A damage function that indicates the relationship between flood depth and damage is important to quantify natural catastrophe risks. Previous studies estimated the flood damage ratio using theoretical methodologies and in-person interviews. Although it is difficult to obtain actual damage information, it can be reflected in damage functions using insurance loss data. This work aims to develop damage functions for buildings and their contents using insurance loss data from the 2015 Kanto–Tohoku heavy rainfall incident. First, we collected information on the insurance losses and calculated damage ratio by property. Second, we analyzed inundation from the Kinugawa river using the flood model. Finally, we combined the simulation results with the damage ratio and developed flood damage functions as useful risk-assessment tools.

Key Words: flood damage function, insurance loss, Kanto–Tohoku heavy rainfall, inundation depth

1. INTRODUCTION

Economic and insurance losses caused by natural disasters are increasing globally, and the increase in occurrences of storm and flood disasters that directly affect insurance losses has become particularly significant\(^1\). In Japan, since 1991, insurance payouts exceeding 140 billion yen on average have occurred because of storm and flood damage every year\(^2\). For such natural disaster risks, property insurance companies use catastrophe risk models to quantify the risk of their insurance contracts and perform risk evaluations that consider the insurance underwriting decisions and geographical deviations of insurance coverage\(^3\).

The natural disaster model consists of three modules: the hazard module, vulnerability module, and financial module. In the natural disaster model, we calculate the wind speed and flood inundation depth using the hazard module; convert this information into the damage ratio of properties, such as houses using the vulnerability module; and finally obtain the insurance loss that considers the insurance contract conditions using the financial module.

In the vulnerability module, the tool that converts information, such as inundation depth, into the damage ratio is called the damage function, where the "Flood Control Economic Survey Manual (draft)" by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) is a representative example for flood control\(^4\). This damage function was developed based on a survey conducted from 1993 to 1996. Because 20 years have passed, there
have been deviations in the assumptions regarding the housing materials and facilities at that time compared with the present\(^5\). Therefore, MLIT is working to update the damage function. Although the research by Suzuki et al.\(^6\) can be cited as a study that investigated the inundation depth and damage ratio based on flood damage, the number of studies is small.

After the heavy rainfall incident in the Kanto–Tohoku area in September 2015, insurance claims amounting to 45 billion yen or more were paid out because of flooding in areas such as Joso city of Ibaraki prefecture\(^7\). Although detailed information on individual properties, such as the address, damage ratio information, and inundation depth, can be obtained from the payment report based on the damage certificate of the property insurance company, the integrity of the origin of the inundation depth and the completeness of the inundation depth information are insufficient. Therefore, in this study, we estimated the inundation depth distribution of the area around Joso city using a flood simulation and developed flood damage functions for the Kanto–Tohoku heavy rainfall incident by linking the estimated result with the results of the damage survey to accumulate information on the flood damage function.

2. CHARACTERISTICS OF THE DAMAGE CAUSED BY THE KANTO–TOHOKU HEAVY RAINFALL INCIDENT OF SEPTEMBER 2015

On September 9–10, 2015, because of Typhoons 17 and 18, moist air flowed from the south, forming a linear rainfall belt with a width of 100–200 km extending in the North–South direction in the Kanto and Tohoku regions\(^8\). This brought heavy rainfall, primarily to the Tochigi prefecture. In Nikko city, Imaiichi, the daily rainfall reached 366.5 mm and 233.0 mm on September 9 and 10, respectively\(^9\), which were the first and fourth highest rainfall amounts in recorded history. This heavy rainfall became particularly remarkable in the Kinugawa river basin, and the water level at the Hiraikata water-level observation station, downstream of Kinugawa river and Mitsukaido, exceeded the maximum recorded water level and the planned high-water level. The flood exceeding the flow capacity caused inundation and overflows at seven locations in the lower part of the Kinugawa river, including large-scale flooding and inundation in Wakamiya in Joso city, Ibaraki prefecture. Furthermore, in Misaka town of the same city, a levee breach spanning a width of 200 m or more occurred. Because of this flood, in Joso city, 53 houses were completely destroyed, 1,578 houses were extensively damaged, 3,476 houses were moderately damaged, and a total of 3,220 houses were inundated above and below the floor level\(^10\). In addition, the flood was characterized by such damage as the washing away of houses and debris collision caused by the breach in the levee.

