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Action difficulty evaluation for high-rise buildings based on questionnaire and strong-motion records

SUZUKI Nina[1,a *], HATADA Tomohiko[2,b], HIDA Takenori[3,c], LIU Hong[1,d], NAGANO Masayuki[1,e]

[1] Tokyo University of Science, Noda-shi, Chiba, Japan

[2] Kajima Technical Research Institute, Kajima Corporation., Chofu-shi, Tokyo, Japan

[3] Ibaraki University, Hitachi-shi, Ibaraki, Japan

[a]7118072@alumni.tus.ac.jp, [b]hatada@kajima.com, [c]takenori.hida.mn75@vc.ibaraki.ac.jp
[d]liu_hong@rs.tus.ac.jp, [e]nagano-m@rs.tus.ac.jp

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Abstract. The present study describes the evaluation of feelings of difficulty faced by residents in performing actions during earthquakes (hereinafter, action difficulty) based on questionnaire surveys and strong-motion records for high-rise RC residential buildings having over 20 stories with seismic dampers or seismic isolation devices applied. In the recent structural design of buildings, both ensuring structural safety, such as the preservation of human lives during earthquakes, and evaluating the security of people in the buildings from the viewpoint of resilience, such as their continuous functionality and reduction of anxiety, are necessary. In the present study, focusing on the degree of the action difficulty, we propose a new evaluation formula based on the results of questionnaire surveys during earthquakes to evaluate the security of people in buildings. First, we analyze past questionnaire survey results in detail for the residents of high-rise residential buildings and show that the action difficulty is greatly reduced in seismically isolated buildings, as compared to earthquake-resistant buildings. On the other hand, for seismic response controlled buildings with steel dampers, no significant effect is determined in terms of action difficulty based on questionnaire surveys after massive earthquakes. Second, based on the relationship between the strong-motion records and the results of questionnaire surveys for the residents of high-rise buildings for the 2011 off the Pacific coast of Tohoku earthquake, we propose a new evaluation index to evaluate the security of people in the buildings and develop an evaluation formula for action difficulty. Third, we construct three-dimensional frame models with seismic dampers or seismic isolation devices in an existing high-rise RC residential building and evaluate the action difficulty for residents on each floor based on the proposed formula. Finally, we evaluate action difficulty during a medium-scale earthquake. The results indicate that the application of oil dampers and seismic isolation devices contributes to improving the security of people in buildings.

Introduction

In Japan, there are more than 1,400 high-rise residential buildings with more than 20 stories, which have been constructed since the 1970s. Most of these buildings are moment-resisting reinforced concrete (RC) structures, and buildings built in the early years were earthquake-resistant. An increasing number of buildings have been fitted with seismic dampers or seismic isolation devices in recent years. Such devices are effective in reducing shaking and improving the comfort and security of building residents. In the current social situation, there is a need to evaluate not only structural safety, such as the preservation of human lives, but also resilience, such as fear relief of residents and continuous usability of buildings after a disaster [1].

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Several evaluation methods that focus on security, such as indoor damage, have been proposed. However, there are few studies focusing on resilience evaluation, for example, by determining the effects of seismic dampers or seismic isolation devices from the viewpoint of security. The authors proposed an evaluation formula for the anxiety that occurs during earthquakes and the difficulty faced by residents in performing actions during earthquakes (hereinafter, action difficulty) based on the results of questionnaire surveys following the 2011 off the Pacific coast of Tohoku Earthquake (hereinafter referred to as the 3.11 earthquake) [2]. However, it has been considered necessary to take countermeasures against large-scale earthquakes, as well as medium-scale earthquakes that occur once every several years from the viewpoint of security.

Therefore, the present study places emphasis on action difficulty to evaluate the security of people in buildings. First, we analyze the results of questionnaire surveys focusing on the application of seismic dampers or seismic isolation devices. Then, based on the relationship between the strong-motion records and the questionnaire surveys, we propose an evaluation formula for action difficulty based on a new evaluation index. Next, we construct a three-dimensional frame model of an existing high-rise RC residential building with seismic dampers or seismic isolation devices and conduct a seismic response analysis to compare the accuracy of the results obtained using the evaluation formula and those of the questionnaire surveys. Furthermore, we analyze the effect of reducing action difficulty when seismic dampers or seismic isolation devices are applied.

