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EVALUATION OF SEISMIC PERFORMANCE OF HIGH PRESSURE GAS EQUIPMENT AGAINST LARGE-SCALE EARTHQUAKE

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Abstract

In the near future, the occurrence of large-scale earthquakes of M7 to M9 class, such as the Nankai Trough Earthquake and the Tokyo Inland Earthquake, are expected in Japan. This study is to evaluate the seismic performance of high pressure gas equipment against such large-scale earthquakes.

For 9 types of high pressure gas equipment such as spherical reservoir and flat bottom cylindrical reservoir etc., the typical model for each type of high pressure gas equipment with those standard structural specifications according to the earthquake resistant design standard were examined. Dynamic non-linear analyses of each high-pressure gas equipment were conducted at several thousands to ten thousands sites affected by the assumed Nankai Trough Earthquake and the assumed Tokyo Inland Earthquake, using earthquake motion data of the two large-scale earthquakes released from the Cabinet Office of Japanese Government (see Fig.1). Dynamic non-linear analyses were conducted applying the simplified model of one degree of freedom system with its foundation fixed, and the simplified sway-rocking spring model considering dynamic soil-structure interaction. From the dynamic non-linear analyses, the seismic margin and the earthquake damage possibility of high pressure gas equipment were evaluated (see Fig.2).

As a result, it was found that the high pressure gas equipment according to the earthquake resistant design standard has seismic margin appropriately and is unlikely to be damaged by the Nankai Trough Earthquake and the Tokyo Inland Earthquake. However, there were areas beyond the design ground motion and the possibility of damage can not be excluded depending on the areas. The rationality of site-specific seismic design is suggested.

This study included the results of the researches [1, 2, 3, 4] commissioned by the Ministry of Economy, Trade and Industry.

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Keywords: high pressure gas equipment; evaluation of seismic performance; dynamic non-linear analysis

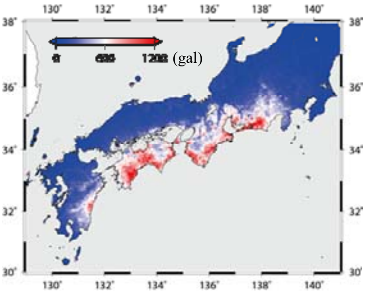


Fig. 1 – Ground surface acceleration
(The Nankai Trough Earthquake)

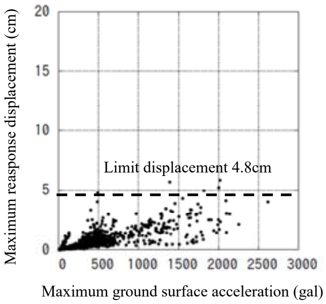


Fig. 2 – Analytical result of spherical reservoir
(The Nankai Trough Earthquake)

1. Introduction

In the near future, the occurrence of large-scale earthquakes of M7 to M9 class, such as the Nankai Trough Earthquake and the Tokyo Inland Earthquake, is expected in Japan [1, 2, 3]. This study is to evaluate the seismic performance of high pressure gas equipment against such large-scale earthquakes.

For 9 types of high pressure gas equipment such as spherical reservoir and flat bottom cylindrical reservoir etc., the typical model for each type of high pressure gas equipment with standard structural specifications according to the earthquake resistant design standard were examined. Dynamic non-linear analyses of each high-pressure gas equipment were conducted at thousands to ten thousands sites affected by the assumed Nankai Trough Earthquake and the assumed Tokyo Inland Earthquake, using earthquake motion data of the two large-scale earthquakes released from the Cabinet Office of Japanese Government. Dynamic non-linear analyses were conducted applying the simplified model of one degree of freedom system (in the following, 1-DOF model) with its foundation fixed, and the simplified sway-rocking spring model (in the following, SR model) considering dynamic soil-structure interaction. From the dynamic non-linear analyses, the seismic margin and the earthquake damage possibility of high pressure gas equipment were evaluated.

