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# SEISMIC SAFETY EVALUATION OF HOKKEDO HALL IN TODAIJI-TEMPLE, WORLD HERITAGE － PART 1: SHAKING TABLE TEST OF FULL-SCALE MODEL OF STATUE OF BUDDHA

**Morii Masayuki[1], Fujita Yuki[2], Mikoshiba Tadashi[3] and Hanazato Toshikazu[4]**

[1] National Research Institute for Cultural Properties, Tokyo
13-43 Ueno-park, Taito-ku, Tokyo 110-8713, JAPAN
e-mail: morii@tobunken.go.jp

[2] IIJIMA Structural Design Office
1-25-1 Aoi, Higashi-ku, Nagoya city, Aichi 461-0004, JAPAN
yuki@iijima-sd.co.jp

[3] National Research Institute for Earth Science and Disaster Prevention,
3-1 Tennodai, Tsukuba city, Ibaragi 305-006 , JAPAN
miko@bosai.go.jp

[4] Graduate School of Engineering, Mie University
1577 Kurimamachiya-cho, Tsu city, Mie 514-8507, JAPAN
hanazato@arch.mie-u.ac.jp

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**Abstract.** *The Buddhist statues, which have been taken good care for a long time in Japan, have suffered earthquake damage. However, there have been only a few studies on seismic behavior of those statues in temples. In the present study, we focused the seismic safety of the Buddhist statues at the Hokkedo Hall of Todaiji Temple, registered as World Cultural Heritage in Nara. In this ancient building constructed in 8th century, there are a number of famous Buddhist statues, where most of them are designated as national treasures. Both the building and the Buddhist statues have survived against historical large earthquakes. In this paper, the shaking table test of a full-scale model of one of the Buddhist statues enshrined in the Hokkedo Hall was conducted to study the actual seismic performance of statues. We manufactured a model of which structural condition and mass distribution were the same as the original one, as those conditions would affect significantly its dynamic behavior. During the shaking tests, in addition to usual measurements, we directly measured dynamic displacement by image processing technique using LED lamps and high-speed cameras. As results of the tests, the model statue walked on the shaking table, and finally survived against the extremely strong motions recorded during the Kobe Earthquake. These test results demonstrated seismic safety of such Buddhist statues of which gravity center were enough low. The test also indicated that the joint between the pedestal and the base of the legs was vulnerable.*

# 1 INTRODUCTION

After the occurrence of Southern Hyogo prefecture Earthquake in 1995, measures against near-field earthquakes have been taken for three-dimensional works displayed in museums such as lowering their center of gravity or installing a seismic isolator. In Japan, as in the case with Tensho earthquake in 1586 that caused 600 Buddhist statues to fall over in Sanjusangen-do Hall in Kyoto, there are many cases of damage to classically cherished Buddhist sculptures in past earthquakes and similar measures have been taken as with the museum displays [1]. However, the investigation for determining the performance of seismic isolators is improper, and evaluation and maintenance after installation is insufficient in many cases. For standing statues in some cases in particular, no earthquake countermeasures have been taken simply because there is no record of fallen statues in the past.

Hokkedo Hall is a major part of Todaiji Temple, a World Cultural Heritage site, and it has undergone no major rebuilding since its construction in the eighth century. It has been confirmed that the many Buddhist statues enshrined in the Hokkedo Hall were made in the eighth century and retain their original form although traces of past repair can be confirmed in some statues [2]. Recently, nationwide predictions of ground motion have come to be conducted in Japan. According to these predictions, there are active faults to the east of the Nara Basin where Todaiji Temple is located and it is estimated that a very large earthquake will cause a maximum acceleration of 626 Gal. Thus, it is necessary to take fall-prevention measures for Buddhist statue groups enshrined in the temple as soon as possible.

To prevent the group of Buddhist statues from falling during an earthquake, it is necessary first to clarify the behavior of the group of Buddhist statues during an earthquake, and then, conduct a seismic-capacity evaluation on the building. The present study composed of two papers, part 1 and part 2. Seismic performance of the Buddhist statues is described in this paper, Part 1. The following paper, Part 2, shows seismic diagnosis of the building structure. In this paper, Part 1, to obtain accurate information of the behavior of the group of Buddhist statues during an earthquake, the authors conducted a vibration test using a large-scale vibrating table on a full-scale mockup manufactured based on three-dimensional measurement results and a structural drawing and examined the earthquake-proof safety of the building. This paper reports the result of the vibration test on the full-scale mockup of standing statues using the large-scale vibrating table.

