The heavy rain in July 2018 led to debris flows in mountainous residential areas, causing severe damage in western Japan. In Japan, mountainous streams where debris flows originate from the valley exit are often concealed by culverts upstream of the residential areas. Therefore, during the disasters that occurred in Kobe City and Hiroshima City due to the heavy rain in July 2018, culverts that existed upstream of the residential area were blocked by sediment, and debris flows moved down along the roads connected to the culverts. Furthermore, the slopes of the roads were steep, and debris flow in Kobe showed high mobility owing to the presence of fine sediment from the deposited granite sediment layer. Therefore, sediment extensively encroached into the residential areas. In this study, we aimed to analyze the disaster situation focusing on culverts and roads existing in residential areas based on field surveys. We conducted numerical simulations by applying a high-resolution digital elevation model (DEM) and digital surface model (DSM) to describe the disaster scenario. From simulation results, applying DSM in residential area described the disaster situation better than DEM. Furthermore, we considered disaster mitigation planning and proposed safe landuse in residential areas based on the simulation results.

Key Words: 2018 July heavy rain, debris flow, residential area, culvert, road, numerical simulation

1. INTRODUCTIONS

Due to the heavy rain in July 2018, many sediment-related disasters occurred in mountainous residential areas and caused serious damage in western Japan. In Japan, residential areas located in alluvial fans often develop up to the steep slopes of mountainous areas due to scarcity of land. Therefore, severe damage to both life and property occurred in residential areas due to debris flows caused by the heavy rain in July 2018.

Mountainous streams where debris flows originate from the valley exit are often concealed by culverts upstream of the residential area. Furthermore, roads in mountainous areas have been constructed by filling valleys, and culverts are used for drainage purposes. Culvert drainage system performs effectively in normal rainfall conditions. However, it is reported that sometimes these are blocked by sediment and woody debris in large rainfall events causing sediment-related disasters. Moreover, the residents may not be able to recognize the risk of debris flows because the flow path is concealed by culverts in residential areas.

During the disaster that occurred in Kobe City and Hiroshima City due to the heavy rain in July 2018, the culverts located upstream of the residential areas were blocked by sediment, and debris flows moved
down along the roads connected to the culverts. Furthermore, the road slopes were steep in both areas, and debris flow in Kobe showed high mobility due to the presence of fine sediment of granite. Sediment extensively encroached into the residential areas and caused huge damage. These disasters have occurred in typical mountainous residential areas in Japan. Therefore, the risk of debris flow damage seems to be similarly high in other mountainous residential areas.

In this study, we aimed to analyze the debris flow disaster situation, mainly focusing on culverts and roads situated in residential areas, through field surveys. We also conducted numerical simulations to describe disaster situations such as debris flow influence area and detailed risk distribution. By applying simulations, we also aimed to provide information for disaster mitigation measures. We considered and proposed measures with safe land use in residential areas instead of usual measures, such as sabo dams as structural measures and evacuation and warning as nonstructural measures. Generally, residents seem to receive the usual measures provided by the local government passively. Therefore, we also aimed to describe the effectiveness of the simulations. Simulations enable residents to not only evaluate the provided measures but also consider other measures, leading residents to play a major role in effective disaster mitigation works.

2. TARGETS OF 2018 DISASTER

We focused on two debris flow disasters that occurred in residential areas due to the heavy rain in July 2018: Kobe City and Hiroshima City cases.

(1) Kobe City, Hyogo Prefecture

Owing to the heavy rain in July 2018, debris flow occurred in Shinohara-dai, Kobe City, Hyogo Prefecture on July 6th, 2018. A small landslide occurred at the upstream of the residential area and caused a debris flow that expanded due to erosion when moving down toward the mountain stream and finally encroached into the downstream residential area (see Fig.1). The target area’s basin is approximately 0.06 km². The volume of the landslide was estimated to be approximately 3900 m³, including voids, calculated from the difference between before and after the disaster DEM captured with airborne LIDAR. In the riverbed of the mountain stream where the debris flow moved down, there was a thick layer of weathered granite sediment deposit which was eroded by this debris flow. The particle size test showed that the ratio of clay and sand with a particle size of 2 mm or less was 70 %. When we conducted a field survey 10 days after the disaster, we found deposition of the mentioned fine sediment due to debris flow on the valley exit, just upstream of the residential area. Furthermore, when walking on the deposition, we noted that some parts became muddy, and seemed to change from solid phase to fluid phase. Contrarily, we also found sediment with diameters of several centimeters on the torrent riverbed, and some gravel with 0.6–1.0 m diameter also existed.

As shown in Fig.2 a, a cross-river structure is set downstream of the torrent near the valley exit. The torrent is connected to the culvert in downstream, as shown in Fig.3 and Fig.4. The vertical shaft approximately 4.0 m depth is located upstream of the culvert. Two hume pipes with a diameter of 0.8 m are buried in parallel at the bottom of the shaft, as shown in Fig.4.

