# Study on Seismic Response of Escalator in Consideration of Interaction with Building During Large Earthquakes

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**Keywords**: escalator, analytical model, overlap allowance, seismic motion, slide friction

**Abstract.** In Great East Japan Earthquake in 2011, fall accidents of escalator body occurred. In the fall accidents, the escalators connected the third floor and the second floor. These occurred in commercial facilities of steel frame buildings. In general, escalators are mounted within the building structure without being fixe to the beam of the building. The cause of the fall accidents was that the escalators came off the beams of the buildings as a result of the great earthquake more than expected. After the escalator accidents, the quake resistance standard was revised in Japan. According to this standard, the layer displacement of buildings to be expected during an earthquake is more than before. However, it is considered that a non-fixed part of an escalator collides with a beam of a building by an earthquake. In addition, the collision may give compression and residual displacement to the escalator. Therefore, the purpose of this study is to grasp dynamic behavior of an escalator at an earthquake which considers impact with the beam. In this paper, behavior of an escalator during earthquakes is compared by difference of restoring force characteristics of escalators and confirm the validity of the bi-linear model. In addition, as a preliminary analysis for the vibration experiments, dynamic behavior of escalators during large earthquake is investigated by a seismic response analysis model which considers interaction with the building.

## 1 INTRODUCTION

An escalator is a method of vertical transportation. For example, the escalator connects a floor from another floor in buildings. In general, one side or both sides of escalators are not fixed to a beam of building in order to not deform the escalator. However, in Great East Japan Earthquake in 2011, four fall accidents of escalator bodies occurred [1]. In the fall accidents, the escalators connected the third floor and the second floor. These occurred in commercial facilities of steel frame buildings. The cause of the fall accidents was that the escalators came off from the beams of the buildings by the great earthquake more than expected. From the above-mentioned background, there is a need to clarify behavior by an escalators during an earthquake. In this paper, these elasto-plastic properties are approximated by a bi-linear model and a multi-linear model, and both models are compared. In addition, dynamic behavior of an escalator for vibration experiment is investigated by seismic response analysis which considers interaction with the building.

## 2 STRUCTURE OF ESCALATOR

Diagrammatical view of the escalator is shown in Fig.1. The escalator consists of steps, handrails, transport equipment parts and a truss that supports these transportation parts. As shown in equation (1), (2) and (3), the length of the overlap allowance is determined by escalator technology standard in Japan [2]. Where $C$ is the gap between the beam of the building and the escalator, $H$ is the height, $\gamma$ is the layer deformation angle of building and 20 [mm] is margin of the overlap allowance.

$$B \geq \sum \gamma H + 20 \qquad (\sum \gamma H - C \leq 0) \tag{1}$$

$$B \geq \sum \gamma H + 20 \qquad (0 \leq \sum \gamma H - C \leq 20) \tag{2}$$

$$B \geq 2\sum \gamma H - C \qquad (20 < \sum \gamma H - C) \tag{3}$$

After the escalator accidents, the quake resistance standard was revised in Japan. According to this standard, the layer displacement of buildings to be expected during an earthquake is more than before. The layer deformation angle for design before the revision of quake resistance standard was less than 1/100 [rad]. However, after the revision of quake resistance standard was 1/40 [rad] in principle, and 1/24 [rad] or more when the structural calculation was not done. It is considered that the layer deformation of the building at the medium-scale earthquake is 1/200 to 1/120 [rad]. This value obtained by estimating five times is 1/40 to 1/24 [rad] of new standard value.

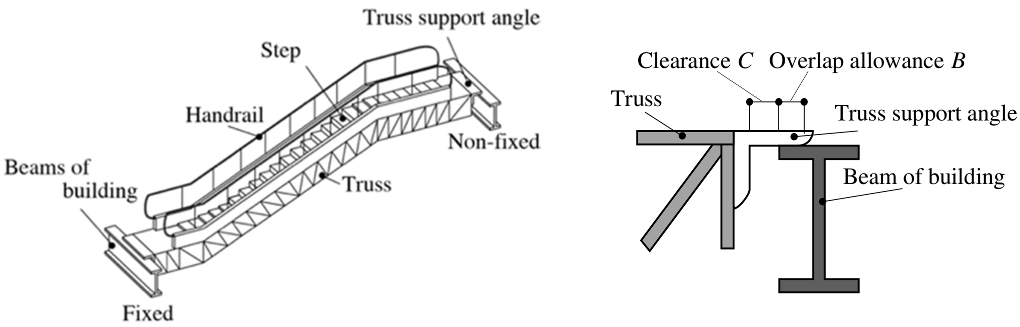



**Figure 1 Escalator system and the non-fixed side of the escalator**

## 3 ANALYTICAL MODEL

### 3.1 Analytical model of escalator

Target in this study is an escalator that is installed in the beam of building with fixation at the bottom side and non-fixation at the top side. This analytical model is considered that a non-fixed part of an escalator collides with a beam of a building by an earthquake [4]. In addition, this analytical model is considered that the sliding friction occurs between the beams of building and escalator. Therefore, the damping force, friction force, inertial force, and the restoring force are exerted on the escalator. As this point, it is assumed that the response of the building is not affected by the behavior of the escalator.