3. COLLECTION OF INSURANCE PAY-OUT INFORMATION

In addition to the detailed attribute information, such as addresses, roofing columns, utilities, number of stories, and inundation depth, the payment reports of general insurance companies contain information on the insured value, which is the monetary value of the insurance target, and the certified damage amount. Most of the inundation depths described are measured either from above the floor or from the ground. In this section, we extracted the address information and damage ratio of the buildings and contents from the payout information report for the cities that were particularly damaged, namely, Joso, Tsukubamirai, and Shimotsuna in Ibaraki prefecture. The damage ratio given here indicates the certified damage amount divided by the insured value.
The number of items in the extracted payout information was 136 for buildings and 166 for contents. The attribute breakdown of the extracted information is shown in Fig.1. The majority of the columns of the buildings and contents were wooden, and approximately 30% of the contents had unknown structure. Most of the buildings were either one- or two-story. There were many buildings with small damage ratios, and the number of buildings tended to decrease as the damage ratio increased. However, the number of contents with a damage ratio exceeding 0.9 is projected as 29 cases (Fig.2). This is because the contents are often objects, like furniture, that are placed on the floor; they are considered more susceptible to damage, even at low inundation depths, than buildings.

4. ESTIMATION OF INUNDATION DEPTH DISTRIBUTION

Because of the government’s view and past research showing the relationship between inundation depth and damage ratio, it is known that there is a correlation between the inundation depth caused by flooding and the damage ratio of houses. In this section, we estimate the maximum inundation depth associated with the damage ratio of each property shown in Section 3. First, we observed the maximum inundation depth data of an arbitrary location by a field survey. Subsequently, we estimated the maximum inundation depth distribution by numerical analysis of the flood. Finally, by comparing the observed and estimated values of the maximum inundation depth, we verified the accuracy of the numerical analysis.

(1) Field survey

The target area of the survey was mainly Joso city in Ibaraki prefecture and the area around the left bank of the Kinugawa river, where remarkable inundation damage occurred when an area of about 40 km² was flooded1) by the levee breach and overflow of the Kinugawa river. The field survey was conducted twice, once each on September 14 and October 5, 2015. In the first survey, an outline survey of the levee breach location and the overflow location and an inundation depth investigation of the northern part of the target area were conducted. In the second survey, an exhaustive inundation depth investigation of the target area was conducted. In the outline survey, we recorded photographs of the broad topographical changes caused by external flooding in the locations of the levee breach and overflow. In the inundation depth investigation, in addition to marking on a map the locations where traces of inundation were found, the height from the ground to the inundation trace were recorded for 31 locations.

(2) Numerical model used in flood analysis

We performed simultaneous analyses by combining the MIKE11 module, which performs the one-dimensional unsteady flow analysis, and the MIKE21 module, which performs two-dimensional analysis, using MIKE powered by DHI. The continuity equation of the one-dimensional unsteady flow analysis is shown in Equation (1), and the equation of motion is shown in Equation (2).

\[
\frac{\partial Q}{\partial t} + \frac{\partial (Q^2/A)}{\partial x} + gA \frac{\partial h}{\partial x} + gQ|Q| C^{AR} = 0
\]  

Here, \( Q \) is the flow rate, \( q \) is the flow per unit width, \( A \) is the cross-sectional area of the flow, \( h \) is the depth of the water, \( C \) is Chezy’s resistance coefficient, and \( R \) is the hydraulic radius. The continuity equation of two-dimensional unsteady flow analysis is shown in Equation (3), and the equation of motion is shown in Equations (4) and (5).

\[
\frac{\partial k}{\partial t} + \frac{\partial (pq)}{\partial x} + \frac{\partial (pq)}{\partial y} + gh \frac{\partial \xi}{\partial x} + \frac{gp\sqrt{p^2 + q^2}}{C^2 h^2} - (4)
\]

\[
\frac{1}{\rho_w} \left( \frac{\partial}{\partial x} \left( h \tau_{xx} \right) + \frac{\partial}{\partial y} \left( h \tau_{xy} \right) \right) - \Omega_q - fV_y + \frac{h}{\rho_w} \frac{\partial}{\partial x} \left( p_a \right) = 0
\]

\[
\frac{1}{\rho_w} \left( \frac{\partial}{\partial x} \left( h \tau_{yx} \right) + \frac{\partial}{\partial y} \left( h \tau_{yy} \right) \right) + \Omega_p - fV_x + \frac{h}{\rho_w} \frac{\partial}{\partial y} \left( p_a \right) = 0
\]

Here, \( \xi \) is the water level; \( p \) and \( q \) are the flow fluxes in the \( x \) and \( y \) directions; \( f \) is the effect of wind friction; \( V_x, V_y \), and \( V_r \) are the wind velocities; \( \Omega \) is the Coriolis parameter; \( \rho_w \) is the density of water; \( p_a \) is the atmospheric pressure; and \( r \) is the effective frictional stress. Furthermore, the overflow formulae to calculate the mutual exchange of flow rates of the models are given by Equations (6), (7), and (8).

