Journal of Disaster Science and Management (2025) 1:5
https://doi.org/10.1007/s44367-025-00005-3

RESEARCH

Assessment of debris flow risk according to damage type

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Received: 6 January 2025 / Accepted: 13 March 2025

Abstract
The spatial distribution of hazard risk due to debris flows is discussed using a horizontal two-dimensional numerical simulation of debris flow, and the hazards are evaluated according to the type of damage. Compared to the hazard areas between the flow depth of the debris flow and the building destruction, many of the areas inundated by debris flows are outside the hazardous area for building destruction. Compared to the hazard areas between the building destruction and the sediment deposition, there is almost no overlap between the two areas. In other words, the area away from the stream exit does not suffer from severe damage such as the destruction of buildings, but it is not completely free from damage due to the accumulation of sediment on the site and the inflow of sediment into the houses. It is important to evaluate the hazard level for various types of damage when considering the hard and soft countermeasures against debris flow damage.

Keywords Debris flow · Risk assessment · Numerical analysis · Sediment disaster · Damage type

Introduction

In August 2014, a debris flow disaster occurred in Asaminami, Hiroshima City, Japan, resulting in 77 victims, including disaster-related deaths, and extensive damage to buildings, with 133 totally destroyed and 122 partially destroyed.

In Japan, where mountainous areas occupy about 3/4 of the land and there are few plains suitable for residential areas, houses are built at the foot of mountains and sometimes on the slopes of mountainous areas that were at risk of debris flow disasters. The Sediment Disaster Prevention Act has now been enacted by Japanese national/local governments, and sediment disaster warning zones (yellow zones) and sediment disaster special warning zones (red zones) have been established. In areas designated as sediment disaster special warning zones (red zones), structural restrictions have been placed on buildings, and existing buildings have been advised to relocate. In addition, there is a need for more detailed information to be used in evacuation plans to reduce the damage caused by debris flows (Nakamoto et al., 2022).

In recent years, some numerical simulations have been conducted on debris flows, and the inundation process of debris flows in residential areas can be estimated (Nakatani et al., 2017; Takebayashi et al., 2015; Wang et al., 2008; Begueria et al., 2009; Pirulli et al., 2010; Chiang. et al., 2012; Gregoretti et al., 2016; Vagnon et al., 2019).

The information obtained using numerical analysis of debris flows is very useful. Some studies (Hasegawa et al., 2019; Nakatani et al., 2020) have examined risk distributions using numerical simulations of debris flows as a reference for evacuation planning. However, a one-dimensional model with constant river width was used to analyze debris flows flowing into residential areas, and debris flow hydrographs due to changes in flow width were not evaluated. When predicting the amount of sediment discharged from a stream based on the thickness of unstable sediment that can be measured in the field, a two-dimensional analysis that can evaluate changes in flow width is considered to be effective. In addition, insufficient knowledge has been obtained regarding the effects of the layout of buildings and roads in residential areas on damage types caused by debris flows, as well as the evaluation of hazard levels according to damage types.

In this study, the spatial distribution of hazard risk due to debris flows is discussed using a horizontal two-dimensional numerical simulation of debris flow, and the hazards are evaluated according to the type of damage.

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Damage type by debris flow

Debris flows inundating residential areas cause various damages. Figure 1 shows the damage caused by debris flows in Hiroshima City, Kure City, and Aki County, Hiroshima Prefecture, Japan, in 2014 and 2018 (Hiroshima prefecture, 2015, 2019).

Figure 1a–d shows the damages caused by the debris flows that flowed through the residential areas. All of them are

Fig. 1 Damage caused by debris flow; (Hiroshima prefecture, 2015, 2019)

located just downstream of the stream exit. The erosion of the bed and banks and the erosion of the ground in residential areas due to the relatively large flow depth and velocity were observed. Therefore, it is dangerous to evacuate outside the house during occurrences of debris flow.

Figure 1e, f shows the damage to houses caused by debris flows. Houses are destroyed by the impact of debris flows, and damage to houses occurs when the hydrodynamic forces acting on houses from debris flows are large. The houses in the target area are almost completely destroyed, and vertical evacuation by moving to the second floor or higher of the house is not effective.

Figure 1g, h shows the damage caused by the accumulation of sediment from a debris flow. The area downstream from the exit of the stream where the debris flow occurred is a point where the ground gradient is small, and sediment with a relatively small grain size is deposited. No damage to buildings or erosion of the ground was observed, but some damage was caused by sediment flowing into houses. The accumulation of sediment on roads causes traffic disruption and requires a great deal of time and labor to remove the sediment after the disaster for restoration.

As described above, there are various types and causes of damage by debris flows, and damage locations are varied. It is necessary to evaluate debris flow hazards according to these factors to consider countermeasures against debris flows and evacuation methods from debris flows.

Research methods

Numerical analysis model

In this analysis, a horizontal two-dimensional debris flow model (Takebayashi et al., 2020; Jonathan M. Nelson et al., 2016) is used for a two-layer flow with a laminar layer near the bed and a turbulent layer above the laminar layer for a water and sediment mixture. The model of Egashira et al. (2004) is used as the constitutive law of the laminar flow regime.

