments for the tall towers in Indonesia
(Seismic design code of SNI-02-01726-2002, Seismic zone 6, Importance factor = 1.0,
Reduction factor (R) =2.9 (same as UBC))

(3) The Philippines

The design horizontal elastic response spectra for the Philippines are shown in Figure 6.

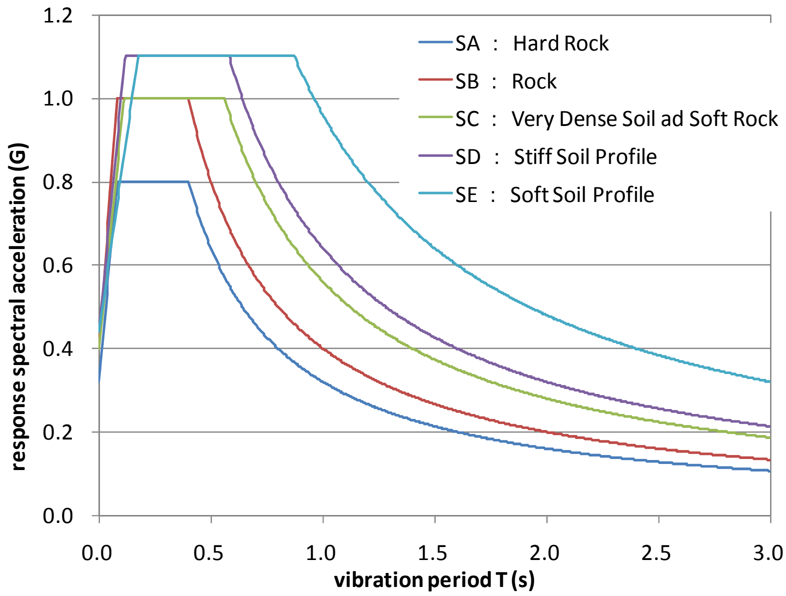



Figure 6. Horizontal elastic response spectra for earthquake in the Philippines (Seismic design code of NSCP 2010, Seismic zone 4, Damping factor = 5%)

The distributions of the seismic shear forces and bending moments on a sample model of the tower are shown in Figure 7.

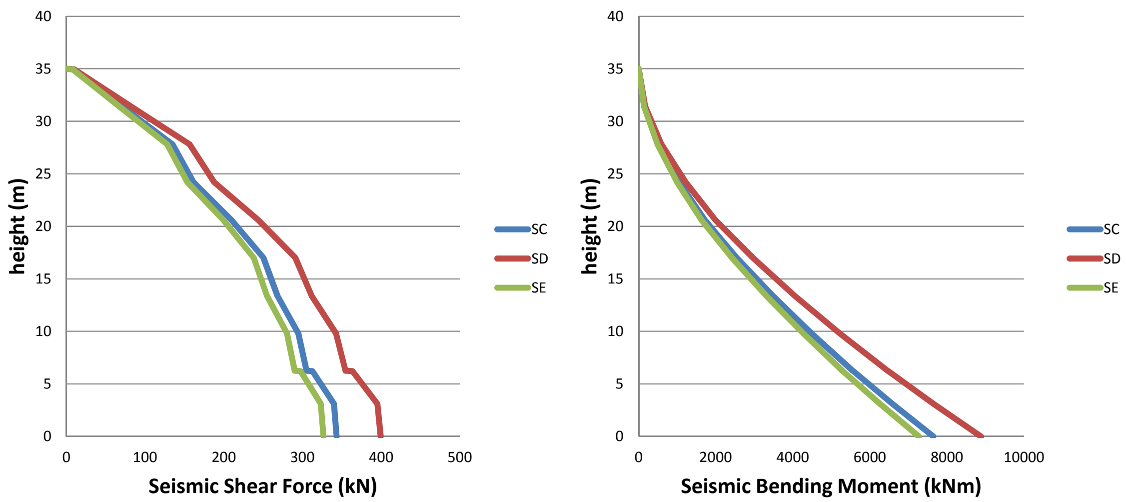
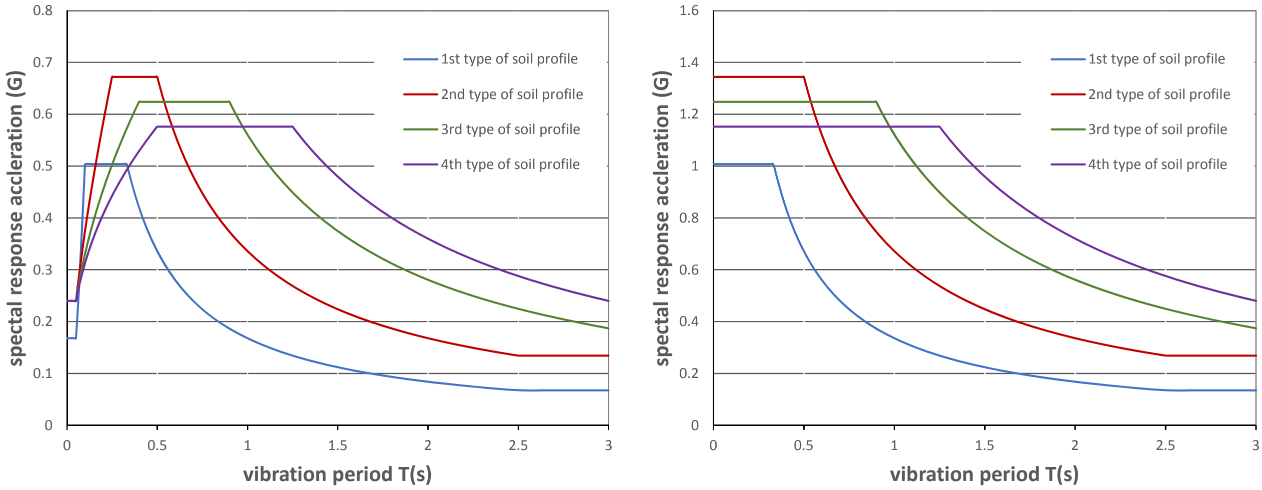