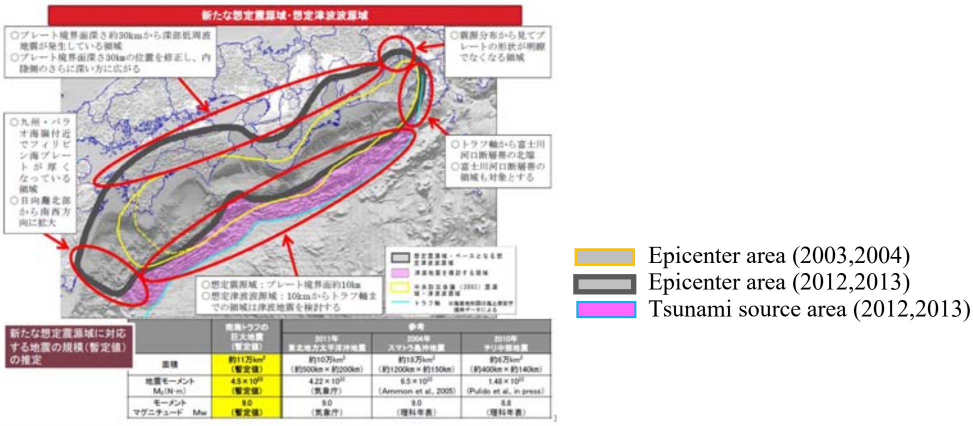
This study included the results of the researches [4, 5, 6, 7] commissioned by Ministry of Economy, Trade and Industry.

2. Overview of the Nankai Trough Earthquake and the Tokyo Inland Earthquake

From the Central Disaster Management Council of the Cabinet Office, the damage assumption of the Nankai Trough Earthquake and the Tokyo Inland Earthquake was released in 2003 and 2004, and revised in 2012 and 2013, respectively [1, 2, 3].

In the revision of the Nankai Trough Earthquake, those independencies of the Tokai, Tonankai and Nankai Earthquakes along the Nankai Trough were reviewed and changed to they were expected to occur simultaneously. Furthermore, the epicenter area was extended to Bungo Channel and Seto Inland Sea side etc., and the expected Mw was increased from 8.7 to 9.0 (Mw 9.1 considering the tsunami source area, see Fig.1). It was positioned as the largest possible earthquake. 4 cases of basic case, land side case, east side case and west side case were assumed as the arrangement of strong-motion generation area, and strong-motion fault parameters, surface ground model (AVS30 and seismic intensity increment, 250×250m mesh) etc. were released. For 2 cases of basic case and land side case, strong motion (acceleration) waveforms (1x1 km mesh, actually 5x5 km mesh) were also released at engineering bedrock (appearance of layer with Vs=350 to 700m/s) [8].

On the other hand, similar data was released for the assumed 26 earthquakes even in the case of the reviewed Tokyo Inland Earthquake, but the strong motion (acceleration) waveform at engineering bedrock was released only for the Tokyo Metropolitan Nanbu Earthquake [9].



	南海トラフの巨大地震（暫定値）	参考 2011年 東北地方太平洋沖地震	参考 2004年 スマトラ島沖地震	参考 2010年 チリ中部地震
面積	約11万km² （暫定値）	約10万km² （約500km×約200km）	約18万km² （約1200km×約150km）	約6万km² （約400km×約140km）
地震モーメント M_0(N·m)	4.5×10^{22} （暫定値）	4.22×10^{22} （気象庁）	6.5×10^{22} （Ammon et al., 2005）	1.48×10^{22} （Pulido et al., in press）
モーメントマグニチュード Mw	9.0 （暫定値）	9.0 （気象庁）	9.0 （理科年表）	8.8 （理科年表）

Fig. 1 －Reviewed epicenter area of the Nankai Trough Earthquake [Added to 1]

3. Estimation of ground surface acceleration by simple formula

Applying the simple formula proposed by Suetomi et al. [10, 11], the ground surface acceleration was estimated using the acceleration waveforms released from the Cabinet Office for the affected area of the Nankai Trough Earthquake and the Tokyo Inland Earthquake. The formula was an empirical one that estimates the maximum acceleration on the ground surface, using the maximum acceleration on the engineering bedrock and the AVS 30, and considering it's leveling out by the effect of the non-linear response of the ground.

Fig.2 and Fig.3 show an example of the estimation results of the maximum acceleration on the ground surface for both earthquakes obtained by applying the formula. The maximum value of the design horizontal acceleration is 600gal. In these figures, areas smaller than 600 gal were shown in blue and those larger than 600gal were shown in red, and the darker the color, the further away from 600 gal.

From the results, it could be understood that there were many areas exceeding the designed horizontal maximum acceleration 600 gal. Focusing on the maximum value, in the Nankai Trough Earthquake of the land side case, the ground surface acceleration was predicted more than about 1800 gal in a part of Shizuoka Prefecture. On the other hand, even in the case of the Tokyo Inland Earthquake, extremely large ground surface acceleration was predicted up to about 1000 gal.

