COMPARISON OF U.S. SEISMIC FRAGILITY DATA WITH JNES TEST DATA FOR MOTOR-OPERATED VALVES, FANS, AND TANKS

Jinsuo R. Nie[1], Charles H. Hofmayer[2], and Scott P. Stovall[3]

[1] Scientist, Nuclear Science & Technology Department, Brookhaven National Laboratory, Upton, NY (jnie@bnl.gov)
[2] Consultant, Nuclear Science & Technology Department, Brookhaven National Laboratory, Upton, NY
[3] Engineer, U.S. Nuclear Regulatory Commission, Washington, DC

ABSTRACT

This paper presents a comparison of the U.S. seismic fragility data for motor-operated valves, fans, and tanks, with those developed by the Japan Nuclear Energy Safety Organization (JNES) based on its extensive seismic fragility tests. The purpose of the JNES test program was to improve the quality of the seismic fragility capacity database by determining realistic equipment fragility capacities from full-scale shaking table tests (except for tanks), and consequently to allow more accurate seismic probabilistic risk assessments (SPRAs) to be performed to quantify the risk of nuclear power plants during beyond-design-basis earthquakes. The goal of the comparison presented in this paper was to assess the impact that the new test results may have on current SPRAs and how these results can be utilized for future SPRAs. It was concluded that the fragility capacities, either obtained directly from full-scale shaking table tests or estimated from the JNES test-based methods, were in general much higher than or confirmed those used in the U.S. SPRA practice. The JNES test results, including the test-based evaluation methods, are recommended for consideration by fragility analysts in performing future SPRAs; however, cautions must be exercised to assess the applicability of the JNES results to any specific situation that may not be necessarily consistent with the test conditions.

INTRODUCTION

As part of collaborative efforts between the United States and Japan on seismic issues, the U.S. Nuclear Regulatory Commission (NRC) and Brookhaven National Laboratory (BNL) are continuing an effort of evaluating the Japanese equipment fragility tests for use in seismic probabilistic risk assessment (SPRA) for U.S. nuclear power plants (NPPs). This paper presents a comparison of the U.S. seismic fragility data for motor-operated valves, fans, and tanks, with the equipment fragility tests performed by the Japan Nuclear Energy Safety Organization (JNES). This study is a continuation of a previous study published in a SMiRT21 paper by Ali et al. (2011), entitled "evaluation of JNES equipment fragility tests for use in seismic probabilistic risk assessment for U.S. nuclear power plants: an overview."

JNES conducted a multi-year equipment fragility test program to obtain realistic equipment fragility capacities for use in the SPRAs of NPPs in Japan. This test program started in 2002 and continued through 2012. The purpose of this test program was to improve the quality of the seismic fragility capacity database by determining realistic equipment fragility capacities from full-scale shaking table tests (except for tanks), and consequently to allow more accurate SPRAs to be performed to quantify the risk of NPPs during beyond-design-basis earthquakes. This program consists of the tests of a series of safety significant equipment, which are typical for boiling water reactor (BWR) and pressurized water reactor (PWR) plants in Japan. The JNES test program was scheduled in two phases: Phase I includes large horizontal shaft pumps, large vertical shaft pumps, electrical panels, and control rod insertion capability; and Phase II includes fans, valves, tanks, support structures, and overhead cranes. This paper summarizes the results of BNL application of the JNES fragility data for motor-operated valves, fans, and tanks.

The goal of the study presented in this paper was to compare the JNES fragility test results with the fragility data/methods typically used in current U.S. SPRAs of nuclear power plants and to assess the impact that the new test results may have on current SPRAs and how these results can be utilized for future SPRAs. The results of this study are also useful for seismic margin analyses (SMAs), which are important in design certification (DC) or combined license (COL) applications because of the lack of full SPRAs at the DC or COL stage.

