Report on Seismic Damages of Lifts and Escalators by Large Earthquakes in Japan

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Keywords: earthquake damage, the great east earthquake, seismic design guideline

Abstract. The devastating earthquake of Mw9.0, so-called the Great East Japan Earthquake, hit the Tohoku district, north east part of Japan on March 11, 2011. About 16,000 people died and 2,500 people were missing by the strong motion and tsunami, and the economic damage was estimated about 16.9 trillion yen in addition to the influence by the nuclear accident of Fukushima Daiichi Nuclear Power Plant. In addition to the main shock, many strong aftershocks occurred in the long term. After that, a strong near-field earthquake called Kumamoto Earthquake occurred in 2016 in Kyushu district of Japan.

The buildings, houses and industrial facilities were damaged in these earthquakes, and various kinds of mechanical equipment set in these structures were also damaged. The Japan Society of Mechanical Engineers (JSME) has set up an investigation committee which has investigated the seismic damage of mechanical equipment in these industrial facilities, for the purpose to understand the situation and cause of the damages in such facilities to contribute to improvement of preparedness for the forthcoming earthquake.

Additionally, investigation regarding lifts and escalators was mainly carried out by the Japan Elevator Association. This paper provides a summary of the investigation regarding the lifts and escalators to contribute to improving the seismic design for forthcoming destructive earthquakes. Typical damage of the lifts and escalators utilized in buildings are also shown in this paper. Although many of the buildings were hit by unexpected massive earthquakes, the damage of the lifts and escalators designed according to the newly Seismic Design Guideline issued in 2009 seems to have been reduced a certain level.

1 INTRODUCTION

Approximately 20% of earthquakes having a Magnitude of 6 in the whole earth occur in Japan and its surroundings, although the area is only 0.1% of the whole earth [1]. This is because Japan is located on the west side of the circum-Pacific seismic zone, and on 4 plates. The oldest record of the earthquake in Japan is year 416 AD.

The first electric passenger lift in Japan was installed in a building in Tokyo in 1890 [2]. However, the building collapsed due to a large earthquake in 1923. After that, lifts in Japan have experienced various large earthquakes, and the Seismic Design Guideline in Japan was revised according to the damage from earthquakes. In this decade, two large earthquakes attacked Japan. One is the Great East Japan Earthquake in 2011, which was the largest earthquake ever observed in Japan. The earthquake had large energy, long duration time and many aftershocks. The other was the Kumamoto Earthquake in 2016 that occurred in the Kyushu Region. In the series of Kumamoto Earthquakes, two large earthquakes had Japan Meteorological Agency (JMA) seismic intensity 7, which is the highest level of the scale to have occurred in Japan.

This paper provides changes of the Seismic Design Guideline in Japan and analyzes damage of lifts and escalators from the Great East Japan Earthquake in 2011 and the Kumamoto Earthquake in 2016.

2 CHANGES OF SEISMIC DESIGN GUIDELINE IN JAPAN

Table 1 shows a history of major earthquake and seismic standards or guidelines.

Before 1971, no official seismic design guideline was established in Japan, so seismic design guidelines established by each company were applied.

In 1972, the Disaster Prevention Standard was established by the Japan Elevator Association. This establishment is based on the damage of lifts by the San Fernando Earthquake in 1971. In the earthquake, a counterweight fell and collided with a car. Thus, the standard considered derailment of cars and counterweights, prevention of overturning of traction machines and control systems, seismic emergency operation and so on.

In 1981, a Seismic Design Guideline was established by the Building Center of Japan based on the damage of lifts from the Miyagi Earthquake in 1978. In the earthquake, derailment of counterweights, movement of traction machines etc. occurred. In addition, Enforcement Ordinance of Construction Standard Law in Japan was revised in 1981, so the Seismic Design Guideline reflected it. The Seismic Design Guideline considered improvement of countermeasures against derailment of cars and counterweights, improvement of prevention of overturning of traction machines and control systems, improvement of countermeasures against entanglements of ropes and so on.