\[
Q = wC_1 h_1 \quad (h_2/h_1 \leq 2/3)
\]

\[
Q = \frac{3}{2} \sqrt{3} C_2 h_2 \quad (h_2/h_1 > 2/3)
\]
Here, \( w \) is the width of the levee breach, \( C_f \) is the corrected flow coefficient, \( h_1 \) is the overflow water depth in the upstream side, \( h_2 \) is the overflow water depth in the downstream side, \( C \) is the flow coefficient before correction, \( L \) is the levee top width, and \( n \) is Manning’s roughness coefficient.

In the one-dimensional unsteady flow analysis, using the cross-sectional diagram of the river managed by MLIT, we entered the river cross-sectional data and modeled the section from Kinugawa Mitsukaido river water-level station in the downstream of Kinugawa river to the Hirakata water-level station as the river channel. The roughness inside the river channel was uniformly set to 0.03 within the section, and the boundary condition was set based on the observed water levels at the upstream and downstream ends such that it was consistent with the time-series water level at the Kamanawa water-level observatory. The period of calculation, including the steady calculation, was set from 0:00 on September 7, 2015, to 0:00 on September 12, 2015.

\[
C_f = \sqrt{\frac{2g}{2g/C^2 + \frac{2gL}{h_1}}}^{4/3} \tag{8}
\]

In the two-dimensional unsteady flow analysis, we corrected the 5-m mesh elevation data of the Geospatial Information Authority (GSI) of Japan and the 7.5-m mesh land cover data of Japan Aerospace Exploration Agency (JAXA) into a 10-m × 12.33-m mesh (Fig.3). Using the water levels of both the models and the crest heights of both banks of the river channel as the boundary conditions for the one-dimensional analysis (blue line in Fig.3) and the two-dimensional analysis (colored portion of Fig.3), we calculated the outflow and inflow according to Honma’s overflow formula. Based on the information\(^{11}\) reported by MLIT, changes in the river cross-section caused by the overflow at Wakamiya and the levee breach in Misaka town were modeled in time series, as shown in Fig.4. Because the inundation damage of the target area of analysis was caused mainly by fluvial flood, pluvial flood was not considered in the model.

(3) Results of estimation of inundation depth distribution

In the one-dimensional unsteady flow analysis of the time-series water level at the Kamanawa water-level station, we reproduced the observed values well (Fig.5). The observed and estimated results of the inundation depth are shown in Fig.6. The flood extent data were provided by GSI. The inundated area according to this analysis was 41.707 km\(^2\), which matched well with the published value of 40 km\(^2\). When the product of the estimated maximum inundation depth per mesh and mesh area was added to the number of flooded meshes, the result was 61,200,000 m\(^3\), which matched well with the value of 63,800,000 m\(^3\) reported by Sayama et al.\(^{12}\).

The estimated results of inundation depth were verified by comparison with the observed results of this study (Fig.7). The root-mean-square value of the difference between the observed inundation depth and the inundation depth from the analysis results was 0.465 m, which showed good reproducibility in general, although a slight underestimation was
observed. In this disaster, because large-scale sand blasts were confirmed at locations 500 m upstream, 800 m downstream, and a further 8 km downstream from the levee breach location (Points A, B, and C, respectively, in Fig.6)\(^{11}\), it is believed that, in some areas, flooding occurred because of leakage of river water. Comparison of the estimation results of the inundation depth distribution of this study with the inundation range published by the GSI \(^{13}\) showed that the results were underestimated in the vicinity of Points A and C in Fig.6. Furthermore, during the analysis period, because approximately 7,800,000 m\(^3\) of water was drained around Mitsukaido district, the estimated inundation depth in the area tends to be excessive. Therefore, a more detailed analysis considering the leakage and drainage phenomena is necessary.

5. DEVELOPMENT OF DAMAGE FUNCTION

In this section, using the inundation depth distribution estimated in Section 4, we determine the damage function based on the insurance payout information in Section 3.

(1) Method of development of damage function and regression coefficient

First, we extracted the damage ratio data used in the development of the damage function from the insurance payout information. Specifically, we extracted those structures that had one or two stories and within the inundation depth distribution estimated in Section 4.

Subsequently, after rearranging the damage ratio data by the size of the corresponding inundation depth, as shown in Table 1, the inundation depth was classified so that the information of each building was smoothed, and the average damage ratio for each class was calculated. The categories and number of buildings in the category are shown in Table 2. The average value of the data within the class was used as the inundation depth. For each class obtained, the damage function was determined from the relationship between the inundation depth and damage ratio.