Indoor damage based on questionnaire surveys

Outline of questionnaire surveys

In a previous study [3], based on the different structural forms of high-rise residential buildings located in the same area (Kanagawa Prefecture, Japan), the results of questionnaire surveys on indoor damages at the time of the 3.11 earthquake were compared between earthquake-resistant, seismic response controlled, and seismically isolated buildings. The survey items and evaluation values for action difficulty are categorized in Table 1.

In this study, we focused on the questionnaire survey results for two different types of earthquakes, the 3.11 earthquake, which was a trench-type earthquake, and the 2016 Kumamoto earthquake, which was an inland earthquake. An overview of the surveyed buildings is listed in Table 2. All of the buildings are moment-resisting reinforced concrete (RC) structures, except for Building U, which is a steel-reinforced concrete (SRC) structure. Although the number of questionnaire responses for some buildings is not large, it is the only information available in the absence of strong-motion records.

Table 1 Survey items and evaluation values

Action difficulty	Value
Tossed by shaking due to earthquake, could not do anything	4
Unable to stand	3
Difficulty in walking or moving	2
Obvious feeling of shaking, no difficulty in doing anything	1
Slight shaking, no difficulty in doing anything	0

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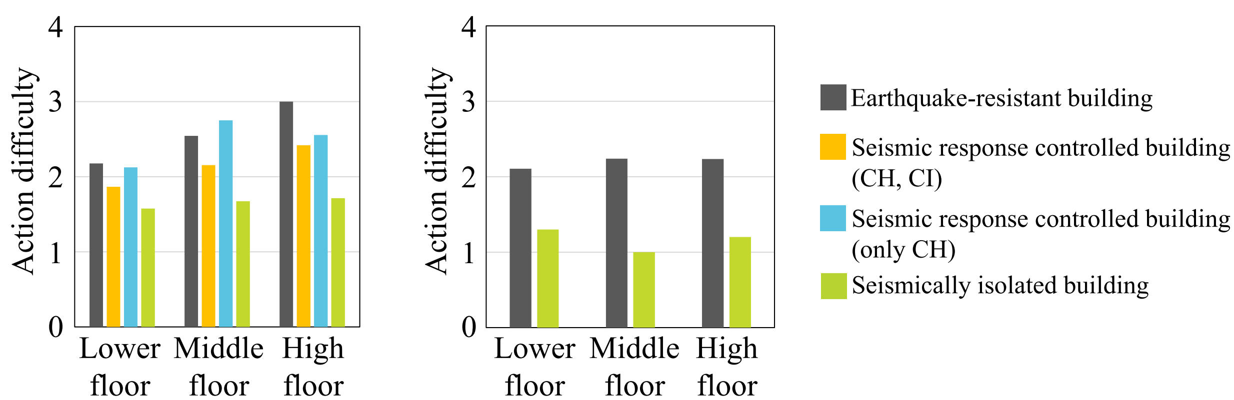
Table 2 Outline of target buildings ( ): number of people in rooms

Earthquake	Building code	Completion date	Number of floors	Number of answers	Structure	
3.11 (2011)	T	2004	35	51(22)	Earthquake-resistant building	
	U	2007	40	66(23)	Earthquake-resistant building	
	CH	2008	34	66(25)	Seismic response controlled	Low-yield-point steel damper
	CI	2007	41	85(35)		Core wall
	DA	2006	30	258(101)	Seismically isolated building	
	DB	2007	30	144(53)	Seismically isolated building	
Kumamoto (2016)	ED	2012	19	63(58)	Earthquake-resistant building	
	EE	2010	35	27(27)	Seismically isolated building	

