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STUDY OF THE SEISMIC RESPONSE OF VERTICAL STEEL VESSELS

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บทคัดย่อ

การคำนวณแรงแผ่นดินไหวที่กระทำต่อโครงสร้างหอกลั่นเหล็กแนวตั้งสามารถคำนวณได้ 2 วิธี คือ วิธีแรงสถิตเทียบเท่าและวิธีเชิงพลศาสตร์ ผู้ออกแบบส่วนใหญ่นิยมใช้วิธีแรงสถิตเทียบเท่าเนื่องจากเป็นวิธีที่เข้าใจง่าย แต่สำหรับโครงสร้างหอกลั่นเหล็กแนวตั้งที่มีความไม่สม่ำเสมอของมวล การคำนวณด้วยวิธีแรงสถิตเทียบเท่าอาจไม่สอดคล้องกับพฤติกรรมตามความเป็นจริงของโครงสร้าง การศึกษานี้มีวัตถุประสงค์เพื่อประเมินผลตอบสนองของโครงสร้างหอกลั่นเหล็กแนวตั้งต่อแรงแผ่นดินไหว โดยเปรียบเทียบผลตอบสนองที่เกิดขึ้นในรูปของแรงเฉือนที่ฐานและโมเมนต์ที่ฐาน จากการคำนวณแรงแผ่นดินไหวระหว่างวิธีแรงสถิตเทียบเท่ากับวิธีเชิงพลศาสตร์แบบสเปกตรัมการตอบสนองแบบโหมด ด้วยแบบจำลองอย่างง่ายและไฟไนต์เอลิเมนต์แบบจำลอง 3 มิติ โดยโปรแกรม STAAD Pro และใช้ค่าความเร่งตอบสนองเชิงสเปกตรัมที่คาบการสั่นของโครงสร้างในกรณีต่างๆ จากพื้นที่ศึกษาแอ่งกรุงเทพ โซน 5 ตามมาตรฐานการออกแบบอาคารต้านทานการสั่นสะเทือนของแผ่นดินไหว มยผ. 1302 ผลการศึกษาพบว่าการวิเคราะห์แรงแผ่นดินไหวด้วยแบบจำลองเกือบทุกแบบ โดยวิธีเชิงพลศาสตร์ให้ค่าแรงเฉือนที่ฐานน้อยกว่าวิธีแรงสถิตเทียบเท่าที่ 25-36% สำหรับกรณี Empty และ 23-32% สำหรับกรณี Operation ยกเว้นการวิเคราะห์ด้วยแบบจำลองอย่างง่ายโดยการรวมมวลไว้จุดเดียว (Single Lump Mass) จะให้ค่าแรงเฉือนที่ฐานใกล้เคียงกันทั้งสองวิธี โดยวิธีเชิงพลศาสตร์ให้ค่ามากกว่าเพียง 2.7% และ 1.7% สำหรับกรณี Empty และ Operation ตามลำดับ

ABSTRACT

Seismic analysis of vertical steel vessels can be performed by using an equivalent static force procedure and a dynamic analysis method. The equivalent static method is commonly used to determine earthquake load because it is a simple design method. However, a dynamic analysis may be required in the case of unusual structures that have significant irregularities in mass, such as vertical steel vessels with differences in mass distribution. This study aimed to evaluate the seismic response of vertical steel vessels by comparing the results of base shear and overturning moment between the equivalent static method and modal response spectrum analysis by simplified model and 3D finite element model that used STAAD Pro for creating the geometry of a vertical steel vessel. The acceleration used for seismic analysis of Bangkok's soft soil area (Zone 5), referring to the standard for earthquake-resistant design of structures (DPT. 1302-52), depends on the period of vibration on the vertical steel vessel in each load case. The results of the study indicated that almost all analytical models by dynamic analysis method resulted in base shear *around 25-36% lower than that analyzed by the equivalent static method for empty condition and 23-32% for operation condition, excluding the simplified model (single lumped mass model), which yielded base shear close to the equivalent static analysis method at 2.7% and 1.7% higher for the empty and operation conditions, respectively.*

