16TH EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING
THESSALONIKI 18 - 21 JUNE 2018

EFFECTIVENESS OF THE FAULT-ZONING ACT ON THE 2016 KUMAMOTO EARTHQUAKE

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ABSTRACT

The present study examines the effectiveness of land-use regulations for preventing damage from disasters, using the Kumamoto Earthquake as its subject. Focusing on the Futagawa–Hinagu fault zone, that moved during the Kumamoto Earthquake, we ran a damage simulation that applied land-use regulations (construction regulations) to nearby urban areas. Thereafter, we measured and evaluated both physical and economic damage before and after the land-use regulations were applied to observe any difference in damage between the two.
We found that by instituting land-use regulations in the zone surrounding the active fault, the damage could have been significantly reduced in areas that experienced JMA SI 7 (Japanese seismic-intensity scale) tremors during the Kumamoto Earthquake; however, only 0.3% of the buildings were in these areas. In the areas with the most damage, the land-use regulations could have reduced the damage by 8.9%.
It is highly possible that directly applying foreign land-use regulations to the Japanese situation will not provide sufficient benefits to offset the economic loss incurred during normal times because of these regulations. Thus, to be effective, disaster-prevention-oriented land-use regulations in Japan must be adapted to the specific conditions relating to earthquake damage sustained in Japan.

Keywords: Seismic risk; active fault; land-use regulation; Kumamoto earthquake; damage prediction

1.INTRODUCTION

The region surrounding Japan is formed atop a complex stress field where multiple tectonic plates converge, making it especially prone to earthquakes. In the past, much loss of life and property has occurred during severe seismic events, particularly those striking urban areas, e.g., the 1995 Kobe Earthquake (Mw6.9) and the 2016 Kumamoto Earthquake (Mw7.1).
In the Kumamoto earthquake, the damage statistics, which show the extent of the catastrophe, are as follows: 255 deaths, 2,795 injuries, and 217,211 destroyed houses (Kumamoto Prefectural Report 2016, Cabinet Office Report 2016). Damage to production facilities and social infrastructure also damaged the living base and infrastructure of local residents in the disaster area. In the Cabinet Office’s analysis of the impact on the economy, the estimated damage in the Kumamoto Prefecture and Oita Prefecture is approximately ¥2.4 to 4.6 trillion. The total stock of social capital, housing, private enterprise facilities, etc. in the Kumamoto and Oita Prefectures is estimated to be approximately ¥63 trillion. Thus, approximately 3.8 to 7.3% of stock was damaged by the earthquake.
In addition, Kumamoto Prefecture suffered damage from the Futagawa–Hinagu fault zone, which slid in the Kumamoto earthquake. However, countermeasures against this damage mainly focused on soft countermeasures, e.g., early warning and evacuation arrangements and providing everyday goods. It was not possible to regulate the land use around the fault or the seismic performance of the buildings. Further, active risk control could not be done.
According to the Headquarters for Earthquake Research Promotion, there is a 96.5% chance that one of the main faults in Japan will cause another major earthquake within the next 30 years. While the

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likelihood that any particular active fault will cause a severe quake is low, the possibility that one of them will move—and what should be done in response—must be seriously considered in advance. Further, in recent years, although the protection of human life has, of course, remained a top priority, the prevention of property loss and the promotion of speedy economic recovery have also become increasingly emphasized. Local governments and municipalities have turned their attention to swiftly enabling the affected citizens to return to normal daily life. Accordingly, damage prevention and reduction have become more substantial responsibilities.

Generally, efforts to prevent and reduce damage fall into two categories: risk control and risk finance. The Act for the Promotion of Earthquake-Proof Retrofitting of Buildings, which emphasizes the improvement of buildings' earthquake resistance and enhances their ability to maintain business continuity, is an example of risk control. The Act Concerning Support for Reconstructing the Livelihood of Disaster Victims and acquiring earthquake insurance are examples of risk finance. Risk control and risk finance function as the two wheels on a car axle—one cannot rely on only one kind of policy or the other; a proper balance must be struck between the two. This is particularly true when dealing with the risks presented by major disasters, e.g., earthquakes. Responses focused solely on finance are insufficient; risk control must be implemented first.

