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수평원통형 저장탱크의 지진취약도 해석

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Seismic Fragility Analysis of Ground Supported Horizontal Cylindrical Tank

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Abstract: The fragility analyses for the partially filled horizontal cylindrical tank having a flexible wall were conducted to evaluate seismic performance. An equivalent simplified model with two lumped masses representing to impulsive and convective masses was used to represent the liquid storage system. This simplified model was validated by comparing its time history analysis results with the 3D FSI model results. The horizontal tank was analyzed under bi-directional excitations. Seismic fragility curves for the stability were developed in transverse and longitudinal directions. Fragility curves show that seismic damage for the horizontal storage system is more susceptible in the transverse direction.

Keywords: Horizontal cylindrical tanks, fluid-structure interaction, simplified model, fragility curve

1. Introduction

Several studies have been done in the past for finding seismic response behavior of cylindrical and rectangular storage tanks, however, there are very few studies regarding the seismic response analysis of the horizontal and spherical storage tanks. Like other storage structures, horizontal tanks also suffered the seismic damages on past earthquake events. Horizontal cylindrical tanks are mostly used in the industrial area with the purpose to store the chemicals and oils which are highly hazardous to the environment and flammable upon its collapse of leakage. The consequence of the failure of facilities in chemical plants will result in catastrophic damage like toxic gas diffusion and fire hazards.

Seismic analysis of the chemical plant facilities can be done by finite element analysis with different approaches that are by formulating a detailed 3D FSI model and a simplified mechanical mass-spring model. Housner(1963) formulated the simplified mass-spring model for the ground supported cylindrical tank. The modal superposition method was adopted for seismic evaluation of the flexible cylindrical tanks by the finite element approach with experimental verification(Haroun, 1980). Malhotra et al.(2000) have proposed a simple procedure for analyzing the vertical cylindrical storage tank with the account of impulsive and convective(sloshing) masses action in flexible tanks. The remarkable study made by Karamanos et al.(2006) formulated the expressions for calculating the dynamic properties of the spherical and horizontal storage tank system. In their study, they investigated the effect of sloshing in the horizontal and spherical tanks during earthquakes by SDOF representation of the storage system. In general, it is important to know the seismic capacity of the critical facilities over the wide range of earthquakes which can be obtained by formulating the seismic fragility curves to each of the facilities of the industrial plant. Even though a number of studies regarding seismic fragility assessment of cylindrical and rectangular tanks have been done, yet seismic fragility of the horizontal cylindrical tank has not been developed by formulating simplified finite element models.

This paper focuses on the seismic safety of the partially filled horizontal cylindrical tank. Therefore, fragility analyses were performed with the simplified model at the desired performance level. The overall study shows that seismic damage for the horizontal storage system is more susceptible in the transverse direction.

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•본 논문에 대한 토의를 2020년 1월 31일까지 학회로 보내주시면 2020년 2월호에 토론결과를 게재하겠습니다.

2. Subject

2.1 Finite element model formulation

In this study, finite element analyses were made with two different approaches, namely the FSI model and the simplified model. FSI analyses are performed in the FEM program ANSYS(Canonsbug, 2012). Since the FSI model tends to represent the exact structure, the structural components like saddles, tank wall, and contained fluid were modeled. The tank wall is modeled by four-node shell element having six degrees of freedom at each node called SHELL181. The supporting saddles were modeled by a 20-node solid element called SOLID186.

The liquid inside the tank is modeled by the FLUID80 element which has three translational degrees of freedom at each node. These elements are suitable to model as a liquid inside the vessel without any flow rate. The behavior of the fluid is represented by the Lagrangian approach and fluid is considered as incompressible, irrotational and inviscid(Wilson and Khalvati, 1983). For the interaction between the shell and the fluid element surface-to-surface contact by the element type CONTACT174 and TARGET170 supporting the Coulomb's friction model was used.

