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DEVELOPMENT OF SEISMIC DESIGN CODE FOR HIGH PRESSURE GAS FACILITIES

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ABSTRACT: Seismic design of high-pressure gas facilities had been carried out in accordance with MITI notification 515 "Seismic Design Code" established in 1981. The Great Hyogoken-nanbu Earthquake occurred in 1995. Some facilities and piping systems were damaged due to ground displacement (settlement and/or lateral movement) induced by liquefaction. Having learned from the experiences, the seismic design code was amended in 1997. This paper introduces requirements in the new seismic design code and the evaluation method of Required Seismic Performance proposed.

Key Words: Seismic Design Code of the High Pressure Gas Facilities, 2-step design assessments, Level 1 earthquakes, Level 2 earthquakes, liquefaction of soil, nonlinear deformation, Required Seismic Performance

INTRODUCTION

After the experiences of Niigata earthquake of 1964 and Tokachi-oki earthquake of 1968, the Safety Division of the Industrial Location and Environmental Protection Bureau of the Ministry of International Trade and Industry(MITI) issued the Seismic Design Code (MITI 1981), which took effect in 1982. Since 1982, vessels and tanks of High Pressure Gas (called "HPG") facilities under the control of the "High Pressure Gas Safety Law" have been designed in accordance with the Seismic Design Code.

The Hyogo-ken Nanbu earthquake in 1995 (called "Kobe Earthquake") caused tremendous huge damage to the urban area. Damage to piping systems and foundations of HPG facilities was serious, but mild in towers, vessels and tank storages, which are included in the scope of the Seismic Design Code.

The "Basic Disaster Management Plan" was revised by the Central Disaster Management Council in July 1995. It requires introducing two-step earthquake assessments for key facilities in society, including HPG facilities. Design Base Earthquakes for those facilities shall be both "a probable strong earthquake during the service life of the facilities" (called "Level 1 earthquake"), and "a possible strongest earthquake with extremely low probability of occurrence" (called "Level 2 earthquake").

The Seismic Design Code (MITI 1997) was amended in MITI Notification No. 143 on March 25, 1997 after the review and investigation by the Seismic Safety Promotion Committee set up in the High Pressure Gas Safety Institute of Japan (called "KHK") under the charge of the former Ministry of International Trade and Industry, now the Ministry of Economy, Trade and Industry.

In the previous code, ensuring the seismic performances of HPG facilities against earthquakes exceeding Level 1 was not required, and the seismic design of piping systems was beyond its scope. In the new code, seismic performances against Level 2 earthquakes are defined, and the design criteria are extended to the elastoplastic region. Therefore, nonlinear analysis is newly required in the seismic design of the HPG facilities, and the seismic design of piping systems is included in the scope of the code.

SEISMIC DESIGN CODE BEFORE KOBE EARTHQUAKE

Before 1960s, HPG facilities were designed to resist earthquakes according to Japanese Building Code. After the experiences of Niigata earthquake of 1964 and Tokachi-oki earthquake of 1968, the Seismic Design Code (MITI 1981) was issued in MITI Notification No. 515, Oct. 1981. All new HPG facilities in Japan were to be designed following the Code effective after April 1982. The principles of the Seismic Design Code are as follows.

(1) HPG facilities shall be designed to resist Design Base Earthquakes equivalent to "Possible strongest earthquake during the service life of the facilities". Maximum ground acceleration of the Design Base Earthquake was stipulated to be 300 Gal in the highest seismic Zone.
(2) HPG facilities are required to be designed to resist the Design Base Earthquake in accordance with Seismic Importance which is defined in the Code, by evaluating the potential hazards to the public, the properties and the environments near those facilities.
(3) The scope of application is towers, vessels and tanks with greater volume or weight than those stipulated in the code, including their supporting structures and their foundations, which are called "Seismic Design Structures" in the Code. (piping systems are not included).
(4) The seismic analysis of structures shall be performed by dynamic analysis or by modified equivalent static analysis. In both cases, the dynamic properties of the structure shall be taken into account.
(5) The Seismic Design Structures are required to remain operable during and after Design Base Earthquakes, according to Seismic Importance of the facilities.

The "High Pressure Gas Safety Institute of Japan" published the method and procedure of seismic design based on the Seismic Design Code as "Guidelines for Seismic Design of High Pressure Gas Facilities" (KHK 1983) in the following year.