With Suzuki et al.\(^{6}\) as a reference, using the natural logarithm of inundation depth \(x\), the damage ratio \(P_D(x)\) was assumed to be represented by the cumulative distribution function of standard normal distribution. In other words,

\[
P_D(x) = \Phi\left(\frac{\ln x - \lambda}{\zeta}\right)
\]

Here, the coefficients \(\lambda\) and \(\zeta\) are the average value and standard deviation of \(\ln x\) that are obtained by the least-squares method using the probability plotting paper, respectively, as shown in Fig.8. Consequently, the regression coefficients based on the average value of each class were obtained (Table 3). Although the determination coefficient \(R^2\) was

![Fig.6 Observed and analysed maximum inundation depth.](image)

![Fig.7 Validation result of inundation depth.](image)

<table>
<thead>
<tr>
<th>Inundation depth by class (m)</th>
<th>Damage ratio</th>
<th>Average damage ratio by class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inundation depth (m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.338</td>
<td></td>
<td>0.188</td>
</tr>
<tr>
<td>0.154</td>
<td>0.120</td>
<td></td>
</tr>
<tr>
<td>0.170</td>
<td>0.044</td>
<td></td>
</tr>
<tr>
<td>0.473</td>
<td>0.029</td>
<td></td>
</tr>
<tr>
<td>0.474</td>
<td>0.169</td>
<td></td>
</tr>
<tr>
<td>0.597</td>
<td></td>
<td>0.218</td>
</tr>
<tr>
<td>0.914</td>
<td></td>
<td>0.317</td>
</tr>
<tr>
<td>1.345</td>
<td></td>
<td>0.283</td>
</tr>
<tr>
<td>2.043</td>
<td></td>
<td>0.364</td>
</tr>
</tbody>
</table>


\(\Phi\) is the cumulative distribution function of the standard normal distribution.
slightly lower at 0.541 for the contents, it had a higher value of approximately 0.9 for all buildings.

The inundation depth of the damage function shown below has an upper limit of 2.5 m based on the higher value of approximately 0.9 for all buildings.

Furthermore, the relation between inundation depth and housing damage ratio of the “Flood Control Economic Survey Manual,” used in the economic evaluation of flood control measures, is also shown in the same figure. Group A has a ground gradient of less than 1/1000, Group C has a ground gradient of 1/500 or more, and Group B is in the middle. Although each group in general shows a good correspondence with the damage ratio of this study when the inundation depth is 1 m or more, when the inundation depth is less than 1 m, the value is less than that of this study. In the damage ratio of the flood control economic survey data, it has been pointed out that it does not consider cases in which the replacement of the entire wall occurs, even when only a part of the inner wall material or heat-insulating material is inundated and the cases where sludge-removal cost occurs, even when the inundation occurs only below the floor. Because this study includes the amount of damage conforming to such cases, the damage ratio is considered to be relatively high. In addition, when the inundation depth is small, even when normally inundated, the number of cases without damage will tend to be relatively large. In this study, because the damage function is developed based on the insurance payout information, properties with no damage are not considered. This is one of the causes of the deviation in each damage function when the inundation depth is less than 1 m.

The building damage function of two-story buildings by the structure obtained in the previous section is shown in Fig.10. The structure was estimated from the information on the attributes of columns in the insurance payout information. Because the data were inadequate for Reinforced Concrete (RC) structures, they were excluded. The reason for the damage ratio of wooden structures being

### Table 2 Classification of number of stories and structure for the development of damage function.

<table>
<thead>
<tr>
<th>Buildings</th>
<th>Without number of stories</th>
<th>Without structure classification</th>
<th>Number of data</th>
<th>Number of categories</th>
<th>Number of houses in the category</th>
</tr>
</thead>
<tbody>
<tr>
<td>One-storied</td>
<td>Without structure classification</td>
<td>24</td>
<td>5</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Two-storied</td>
<td>Without structure classification</td>
<td>81</td>
<td>5</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Contents</td>
<td>Without number of stories classification</td>
<td>89</td>
<td>5</td>
<td>17</td>
<td></td>
</tr>
</tbody>
</table>

![Fig.8](image-url) Probability paper display of the relationship between inundation depth and building damage ratio by number of stories.