In 1998, a Seismic Design Guideline was issued by the Building Center of Japan based on the damage of lifts and escalators from Kobe Earthquake in 1995. In the earthquake, counterweights fell, and equipment in machine rooms moved and overturned. In addition, damage of escalators was also reported. Therefore, the new Seismic Design Guideline considered addition of countermeasures against falling of counterweight blocks, the increase of design earthquake level and so on. In addition, the seismic design of escalators was newly described in the guideline.

In 2009, the Seismic Design Guideline was revised based on the damage of lifts from the Mid Niigata Prefecture Earthquake in 2004 and the Northwestern Chiba Earthquake in 2005. In the Mid Niigata Prefecture Earthquake, long period seismic waves that had predominant periods of more than a few seconds were generated in Tokyo, so high-rise buildings and wire ropes of lifts resonated. In the Northwestern Chiba Earthquake, many lifts were stopped for a long time by the earthquake emergency operation, and passengers were trapped in lifts, although this earthquake was smaller than other destructive earthquakes. Thus, the revised guideline considered countermeasures against resonance of long ropes, improvement of earthquake emergency operation and so on.

In 2014 and 2016, the Seismic Design Guideline was revised based on the damage of lifts and escalators from Great East Japan Earthquake in 2011 [3]. Lifts and escalators damaged by the earthquake as describe hereinafter, because the earthquake was the largest earthquake ever observed in Japan. In addition, 4 escalators in shopping malls fell from floors of buildings. Thus, the revised guideline considered countermeasures of the falling of escalators, assessment of major support parts of lifts and so on.

Table 1 History of major earthquake and seismic standard or guideline in Japan

Year	Earthquake	Standard / Guideline
1971	San Fernando Earthquake	
1972		Disaster Prevention Standard
1978	Miyagi Earthquake	
1981		Seismic Design Guideline (1981)
1995	Kobe Earthquake	
1998		Seismic Design Guideline (1998)
2004	Mid Niigata Prefecture Earthquake	
2005	Northwestern Chiba Earthquake	
2009		Seismic Design Guideline (2009)
2011	Great East Japan Earthquake	
2014		Seismic Design Guideline (2014)
2016	Kumamoto Earthquake	Seismic Design Guideline (2016)

3 DAMAGE FROM GREAT EAST JAPAN EARTHQUAKE IN 2011

3.1 Summary of earthquake

The Great East Japan Earthquake is a series of disasters that originated in the off Pacific coast Tohoku Earthquake on March 11, 2011 at 14:46 JST. The hypocenter of the earthquake was at approximately 130 km east-southeast of the Oshika Peninsula, at a depth of 24 km [4]. The moment magnitude of the earthquake was 9.0, which was the largest among seismic records in Japan. Strong ground motion and tsunamis were generated by the earthquake, so that about 16,000 people died, about 2500 people are missing, more than 120,000 buildings were completely collapsed, and more than 280,000 buildings were partially collapsed [5].

The earthquake has many features compared with conventional destructive earthquakes. For example, duration of the main shock was very long, at about 6 minutes, and the seismic wave was transmitted to the whole area of Japan. Another feature was the very large tsunami. The maximum wave height was more than 9.3 m, but actual height was not clear because the observation point was damaged by the tsunami. The maximum water level height that was supposed from trace or watermark was more than 20 m, and the maximum run-up height was more than 40 m. About 90% of victims died due to drowning in tsunamis, and much equipment in industrial facilities were covered with sea water. Additionally, lots of aftershocks occurred, the number of aftershocks with a magnitude more than 5 was 779 as of April 30, 2012 [4].