KEYWORDS: Vertical steel vessel, Finite element analysis, Seismic response, Equivalent static method, Dynamic analysis

1. Introduction

Study concerning the theory of seismic response aims to understand the derivation of earthquake load, the dynamic properties and the behavior of structural vibration, which could serve as a guideline for reducing damage. Structures used in the petrochemical industry are designed to emphasize safety. A vertical steel vessel is an important structure because there is the constant risk of leaks for chemical and flammable substances. A vertical steel vessel is often located in the processing unit of petrochemical factories. Its primary structure is made of carbon steel sheeting. This researcher is interested in studying such structures.

The Department of Public Works and Town and Country Planning has stipulated a Ministerial Regulation B.E. 2550 prescribing the load capacity, resistance, and durability of buildings, as well as the bearing capacity of soil supporting buildings for seismic resistance. It is required that individuals who conduct such design calculations must calculate the buildings to withstand the seismic waves caused by earthquakes using the dynamics calculation method. The structure of vertical steel vessels in this study can be classified as an irregular structure that has irregularities in mass distribution, which requires the dynamics analysis method. Therefore, this study aimed to investigate the seismic responses of vertical steel vessels and compare the responses derived from the analysis of each calculation method for vertical steel vessels with different sizes and heights.

2. Objective of the Study

This study aimed to better understand the theory of earthquake load in relation to the structure of vertical steel vessels using the dynamic method. Comparison of the differences in the seismic response of vertical steel vessels at the support between equivalent static method and dynamic method was also carried out. A simplified model and 3D finite element model were employed to compare the differences in the seismic response of vertical steel vessels with different sizes and heights.

3. Scope of the Study

The analysis of the seismic response of vertical steel vessels was examined using by the equivalent static method using spectral response acceleration according to the standard for earthquake-resistant design of structures (DPT. 1302) and referring to the equation for calculating the period of vibration according to the Guidelines for seismic evaluation and design of petrochemical facilities. The study site was located in Bangkok's soft soil area (Zone 5). The seismic response of vertical steel vessels was investigated by using modal response spectrum analysis. It was the Linear-dynamic analysis. The models were created by STAAD Pro, including a simplified model and 3D finite element model. Analysis was based on the response occurring from the weights of vertical steel vessels in two cases, consisting of empty weight and operation weight. Evaluation of seismic response of vertical steel vessels was done by comparing the results of natural period, mode of vibration, base shear and overturning moment of each theory.

The effects of soil-structure interaction, weight of piping attached to vertical steel vessels and liquid sloshing effects in vertical steel vessels were not considered.

4. Description of Vertical Steel Vessel

The vertical steel vessels, also known as columns or towers in this study, consisted of two sets including 2440-V20 vertical steel vessel and 2440-V24 vertical steel vessel. The diameter, height and weight of the structures for both vertical steel vessels were different. In this study, the weights of the vertical steel vessels combined earthquake load consisted of two cases including empty and operation conditions. These were most likely to occur with earthquakes. The 2440-V24 vertical steel vessel is a tray column with 2.8 meters inside diameter (D) and 37 meters height (H). The thickness of the shell elements is different at each section of height. The average shell thickness is 16 millimeters. Empty weight is 98,905 kilograms, while operation weight is 107,305 kilograms.

The 2440-V20 vertical steel vessel is a tray column assembled using a thin-wall cylindrical and conical piece at the base to a height of 3.4 meters. It has a conical shape with an inside diameter at the base of 3.86 meters and an inside diameter of 2.6 meters at a height of 3.4 meters and above. A height is 60.2 meters. Shell thickness is different at each section of height. The average shell thickness is 25 millimeters. Empty weight is 155,870 kilograms and operation weight is 175,838 kilograms.