DAMAGE TO HIGH PRESSURE GAS FACILITIES IN KOBE EARTHQUAKE

In the Kobe earthquake, which struck on 17 January 1995, no human loss was a result of the failure of HPG facilities. However, some HPG facilities did suffer damage. The event caused a minor hazard, the leakage of liquefied petroleum gas from a storage tank located on the southern coast of Kobe city. This was the most notable damage to HPG facilities, and it caused a large amount of LP-gas in the liquid phase, to leak from the inlet/outlet piping flange connection of an LP-gas storage system. As the leakage rate increased with subsequent aftershocks, on January 18, 70,000 residents who lived nearby were advised to evacuate by the Disaster Rescue Headquarters of Kobe city.

The outline of the incident is as follows. Immediately after the earthquake, due to liquefaction of the area, almost the entire site was covered with muddy water of 30 to 40 cm in depth. The ground throughout the site sank vertically and was displaced horizontally toward the sea. The maximum amount of ground settlement was 75 cm and that of horizontal displacement was 150 cm in the area closest to the south shore. The concrete structures for shore protection tilted and were displaced toward the sea by 3 m. The dike made of concrete and surrounding the HPG tanks sank by 50 to 70 cm with inclination. Lateral displacement of the ground caused the joints of the dikes to break and open. The maximum opening was approximately 60 cm.

The LP-gas leaked in the liquid state at the connection of the stop valve and the inlet/outlet piping nozzle to Tank No. 101 which is a flat- bottomed cylindrical double-shell tank with the capacity of 20,000 kl and the stock of 6,700 kl at the time of the incident.

The causes of the leakage were as follows. Due to ground liquefaction, the vertical ground settlement of 50 to 75 cm and horizontal ground displacement of 30 to 75 cm caused the LP-gas to leak from the nozzle flange connection between the tank and the piping that was pulled toward the sea.

Other leakages were also observed at seven piping connections in the same storage yard. However, these seven leakages did not persist due to the reduction of the force and moment applied to the connection and/or by fastening additional bolts at their flanges.

OUTLINE OF NEW SEISMIC DESIGN CODE FOR HIGH PRESSURE GAS FACILITIES

Learning from the Kobe Earthquake, the Seismic Design Code was amended in MITI Notification No. 143 on March 25, 1997 (MITI 1997), after reviews and investigations by the "Seismic Safety Promotion Committee " set up in KHK under the charge of the former MITI, now the Ministry of Economy, Trade and Industry.

Main items of the new code for HPG facilities are as follows

(1) Introduction of two-step earthquake assessments
The Basic Disaster Management Plan revised by the Central Disaster Management Council, July 1995, requires "two-step earthquake assessments"
Level 1 earthquakes and Level 2 earthquakes are defined and the required seismic performances are stipulated.

(2) Seismic Design Code for liquefaction of soil
Regarding foundations, damage is caused by ground liquefaction. The required performance against ground liquefaction is added to the Seismic Design Code.

(3) Seismic Design Code for piping systems
Regarding piping, which was beyond the scope of the previous Seismic Design Code, because some damage was incurred, the seismic required performance of piping is added in the new code.

Introduction of two step assessments

As the first item above, "two-step earthquake assessments" for HPG facilities, the seismic design flow diagram is presented in Fig. 1.

Towers, vessels, tanks, piping and their supporting structures and foundations of HPG facilities must be designed to resist earthquakes. All of these "Seismic Design Structures" are classified according to Seismic Importance (Ia, I, II, III). In the 1st-step seismic assessment, the maximum ground acceleration of Design Basis Earthquake is specified in accordance with Seismic Importance. The performance of the seismic design structures during and after a Level 1 earthquake must be such that the facilities maintain their operational functions. The 2nd-step assessment is executed only for facilities of higher Seismic Importance (Ia, I). The maximum ground acceleration of Design Basis Earthquake is specified in accordance with the Seismic Importance. The performance of the seismic design structures during and after a Level 2 earthquake must be such that the facilities shall not cause loss of human life.