The simplified model is formulated with the beam element connected with rigid and convective links for impulsive and convective masses respectively. According to Eurocode 8(2006), the horizontal cylindrical tank should be analyzed for seismic actions along the longitudinal and horizontal transverse direction. The approximate hydrodynamic pressure generated by seismic actions in both longitudinal and transverse directions can be obtained by considering an equivalent rectangular tank with the same depth and volume as actual tank. Study made with this approach by converting the horizontal tank into equivalent rectangular by Carluccio et al.(2008) agreed well with the base shear component. According to Eurocode 8, the horizontal cylindrical tank can be equivalently model as a rectangular tank for the H/R range between 0.5 to 1.6. H and R are the liquid height and the radius of the horizontal tank, respectively. Therefore, in this study the simplified model is prepared by converting the horizontal tank to equivalent rectangular tank and transferring the liquid mass through convective mass and impulsive mass using elastic and rigid links respectively. The validity of the partially filled horizontal liquid storage tank is evaluated for the ground-based staged horizontal tank is presented.

2.2 Modeling

2.2.1 3D -FSI Finite Element Model

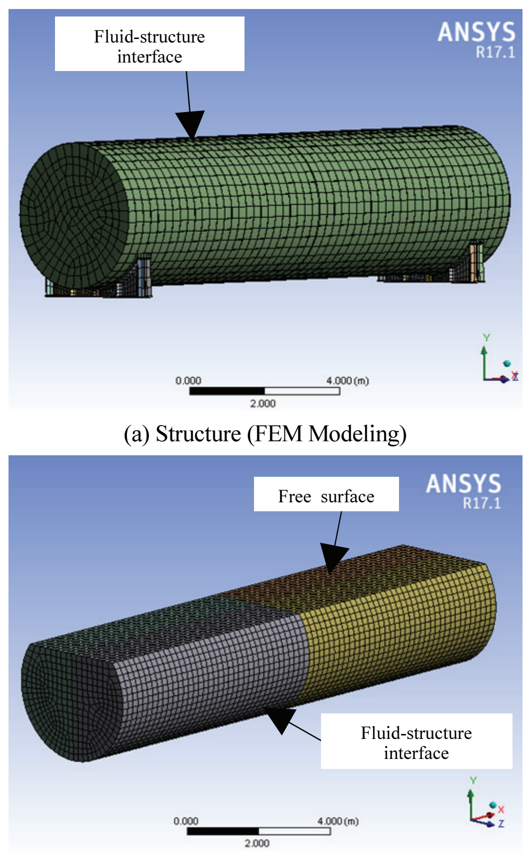
The structure analyzed in the present study is the typical ground-supported horizontal cylindrical storage tank with a volume of 188 m^3. The liquid volume in the tank is 85%. The

Table 1 Geometrical properties of the horizontal tank

Length of the tank	15 m
External diameter	4 m
Thickness of the tank wall	0.012 m
Thickness of the saddles	0.02 m
Width of the steel saddles	3.4 m

Table 2 Mechanical properties of the horizontal tank

Design strength of the steel tank	360 MPa
Design Strength of the supporting saddles	230 MPa
Sonic velocity of the liquid	1,616 m/s
Poisson's ratio of steel	0.3
Density of steel	7,850 kg/m^3
Young modulus of the steel	2 x 1011 N/m^2



(a) Structure (FEM Modeling)

(b) Liquid (BEM Modeling)

Fig. 1 Finite element idealization for the 3D detailed model liquid contained in the tank is butane of density of 603 kg/m^3. The subdivision of the finite element and boundary element of the tank considered is presented in Fig.1. The geometrical properties of the storage system are given in Table 1 and the material properties are given in Table 2.