The active fault laws put in place in New Zealand and in the U.S. state of California are instructive examples of proactive risk-control efforts. These laws take the form of land-use regulations related to the importance of buildings and the level of danger involved in the areas surrounding active faults. Although Japan has similar regulations, e.g., in the Tokushima Prefecture, these regulations have not been established as laws. The Headquarters for Earthquake Research Promotion has been proactively promoting the information and results from studies conducted on the main faults; however, it cannot clearly express that this information has been actively applied to the administration of these areas. Against this background, land-use regulations have been considered significant obstructions to economic development, and their effectiveness is insufficiently clear. Accordingly, land-use regulations with the aim of risk control evidently require further examination and debate.

The present study aims to advance this examination of risk-control-oriented land-use regulations by measuring and evaluating the effectiveness of these types of laws. Focusing on the Futagawa-Hinagu fault zone, which moved during the Kumamoto Earthquake, we ran a damage simulation that applied land-use regulations to nearby urban areas. The physical and economic damage before and after the application of these land-use regulations were measured and evaluated to determine the extent of the difference between the two. By ascertaining the possible amount of damage that could be reduced through the application of land-use regulations, a proper debate on the effectiveness of land-use regulations for the prevention of earthquake damage can be conducted.

2. LAND-USE REGULATION VIA ACTIVE FAULT LAWS

2.1. Cases in Other Countries

Earthquakes caused by active inland faults sometimes occur near urban areas and can cause extremely high levels of damage. In the state of California, U.S.A., and in New Zealand, efforts have been made to mitigate earthquake damage by using land-use regulations in areas surrounding active faults. The efforts made to regulate land use in California and New Zealand (Nakata 1990, Nakata and Kumamoto 2003, Banba 2003, Meguro and Ohara 2008, etc.) are introduced in this section.

In California, the major damage caused by the large shift of a surface fault during the 1971 San Fernando Earthquake led to the passing of the Alquist-Priolo Earthquake Fault Zoning Act of 1972, which regulates construction in the area around an active fault. Every municipality established building regulations governing new construction and large-scale renovation activities within the fault zone. The fault zone extended from both sides of the surface trace of the fault at a width of approximately 0.4 km (0.2 km on each side).

The building regulations, meant for residential buildings, exempted from their purview detached housing with wooden or steel frames consisting of less than two stories or four doors. Further, if research revealed the presence of new active faults, the buildings must be set back 15 m from the fault. Buildings constructed before 1972 were designated as non-conforming, but they were allowed to remain in place as long as major renovations were not conducted.

This law addressed the seismic risk posed by deformations of the ground stemming from fault displacement. However, it did not address other risks posed by earthquakes, e.g., vibration, liquefaction, post-earthquake fires, and landslides. These hazards were supposed to be otherwise specified in the 1990 Seismic Hazards Mapping Act but were substantially addressed through the observance of the 2001 California Building Standards Law.

In 2004, New Zealand established the "Planning for Development of Land On or Close to an Active Fault" guidelines for the planned development of land near active faults. Similar to the California law, these land-use regulations are guidelines, not laws, which make them a special case. These regulations governing construction in fault zones are set up for flexibility; i.e., they consider the specifics of the fault in question (recurrence interval, complexity, etc.) and the use of the building (its level of importance). Further, every municipality can either strengthen or relax the administration and standards according to the situation and specifics of the region.

As an example of how these guidelines work, consider their application in the city of Wellington and Kapiti Coast County. In Wellington, a fault zone is designated as 20 m on either side of an active fault; within this zone, basically, only detached housing is permitted to be built. Moreover, similar to the California law, these guidelines only address damage arising from deformation of the ground stemming from fault displacement, and do not address other causes of earthquake damage, e.g., vibration, liquefaction, post-earthquake fires, and landslides.