The equilibrium bed gradient θ_e, along the flow direction in two-layer flow, is as follows (Takebayashi et al., 2020):

$$\tan \theta_e = \frac{\left(\frac{\sigma}{\rho} - 1\right)\overline{c}}{\left(\frac{\sigma}{\rho} - 1\right)\overline{c} + 1} \frac{h_s}{h} tan \varnothing_s \quad (1)$$

where r is the density of the liquid, s is the density of the sediment, h is the flow depth, h_s is the laminar layer thickness, and f_s is the internal friction angle of the sediment (= 34°). $\overline{c}$ is the sediment concentration averaged over the flow depth and has the following mass conservation law (Egashira et al., 2004) relationship:

$$\frac{\partial \overline{c}h}{\partial t} + \frac{\partial \overline{c}hu}{\partial x} + \frac{\partial \overline{c}hv}{\partial y} = E \quad (2)$$

where t is time, u and v are velocity components in the x and y directions, and E is the erosion rate of the bed as follows (Egashira et al., 2004):

$$\frac{E}{\sqrt{u^2 + v^2}} = c_* \tan\left(\theta - \theta_e\right) \quad (3)$$

where c_* is the volume concentration of sediment in the static sedimentary layer, and θ is the bed gradient along the flow direction. Positive and negative values of E indicate erosion and deposition, respectively.

The bed level equation is as follows, where the erosion and deposition of the bed are represented by the erosion rate E.

$$\frac{\partial z_b}{\partial t} = -\frac{E}{c_*} \quad (4)$$

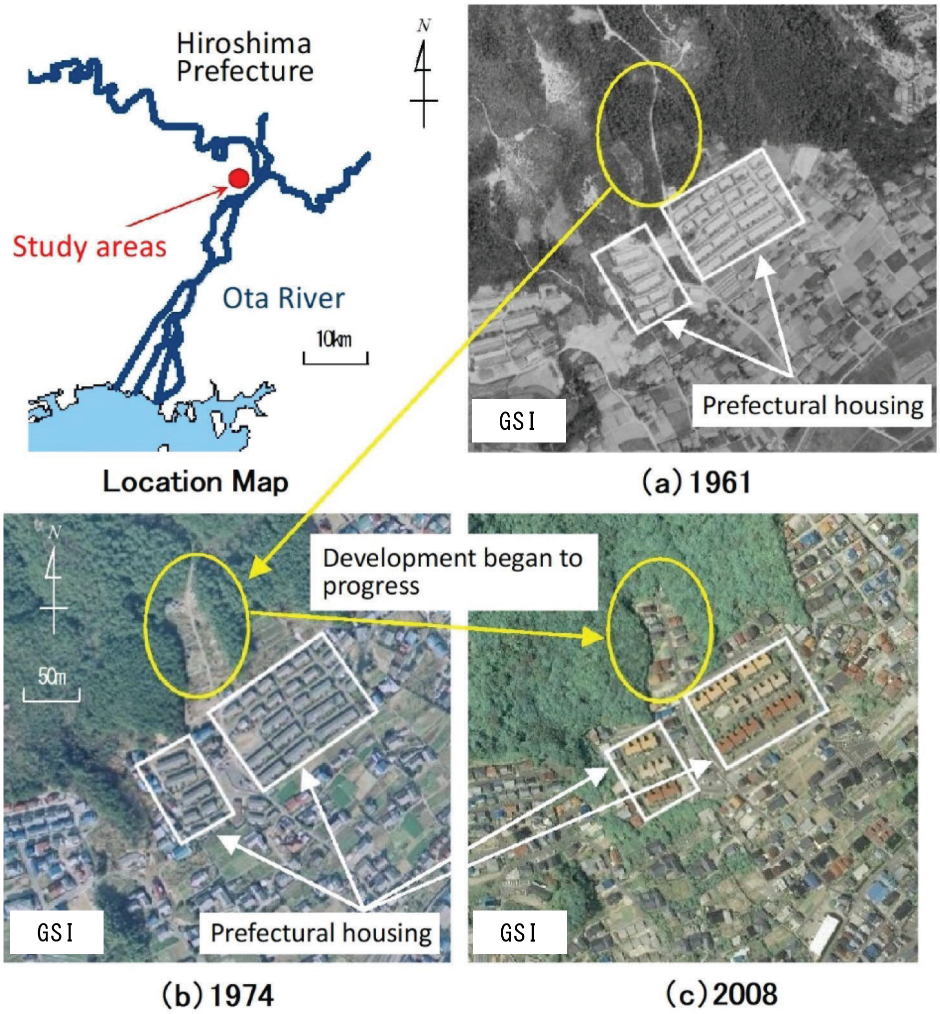
The numerical analysis model does not require the assumed water or debris flow discharges as upstream boundary conditions because the debris flow is initiated by slope failures, as in the real phenomenon. The entire section is solved as a two-dimensional planar model, so erosion and deposition of debris flow can be evaluated in all analysis domains.

The reproducibility of the flow characteristics of the debris flow by this model was confirmed by Takebayashi et al. (2014) and Takebayashi (2016) to be reproducible for the horizontal distribution of the debris flow inundation area, as well as the land deformation after the disaster (Takabayashi, 2016) and others.

Study areas

Study area is Yagi 3 chome, Asaminami, Hiroshima City, Japan, which was severely damaged by the debris flow caused by the August 2014 torrential rains. The center of each photo is the prefectural Midorigaoka Residence. The yellow oval in the figure (Fig. 2) indicates that the area at the exit of the debris flow stream has been developed as the residential area, and several houses have been built after 1974. The prefectural Midorigaoka Residence is located downstream of the developed area and was reconstructed with reinforced concrete structures between 1974 and 2008.

Fig. 2 Study areas



Risk assessment method

In order to evaluate the risk of debris flows inundating residential areas, three numerical analyses were conducted by changing the flow discharge of the debris flows. The risk of debris flow for each area was evaluated in four levels by examining how many numerical analysis results exceeded the threshold value. In this study, the risk level was defined as Level 1–Level 4 in Fig. 3, and the areas were color coded to indicate the level of risk.

