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THE SEISMIC DESIGN MARGINS FOR SPHERICAL GAS TANKS

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SUMMARY

A major earthquake that occurred in Japan was used as an experiment to verify the adequacy of seismic design. We studied our current seismic design margins based on the elastic theory and using data observed in the Great Hanshin Earthquake of 1995.
While a study of this sort should be treated statistically, the fact that there was only one set of data led us to employ quantitative analysis. In some cases, we found a margin of 1.4 to 4.8 times between the actual seismic behavior and the design basis (e.g., carbon steel pipe STK400). The reduction effect of the input ratio of waves depends largely on the foundation structures. In the case of liquid storage tanks, the liquid level during an earthquake is an important margin factor. The strength margin depends largely on the margins of stress evaluation and material strength.

The relation between the peak horizontal ground acceleration (A) and peak horizontal velocity (V) is shown in the following formula: $A=31.6210^{v/80}$.

When seismic design is formulated by considering the plastic zone of the material at high-level motion, the force method using responded acceleration must be combined with the motion energy method using responded velocity.

INTRODUCTION

The Great Hanshin Earthquake of January 17, 1995 was the most damaging seismic event in Japan since the Great Kanto Earthquake of 1923.With a magnitude of 7.2, it created intense motion in the spherical gas tanks near the epicenter. This was the first serious earthquake to occur since the construction of spherical gas tanks began in Japan.

There was no damage in the structure or piping of these spherical gas tanks. The earthquake was a major test for verifying the appropriateness of their seismic design. Based on this experience, this report describes seismic margins and other points to be considered in future seismic design, using spherical gas tanks as an example.

ACCELERATION SUSTAINED BY SPHERICAL GAS TANKS

Ground acceleration as high as 833 gal was recorded at the H gas supply station near the fault, and 792 gal was recorded at the N station 2-3 km away from the fault. Table 1 shows the specifications of the spherical gas tanks at H and N stations.

The responded acceleration acting upon these spherical gas tanks is summarized in Table 2, as well as the responded acceleration when their braces yielded. In spite of the large acceleration that they sustained, the H station tanks showed no localized damage at all, and the elongation of the braces of the N station tanks remained as low as 0.09%. The reasons for this will be discussed.

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Table 1 Specifications of spherical gas tanks at H and N stations

	H station	N station
Geometrical capacity	17148 m^3	16670 m^3
Inside diameter	32000 mm	31700 mm
Central height	15300 mm	17300 mm
Designed pressure	7 kg/cm^2	6 kg/cm^2
Shell	HT62 Thickness 31 mm	HT80 Thickness 22 mm
Upper support	HT62 16 pieces x 620.2 mm D x 18 mm T	HT80 14 pieces x 480 mm D x 7 mm T
Lower support	STK41 609.6 mm D x 12.7 mm T	SS41 480 mm D x 7 mm T
Brace	Pipe type: STK41 318.5mm D x 10.3 mm T	Tie rod type: SS41 70mm D
Foundation	Cylindrical beam, Bent 96 pieces (800 mm D x 5 mL)	Annular and radial beam, RC pile 56 pieces (350 mm D x 14 mL)
Number	2	4
Year of construction	1976	1960-1966
Seismic design	Modified seismic method seismic coefficient 0.6 (0.3 x 2)	Static seismic coefficient method seismic coefficient 0.3

Table 2 The responded acceleration sustained by tanks

Station	Ground max acceleration	Characteristic period	Responded acceleration (a)	Responded acceleration of brace yield point (b)	Ratioa/b
H	833 gal	0.33 sec	833 x 2.06 = 1716 gal	938 gal	1716/938 =
N	792 gal	0.80 sec	792 x 1.2 = 950 gal	348 gal	950/348 =

FACTORS INFLUENCING EARTHQUAKE RESISTANCE

Because the motions of an earthquake are conveyed to supporting structures through the foundation and the ground, there are two factors that influence earthquake resistance.

The first is the seismic load, such as the characteristics of the earthquake and the foundation, and the second is the aseismatic structure, such as the design, construction, inspection, and maintenance of the supporting structures and foundation structures.

Hence, we investigated the factors that influenced the earthquake resistance of the spherical gas tanks. The seismic load factors are as follows.