3.2 Investigation method

An investigation regarding damage of lifts and escalators from the earthquake was mainly carried out by the Japan Elevator Association [6]. The investigation was started from July when aftershocks decreased, because restoration of lifts and escalators was a priority just after the earthquake. Target earthquakes for the investigation were the main shock and aftershocks more than JMA seismic intensity 5+ that occurred until June. Targets machines were lifts and escalators which members of the Japan Elevator Association inspected, but small freight lifts were excepted from the investigation. Existence of damage, edition of the Seismic Design Guideline and so on were investigated by a questionnaire. Contents of the questionnaire was determined based on examples of damage reported in the Kobe Earthquake in 1995.

3.3 Damage of lifts

As a result of the investigation by using the questionnaire, damage was found in 8,921 out of 367,912 cases, so the incidence ratio was 2.43%

Figure 1 shows incidence ratio by JMA seismic intensity scale. The JMA seismic intensity is calculated from ground acceleration during an earthquake considering frequency components, and the minimum level is 0, the maximum level is 7. As shown in Fig. 1, more than 1/4 of lifts that were installed in area of the JMA seismic intensity 7 were damaged.

Figure 2 shows damage of lift by parts. As shown in Fig. 2, entanglements of ropes accounted for 1/4 of total damage. The reason was that large areas in Japan including Tokyo where many buildings exist were affected by the earthquake. Vibration of ropes relates to height of a building, length of a rope, the ground condition and so on. For example, Tokyo is located on a sedimentary layer, and long period seismic waves are excited by the layer. In general, high-rise buildings and long wire ropes have long natural period, so that there are risks of resonance.

Then many damages by flooding also occurred. This is a one of the features of the Great East Japan Earthquake. Other mechanical structures were also damaged by large tsunamis [7].

In addition, a lot of damage that was caused by interaction with buildings such as entanglements of ropes, deformation of rails, damage of hoistway equipment and so on occurred. Close cooperation with structural engineers of buildings is strongly recommended to reduce the damage of lifts.

Falling of counterweight blocks occurred, similarly to in past destructive earthquakes. Although the numbers of falling counterweight blocks waere few, it may cause human damage. However no falling of counterweight blocks in lifts that were designed by applying Seismic Design Guideline issued in 2009 occurred. Therefore, the guideline was revised effectively.

Figure 3 shows relationship between edition of Seismic Design Guideline and incidence ratio. Incidence ratio decreased with the edition, thus revisions were effective.

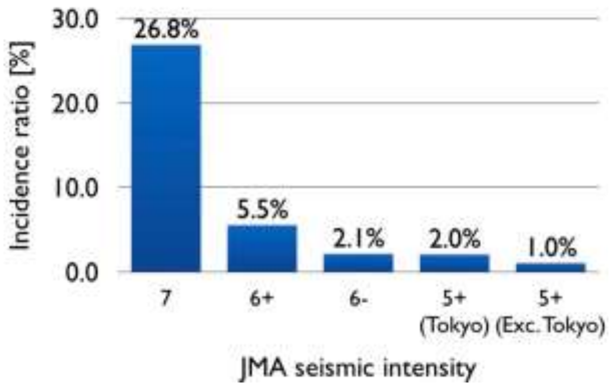

Figure 1 Incidence ratio of lift by Japan Meteorological Agency seismic intensity scale (Great East Japan Earthquake in 2011)