Numerical analysis conditions

The analysis area is the 2 km × 0.7 km area from the head of the main stream to the railway track (Japan Railway Kaji Line) shown in Fig. 4. The topographic data used in the analysis was 1 m DEM data (topographic data before the disaster) obtained by the Ministry of Land, Infrastructure, Transport and Tourism of Japan in 2009. The numerical analysis grid was a 2 m × 2 m square grid.

Two types of conditions are set up: one in which buildings are not considered, and the other in which buildings are considered. The building layout is shown in Fig. 5, which is the condition of the building site in 1974, when housing development began (houses were actually constructed) at the location indicated by the yellow circle in Fig. 2. The buildings are treated as impermeable, non-overtopping, and non-destructive structures.

In this analysis, debris flows are assumed to originate from slope failures. Takebayashi et al. (2015) tried several sizes of a slope failure when they reproduced a numerical simulation of a debris flow disaster that occurred in Yagi 3 chome, Asaminami, Hiroshima City, Japan, due to the August 2014 heavy rain. However, due to the long transport distance of the debris flow and the abundance of unstable sediment in the stream, the amount of sediment in the slope

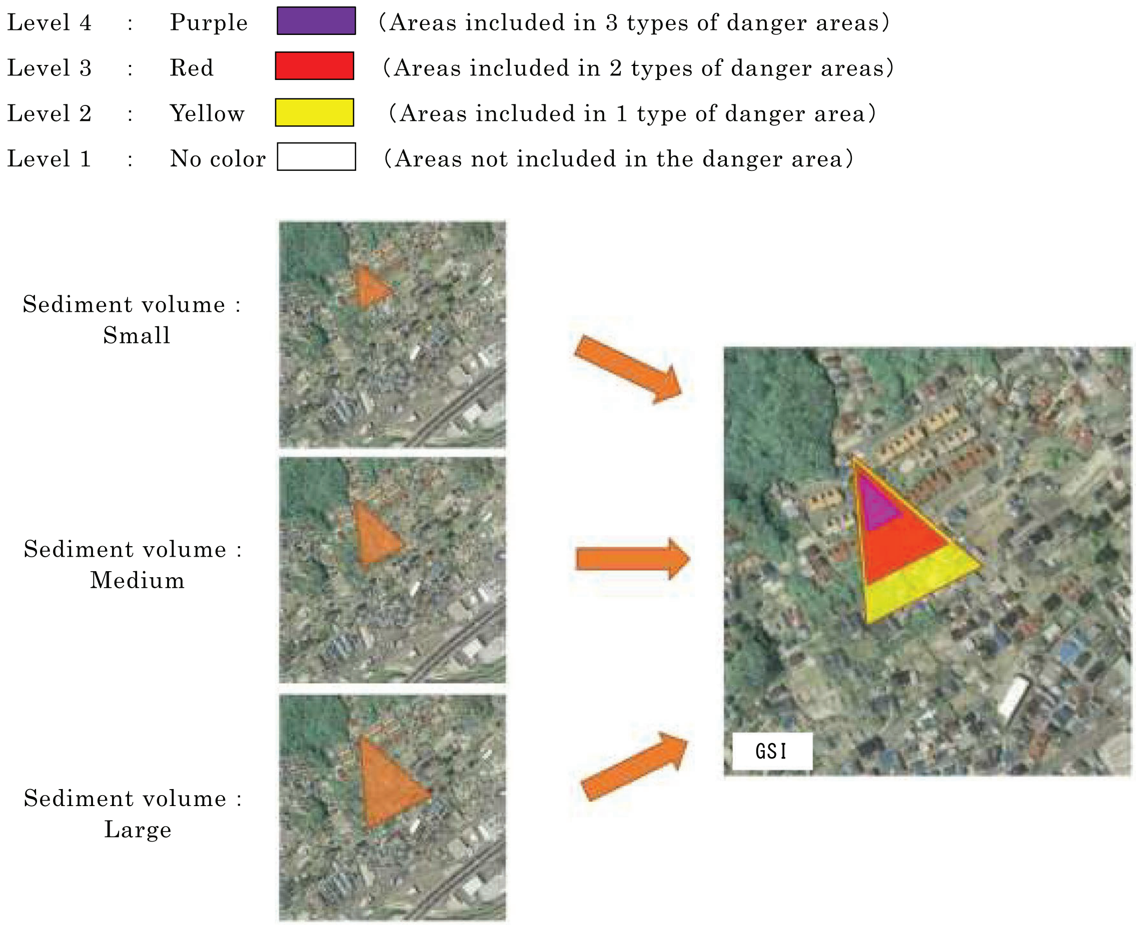


Fig. 3 Illustration of risk assessment

failure has little effect on the flow characteristics of the debris flow into the residential area. Therefore, the sediment volume of debris flow to the residential area is expressed by changing the maximum unstable sediment depth in streams (maximum erosion depth). The maximum erosion depth was set to 0.3 m, 0.5 m, and 1.0 m, respectively. Since the purpose of this numerical simulation is to evaluate the risk according to different types of damage caused by debris flows, only slope failure near the head of the main river, shown in Fig. 4, was considered.

Risk assessment considering damage type

Focusing on the damage caused by debris flows that flooded residential areas from the stream exit, as shown in Fig. 1, damage caused by building destruction, and damage caused by sediment accumulation, we used numerical simulation of debris flows to evaluate the risk according to each type of damage.

Assessment of risk due to debris flow

Flood hazard maps often use the depth of inundation to assess the risk of damage. This is because many houses are inundated above floor level when the inundation depth is 0.5 m or greater, and water can easily penetrate into houses. Therefore, here we attempt to evaluate risk using the flow depth of debris flows as an indicator.

