Subject IDs: SI15
TC/ATC # (optional):

Earthquake resistance evaluation of a spherical gas holder considering its ultimate state due to liquefaction-induced differential settlement of sandy ground

Mio Kobayashi[1] and Toshihiro Takaine[2]

[1] Supply Control and Disaster Management Dept., Tokyo Gas Co., Ltd., 1-5-20, Kaigan, Minato-ku, Tokyo 105-8527, Japan.
[2] GEOASIA Research Society, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan.

ABSTRACT

In this study, we proposed a seismic stability assessment method focusing on the ultimate state as a countermeasure against a severe case of a spherical gas holder requiring high safety standards. We conducted a detailed earthquake behavior evaluation by combining both soil-water coupled analysis and nonlinear response analysis of the holder. In the evaluation, pile support was assumed to be destroyed due to liquefaction and the holder was placed on an unequal ground surface by the remaining sound piles. The results showed that no fatal damage was caused to the holder on the ground and that the ultimate seismic performance evaluation of the holder could be implemented by this method.

Keywords: spherical gas holder; liquefaction; ultimate state; soil-water coupled finite deformation analysis

1 INTRODUCTION

After the Hyogo-ken Nanbu earthquake, many cases of damage to pile foundation structures, including cases caused by liquefaction, were reported. Although the liquefaction-resistant seismic designs of the pile foundations of various structures were developed, taking into account such damage cases, a more detailed and logical approach is required when dealing with liquefaction or ground displacement caused by a level-2 earthquake. As spherical gas holders (hereinafter referred to as holders), which call for high safety standards, need to be able to deal with even more intense scenarios, we have studied afresh the method of evaluating the ultimate state of the holder assuming differential settlement due to soil liquefaction. In this report, we present examples of the evaluation based on this study.

2 PROPOSAL OF SEISMIC PERFORMANCE EVALUATION METHOD FOCUSING ON THE ULTIMATE STATE OF THE HOLDER

While adhering to existing seismic resistance standards, bearing in mind “the Basic Act for National Resilience” (Cabinet Secretariat, 2013), the seismic performance of the holder must have a margin for structural safety and proof stress, ensuring an ultimate state in which it does not collapse locally or entirely, to avoid the worst eventuality. In other words, it is important to be able to deal with highly intense scenarios.

The existing seismic resistance standard (Japan Gas Association, 2014) has adopted the concept of performance-based requirement to the elasto-plastic performance design. Therefore, in this report, we study afresh the method of evaluating the holder. The method is a combination of (1) the analysis of the ground response by the soil-water coupled finite deformation analysis code (Noda et al., 2008) (GEOASIA equipped with SYS Cam-clay model, Asaoka et al., 2002) and (2) the nonlinear response analysis of the spherical gas holder by ABAQUS. This method evaluates the seismic resistance focusing on the ultimate limit of the holder.

Fig. 1 shows the flowchart of the seismic performance evaluation of the method. First, the object is modeled using the topography of the location and ground information. The design specifications of the holder and analysis conditions, such as material constants, are set ((1), (2)). Further, one-dimensional (1D) and two-dimensional (2D) analyses of the ground response are performed to calculate the maximum ground settlement amount δ_{max} ((3)-(5)). Subsequently, the same settlement amount δ_{max} is treated as the differential settlement, and a nonlinear response analysis of the inclined holder is conducted ((6)). The response values, such as the damping force and relative displacement, are calculated for each member of the holder ((7)). The seismic performance of the holder is evaluated by comparing the response value ((7)) with the tolerance value of each member of the holder ((8)).

The examples of applying this method to a holder in the alluvial lowland areas of southern Kanto are presented in the following sections.