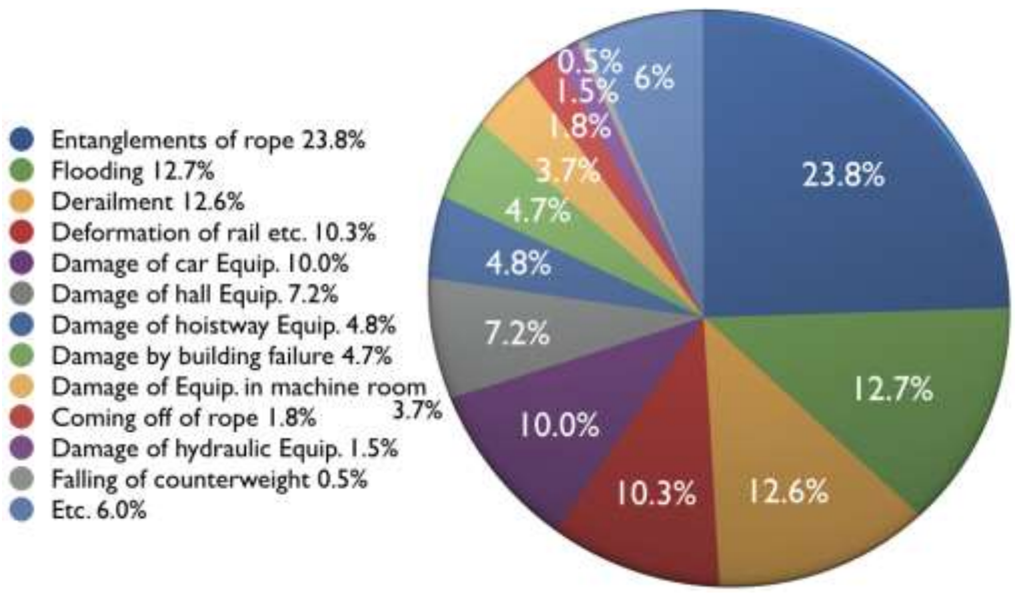

Figure 2 Damage of lift by cause (Great East Japan Earthquake in 2011)

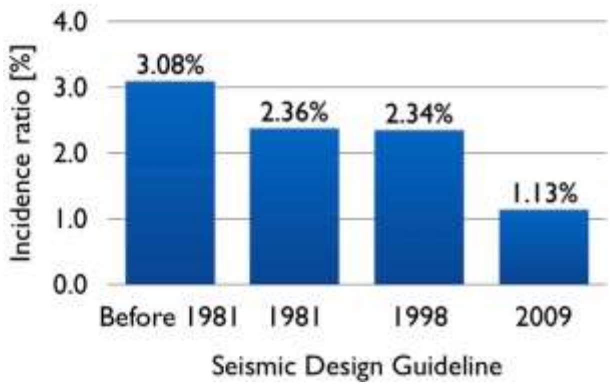

Figure 3 Relationship between edition of Seismic Design Guideline and incidence ratio of lift (Great East Japan Earthquake in 2011)

3.4 Damage of escalator

Damage of escalators was found in 1,598 out of 40,967 cases, so the incidence ratio was 3.90%

Figure 4 shows damage of escalators by parts. As shown in Fig. 4, damage by flooding, one of the features of the Great East Japan Earthquake, accounted for 1/5 of total damage. Apart from that, damage such as position shift and damage of landing plates occurred. This damage might be caused by interaction between buildings and escalators.

In addition, 4 escalators in shopping malls fell from floors of buildings. Although the number of falling escalators were few, it may cause human damage if passengers are on the escalators. Therefore, a project and revision of the guideline regarding fall accidents were carried out after the earthquake.

Figure 5 shows the relationship between edition of Seismic Design Guideline and incidence ratio. Damage incidence ratio of escalators before 1998 was small compared of escalators that were designed by applying Seismic Design Standard issued in 1998. On the other hand, the ratio of escalators after 2009 decreased.