2.2.2 Simplified Finite Element Model

The simplified model is developed as two mass system as recommended by literature(Karamanos et al., 2006). Finite element software SAP2000 is used to form the analysis of the simplified model. The simplified 2D model is prepared in such a way that the wall of the tank is modeled by beam elements with equivalent stiffness. In the current study, the liquid depth is 3.17m and the radius is 2m, therefore H/R ratio is 1.58. The two equivalent tank models were created of equal volume with the original cylindrical tank for evaluating the longitudinal and transverse seismic effects separately. Both equivalent models have the same liquid volume and depth, but different tank sizes. The dynamic properties of the equivalent tanks are calculated based on the IITK-GSDMA guidelines(Barton and Parker, 1987]. The equivalent simplified mass-spring models of rectangular tanks are shown in Fig. 2. The liquid element in the horizontal tank is

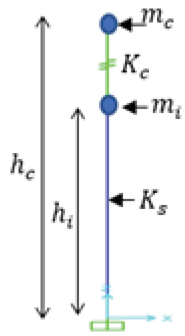


Fig. 2 Equivalent model for simplified analysis of rectangular storage tank

Table 3 Parameters of the simplified models in both directions

Parameters	Longitudinal	Transverse	Remarks
m_c/m	0.729	0.328	- 'm' represents mass - 'h' represents height - subscript 'c' represents convective - subscript 'i' represents impulsive - superscript (') represents tank wall
m_i/m	0.243	0.671	
h_c/h	0.517	0.659	
h_i/h	0.375	0.481	
$h_c^{'}/h$	2.620	0.75	
$h_i^{'}/h$	1.92	0.55	

represented by the mass-spring system. The calculated dynamic properties for the tanks are presented in Table 3.

2.3 Time history Analyses

2.3.1 3D detailed model

The seismic responses of the horizontal tank under bi-directional ground excitations were observed. The horizontal ground motions were applied simultaneously in longitudinal and transverse axes.

The past earthquake records are not enough and suitable for seismic analyses, hence a set of artificial ground motions were developed and used in this study to find the seismic analyses. The ground acceleration for the total duration of 20sec was developed along with the longitudinal and transverse directions with peak ground acceleration(PGA) of 0.154g. Fourteen random seismic excitations compatible to the design response spectrum specified in the Korea seismic design code were generated. To generate the artificial ground motions the stationary process is multiplied by the envelope function, the envelope function is taken from the seismic design code with a short period of 0.02sec and a long period of 3.0sec, the time step size of 0.01sec is used. Artificial ground motions are generated using the program SIMQKE. The matched random ground motions with the target spectrum are shown in Fig. 3.

Time history analyses were carried with the modal superposition technique. To characterize the convective and impulsive responses along with the time domain the time step of 0.01sec was used. More than 200 modes were utilized so that the ratio of accumulated mass to the total mass becomes more than 90% to capture the convective and impulsive responses in the analyses. The time history results of the detailed 3D model are

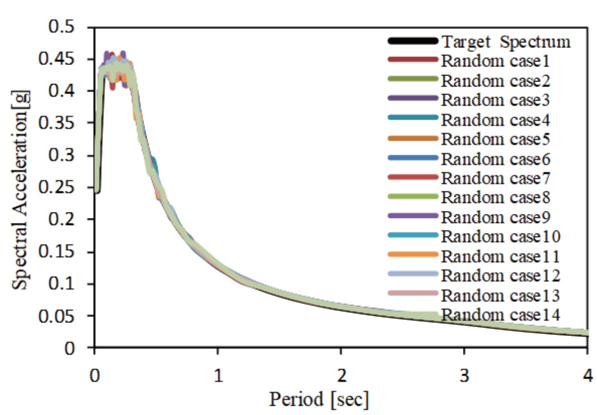
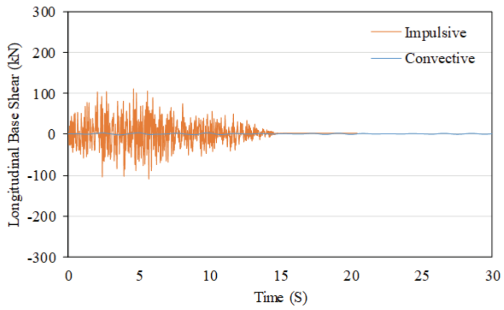