Figure 6 shows the analysis results for the case where the maximum flow depth of 0.5 m or greater is set as the threshold, and the presence of buildings is not considered. The area of Level 4 almost coincides with the analysis results for the maximum erosion depth of 0.3 m, and the areas of Level 3 and Level 2 also coincide with the analysis results for the maximum erosion depths of 0.5 m and 1.0 m, respectively. From Fig. 6, the maximum erosion depth is deeper, the flow rate of the debris flow is larger, and the danger area is also expanding accordingly. The difference between Level 2 and Level 3, where the difference in maximum erosion depth is 0.5 m, is considerably larger than the difference

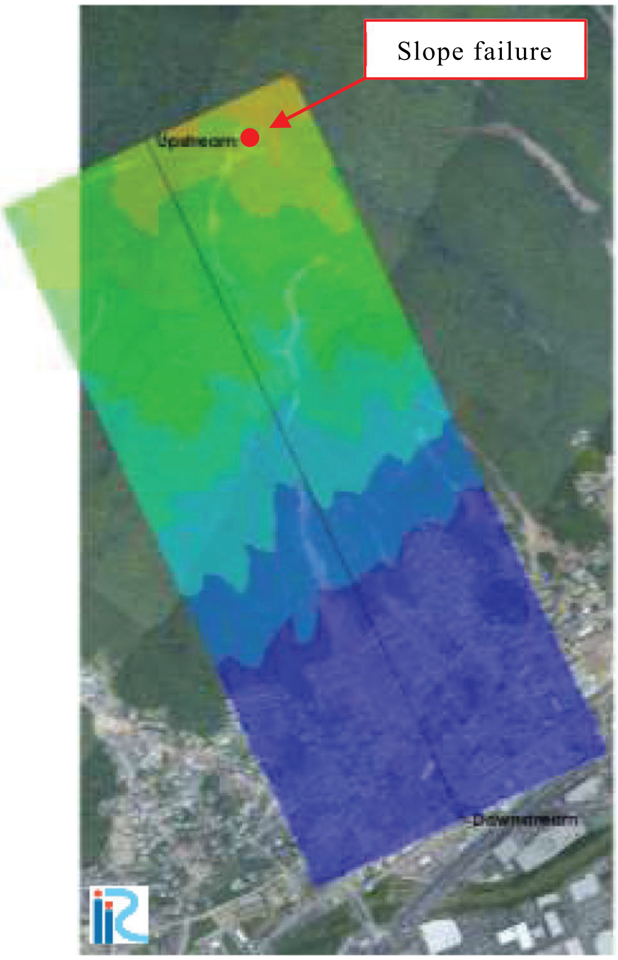


Fig. 4 Analysis areas

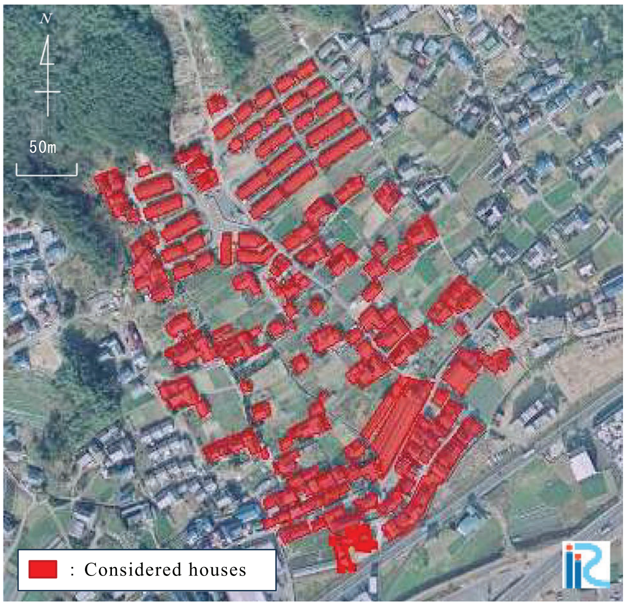


Fig. 5 House placement condition

between Level 3 and Level 4, where the difference in maximum erosion depth is 0.2 m. This is due to the change in the flow width (erosion area) associated with the development of debris flow in a stream. In other words, the maximum erosion depths of 0.3 m and 0.5 m differ greatly in the flow width of the stream, resulting in a large difference in the debris flow rate into the residential area, while the maximum erosion depths of 0.5 m and 1 m do not differ greatly in the flow width of the stream, resulting in no difference in the debris flow rate into the residential area. The above results indicate that this analysis can directly derive the relationship between the thickness of unstable sediment in the stream, which can be measured in the field, and the risk of sediment disasters, and is a very effective method for assessing the risk in the field.

Figure 7 shows the yellow zone and the red zone of the hazard area at the target site. As can be seen from the comparison with Fig. 6, the outline of the sediment disaster hazard warning area (yellow zone) in Fig. 7 is relatively similar to that of the hazardous area in Fig. 6. On the other hand, even within the yellow zone, there is a distribution in the degree of risk due to debris flow inundation.

Next, Fig. 8 shows the results of the analysis when buildings are considered. Unlike the case where no buildings are considered, the hazardous area extends to the area indicated by the white circle in Fig. 8. This is because the debris flow is divided into west and east sides due to the impact of the debris flow with the buildings. On the other hand, the debris flow down the slope of the residential area flowed in a straight line along the road, and the inundation area of the debris flow was smaller than that without considering the buildings. Figure 9 shows the spatial distribution of the maximum flow depth for a maximum erosion depth of 0.5 m. From Fig. 9, it can be seen that more sediment is deposited upstream of the buildings. This results in a decrease in the amount of sediment flowing downstream of the residential area and a narrowing of the hazardous area downstream of the residential area.

The same trend was observed in the analysis results for 0.3 m and 1.0 m.