![Fig.9](image-url) The building damage function obtained in the preceding section is shown in Fig.9. The damage ratio of a one-story building is higher than that of a two-story building. This is considered to reflect the tendency of the proportion of the damage amount caused by inundation in the first floor to the price of the whole building becoming larger for one-story buildings than for two-story buildings. Furthermore,

### Table 3 Regression and determination coefficients of damage function.

<table>
<thead>
<tr>
<th>Buildings</th>
<th>Without number of stories classification</th>
<th>Without structure classification</th>
<th>λ</th>
<th>ζ</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>One-storied</td>
<td>Without structure classification</td>
<td>1.74</td>
<td>3.836</td>
<td>0.943</td>
<td></td>
</tr>
<tr>
<td>Two-storied</td>
<td>Without structure classification</td>
<td>-0.304</td>
<td>1.769</td>
<td>0.944</td>
<td></td>
</tr>
<tr>
<td>Contents</td>
<td>Without number of stories classification</td>
<td>1.967</td>
<td>3.436</td>
<td>0.861</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Without structure classification</td>
<td>1.826</td>
<td>2.355</td>
<td>0.889</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.046</td>
<td>3.685</td>
<td>0.945</td>
<td></td>
</tr>
</tbody>
</table>

- The reason for the damage ratio without the classification of the number of stories being close to two is that the damage ratio data contain more two-story buildings than one-story buildings. Furthermore, the classification of the number of stories being close to two is considered. This is one of the causes of the deviation in each damage function when the inundation depth is 1 m or more, when the inundation depth is less than 1 m, the value is less than that of this study. In the damage ratio of the flood control economic survey data, it has been pointed out that it does not consider cases in which the replacement of the entire wall occurs, even when only a part of the inner wall material or heat-insulating material is inundated and the cases where sludge-removal cost occurs, even when the inundation occurs only below the floor. Because this study includes the amount of damage conforming to such cases, the damage ratio is considered to be relatively high. In addition, when the inundation depth is small, even when normally inundated, the number of cases without damage will tend to be relatively large. In this study, because the damage function is developed based on the insurance payout information, properties with no damage are not considered. This is one of the causes of the deviation in each damage function when the inundation depth is less than 1 m.

| Contents     | Without number of stories classification | Without structure classification | 0.188 | 2.449 | 0.541 |
higher than that of steel structures can be attributed to
the water resistance of the material.

(3) Content damage function

The content damage function obtained in Section
(1) is shown in Fig.11. Furthermore, as in the pre-
ceding section, the relationship between the inundation
depth of the flood control economic survey
manual and the damage ratio of the household goods
is also shown in the figure. Although it showed a
good correspondence with the damage ratio of this
study when the inundation depth was in the range of
0.5 m to 2 m, for inundation depths of less than 0.5 m,
it became lower than in this study. With respect to the
contents, as shown in Fig.2, because there were many
data with a damage ratio of approximately 100% and
their corresponding inundation depths were less than
0.5 m, the damage ratio of this study tended to be
higher.

6. CONCLUSION

In this study, we developed a flood damage func-
tion by estimating the maximum inundation depth
associated with the insurance payout information for
the area around Joso city, Ibaraki prefecture, where a
large-scale inundation by river water was caused by
the September 2015 Kanto–Tohoku heavy rainfall
incident. It is shown that, in addition to the methods
of past studies, such as hearings and numerical
analyses, insurance payout information can also be
utilized for the development of damage functions.

In the numerical analysis of flooding, we esti-
mated a unified and highly accurate inundation depth
associated with the insurance payout information.
The replicability of the inundated area around the
southern part of the flooded area and the river
channel is expected to improve by modeling the
leakage and drainage.

The building damage function and the content
damage function were developed by the collection
and analysis of insurance payout information.
Through comparison of the damage function of the
Ministry of Land, Infrastructure, Transport and
Tourism with the results of this study, it was found
that there was a deviation in the damage ratio, espe-
cially in the portions where the inundation depth was
low. Furthermore, because the damage ratio of the
building was greatly influenced by its number of
stories and structure, it is suggested that the damage
estimation be refined using the damage function that
corresponds to the attributes of the building.

Because the maximum inundation depth used in
the development of the damage function in this study
was based on estimation, calculation errors were
present. In the future, development of a damage
function that absorbs the calculation errors of flood
analysis by constructing the damage ratio distribu-
tion around the average damage ratio and calibrating
the damage function by utilizing the flood insurance
payout information accumulated by the insurance
companies is anticipated.
REFERENCES
10) Ibaraki Prefecture Disaster Prevention and Crisis Management Division : Damage and Measures of the Prefecture due to the Kanto–Tohoku Heavy Rainfall in September 2015 (As of 4:00 pm on March 1, 2016).

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