2.2. Establishment of Land-Use Regulations in Japan

As was shown in Section 2.1, the land-use regulations established in California and New Zealand were primarily aimed at minimizing earthquake damage stemming from ground deformation caused by fault displacement. The active faults in California and New Zealand are strike-slip faults, which largely slide horizontally, making the fault-displacement direction simple to ascertain. Accordingly, a very small distance from the fault can be designated as the area to avoid. In Japan, however, the stress field within the crust is very complex, and displacement can be caused by different kinds of faults, including normal, reverse, and strike-slip faults. Further, considering past examples of earthquake damage sustained in Japan, more damage resulted from vibrations than ground deformations caused by fault displacement. In order to prevent damage from vibrations, it is necessary to take many distances from the active fault.

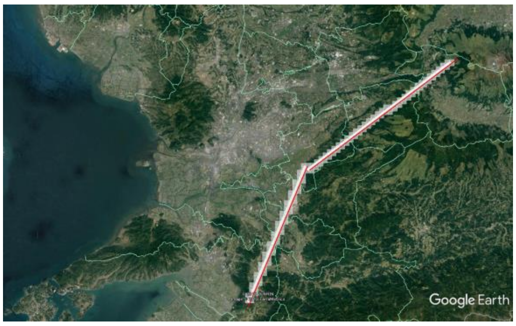
The present study ran a damage simulation on the Futagawa section of the Futagawa fault zone and the Takano–Shirahata section of the Hinagu fault zone, which underwent displacements during the Kumamoto Earthquake, and applied land-use regulations and building codes for earthquake-resistant construction to these areas. In addition, to guide the parameters for the faults' geometry, the Seismic Hazard Maps (2014) were used. The analytical cases established in the present investigation are listed in Table 1.

In Cases 1-1 through 1-4, a regulated area was designated at a set distance on both sides of the fault, as was done in California and New Zealand. The fault zones designated for each case are shown in Figure 1. As indicated in the figure, the width of the fault zones for Cases 1-1 through 1-4 were gradually increased—starting at 0.4, then 0.8, 2.0, and finally, 4.0 km. As a reference, the designated fault-zone width was 0.4 km, similar to that used in California. All types of construction were forbidden within the designated fault zones in the simulation.

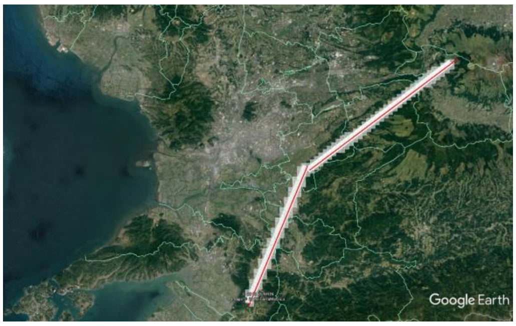
In Cases 2-1 through 2-2, the areas that would be affected when the predicted Japan Meteorological Agency Seismic Intensity (referred to as JMA SI) of the fault exceeded set levels were identified. In this regard, the JMA SI values shown on the seismic hazard maps were used in the simulation. The fault zones designated in each case are shown in Figure 2. As shown in this figure, the magnitude for Case 2-1 was over 7, whereas in Case 2-2, the magnitude was 6. Accordingly, the affected areas in Cases 2-1 and 2-2 were increased. Within the designated fault areas, the earthquake performance of a building was designed according to more recent standards for earthquake-resistant structures.

Table 1. Analytical cases for damage simulation.