Figure 7. Distributions of seismic shear forces and bending moments for the tall towers in the Philippines (Seismic design code of NSCP 2010, Seismic zone 4)

(4) Japan

A seismic design code of HPGF-KHK (High Pressure Gas Safety Act in Japan) was applied to the tower, and the design horizontal elastic response spectra for Japan are shown in Figure 8.




(a) Earthquake Level 1 (b) Earthquake Level 2

Figure 8. Horizontal elastic response spectra for earthquakes in Japan
(Seismic design code of HPGF-KHK, Seismic importance class I, Zone SA, Damping factor = 5%)

The distribution of the seismic shear forces and bending moments on a sample model of the tower is shown in Figure 9.

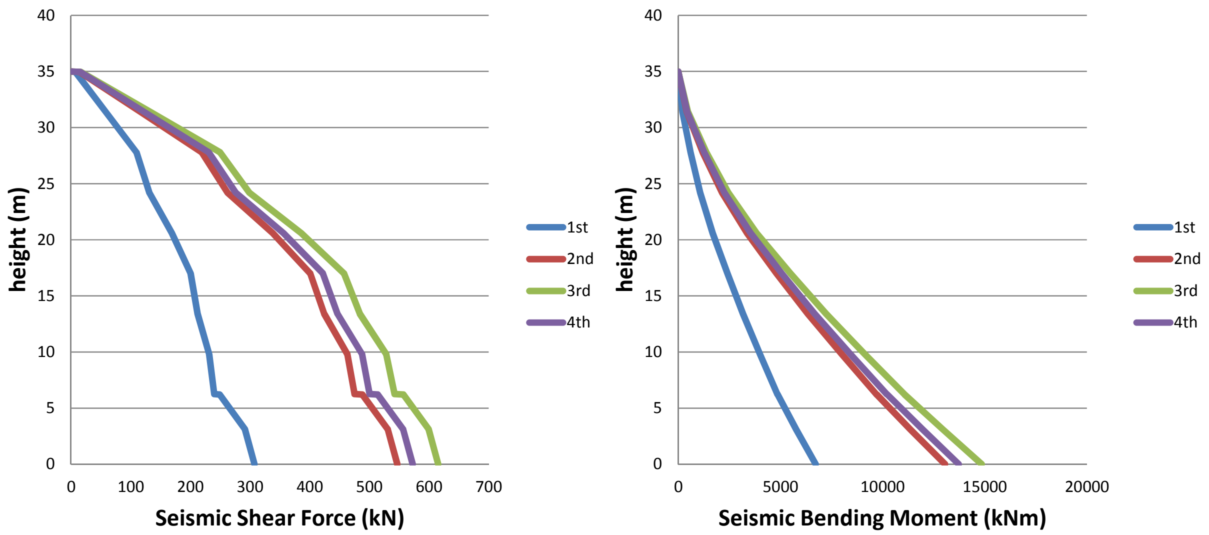
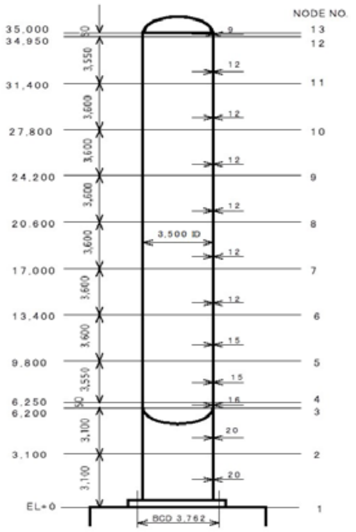