# 2 ABOUT HOKKEDO HALL AND ENSHRINED BUDDHA STATUES

Hokkedo Hall (Figure 1) is one of the buildings of Todaiji Temple, the head temple of the Kegon sect, and it is located to the east of Nara City and was designated as a national treasure in 1951. Hokkedo Hall is the oldest of the buildings in Todaiji Temple and is said to be the remains of Konshuji Temple which supposedly existed before the foundation of Todaiji Temple according to the temple's history. There are many explanations about the foundation of the hall and no definitive answer has been given yet. However, the most widely held explanation is that the hall was founded around 749 because the "Kensakudo Hall" recorded in "Todaiji Temple Shiizu" almost corresponds to the location of the existing Hokkedo Hall, according to one explanation. The Hokkedo Hall underwent several repairs up to the present. It is said that the hall was originally a Yosemune-zukuri (hipped roof) style structure where the Shodo hall (the inner shrine) and the Raido (worship hall) were built in a row but the Raido was reconstructed to a hip-and-gable roof structure and the two buildings were joined with Nakanoma room and the roof truss during a repair carried out in 1264 [3]. The reconstruction provided the Raido with a "Daibutsuyo" look that features a style of Japanese Buddhist temple architecture of the Kamakura period. The architectural style of Hokkedo Hall is an elaborate combination of Tenpyo (Shodo hall) and Kamakura architecture (Raido), and is valuable remains in Japanese architectural history in addition to its structure (Figure 2).

The dual octagonal Shumidan (Buddhist altars) is placed at the center of the architectural Shumidan in the Shodo hall Naijin (inner sanctuary) of the Hokkedo Hall, and sixteen Buddhist statues are enshrined around Fukukensaku Kannon, which is the principle image, on the octagonal Shumidan and architectural Shumidan (Figure 3). Of the Buddhist statues enshrined in the Hokkedo Hall, 12 statues are designated as national treasures and the remaining four statues as important cultural properties. Of the 16 Buddhist statues, nine statues of relatively high height were made with the dry lacquer technique in which a wooden frame supports the outer hull made with linen clothes pasted by Japanese lacquer [4]. Five of them are clay and two are wooden. The two wooden statues were supposedly made in the Kamakura Period while the other 14 statues in the Tenpyo Period. Due to the repair work that started in May 2010, the group of Buddhist statues was relocated from the Shumidan and restoration work was performed on some of the statues. At the opening of the Todaiji Temple museum in May 2011, clay statues were relocated to the museum. The other Buddhist statues were returned to the Shumidan after its repair work was finished in 2013.

Figure 1: Building's appearance (Hokkedo Hall in Todaiji Temple, right: south facade, left: east facade).

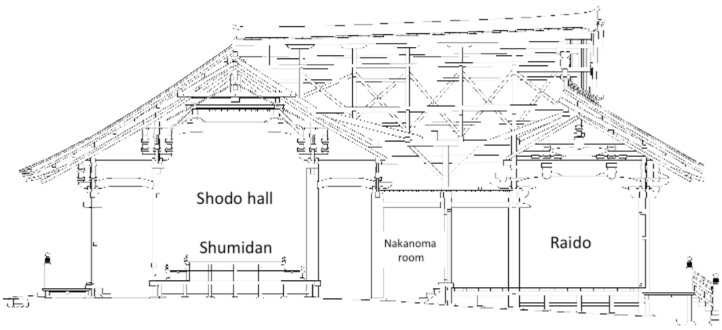


Figure 2: Sectional view of Hokkedo Hall.

Figure 3: Group of Buddhist statues in Hokkedo Hall.