Earthquake characteristics

The motion (amplitude and spectrum) that enters the foundation of the tanks is fixed by the factors of magnitude, distance and direction from the fault, geographical features, and amplification in the ground. The responded spectrum used on the current seismic design was made from past earthquake data. The standard responded spectrum of epicentral high-level motion has been determined for each piece of equipment since the Great Hanshin Earthquake. But high-level motion for a continued and long period of time has not been observed, and is not considered in the spectrum.

Foundation characteristics

Observation(2) of LNG aboveground storage response at the earthquake showed that the response amplification ratio in the ground is less than 1.4 times and is smaller than the design basis.

Conveyance of earthquake motions from ground to foundation

Seismic design based on peak horizontal acceleration uses the assumption that the acceleration on the foundation is equal to the ground surface acceleration. But according to actual observation(2) of LNG aboveground storage, the conveyance ratio from the ground to the foundation is 0.75-0.9 and input motion is reduced.

Characteristic period

The characteristic period of tanks with tie rod braces extends with the yielding of the braces. The characteristic period of the H station tank changed from 0.8 second to 1.5 seconds with the yielding of the brace.

Response ratio

The design response ratio of the tanks is fixed by the primary characteristic period and the damping coefficient, using the standard response diagram. The magnification factor of the response actually changes with the characteristic period, namely the stiffness when using the spectrum of observed motion. As stated above, the primary characteristic period lengthens at the yield point of the tie rod brace, and energy is absorbed by plastic deformation. As a result, the actual response is different from the design response, and the magnification factor of the response becomes smaller.

The value used for the damping coefficient of the tanks when designing is 3% for pipe braces and 5% for tie rod braces. These values have been measured by a shake test. In this test, the motion is small and the damping of the supporting structure is measured, so the damping coefficient is small. The motions of the earthquake are conveyed from the ground to the foundation. The foundation of the tank is constructed from cylindrical beams or annular, radial beams supported by many piles. During large motions, damping of the underground transmission is expected and the actual damping coefficient is larger than the design damping coefficient. According to observation(2) of LNG aboveground storage, the damping coefficient is about 10% when using piles and the magnification factor of response becomes smaller than the design value.

Weight

The tanks are not usually full, ranging from 20-95% during use. The weight of the contents is less than the design weight and influences the seismic load. But in the case of spherical gas tanks, because the content is a gas and the weight is about 10% of total weight, a change in the contents has only a small influence on the seismic load. In this case, since the earthquake occurred in the early morning, the gas pressure was near maximum. But the weight of the gas was 15% less than the design weight and had little influence on the total weight. The weight of the contents in liquid storage tanks, such as LPG tanks, is 10 times as much as the weight of tank itself. Liquid volume therefore greatly influences both the total weight and the seismic load.

On the other hand, the aseismatic structure factors are as follows.

Characteristics of the restoration force of the supporting structure

The structure of spherical gas tanks is approximately axially symmetrical and simple. The braces support the horizontal seismic load and the supports support the vertical seismic load. If the braces should yield, the restoration force changes but does not decrease. The characteristics of the restoration force of the supporting structure are essentially earthquake resistant.

Stress calculation method

The stress acting upon the tank must be calculated by a proper structural analysis method. The accuracy of this analysis is influenced by modeling. Usually, models on the safe side are selected.

Judgement of the stress calculation result

Designers provide a margin for calculated stress against allowable stress. User designers, in particular, have a tendency to provide a large margin and select standard sizes that are larger than design sizes. In the case of the H station tanks, the margin was 1.42.It is usually over 1.05.

Thickness of pipes and plates

The thickness that is actually measured must not be less than the minimum thickness allowed when designing. The actual thickness is usually larger than the design thickness, in order to subtract the negative side of the thickness tolerance specified in standard and fabricating tolerances. Table 3 shows a comparison of actual thickness and design thickness in the parts of the H station tanks. The braces and lower supports are more than 6% thicker.

Table 3 Comparison of actual thickness and design thickness in tank parts

	Shell	Brace	Lower support
No. 1	1.028	1.062	1.069
No. 2	1.042	1.060	1.082

(11)Material strength

Material standards, for example JIS, specify a minimum strength to assure compliance. When manufacturers fabricate materials, they guarantee that the strength actually measured is greater than the specified strength. The margin of strength is particularly large when mil sheets are required.

Table 4 shows the statistical value of yield strength.

Table 4 Statistical value of yield strength(3)

Steel sort	Thicknessmm	Yield strength (kg/mm^2) (center)	Margin
SS400	2 t 6	30.0	1.25
	6 t 40	27.9	1.16
STK400	6 t 12	38.8	1.61

Design temperature

The design temperature is decided on the basis of the past minimum measured temperature. The selection of materials is based on this temperature. The temperature used is thus higher than the design temperature. Also, when the braces yield during high-level motion, they become heated and their toughness increases.

