Seismic Analysis of an SPB Tank Installed in the Offshore GBS LNG Terminal

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A preliminary design of LNG tank for the offshore GBS (Gravity Based Structure) LNG terminal has been conducted using the unique IHI-SPB (Self-supporting Prismatic shape IMO type B) technology. The SPB tank system achieves the robust and high reliable design, and has been applied not only to LNG carriers but also to the world's first. LPG FPSO. Moreover the SPB tank system should be one of the most suitable tank system for GBS. The tank is independent from the concrete GBS and insensitive to dynamic behavior of GBS due to tsunami or other environmental loads and accidents on the GBS. The SPB tank system can also resist the sloshing loads of LNG caused by earthquakes. This paper presents the seismic response analysis of the tank and study on seismic isolation system.

1. Introduction

Demands for natural gas as clean energy are rapidly increasing worldwide. In LNG field, new demands are growing in China, India, etc. in addition to the demands of existing major LNG consuming countries including Japan, South Korea, and Taiwan, and the introduction of LNG for addressing energy shortages is planned in Europe and the U.S., where pipelines are mainly used conventionally. Therefore, a significant increase in demands of LNG is expected.

Particularly in the U.S., realization of offshore LNG facilities are strongly desired because of growing opposition movements of local residents against the construction of onshore receiving terminals as well as a significant increase in demands.

In response to these movements, IHI Marine United Inc. (hereinafter called IHIMU) is continuing activities for the realization of offshore LNG facilities using the SPB type LNG storage tank system. The SPB tank system is a low-temperature liquid gas storage tank system and developed on its own. It is regarded as a tank system that can be widely applied to offshore facilities such as FPSO (Floating Production Storage and Offloading Unit) as well as various sizes of liquefied gas carriers. Using this system, the world's first LPG FPSO has been realized.

A facility with an SPB tank installed in a gravity based offshore concrete structure called GBS (Gravity Based Structure), is proposed as one of the offshore LNG facilities that stores and supplies LNG. In order to design the SPB tank installed in the GBS, a method for accurately analyzing structural responses to seismic loads must be established. If seismic loads exerted on the SPB tank are significant at the installation site, it will be required to reduce the loads by seismic isolation technology such as applied to onshore buildings or bridges in order to minimize the tank structural weight and optimize the capital expenditure.

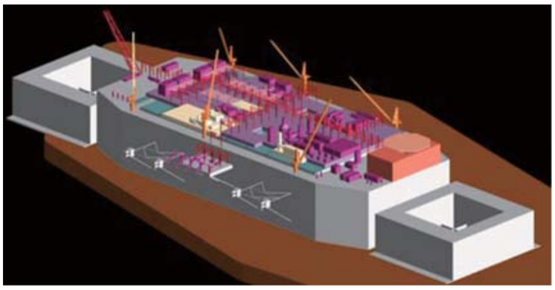
This paper presents a direct numerical simulation method for the structural response analysis of the tank to seismic loads using a nonlinear time transient response analysis code, and the application to the large SPB tank on the GBS.

2. Method for analyzing structural responses

Figure 1 (1) shows a schematic of a GBS and an SPB LNG storage tank installed in it. The LNG storage tank assumed in this paper is a prismatic-shaped tank made of stainless steel (SUS304) measuring 140 m in length, 38 m in width, and 26 m in height with an LNG storage capacity of 125 000 m^3. The tank is self-supported on the concrete structure through plywood blocks at the bottom.

A modal synthesis analysis (linear modal response analysis) based on response spectrum is widely applied to the design of ships for vibration prevention and the design of onshore structures for earthquake-resistance. It is required, however, to apply the time transient response analysis for a large prismatic-shaped tank

(a) Offshore LNG receiving terminal



(b) Transverse section

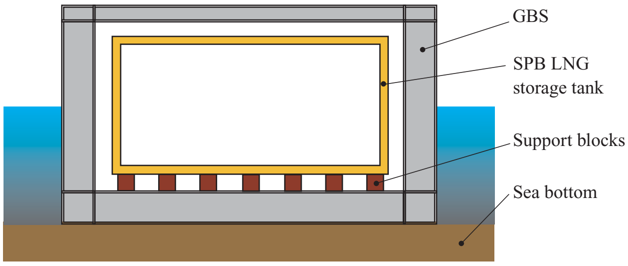


Fig. 1 GBS and SPB LNG tank concept

such as discussed in this paper, which has many natural vibration modes in the frequency range (under 40 Hz) to be addressed for seismic analysis, in order to predict seismic response with high accuracy. The capability of analyzing nonlinear damping behaviors is also required for optimum design, because the hysteresis characteristics of seismic isolation devices (such as high damping rubber bearings) are nonlinear.