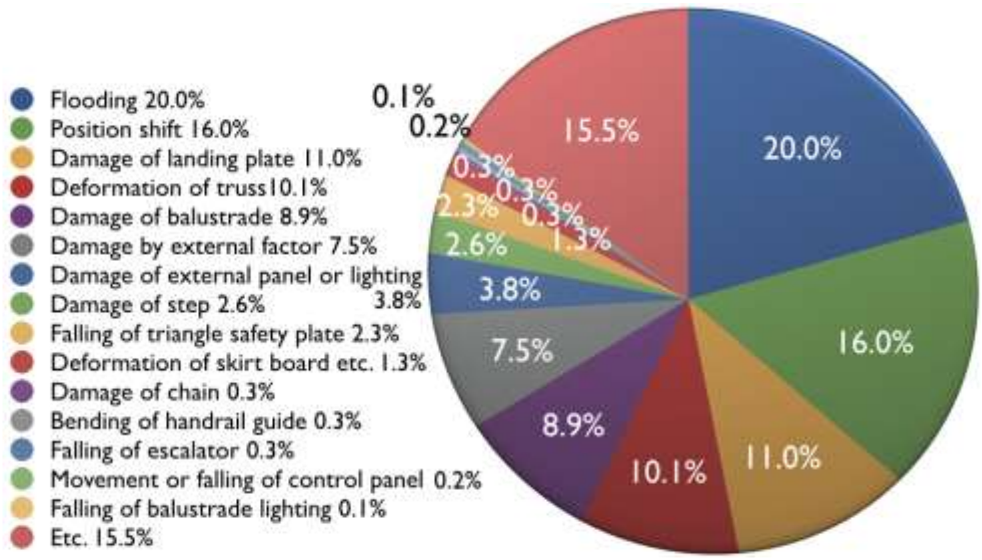

Figure 4 Damage of escalator by cause (Great East Japan Earthquake in 2011)

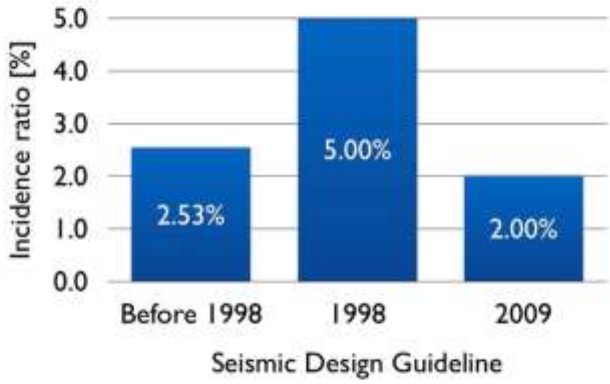

Figure 5 Relationship between edition of Seismic Design Guideline and incidence ratio of escalator (Great East Japan Earthquake in 2011)

4 DAMAGE FROM KUMAMOTO EARTHQUAKE IN 2016

4.1 Summary of earthquake

On April 14, 2016 at 21:26 JST, a strong earthquake having moment magnitude 6.2 occurred in Kyushu Region in the southwest part of Japan. The hypocenter of the earthquake was Kumamoto Prefecture, with a depth of 11 km. The JMA seismic intensity was 7, which is one of the largest level of intensity, but this was a foreshock. About 28 hours later, on April 16 at 1:25 JST, another strong earthquake having moment magnitude 7.0 occurred in same area, at a depth of 12 km. This was a main shock. The series of earthquakes caused the death of 228 people (this includes earthquake related-death). More than 9,000 buildings were completely collapsed, and more than 45,000 buildings were partially collapsed [8]. The features of the earthquake was strong ground motion and landslides. Industrial facilities in Kumamoto Prefecture were damaged by the earthquake, and the main cause of damage of mechanical structures was strong vibration [9].

4.2 Investigation method

The same investigation method as the Great East Japan Earthquake was applied, namely investigation using the questionnaire conducted by the Japan Elevator Association from June to July [10]. Target earthquakes for the investigation were the foreshock, the main shock and 3 aftershocks more than JMA seismic intensity 5+ that occurred in April.

4.3 Damage of lifts

As a result of the investigation by using the questionnaire, damage was found in 1,027 out of 95,424 cases, so the incidence ratio was 1.08%. This result was smaller than the Great East Japan Earthquake.

Figure 6 shows damage of lift by parts. As shown in Fig. 6, damage related to buildings such as entanglements of ropes, damage of rails, entrance halls and so on mainly occurred. Five cases of falling of counterweight blocks occurred, but these happened at lifts that were designed by using the Seismic Design Guideline issued in 1981 or before.

Figure 7 shows the relationship between edition of Seismic Design Guideline and incidence ratio. Incidence ratio decreased with the edition as well as the Great East Japan Earthquake, thus effectiveness of the revision was confirmed.