From interviews and reports of the disaster⁴, we found that the culvert at the valley exit was blocked with sediment when debris flow occurred. Therefore, the flow moved down on the road, as shown in Fig.2 b, instead of moving inside the pipe connected to the culvert. When the flow moved along the roads in the residential area, flooding and deposition occurred widely and caused much damage.

![Fig.1 Sediment transport outline in Shinohara-dai (left: blue arrows showing the sediment movement direction, added in the report⁵) and bird’s eye view of the target basin (right).](image-url)
Fig. 2 Sediment movement in Shinohara-dai residential area (left: showing ortho photo taken from Geospatial Information Authority of Japan, GSI) and situation of the valley exit after the disaster (right).

Fig. 3 Valley exit situation in Shinohara-dai (left: photo captured during field survey) and vertical shaft (right: photo captured after excavation from upstream).

Fig. 4 Details of the culvert on valley exit in Shinohara-dai.
The sediment-moved area, including the deposition area, was estimated as 7,400 m² from the traces. In Fig. 2 left, the sediment moved area shown in Fig. 1 left is indicated in red color on an ortho photograph taken from the Geospatial Information Authority of Japan (GSI). In the residential area, sediment deposition occurred on the roads extending from the valley exit. Because the flow moved along the roads, a part of the sediment moved area extended outside of the high-risk area for debris flow, designated by the local government. Most of the building damage in residential area was caused by inundation, including sediment deposits above/below floor level, and structures of some buildings’ were severely affected leading to their collapse.

However, the building located at the valley exit was directly hit by debris flow, as shown in Fig. 2 c. Some of the walls were damaged probably due to the direct impact of sediment and gravel. The road upstream of the building c located eastward had a slope of 1/10 (as shown in Fig. 2 b). After the disaster, the debris flow movement trace was found to be approximately 0.7 m in height from the road surface.

It had been reported that a small-scale sediment runoff occurred around 15:00 on July 6th. Afterwards, a larger-scale runoff, assumed to be the debris flow event, occurred around 20:30 on July 6th.

In Fig. 5, the rainfall conditions in Shinohara-dai is described, using Meteorological Agency Radar-rain gauge analyzed precipitation (Mesh No. 52350187). From 0:00 on 4th July to 15:00 on 6th July, the cumulative rainfall was approximately 600 mm and the largest hourly rainfall was 35 mm. During that period, there were several rainfall elements consisting of 6 h–7 h of continuous precipitation with 100 mm–150 mm, and the rainfall continued for three days. Although individual element was not significantly large, the elements occurred several times in 3 days. The hourly rainfall was not considerably large at that time. However, the long continuous rainfall resulted in a large cumulative rainfall and caused the debris flows.

Shinohara-dai is a residential area located on a 3–5 degrees, which is relatively steeper and can be classified as debris flow deposition area, as shown in Fig. 6. Because the debris flow torrent was concealed by the culvert and connected to the road, the residents might not be able to recognize the risk of debris flows.

(2) Hiroshima City, Hiroshima Prefecture

In Yanohigashi 7, Aki-ku, Hiroshima City, Hiroshima Prefecture, landslides and debris flows occurred from four adjacent torrents around 20:00 on July 6th due to the heavy rain in July 2018. In this area, the torrent, called No.13, was severely affected. The target area’s basin is approximately 0.12 km² and the average slope is approximately 22.2 degrees. The No.13 torrent consists of two branches: left and right. The volume of sediment that moved to the downstream dam was estimated to be approximately 12,500 m³, including voids, calculated from the difference between before and after the disaster DEM taken with airborne LIDAR. The estimated sediment volume is the total of the both branches. It is assumed that debris flow occurred and developed due to riverbed erosion while moving down the torrent. A check dam for forest conservation was constructed downstream of the branches in March 2018 as shown in Fig. 7. The effective height, length, and top width of the dam is 6.5 m, 25 m, and 2.5 m, respectively. The debris flow caused a sediment deposition of 1,700 m³ upstream of the dam with 2–3 degrees. In addition, 10,800 m³ of sediment moved to the downstream residential area. In both branches, exposed basement rock existed with 20 m height from ground surface located in several tens of meters upstream of the dam. Most of the geological characteristics were granite while some rhyolite and mudstone were also found. When we conducted a field survey on August 1st 2018, the largest diameter of the dam’s upstream deposit was approximately 50 cm and several centi-
meters in diameter were also found, as shown in Fig.7.

Figure 8 left shows the moved sediment distribution of the disaster and the high risk area for debris flow, designated by the local government after the 2018 disaster. In addition, the damaged buildings are indicated in Fig.8 left.