The vertical steel vessels are self-supporting equipment and the material specification of shell elements is carbon steel sheet, SA516 Grade 60, according to the standard of ASTM, which is ductile material commonly used for pressure vessels. The modulus of elasticity varies according to the design condition, as illustrated in Table 2.

5. Seismic Analysis Procedure and Analytical Model

The seismic response analysis of vertical steel vessel was divided into two methods consisting of the equivalent static method from computation by using excel and the dynamic method from creating an analytical model by STAAD Pro. The weights of vertical steel vessel components were considered from vertical steel vessel elements and attachments consisting of: (1) Self-weight, (2) Insulation & Fireproof, (3) Sieve Tray & Distributor, (4) Nozzle & Flange, (5) Platform & Handrail and (6) Liquid.

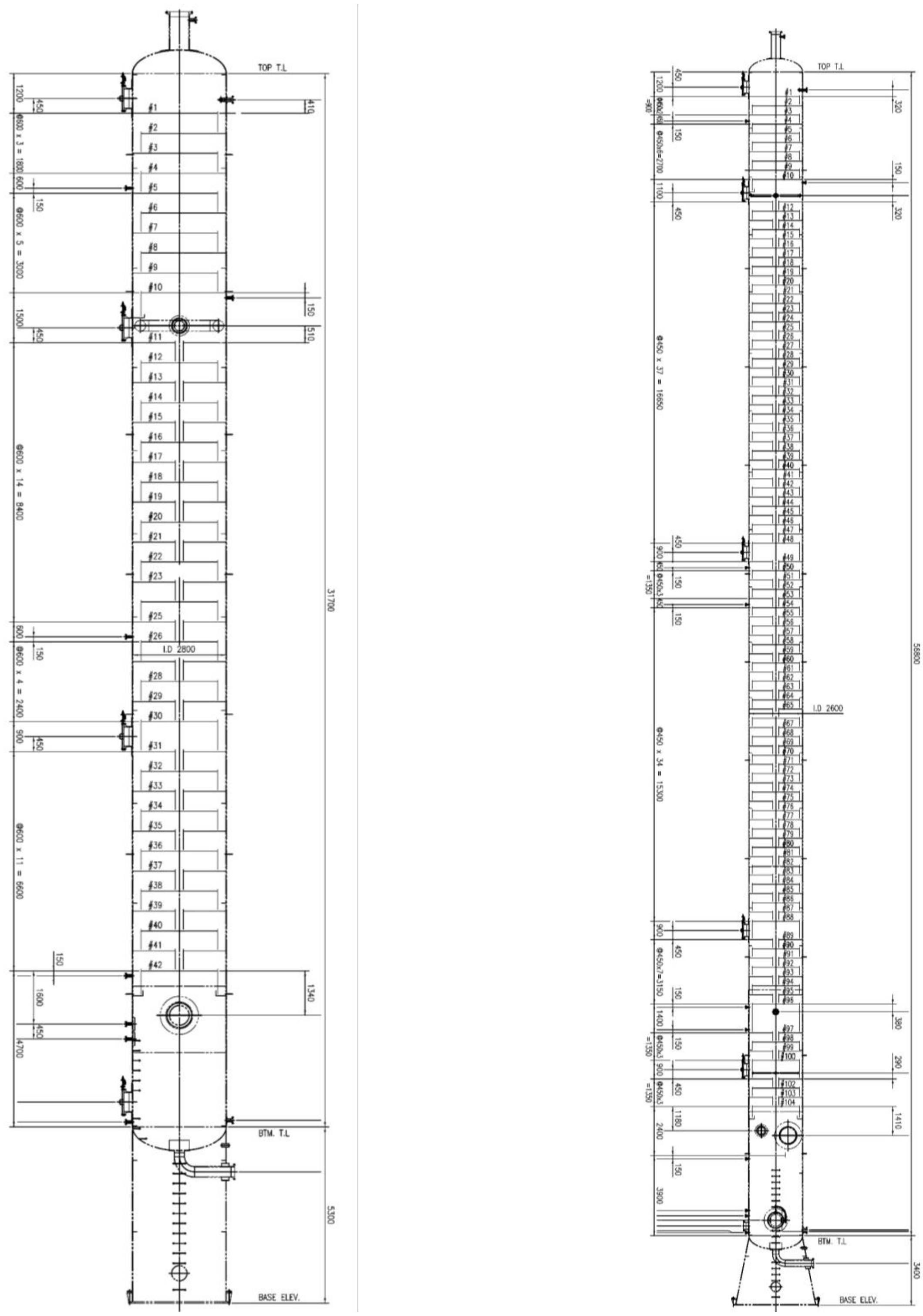
5.1 Procedure for analysis of the equivalent static method