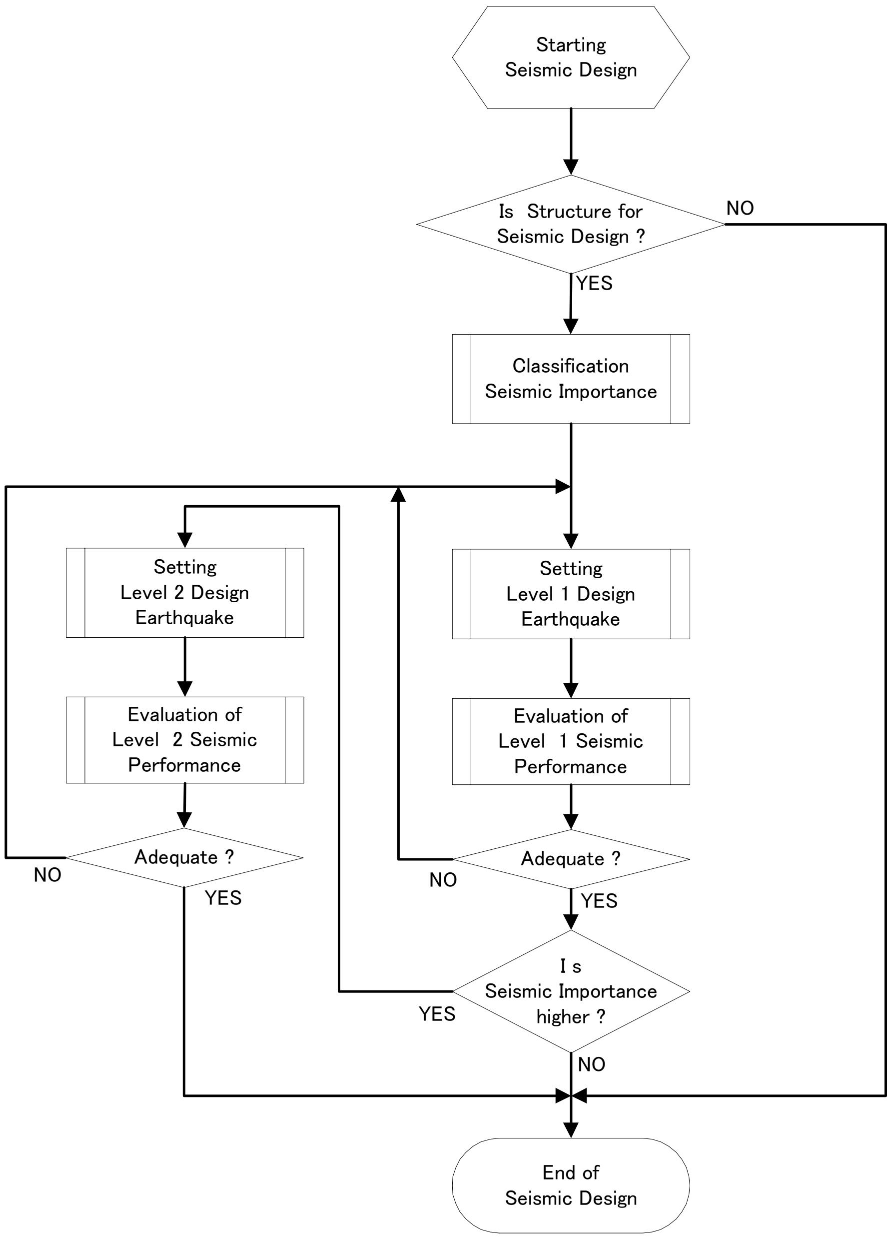

Fig. 1 Seismic Design Procedure

The Design Base Earthquake

In the previous code for HPG facilities, the Design Base Earthquake was defined as an earthquake that occurs once or twice in a period of one hundred years, such as the Local Yokohama, Tokyo earthquake of 1880. The Level 1 earthquake is defined as a probable strong earthquake that occurs during the service life of the plant. By considering the above two definitions, the Level 1 earthquake in the new code is the same as defined in previous code. The maximum ground acceleration of Level 1 earthquake for design (called “Level-1 Design Basis Earthquake” or “L-1 DBE”) is defined as 300 gal in the most seismically active areas of Japan, the Kanto and Tokai regions.

The Level 2 earthquake is defined as a possible strongest earthquake with extremely low probability of occurrence.

The definition of Design Base Earthquakes is as follows.

The peak ground accelerations, PGA, of a Design Base Earthquake are defined as

$$\alpha_H = 150\mu_k \ \beta_1\beta_2\beta_3 \qquad \text{(gal)} \tag{1}$$
$$\alpha_V = 75\mu_k \ \beta_1\beta_2\beta_3 \qquad \text{(gal)} \tag{2}$$

in which α_H and α_V : the peak maximum horizontal and vertical ground accelerations of Design Base Earthquake, respectively. β_1 : the Seismic Importance factor of the seismic design structure, and its value is in the range 1.0 to 0.5, β_2 : the Seismic Zoning factor, and its value is in the range 1.0 to 0.4 for Level 1 and 1.0 to 0.7 for Level 2 earthquakes, β_3 : the ground multification factor in suface soil layers, and its value is 2.0, but 1.4 for hard rocks. μ_k : the Earthquake level factor, whose value is 1.0 for Level 1 earthquakes, and 2.0 or greater for Level 2 earthquakes.