In Fig.8 right, the bird’s eye view of the No.13 torrent including the upstream basin is shown. In the upstream side of the high-risk area, buildings were destroyed and a deposition of several meters occurred. The arrow b in Fig.8 shows the road located between the destroyed buildings in upstream, and the arrow c shows the road located between the destroyed buildings downstream of arrow b. Debris flow occurred and moved along the roads b and c.

Fig.7 Check dam for forest conservation in Yanohigashi torrent No.13 (upper left), deposition of dam upstream (upper right) and upstream situation of the dam (bottom).

Fig.8 Sediment movement in Yanohigashi torrent No.13 (left: added in Hiroshima Prefecture’s report6)) and bird’s eye view of the target basin(right).

Fig.9 Valley exit situation in Yanohigashi torrent No.13 (location of a-c is described in Fig.7).
Furthermore, buildings located at the north-side outer edge of the high-risk area downstream were damaged, as shown in Fig. 8 d, and significant deposition occurred around the buildings. Within the northeast of the high-risk area shown in Fig. 8 e, all roads in the north–south direction were exposed to deposition, indicating that the entire area is highly hazardous.

On the downstream of the dam, the underground channel was set at the bottom of the roads covered with gratings, as shown in Fig. 9. However, the box culvert with 80 cm height and 140 cm width was blocked with sediment when debris flow occurred, as shown in Fig. 9 a. Therefore, the debris flow moved along the road from the culvert point instead of the underground channel, similar to that in the Kobe case. When the debris flow moved along the roads, as shown in Figs. 9 b and c, buildings facing the road were seriously damaged.

3. DEBRIS FLOW SIMULATIONS

For the debris flow simulations, we used a geographic information system (GIS)-related Hyper KANAKO system7). In the Hyper KANAKO system, the numerical simulation of the debris flow was based on the model presented by Takahashi8),9) considering the erosion/deposition due to equilibrium concentrations. The model also included equations of momentum considering riverbed shearing stress, continuation, riverbed deformation, and erosion/deposition. Moreover, an integrated model10),11) incorporating the influences on one-dimensional (1D) simulation areas such as the steep mountainous valley area and 2D simulation areas, such as alluvial fans, was applied. The authors have applied Hyper KANAKO to other debris flow cases and confirmed the validity of the behaviors and distributions in residential areas12),13). For the simulations, we assumed that culverts located on the valley exit were blocked and debris flows moved down on the roads from the culverts located in both target areas.

(1) Landform data

We applied the DEM data, the ground elevation in which the heights of the buildings and trees were excluded, and the DSM data that included both heights of the buildings and trees with a 1 m mesh resolution. Generally, DEM data are applied for simulations and consider the landform change. For the simulation, we used the DEM and DSM data recorded before the 2018 disaster using airborne LIDAR.

For the simulation conditions, the upstream torrent where debris flow occurred and the developed area were considered for 1D simulation, and the downstream alluvial fan residential area was considered for 2D simulation. In the 1D area, we applied DEM data for both targets to avoid the effect of trees in the torrents. In Kobe, 1D area was set from the landslide shown upstream of the torrent to the valley exit, as shown in Fig. 4. Yanohigashi torrent No.13 in Hiroshima consisted of two branches, and the transported sediment was larger from the right branch located on the north side. Because the Hyper KANAKO system did not correspond to confluences in the 1D area, we set the right branch as the 1D area. On the upstream side of the right branch, a landslide steeper than 30 degrees existed. Therefore, we set the 1D upstream end as downstream of the landslide, and the downstream end as point a shown in Fig. 8 located in the high-risk designated area. The check dam for forest conservation located in the 1D area was described as a fixed bed landform from the DEM data.

Fig. 10 Simulation target in Shinohara-dai, Kobe (background ortho photo from GSI, 2D area is same as Fig. 2 left red square outline).

Fig. 11 Simulation target in Yanohigashi torrent No.13, Hiroshima (background ortho photo provided by Hiroshima Prefecture was taken after the disaster).
The river width was set as 10 m, and the interval of simulation points was set as 5 m in the 1D area for both targets, as shown in Fig.10 and Fig.11. The Rokko River is described as the R river in Fig.10.

In the 2D area, we applied DEM and DSM data for comparison. Because the data were obtained with high resolution, both data described the building foundation in the residential area. In DSM, the building heights are also included. Therefore, the elevation difference between buildings and roads is more visible in DSM than in DEM. This is because the debris flow concentrated on the road owing to the elevation lower than the surrounding area can be expressed in DSM. On the other hand, because the DSM expresses the building as the ground height, the ground height does not change even when facing a large fluid force. Therefore, the simulations using DSM also sufficiently assume strong buildings that never collapse. Considering the simulation mesh resolution that can describe the buildings and roads in residential areas, we set 2 m mesh for Kobe and 1 m mesh for Hiroshima. For both targets, we set the landform as a fixed bed in 2D areas so that erosion cannot occur except for the debris flow deposition to be eroded by subsequent flows.