Assessment of risk due to debris flow velocity

In July 2018, as shown in Fig. 10, many automobiles on a steep road were washed away by a debris flow in Yano Higashi, Aki, Hiroshima City, Japan. The flow depth of the debris flow on the road was less than 20 cm, and the velocity was about 1–2 m/s, which is not the fluid force that would have swept away automobiles if they were in clear water. This is considered to be due to tire slippage caused by the presence of fine sediment. In this risk assessment, the maximum flow velocity of 1 m/s is used as a threshold value and

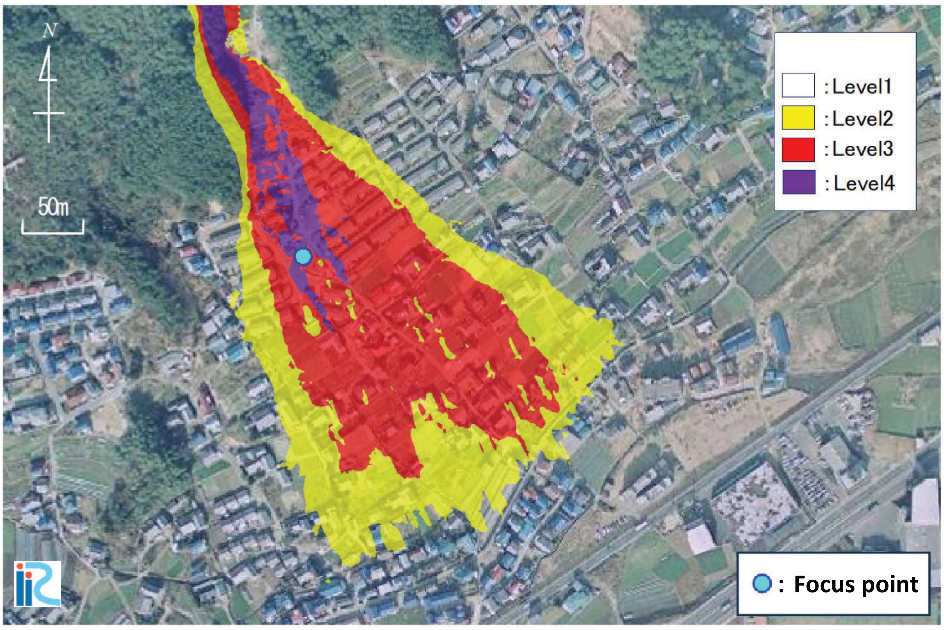


Fig. 6 Risk distribution (Depth-Max: not consider houses)

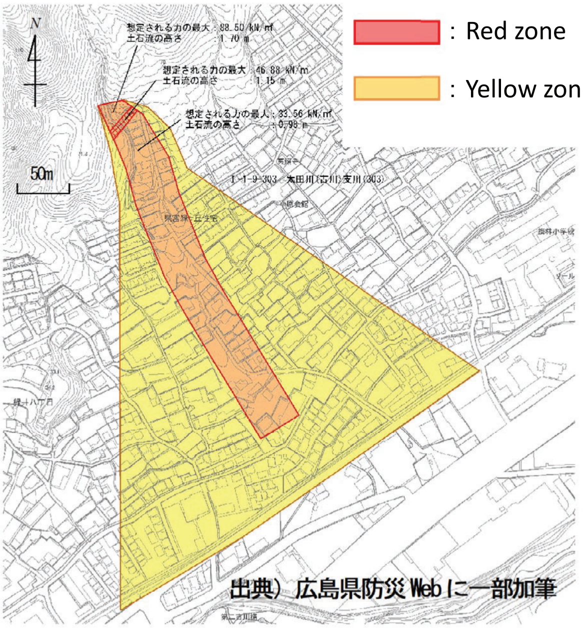


Fig. 7 Sediment disaster risk areas by Hiroshima Prefecture

is attempted to evaluate the risk using the velocity of the debris flow.

Figure 11 shows the numerical analysis results without considering buildings, and Fig. 12 shows the results with buildings. The same trend is observed when buildings are considered, and a comparison between Figs. 8 and 12 shows that the hazardous areas of Level 2–Level 4 are almost similarly distributed. This is one of the characteristics of debris flows. If the flow is only water, the flow rate changes little in the downstream direction, so a slower road gradient slows down the flow velocity and deepens the water depth, while a steeper road gradient speeds up the flow velocity, and the water depth becomes shallower. On the other hand, in the case of debris flow, the discharge of debris flow decreases with the deposition of sediment from debris flow, and this is because the flow velocity often slows down as the flow depth decreases.

Assessment of risk due to destruction house

The Building Standards Law and other laws ensure that buildings are resistant to seismic shaking. However, there are no provisions against debris flows, so buildings may collapse if they are hit by debris flows. In particular, the destruction of wooden houses by debris flows occurs very often. The safest evacuation method is considered to be to move to a nearby shelter before a heavy rainfall, but evacuation to a shelter is often difficult at night or during a heavy rainfall. On the other hand, vertical evacuation by moving to the second floor or higher of a house is also effective as a means of ensuring safety, but moving to the upper floors is effective only when there is no danger of the house collapsing. Therefore, it is necessary to have a guideline for the level of debris flow that would cause a building to collapse.