MOTOR-OPERATED VALVES

JNES performed a series of seismic tests of motor-operated valves (MOVs) for the purpose of acquiring capacity data under horizontal excitations up to 10 g or more and under vertical accelerations over 1 g. The tests included three 5-cm [2-inch] motor-operated globe valves, three 8-cm [3-inch] motor-operated gate valves, one 41-cm [16-inch] motor-operated gate valve, and one 51-cm [20-inch] motor-operated butterfly valve. Figure 1 shows the test set-up for these valves. The names of the manufacturers and some basic parameters about the valves are available in a NUREG/CR (Nie et al. to be published in 2013).

The main goals of the tests were to: (1) ensure the operability of the valves to open and close during or following an earthquake, (2) ensure seat leakage limits, and (3) ensure the structural integrity of the valve pressure boundary for the maximum static and dynamic differential pressures on the body of the valve.

The JNES tests showed that, except for some specific globe valves, the operability of motor-operated valves was confirmed for acceleration levels from 9.5 to 12.3 g. Some globe valves required to be operable during an earthquake may not achieve these acceleration levels, unless the clutch lever is detached during operating conditions. For all test specimens, the seat leakage was verified to be less than the leakage limits and the pressure boundary integrity was demonstrated. The tests showed that the yoke of motor operated valves were vulnerable for low cycle fatigue and it was recommended that the structural integrity of the yoke be validated for the reported response acceleration at the actuator.

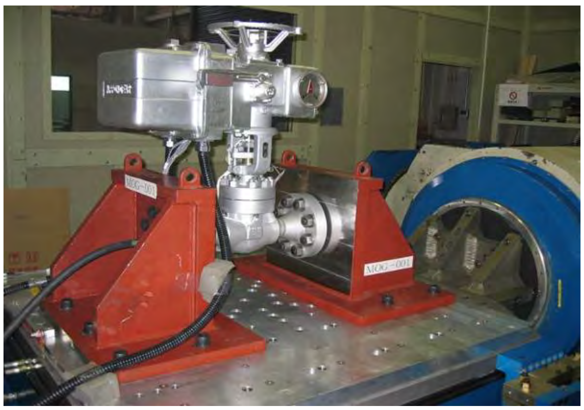
The fragility values of the JNES tested valves were compared to those reported in the following reports:

- NUREG/CR-4334, August 1985, “An Approach to the Quantification of Seismic Margins in Nuclear Power Plants”
- EPRI NP-5223, Rev 1, January 1991, “Generic Seismic Ruggedness of Power Plant Equipment”
- NUREG/CR-4659, Vol 4, June 1991, “Seismic Fragility of Nuclear Power Plant Components (Phase II) – A Fragility Handbook on Eighteen Components)”
- EPRI NP-6041-SL, Rev 1, August 1991, “A Methodology for Assessment of Nuclear Power Plant Seismic Margin”

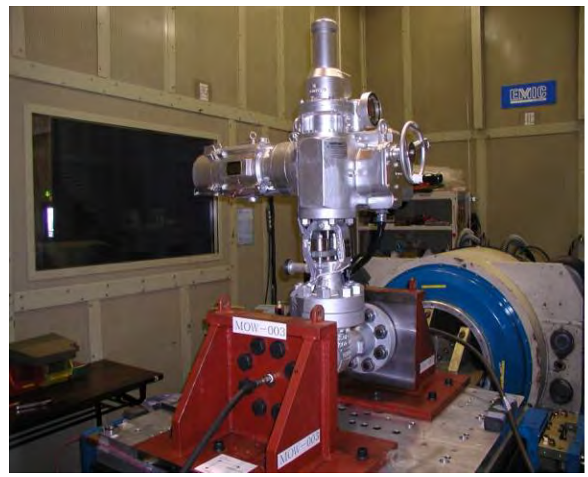
Overall, the recent JNES valve tests demonstrate significantly higher capacities for motor operated valves when compared with the 3 g capacities used in design, as well as the general observation that valves typically have double this capacity. NUREG/CR-4334 reports the median valve functional capacities in a range of 1 – 13 g. These capacities are apparently based primarily on analysis; therefore, the JNES tests provide confirmation of the operability of valves at the reported high acceleration levels.