Figure 2 shows the analytical model of escalator. In Fig.2, $m_e$ is the mass of escalator, $F_e$ is the stiffness of escalator truss, $c_e$ is the damping coefficient of escalator truss, $\mu_s$ is the static friction coefficient of escalator, $\mu_d$ is the dynamic friction coefficient of escalator, $x_e$ is the displacement of the escalator, $k_s$ is the stiffness of the beams of building, $c_s$ is the damping coefficient of the beams of building, $x_L$ is the displacement of the building on the lower floor, $x_s$ is the displacement of the building on the upper floor. Table 1 shows parameters of escalator. The 1st stiffness $k_1$ of the escalator truss is calculated using results of compression experiment in past.

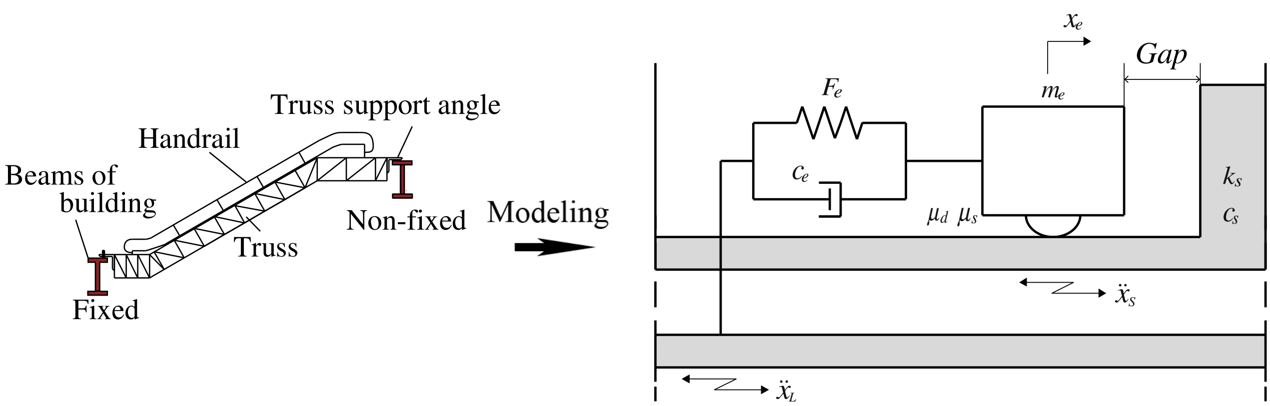



**Figure 2 Analytical model of escalator**

**Table 1 Parameter of escalator**

| Mass of escalator $m_e$ [kg] | 1st stiffness $k_{e1}$ [N/m] | 2nd stiffness $k_{e2}$ [N/m] | Yield disp. $x_y$ [m] | Damping ratio $\zeta_e$ [%] | Friction coefficient $\mu_s$ , $\mu_d$ | Gap [m] |
|---|---|---|---|---|---|---|
| 8000 | $2.75\times10^7$ | $1.10\times10^5$ | 0.02 | 1 | 0.25 | 0.03 |

### 3.2 Restoring force characteristics of escalator

In this study, the bi-linear model determined by the material characteristic of the escalator and the multi-linear model obtained in the compression experiments of escalators were used as the restoring force characteristics of the escalator. In the previous study, the analysis result of Truss A was shown [5]. In this study, in order to confirm the accuracy of the analysis model, the analysis result of Truss B was added. Figure 3 and 4 show a load-displacement curve. This analysis compares the result of the bi-linear model and multi-linear model.

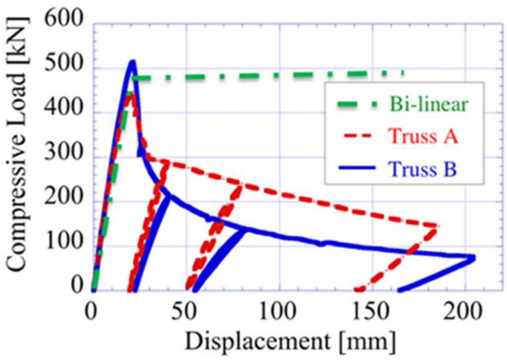



**Figure 3 Load-displacement curve from experiment result and bi-linear model**

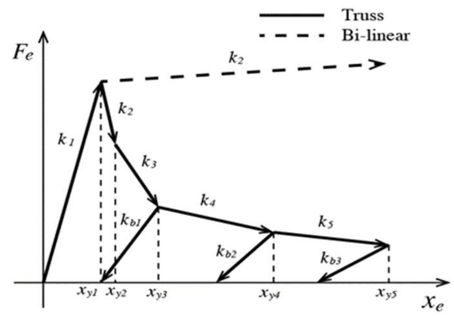



**Figure 4 Load-displacement curve by linear**

**Table 2 Parameter of escalator truss stiffness**

<table>
<tr><th></th><th>Bi-linear</th><th>Truss A</th><th>Truss B</th></tr>
<tr><td>2nd Stiffness $k_2$ [N/m]</td><td>$1.1\times10^5$</td><td>$-2.7\times10^7$</td><td>$-4.55\times10^7$</td></tr>
<tr><td>3rd Stiffness $k_3$ [N/m]</td><td>-</td><td rowspan="3">$-9.7\times10^6$</td><td>$-7.9\times10^6$</td></tr>
<tr><td>4th Stiffness $k_4$ [N/m]</td><td>-</td><td>$-1.8\times10^6$</td></tr>
<tr><td>5th Stiffness $k_5$ [N/m]</td><td>-</td><td>$-4.8\times10^5$</td></tr>
</table>