The authors Nakamoto et al. (2018) used numerical simulations of debris flows to evaluate the stresses acting on buildings and reproduce relatively well the conditions of total and partial destruction of buildings by debris flows. The

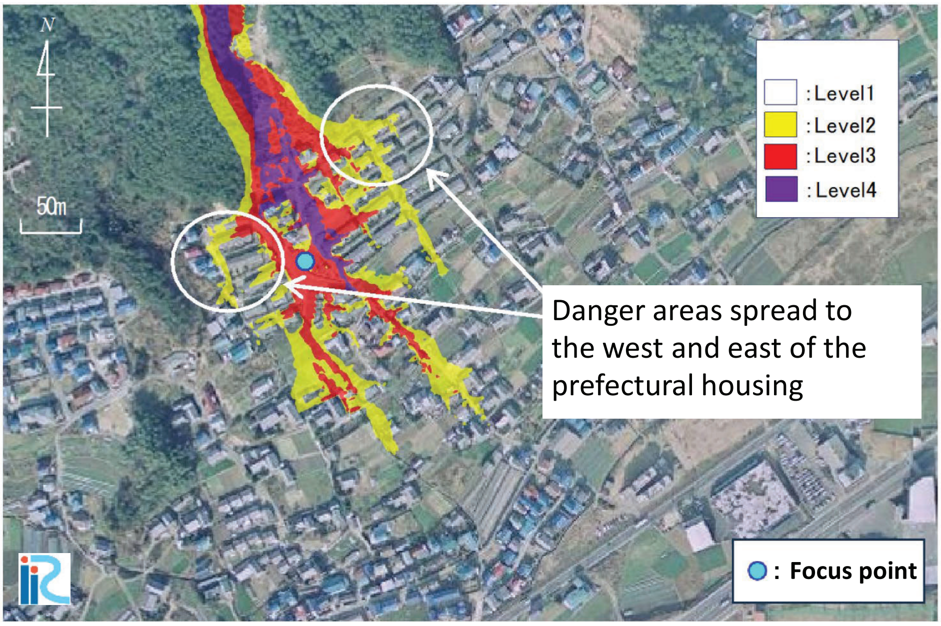


Fig. 8 Risk distribution (Depth-Max: consider houses)

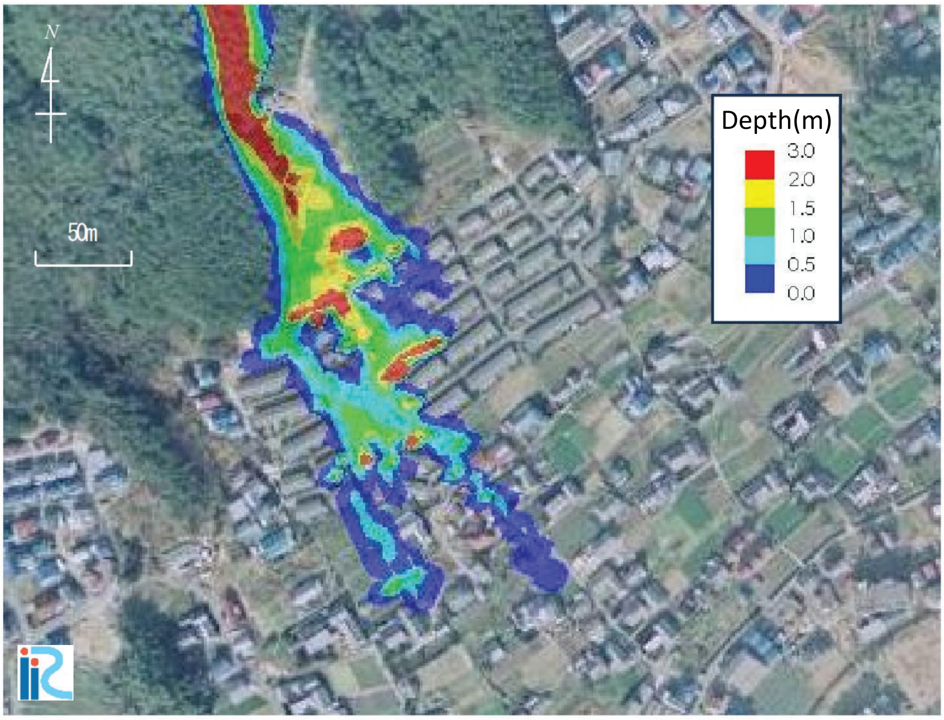


Fig. 9 Maximum flow depth (maximum erosion depth 0.5 m)

stresses acting on houses due to debris flows (F_{hx}) can be evaluated as the sum of the static pressure from the hydrostatic approximation and the fluid force from the kinetic energy, using the following equation:

$$F_{hx} = \frac{1}{2}\rho_m g h^2 \cos\theta + \rho_m h u^2 \quad (5)$$

where g is the gravity, and ρ_m has the following relationship:

$$P_m = (\sigma - \rho)\,\overline{c} + \rho \quad (6)$$

In this section, the risk of building destruction by debris flows is evaluated using the stress acting on the building as an indicator, based on Eq. (5). The danger zone for building destruction by debris flows is defined as the area where the maximum stress acting on the building is greater than or equal to the critical stress for building destruction. Although

Fig. 10 Debris flow in Yano Higashi, Aki, Hiroshima City, Japan. (Courtesy:Hiroshima Home TV)