Case	Regulation Overview	Regulated Area (Fault-Zone Width)	Area Subject to Regulation
Case 1-1	Construction Forbidden	0.4 km	48.25 km^2
Case 1-2		0.8 km	64.25 km^2
Case 1-3		2.0 km	110.25 km^2
Case 1-4		4.0 km	193.75 km^2
Case 2-1	Building Performance Set According to New Earthquake-Resistance Standards	Estimated for JMA SI: 7	12.25 km^2
Case 2-2		Estimated for JMA SI: Upper 6	319.25 km^2



(a) Case 1-1: Width 0.4 km (0.2 km each side)



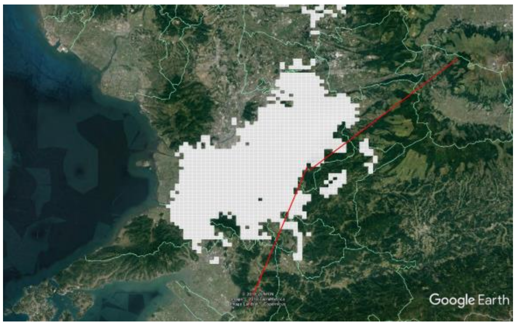
(b) Case 1-2: Width 0.8 km (0.4 km each side)

(c) Case 1-3: Width 2.0 km (1.0 km each side)

(d) Case 1-4: Width 4.0 km (2.0 km each side)

Figure 1. Land-use regulation zones (construction forbidden)

(a) Case 2-1: Estimated JMA SI: 7



(b) Case 2-2: Estimated JMA SI: Upper 6

Figure 2. Land-use regulation zones (regulating earthquake performance)

3. OVERVIEW OF THE DAMAGE SIMULATION

3.1. Establishing the Exposure

"Exposure" is defined as the number of households and buildings vulnerable to earthquake hazards. The exposure figures used in the present study are based on official sources, e.g., the mesh-block datasets from the Population Census (2010), the Housing and Land Survey (2013). Accordingly, the number of buildings from the fixed-asset-value working-paper overviews, the age of the buildings from the Housing and Land Survey (2013), and the number of households from the Population Census (2010) were derived.

The households and buildings in Kumamoto Prefecture were used as the subjects. Moreover, because the mesh-block datasets from the Population Census (2010) were calculated at a mesh of 500 m for all of Japan, the resolution of the present study was set at the same value, condensing the exposure to a mesh of 500 m for analysis. Buildings listed on the working-paper fixed-asset overviews as private housing, shared housing, boarding houses, combined residential and farming houses, storehouses, and attached structures were defined as "residences."

3.2. Establishing the Hazards

The distribution of the strong earth motion during the Kumamoto Earthquake was determined using data from the Quick Estimation System for Earthquake Maps Triggered by Observation Records made available by the National Institute of Advanced Industrial Science and Technology.

During the Kumamoto Earthquake, both a foreshock and the main quake occurred. By comparing the intensity of the foreshock to the main quake, it became clear that the strong motion intensity of the foreshock was encompassed by that of the main quake. Therefore, data from the main quake were used in the investigation. The distribution of strong ground motion during the main Kumamoto Earthquake is shown in Figure 3.

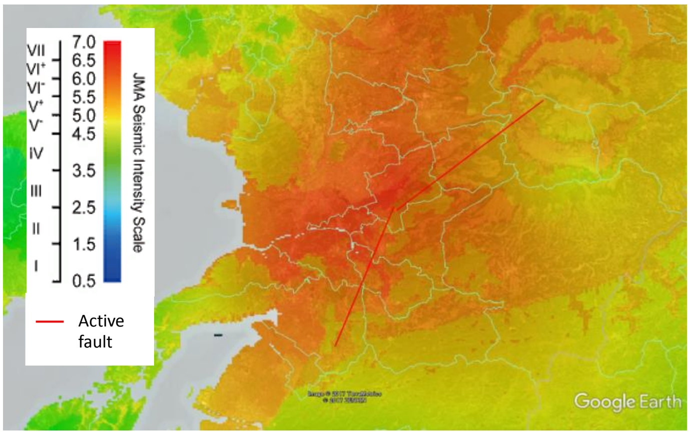


Figure 3. Strong ground-motion distribution during the Kumamoto Earthquake

3.3. Methods for Damage Assessment

3.3.1. Estimating the Earthquake Damage

Various methods for estimating earthquake damage to buildings have been proposed by the government and municipalities. Currently, for simplicity and convenience, the building earthquake-damage estimation methods commonly consist of techniques based on damage-ratio functions. In this regard, the present study employed the damage-ratio function calculated by Murao and Yamazaki (2000, 2002), which is widely used by municipalities to estimate earthquake damage. For calculating the number of collapsed buildings, we employed the damage grade proposed by Okada and Takai (1999). The figures were generated by multiplying the ratio of the D4 damage (complete destruction) to the D5 damage (destruction by crushing) by the damage-ratio function.