### 3.3 Equation of motion of analytical model of escalator

Equation of motion can be classified into three cases. The three equations of motion are devised, in consideration of influence by the slide friction and the collision occurred between the escalator and the building beams. Equation (4) shows the case that sliding does not occur. Equation (5) shows the case that sliding occurs. Equation (6) shows the case that collision with the building beams occurs. This equation has been shown in previous study [5].

$$\text{Case1 :} \quad \ddot{x}_e = \ddot{x}_s \quad \dot{x}_e = \dot{x}_s \quad x_e - x_s = const \tag{4}$$

$$\text{Case2 :} \quad m_e\ddot{x}_e + c_e\dot{x}_e + F_e + \mu_d \frac{1}{2} m_e g \cdot \mathrm{sgn}(\dot{x}_e - \dot{x}_s) = -m_e\ddot{x}_L \tag{5}$$

$$\text{Case3 :} \quad m_e\ddot{x}_e + c_e\dot{x}_e + F_e + \mu_d \frac{1}{2} m_e g \cdot \mathrm{sgn}(\dot{x}_e - \dot{x}_s) + k_s\{(x_e - x_s) - Gap\} + c_s(\dot{x}_e - \dot{x}_s) = -m_e\ddot{x}_L \tag{6}$$

### 3.4 Analytical model of building

In this analysis, it is assumed that the escalator is installed in the three-storey steel-flame building, the response of each layer are input into the escalator analysis model. The primary natural period is 0.744 [s]. Figure 5 shows the analytical model of building. In Fig.5, $m_{si}$ is the mass, $c_{si}$ is the damping coefficient, $k_{si}$ is the 1st stiffness, $Q_{si1}$ is 1st yield load, $Q_{si2}$ is 2nd yield load, $\alpha_{si1}$ is 2nd stiffness degradation rate, $\alpha_{si2}$ is 3rd stiffness degradation rate, $\ddot{z}_H$ is the horizontal input seismic acceleration.

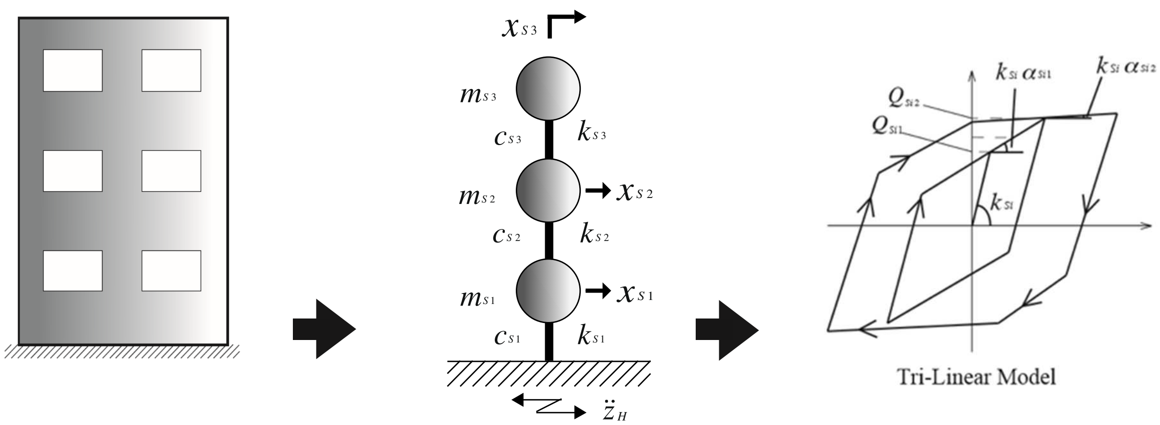



**Figure 5 Analytical model of building**

**Table 3 Parameter of building**

| Layer | Mass $m_s\times10^6$ [kg] | 1st Stiffness $k_{s1}\times10^9$ [N/m] | 1st Yield Disp. $x_{y1}$ [m] | 2nd Stiffness $k_{s2}\times10^9$ [N/m] | 2nd Yield Disp. $x_{y2}$ [m] | 3rd Stiffness $k_{s3}\times10^9$ [N/m] |
|---|---|---|---|---|---|---|
| 3 | 11.21 | 3.48 | 0.012 | 1.25 | 0.047 | 0.623 |
| 2 | 9.2 | 3.68 | 0.016 | 1.25 | 0.066 | 0.736 |
| 1 | 9.7 | 3.83 | 0.019 | 1.38 | 0.075 | 1.23 |

# 4 SEISMIC RESPONSE ANALYSIS

## 4.1 Input seismic wave

Figure 6 shows the time history waveform and the response spectrum of the input seismic wave. In this paper, the K-NET Sendai NS Original wave observed at Sendai in the Great East Japan Earthquake was used. K-NET Sendai NS Original wave was obtained from Strong-motion Seismograph Network of National Research Institute for Earth Science and Disaster Prevention (K-NET), observation point is MYG013 [3]. Predominant period of K-NET Sendai NS Original wave is about 0.6~0.7 [s].