5.1.1 Determine the spectral response acceleration (S_a)

5.1.2 Determine the seismic design category and identify the occupancy importance factors of vertical steel vessels (I)

5.1.3 Determine the response modification factor (R) according to the Guidelines for Seismic Evaluation and Design of Petrochemical Facilities [2]

5.1.4 Determine the effective weight of the structure and consider as lump mass to each section of vertical steel vessels



(a) (b)

Figure 1 (a) 2440-V24 Vertical Steel Vessel, (b) 2440-V20 Vertical Steel Vessel

5.1.5 Calculate the natural period of vibration (T) according to the Guidelines for Seismic Evaluation and Design of Petrochemical Facilities [2]

$$T = \left(\frac{H}{100}\right)^2 \sqrt{\frac{\sum \omega \Delta\alpha + \frac{1}{H}\sum W\beta}{\sum E D^3 t \Delta\gamma}} \quad (1)$$

Where:

T	=	period of vibration (sec)	H	=	overall height (ft)
ω	=	distributed weight (lbs/ft) of each section	W	=	Weight (lb) of each Concentrated Mass
D	=	diameter (ft) of each section	t	=	shell thickness (inch) of each section
E	=	modulus of elasticity (millions of psi)			

α, β and γ are coefficients for a given level depending on h_x/H ratio of the height of the level above grade to the overall height. $\Delta\alpha$ and $\Delta\gamma$ are the difference in the values of α and γ, from the top to the bottom of each section of uniform weight, diameter and thickness. β is determined and for each concentrated mass.

5.1.6 Calculate the seismic response coefficient (C_S)

5.1.7 Calculate base shear and distribution shear as horizontal force to vertical steel vessels and calculate overturning moment

5.2 Procedure for analysis of the dynamic method

5.2.1 Create a model of vertical steel vessel structure and apply load in the STAAD Pro program consisting of self-weight and weights of vessel elements. The models are separated into empty and operation conditions

5.2.2 Analyze the natural frequency, natural period of vibration and numbers of mode of vibration of vertical steel vessels

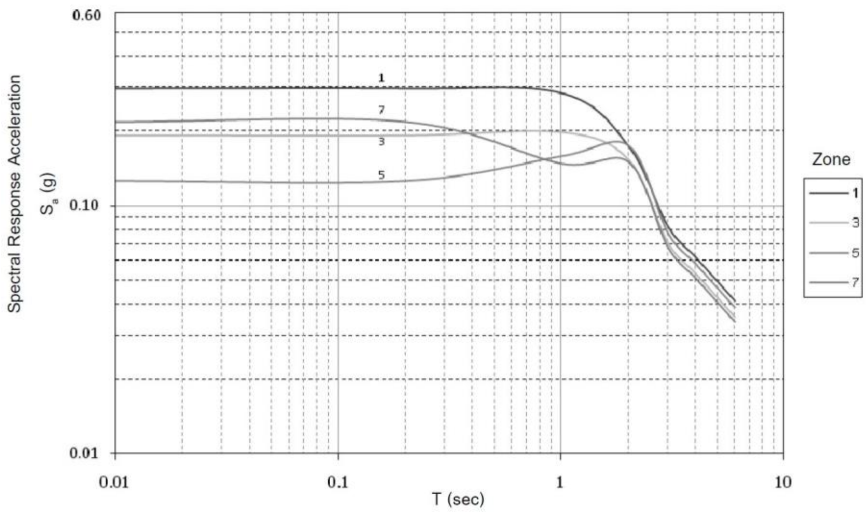
5.2.3 Analyze structures by modal response spectrum by input spectral response acceleration parameter into the program