On the other hand, not all of the fluid in a tank generates inertial force in proportion to the magnitude of the seismic load (acceleration), and some of the fluid generates hydrodynamic forces induced by the oscillation of the free surface. The fluid mass that generates the inertial forces in proportion to the seismic acceleration is called an ‘Impulsive mass,’ and the fluid mass that generates the hydrodynamic forces induced by the oscillation of the free surface is called a ‘Convective mass.’ ‘Impulsive mass’ affects the tank structural responses significantly. Therefore, the analysis code used for a seismic response analysis must be suitable for the calculation of impulsive mass.

In order to meet the above requirements, we have established a calculation method using ABAQUS, which is used for nonlinear analysis, in conjunction with NASTRAN, which is widely used for linear structural and vibration analysis of ships. **Table 1** shows a comparison of analysis functions between NASTRAN and ABAQUAS, and **Fig. 2** shows a procedure of seismic response analysis for an SPB tank.

The impulsive mass can be directly calculated by using the NASTRAN virtual mass calculation function. However, because NASTRAN is basically a linear analysis code, useless results are often obtained for strong nonlinear models. ABAQUS is more suitable for nonlinear calculation, but complicated fluid modeling and large-scale calculation are necessary to calculate the impulsive mass using fluid-structure interaction analysis for this SPB tank. It is not suitable to use ABAQUS for all processing of seismic response

Table 1 Comparison between NASTRAN and ABAQUS

Functions	NASTRAN	ABAQUS
Bilinear characteristics (load-strain, damping)	△	○
Calculation of impulsive mass	○	△
Modal synthesis analysis based on response spectrum	○	○
Time transient response analysis (linear)	○	○
Time transient response analysis (nonlinear)	△	○

(Note) ○ : Suitable
△ : Unsuitable depending on conditions

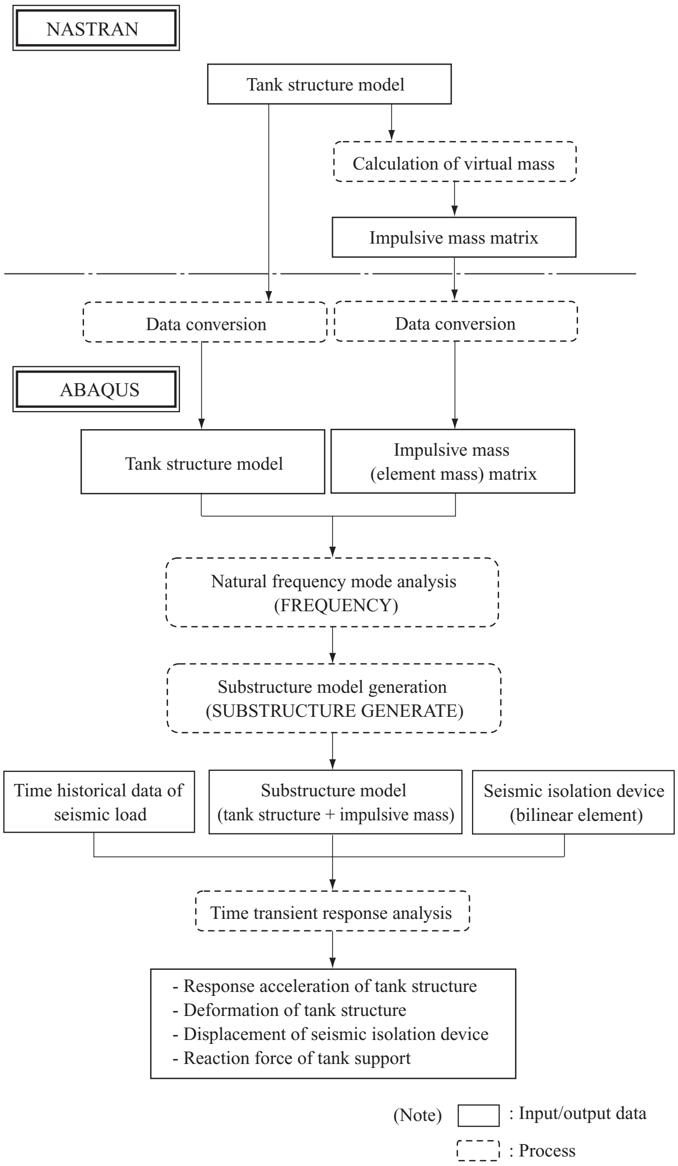


Fig. 2 Procedure of seismic response analysis for SPB tank

analysis of this tank. Base on this consideration, only virtual mass was calculated by NASTRAN, and this virtual mass was converted into an ABAQUS model to carry out the nonlinear analysis by ABAQUS. In addition, in order to reduce the calculation-scale, the substructure method was applied to a tank body and virtual mass excluding tank supports.

The high damping rubber bearing (HRB) in practical use in onshore structures was studied for use in the horizontal seismic isolation device of this tank. The bilinear kinematic hardening model that is commonly used for seismic analysis, is applied to the modeling of the rubber bearing.