It is noted that the U.S. practice shows much higher capacities for the valve operators than reported in the JNES tests. The U.S. data is based on testing. However, the JNES tests are primarily aimed at demonstrating the operability of the entire valve assembly, which includes the valve body, yoke and motor operator.

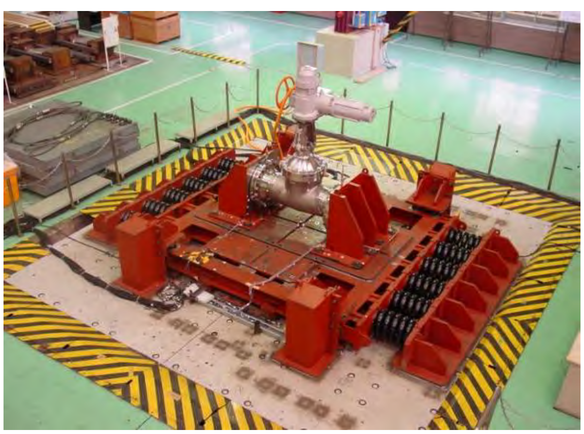
The JNES tests recommended that the structural integrity of the yoke be validated for the reported response acceleration at the actuator. This recommendation is consistent with the U.S. practice. However, the JNES test observation regarding the malfunction of the clutch lever on certain valves is an item not identified in U.S. practice that may need further consideration in cases where valves are required to operate during an earthquake.



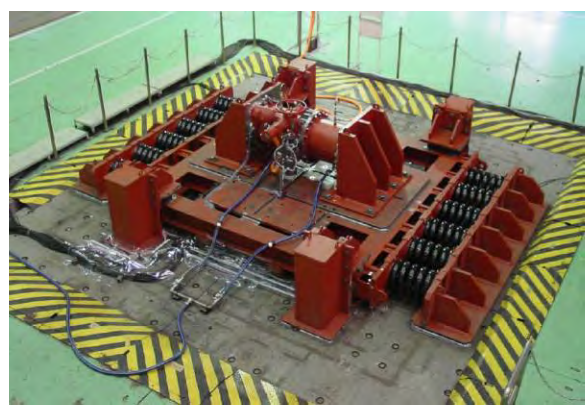
2 inch motor-operated globe valve



3 inch motor-operated gate valve



16 inch motor-operated gate valve



20 inch butterfly valve

Figure 1 Vibration tests of motor-operated valves
(Courtesy of JNES)

MOTOR-OPERATED FANS

JNES performed a series of seismic tests of motor-operated fans in ventilation systems for the purpose of acquiring capacity data under horizontal excitations up to 6 g or more and under vertical accelerations over 1 g. The tests included a motor-operated centrifugal fan with coupling which is used as a Control Room Emergency Air Supply fan and a motor-operated axial fan without coupling which is used as a Control Room Recirculation fan. The centrifugal fan was tested both with and without labyrinth seals, while the axial fan was tested without labyrinth seals. Some fans are fabricated with a labyrinth seal fabricated on the main rotational shaft to help prevent leakage. Both fans are required to be operable after an earthquake. Additional information about the test fans, including the name of the manufacturer, is available in a NUREG/CR (Nie et al. to be published in 2013). Figure 2 illustrates the two types of fans that were tested.

In addition to acquiring higher capacity data, another objective of the tests was to identify failure modes of motor-operated fans. JNES also used the test data to develop a procedure to qualify the seismic capacity of motor-operated fans.

