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Seismic Fragility Evaluation for Anchorage of Skirt Supported Vertical Tank

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1. Introduction

Skirt supported vertical tanks such as a volume control tank in Nuclear Power Plants (NPPs) have a supporting skirt and are equipment with the relatively low and critical seismic fragility for anchorage, since the ratio of height to diameter is larger (slender tank) than that horizontal tanks. The anchorage of these tanks is affected by the seismic demands caused by the fluid movement and should be assessed in a more realistic and accurate way. The Finite Element Analysis-Computational Fluid Dynamics (FEA-CFD) analysis is the most accurate way for analysis of the fluid-structure interaction (FSI), but this method requires three dimensional modeling and many steps for analysis, so it takes a lot of time to get the results.

It is necessary to find an alternative to the anchorage evaluation using FEA-CFD analysis. The exact same results as the FEA-CFD analysis results could not be obtained, but the very similar results can be obtained by the simple procedure.

This study describes the several methods for the anchorage fragility considering seismic induced fluid dynamic effect, selects the feasible methods and suggests the alternative method instead of the FEA-CFD analysis. It is expected that the anchorage evaluation will be reliably evaluated in a short time if the alternative method is used.

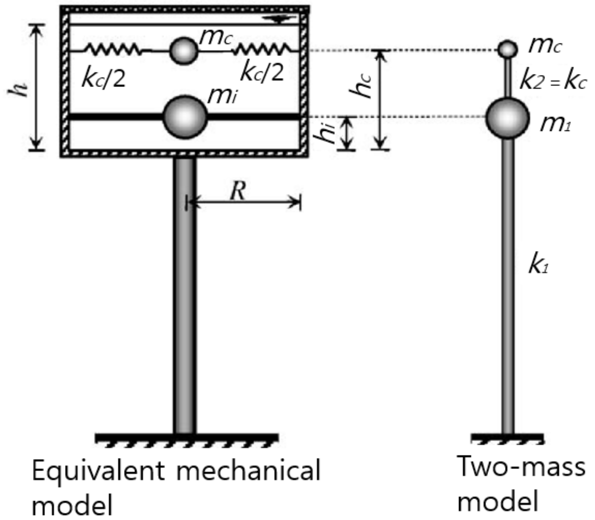
2. Methods and Results

2.1 General Concept and Current Reference Survey

The seismic demand of the anchorage is affected by fluid dynamic effect that are divided into impulsive mode and convective mode. The impulsive mass acts as an added mass on the tank shell and the convective mass is applied like a spring-lumped mass model. Seismic fluid responses for impulsive mode and convective mode are calculated using the mass and spring models.

The calculation formulas with this model is presented in several commercial codes such as API650, EPRI NP-6041, ACI350.3-06, ACI371R-08. Most of these references have the same formulas except for several parameters. The parameter calculation formulas for the center height of the impulsive force “including the floor pressure” is selected from API650 because it has the most conservative value for assessing the seismic responses and the anchorage fragility. The damping ratio for the impulsive mode and the convective mode for the steel tank is 5% and 0.5% respectively [1].

Commercial codes deal primarily with flat-bottom vertical-cylindrical tanks without a support which are easily evaluated in accurate basis. However, the formulas and the evaluation concept are not clear for the vertical-cylindrical skirt supported (elevated) tank, which is the main concern of this study. This tank has a support like the skirt (short compared to the tank body length) that positions the tank bottom in a high level from the floor and is difficult to evaluate.



m_c : *Effective convective fluid mass*
m_i : *Effective impulsive fluid mass*
m_v : *Tank body (shell, roof, floor) mass*
m_{ss}: *Tank supporting structure(skirt) mass*
m_1 : *Applied mass for impulsive mode natural frequency*
k_c : *Stiffness of convective mode of non-supported tanks*
k_1 : *Stiffness of supporting support(skirt)*
k_2 : *Stiffness of convective mode of supported tanks*

Figure 1. Two mass-spring model for the elevated tank [2]