As described later, ground dynamic nonlinear analyses were conducted at several thousands to tens of thousands sites in the affected areas of both earthquakes using ground data of the Nationwide Digital Ground Map [12], and the acceleration response of the ground surface is calculated. The details were omitted, and comparing the two results, the correlation coefficient in the case of linear approximation is around 0.8, and except for some large values by ground dynamic nonlinear analyses, the ground surface maximum acceleration by the simple formula was generally consistent with the acceleration of nonlinear dynamic analyses.

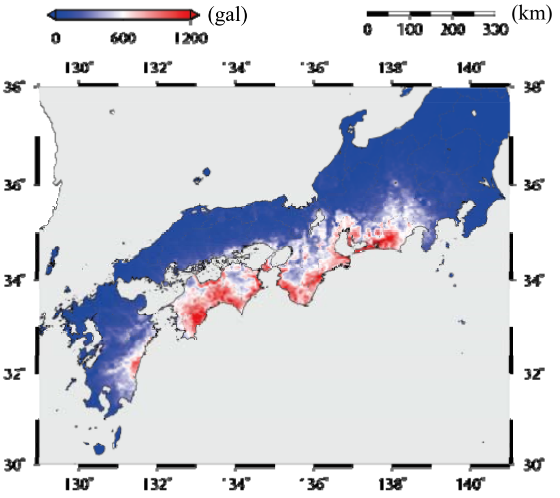


Fig. 2 — Ground surface acceleration
(The Nankai Trough Earthquake, Land side case)

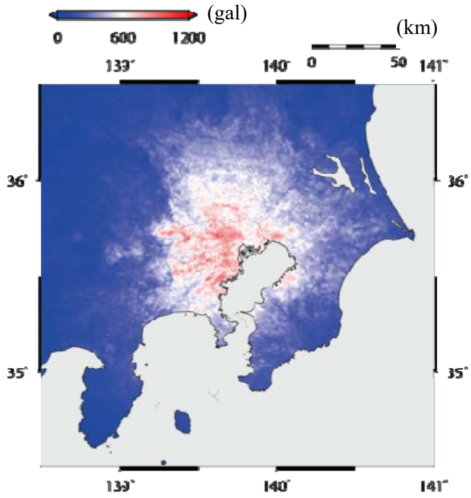


Fig. 3 — Ground surface acceleration
(The Tokyo Inland Earthquake)

4. Evaluation of seismic margin and earthquake damage possibility of high pressure gas equipment by dynamic nonlinear analyses

4.1 Target equipment

As high pressure gas equipment, typical nine types of equipment with standard specifications were modeled. Nine types of high pressure gas equipment were spherical reservoir (tie rod brace), spherical reservoirs (steel tube brace, reinforcement at brace intersection, no reinforcement), flat bottom cylindrical reservoir, vertical cylindrical reservoir, horizontal cylindrical reservoir and towers (skirt support, leg support, lug support). As an example, the structural specifications of the spherical reservoir (tie rod brace) and the foundation were shown in Fig.4 and Fig.5. The specifications of the models were aligned to typical examples computed in the earthquake resistant design standard.

Main dimensios

Storage : Flammable gas
Storage capaciry : 1,000m^3
D_S = 12,410mm
H_C = 8,000mm
H_1 = 7,206mm
H_2 = 6,000mm

Dimensions and materials of main components

Spherical shell : SPV490Q
Upper support column : 406.4$^{\phi}$×9.5^{t} , SPV490Q
Lower support column : 406.4$^{\phi}$×9.5^{t} , STK400
Tie rod brace : 70$^{\phi}$, SS400

Seismic specifications

Importance I : β_1=0.8
Regional division A : β_2=0.8
Ground type 4 : β_3=2.0
Seismic coefficient at ground surface : K_H=0.384
Seismic coefficient of reservoir : K_{MH}=0.922