Figure 9. Distributions of seismic shear forces and bending moments for the tall towers in Japan
(Seismic design code of HPGF-KHK, Importance factor =0.8, Zone SA)

### 2.2.3 Comparison of results

From the results of the calculation, the minimum required thicknesses are listed in Table 2.

Table 2. Minimum required thicknesses of shell and skirt of a tall tower




| | Japan | Viet Nam | Indonesia | Philippine |
|---|---|---|---|---|
| t12 (mm) | 9 | 9 | 9 | 9 |
| t11 (mm) | 12 | 12 | 12 | 12 |
| t10 (mm) | 12 | 12 | 12 | 12 |
| t9 (mm) | 12 | 12 | 12 | 12 |
| T8 (mm) | 12 | 12 | 12 | 12 |
| t7 (mm) | 12 | 12 | 12 | 12 |
| t6 (mm) | 12 | 12 | 12 | 12 |
| t5 (mm) | 15 | 12 | 12 | 12 |
| t4 (mm) | 15 | 12 | 12 | 12 |
| t3 (mm) | 16 | 12 | 12 | 12 |
| t2 (mm) | 17 | 13 | 14 | 11 |
| t1 (mm) | 17 | 13 | 14 | 11 |
| Natural period (s) | 0.61 | 0.69 | 0.68 | 0.71 |
| Ope. Wt (kN) | 1,437 | 1,388 | 1,394 | 1,377 |

### 2.3 Consideratıons

The calculation result shows that the seismic performance of the tower is dependent on the minimum required thicknesses as expected.

In case of Japan, the thicknesses of pressure parts below the level of 13.4 m are governed by seismic loads. However, in cases of the other three countries, only the thicknesses of the supporting skirts are governed by seismic loads. From the results, it is established that the sequence of the required thicknesses of the supporting skirts decreases in the order—Japan, Indonesia, Vietnam, and the Philippines.

Considering that the seismological conditions and seismic design requirements are different in these countries, it is suggested that a simple comparison should not be easily made. However, the results of Table 2 might be useful in determining the difference in the seismic design codes and magnitudes of the seismic loads in these countries.

The plant facilities of the three countries and Japan are designed using the highest value of design acceleration spectrum based on the ultimate strength design. However, the value of the highest design spectrum of the Japanese code is higher than that of the other three countries, because the return period of the Japanese code is 1000 years, while that of the other three countries is 475 years. Hence, the required thickness of the supporting skirts is different because of this reason.

During the Great East Japan Earthquake, the towers in the east Japan area experienced ground motions of more than 1000gals in terms of peak ground acceleration (PGA) exceeding that of 1000 years return period and retained air tightness. "The safety of the plant shall be kept against an earthquake with a 1000 years return period", is referred to as level 2 seismic performance and the maximum values of PGA corresponding to the earthquake with a 1000 years return period is 600 gals for the most important facilities in the most earthquake-prone regions in Japan.