Accuracy of fabrication and assembly

Inaccurate fabrication and assembly, for example, slanted supports, deformed angles or poorly aligned butt welded joints, increase the amount of stress acting on parts.

Quality of welded joints

Residual stress or defects in welded joints cause the strength of the welded joints to fluctuate and toughness to be reduced.

Accuracy of inspections

In the past, the welded joints of supporting structures were not often inspected bynondestructive means. With regard to fractures, this is a disadvantage.

Aging of materials

The strength of materials in use changes with age due to, for example, general corrosion, stress corrosion, and fatigue. There is no corrosion allowance provided for supporting structures because it is assumed that painting prevents corrosion. Fatigue is also not considered during design, except in the case of pressure vessels.

SEISMIC DESIGN MARGINS

() Plus side margins

The plus side margin factors that are quantifiable in the case of ground surface motion on current elastic design include (3) Conveyance of earthquake motions from ground to foundation, (5) Response ratio, (6) Weight, (9) Judgement of the stress calculation result, (10) Thickness of pipes and plates, and (11) Material strength. Table 5 summarizes the margins of the plus side factors. The margin is decided case by case, but, except for the seismic load decreasing effect of the content weight, the margin of the seismic load is 1.4-2 times in the case of good conditions, and the margin of aseismatic structures is 1.05-1.7 times in the case of SS400, but the value changes according to the kind of materials. Therefore, the main reasons why the spherical gas tanks at H station were in the elastic zone are estimated to be, in the case of the seismic load, (1) the damping coefficient was large in the foundation and the response ratio was small, (2) a decrease of input occurred in the conveyance of the earthquake motions from the ground to the foundation, and in the case of aseismatic structures, except for the judgement of the stress calculation result, (3) the margin of the material strength was large, and (4) the thickness of the pipes and plates had sufficient margin. Further, the main reasons why the braces of the spherical gas tanks at N station were 0.09% in the plastic zone in spite of the approximate 2.7 times seismic force of the elastic limit, are estimated to be the characteristics of the restoration force of the spherical tank supporting structure added to the above reasons. The tie rod braces made from SS400 absorbed energy when they yielded and the compressed stress constantly acted upon the supports from the brace. The tank responded again in the short period after responding in the long period. The short period acceleration response and the long period velocity response were repeated in the plastic zone. The restoration force of the tank supporting structure did not decrease in the plastic zone.

Minus side margins

The minus side margin factors include (13) Accuracy of fabrication and assembly, (14) Quality of welded joints (residual stress or defects, and reduced toughness in welded joints), (15) Accuracy of inspection, and (16) Aging of materials. The repeat numbers (continuation time) of large motions do not affect the earthquake resistance of the tank in the elastic zone. But in the plastic zone, they become a minus side margin factor. A structure in which the restoration force in the plastic zone does not decrease has no problem as long as the responded acceleration does not exceed the responded acceleration that it was subjected to up to that point. A structure in which the restoration force decreases according to the lengthening of the period in plastic zone, for example, a concrete structure or a buckled steel structure, will have a problem in the long period velocity response. The response spectrum used in the current seismic design is determined from past earthquakes. Because there were only few records of large, continuous motions in the past, this is now a subject for further study. We do not generally consider fabrication or usage risks in design margins other than for factors that are decided in advance, such as fabricating tolerances or corrosion allowances. We expect that fabrication or usage risks do not eat up the design margin because we do our best to control them case by case. But actually, errors do happen in fabricating; residual stress, defects, and changes in strength do exist in welded joints; and materials do age during use. If we do not conduct adequate tests and inspections during construction, or provide proper maintenance, the design margin will in fact be eaten up. In this case, the spherical gas tanks were inspected adequately during construction and properly maintained. It is assumed that there was no minus side margin.