3. Verification of analysis method based on model tank test

3.1 Outline of model test

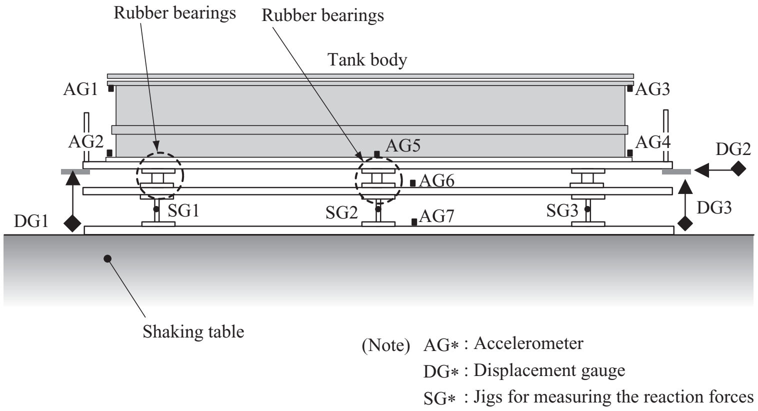
In order to verify the accuracy of this analysis method, responses to seismic loads were measured using the model tank shown in **Fig. 3**, and the measurement was compared with time transient response analysis using an analysis model obtained by the correctly represented model tank. The model tank body measures $L \times B \times D = 3\ 500 \times 600 \times 600$ mm, and is made of acrylic resin. Tests were conducted under the following 2 conditions for fixation of the tank bottom. One condition (seismic non-isolation) was that it was fixed on a shaking table via jigs for measuring the reaction forces, and the other condition (seismic isolation) was that rubber bearings were inserted between the tank bottom and the jigs. Jigs for measuring the reaction forces and rubber bearings were installed at 4 locations in the corner parts of the tank and 2 locations in the middle part of the tank.

For the seismic load (seismic wave), JMA-KOBE (that recorded the Kobe Marine Meteorological Observatory on the occasion of the Southern Hyogo Prefecture Earthquake in 1995) as shown in **Fig. 4** was applied. For the time axis, similarity correction was conducted by multiplying actual seismic waves by the square root of the scale ratio.

3.2 Comparison between test result and calculation result

Response acceleration without seismic isolation in the Y direction (tank width direction) is remarkable. Therefore, with attention focused on the acceleration

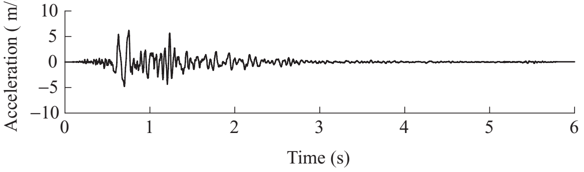
(a) Arrangements of jigs for measuring the reaction forces and rubber bearings



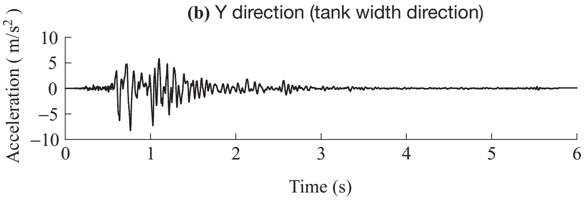
(b) Test condition

Fig. 3 Model tank for exciting test

and the reaction forces at the tank bottom supports in the Y direction, a comparison between the measured value and the calculated value is shown in **Fig. 5**. The difference between the measured value and the calculated value in a seismic non-isolation condition was approximately 20%. And the difference in a seismic isolation condition was less than 10%. The reason for the smaller difference between the test and the calculation in seismic isolation conditions is thought to be that the installation of rubber bearings prevented higher-order local vibration modes from occurring and lower-order vibration modes in which the whole tank vibrated become dominant. It was verified that the accuracy of this calculation method was sufficient for SPB tank design.

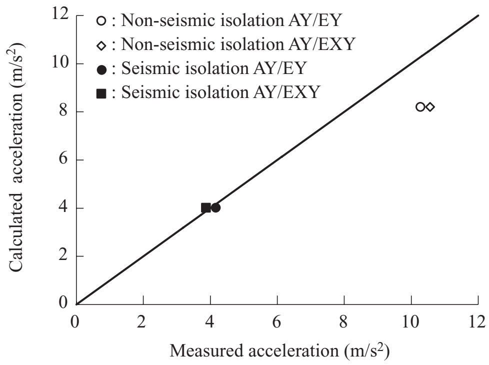


(a) X direction (tank longitudinal direction)