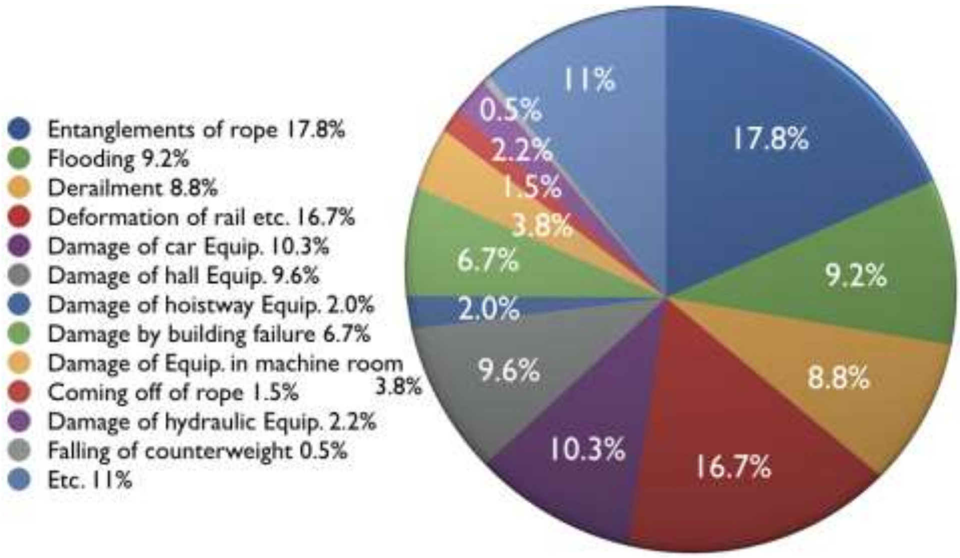

Figure 6 Damage of lift by cause (Kumamoto Earthquake in 2016)

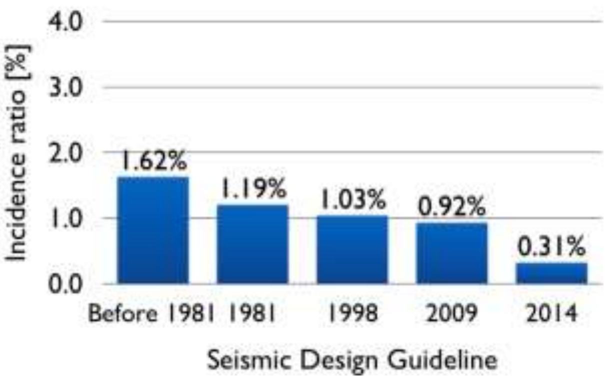

Figure 7 Relationship between edition of Seismic Design Guideline and incidence ratio of lift (Kumamoto Earthquake in 2016)

4.4 Damage of escalator

Damage of escalators was found in 330 out of 8,744 cases, so the incidence ratio was 3.77%

Figure 8 shows damage of escalators by parts. As shown in Fig. 8, damage mainly occurred in landing plates, external panels or lighting, and this damage was related to interaction with building. In addition, no fall accident of escalators occurred.

Figure 9 shows relationship between edition of Seismic Design Guideline and incidence ratio. Although incidence ratio of escalators after 2014 was small, the ratio increased with the edition. In order to clarify reason of this result, investigation in consideration of buildings is needed.