Table 5 Plus Side Margin Factors

Plus Side Factors	Design Value	Actual Value	Margin
Conveyance of earthquake motions from ground to foundation	1.0	0.75 - 0.9	1.11 - 1.33
Damping coefficient	3% or 5%	10%	
Characteristic period	short	long	
Coefficient to multiply to the standard response factor	1.19, 1.0	0.78	1.28 - 1.52
Weight	100%	20 - 95%	
Margin of seismic load based on ground surface			**1.42 - 2.00**
Judgement of stress calculation result	70 - 95%	100%	1.05 - 1.42
Thickness of pipes and plates	100%	100 - 106%	1.0 - 1.06
Yield Strength (SS400)	100%	100 - 116%	1.0 - 1.16
Yield Strength (STK400)	100%	100 - 161%	1.0 - 1.61
Margin of aseismatic structure		**For (SS400)** **For (STK400)**	**1.05 - 1.74** **1.05 - 2.42**

Total margin: For (SS400) 1.49 - 3.48

For (STK400) 1.49 - 4.84

SEISMIC DESIGN FOR HIGH-LEVEL MOTION

Fig. 1 shows the relation between peak horizontal ground acceleration and peak horizontal ground velocity for past earthquakes. The ratio of velocity increase accompanying acceleration increase is smaller for large motions. Fig. 2 shows the relation between peak horizontal ground velocity and peak horizontal ground acceleration for past large earthquakes. The relation between peak horizontal ground acceleration (A) and peak horizontal velocity (V) is shown in the following expression.

$A=31.6210^{v/80}$

At high-level motion, velocity is lower proportionately than acceleration. For example, acceleration increases from 400 gal to 1200 gal (3 times)), while velocity increases from 89 kine to 120 kine (only 1.35 times).Consequently, the seismic force increases 3 times, but the motion energy increases only 1.82 times (equal to square 1.35).

If the seismic strength is increased 2 times in the elastic zone of a spherical tank, the maximum responded acceleration at the brace yielding point becomes 2 times as calculated by the force method using responded acceleration. On the other hand, if the displacement of the supporting structure becomes 2 times, the same effect is obtained. From this fact, if mild steel is used as the brace material, the compressed stress acting upon the supports from the brace will be constant, the braces will absorb seismic energy at yielding, and the acceleration response and velocity response will be repeated with earthquake resistance in the plastic zone as mentioned above.

From now on, when we conduct seismic design considering the plastic zone of the material at high level motion, we must combine the force method using responded acceleration with the motion energy method using responded velocity.