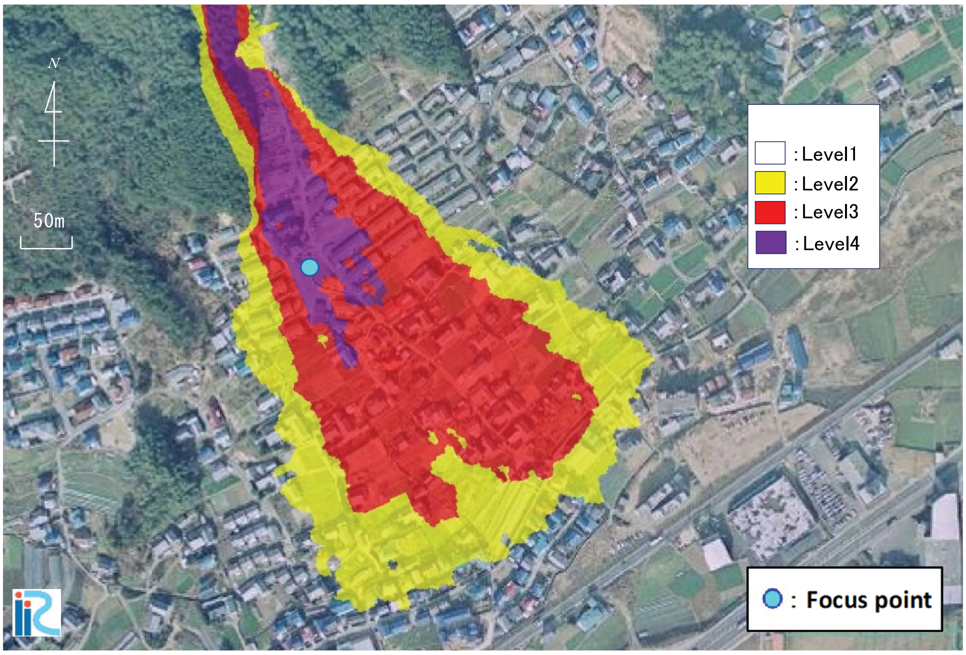


Fig. 11 Risk distribution (VelocityMax: not consider houses)

the critical stress for building destruction is considered to vary depending on the structure of the building, the threshold of the critical stress for building destruction was set at 200 kN/m based on the results of the reproduced calculations by the authors Nakamoto et al. (2018). Here, in order to assess the risk to the land geometry, the building is not considered.

Figure 13 shows the results of the analysis of the hazardous area due to building failure, indicating that some of the buildings near the stream exit are included in the Level 2 hazardous area. However, the hazardous area does not extend to the downstream area. Compared to the hazardous area based on the flow depth of the debris flow (Fig. 6), many of the areas inundated by debris flows are outside the hazardous area for building destruction. In other words, even within the inundation area of a debris flow, the flow area of a debris flow with strong fluid force enough to destroy a building is narrow, indicating that many buildings can be secured by vertical evacuation, such as moving to the second floor or higher of a building.

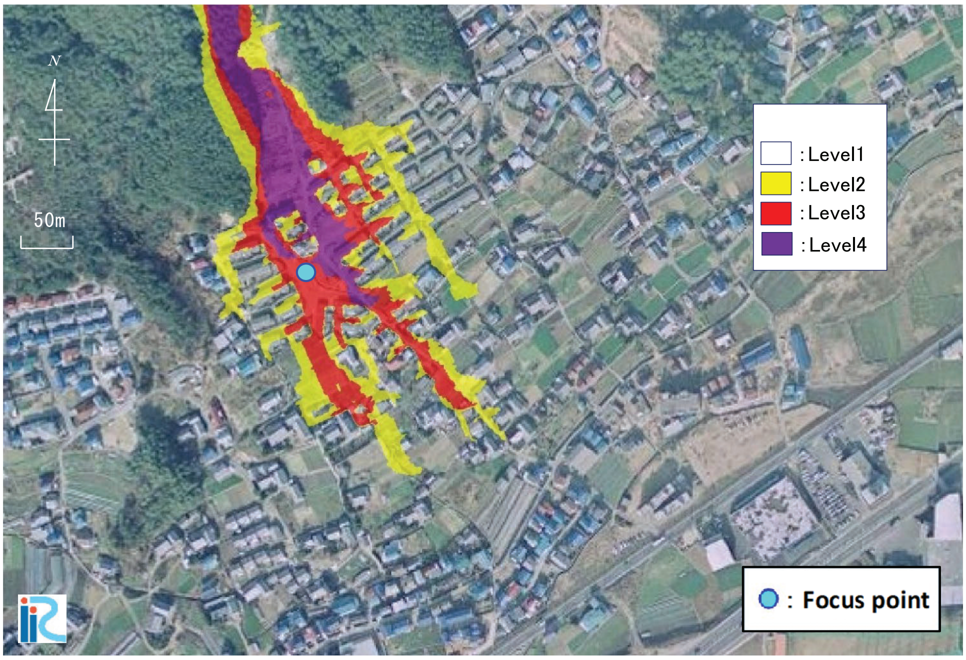


Fig. 12 Risk distribution (VelocityMax: consider houses)

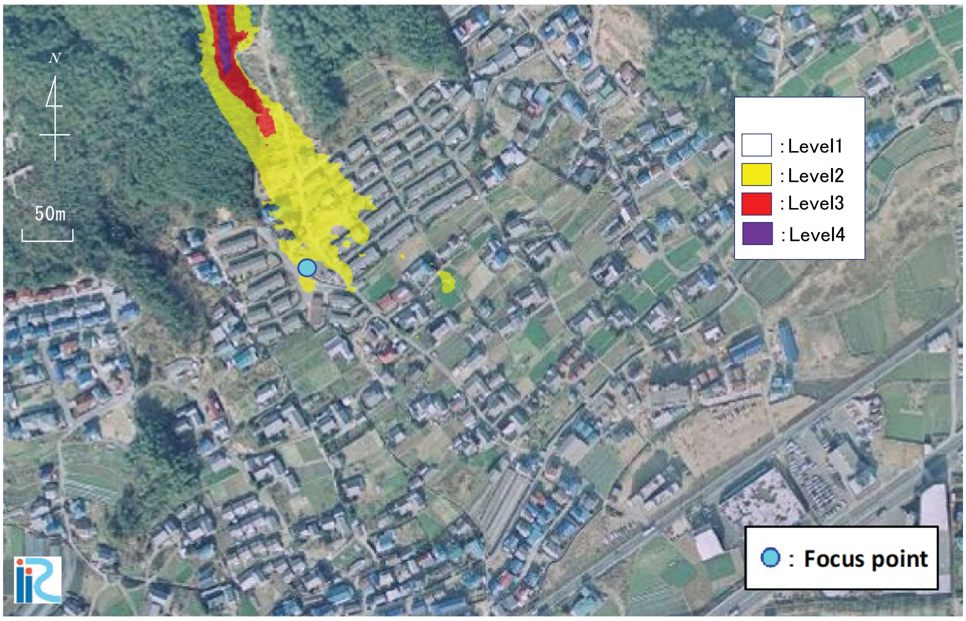


Fig. 13 Risk distribution (destruction house)