Action difficulty analysis

Figure 1 shows the average action difficulty for different structural forms based on the questionnaire surveys. Regardless of the residential floor, the action difficulty was the largest in earthquake-resistant buildings, followed by seismic response controlled buildings and seismically isolated buildings. In particular, seismically isolated buildings show a significant reduction in the degree of action difficulty compared to earthquake-resistant buildings. Therefore, seismically isolated buildings appear to be effective in reducing action difficulty for both trench-type and inland earthquakes. The seismic response controlled buildings (CH and CI) also exhibited smaller action difficulty compared to earthquake-resistant buildings. However, due to the CI being a special structural type with core walls [4] equipped with oil dampers at the top, its effect on period elongation should be taken into account. Moreover, the perception of shaking is affected by the frequency component, and the probability of perception tends to be reduced with decreasing frequency [5]. It can be assumed that the residents have fewer action difficulties in building CI at low frequency. Therefore, it is difficult to take the core-wall-type building CI as a targeted seismic response controlled building to verify the response reduction by additional damping, so CI will not be taken into further consideration, and only building CH with low-yield-point steel dampers will be used for comparison. In the case of building CH, the action difficulty is not much different from that of the earthquake-resistant buildings. Therefore, steel dampers are not expected to have a significant effect for earthquakes of intensity 5 or higher from the viewpoint of reducing action difficulty.



(a) 3.11 earthquake (b) Kumamoto earthquake

Figure 1 Action difficulty based on questionnaire survey.

Evaluation formula for action difficulty

In previous studies [2,6,7], based on questionnaire surveys results (the residents of 14 high-rise buildings) and strong-motion records for the 3.11 earthquake, formulas were proposed to evaluate the relationship between the maximum absolute acceleration and maximum absolute velocity of the floor response and the action difficulty, R_D. However, in order to evaluate the security of people in the buildings, it is necessary to determine not only the maximum response but also the entire time history waveform. Therefore, based on the same strong-motion records and questionnaire surveys, we propose new evaluation formulas with the square root of the sum of the squares for the entire duration of floor responses as an index (hereinafter referred to as accumulation value). The accumulation value a_r is calculated as the sum of the squares of the two horizontal components x_i and y_i at each step multiplied by the time step Δt, as follows:

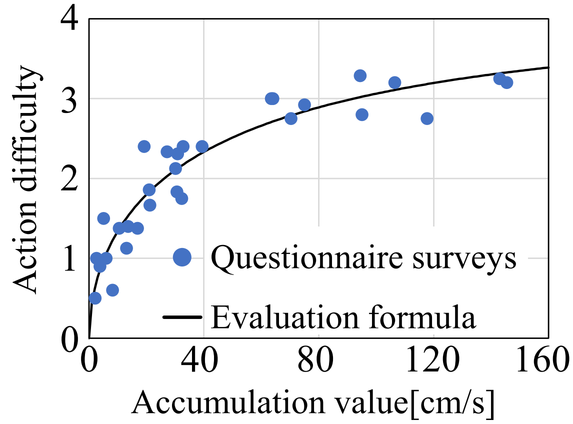


Figure 2 Relationship between accumulation value and action difficulty.

$$a_r = \Delta t \sqrt{\sum (x_i^2 + y_i^2)} . \quad (1)$$

Questionnaire surveys were conducted for five consecutive floors near the floor where the strong-motion seismographs were installed, and the average action difficulty was used for the lower floor, medium floor, and high floor. Data with fewer than three questionnaire responses were excluded because of their large variability, and only data with four or more responses were used. The relationship between a_r and R_D is approximated based on the Weibull distribution, as follows:

$$R_D(a_r) = 4\left\{1 - \exp\left[-\left(\frac{a_r}{51.0}\right)^{0.552}\right]\right\} . \quad (2)$$

The relationship between the accumulation value and the action difficulty is shown in Figure 2, and the approximate equations correspond well to the results of the questionnaire surveys.

Action difficulty evaluation from structural response analyses

Although strong-motion records are available for some questionnaire-targeted earthquake-resistant buildings at the time of the 3.11 earthquake, there are few records for seismic response controlled and seismically isolated buildings. We constructed hypothetical building models with additional seismic dampers or seismic isolation devices based on an existing earthquake-resistant RC residential building in Tokyo, and evaluated the action difficulty dependence on the type of building from the seismic response analysis.