5.2.4 The seismic responses from analyses in all modes were combined by using the method of Complete Quadratic Combination or CQC for accurate results.

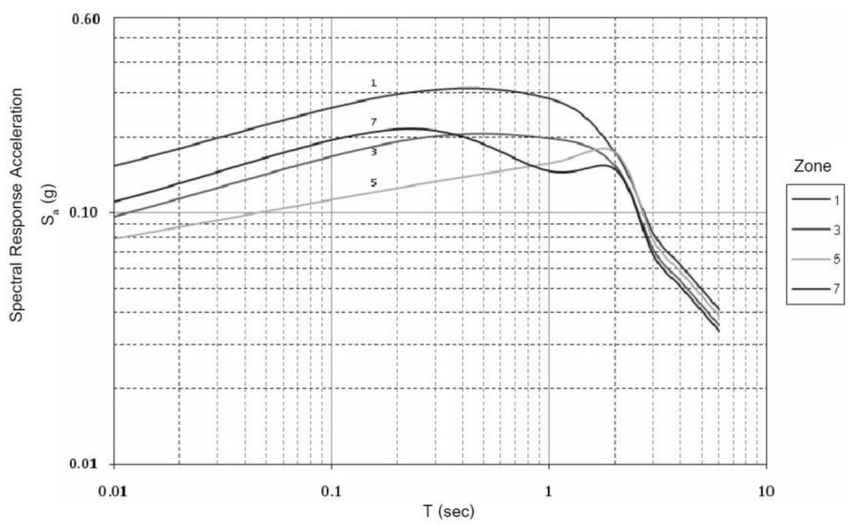
5.3 Analytical model

The vertical steel vessels modeled for dynamic analysis consisted of simplified models and a 3D finite element model. Simplified models were divided into two cases consisting of a single lumped mass model and multiple lumped mass model. The single lump mass model in this study created the geometry of the model while giving the member properties. The weight was added as a force to a node in three global directions. Mass was considered lumped to form a single mass at the centroid of gravity of the vertical steel vessel. Similarly, the distributed mass for multiple lumped mass model were considered lumped by 118 masses throughout the vessel height for the 2440-V20 vertical steel vessel and 58 lumped masses for the 2440-V24 vertical steel vessel.

For the 3D finite element model, a shell element is applied as thin-wall, which resembles the steel sheet walls of vertical steel vessels. The walls are thin when compared to the vessel diameter. The shell elements were divided into small plates of approximately 20 cm square. The weights of vertical steel vessel components were applied to the nodes, similar to the simplified model.



(a)



(b)

Figure 2 Design Response Spectrum for Bangkok's Soft Soil Area by DPT.1302
(a) For Equivalent Static Method, (b) For Dynamic Method

It is well known that a steel structure such as a vertical steel vessel has higher flexibility than a reinforced concrete structure. This allows for more lateral deflection when there is lateral force from an earthquake. The seismic response is dependent on the period of vibration, which is a function of the inherent ductility of the vertical steel vessel. Highly flexible (higher period of vibration) vertical steel vessels would have a lower base shear.