Assessment of risk due to sediment deposition

Sediment flowing into residential areas causes damage not only by crashing into and destroying buildings but also by deposition on roads and into gardens of houses. The accumulation of sediment on roads causes traffic disruptions, and the removal of sediment after a disaster requires a great deal of time and labor for restoration.

Therefore, by using the depth of sedimentation of debris flows inundating residential areas as an indicator, the degree of risk due to sediment deposition is evaluated.

The hazardous area for sediment accumulation due to debris flow was defined as a sediment deposition depth of 0.5 m or greater. Here, in order to assess the risk to the land geometry, building is not considered.

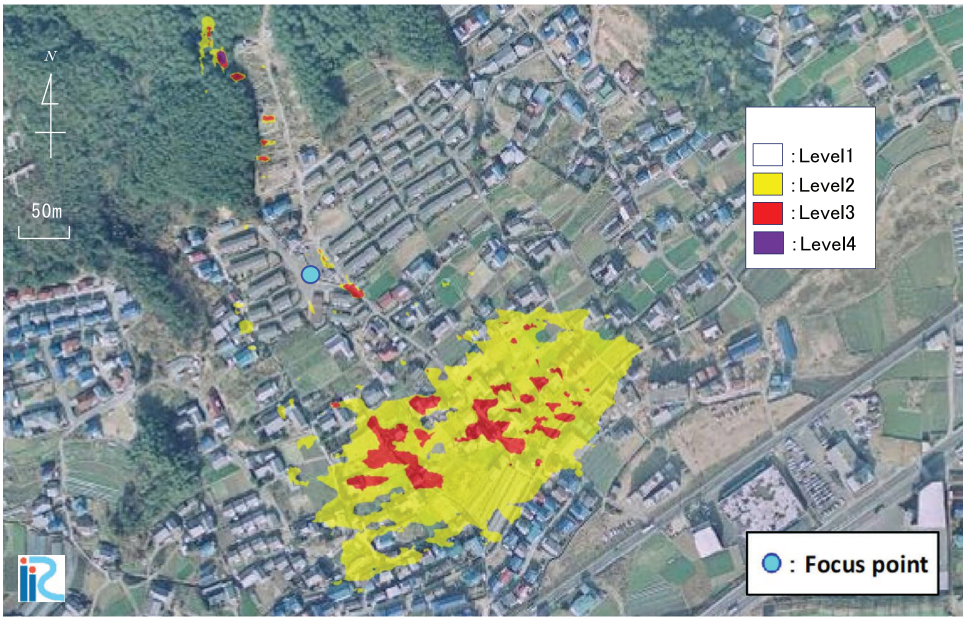


Fig. 14 Risk distribution (sediment deposition)

Figure 14 shows the results of the analysis of the hazardous area due to sediment deposition, which indicates that the Level 2 hazardous area extends downstream in the debris flow inundation zone. Compared with the building destruction hazard area (Fig. 13), there is almost no overlap between the two areas. In other words, the area away from the stream exit does not suffer from severe damage, such as the destruction of buildings, but it is not completely free from damage due to the accumulation of sediment on the site and the inflow of sediment into the houses.

The blue dots in Figs. 13 and 14 indicate that the respective hazard levels are Level 2 in Fig. 13 and Level 1 in Fig. 14. Thus, it is important to evaluate the hazard level for various types of damage when considering the hard and soft countermeasures against debris flow damage.

Conclusions

In this study, the spatial distribution of hazard risk due to debris flows is discussed using a horizontal two-dimensional numerical simulation of debris flow, and the hazards are evaluated according to the type of damage. The results and findings of this study are summarized as follows:

- Based on the results of numerical simulations of debris flows, the hazardous area for debris flows, by evaluating the risk of debris flows, was visually captured.
- The hazardous area is greatly affected by the presence or absence and arrangement of building location. The method used in this study can indicate changes in the hazardous area and evaluate the degree of danger from a debris flow inundating a residential area.
- In the case of debris flow, the discharge of debris flow decreases with the deposition of sediment from debris flow, and this is because the flow velocity often slows down as the flow depth decreases.
- Compared to the hazard areas between the flow depth of the debris flow and the building destruction, many of the areas inundated by debris flows are outside the hazardous area for building destruction. In other words, even within the inundation area of a debris flow, the flow area of a debris flow with strong fluid force enough to destroy a building is narrow, indicating that many buildings can be secured by vertical evacuation, such as moving to the second floor or higher of a building.
- Compared to the hazard areas between the building destruction and the sediment deposition, there is almost no overlap between the two areas. In other words, the area away from the stream exit does not suffer from severe damage, such as the destruction of buildings, but it is not completely free from damage due to the accumulation of sediment on the site and the inflow of sediment into the houses.
- It is important to evaluate the hazard level for various types of damage when considering the hard and soft countermeasures against debris flow damage.

Author contribution H.N. and H.T. and M.F.wrote the main manuscript text. All authors reviewed the manuscript.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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