According to the reference [1~6], each impulsive mass and the convective mass is the same between the elevated tank and the non-elevated tank, but each center of impulsive mass and the convective mass for the elevated tank increases by the height of the support of the elevated tanks. The horizontal base shear force, the overturning moment and the fundamental frequency of the elevated tank are different from those of the non-elevated tank due to the difference of the impulsive mode response for the elevated tanks. The fundamental frequency of the vibration for the impulsive mode of the elevated tank is expressed,

$$k_1 = \frac{3EI_c}{l_{cg}^{\ 3}} \qquad T_i = 2\pi\sqrt{\frac{m_1}{k_1}} \qquad f_i = \frac{1}{T_i}$$

E : *Young' modulus of the support material*
l_{cg} : *Height of vibrating point of m_1*
I_c : *Moment of inertia of the support gross section*
T_i : *Natural time period of impulsive mode*
f_i : *Fundamental frequency of impulsive mode*

The methods for calculating the horizontal shear mass and the overturning moment are summarized in three ways in table 1. Those are determined by the applied mass, the height of vibrating point for calculating the impulsive fundamental frequency, and other parameters. Generally, the applied effective lumped mass and the height of vibrating point of this mass are main parameters while the other parameters are depending on the material property and the section area of the support.

Table 1. Main parameters of impulsive mode for each method

Method	m_1	l_{cg}	Ref.
1	$m_i + m_v + 0.66m_{ss}$	Impulsive mass center	[2]&[5]
2	*By work equation	Impulsive mass center	[3]
3	$m_i + m_v + m_{ss}$	Impulsive mass center	[2]

*By work equation: This term is used in reference [3] and means that the product of the mass (or weight) and the height of the mass center is the moment. The total moment is equal to the sum of each mass and its center. The final applied mass m_1 is derived from total moment divided by the height of the impulsive mass center.

Now, the main focus is on finding the best way to obtain the impulsive mode shear force and the overturning moment. The two example cases are reviewed in the following section. Case 1 is about FEA-CFD analysis results. Case 2 is about FEA with added mass and spring-mass (FEA-AMSM) analysis results.

2.2 Finding the differences between example analysis results and above simplified calculation method results

As case 1, it is stated that the base shear and the base overturning moment by the method 2 in 'section 6.2.5 of reference [3]' for the elevated tank with the long support are 94.3% of the results by FEA-CFD analysis. In order to confirm the results by the method 1 and 3 in this study, the further calculations were executed and summarized in table 2.

Table 2. Case 1 results for impulsive and convective mode (FEA-CFD analysis)

Method	Effective impulsive mass(%)	SRSS total overturning moment(%)	Impulsive fundamental frequency (Hz)
FEA-CFD	100 [3]	100 [3]	1.955 [3]
1	107.5	107.5	2.667
2	94.3 [3]	94.3 [3]	2.976 [3]
3	122.6	122.6	2.492

*SRSS : Square root of the sum of squares

It is clear that the method 2 is not appropriate for evaluation of the seismic force due to the fluid seismic effect and the method 1 is based on the ACI code [5] and the Houser [2] modeling. The method 3 is the most conservative and recommended by Priestley et al. [2].

As another example case, the FEA-AMSM analysis results (case 2) in our actual plant design about responses of two modes are compared with the results calculated by each method in this study. In this case, the impulsive mass and the convective mass are preliminary calculated based on the formulas of the commercial codes. The impulsive mass is applied as the added mass [2] and the convective mode is applied as the spring-mass system.

