ANALYSIS OF EARTHQUAKE EFFECTS ON BELLE II DETECTOR AND SUPERKEKB ACCELERATOR

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Abstract

Japan is the place in the world where earthquakes occur frequently. When an earthquake occurs, displacement can give rise to damages to infrastructure, facilities, and experimental devices. However, when the structure is made to shake at the same phase with the floor by seismic design, damage due to an earthquake can be minimised. Mostly, damage to equipment as a consequence of an earthquake is caused by the relative displacement or disappearance of gap between detectors, although counter measures such as installing bellows at beam pipes or provision of gap have been implemented in advance. The relative displacement owing to an earthquake is predicted by performing response spectrum analysis (RSA), and the relative displacement is measured with laser displacement sensors and acceleration sensors installed between the Belle II detector and the floor. This paper presents the results of the relative displacement calculation by performing RSA and the measurement of relative displacement during an earthquake on Belle II detector.

INTRODUCTION

On November 1st, 2021, an earthquake with intensity 3.5 as per the Japanese Meteorological Agency (JMA) scale struck the Japanese High-Energy Accelerator Research Organization, also known as KEK. At this time, a superconducting-quadrupole magnet, the so called QCS shown in Fig. 1, at interaction region of Super KEKB accelerator was shutdowned by a quench trigger, hereafter it is called as the QCS quench. [1,2,3]. The magnetic field is formed by combination of both that of the QCS and that of the Belle II solenoid installed in the Belle II detector; size of the Belle II detector is $8 \times 8 \times 10$ m (length, width, and height), respectively. Total weight is 1400 tons as shown in Fig. 2 [4].

Figure 1: Superconducting quadrupole magnet (QCS) installed in the Belle II detector.

Cause of the quench was assumed to be the induced voltage that was generated owing to movement of the QCS and the Belle II solenoid during earthquake. Most likely, the coupling magnetic fields were disturbed by the shaking caused by the earthquake. If this reasoning is accurate, then there is possibility of damage to the beam pipe connected to the QCS and disappearance of the gap between the sub-detectors of the Belle II detector.

Figure 2: Picture of the Belle II detector.

So, to probe the cause of the QCS quench and establish a relationship between relative displacement and earthquakes, the relative displacement between the QCS and the BELLE II detector was investigated. At first, seismic RSA/FEM calculations were carried out to estimate the relative displacements of the Belle II and the QCS with reference to earthquake occurrences. In addition, relative displacement measurements were carried out during earthquakes using laser displacement sensors and accelerator sensors by setting up triggers and compared to the results of seismic RSA/FEM analyses subsequently.

SEISMIC RSA/FEM

To calculate the relative displacement of the Belle II detector and the QCS, certain seismic analyses were done
with data gathered from the measurements of the earthquake waves. The earthquake data were obtained from the National Research Institute for Earth Science and Disaster Resilience (NIED), which is also researching earthquakes and is located 3 km from KEK in the same neighbourhood [5].

**Earthquake on November 1st, 2021**

An earthquake with 3.5 intensity occurred on November 1st, 2021, with its epicentre 300 km away from KEK at a depth of 50 km. The time history of the earthquake in three directions is shown in Fig. 3.

To perform a seismic RSA/FEM analysis, an input response spectrum is needed. So, the time history of earthquake was converted to the acceleration response spectrum as shown in Fig. 4. The damping ratio was assumed to be 5% [6].

Figure 4. Accelerator response spectrum in three directions for the earthquake, November 1st, 2021, at NIED.

Seismic analysis for QCS

RSA was carried out to get the maximum relative displacement of QCS by inputting the acceleration response spectrum. As a first step, the modal analysis calculation was carried out to obtain the natural frequencies of the QCS, and the first natural frequency of the QCS was determined to be 31 Hz. Then the RSA was carried out by inputting the response spectrum to the constraint points of the FEM model. The maximum displacement was calculated to be 0.014 mm at the top of QCS, as shown in Fig. 5. The reason for this small value can be attributed to the fact that the first natural frequency of the QCS is almost out of the earthquake frequency region, as shown in Fig. 4. Therefore, relative displacement between the QCS and the floor would not occur until the first mode of natural frequency is reached, i.e., the QCS shaking is in the same phase with the floor until the first mode of natural frequency is reached. Maximum displacement would be attained after passing the first mode of natural frequency.