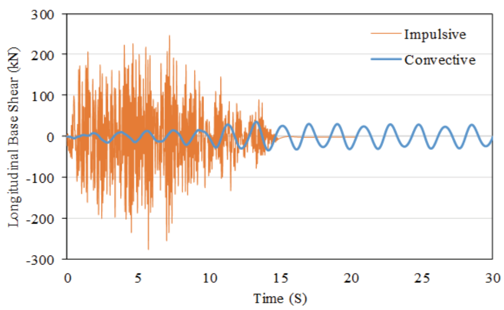
Fig. 3 Design response spectrum with matched cases

Table 4 Time history responses with 3D model

Responses	Direction	Convective	Impulsive	Total (SRSS)
Base Shear (kN)	Longitudinal	2.73	110.69	110.72
	Transverse	35.60	275.89	278.17
Overturning Moment (k-Nm)	Longitudinal	6.86	552.87	552.91
	Transverse	70.97	649.99	653.85



(a) Longitudinal response

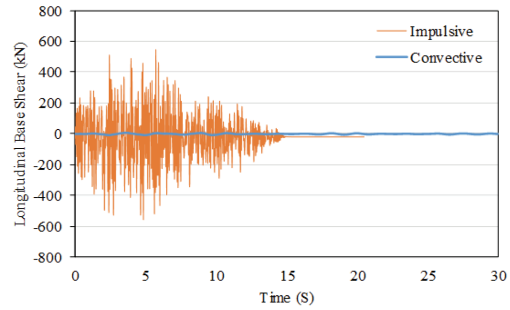


(b) Transverse response

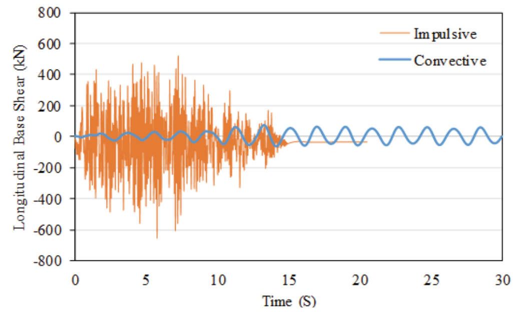
Fig. 4 Response of base shear

presented in Table 4. Fig. 4 and 5 illustrate the time history response of the detailed 3D model.

From time-history results, it can be concluded that the effect of the convective component is less as compared to the impulsive component. To observe the liquid sloshing behavior in earthquake, the total vibration time is extended up to 30s even though the actual vibration stops at 20 s. As it can be seen in Figure 4 and 5 that the sloshing(convective) reaction continues even after the 20s where the impulsive reaction stops. It should be noticed that the impulsive response occurs earlier than the convective response. Figure 4 and 5 illustrate that the sloshing phenomena start after the peak response of the impulsive component. Furthermore, in the case of the horizontal tank the transverse seismic action is comparatively higher than the longitudinal as expected. The transverse base shear is almost 2.5 times higher than the longitudinal base shear. Similarly, the transverse overturning



(a) Longitudinal response



(b) Transverse response

Fig. 5 Response of overturning moment

moment is 14% higher than the longitudinal overturning moment. This illustrates that the transverse directional seismic results are higher than the longitudinal directional seismic results.

2.3.2 Simplified model

In the simplified fluid-structure interaction model, the impulsive and convective masses at their respective heights, together with the associated stiffness and the spring topology are modeled. The dynamic properties of the simplified model are illustrated in Table 3. The damping ratio of 5% is used for the impulsive mode and 0.5% is used for the convective one.

The mass of the liquid is 96.615 t corresponding to the filling ratio of 85% and the mass of the tank is 27.81 t. This filling ratio corresponds to the fluid height to radius ratio(H/R) of 1.58. For the excitation in the longitudinal direction, the impulsive mass corresponding to 24 t is 25% of the liquid mass and 72 t is 75% of the liquid mass. Similarly, for the transverse direction, the impulsive mass corresponding to 65t is 67% of the liquid mass and the convective mass corresponding to 31 t is 33% of the liquid mass.

Table 5 illustrates the seismic base shear and overturning moment results for the simplified model. The difference in base shear results for the 3D FSI model and simplified one is 11% for longitudinal direction and 6% in the transverse direction.