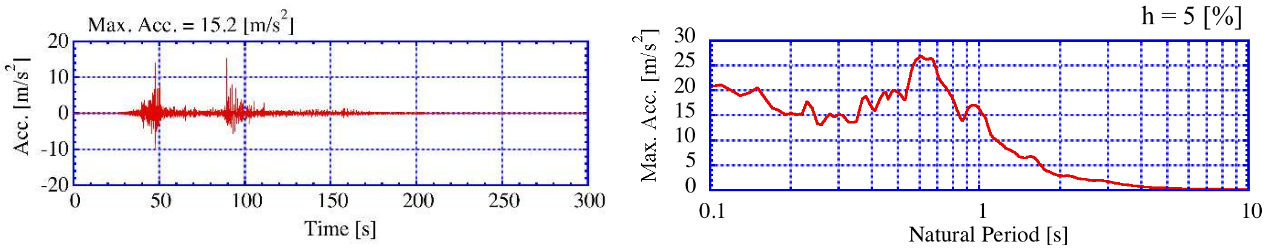



**Figure 6 Time history wave and response spectrum**

## 4.2 Results of seismic response analysis of building

Figure 7 shows result of seismic response analysis of the building. In Fig.7, the maximum acceleration of each floor, the maximum layer displacement, and the maximum layer deformation angle from the left. This building did not amplify the ground acceleration. In addition, the largest layer deformation angle was 2nd layer. From this, it is considered that there is a high risk of falls on escalator installed between 2nd and 3rd floor and above.

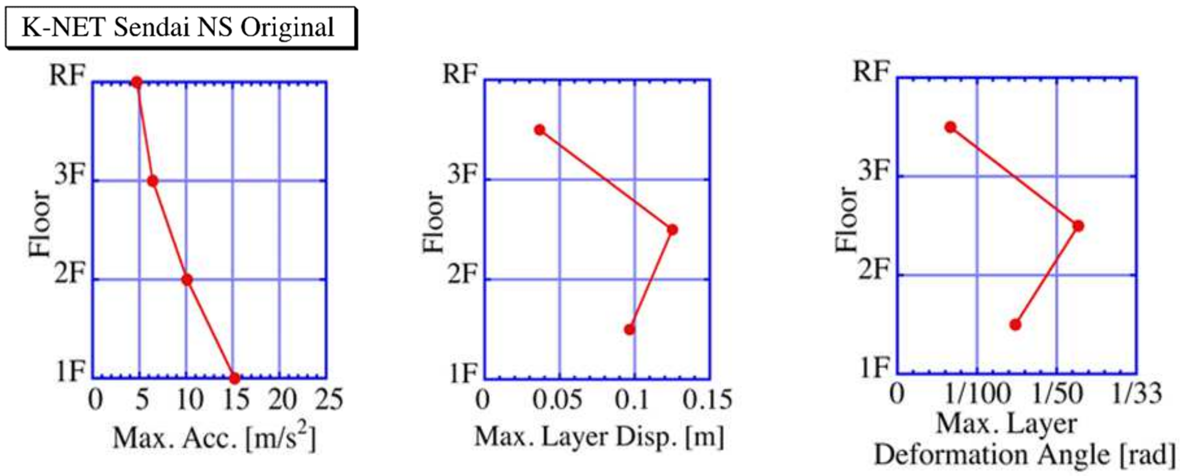



**Figure 7 Response maximum values of each layer**

## 4.3 Results of seismic response analysis of escalator

Figure 8 shows results of seismic reply analysis of escalator that is installed between 2nd and 3rd floor. When the state of escalator shifted to Case3, the response of the escalator becomes big value, because large force is generated on the escalator by collisions. As shown in restoring force of escalator, plastic deformation and residual displacement were remained. As shown in analysis results of the bi-linear model and the multi-linear model, the big difference of response was not confirmed. Therefore, influence of restoring force characteristics on the seismic behavior of the escalator is little. Figure 9 shows the maximum response values of slide displacement. In the case of the old standard, the maximum response values of the slide displacement of the escalator is higher than the value of overlap allowance, therefore the possibility of falling is high. In the case of the new standard, the maximum response values of the slide displacement of the escalator is below the value of overlap allowance, therefore the possibility of falling is low.