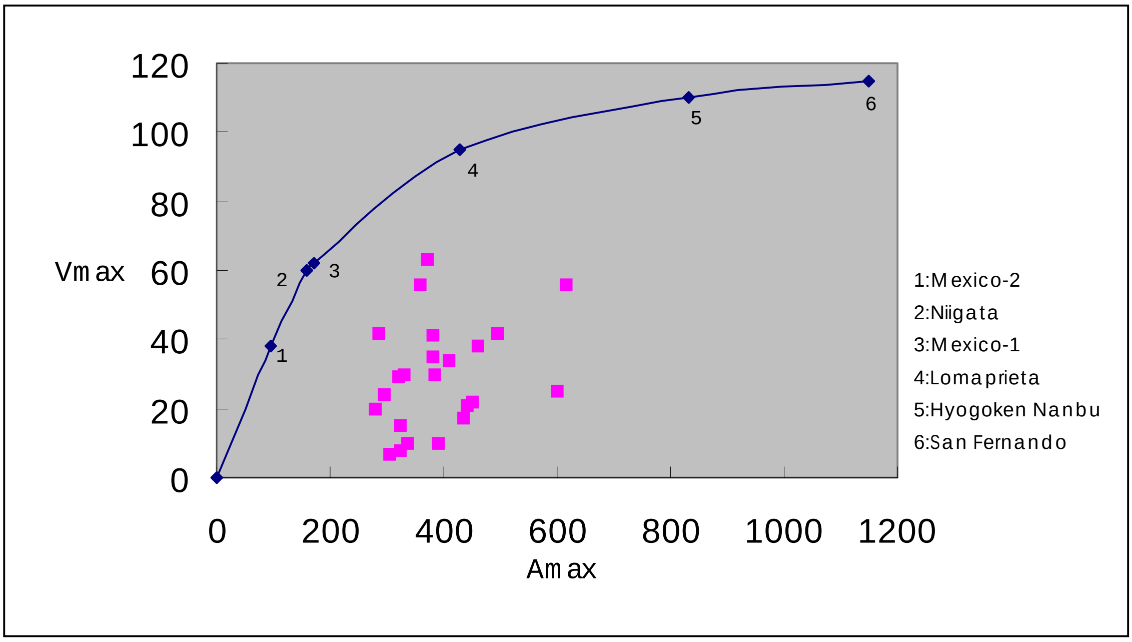

Fig.1 The relationship between peak acceleration and peak velocity on the ground

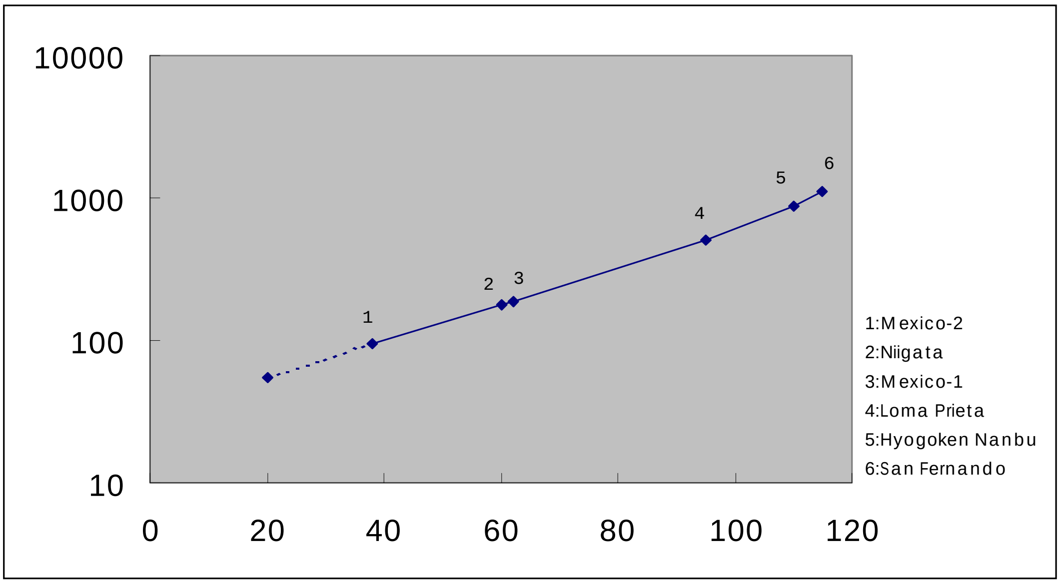

Fig.2 The relation between peak velocity and peak acceleration of past large earthquakes

CONCLUSION

In this paper, we investigated the factors that influence the earthquake resistance of spherical gas tanks, studied the current seismic design margins based on elastic theory, and explained the reasons why there no damage occurred in the function of spherical gas tanks in the Great Hanshin Earthquake of 1995.

While a study of this sort should be treated statistically, the fact that there was only one set of data led us to employ quantitative analysis. In some cases, we found a margin of 1.4 to 4.8 times between the actual seismic behavior and the design basis (e.g., carbon steel pipe STK400). The reduction effect of the input ratio of waves depends largely on the foundation structures. In the case of liquid storage tanks, the liquid level during an earthquake is an important margin factor. The strength margin depends largely on the margins of stress evaluation and material strength.

We found the major prerequisites to be as follows.

Based on the elastic-plastic analysis of supporting structures, supports must be made
stronger than braces in order to increase the restoration force of the supporting structures.
A flexible pipe, such as an S-shaped pipe, should be used in the bottom of the spherical
tank to withstand the three-axial responded displacement of the tank.
Foundation structures must be given sufficient earthquake resistance by the use of
annular, radial or cylindrical beams as foundation parts. Foundation and supporting
structures must be connected firmly by anchor bolts and shear bars, so that the actual
damping coefficient is less than that used in the design stage.
The actual parts must be thicker and stronger than those used in the design stage.
The tanks must be properly manufactured, inspected and maintained.

Design margins should not be used to compensate for the uncertainties of designers or operators. Instead, the margins should be used to cope with the uncertainties of earthquakes as a natural phenomenon. Anti-fracture design methods should be used for tanks and all other important structures.

REFERENCES

(1) A. Takiguchi, Y. Ueno, [Revaluation of Seismic Design for Spherical Gas Holder], Journal of High Pressure Institute of Japan, Vol.37, No.2 (1999), p. 34

(2) A. Takiguchi, Y. Fuchimoto, D. Okai, T. Nisizaki [Verification of Seismic Design for LNG Aboveground Storage], Journal of High Pressure Institute of Japan,
Vol. 37, No. 5 (1999),

(3) Japan Architecture Academy [Standard for Limit State Design of Steel Structures], (1990)

(4) Japan Gas Association [Standard for Spherical Gas Holder] (1989)