Subject IDs: SI15
TC/ATC # (optional):

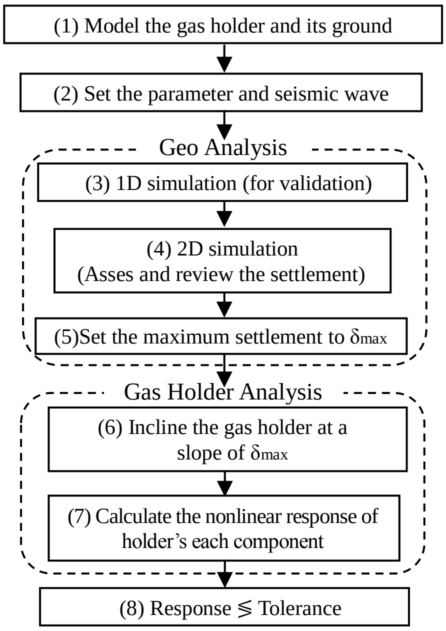


Fig. 1. Earthquake resistance evaluation flow for a spherical gas holder considering its ultimate state.

3. ONE-DIMENSIONAL ANALYSIS

3.1 Analysis conditions

The examined location had soft ground consisting of 10 layers from the surface layer, as shown in Fig. 2, with a loose sand layer value of N < 10 up to a depth of 2-8 m and a soft clayey soil layer with N of almost zero up to 15 m further below. The layers are also shown in Fig. 2. The following two cases were implemented in 1D analysis, using the 1D finite-element mesh of Fig. 3.

(1) Examine only the behavior of the ground without considering the holder load (Case 1).
(2) The state when the pile does not function is considered to be the state immediately after the earthquake (Case 2).

The holder load was considered to be a distributed load. In the initial state of the ground, the degree and specific volume of the structure (Asaoka et al., 2002) were assumed to be uniform in each layer, and the over consolidation ratio was assumed to be distributed in the vertical direction according to the overburden pressure. The groundwater level (GL) is -1.35 m, the ground surface is the drainage boundary, and the pore water pressure of the subsurface groundwater is negative in the hydraulic boundary conditions, depending on which mean effective stress was increased. Furthermore, the bottom of the ground, which is the engineering base surface, was set as the bottom viscous boundary (V_s = 420 m/s, Lysmer et al., 1969) and the condition of equal displacement was imposed on the nodes at the same level as the end elements of the ground.

3.2 Analysis result

Analysis was conducted from the input of a level-2 earthquake in the horizontal direction of all the nodes on the bottom surface, based on the Seismic Design Guidelines for Production Equipment etc. (Japan Gas Association, 2012) (Fig. 4), until the completion of consolidation. Fig. 5 (a) shows the time history of settlement. Settlement of the 2nd layer "silty sand" began toward the end of the earthquake and the settlement of the 3rd layer "sandy silt" and the 4th layer "silty clay" began a day later. The calculations show that the settlement was nearly complete after 10,000 days and the settlement amount was 0.211 m on the ground surface.

Fig. 6 shows the mean effective stress reduction ratio at the end of the earthquake and the behavior of the soil element at the lowermost end of the 2nd layer. The mean effective stress reduction ratio becomes ~1.0 in the 2nd layer, leading to liquefaction, and the horizontal displacement becomes large. The amount of settlement of the 2nd layer "silty sand" after liquefaction was calculated assuming D_r = 40%, based on previous studies (Ishihara and Yoshimine, 1992). The settlement according to the calculation is roughly in agreement with the analysis results (Fig. 5 (a)), showing that the material constants used in the analysis were appropriate.

Fig. 5 (b) shows the time history of the ground settlement of Case 2. The settlement amount was 0.415m on the ground surface. Cases 1 and 2 have almost the same timing of settlement of the 2nd, 3rd, and 4th layer.

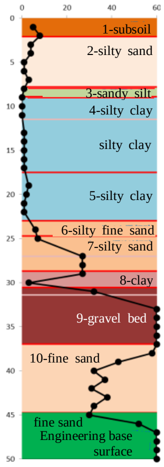


Fig. 2. Geological column.

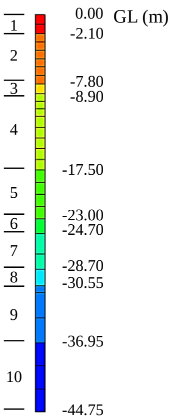


Fig. 3. 1-D FE mesh.