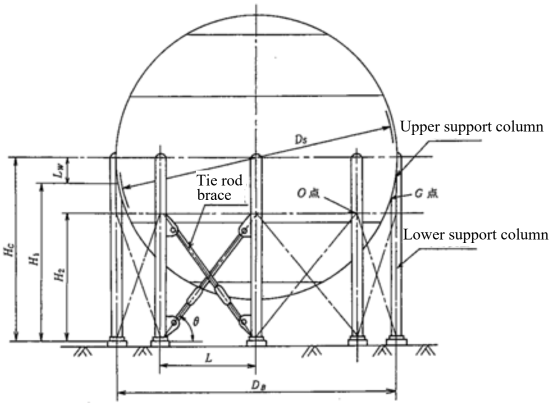
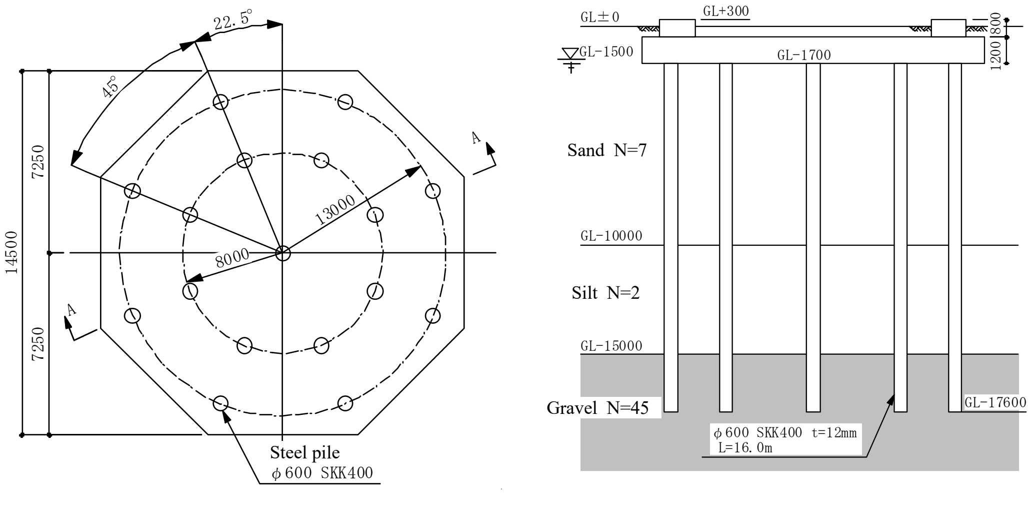


Fig. 4 —Structural specifications of the spherical reservoir (tie rod brace)



(a) Pile arrangement (b) Section A—A

Fig. 5 — Structural specifications of the spherical reservoir (tie rod brace) foundation

4.2 Modeling

Dynamic non-linear analyses of high pressure gas equipment were conducted at several thousands to tens of thousands sites for the affected areas of the Nankai Trough Earthquake and the Tokyo Inland Earthquake, which would be described later. For this reason, dynamic non-linear analyses were conducted by applying 1-DOF model and SR model which simplified each high pressure gas equipment.

The non-linear characteristics of each high-pressure gas equipment were set up with conducting pushover analyses by means of three-dimensional FE static non-linear analyses with its foundation fixed. As an example, Fig.6 and Fig.7 show the pushover analysis model and result of the spherical reservoir (tie rod brace). The spherical shell was modeled with linear shell elements, the support columns with non-linear shell elements, and the tie rod braces with non-linear rod elements. In the dynamic non-linear analysis, a normal bilinear hysteresis curve was set up based on the push over analysis result shown in Fig.7. In addition, the limit displacement where failure occurs in the high pressure gas equipment was set up by the 1G vibration test [4] (see Photo 1) etc. as well as by each member's yield, buckling state and judgement with twice elastic slope method etc.

In addition, the sway and rocking springs of the foundation and ground in the SR model were set up with reference to the document [13]. The ground conditions were adopted for each target site in the affected area of the Nankai Trough Earthquake and the Tokyo Inland Earthquake for setting up the springs. On the other hand, regarding the foundation, a pile foundation was assumed as shown in Fig.5. The specifications of the pile foundation were set up assuming a typical loose ground in the seaside area where high pressure gas equipment was often installed, and the same specifications were set up for each target site. Assuming the loose ground was conservative because the specifications of the pile foundation become more rigid and the influence of dynamic interaction was evaluated smaller.