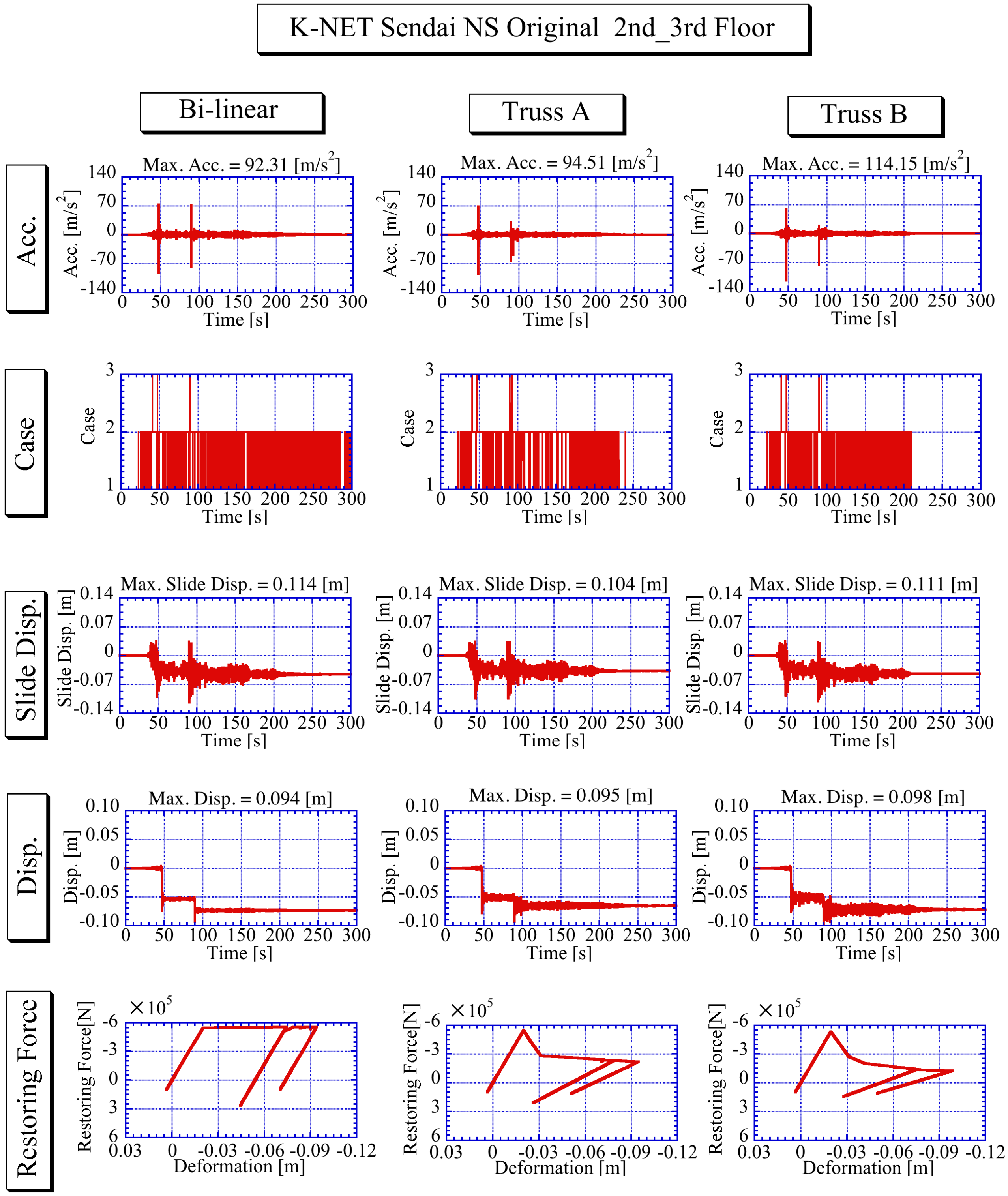



**Figure 8 Earthquake reply analysis result of the escalator between 2nd and 3rd floor**

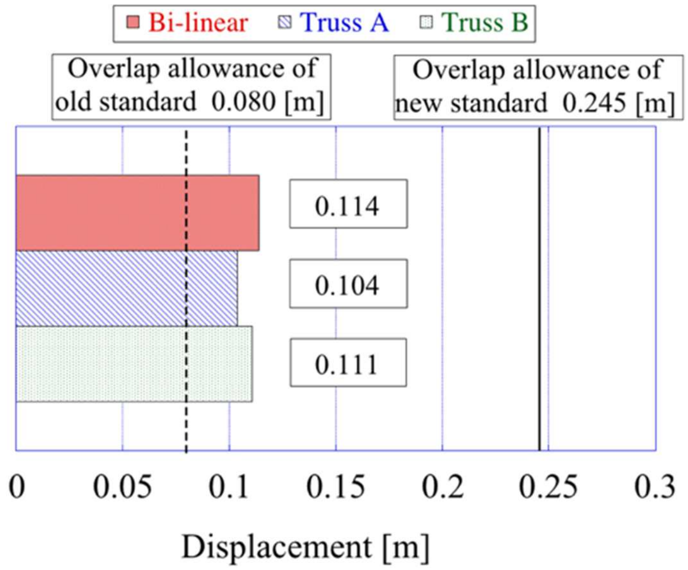



**Figure 9 Maximum response values of slide displacement**

# 5 PRELIMINARY ANALYSIS FOR VIBRATION EXPERIMENT

## 5.1 Vibration experiments

Vibration experiments using 0.3 scale models are planned. In this experiments, it is necessary to clarify the seismic behavior of the escalator including collision phenomenon. Figure 10 shows experimental setup used for vibration experiments. experimental setups is composed of an escalator model and buildings model. This experimental setup shakes only in the horizontal uniaxial direction.