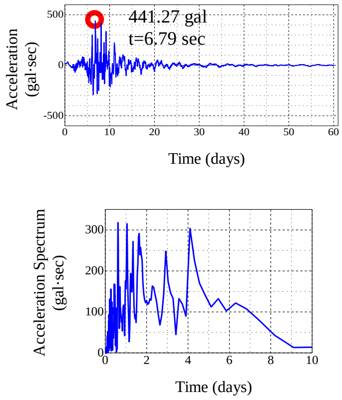
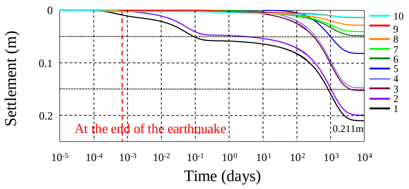
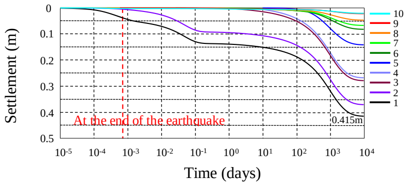


Fig. 4. Input earthquake motion.

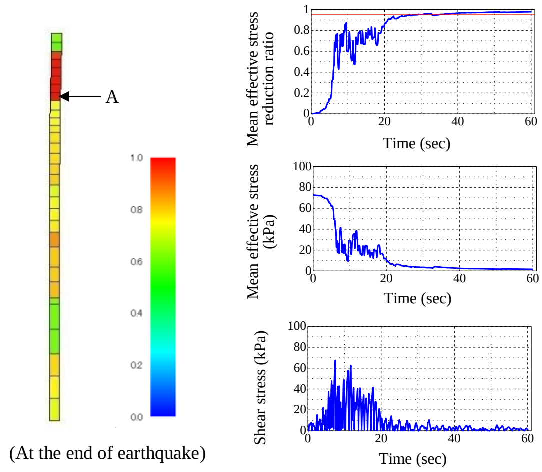


(a) case 1 (without the holder load)



(b) case 2 (with the holder load)

Fig. 5. The time history of the ground settlement at the case 1 and 2.



(At the end of earthquake)

Fig. 6. Mean effective stress reduction ratio and behavior of the soil element A at the lowermost end of the 2nd layer.

4. PLANE STRAIN TWO-DIMENSIONAL ANALYSIS (IMPACT ASSESSMENT OF GROUND INCLINATION)

4.1 Analysis conditions

In order to investigate the effect of the inclined lower part of the 2nd layer, 2D analysis was conducted on a horizontally stratified ground and on an inclined ground. Fig. 7 shows the mesh diagram. The layer classification and boundary conditions of the ground are the same as those described above. In the inclined ground, the 2nd layer has a width of 59.53 m below the holder and an inclination of 1/31. As the holder is also modeled in 2D plane strain conditions, it was reproduced by adding finite elements (Fig. 8), and the effects of a level-2 earthquake (Japan Gas Association, 2012) (Fig. 4) were horizontally input simultaneously with the loading. The analysis was then conducted until completion of consolidation. To model the holder, the loads were made equivalent, as shown in Fig. 8. Regarding the rigidity, the elastic modulus of the support was determined such that the cycle at which the horizontal displacement of the top was maximum matched the natural period of the holder, which was 0.786 s.