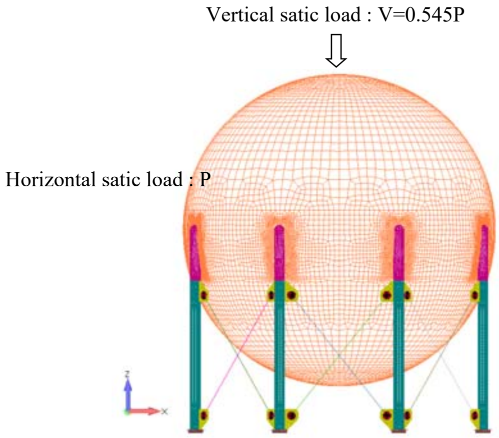


Fig. 6 — Pushover analysis model of spherical reservoir (tie rod brace)

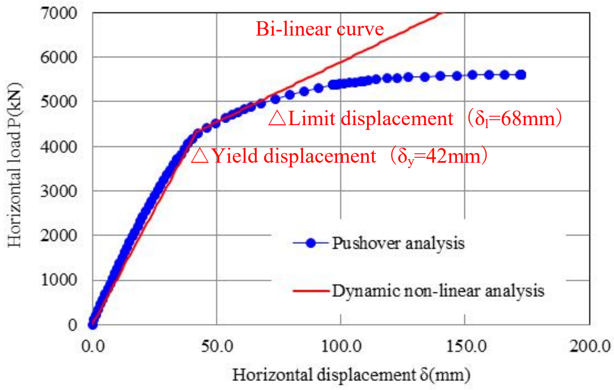


Fig. 7 — Pushover analysis result of spherical reservoir (tie rod brace)

Photo 1 — 1G vibration test of spherical reservoir (steel tube brace) model [4]

4.3 Evaluation of seismic margin

Dynamic non-linear analyses of high pressure gas equipment were conducted for the sites using the ground data released from the Nationwide Digital Ground Map [12] in the affected areas of the Nankai Trough Earthquake and the Tokyo Inland Earthquake. Dynamic non-linear analyses were conducted by applying 1-DOF model and SR model which simplified each high pressure gas equipment, assuming that the 9 types of high-pressure gas equipments described above were installed at each target site. The target sites were approximately 2,000 for the Nankai Trough Earthquake and about 17,000 for the Tokyo Inland Earthquake.

At first, the ground dynamic non-linear analyses were conducted with the released acceleration waveform on the engineering bedrock of the Nankai Trough Earthquake and the Tokyo Inland Earthquake as the input earthquake motion, and the acceleration waveform on the ground surface, ie input earthquake motion to 1 DOF model and SR model was calculated (see Fig.8). The strain dependence of the shear stiffness and damping factor of the ground was expressed by the modified Ramberg-Osgood model [14, 15] based on the proposed formula by Yasuda et al. [16]

The seismic margin of the high pressure gas equipment was evaluated as an acceleration ratio R, as shown in the following formula; a ratio of the ground surface acceleration A at which failure occurred in the high pressure gas equipment to the design ground surface acceleration B according to the earthquake resistant design standard. A was obtained from dynamic non-linear analyses, as the state reaching the above-mentioned limit displacement was failure. In addition, A was taken as the lower limit of the 95% reliability, and it was calculated as the minimum value of both earthquakes.

$$R = A/B \tag{1}$$

R：Seismic margin (Acceleration ratio)
A：Ground surface acceleration at which failure occurs in high pressure gas equipment
B：Design ground surface acceleration

Table 1 shows the seismic margin of each high pressure gas equipment. Spherical reservoir (tie rod braces), spherical reservoirs (steel tube braces, reinforcement at brace intersection, no reinforcement) and flat bottom cylindrical reservoir have lower seismic margins, while vertical cylindrical reservoir, horizontal cylindrical reservoir and towers (skirt supports, leg support, lug support) have relatively higher seismic margins. At first, dynamic nonlinear analyses were conducted by applying 1-DOF model with its foundation fixed. However, for spherical reservoir and flat bottom cylindrical reservoir with lower seismic margins, dynamic nonlinear analyses were conducted by applying SR model considering dynamic soil-structure interaction and the seismic margin of them was re-evaluated more strictly. For the dynamic soil-structure interaction, centrifuge vibration test [6] (see Photo 2) has been conducted and it’s effects has been evaluated. Also, for SR model, three-dimensional FE dynamic non-linear analyses were conducted to confirm its applicability. For further details, see references [6, 7].

As a result, the acceleration ratio of each high pressure gas equipment exceeds 1.0, and the high pressure gas equipment according to the earthquake resistant design standard had seismic margin appropriately.