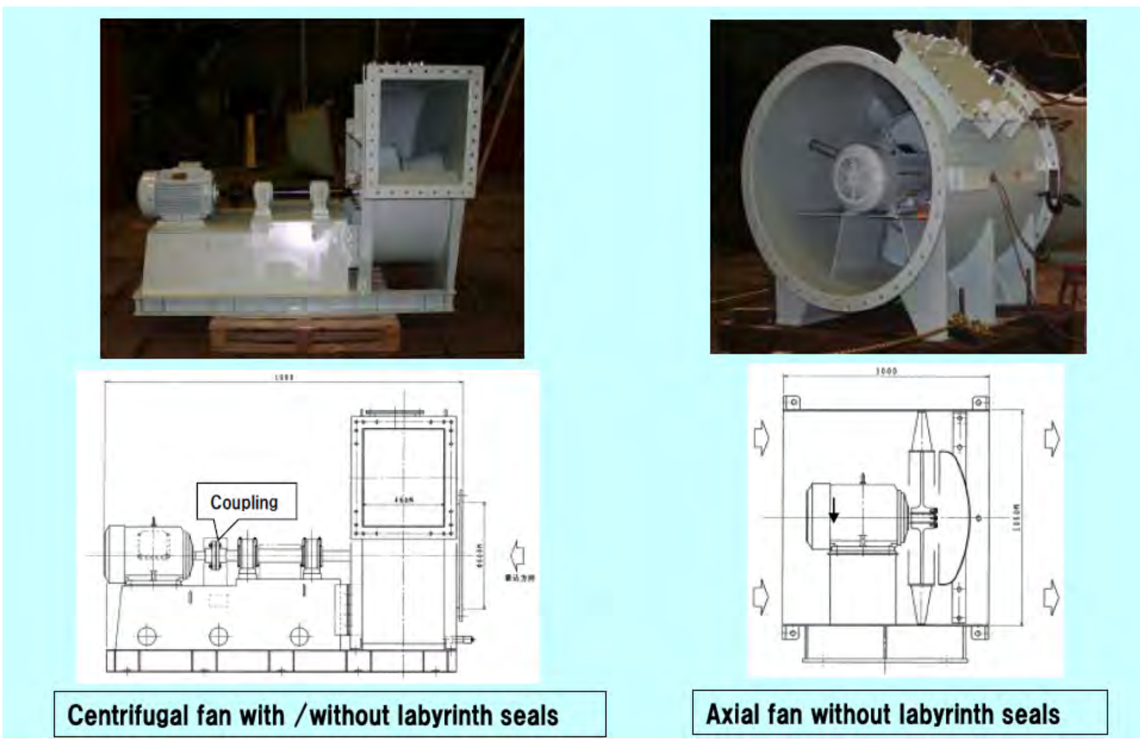


Figure 2 Two types of tested centrifugal and axial fans
(Courtesy of JNES)

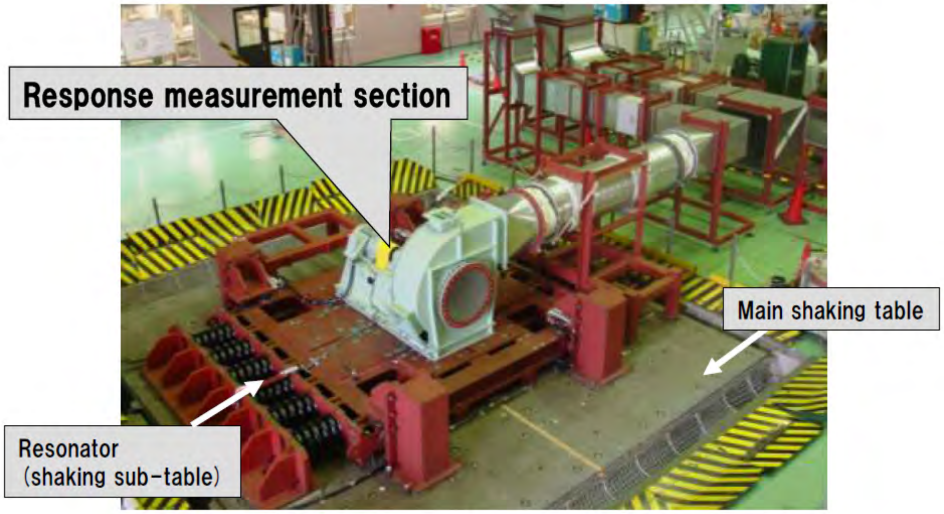


Figure 3 Vibration test of centrifugal fan
(Courtesy of JNES)

The tests identified the wearing-out of labyrinth seals as a new failure mode at high response accelerations. For horizontal accelerations, fans with labyrinth seals had a functional failure at 5 g, while fans without labyrinth seals maintained function up to 7.8 g. For vertical accelerations, fans with and without labyrinth seals maintained function up to 4 g. These acceleration levels were reported at the bearing bracket of the fan.