3.3.2. Estimating the Economic Damage

To quantify the economic damage, we used the estimates provided by the Disaster Management Report (2014). The economic damage considered by the present study was classified into two categories: Buildings as fixed assets (wooden and non-wooden residences) and household goods. The following equations were employed to calculate the economic damage to these two categories. For these equations, the construction cost per unit of new housing and the estimated unit price of goods per household are listed in Tables 2 and 3, respectively. The unit costs are based on the Construction Statistics Annual Report (2010), the National Tax Agency Report (2014), and the record of the number and age of households by the Population Statistics (2014).

Cost of Building Damage = (Number of Totally Destroyed Buildings + Number of Partially Destroyed Buildings × 0.5) × Price of Necessary Construction per Unit of New Housing (1)

Cost of Damage to Household Goods = (Number of Collapsed Buildings + Number of Totally Destroyed Buildings × 0.5) × Unit Price of Household Goods per Household (2)

Table 2. Unit prices for housing damage.

Type of Structure	Price for Necessary Construction per Unit of New Construction (by ¥1000)
Wooden Residential	19,000
Non-wooden Residential	126,000

Table 3. Unit prices for household-good damage.

<table>
<tr><th rowspan="2">Age of Household Head</th><th colspan="3">Unit Price of Household Goods per Household (¥1000)</th></tr>
<tr><th>Couple</th><th>Single</th><th>Average</th></tr>
<tr><td>≤ 29</td><td>5,000</td><td rowspan="4">3,000</td><td rowspan="4">8,030</td></tr>
<tr><td>30–39</td><td>8,000</td></tr>
<tr><td>40–49</td><td>11,000</td></tr>
<tr><td>≥ 50</td><td>11,500</td></tr>
</table>

4. RESULTS OF THE DAMAGE SIMULATION

4.1. Distribution of Buildings within Fault Zones for Each Order of Magnitude

Combining the earthquake hazards and exposures defined in Section 3 with those in the fault zones described in Section 2.2 made it possible to determine the building distribution within each fault zone for each magnitude. The results of this investigation are listed in Table 4. As this table indicates, the number of buildings subject to regulation in Cases 1-1 through 1-4 ranges from 6,368–29,880 structures, whereas in Cases 2-1 and 2-2, the number ranges from 406–29,859. The number of buildings included in the fault zones described in these cases constitutes approximately 0.1–3.8% of the total number of buildings in all of Kumamoto Prefecture; thus, the number of buildings subject to regulation is extremely small. Further, by comparing Case 1-1 with Case 1-4, it was found that, despite the fault-zone area of the latter increasing to approximately 10 times greater than that of the former, the number of buildings affected only rose by approximately 4.7 times.

The population in the Futagawa-Hinagu fault zone is concentrated in a small area. Therefore, even as the area of the fault zone increased, the number of affected buildings did not increase as much. Moreover, when examining the list in Table 4, it is observed that the buildings in Cases 1-1 through 1-

4 made up approximately 10.6–61.0% of the number of buildings in the entirety of the Kumamoto Prefecture affected by JMA SI 7, whereas those in Cases 2-1 through 2-2 were only approximately 0.0–38.1% of that number.

The simulation covered the zones around the active faults, but did not include the number of buildings in the area affected by the JMA SI 7 area. This discrepancy in the area affected by strong ground motions may be influenced by a number of factors, e.g., the difference between the fault behavior predicted by the Seismic Hazard Maps and what actually occurred during the earthquake, as well as differing surface-amplifications effects.

Table 4. Building distribution in fault zones.