Table 5 Time history responses of simplified model

Responses	Direction	Results
Base Shear (kN)	Longitudinal	124.15
	Transverse	263.72
Overturning Moment (k-Nm)	Longitudinal	479.43
	Transverse	680.18

Similarly, for the overturning moment the difference is 16% and 0.4%. As the seismic analysis results compare favorably, the simplified model here can represent the FSI model for further fragility analysis.

2.4 Seismic Performance Evaluation

2.4.1 Limit states

The seismic performance of the horizontal cylindrical tank is evaluated by time history analyses. In addition to 14 artificial ground excitations as mentioned above a set of 18 natural earthquake records were selected from the Pacific Earthquake Engineering Research(PEER) ground motion database as shown in Table 6. The selected ground motions include the bi-directional horizontal ground motions. Table 6 shows the magnitudes and PGA in longitudinal and transverse directions for all the selected set of ground motions. Each record was scaled to 10 sets of ground motions of a gradual increase in intensity level.

The seismic performance of the tank considered should be done by developing the fragility curves. The non-anchored tanks and pipe connected tanks are susceptible to damage due to lateral movement and rotation of the tank to saddle(Sezen and Whittaker, 2004). On the other hand, those with anchored base and rigidly connected saddles may be susceptible to buckling of the tank wall(Burgos et al., 2018).

Therefore, to evaluate the fragility curves, the engineering demand parameters, EDPs, need to be defined. With the overview of the past failure history of the horizontal tanks, the EDPs shown in Table 7 have been assumed in this study: overturning moment and sliding failure(Sezen and Whittaker, 2006). Once the EDPs are selected, the performance of the tank will be determined by assigning the limit state threshold values for each defined EDPs. In the horizontal cylindrical tank, the seismic fragility curves should be developed for both longitudinal and transverse directions. Overturning fragility is computed based on the design limit values for overturning in longitudinal and transverse directions, and sliding fragility is computed based on maximum horizontal base shear.

2.4.2 Fragility analysis results

Seismic fragility curves of the examined ground-supported horizontal cylindrical tank are shown in Fig. 6 and 7. Table 8 lists

Table 6. Earthquake records for input ground motions

S. N	Earthquake	Magnitude	Station	PGA(g)	
				X(g)	Y(g)
1	Azna,USA	4.92	Pinyon Flat	0.079	0.131
2	Gulf of Aqaba,Israel	7.2	Eilat	0.092	0.080
3	Borrego Mtn	6.63	El Centro Array #9	0.132	0.057
4	Coalinga-01, USA	6.36	Parkfield - Fault Zone 11	0.078	0.087
5	Dursunbey,Turkey	5.34	Dursunbey	0.223	0.287
6	Corinth,Greece	6.6	Corinth	0.236	0.296
7	Kocaeli,Turkey	7.51	Fatih	0.188	0.161
8	Morgan Hill,USA	6.19	Halls Valley	0.156	0.312
9	Kobe, Japan	6.9	Nishi-Akashi	0.483	0.464
10	Imperial Valley-02, USA	6.95	El Centro Array #9	0.280	0.210
11	Imperial Valley-06, USA	6.53	Delta	0.235	0.349
12	Chi-Chi, Taiwan-04	6.2	HWA051	0.014	0.015
13	Parkfield,USA	6.19	Cholame - Shandon Array #5	0.145	0.443
14	Northridge-01, USA	6.69	Hollywood - Willoughby Ave	0.135	0.250
15	Coalinga-01, USA	6.36	Cantua Creek School	0.225	0.288
16	Chichi,Taiwan	5.28	CHY002	0.147	0.024
17	San Fernando,USA	6.61	Castaic - Old Ridge Route	0.320	0.275
18	Tabas,Iran	7.35	Ferdows	0.093	0.104

Table 7 EDPs and limit states for fragility evaluation of horizontal tanks

Failure mode	EDP	Limit state	Threshold values
Overturning	Overturning moment	Overturning moment limit	6788.82(L) 1556(T)
Sliding	Base shear	Base shear ($F_{sliding} = \mu \times W$)	460 kN