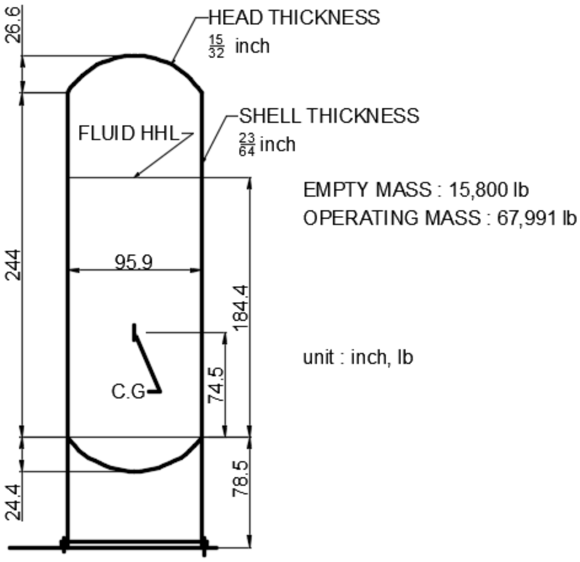


Figure 2. Outline of vertical elevated tanks

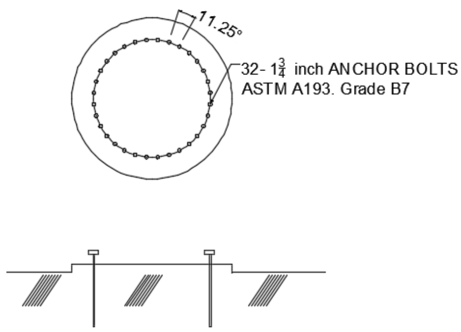


Figure 3. Schematic arrangement of anchor bolts

Table 3. Case 2 effective mass and fundamental frequency for impulsive mode (FEA with added mass & spring-mass analysis)

Method	Effective impulsive mass(%)	Impulsive fundamental frequency (Hz)
FEA - AMSM	100.0	11.196
1	102.0	11.556
2	94.9	11.984
3	103.4	11.484

The impulsive fundamental frequency is similar regardless of the evaluation method and it is not possible to define which method is the best solution. Seismic force is determined by the spectral acceleration (5% damping) depending on the fundamental frequency. The convective fundamental frequency is 0.616 Hz in this case.

In this study, the seismic acceleration is based on reference spectrums in Figure 4. The convective mode acceleration is 0.414g at its fundamental frequency and the impulsive mode acceleration for each method is listed in Table 4.

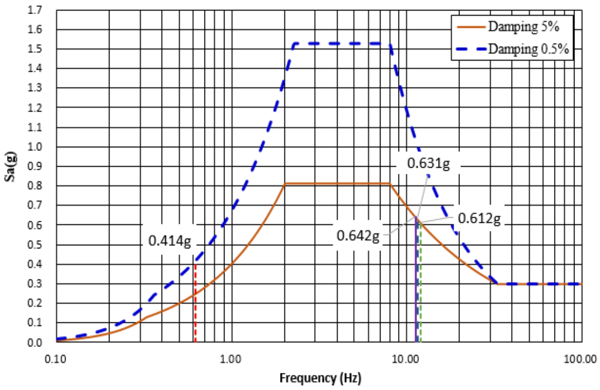


Figure 4. Example of reference spectrums

The SRSS base shear forces and the overturning moments were calculated and compared in the following table 4.

Table 4. Case 2 SRSS results

Method	Impulsive spectral acceleration (g)	SRSS base shear force(%)	SRSS overturning moment(%)
FEA - AMSM	0.642	100	100
1	0.628	100.8	100.8
2	0.612	98.5	98.5
3	0.631	102.5	102.5

2.3 Calculation for the anchorage fragility considering the impulsive mode and convective mode for case 2

The vertical fluid mode is considered and the same response is applied for all evaluation methods. The 5% damping for the vertical fluid mode is selected and the spectral acceleration is 0.35g at its fundamental frequency 26.71Hz that is calculated according to ACI code [6]. In this study, the anchorage fragility evaluation was performed and expressed in High Confidence of Low Probability of Failure (HCLPF) [1]. The ratio of HCLPF value are summarized in table 5.

Table 5. HCLPF [1] ratio for anchorage fragility considering hydrodynamic effect (Case 2)

Method	HCLPF(%)
FEA -AMSM	100.0
1	99.4
2	101.2
3	98.2

3. Conclusions

In NPPs, the fragility of the anchorage of the skirt-supported tanks should be as close to the realistic value as possible and should be a little conservative. The result by method 2 is not conservative and the method 2 shall not be used for anchorage fragility evaluation. Since the method 1 applies the portion of the support mass, it could be concerned that the total mass is not incorporated in the shear fragility evaluation of the anchorage. The method 3 applies the total mass and has the lower and more conservative capacity than the realistic HCLPF capacity. Thus, the method 3 is the available method for the anchorage evaluation of the skirt supported vertical-cylindrical tanks with critical and sensitive anchorage fragility in NPPs.

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