Unit: Structure

JMA SI	Kumamoto Prefecture Overall	Case 1-1: 0.4 km		Case 1-2: 0.8 km		Case 1-3: 2.0 km		Case 1-4: 4.0 km	
	A	B	B/A	C	C/A	D	D/A	E	E/A
7	2238	237	10.6%	458	20.5%	1,023	45.7%	1,365	61.0%
Upper 6	221,088	3,469	1.6%	4,027	1.8%	6,179	2.8%	15,808	7.2%
Lower 6	210,155	2,406	1.1%	3,153	1.5%	5,629	2.7%	11,608	5.5%
Upper 5	128,446	246	0.2%	281	0.2%	443	0.3%	1,084	0.8%
Lower 5	89,178	10	0.0%	11	0.0%	13	0.0%	14	0.0%
4 and Below	142,400	0	0.0%	0	0.0%	0	0.0%	0	0.0%
Total	793,504	6,368	0.8%	7,930	1.0%	13,286	1.7%	29,880	3.8%

JMA SI	Kumamoto Prefecture Overall	Case 2-1: JMA SI 7				Case 2-2: JMA SI Upper 6			
		Total Number of Building in Area		Number of Buildings Subject to Regulation		Total Number of Building in Area		Number of Buildings Subject to Regulation	
	A	B	B/A	C	C/A	D	D/A	E	E/A
7	2,238	0	0.0%	0	0.0%	2,238	100.0%	852	38.1%
Upper 6	221,088	1,045	0.5%	406	0.2%	67,344	30.5%	22,188	10.0%
Lower 6	210,155	0	0.0%	0	0.0%	16,113	7.7%	6,604	3.1%
Upper 5	128,446	0	0.0%	0	0.0%	502	0.4%	214	0.2%
Lower 5	89,178	0	0.0%	0	0.0%	0	0.0%	0	0.0%
4 and Below	142,400	0	0.0%	0	0.0%	0	0.0%	0	0.0%
Total	793,504	1,045	0.1%	406	0.1%	86,198	10.9%	29,859	3.8%

4.2. Economic Damage Before and After the Application of Land-Use Regulations

The results of the economic damage simulations conducted before and after the application of land-use regulations are listed in Table 5. Firstly, the economic damage sustained by the buildings (both residential and non-residential) in the Kumamoto Prefecture was estimated by the Director General for Economic and Fiscal Management, Cabinet Office, to be from ¥1.6–3.1 trillion. On the other hand, the results of the simulation totaled approximately ¥1.6 trillion (residences only). Although a margin of error exists in the building and economic damage estimation, it is deemed that the general scale of the damage has been captured.

Examining the economic damage sustained for each order of magnitude listed in Table 5, the amount of damage sustained under JMA SI Upper 6 was the largest, followed by JMA SI Lower 6, then, JMA SI Upper 5, and finally, JMA SI 7. The area affected by the Upper 6 magnitude quake had the greatest number of buildings subjected to the highest intensity of shaking, resulting in the largest amount of damage. On the other hand, the area affected by JMA SI 7 had the highest intensity of shaking but had the fewest number of buildings, resulting in a small amount of damage; hence, it only constituted a relatively small proportion of the overall damage.

Comparing the economic damage after with that before the application of land-use regulations, the amount of damage in the area affected by JMA SI 7 significantly decreased—approximately 8.8–

65.6% for Cases 1-1 through 1-4. The overall damage for the same cases decreased by approximately 1.6–8.9%, showing that this effect is limited. As previously mentioned, this is because the amount of damage sustained within the area affected by JMA SI 7 constitutes only a small proportion of the overall damage. Further, in Case 2-1, the area subject to regulation is very small, resulting in an approximately 0.1% reduction in the amount of damage, compared with the overall amount. In Case 2-2, a well-balanced decrease in damage was observed in the areas affected by JMA SI 6 (Upper and Lower) through JMA SI 7. The reduction was approximately 8.0%, compared to the overall damage.

Table 5. Economic damage before and after application of land-use regulations.