4.2 Analysis result

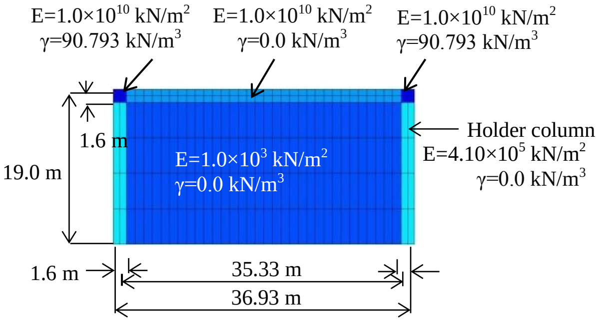
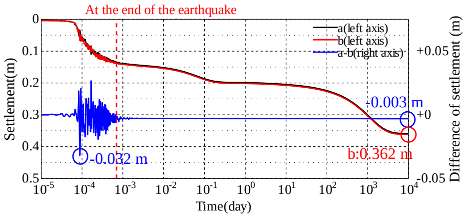
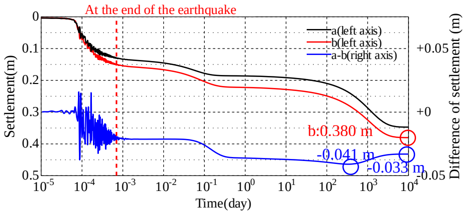


Fig. 8. Modeling the gas holder in 2D plain strain condition.



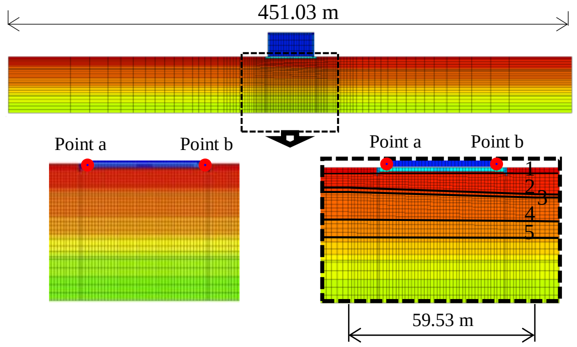
(a) Horizontally stratified ground



(b) Inclined ground

Fig. 9. Settlement at the bottom of the holder foundation and the difference in the settlement between points a and b.

Fig. 9 shows the settlement at points a and b at the bottom of the holder foundation (Fig. 7) and the difference in the settlement amount between points a and b. In the horizontally stratified ground, the final settlement amount at point a is 0.362 m, which is ~0.05 m less than that found in the 1D analysis. The maximum deferential settlement on the inclined ground is 0.041 m. Although the settlement amount is relatively large, the differential settlement is small. Even on the inclined ground, the inclination of the settlement is not greater than 1/900.



(a) Horizontally stratified ground (b) Inclined ground

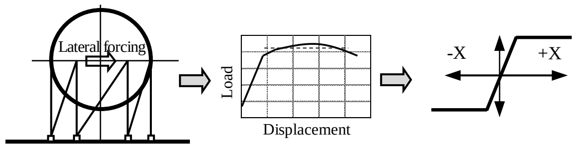
Fig. 7. 2D FE mesh.

In the 2D plane strain analysis, the pile was completely destroyed and hence the supporting function was totally absent. These results show that although a settlement of ~0.4 m can occur in the holder foundation after the earthquake, as long as the inclination is not greater than that observed in the lower part of the 2nd layer (Fig. 7 (b)), the impact on the differential settlement of the foundation is extremely limited.

5. NONLINEAR TIME HISTORY RESPONSE ANALYSIS OF THE HOLDER

5.1 Analysis conditions

In this analysis model, the spherical body is regarded as a rigid body and replaced with a framework. The column base of the holder, tie rods, and braces are treated as elastic, perfectly plastic bodies of a nonlinear material. The general-purpose finite-element analysis



(1) Modeling and calculating the lateral force response of gas holder (2) Load displacement curve with an extremely inclined state (3) Defining the load displacement relationship applied to this evaluation

Fig. 10. Procedure of spherical gas holder analysis.