Outline of target building and construction of earthquake-resistant building model

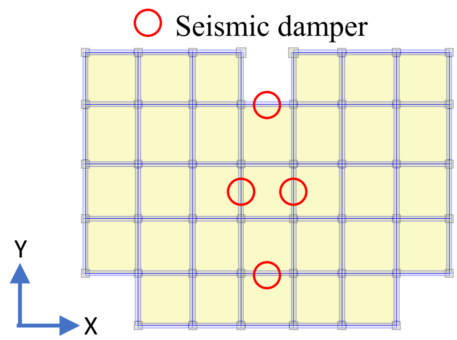
The building used in the present study is a 38-story moment-resisting RC frame structure constructed in 2000. The building is located in Tokyo and suffered from the October 7, 2021 (Mj 6.1) earthquake in the northwestern part of Chiba Prefecture with a seismic intensity of 5 or higher on the Japanese scale.

We constructed a three-dimensional frame model (hereinafter referred to as the earthquake-resistant building model) based on the design documents. Beams were modeled using bending-shear elements with nonlinear flexural springs at both ends. The flexural and axial behavior of the columns was represented by multi-spring models, with nonlinear multi-spring elements for concrete and steel at the column ends connected with axial and bending-shear elements. The hysteresis characteristics of the beams and columns were modeled using the Takeda model [8]. The model was fixed at the base, and each layer was assumed to have a rigid floor. The damping of the building was assumed to be of the internal viscous type, and the damping constant was assumed to be proportional to the instantaneous stiffness of 1% of the first-order natural period [9].

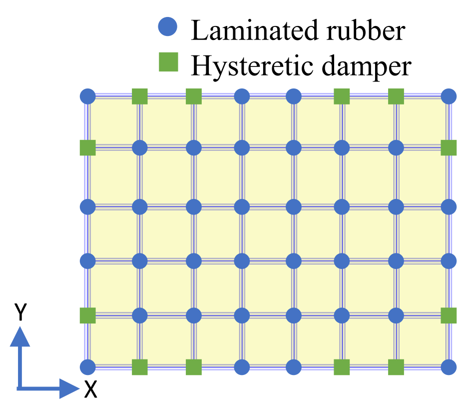
Seismic response controlled building models

The seismic response controlled building models shown in Figs. 3(a) and 4 were constructed with additional application of seismic dampers to the original earthquake-resistant building model. A total of 152 dampers are installed in all layers, two in the *x* and *y* directions for each layer. As seismic response controlled devices, steel dampers or oil dampers are used.

The steel damper with stud and gusset plates was modeled by bending shear elements with trilinear hysteretic systems. The additional stiffness of the steel dampers was set to be approximately 10% of the initial shear stiffness of the original building model. The oil dampers were modeled as a Maxwell-type model with a relief load mechanism at the dashpot, and the model was connected to the end of the truss element replacing the brace at the corresponding position in the 3-D frame model.

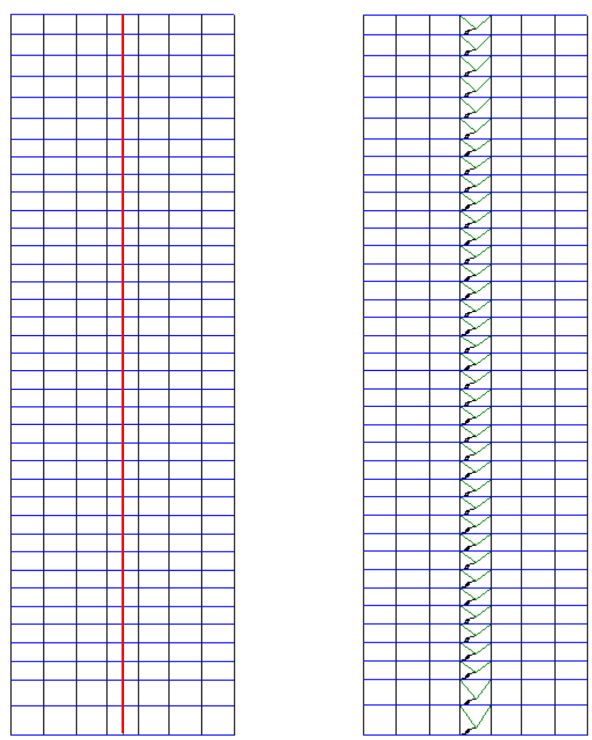


(a) Typical floor plan
(Seismic response controlled building)



(b) Arrangement of isolation devices

Figure 3 Floor plans.