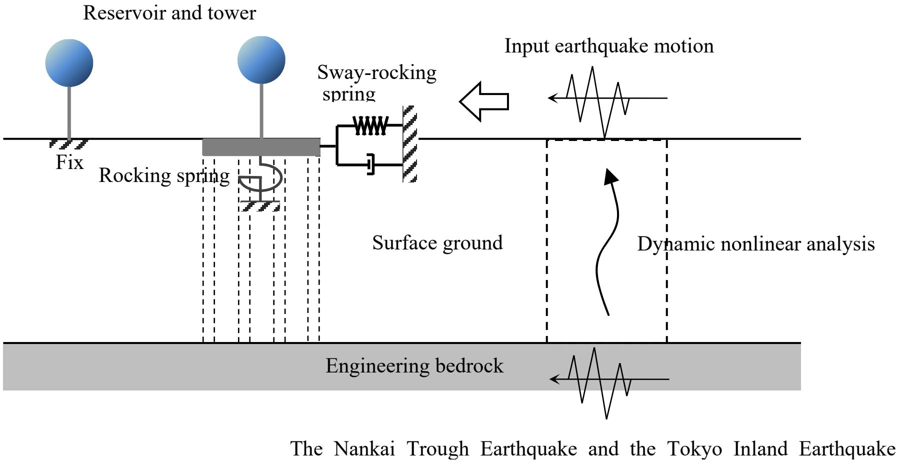


Fig. 8 － Input earthquake motion to 1 DOF model and SR model

Table 1 ― Seismic margin of high pressure gas equipment

No.	High pressure gas equipment	A(gal)	B(gal)	Seismic margin A/B
1	Spherical reservoir (tie rod brace)	503	384	1.31
2	Spherical reservoir (steel tube brace, reinforcement at brace intersection)	788	480	1.64
3	Spherical reservoir (steel tube brace, no reinforcement)	579	480	1.21
4	Flat bottom cylindrical reservoir	706	600	1.18
5	Vertical cylindrical reservoir	1399	384	3.64
6	Horizontal cylindrical reservoir	1757	420	4.18
7	Tower (skirt support)	1256	480	2.62
8	Tower (leg support)	1757	336	5.23
9	Tower (lug support)	877	480	1.83

Note; No.1～4 : Results of dynamic non-linear analyses with SR model
No.5～9 : Results of dynamic non-linear analyses with 1-DOF model

(a) Spherical reservoir-pile foundation-ground model (b) Spherical reservoir model

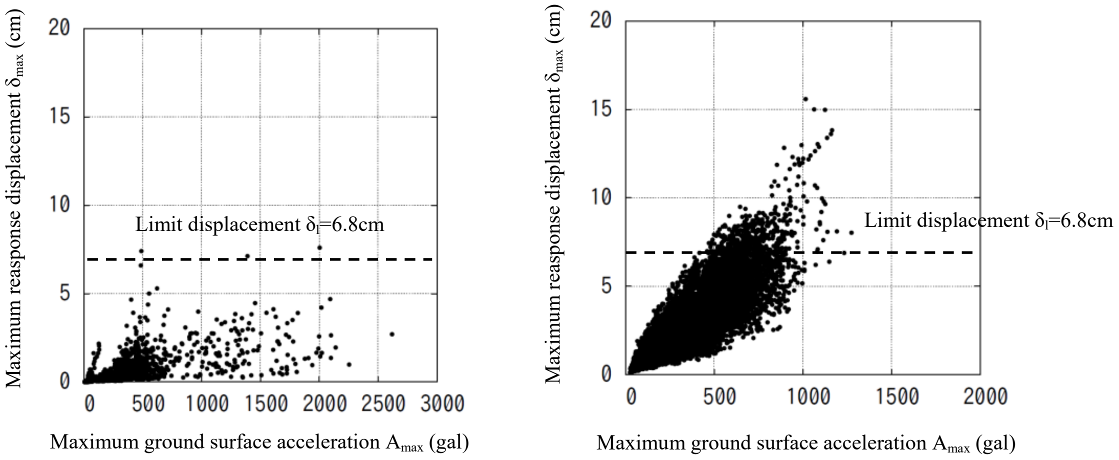
Photo 2 ― Centrifuge vibration test of spherical reservoir model [6]

4.4 Evaluation of earthquake damage possibility

The earthquake damage possibility of typical nine types of high pressure gas equipment was evaluated by the dynamic nonlinear analyses in the affected area of the Nankai Trough Earthquake and the Tokyo Inland Earthquake similar to the previous section.