However the towers in the east Japan areas were designed using design ground motion of approximately 300 gals, which is equivalent to the ground motion for the level 2 seismic performance, because the lower values of the importance factors and the local factors are applied. Consequently, if the towers are designed using the Japanese seismic design code, it is assumed that they can withstand the design earthquake with a certain margin, which will be discussed in the next section.

## 3. Margins of the seismic design for Japan

The towers designed by the Japanese seismic design code retained air tightness after they experienced the inertial force of the ground motions due to the Great East Japan Earthquake, which exceeded their code-specified ground motions. Hence, the extent of the margin of the seismic design for plant facilities draws additional attention.

### 3.1 The study results of the margins

Based on the lessons learnt from the Great East Japan Earthquake, "Report of Investigation Study on Evaluation of Seismic Reinforcement for High Pressure Gas Facilities" [2] was issued in March of 2015, in which the current seismic design code of Japan was reviewed.

In this report, the limit acceleration of standard models of plant facilities using static elastoplastic analysis are defined as an acceleration of the limit state causing the collapse. And the ratio of the limit acceleration to the design acceleration is defined as the margin of seismic design. Considering the tower model including the tower of the same specification as discussed in this study, the acceleration ratio, i.e., the margin, was estimated at the extent from twice to four times.

### 3.2 Sensitivity of each damage mode to design acceleration on the ground

In the authors' study,[3] sensitivity analysis was conducted using design acceleration as a variable that considered each damage mode of the tower and the foundation shown in figure 10.

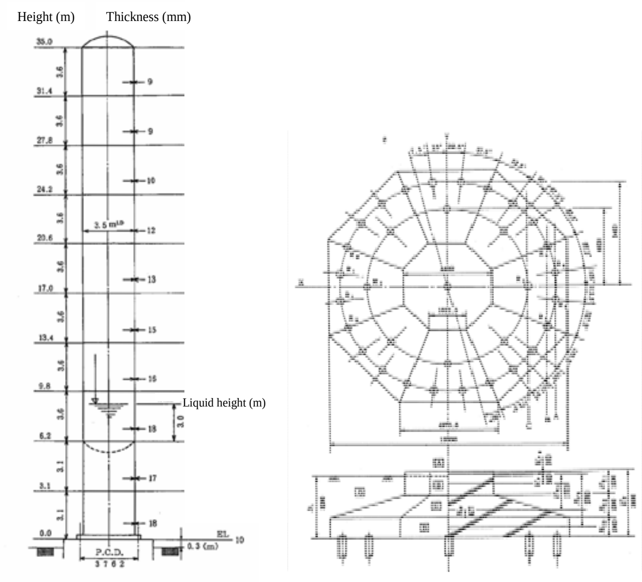



Figure 10. Calculation model for sensitivity analysis of a tall tower and the foundation

Using the evaluation method for level 2 seismic performance of the seismic design code in Japan, response non-elastic displacement ratios of each damage modes are calculated in this sensitivity analysis.

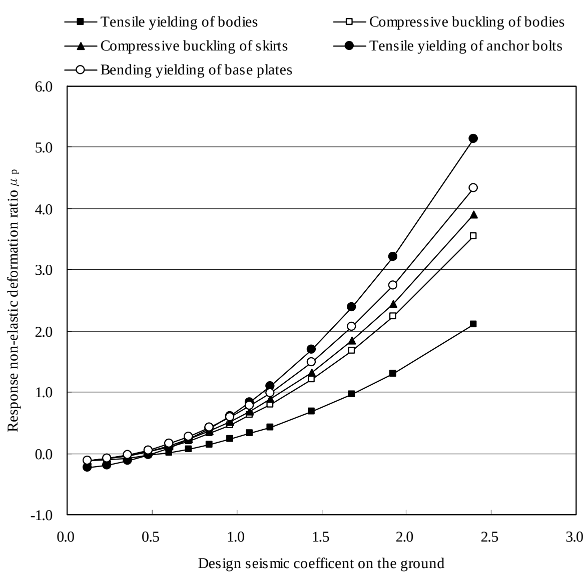



Figure 11. Relationship between design seismic coefficients on the ground (SCG) and nonelastic deformation ratios for towers