Seismic analysis for Belle II detector

Similar to QCS, the RSA for Belle II detector was carried out. Microtremors were measured on the Belle II detector with the solenoid turn off to observe the vibration characteristics, as shown in Fig. 6.

Figure 6: Measured vibration of the Belle II
The red and blue solid lines show results of the natural frequencies measured in the horizontal direction. It can be observed that the peaks occurred near the 4 to 5 Hz range, approximately. So, this is the first mode of natural frequency of the Belle II detector.

![Figure 8: Result of seismic analysis](image)

The first mode is supposed to be the rigid body, i.e., the Belle II detector is shaking with the same shape. The pedestal to install the Belle II detector has been designed as a flat Teflon sheet support system to facilitate its unhindered movement in the horizontal direction as well.

**Table 1: RSA/FEM Calculation of displacements**

<table>
<thead>
<tr>
<th>Date</th>
<th>Intensity</th>
<th>QCS Displacement</th>
<th>Belle II Displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apr. 12th, 2020</td>
<td>3.5</td>
<td>0.065mm</td>
<td>2.1mm</td>
</tr>
<tr>
<td>Mar. 20th, 2021</td>
<td>3.5</td>
<td>0.017mm</td>
<td>0.7mm</td>
</tr>
<tr>
<td>Nov. 1st, 2021</td>
<td>3.5</td>
<td>0.014mm</td>
<td>0.8mm</td>
</tr>
<tr>
<td>Mar. 16th, 2022</td>
<td>4.3</td>
<td>0.023mm</td>
<td>3.4mm</td>
</tr>
</tbody>
</table>

To realize such a support system, a FEM model as shown in Fig. 7 was made with eight columns around the Belle II detector that are fixed to the floor. The columns and the Belle II detector are connected by springs in the horizontal direction. The spring constant of each of these springs was adjusted to the first mode at approximately 5 Hz by performing modal analysis.

![Figure 9: Acceleration response spectrum of the earthquake, April 19th, 2022, at NIED.](image)

The first natural frequency was calculated to be 4.7 Hz in the horizontal direction. An attempt to calculate the natural frequency in the vertical direction was not taken because a significant resonant peak was not observed: refer Fig. 6. Because the seismic load in the vertical direction is substantially lower than that in the horizontal direction (Fig. 4), the vertical displacement can be ignored.

Subsequently, RSA was carried out. The RSA result for the Belle II detector was calculated to be 1 mm, as shown in Fig. 8.

![Figure 10: RSA calculation (Upper) and measurement data of gap sensor (Lower)](image)

In Table 1, the RSA results are summarised together with the measurements of other earthquake occurrences during which the QCS was also quenched, except for the case of Apr. 12th, 2020. It can be observed from this list that the displacement during the earthquake that occurred on Apr. 12th, 2020, is three times that of the earthquake that occurred on Mar. 20th, 2021, even though they both recorded the same intensity level. This difference can be attributed to the differences in the accelerometer response, at natural frequency, of the Belle II detector and QCS. The accelerometer responses are 160 and 140 gal on Apr. 12th at 5 and 20 Hz, respectively, while they are 60 and 35 gal on Mar. 20th.

Based on the aforementioned RSA result of QCS and Belle II detector, the cause for the QCS quench can be attributed to displacement of the Belle II detector and not that of the QCS by itself.

**EARTHQUAKE ON APRIL 19TH, 2022**

On April 19th, 2022, an earthquake with intensity level 3 occurred at KEK. In this instance, gap sensors had already been installed and were ready to record the displacement measurements. One gap sensor installed on the QCS measures the gap between the QCS and the wall of the Central Drift Chamber (CDC) in the Belle II detector,
thereby enabling comparison of the displacements, between the RSA/FEM calculations and the actual measurements. Also, time history measured at NIED was converted to the acceleration response spectrum with 5% damping as shown in Fig. 9.