## 3 VIBRATION TEST ON FULL-SCALE MOCKUP

Based on the vibrating table test using miniature models, the authors showed that it was possible to predict rollover to some extent according to the past fall limit acceleration if the Buddhist statues were assumed to be rigid bodies [5, 6, 7]. However, a test result using miniature models had problems of similarity rules and did not necessarily represent the actual phenomenon. Many objective Buddhist statues were made with the hollow dry lacquer technique and lack rigidity, so it was hard to assume they were rigid bodies. Then, falling prediction of Buddhist statues was conducted under conditions close to the real situation by performing a vibration test on a full-scale mockup reproducing the structure of Buddhist statues with the use of the large-scale uniaxial vibrating table.

### 3.1 Overview of test piece

In a miniature model test, it was desirable to verify the scale effect by using the objective Agyo statue of Kongo-rikishi made with the dry lacquer technique. However, it was not easy to examine the specifications such as mass, employed materials and structure because the Buddhist statues are designated as national treasures. Thus, testing was conducted on a dry lacquered standing statue of Jikokuten (Figure 4) because information on the statue of Jikokuten was available to some extent and there existed many statues of the same type and whose size and structure were similar to those of the statue of Kongo-rikishi. Made with the dry lacquer technique, the standing statue of Jikokuten has a height of 350.4 cm, a total weight of 231.5 kg, and a dry lacquer thickness of approximately 5.0 to 6.0 mm.

Because it was impossible to perfectly reproduce a Buddhist statue of a complex shape in making a test piece, the test piece was designed so that possible falling conditions were equivalent to those of the actual Buddhist statue. The test piece was the same as the actual statue in aspects including the total weight, center gravity height, total height, and shape of bottom. The center gravity height of the dry lacquered standing statue of Jikokuten was not known but it was very important to know the center gravity height to calculate the shape factor used in falling prediction. After the Buddhist statue was divided into 15 layers in the height direction, as shown in Figure 5, the weight of each layer was estimated based on 3D data of the statue and the center gravity height was calculated by the following formula:

$$\Sigma_i m_i = M \tag{1}$$

$$h_g = \frac{\Sigma_i m_i \times h_i}{M} \tag{2}$$

where $m_i$ = mass in $i$-section, $M$ = total weight, $h_i$ = $i$-section height, $h_g$ = center gravity height. Table 1 shows the result of calculating the center gravity height. Calculation was performed on the assumption that the dry lacquer had a thickness of 6.0 mm, dry lacquered section had a specific gravity of 1.13 g/cm$^3$, and Japanese cypress has a specific gravity of 0.44 g/cm$^3$.

A full-scale mockup was designed and its calculated center gravity height, total weight, total height, and bottom shape were made the same as those of the actual dry lacquered standing statue of Jikokuten. As in the case with the standing statue of Jikokuten, the center gravity height of the full-scale mockup was calculated. The sectional view and bottom view of the full-scale mockup are shown in Figure 6 and the center gravity height in Table 1. Although the standing statue of Jikokuten was made with the dry lacquer technique, paper clay, which was relatively easy to process, was used as a substitute due to cost and workability issues. Tortoise-shell shape wire nettings and wires were used as substrate materials to compensate for a lack of strength and the surface was varnished to prevent it from peeling and cracking. Cast-iron nails, etc. were generally used in joints but mounting hardware was used to improve workability. To adjust the center gravity height, nineteen 200×200-mm steel sheets having a thickness of 9 mm and 12 mm were used as deadweights (64.26 kg).

Figure 4: Dry lacquered standing statue of Jikokuten (left: appearance, right: x-ray image).

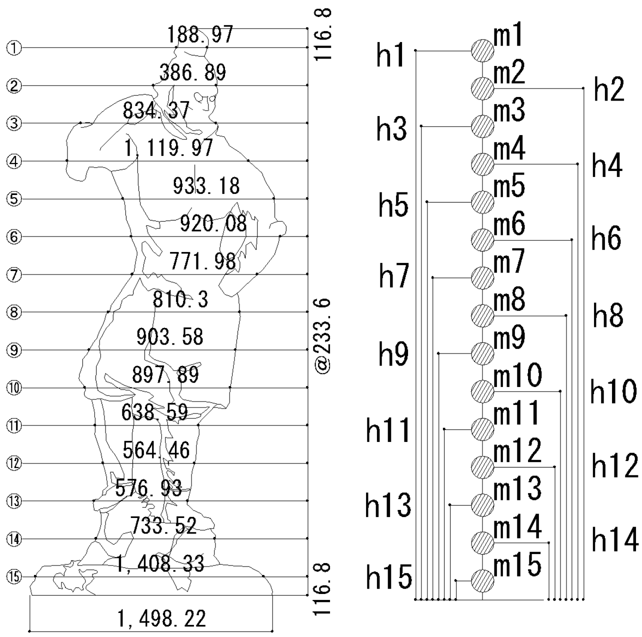


Figure 5: Split locations used for center gravity height calculation.