Table 1 Design Criteria for Seismic Analysis of Each Method

Design Assumption	Equivalent Static Method	Dynamic Method by Modal Response Spectrum		
		Simplified Model		3D Finite Element Model
		Condition 1	Condition 2	
Base Support	Fixed	Fixed	Fixed	Fixed
Damping	-	5%	5%	5%
Lump Mass	Multiple Lumped Mass	Single Lumped Mass	Multiple Lumped Mass	Multiple Lumped Mass
Combining Modes	-	CQC	CQC	CQC
Analysis Program	Excel	STAAD Pro	STAAD Pro	STAAD Pro

Table 2 Modulus of Elasticity for Vertical Steel Vessel in Each Case

Vertical Steel Vessel	Modulus of Elasticity (E), kg/cm^2	
	Empty	Operation
2440-V20	2,062,603	1,951,738
2440-V24	2,062,603	1,843,648

Note: Modulus of elasticity for SA516 Grade 60 carbon steel sheet for operation condition depends on the design temperature by vendor information according to ASME II, part D [3]

6. Results and Discussion

The results consisted of base shear and overturning moment. The seismic responses from each method and each load case were compared.

6.1 Base Shear

The results of base shear from combining modes by the CQC method were different for each analysis method. Base shear was analyzed by dynamic method of 2440-V20 vertical steel vessel, with the highest height and highest weight in the case study. When compared to the equivalent static method, as illustrated in Tables 3 and 4, it was found that the analysis of simplified model (single lumped mass) gave a lower value in empty and operation conditions at 27% and 25.2%, respectively. The simplified model (multiple lumped mass) gave a lower value in empty and operation conditions at 34.9% and 31.9%, respectively. The 3D finite element model gave a lower value in empty and operation conditions at 35.7% and 32.2%, respectively. For the 2440-V24 vertical steel vessel, a vessel with height and weight less than the 2440-V20 vertical steel vessel, it was found that the analysis of simplified model (single lumped mass) gave a higher value in empty and operation conditions at 2.7% and 1.7%, respectively. The simplified model (multiple lumped mass) gave a lower value in empty and operation conditions at 25.1% and 23.5%, respectively. The 3D finite element model gave a lower value in empty and operation conditions at 26.2% and 25.6%, respectively.