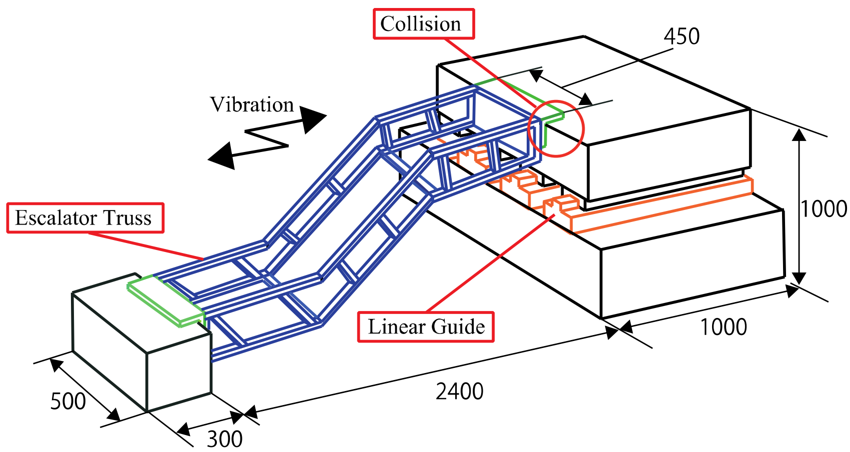



**Figure 10 Schematic of experimental setup**

## 5.2 Coupling analysis

It is the developed analysis model that can confirm the dynamic behavior of an escalator in consideration of interaction with a building. This analysis model is called a coupling analysis model. Target in this study is an escalator that is installed in the beam of building with fixation at the bottom side and non-fixation at the top side. This analytical model is considered that a non-fixed part of an escalator collides with a beam of a building by an earthquake.

### 5.3 Equation of motion in analytical model

Equation of motion of the escalator already indicated (Equation (4), (5), (6)). In addition, equation of motion of the building can be classified into three cases. The three equations of motion are devised, in consideration of influence by the motion of escalator. Equation (7) shows the case that sliding does not occur. Equation (8) shows the case that sliding occurs. Equation (9) shows the case that collision with the construction beams occurs.

Case1 : $$m_s\ddot{x}_s + c_s\dot{x}_s + k_s x_s - \mu_d \frac{1}{2} m_e g \cdot \mathrm{sgn}(\dot{x}_e - \dot{x}_s) = -m_s \ddot{z}_H \tag{7}$$

Case2 : $$m_s\ddot{x}_s + c_s\dot{x}_s + k_s x_s + \frac{1}{2} m_e \ddot{x}_e = -m_s \ddot{z}_H \tag{8}$$

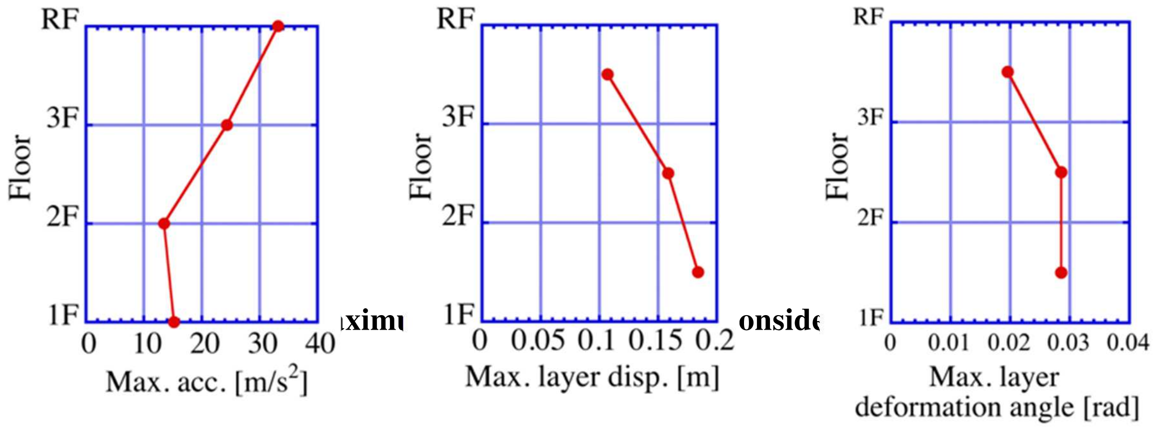
Case3 : $$m_s\ddot{x}_s + c_s\dot{x}_s + k_s x_s - \mu_d \frac{1}{2} m_e g \cdot \mathrm{sgn}(\dot{x}_e - \dot{x}_s) - \left[ k_s \left\{ (x_e - x_s) - Gap \right\} + c_s (\dot{x}_e - \dot{x}_s) \right] = -m_s \ddot{z}_H \tag{9}$$

### 5.4 Analytical model for vibration experiments

It is assumed that the experimental setup of building used in the vibration experiment does not cause plastic deformation. Therefore, the analysis for the vibration experiment is performed assuming that the building is not plastic. Table 4 shows the parameters considering only the 1st stiffness of the three-story steel frame building. In addition, Fig.11 shows result of seismic response analysis of the building. The input seismic wave is similar to that in parameters of Fig.6.
As the result of analysis, when considering that the building is not plasticised, it can be confirmed that the response value of layer displacement is the maximum in the first layer. Therefore, the vibration experiment is performed assuming the escalator installed in the first layer of the building.

**Table 4 Parameter of building considering the 1st stiffness**

| Layer | Mass $m_s$×10$^6$ [kg] | 1st Stiffness $k_{s1}$×10$^9$ [N/m] | Natural period $T_s$ [s] |
|---|---|---|---|
| 3 | 11.21 | 3.48 | 0.744 |
| 2 | 9.2 | 3.68 | |
| 1 | 9.7 | 3.83 | |




## 5.5 Preliminary analysis

In this analysis model of the building, the three mass point model is simplified to one mass point. Figure 12 shows the simplification of the mass point.