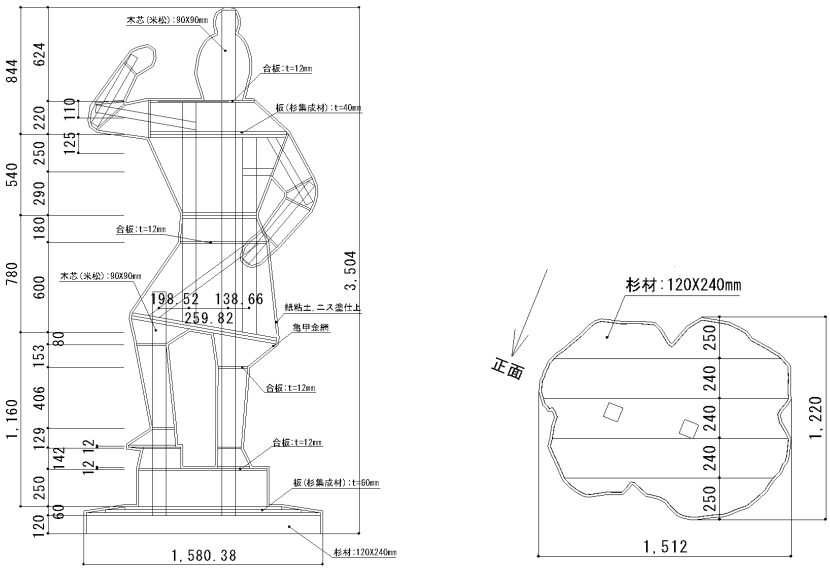


Figure 6: Drawing of test piece.

Table 2: Specification list.

| | Standing statue of Jikokuten | | Model |
|---|---|---|---|
| | Actual value | Calculation | |
| Bottom area ($m^2$) | 1.476 | 1.476 | 1.476 |
| Surface area ($m^2$) | 11.87 | 11.86 | 8.85 |
| Dry-lacquered area ($m^2$) | 10.39 | 10.38 | 7.38 |
| Total weight (kg) | 231.50 | 228.46 | 231.25 |
| Center gravity height (cm) | | 81.92 | 81.85 |

### 3.2 Overview of test

Because the past study showed that vertical vibration causes little effect on rollover, vibration was performed using the vibration table excited horizontal direction, which was developed by the National Research Institute for Earth Science and Disaster. Because it had been confirmed that the friction between the test piece and the installation surface was a major factor of falling conditions, a simplified floor was made with plywood on the vibrating table as shown in Figure 7 and vibration test was conducted on the floor. The friction coefficient of plywood used in the floor was about 0.5 to 0.6. It was recognized that the friction coefficient had no correlation to the weight and installation area of the object. However, as in the case of plywood, which had irregularities on its surface, friction was apt to increase as the weight of an object subjected to friction increases due to the effect of the object penetrating the plywood. Thus, it was estimated that the friction coefficient was larger than the measured value. Because the test piece might be damaged in case of a rollover during excitation, the head of the test piece was tied with a wire rope provided with allowance so that the behavior during vibration would not be affected by using the adjustable ceiling crane mounted on the top of the vibrating table. A list of input waves is shown in Table 2. It was easy to perform verification using a harmonic sine wave as with the miniature model test. However, only the seismic wave was the excitation exceeding the falling limit acceleration because the performance of the vibrating table gave rise to concerns about potential impacts on the peripheral facilities due to easy propagation of the harmonic sine wave. It was confirmed that a harmonic sine wave causes no falling because it was below the fall limit acceleration.