Dynamic characteristics are determined from the “Response spectrum as multiplication factor” for Seismic Zoning and the soil structure.

The maximum ground acceleration of L-2 DBE is the value from 420 to 600 gal in accordance with Seismic Zoning. The stipulation is based on the following discussions.

In the case of HPG facilities, the entire country is mapped as four zones, which is compatible with the Japanese Building Code. However, when considering Level 2 earthquakes, it is not economically feasible for all facilities in a zone to be designed to resist the highest acceleration to be expected in the same zone. Locations where highest acceleration is expected are seismically limited to near active faults. The accelerations at the other most locations in the same zone are of lower levels. The DBE in this code is defined by the acceleration expected at the larger area in the same zone. HPG facilities located at sites where acceleration higher than the defined level is expected would be designed according to the owner’s discretion.

In the Kobe earthquake, the maximum ground acceleration is 818 gal, as reported by the Kobe Ocean Meteorological Observatory. However, no serious damage of nearby HPG facilities was observed, which were designed to resist DBE of 240 gal. Now seismology is developing and advancing but it is difficult to determine a reliable and economically feasible DBE that can be universally applied to all HPG facilities under the jurisdiction of the HPG safety law.

Many organizations are now making efforts to obtain data and knowledge regarding future earthquakes. The Headquarters for Earthquake Research Promotion is evaluating about 100 important active faults throughout Japan. Such efforts will be effective for improving the seismic design of HPG facilities in the future.

Many seismologists say that there are no observations of active faults associated with earthquakes of JMA Magnitude less than 6.5. Therefore, such earthquakes could occur anywhere in Japan. The minimum ground surface acceleration of Level 2 earthquakes is stipulated in the Code to be 420 gal, which acceleration is expected in an area near the epicenter of a Magnitude 6.5 earthquake.

Effects of liquefaction of soil

HPG facilities located in areas in damages of soil liquefaction shall be designed under the conditions of liquefied ground. The ground liquefied behind quay walls flows toward the sea due to the movement of the quay walls in the event of an earthquake. Vessels, tanks and their foundations may move vertically and horizontally.

The HPG piping systems are pulled to breakage and HPG leaks due to the relative displacements of the vessel, tank and supporting structures.

In order to evaluate the Required Seismic Performance, the guideline (KHK, 2000) proposes the formulation (Yasuda 2000) of vertical and horizontal movement and inclination angle of vessels, tank and supporting structures, established from the data observed after the Kobe earthquake and the Niigata earthquake of 1964.

For an example of computing the movement on the bases of the formulation, quay walls will move by 3.0 m and the ground will move by 66 cm horizontally and 46 cm vertically at the point of a distance from the quay wall by 45 m. Vessels, tanks, piping, their supporting structures and foundations must be designed under the condition of those ground movements. Very large relative displacement imposes load on Vessels, tanks, piping systems and their supporting structures.

Required seismic performance

As previously mentioned, based on the Japanese Basic Disaster Management Plan 1995, HPG facilities are designed to avoid the loss of their functions during and after Level 1 earthquake and to prevent hazardous effects to the public, properties and environment during and after Level 2 earthquake.

Level 1 Required Seismic Performance

The seismic design structures shall maintain "Level 1 Required Seismic Performance" in the event of a Level 1 earthquake. In order that the HPG facilities do not lose their functions during Level 1 earthquake, the Level 1 Required Seismic Performance (L1-RSP) of seismic design structure is defined to be such that HPG facilities incur no fatal residual deformation and no persisting leakage of HPG during and after the Level-1 Earthquake.

The Required Seismic Performance is aimed to enable facilities to continue operations during and after the Level 1 earthquake. Regarding the design criteria for L1-RSP the code specifies that the computed stresses for seismic design should be less than or equal to the yielding stress of material or the critical stress for buckling, and also that there be no leakage from connections at the pressure boundaries such as flange connections.

$$\sigma_{compute} \leq \sigma_{allowable} \tag{3}$$

in which $\sigma_{compute}$: maximum stress for evaluation computed using the formula provided in the code, and $\sigma_{allowable}$: allowable stress equal to yield stress as specified in the code.

The failure mode and design criteria and formula for evaluating L1-RSP are the same as described in the previous code.

Level 2 Required Seismic Performanc

The seismic design structures shall maintain "Level 2 Required Seismic Performance in the event of Level 2 earthquake".