The JNES test program also developed a set of procedures to determine the seismic capacity of fans by a combination of testing and analysis. The procedures include the performance of response analyses to demonstrate structural integrity. The items to be addressed include: stress of anchor bolt, stress of mounting bolt of the motor, stress of mounting bolt of the fan casing, stress of main shaft, force of bearing, relative displacement between impeller and casing, and gap of the coupling.

The fragility values of the JNES tested fans were compared to those reported in the following reports:

- NUREG/CR-4334, August 1985, "An Approach to the Quantification of Seismic Margins in Nuclear Power Plants"
- EPRI NP-6041-SL, Rev 1, August 1991, "A Methodology for Assessment of Nuclear Power Plant Seismic Margin"

The recent JNES tests demonstrate significantly higher capacities for motor-operated fans than reported in U.S. practice. The JNES tests did not identify fan shaft bending and binding at these high capacities as reported NUREG/CR-4334, but did identify wearing-out of labyrinth seals as a new failure mode at high response accelerations. The JNES tests did not address fans mounted on vibration isolators, which are addressed in U.S. practice with cautionary notes. U.S. practice emphasizes the evaluation of anchorage and supports which is highlighted in the screening criteria as described in EPRI NP-6041. The JNES analysis procedures outline a number of other items which may be useful in developing future check lists to be included in any criteria that use analyses to determine fan seismic capacity.

TANKS

The elephant foot bulge (EFB) is the most likely way for a tank shell to buckle at the base under seismic loading. However, an initiation of EFB in a tank does not necessarily indicate its failure and many tanks can continue to contain fluid content even after a substantial level of EFB has developed. The JNES seismic capacity test program for tanks was an effort to develop methods for the estimation of the ultimate seismic capacity of tanks beyond EFB. The JNES tests and the corresponding development of ultimate strength estimation methods were performed for two categories of tanks: (1) tall tanks, which have height/radius (L/R) ratio greater than 1.4, and (2) short tanks, which have L/R ratio smaller than 1.4.

Tall cylindrical tanks that are of risk-significance, but having relatively low fragilities in Japan nuclear power plants (NPPs), include refueling water storage tanks and condensate storage tanks for PWR plants and light oil tanks and condensate storage tanks for BWR plants. The specimens used in the JNES tank tests were 1/12 or 1/20 PWR model tanks. The test program included two kinds of tests: (1) evaluation method verification tests, which involved dynamic and static tests of aluminum tanks, and (2) static buckling tests, which involved stainless steel and carbon steel tanks. The dynamic and static tests of aluminum tanks were to evaluate the effect of dynamic fluid pressure on buckling behavior and to establish an equivalent method in order to use static tests for the simulation of dynamic loadings. Figure 4 shows the test setups for the dynamic load test and static load test of aluminum tall tanks.

Typical short cylindrical tanks in Japanese NPPs are condensate storage tanks (CSTs) for BWR plants. The test tank specimen was a 1/7.6 model with a diameter of 2.8 m. The height, radius, and wall thickness of the test models were selected so that the height to radius ratio and the radius to wall thickness ratio were similar to those of the actual tank. There were five test tanks of two different wall thicknesses (1.2 mm and 1.8 mm). The material of the test tanks was aluminum so that it was easier to determine the buckling behavior of the tanks (Iijima et al. 2009). Figure 5 shows the test setup for a short tank model.