Table 5 shows parameters of experimental setup that will be used in vibration experiments. These parameters are the 0.3 scale of the full scale model. Since a linear guide is passed through the friction surface between escalator model and building model, the coefficient of friction is assumed to be 0.005 (ideal value of friction coefficient of linear guide), 0.01 (the accuracy of the linear guide is bad) and 0.8 (0.3 scale of the full scale model).

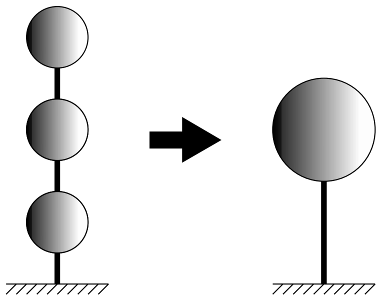


**Figure 12 Simplification of the mass point**

**Table 5 Parameter of 0.3 scale models**

| Escalator | | | | Building | | |
|---|---|---|---|---|---|---|
| Mass | 1st stiffness | 2nd stiffness | Yield disp. | Mass | 1st stiffness | Natural period |
| $m_e$ [kg] | $k_{e1}$ [N/m] | $k_{e2}$ [N/m] | $x_y$ [m] | $m_s$ [kg] | $k_{s1}$ [N/m] | $T_s$ [s] |
| 400 | $6.67\times10^6$ | $-2.40\times10^6$ | 0.0075 | 2000 | $1.59\times10^6$ | 0.223 |

| Gap [m] | Friction coefficient |
|---|---|
| | $\mu_s$ , $\mu_d$ |
| 0.01 | 0.005, 0.01, 0.8 |

### 5.6 Input seismic wave

Figure 13 shows the time history wave and the response spectrum of the input seismic wave. The input seismic wave is assumed as a wave that is used in the vibration experiment and it is scaled by the similarity law. In this paper, 0.3 scale of the K-NET Sendai NS Original 0.25 [m/s] was used.

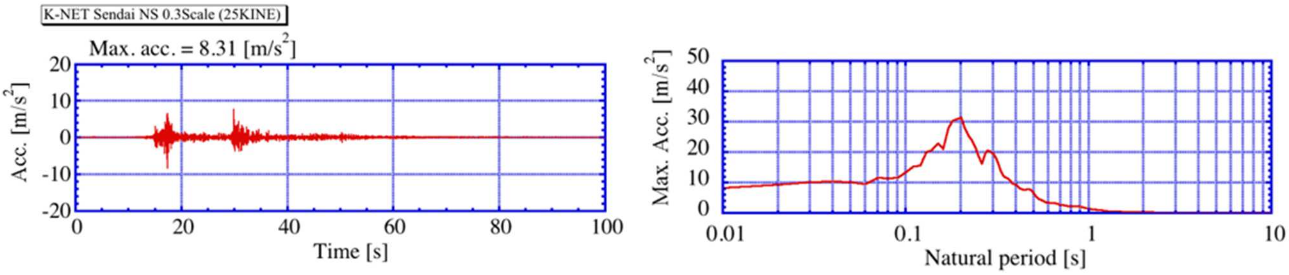



**Figure 13 Time history wave and response spectrum**

### 5.7 Results of seismic response analysis

Figure 14 shows results of seismic response analysis. In Fig.14 the numerical value (0.005, 0.01, 0.8) at the upper part of figure shows the friction coefficient. As shown in restoring force of escalator, plastic deformation and residual displacement are remained slightly. By comparing the analysis results for each friction coefficient, it can be confirmed that slide displacement and deformation of the escalator other than at the time of collision are suppressed as the friction coefficient increases. In addition, this analytical results of the building are confirmed that the behavior of building changes by friction coefficient.

Figure 15 shows the maximum response values of slide displacement. In Fig.15 the numerical value (0.005, 0.01, 0.8) at the upper part of figure shows the friction coefficient. In addition, parameters of overlap allowance are the 0.3 scale of the full scale model. In the case of the old standard, the maximum response values of the slide displacement of the escalator is higher than the value of overlap allowance, therefore the possibility of falling is high. In the case of the new standard, the maximum response values of the slide displacement of the escalator is below the value of overlap allowance, therefore the possibility of falling is low.