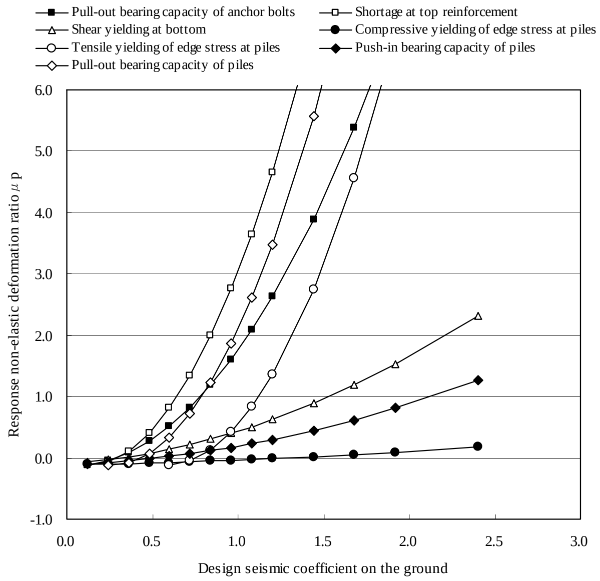



Figure 12. Relationship between design seismic coefficients on the ground (SCG) and nonelastic deformation ratios for foundations

Figure 11 and Figure 12 show the relationship between the design seismic coefficients on the ground and damage modes of the tower/the foundation, respectively. Considering the three damage modes of shortage at top reinforcement, pull-out bearing capacity of anchor bolts, and that of piles, the response nonelastic deformations rapidly increase with the increasing design seismic coefficients on the ground. Regarding these damage modes, it is possible to cause large damage that is equivalent to the response nonelastic deformation, exceeding the allowable nonelastic deformation if the seismic load exceeds the load of the design seismic coefficient.

### 3.3 Considerations

From the study results of seismic design margins, the tower and the skirt designed in conformity with the seismic design code for Japan have margins 2–4 times than that of the allowable ratio values. Moreover, from the sensitivity analysis, it is confirmed that the three damage modes of the foundation are more sensitive than that of the tower and the skirt with respect to the variation in the design seismic coefficient.

Accordingly, it is possible that exceeding the design seismic load will tend to cause greater damage to the foundation as compared to the tower. Hence, it is recommended that seismic countermeasures regarding the three damage modes should be preferentially implemented.

In the previous section 2, the difference in the required minimum thickness for the tower and the skirt conforming with the seismic design code of the three countries and Japan was compared. In this section, as far as the tower and the foundation design by the seismic design code of Japan is concerned, it is shown that the margins of code-specified seismic design can be calculated, and more specifically, the order of damage mode occurrences for large earthquakes and the recommended priority of implementing seismic countermeasures can be estimated. This study approach can be applicable to the other three countries, although some modification may be required due to the difference in the national seismic code systems from the Japanese code. Finally, similar study results on damage modes' sensitivity to earthquakes will be obtained and some useful hints on implementing seismic countermeasures for specific structures will be provided.

## 4. Conclusions

In this study and from the JICA survey results, required seismic performance of plant facilities using the seismic design codes of the three countries and Japan are compared. Moreover, based on the trial design results of the tower, the tower shell thicknesses designed by adhering to each seismic design code are compared. From the results, the required thicknesses of the supporting skirts are shown to be the highest for Japan, followed by Indonesia, Vietnam, and the Philippines, in decreasing order. Considering that the seismological conditions and seismic design requirements vary with each country, it is suggested that a simple comparison should not be performed. However, these results might be significant in understanding the differences in seismic design codes and magnitudes of the seismic loads in these countries.

In the case of towers in Japan, study results of the seismic design margins and damage modes that are sensitive to exceedance of the design seismic load are presented. Consequently, considering a tower model with the same specification as seen in this study, the seismic design margins are estimated as the extent from twice to four times that of the acceleration ratio. Furthermore, it is confirmed that some damage modes of the foundation tend to occur easily with the exceedance of the design seismic load. Accordingly, it is efficient and effective to preferentially implement seismic countermeasures for those sensitive damage modes of the foundations. Although the study results of Japan could not be applied directly to the other countries, a similar procedure of analysis would provide some suggestions for more efficient and effective seismic countermeasures in the other countries.

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