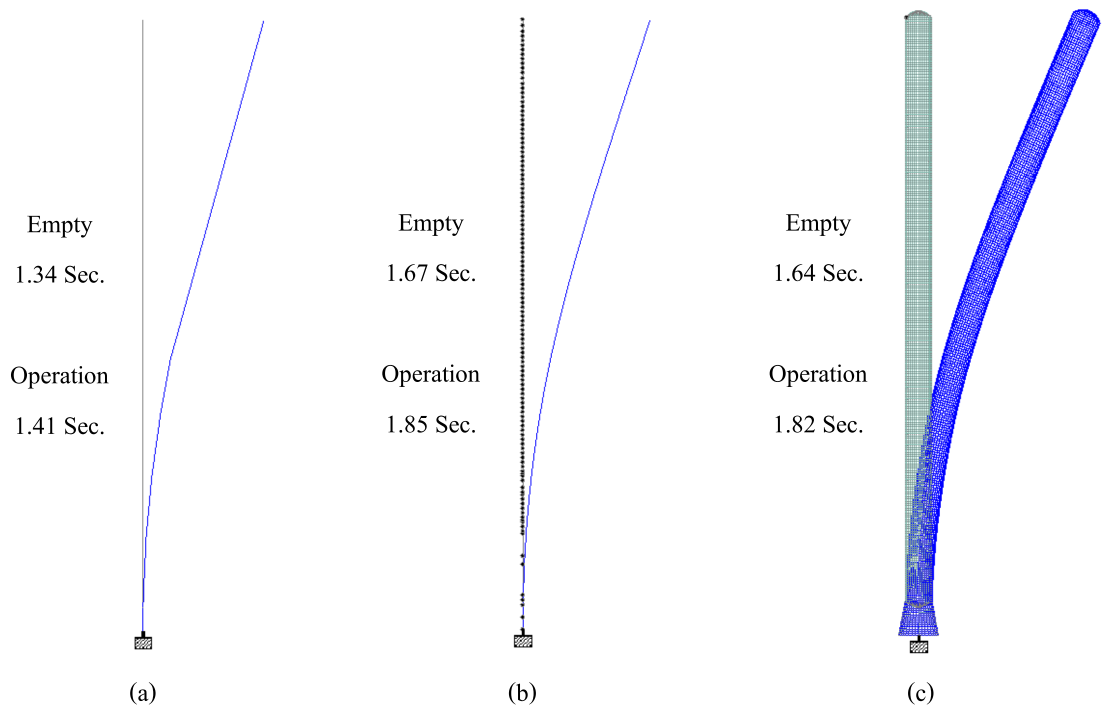


Figure 3 Period of Vibration for Fundamental Mode of 2440-V20 Vertical Steel Vessel by Dynamic Method (a) Single Lumped Mass Model, (b) Multiple Lumped Mass Model, (c) 3D Finite Element Model

Table 3 Base Shear for 2440-V20 Vertical Steel Vessel in Each Case

Load Condition	Equivalent Static Method (kg)	Dynamic Method by Modal Response Spectrum (kg)		
		Simplified Model		3D Finite Element Model
	Multiple Lumped Mass	Single Lumped Mass	Multiple Lumped Mass	Multiple Lumped Mass
Empty	20,419	14,902	13,289	13,138
Operation	23,386	17,487	15,934	15,858

Table 4 Base Shear for 2440-V24 Vertical Steel Vessel in Each Case

Load Condition	Equivalent Static Method (kg)	Dynamic Method by Modal Response Spectrum (kg)		
		Simplified Model		3D Finite Element Model
	Multiple Lumped Mass	Single Lumped Mass	Multiple Lumped Mass	Multiple Lumped Mass
Empty	11,869	12,191	8,894	8,757
Operation	13,306	13,528	10,183	9,898

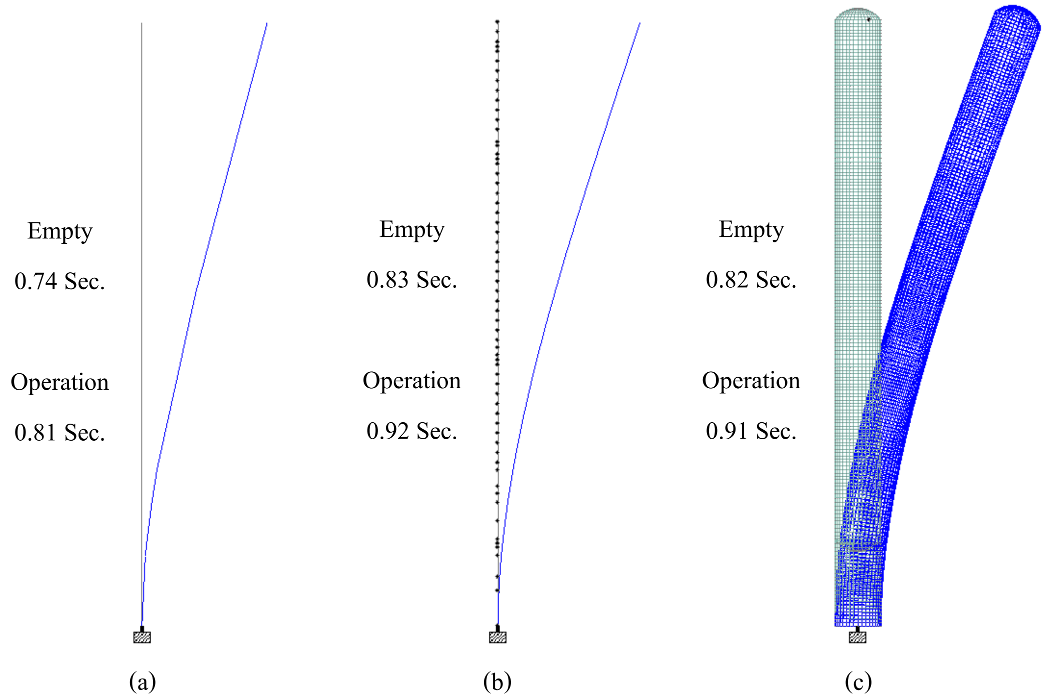


Figure 4 Period of Vibration for Fundamental Mode of 2440-V24 Vertical Steel Vessel by Dynamic Method
(a) Single Lumped Mass Model, (b) Multiple Lumped Mass Model, (c) 3D Finite Element Model