Unit: ¥1 Million

JMA SI	Before Application	After Application							
		Case 1-1: 0.4 km		Case 1-2: 0.8 km		Case 1-3: 2.0 km		Case 1-4: 4.0 km	
	A	B	B/A	C	C/A	D	D/A	E	E/A
7	22,184	20,232	91.2%	17,718	79.9%	10,982	49.5%	7,621	34.4%
Upper 6	1,243,101	1,219,746	98.1%	1,215 053	97.7%	1,200,586	96.6%	1,121 458	90.2%
Lower 6	509,940	505,557	99.1%	504,117	98.9%	498,791	97.8%	485,999	95.3%
Upper 5	30,040	29,952	99.7%	29,939	99.7%	29,899	99.5%	29,698	98.9%
Lower 5	630	629	99.8%	629	99.8%	629	99.7%	629	99.7%
4 and Below	14	14	100.0%	14	100.0%	14	100.0%	14	100.0%
Total	1,805,909	1,776,129	98.4%	1,767,469	97.9%	1,740,901	96.4%	1,645,418	91.1%

	Before Application	After Application			
		Case 2-1 JMA SI 7		Case 2-2 JMA SI Upper 6	
	A	B	B/A	C	C/A
7	22,184	22,184	100.0%	15,887	71.6%
Upper 6	1,243,101	1,241,541	99.9%	1,122 915	90.3%
Lower 6	509,940	509,940	100.0%	492,942	96.7%
Upper 5	30,040	30,040	100.0%	29,864	99.4%
Lower 5	630	630	100.0%	630	100.0%
4 and Below	14	14	100.0%	14	100.0%
Total	1,805,909	1,804,349	99.9%	1,662,252	92.0%

5.CONCLUSIONS

The present study conducted a damage simulation using the 2016 Kumamoto Earthquake as its subject. Focusing on the Futagawa-Hinagu fault zone, which slid during the Kumamoto Earthquake, we ran a damage simulation that applied land-use regulations (construction regulations) to nearby urban areas and compared building and economic damage to assess the effectiveness of these regulations. This investigation was conducted under a restricted set of conditions, the results of which are summarized below:

- The amount of damage sustained during the Kumamoto Earthquake could have been reduced by 1.6–8.9% through the application of land-use regulations (construction regulations) in the zones around the active faults. The amount of damage sustained in the areas affected by JMA SI 4 through JMA SI Upper 6 would have remained largely the same, but damage in the areas affected by JMA SI 7 could have been reduced by a large margin.

- Unfortunately, the damage sustained in the area affected by JMA SI 7 constituted only a small proportion of the total damage, whereas the areas affected by JMA SI 6 (Upper and Lower) had the largest proportion of the total damage. Only a very small proportion of the buildings in these areas were located inside the designated fault zones. Because of this, the amount of damage reduction in these areas because of land-use regulations was limited, constituting an 8.9% reduction at most. Considering the economic costs of land-use regulation during normal times, it is difficult to conclude that the regulations tested in the present study are sufficiently effective.

- The land-use regulations and laws applied in California and New Zealand largely aimed to reduce the damage caused by ground distortion stemming from fault displacement. However, a large proportion of the earthquake damage sustained in Japan comes from vibrations, which were the cause of a large part of the damage in the areas affected by JMA SI Upper 5 through JAM SI Upper 6. It is apparent that simply applying land-use regulations developed outside Japan will not effectively reduce the damage caused by earthquakes within Japan.

- To address the specifics of earthquake damage in Japan, the breadth of the fault zones and the exact content of the regulations applied within those zones must be discussed thoroughly. Further, the effects of these regulations must be measured and evaluated so that proper damage-prevention land-use regulations can be instituted in Japan.

- In this study, the regulations' effect was measured by simply applying the land-use regulations; however, land-use regulation is only one method of earthquake-disaster mitigation. To sufficiently lower the damage influence in an area where serious damage occurs, it is desirable to appropriately combine the regulations with other measures, e.g., earthquake-resistance measures, Business Continuity Planning / Business Continuity Management (BCP / BCM), and insurance programs.

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