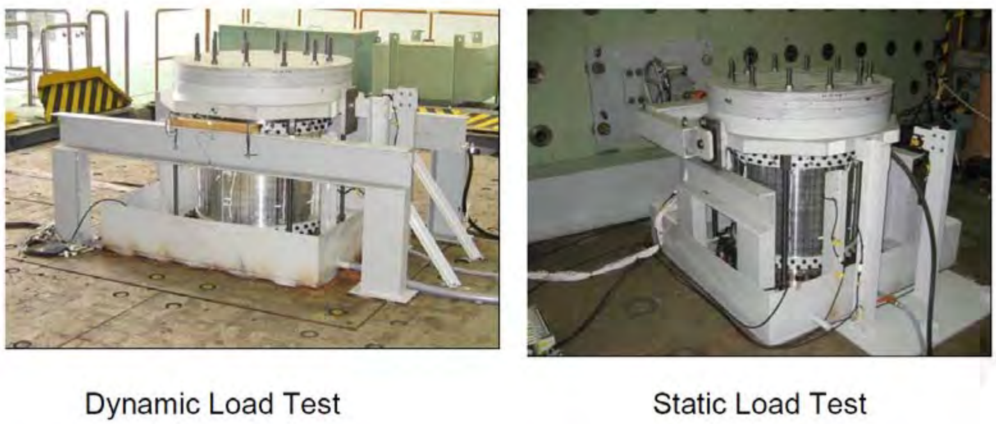


Figure 4 Test setups for the dynamic load tests and static load tests of aluminum tall tanks
(Courtesy of JNES)

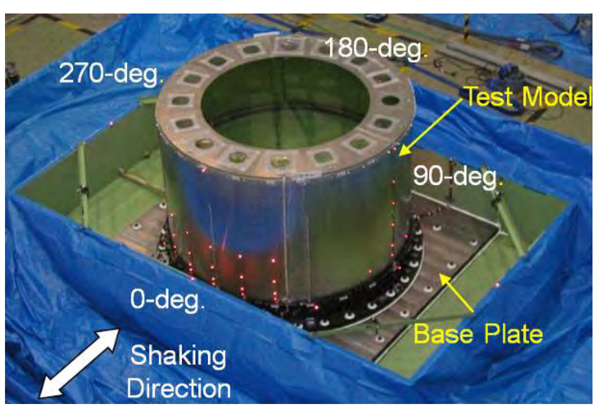


Figure 5 Test setup for short tanks
(Courtesy of JNES)

Methods for seismic fragility analysis of flat-bottom vertical fluid storage tanks have been documented in NUREG/CR-5270 (Kennedy et al. 1989), EPRI NP-6041-SL, Rev. 1 (Reed et al. 1991), and EPRI TR-103959 (Reed and Kennedy 1994). NUREG/CR-5270 introduced two methods, namely the Fragility Analysis (FA) method and the Conservative Deterministic Failure Margin (CDFM) method, to estimate the seismic margins of structures, systems, and components in nuclear power plants. The methods in EPRI NP-6041-SL, Rev. 1 and in EPRI TR-103959 are basically the same as those in NUREG/CR-5270, with some improvements. The CDFM method is used in this study to calculate the seismic fragilities of two example tanks that were analyzed by JNES for the purpose of comparison. To convert the HCLPF capacities calculated using the CDFM method to the median capacities, β_R and β_U, are assumed to be 0.2 and 0.27, respectively.

Since not all information is available for the tall tank and short tank, some parameters had to be assumed based on the two example tanks. The tanks were assumed to be anchored to a reinforced concrete foundation with 78 anchor bolts and the concrete foundation is constructed on a firm site. The Regulatory Guide (RG) 1.60 spectral shapes as representative for the U.S. nuclear power plants were utilized in the calculation. Two coefficients of friction values, 0.55 and 0.7, were considered to assess the sensitivity of seismic fragility.