(a) Steel dampers (b) Oil dampers

Figure 4 Damper location in elevation.

Seismically isolated building model

Referring to a previous study [10], we constructed a seismically isolated building model with an additional 36 laminated rubber and 12 hysteretic dampers placed in the lower part of the first floor of the earthquake-resistant building model. The locations of the seismic isolation devices are shown in Figure 3(b). The MSS model was used to model the seismic isolators. In the present study, it was assumed that there was no restriction on the clearance of the seismically isolated layer, and retaining wall collision was not taken into consideration.

Action difficulty evaluation for four types of buildings

Input seismic waves

Action difficulty was evaluated for four types of buildings, i.e., the earthquake-resistant building, two types of seismic response controlled buildings, and the seismically isolated building, for several input seismic waves. First, seismic responses were calculated using the constructed building models. The input seismic waves were the 3.11 earthquake, the Kumamoto earthquake, and the October 7, 2021 medium-scale earthquake in the northwestern part of Chiba Prefecture. For the 3.11 earthquake, the observed seismic wave from K-NET KNG001 (Kawasaki, Kanagawa), which is located in the same area as the target buildings for the questionnaire surveys on the 3.11 earthquake, was used. For the Kumamoto earthquake, the input seismic wave was from K-NET FKO011 (Kurume, Fukuoka), which is located in the same area as the target building for the questionnaire surveys on the main shock of the Kumamoto earthquake. As a medium-scale earthquake including pulse characteristics, we used records taken in October 7, 2021 at K-NET TKY015 (Higashi Shirahige, Tokyo), which is closest to the target building.

The pseudo-velocity response spectra in Figure 5 indicate that the predominant periods vary depending on the type of earthquake. The action difficulty is estimated based on the calculated floor responses using the evaluation formula. These results are compared with the results for the questionnaire surveys after the 3.11 earthquake and the Kumamoto earthquake described in Section 2.

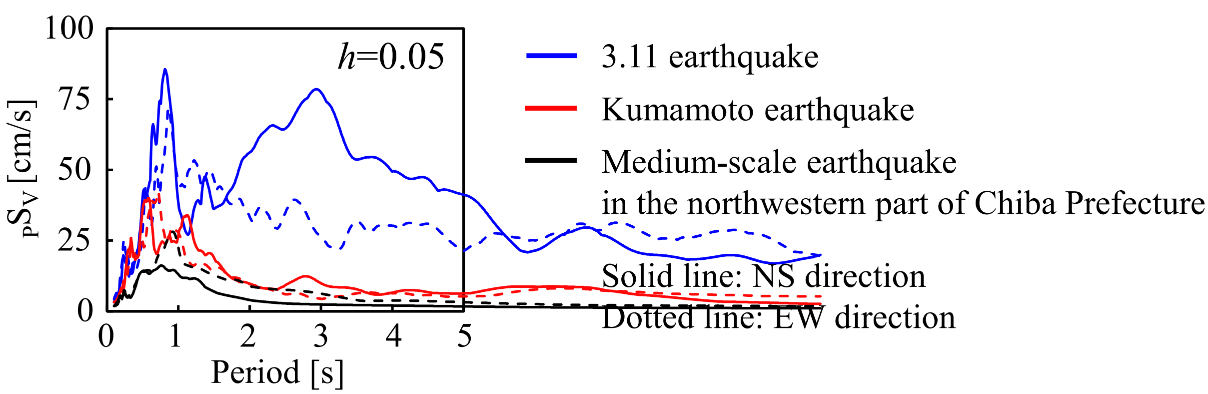


Figure 5 Pseudo-velocity response spectra of input seismic waves.