The authors measured acceleration using an accelerometer, final movement amount, and displacement rate by taking a three-dimensional image measurement and shot some video. Figure 8 shows the accelerometer installation positions and measurement spots of three-dimensional image measurement. Measurement was conducted with the accelerometer using the right shoulder (CH-1) and the foundation (CH-2) of the test piece as longitudinal components (excitation direction is positive) and the front and back of the foundation (CH-3, 4) as vertical components (upward is positive) at a sampling frequency of 100 Hz. In three-dimensional image measurement, light-emitting markers were installed on the test piece, floor and vibrating table to take images of and record the behavior of the light-emitting markers from multiple directions during excitation using a high-speed camera. The difference from the initial coordinate value of each marker was calculated as a displacement based on the analysis of the recorded data. This made it possible to grasp the dynamic behavior accurately.

Figure 7: Floor installed on the vibrating table.

Table 2: List of input wave.

| No. | Input wave | Maximum acceleration (Gal) | Frequency (Hz) | Amplitude (mm) | HPF (Hz) |
|---|---|---|---|---|---|
| 1, 2 | STEP wave | - | 0.05, 0.025 | ±0.5, 5.0 | - |
| 3 – 12 | harmonic sine wave | 400 - 700 | 1.0 – 10.0 | ±1.8 – 101.3 | - |
| 13 | JMA Kobe NS wave | 1029 | - | 200 | 0.1 |
| 14 | K-NET Ojiya EW wave | 1357 | - | 187.4 | 0.5 |
| 15 | data of JR Takatori | 1134 | - | 218.7 | 0.7 |

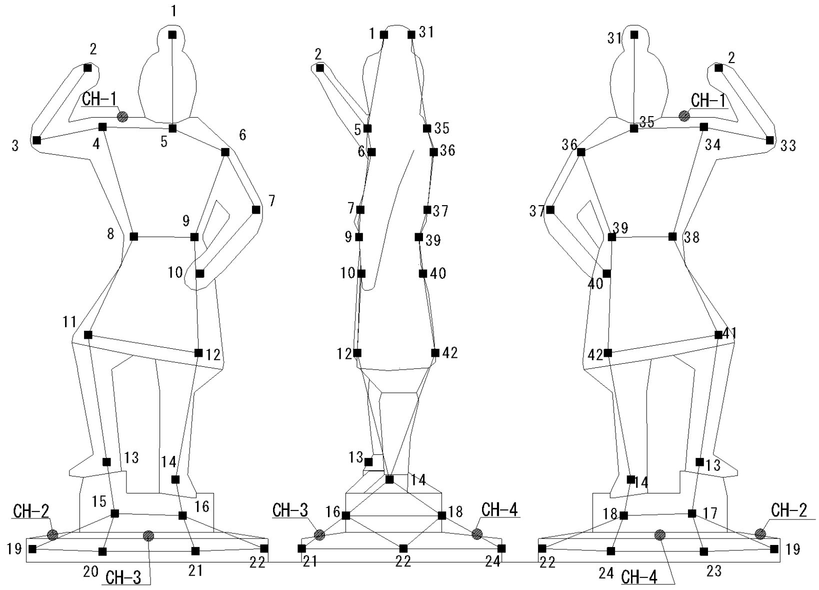

Figure 8: Accelerometer and light-emitting marker installation positions.

## 4 RESULTS AND DISCUSSION

In this test, excitation was performed using the STEP wave to measure the vibration characteristics of the test piece. Figure 9 shows the longitudinal transfer function of the head (No. 1) with respect to the vibrating table (No. 54). In this test, microtremor measurement was conducted on the dry lacquered standing statue of Jikokuten to obtain the basic vibration characteristics. The natural frequency, natural period and attenuation constant obtained from microtremor measurement and STEP wave excitation are shown in Table 3. Figure 9 shows that the test piece had a natural frequency of 2.8 Hz. Because the natural frequency of the standing statue of Jikokuten obtained from microtremor measurement was 2.3 Hz and the weight and shape were equal, it was clarified that the rigidity of the test piece was higher than that of the standing statue of Jikokuten. However, the test piece lacked enough rigidity to assume that it was a rigid body. In a past study, only the falling limit of the object that was assumed to be a rigid body was verified and the rigidity-induced impact on the falling conditions has not been clarified yet. In this study, it would be verified whether or not the fall limit acceleration formula might be applied to low-rigidity objects.