Table 1 JNES Seismic Capacities vs. Median Fragilities Based on the CDFM Method

		Tall Tank	Short Tank
JNES Estimates (g)		2.6	3.0
CDFM Median Fragility (g)	COF = 0.55	0.67 (Sliding)	1.01 (Sliding)
	COF = 0.70	0.74 (Overturning)	1.20 (Sliding)
CDFM Fluid Pressure Capacity (g) Corresponding to CDFM Median Fragility		2.2	2.1
JNES Estimates / CDFM Median Fragility		3.5	2.5

Table 1 presents a comparison of the ultimate seismic capacities that JNES estimated using its test-based methods, and the median fragilities of the same tanks that are estimated using the CDFM method. From a pure numerical point of view, the ultimate seismic capacity estimated using the JNES test-based method is about 3.5 times the larger of the two median fragilities estimated using the CDFM method for the tall tank, and is about 2.5 times for the short tank. It is interesting to note that the non-governing fluid pressure capacities of the two tanks in the CDFM HCLPF calculations are both slightly larger than 2 g and are much closer to the JNES ultimate seismic capacity estimates, which are 2.6 g and 3.0 g for the tall tank and the short tank, respectively.

The JNES fragility tests of tanks identified two failure modes based on the criterion of water leakage through cracks: (1) secondary buckling for tall tanks, and (2) shear buckling for short tanks, both of which occurred in the tests beyond the loading regime for elephant foot bulge to occur. These two failure modes have not been considered explicitly in the U.S. SPRA practice. However, the fluid pressure capacity in the CDFM method, which is associated with the hoop membrane stress failure mode, seems to be in a similar category. Based on the numerical comparisons described above, the JNES test-based methods can lead to significantly higher median seismic fragilities than the CDFM method. The CDFM method uses elephant foot bulge as one of its failure modes and does not explicitly consider the secondary buckling nor the shear buckling failure mode.

It should be pointed out that an actual tank may fail by other modes before it can reach failure modes such as the secondary buckling or the shear buckling limit state. For example, leakage may occur at sumps located at the base of the tank under excessive sliding displacement. A recent NRC Information Notice (NRC IN 2012-01) indicates that the overturning of non-safety related tanks can impact nearby safety related equipment, although leaking of fluid in these tanks may not represent a safety issue. Therefore, the application of the JNES methods should also consider the following failure modes, many of which have already been included in or recommended for additional checks in the CDFM method:

- Sliding, especially when sumps are located at the base of the tank,
- Overturning,
- Foundation failure (soil-foundation-tank interaction),
- Piping and nozzle failures,
- Roof damage from sloshing motion, especially for short tanks where sloshing mode is dominant.

The application of the JNES methods may also need to consider appropriately the interaction effect of multiple directional input motions. The JNES tank tests and the resultant methods for estimating ultimate seismic capacity considered only one directional seismic loading. The CDFM method considers two directional seismic inputs: one in the horizontal direction and one in the vertical direction. The seismic motion in the vertical direction is important to correctly account for the dynamic water pressure.

CONCLUSION

As was the case with the JNES Phase I equipment fragility tests (Ali et al. 2011), the JNES equipment fragility tests of motor-operated valves, fans, and tanks contribute high quality test-based fragility data to the SPRA community. The fragility capacities, either obtained directly from full-scale shaking table tests or estimated from the JNES test-based methods, were in general much higher than or confirmed those used in the U.S. SPRA practice. The JNES fragility test program uncovered failure modes, such as, malfunction of the clutch lever on certain valves, wearing-out of labyrinth seals on fans, secondary buckling for tall tanks, and shear buckling for short tanks, that have not been considered explicitly in U.S. PRA practice. The JNES test results, including the test-based evaluation methods, are recommended for consideration by fragility analysts in performing future SPRAs; however, cautions must be exercised to assess the applicability of the JNES results to any specific situation that may not be necessarily consistent with the test conditions.

It should be emphasized that the fragility data from the JNES equipment fragility tests, as well as from the equipment qualification tests, generic data, or screening levels, must be supplemented with an analysis of the component anchorage and support fragility. In many cases the overall component fragility is governed by anchorage or support capacity.

ACKNOWLEDGEMENTS

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