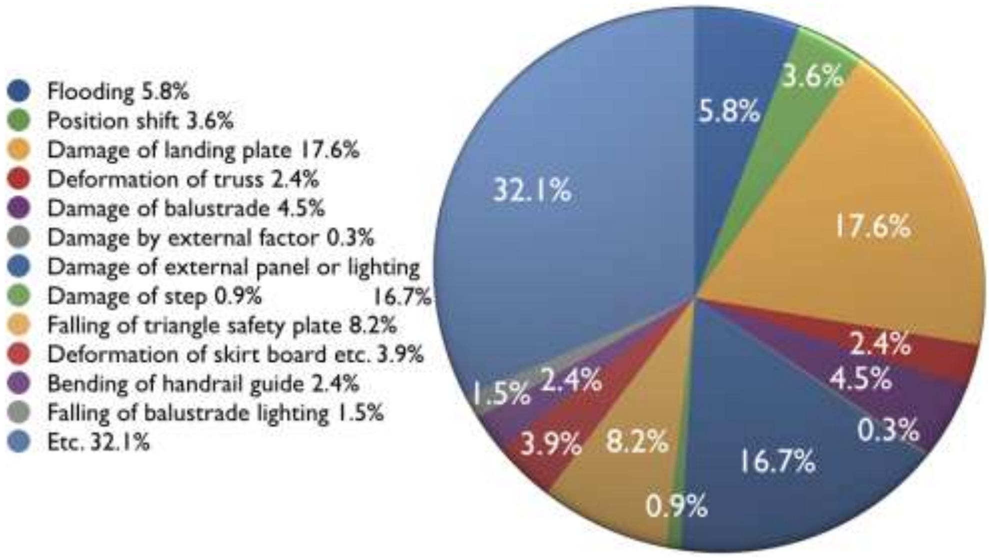

Figure 8 Damage of escalator by cause (Kumamoto Earthquake in 2016)

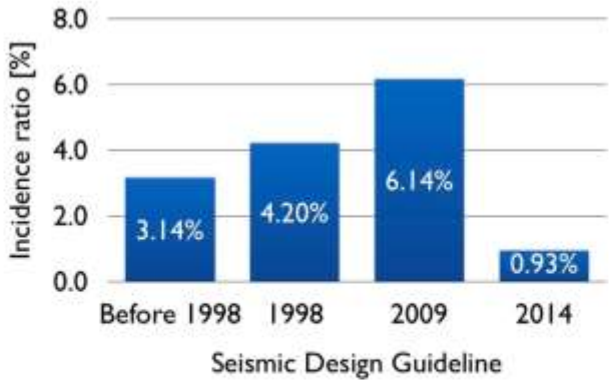

Figure 9 Relationship between edition of Seismic Design Guideline and incidence ratio of escalator (Kumamoto Earthquake in 2016)

5 CONCLUSION

In this paper, changes of the Seismic Design Guideline in Japan, and investigation results regarding damage of lifts and escalators from large earthquakes were reported. The results are summarized as follows;

- Seismic Design Guideline of Japan was revised according to actual damage from large earthquakes. From the investigation results of the Great East Japan Earthquake and the Kumamoto Earthquake, the revision was basically effective to improve seismic reliability of lifts and escalators

- Lifts and escalators are generally installed in buildings. Therefore, close cooperation with structural engineers of buildings is strongly recommended to reduce the damage of lifts and escalators.

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BIOGRAPHICAL DETAILS

Prof. Satoshi Fujita, a JSME (Japan Society of Mechanical Engineers) Fellow, has ten years of management experience as a director, a dean of school of engineering and a vice-president of Tokyo Denki University. He has been engaged in engineering research and development of seismic isolation systems and vibration control systems for buildings or key industrial facilities for over 35 years at both University of Tokyo and Tokyo Denki University. In recent ten years, he has been a committee member of the Panel on Infrastructure Development of Japanese ministry of land, infrastructure and transport (MLIT), and a chair of the Special Committee on Analysis and Evaluation of Lifts, Escalators and Amusement Facilities Accidents and Failures held in MLIT. In addition, he has been a chair of the ISO TC178 Japanese committee.

Mr. Motoo Shimoaki is a managing director of the Japan Elevator Association. He has long experience as an engineer of elevator company.

Dr. Keisuke Minagawa is an associate professor of Saitama institute of technology and is a chair of the Technical Committee of Lifts, Escalators and Amusement Facilities held in JSME (Japan Society of Mechanical Engineers). He has been an evaluator of lift systems and mechanical car parking systems since 2015. He is also an expert of seismic isolation and vibration control.