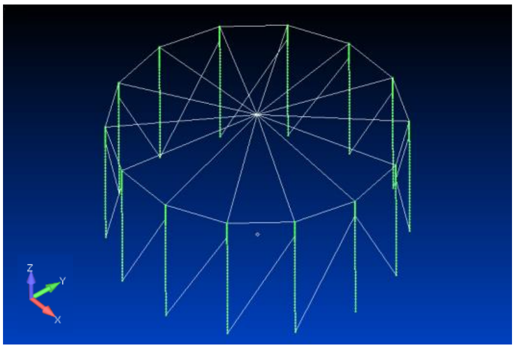


Fig. 11. Analysis model of the holder in the 1st step.

code, ABAQUS, was used, which considers the damping force of the nonlinear damper, the seismic control structure, and also considers the large deformation of the steel material. The analysis was conducted in two steps. In the first step, horizontal displacement is applied to the holder while the holder is inclined toward the center of the spherical body (Figs. 10 and 11), and a load-displacement relationship (spring characteristic) is obtained. As the maximum ground settlement amount δ_{max} shown in the flow of Fig. 1 was obtained as 0.415 m from the response analysis of Sections 3 and 4 (Fig. 5), the inclination of the holder was set to 450 mm.

In the second step, a single-mass system model is set up. This model is composed of a mass point assigned for the entire mass, a horizontal spring obtained in the first step coupled to this mass point, and structural damping and damper attenuation. The model has only one degree of freedom in the horizontal direction. The input seismic waveform was the acceleration response spectrum of the waveform of the Tohoku Region Pacific Offshore Earthquake (K-NET Urayasu, EW) (NIED, 2011), which was generated and processed to conform to the ground-response spectrum diagram of the Seismic Design Guidelines for Production Equipment etc. (Japan Gas Association, 2012).

Table 1. Analysis results of the inclined gas holder (comparing with the permissible value).

Maximum ground settlement δmax (mm)	415
Amount of incline (mm)	450
Strength of holders' support items	OK
Relative displacement at dumper	OK
Damping force at dumper	OK
Respond speed at dumper	OK

5.2 Analysis result

The analysis results are shown in Table 1. The results show that the displacement of the spherical shell due to earthquake motion, damper attenuation force, generation speed, and plastic displacement of support structures were within permissible values, and that no catastrophic damage occurred.

6. CONCLUSION

Focusing on the ultimate state of the spherical gas holder due to differential settlement from the liquefaction of sandy ground owing to level-2 earthquake motion, evaluation of seismic resistance was conducted according to the evaluation flowchart shown in Fig. 1. The results showed that when the support function of the pile had been completely destroyed in the case of an intense scenario, the original inclination of the ground had an extremely limited impact on the seismic resistance of the gas holder. When only a part of the foundation pile remains, as a result of which it cannot be expected to function as a support, the gas holder begins to incline along with the settlement of the sandy ground. This was found to have the greatest impact on the seismic resistance of the gas holder.

Hence, the maximum inclination of the holder foundation that was determined using the maximum ground settlement amount calculated from the ground analysis was assumed to be the ultimate state of the holder. When the seismic resistance of the holder itself was evaluated with the level-2 earthquake, no fatal damage was caused to the holder on the ground to be evaluated.

ACKNOWLEDGEMENTS

In reviewing this dissertation, we have received enormous guidance and advice from Dr Akira Asaoka, Professor Emeritus of Nagoya University, and Dr Toshihiro Noda, Professor of Nagoya University. We express our heartfelt gratitude to them.

REFERENCES

Japanese Cabinet Secretariat (2013). https://www.cas.go.jp/jp/seisaku/kokudo_kyoujinka/index_en.html

Japan Gas Association (2014). Spherical gas holder guidelines.

Lysmer, J. and R.L. Kuhlemeyer (1969): Finite dynamic model for infinite media, ASCE, 95(EM4), 859-877.

Noda, T., Asaoka, A., and Nakano, M. (2008). Soil-water coupled finite deformation analysis based on a rate-type equation of motion incorporating SYS Cam-Clay Model, Soils and Foundations, 48(6), 771-790.

Asaoka, A., Noda, T., Yamada, E., Kaneda, K., and Nakano, M. (2002). An elasto-plastic description of two distinct volume change mechanics of soils, Soils and Foundations, 42(5), 45-57.

Japan Gas Association (2012). Seismic Design Guidelines for Production Equipment, etc.

Ishihara and Yoshimine (1992). Evaluation of settlements in sand deposits, S&F, 32(1), 173-188.

NIED: http://www.kyoshin.bosai.go.jp/kyoshin/.