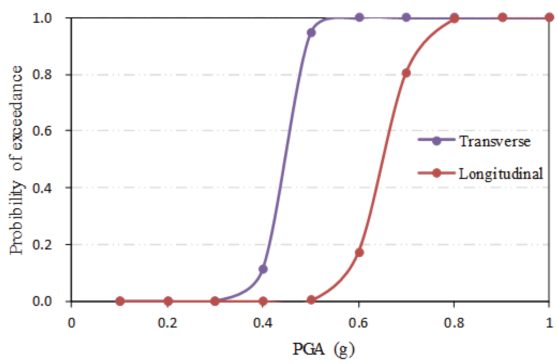


Fig. 6 Fragility curve of sliding

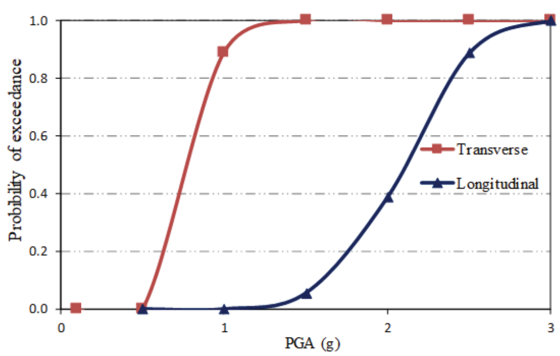


Fig. 7 Fragility curve of overturning

the median and standard deviation of ln(PGA) for fragility functions of defined limit states. From the fragility curves, it is possible to see that the transverse direction is weak against earthquake. The performance point for the sliding of the horizontal tank is 0.3g PGA and failure probability is 90% at 0.5g PGA along the transverse direction. Similarly, the performance point is 0.5g PGA and failure probability of 90% is at 0.7g PGA along the longitudinal direction. On the other hand, the performance point for the overturning of the horizontal tank considered in this study is 0.5g PGA and failure probability is 90% at 1g PGA along the transverse direction. Similarly, the performance point is 1g PGA and failure probability is 90% at 2.5g PGA along the longitudinal direction.

3. Conclusions

In this study, seismic analyses of the ground supported horizontal tank were performed using a 3D detailed model and a simplified one. And the fragility curves were developed for limit states of overturning and sliding. The following conclusions are drawn from the study.

(1) The liquid inside the tank will continue to slosh even after the earthquake vibration stops and the peak responses of the impulsive component and convective component vary. The peak of the impulsive component reaches earlier than the convective component during earthquake vibration.
(2) Seismic response results of the simplified model and the 3D FSI one show agreeable results, therefore the simplified model can be used for developing seismic fragility curves for horizontal cylindrical tanks.
(3) When the design level earthquake (0.154 g horizontal PGA) occurs, the probability of the damage by overturning and sliding is almost 0 %.
(4) The considered horizontal tank will not likely receive any damage from earthquakes of 0.3 g or less PGA.
(5) The performance point of the overturning of the tank is higher than that of sliding.
(6) Fragility curves for the desired limit states show that seismic damage for the horizontal tank is susceptible along the transverse direction.

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요 지 : 유연한 벽체를 가지면서 내용물이 일부분 저장된 수평원통형 저장탱크의 내진성능을 평가하기 위하여 지진취약도 해석을 수행하였다. 충격질량과 유연질량의 두 개의 집중질량을 갖는 등가의 간이모델로 저장탱크를 모델화하였으며, 이 모델의 유효성은 구조물-유체 상호작용을 고려한 3D 해석모델의 응답이력해석을 통해서 검증하였다. 이 등가의 간이모델에 대해서 양방향 지반운동에 대해 지진해석을 수행하였으며 종축방향과 직각방향에 대해 안정성과 관련한 지진취약도 곡선을 도출하였다. 그 결과 수평원통형 저장탱크는 직각방향에 대해서 지진 시 피해가 발생할 가능성이 큰 것으로 평가되었다.

핵심용어 : 수평원통형 저장탱크, 구조물-유체 상호작용, 간이(간편)모델, 지진취약도곡선