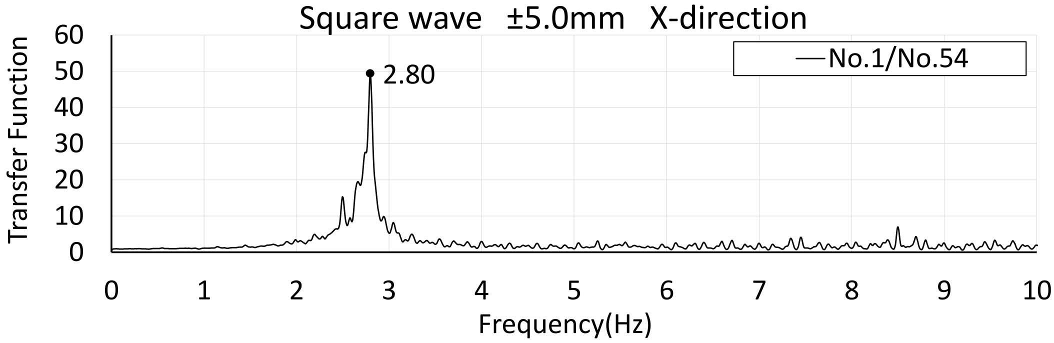


Figure 9: Transfer function of the head with respect to the vibrating table.

Table 3: Basic vibration characteristics of standing statue of Jikokuten and test piece.

| | | Attenuation coefficient h | | Natural frequency (Hz) | Natural period (sec) |
|---|---|---|---|---|---|
| Jikokuten stand statue | Microtremor | 0.0186 | 1.86 % | 2.3 | 0.435 |
| Model | STEP wave | 0.0170 | 1.70 % | 2.8 | 0.357 |

The results of a test conducted using a harmonic sine wave are shown in Table 4. In this test, the input level of the harmonic sine wave was below the fall limit acceleration. Testing was performed to check that the test piece might not be fallen. Although rocking vibration was generated at 1.0 to 5.0 Hz, there was no risk of falling as can be confirmed from the rotation angle. The fall limit rotation angle shown in the table was the static fall limit rotation angle in the longitudinal direction of the test piece (Bx/H = 0.739).

Table 4: Maximum rotation angle in harmonic sine wave excitation.

| Harmonic sine wave | | | |
|---|---|---|---|
| Frequency (Hz) | Maximum rotation angle Rad | Degree | Movement pattern |
| 1.0 | 0.0143 | 0.819 | |
| 2.0 | 0.0491 | 2.815 | |
| 3.0 | 0.0305 | 1.749 | Rocking |
| 4.0 | 0.0086 | 0.495 | |
| 5.0 | 0.0048 | 0.277 | |
| 6.0 – 10.0 | - | - | Static |
| Fall limit rotation angle | 0.6364 | 81.92 | |

The test results of the JMA Kobe NS wave, K-NET Ojiya EW wave and JR Takatori are shown in Table 5. Figure 10 shows the test result of JR Takatori that shows the largest rotation angle of all seismic waves in the excitation test. Figure 10 shows the time history waveform of the rotation angle calculated from the displacement rate of the head (No. 1) and footing (No. 15). The three waves generated a rocking vibration but caused no falling. The static fall limit rotation angle was 36.46° and the maximum rotation angle remained at 15.48° even in JR Takatori having the maximum rotation angle of the three. This shows that there was no risk of falling. Figure 12 shows the state of the test piece at the maximum rotation angle in JR Takatori during three-dimensional image measurement. Because the test piece lacked enough rigidity to assume it was a rigid body, the deformation angle caused by structural members was included in the rotation angle shown in Figure 10. Then, on the assumption that the bottom was a rigid body, the rotation angle of the statue was $R_1$, the rotation angle of the bottom was $R_2$, and the difference was deformation angle D. Figure 11 shows the time history waveform of deformation angle D in JR Takatori. The waveform in Figure 11 shows minute vibration. The vibration was presumably caused by an elastic response of the test piece and the test piece was probably deformed during vibration. Rotation angle $R_1$ included deformation angle D of the structural member. The low-rigidity test piece showed a larger rotation angle in comparison with the object assumed to be a rigid body. Although there was no evidence that the increase in the rotation angle had direct correlation to falling, it was more likely that a falling would occur. Thus, it is necessary to set the limit value to the safer side than the past fall limit.