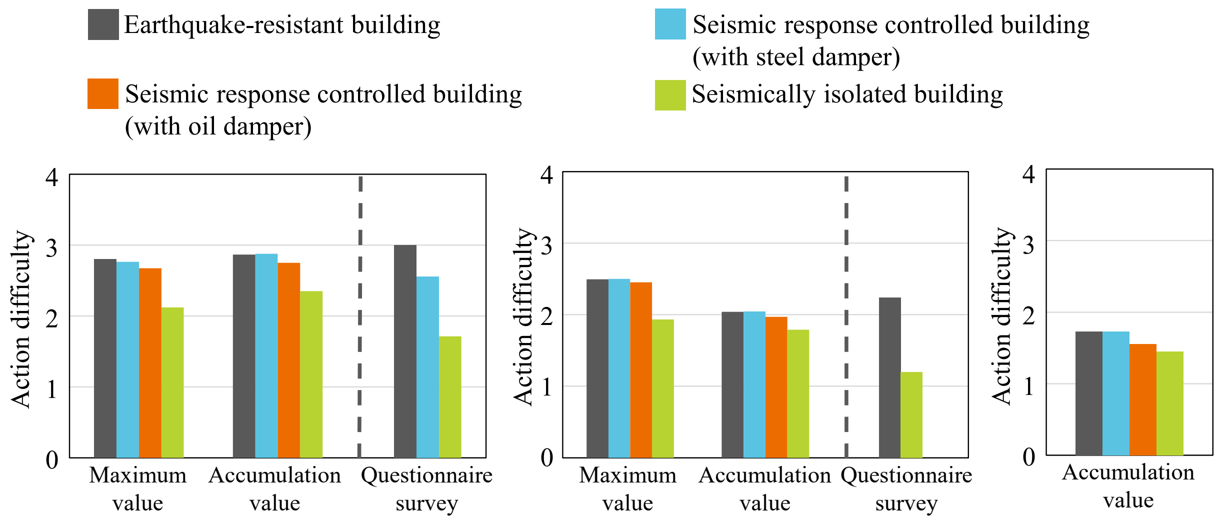
Action difficulty evaluation

Figure 6 compares action difficulty for four types of buildings by applying the response analysis results to the evaluation formula. We evaluated averaged scalar values for the upper 1/3 of floors, corresponding to the high floors, for each event.

In general, action difficulty decreases in the order of earthquake-resistant building and seismic response controlled building with steel dampers, seismic response controlled building with oil dampers, and seismically isolated building.

The results for action difficulty based on the evaluation formula are larger for the 3.11 main earthquake than for the Kumamoto earthquake, which is similar to the results for the questionnaire surveys, indicating that the evaluation formula is applicable to trench-type earthquakes as well as inland earthquakes.

Oil dampers and seismic isolation devices reduce action difficulty not only during large earthquakes but also during medium-scale earthquakes, and play an important role in improving the resilience of buildings.



(a) 3.11 (b) Kumamoto (c) Medium-scale

Figure 6 Action difficulty evaluation for four types of building.

Summary

In the present study, in addition to the safety of the building, we evaluated its security by focusing on action difficulty and attempted to provide a basic discussion on the improvement of resilience with additional seismic dampers and seismic isolation devices. The following is a summary of our findings.

1) The results of the questionnaire surveys showed that action difficulty was larger in earthquake-resistant buildings and seismic response controlled buildings with steel dampers than in seismically isolated buildings. The application of steel dampers is less effective at reducing response, even for large earthquakes, and in improving security.

2) An evaluation formula for action difficulty was developed using the accumulation value of floor response acceleration, and its consistency with strong-motion records was confirmed.

3) A seismic response analysis was conducted for earthquake-resistant, seismic response controlled, and seismically isolated building models, and the results of questionnaire surveys on the 3.11 and Kumamoto earthquakes were compared with the results of the evaluation formula for action difficulty. Reasonably good agreement was found.

4) We showed that the application of oil dampers or seismic isolation devices to earthquake-resistant buildings can reduce action difficulty even for medium-scale earthquakes. Therefore, buildings with these devices can be effective in terms of structural safety as well as security (resilience).

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