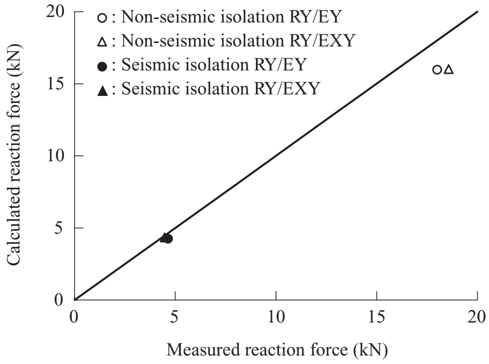


(b) Y direction (tank width direction)

Fig. 4 Seismic load of JMA-KOBE



(a) Y direction (tank width direction) acceleration



(b) Y direction (tank width direction) reaction force

(Note)
AY/ EY : Y direction acceleration at the time of Y direction shaking
RY/ EY : Y direction reaction force at the time of Y direction shaking
AY/ EXY : Y direction acceleration at the time of XY direction simultaneous shaking
RY/ EXY : Y direction reaction force at the time of XY direction simultaneous shaking

Fig. 5 Comparison between model tank tests and FE analysis

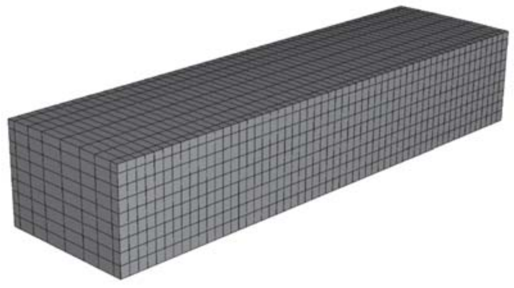
4. Seismic response analysis for expected actual tank

A response analysis on JMA-KOBE seismic waves was carried out by using the expected actual tank model shown in **Fig. 6**. The following two conditions for fixing the tank bottom were studied. One condition (seismic non-isolation) used only plywood support blocks, and the other condition (seismic isolation) used high damping rubber bearings and plywood blocks in combination. The equivalent viscous damping of high damping rubber bearings was assumed to be 20%.

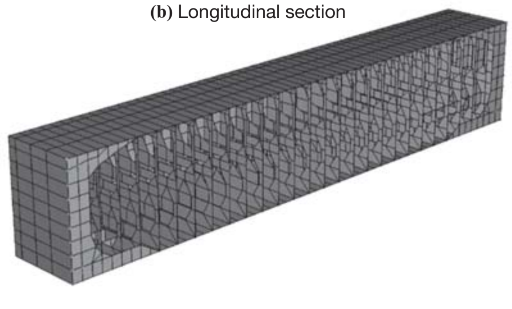
Figure 7 shows tank response acceleration in seismic isolation conditions and non-isolation conditions. Although a response acceleration of up to 8.3 m/s^2 {0.8 G} is expected to occur in seismic non-isolation conditions, horizontal seismic isolation devices can reduce the response acceleration to 40% or less.

5. Conclusion

This paper presents the calculation method for seismic responses of SPB tanks installed in GBS LNG receiving terminals based on nonlinear time transient response analysis. It also presents the accuracy of the calculation

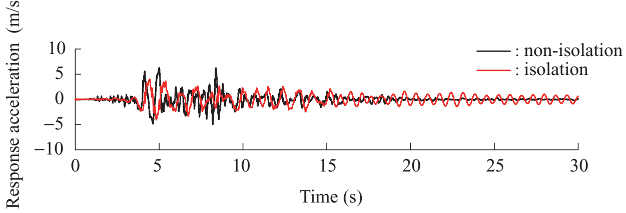


(a) Overall appearance



(b) Longitudinal section

Fig. 6 FE analysis model for full-scale tank


(a) X direction (tank longitudinal direction)

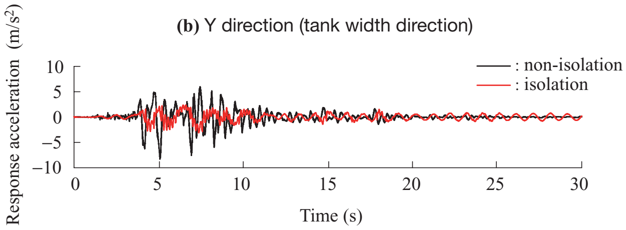

(b) Y direction (tank width direction)

Fig. 7 Response acceleration comparison between isolated tank and non-isolated tank

method based on the comparison between model tests and numerical simulations, and shows an example of analysis for the expected actual tank. It also shows a trial design of horizontal seismic isolation devices for the tank. It is important to accurately predict the seismic responses and seismic isolation effects of larger storage tanks in terms of design and the method presented in this paper makes the achievement of an optimized tank design possible.

REFERENCES

(1) A. Haug, R. Eie, K. Sandvik and E. Aoki : Offshore Concrete Structure for LNG Facilities – New Developments Offshore Technology Conference 15302 (2003. 5)