In order that the damaged HPG facilities have not seriously effect on the public, properties and environment in a Level 2 earthquake, the Level 2 Required Seismic Performance (L2-RSP) of seismic design structure is defined to be such that HPG facilities incur no leakage of HPG during and after the Level 2 earthquake. For HPG facilities, nonlinear deformation due to L2 earthquake is allowed to the extent that it does not induce gas leakage. However, the operations of HPG facilities should not be restarted after a Level 2 earthquake without checking or reviewing the safety.

Regarding the design criteria for L2-RSP, the code specifies that the computed nonlinear deformations for seismic evaluation shall be less than or equal to the allowable nonlinear deformations of the structure.

$$\eta_p \leq \eta_{pa} \tag{4}$$

in which η_p : plastic deformation ratio defined as $\eta_p = \dfrac{\max imum\ deformation}{yield\ \ deformation} - 1$,

and η_{pa} : allowable plastic deformation ratio defined as $\eta_{pa} = \dfrac{allowable\ deformation}{yield\ deformation} - 1$

The allowable deformations shall be determined such that there is no leakage of HPG considering the failure modes of individual seismic structures.

The failure mode of items for evaluating L2-RSP are the same as that for evaluating L1-RSP.

DEVELOPMENT OF SEISMIC DESIGN METHOD FOR VESSELS AND TANKS FOR L2-RSP

The L2-RSP for HPG vessels and tanks shall allow the seismic design structure to incur nonlinear deformation to the extent that it does not induce gas leakage. The design of the HPG structures for L2-RSP requires nonlinear analysis instead of the elastic analysis for L1-RSP.
A new seismic design method, considering nonlinear deformation behavior, for the seismic safety of pressure vessels, tanks and their supporting structures against earthquake was established by Akiyama (Akiyama 1998, Shibata 2004). This method is called the "ultimate design method", and is derived from the equilibrium equation between the input energy exerted by an earthquake and the energy absorption capacity of a structure such as a pressure vessel, tank or piping .

Seismic design criteria for L2-RSP of vessels and tanks have been given in details in the Seismic Design Code (MITI 1997) and in a supplementary guideline (KHK 1998)

DEVELPMENT OF DESIGN METHOD FOR PIPING SYSTEMS FOR L2-RSP

L2-RSP for HPG piping systems shall allow nonlinear deformation (Inaba 2004). The design of HPG piping systems for the evaluation of L2-RSP requires nonlinear analysis, instead of the elastic analysis for L1-RSP. A simplified seismic design method for the evaluation of L2-RSP is proposed (Mukaimachi 2002).The evaluation requires investigations of the effects of both DBE acceleration and DBE displacements (vertical and/or lateral movements) due to soil liquefaction during and after earthquake.

Design criteria for piping components in Level 2 earthquakes, such as bolted flanged joints, expansion joints, and nozzles of equipment, are proposed (Ando 2002). These design criteria are provided by taking into account their failure modes classified according to the data of past damage due to earthquakes (Inaba 2004).

Seismic design criteria of a piping system in the Seismic Design Code and in a supplementary guideline (KHK 2000) have been given, including the design method to resist large lateral displacements of the ground.

CONCLUSION

Learning from the Kobe Earthquake, the Seismic Design Code has been amended, in which Level 2 earthquakes and the Required Seismic Performance are stipulated. In order to evaluate the Level 2 Required Seismic Performance, nonlinear analysis is newly required in the seismic design of the HPG facilities to resist large inertia force and large ground displacement due to soil liquefaction during a Level 2 earthquake.

For towers, vessels and storage tanks, the ultimate design method is adopted, and the criteria and formula are derived to be used in the evaluation of the Level 2 Required Seismic Performance.

For piping, the modified flexibility factor method is introduced in which we evaluate the behavior of piping subjected to extremely large movement of supports by conventional elastic analysis. The behavior of piping systems as well as local elements of piping, such as the bolted flange joint, expansion joint, seismic shut-down valve and elbow, are investigated and verified by the nonlinear FEM and/or experiments.

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The design criteria and formula for evaluating towers, vessels and tanks in the range of plastic deformation were established under review by Dr. Akiyama, Professor Emeritus, University of Tokyo, and all members of the subcommittee on the seismic design of towers, vessels and tanks.

The modified flexibility method and the criteria and formula for evaluating piping components were proposed through discussion with and investigation by Professor Suzuki, Tokyo Metropolitan University, Associate Professor Sawa, Yamanashi University, Mr. Inaba, Toyo Eng'g. Corporation and other members of the subcommittee on the seismic design of piping systems.

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