Table 5: List of maximum rotation angles.

| | JMA Kobe NS wave | K-NET Ojiya EW wave | JR Takatori |
|---|---|---|---|
| Maximum rotation angle $R_1$ | 0.0529 (3.03° ) | 0.1686 (9.66° ) | 0.2702 (15.48° ) |
| Maximum rotation angle $R_2$ | 0.0417 (2.39° ) | 0.1411 (8.09° ) | 0.2607 (14.94° ) |
| Maximum deformation angle D | 0.0191 (1.09° ) | 0.0471 (2.70° ) | 0.0553 (3.17° ) |

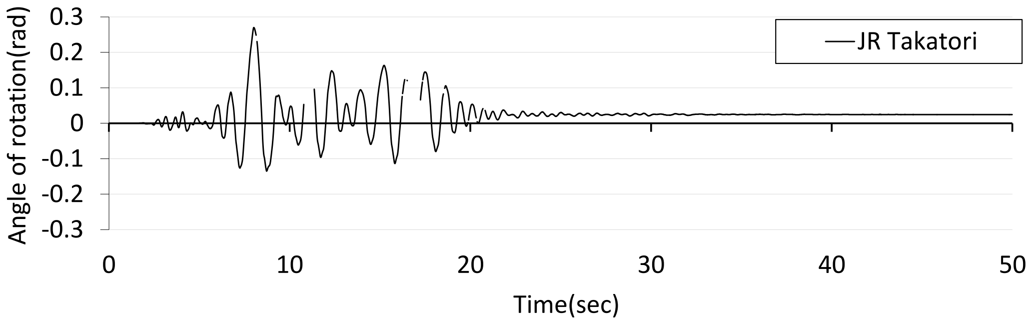


Figure 10: Waveform of rotation angle time history.

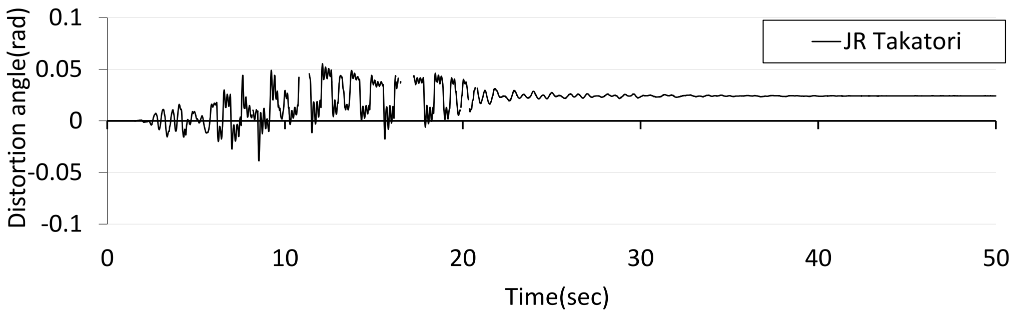


Figure 11: Waveform of deformation angle time history.

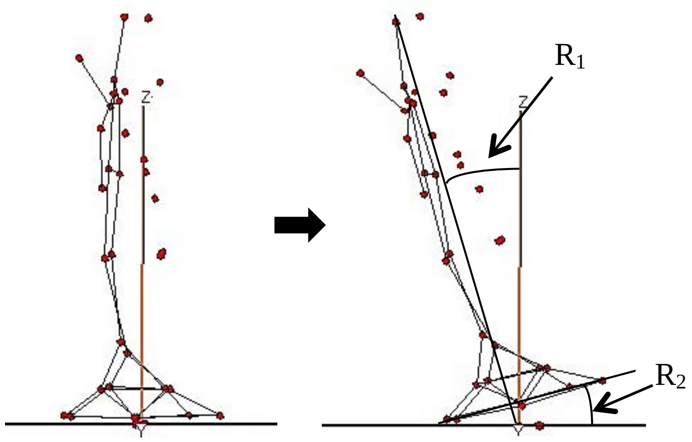


Figure 12: Static image during excitation in JR Takatori.