6.2 Overturning Moment

Overturning moment was calculated from the total horizontal force multiplied by the height of each elevation of distributed lump mass measured from the base. Generally, overturning moment varies according to base shear. The overturning moment of the 2440-V20 vertical steel vessel from dynamic analysis method by simplified model (single lumped mass model) was smaller than the other models despite having higher base shear. This is because considering single lumped mass at the centroid in the center of vertical steel vessels may not reasonably correspond to reality. The comparison of overturning moment is illustrated in Tables 5 and 6.

Table 5 Overturning Moment for 2440-V20 Vertical Steel Vessel in Each Case

Load Condition	Equivalent Static Method (kg-m)	Dynamic Method by Modal Response Spectrum (kg-m)		
		Simplified Model		3D Finite Element Model
	Multiple Lumped Mass	Single Lumped Mass	Multiple Lumped Mass	Multiple Lumped Mass
Empty	921,757	523,085	603,752	586,165
Operation	1,050,847	605,057	722,377	705,080

Table 6 Overturning Moment for 2440-V24 Vertical Steel Vessel in Each Case

Load Condition	Equivalent Static Method (kg-m)	Dynamic Method by Modal Response Spectrum (kg-m)		
		Simplified Model		3D Finite Element Model
	Multiple Lumped Mass	Single Lumped Mass	Multiple Lumped Mass	Multiple Lumped Mass
Empty	318,388	286,752	246,958	241,466
Operation	357,956	315,441	278,916	271,995

7. Conclusions

A vertical steel vessel is considered a cantilever beam, which must respond to vibration and lateral deflection like a flexible structure. This assumption is consistent with the design rule from the Guidelines for seismic evaluation and design of petrochemical facilities [2], which describes that a vertical steel vessel can be considered a flexible structure where the fundamental period is more than 0.06 seconds, like in this case study.

According to the seismic analysis by dynamic method with STAAD Pro, almost all analytical models gave base shear of around 25-36% lower than that analyzed by the equivalent static method for empty condition and 23-32% for the operation condition, excluding the simplified model (single lumped mass model), which gave base shear similar to the equivalent static analysis method at 2.7% and 1.7% higher for empty and operation conditions, respectively.

The equivalent static method produced the highest base shear. It is useful for preliminary design to determine pile capacities and pile cap size of vertical steel vessel because this is a conservative design. However, this method is proper for uniform vertical steel vessels that have regularity in mass distribution, whereas the dynamic analysis method by STAAD Pro model is proper for analysis and accurate design to confirm the strength of the structure. It can also be used to evaluate the strength of existing vertical steel vessel foundations from earthquake loads.

The seismic analysis of vertical steel vessel by dynamic method using 3D finite element model is a method that could estimate values close to actual values. However, it requires more time for producing a structural model as there are many small elements. This may not be suitable for the design of vertical steel vessel foundations that required promptness.

The dynamic method by simplified model as multiple lumped mass model is recommended. It saves time for creating the geometry of a vertical steel vessel. The results are satisfactory and close to the results from 3D finite element analysis.

The analysis of seismic response of vertical steel vessels by equivalent static procedure is an easy-to-understand method. However, calculation for natural period of vibration is complicated when dealing with vertical steel vessels with variable cross sections and significant irregularities in mass distribution. This is because solving equations requires many relevant coefficients. The dynamic method by analytical model is required for accurate results.

Acknowledgements

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