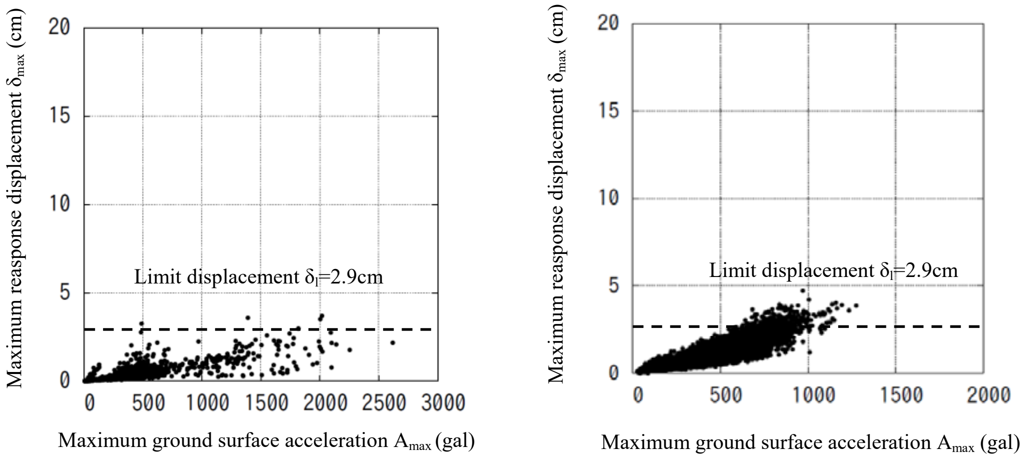
Fig.9 and Fig.10 show the example results of the dynamic nonlinear analyses. In spherical reservoirs and flat-bottomed cylindrical reservoir with lower seismic margin examined in the previous section, there were some sites beyond the limit displacement where failure occurred against the Tokyo Inland Earthquake, but there were a few such sites. Against the Nankai Trough Earthquake, there were few sites beyond the limit displacement. On the other hand, vertical cylindrical reservoir, horizontal cylindrical reservoir, and towers which had higher seismic margins, have few or no sites beyond the limit displacement for both earthquakes.

As a result, it was found that there was little earthquake damage possibility of high pressure gas equipment according to the earthquake resistant design standard against the Nankai Trough Earthquake and the Tokyo Inland Earthquake.



(a) The Nankai Trough Earthquake (land side case) (b) The Tokyo Inland Earthquake

Fig. 9 — Analytical result of spherical reservoir (tie rod brace)



(a) The Nankai Trough Earthquake (land side case) (b) The Tokyo Inland Earthquake

Fig. 10 — Analytical result of flat bottom cylindrical reservoir

5. Conclusion

Against large-scale earthquakes of the Nankai Trough Earthquake and the Tokyo Inland Earthquake that are expected to occur in the near future, we evaluated the seismic performance of high pressure gas equipment by dynamic nonlinear analyses. The obtained findings are summarized as follows.

(i) The high pressure gas equipment according to the earthquake resistant design standard has seismic margin appropriately and is unlikely to be damaged by the Nankai Trough Earthquake and the Tokyo Inland Earthquake.

(ii) However, there are areas beyond the design ground motion and the possibility of damage can not be excluded depending on the areas. The rationality of site-specific seismic design is suggested.

Based on this study, the earthquake resistant design standard for the high pressure gas equipment under the High Pressure Gas Safety Act in Japan was revised from the specification type design standard to the performance specification type design standard on November 14, 2018, in order to be able to apply the site-specific seismic design (implemented on September 1, 2019). This study dealt with the conventional earthquake resistant design standard before revised. The specifications of the conventional design standard were taken over to the High Pressure Gas Safety Institute of Japan Standards (in the following, KHKS) [17, 18], which were designated as exemplified standards. It is considered that the seismic design according to the exemplified standards KHKS conforms to the revised performance specification type design standard (except for applying the site-specific earthquake motion described later). In addition, new engineering knowledge such as application of the site-specific earthquake motion predicted at each site has been introduced in KHKS.

6. Acknowledgements

This study was conducted as the researches commissioned by the Ministry of Economy, Trade and Industry. To discuss and advance the researches, committees of experts were formed in the High Pressure Gas Safety Institute of Japan. We would like to express our gratitude for the guidance to Professor Emeritus Susumu Yasuda of Tokyo Denki University, Professor Hitoshi Morikawa of Tokyo Institute of Technology and other members of the committees.

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