The dominant frequency was set to compare the past fall limit acceleration with three waves — JMA Kobe NS wave, K-NET Ojiya EW wave and JR Takatori. It was required to use the equivalent frequency $F_e$ calculated by the following formula using the maximum acceleration value $A_{max}$ that was one of the indexes representing the dominant frequency of the wave and the maximum velocity value $V_{max}$.

$$F_e = \frac{A_{\max}}{2\pi \cdot V_{\max}} \tag{3}$$

Table 6 shows the equivalent frequency and the maximum acceleration. Although the peak value of acceleration response spectrum was not in perfect agreement with the equivalent frequency $F_e$, the peak value was believed to have correlation with the dominant frequency of seismic wave. The result of comparing this value with the fall limit acceleration using the equivalent frequency is shown in Figure 13. The three waveforms exceeded the fall limit acceleration and a past study showed that there was possibility of a falling. However, in consideration of the rotation angle margin, it was much less likely that the statue would fall unless there were factors that significantly increased the probability of falling (such as a fall and collision) as with this test.

Table 6: Equivalent frequency and maximum acceleration.

| | Maximum acceleration $A_{max}$ | | Maximum velocity $V_{max}$ | Maximum amplitude $D_{max}$ | Equivalent frequency $F_e$ | Equivalent period $T_e$ |
|---|---|---|---|---|---|---|
| | Gal | m/s$^2$ | kine | mm | Hz | sec |
| JMA Kobe NS wave | 1029 | 10.29 | 105.03 | 200.0 | 1.55 | 0.65 |
| K-NET Ojiya EW wave | 1357 | 13.57 | 107.92 | 187.4 | 1.97 | 0.51 |
| JR Takatori | 1134 | 11.34 | 106.68 | 218.7 | 1.69 | 0.59 |

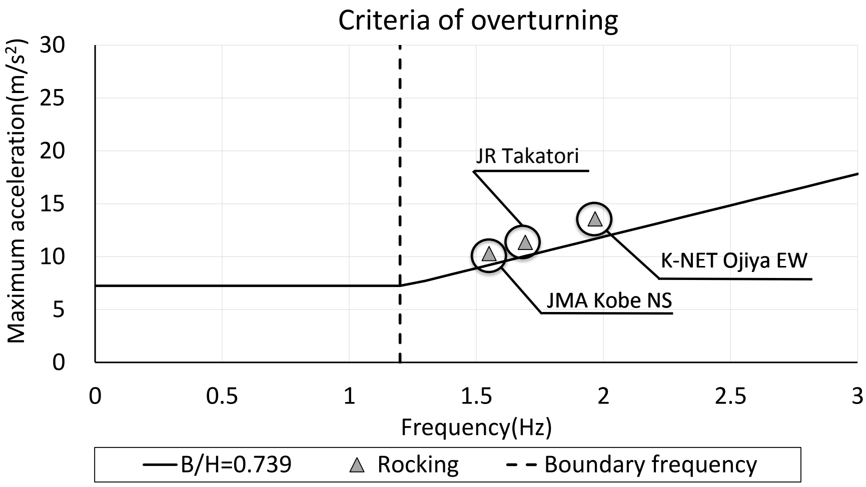


Figure 13: Rollover limit acceleration and movement pattern in input seismic wave.

## 5 CONCLUSION

It was found that the dry lacquered standing statue of Jikokuten enshrined in the Hokkedo Hall in Todaiji Temple would not fall even when there was a strong ground motion with a maximum acceleration of 1000 Gal and a maximum velocity of 100 kine because the statue was stable due to its low center of gravity. The result showed that similar Buddhist statues were less likely to fall during an earthquake unless the shape factor was significantly different. There were concerns that Buddhist statues had a low rigidity and the rotation angle became larger compared to a rigid body due to elastic response during rocking vibration. This might increase the possibility of falling. Because the central wooden core joint of the actual Buddhist statue was weaker and less rigid than the test piece, the statue might have a higher chance of falling than the test piece. The test showed that the test piece never fallen under the input earthquake motion exceeding the fall limit acceleration and that the past fall limit was set to the safe side and adaptable. However, advancing a more detailed study on the fall limit of low-rigidity objects such as Buddhist statues may suggest more versatile falling-prevention measures.

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