Table 2: Comparison of RSA/FEM calculations and measurements by the gap sensor at several earthquakes

<table>
<thead>
<tr>
<th>Date</th>
<th>Intensity</th>
<th>RSA/FEM</th>
<th>Gap sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apr. 19, 22</td>
<td>2.5</td>
<td>0.52mm</td>
<td>0.3mm</td>
</tr>
<tr>
<td>May 3rd, 22</td>
<td>1.3</td>
<td>0.13mm</td>
<td>0.035mm</td>
</tr>
<tr>
<td>May 5th, 22</td>
<td>2.4</td>
<td>0.40mm</td>
<td>0.10mm</td>
</tr>
<tr>
<td>May 8th, 22</td>
<td>0.8</td>
<td>0.05mm</td>
<td>0.019mm</td>
</tr>
<tr>
<td>May 9th, 22</td>
<td>1.0</td>
<td>0.05mm</td>
<td>0.03mm</td>
</tr>
<tr>
<td>May 22, 22</td>
<td>2.4</td>
<td>0.12mm</td>
<td>0.10mm</td>
</tr>
</tbody>
</table>

The calculated maximum displacement of the Belle II detector and the measurement data of aforesaid gap sensor are shown in Fig. 10. In the case of the subject earthquake, the displacement was calculated to be 0.52 mm while the measured value was 0.3 mm, which is quite consistent.

Table 3: Specifications of each sensor

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Piezo</td>
<td>Laser</td>
<td>Capacitive</td>
</tr>
<tr>
<td>I.D.</td>
<td>356B18</td>
<td>LK-80</td>
<td>VT5710</td>
</tr>
<tr>
<td>Company</td>
<td>PCB</td>
<td>Keyence</td>
<td>Onosokki</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>1mV/gal</td>
<td>0.5mm/V</td>
<td>1.6mm/V</td>
</tr>
<tr>
<td>Precision</td>
<td>0.05 gal</td>
<td>0.2 μm</td>
<td>0.6 μm</td>
</tr>
</tbody>
</table>

Data for similar earthquake occurrences are listed in Table 2. A comparison of the values indicates that those obtained from RSA/FEM calculations are always higher than the measured values. Most likely, this could be due to overestimation of the seismic loads.

Figure 11: Left hand side image shows acceleration sensors on top of the Belle II detector and floor. Right hand side image shows the laser displacement sensors.

Until now, the seismic loads were deduced based on the measurement at the ground level in NIED, whereas the Belle II detector is located at 16 m below the ground level (GL-16 m). Consequently, the actual seismic load could be lower.

MEASUREMENT OF EARTHQUAKE ON THE FLOOR AT GL-16M

Measurement system

Acceleration sensors and laser displacement sensors, to measure relative displacement between the Belle II and the floor, were set around the Belle II detector.

Figure 12: Time history at ground and GL-16m

Two laser displacement sensors are installed on the floor to measure displacement of the Belle II detector. Gap sensor is installed on the QCS cryostat to measure displacement of the inner wall of Central Drift Chamber (CDC) installed in the Belle II detector. Specifications of each of the sensors is listed in Table 3.

Figure 13: Acceleration response spectrum at the ground level (GL, blue) and the floor (GL-16m, red) for an earthquake on May 29, 2022
Data was obtained via 8-channel data logger (model: CS-3008-FD) manufactured by imc Test & Measurement GmbH with trigger setting at 5 gal. Images depicting the installation of the sensors are shown in Fig. 11. Tri-axial piezo acceleration sensors are mounted on top of the Belle II detector and the floor.

Earthquake on May 29, 2022

An earthquake with intensity level 3 occurred on May 29th, 2022, at KEK. This earthquake was recorded by the piezo-acceleration sensors and displacement sensors. Acceleration time history recorded at the ground level (Ground, NIED) and data taken on the floor of Belle II detector (GL-16m) are shown in Fig. 12. Acceleration at ground is approximately 15 and 10 gal in the NS and the EW direction, respectively. Acceleration in the vertical direction is lower than that in horizontal direction, which is approximately 8 gal. Because measurements were recorded at 16 m below the ground level, the acceleration measurement values were lower than that recorded at the ground level. The actual acceleration measurement value recorded was 5 gal in both NS and EW directions. In contrast, there is no noticeable difference in the acceleration measurement in the vertical direction in comparison to that obtained at the ground level.

Figure 14: Result of response spectrum analysis

From the time history data, the acceleration response spectrum in three directions is shown in Fig. 13. Blue solid line shows the acceleration response spectrum recorded at the ground level and red solid line shows the acceleration response spectrum recorded at 16 m below ground level.

Comparison of acceleration response spectrum data for the horizontal direction at these two locations revealed that the acceleration response is nearly identical until 2 Hz. Subsequently, the acceleration response at 16 m below ground level decreases with increasing frequency. In contrast, the response spectrum at the ground level increases until 10 Hz, and it attains a maximum value of approximately 50 and 70 gal in the NS and EW direction, respectively. However, there is not much difference in the acceleration spectrum in the vertical direction.