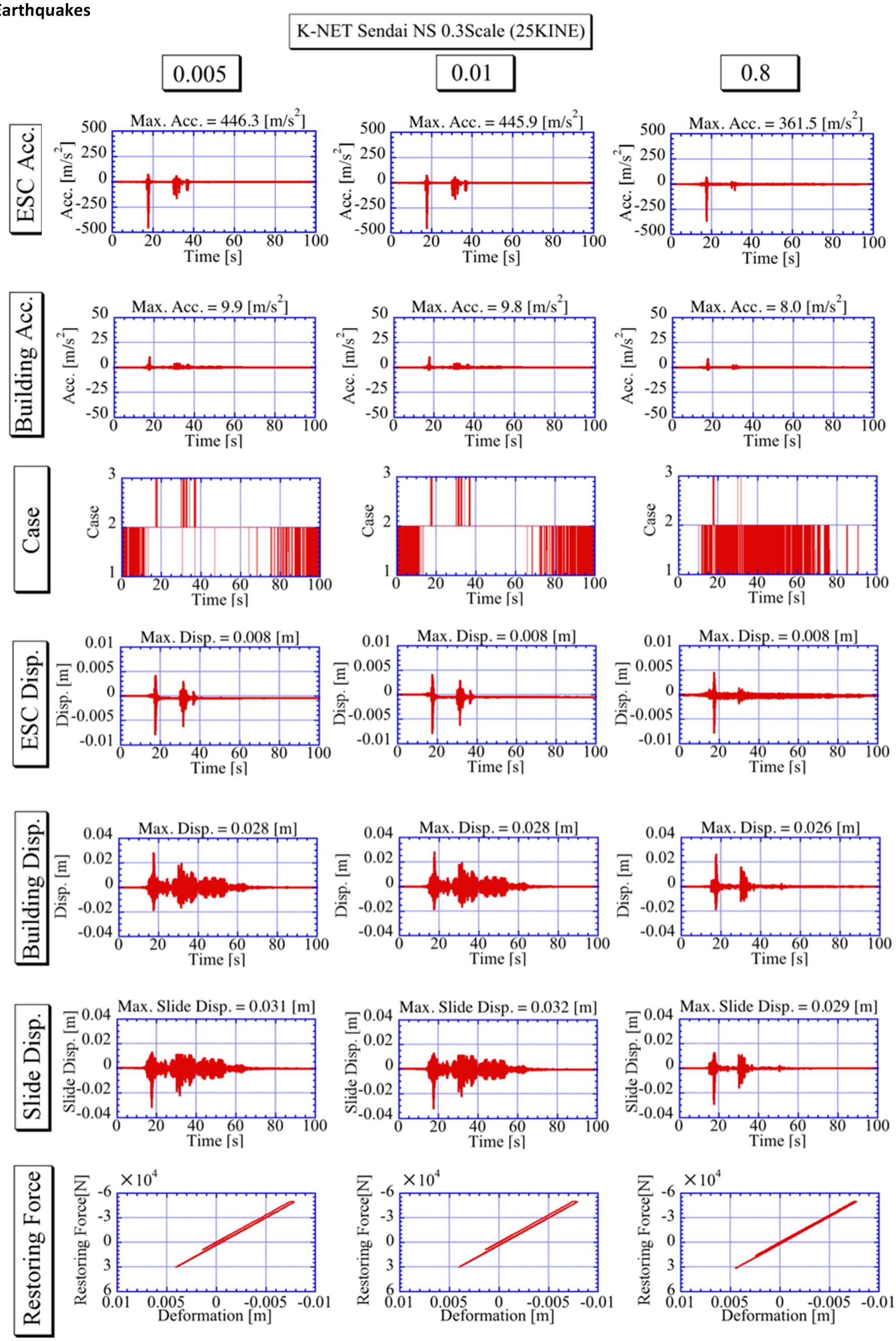



**Figure 14 Seismic reply analysis result**

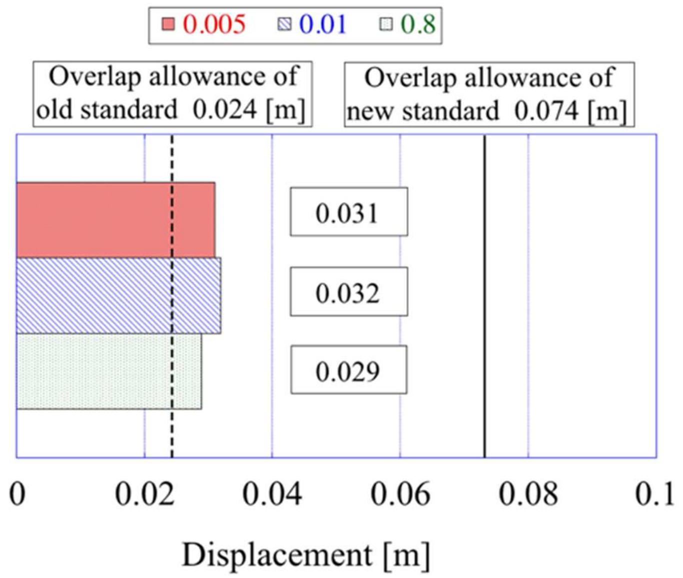



**Figure 15 Maximum response values of slide displacement**

## 6 CONCLUSION

In this study, a model of the escalator that considered the slide friction and the collision of an escalator and the building beams has been developed and analyzed. As the result of analysis, there was not the big difference with multi-linear model and the bi-liner model. Therefore, it is assumed that bi-linear model in consideration of material properties can express simply in behavior at the earthquake of the escalator. In addition, assumed the behavior of the escalator against the Great East Japan Earthquake. As the result, it was confirmed that the escalator to which the new quake resistance standard was applied was safe.

In this study, a model of the escalator that can be confirmed the dynamic behavior of an escalator in consideration of interaction with a building has been developed and analyzed. This analysis model is considered to be effective in examining the results of vibration experiments.

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## BIOGRAPHICAL DETAILS

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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.