Figure 15: Data of gap sensor

The RSA/FEM was carried out with data recorded at 16 m below the ground level (GL-16m) and compared to the data of the gap sensor. The RSA/FEM results and measurement data of the gap sensor are shown in Figs. 14 and 15, respectively. The displacement of the Belle II detector was calculated to be 0.15 mm in the horizontal direction while the maximum displacement measurement is approximately 0.1 mm. It is worth noting here that the calculation and the measurement are in good agreement.

The acceleration response spectrum measured on Jun 19, 2022, is shown in Fig. 16. It can be observed that the acceleration response spectrum in the horizontal direction at the ground level is increasing until 10 Hz, whereas the data obtained at 16 m below ground level is constant beyond 3 Hz. In the vertical direction, the response spectrum obtained at ground level and at 16 m below ground level are similar, except for the frequency range from 4 to 10 Hz. Based on the data, it can be concluded that the characteristics of both the earthquakes that occurred on May 29th and Jun 19th, 2022, are similar.

Figure 16: The acceleration response spectrum at the ground level (GL, blue) and the floor (GL-16m, red) for an earthquake on June 19, 2022

The CORRELATION OF DISPLACEMENT BETWEEN L-SIDE AND R-SIDE

Two QCSs are mounted on both the left side (L-side) and right side (R-side) of the Belle II detector, one on each side. Because configuration of each of the QCSs is different from each other, and their first resonant frequencies are also expected to be different. In this case, the first resonant frequencies of the L-side and R-side QCSs are 31 and 24 Hz, respectively. Consequently, their displacements when an earthquake occurs would also be different. However, if
the resonant frequencies of the two QCSs are out of the earthquake effect, their displacement measurements can be ignored.

Table 4: Summary of displacement measured by the gap sensor at various earthquakes

<table>
<thead>
<tr>
<th>Date</th>
<th>Intensity</th>
<th>L-side (mm)</th>
<th>R-side (mm)</th>
<th>Diff. (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 3rd, 22</td>
<td>1.3</td>
<td>0.0359</td>
<td>0.0364</td>
<td>0.0005</td>
</tr>
<tr>
<td>May 5, 22</td>
<td>2.4</td>
<td>0.099</td>
<td>0.104</td>
<td>0.0053</td>
</tr>
<tr>
<td>May 8th, 22</td>
<td>0.8</td>
<td>0.0189</td>
<td>0.0194</td>
<td>0.0005</td>
</tr>
<tr>
<td>May 9th, 22</td>
<td>1.0</td>
<td>0.0371</td>
<td>0.0353</td>
<td>0.0017</td>
</tr>
<tr>
<td>May 22, 22</td>
<td>2.4</td>
<td>0.091</td>
<td>0.083</td>
<td>0.0084</td>
</tr>
</tbody>
</table>

To confirm this assumption, displacements measured by the gap sensors installed on the L-side and R-side QCSs were compared and the results are listed in Table 4. It can be observed that the displacements measured by the gap sensors on both sides are nearly the same, and it can be concluded that the displacement of both QCSs was in-phase with that of the floor, i.e., there was no relative displacement. Conversely, the Belle II detector was shaking independently of the floor thereby generating relative displacement, which is noteworthy.

CONCLUSION

The evaluation of earthquake effect to the Belle II detector and the QCSs in the Super KEKB accelerator was carried out in this study. The response spectrum analyses (RSA/FEM) were performed for the seismic effects and a few mm maximum displacement was obtained for the intensity 4 earthquake. A number of acceleration, gap, and displacement sensors were installed around the Belle II detector to record the actual displacement measurements during the occurrence of an earthquake and compare with the results of the RSA/FEM analysis. Comparison of the measured data and the RSA/FEM calculations indicated consistency and congruence. Also, it was confirmed that the Belle II detector is shaking independently of the floor, whereas the QCS is shaking in-phase with the floor.

Unfortunately, we have not been successful in fully confirming the modal shape of the Belle II detector that was assumed for the purpose of conducting the RSA/FEM analysis of the Belle II detector. Moreover, the accuracy levels of the sensors and devices used in the present study for the measurements are insufficient to obtain the level of precision required for obtaining displacement measurements during an earthquake. This will be improved by employing higher sensitivity acceleration sensors in future.

ACKNOWLEDGEMENT

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REFERENCES