(2) Simulation conditions

Considering the debris flow scenarios, we assumed that debris flow occurred due to the upstream landslide and also developed during the flow moving down the torrent caused by the river bed erosion in Kobe. The landslide volume was 3900 m$^3$ including voids, and it was reported that there were several rainfall elements with total precipitation of 100–150 mm before the sediment runoff occurred on 15:00 July 6$^6$. When setting the supplied hydrograph of the debris flows, there are several methods to consider which rainfall element affected. Here, we assumed that one element with total precipitation of 100–150 mm in the target basin affected the debris flow. When 100 mm rainfall occurred and the runoff rate was considered to be 0.7 in the mountainous area, the total runoff was calculated as 4200 m$^3$ for the 0.06 km$^2$ basin. The upstream landslide volume without void was calculated as 2535 m$^3$ when $C^*$, volumetric concentration of the sediment in movable bed, was 0.65. The total volume of water and sediment without voids was 6735 m$^3$, considering the upstream debris flow occurred, and the volumetric concentration of the sediment in debris flow is calculated as 0.37. It is known that the debris flow scale does not show a linear relationship with rainfall, and the peak discharge of the debris flow can be larger than the value estimated from the rainfall to the target basin$^{14}$. Furthermore, although the water storage and release mechanism from the mountains is still not explained, it is presumed that water from the rainfall and also stored water in the mountains can be released at once in a short time when causing debris flows$^{12}$. Therefore, based on the reports of debris flow observed in Japan$^{15}$, we supplied discharge from the upstream end in the trapezoid-shape hydrograph. We set with a peak discharge rate of 22 m$^3$/s in a continuous time of 360 s (0–60 s increasing to peak from 0, 60–300 s peak continuing, and 300–360 s decreasing to 0 from peak). The peak discharge of 22 m$^3$/s corresponded with the estimated value calculated from the Manning’s formula with debris flow trace acquired in the field survey. Moreover, the width of the debris flow torrent was approximately 8–11 m and the eroded depth of the torrent was approximately 1–3 m. Therefore, we set 10 m width and 2 m movable bed layer to be eroded in the 1D area in Kobe.

We referred to the field survey in Kobe and considered 0.01 m as the representative particle diameter for sediments behaving as a solid phase in debris flow. The ratio of clay and sand with a particle size of 2 mm or less was 70%. Therefore, we considered the finer materials behaving as a fluid phase in debris flow. Applying Takahashi’s equilibrium concentration$^{8,9}$, we can explain that a higher fluid phase density debris flow will behave in a higher equilibrium concentration on the same slope in comparison with that of a lower density flow. This can explain why a higher fluid density debris flow will reach a mildly sloped area downstream compared with that of a lower density. For the usual stony debris flows in Japan, a fluid density value of 1,180 kg/m$^3$ can describe some of the fine sediment behaving as a fluid phase. However, for the Kobe case containing a large amount of fine particles, we also considered a fluid density value of 1,400 kg/m$^3$ and a debris flow scenario when most of the fine sediments behaved as a fluid phase, as indicated by recent studies$^{16,17}$. We considered the four cases listed in Table 1. Other parameters used in the simulation are presented in Table 2.

In Hiroshima, we assumed that debris flow occurred and developed during the flow moving down the torrent caused by river bed erosion. From the difference between before and after the DEM, aerial photos, and field surveys, we set sediment volume moved downstream as 10,000 m$^3$, including voids. In the 1D area, we set the movable bed layer as 3 m in thickness with a 10 m torrent width. From the flow trace in both side banks of the check dam for forest conservation, we obtained a peak discharge of 158 m$^3$/s using a weir formula with a flow coefficient of 0.6. We considered debris flow occurring only from the right branch, which showed larger sediment movement. We set the scenario because we assumed...
Table 1 Simulation cases in Kobe.

| Case | 2D area landform data | Fluid phase density (kg/m³) |
|------|-----------------------|-----------------------------|
| 1    | DEM                   | 1,180                       |
| 2    | DEM                   | 1,400                       |
| 3    | DSM                   | 1,180                       |
| 4    | DSM                   | 1,400                       |

Table 2 Simulation parameters.

| Parameters                               | Value (unit) |
|------------------------------------------|--------------|
| Simulation time                          | 600 (s)      |
| Time step                                | 0.01 (s)     |
| Representative grain diameter (m)        | 0.01 (m) Kobe |
| Mass density of sediment                 | 2,650 (kg/m³) |
| Internal friction angle                  | 37 (deg)     |
| Concentration of movable bed             | 0.65         |
| Erosion velocity coefficients            | 0.0007       |
| Deposition velocity coefficient          | 0.05         |
| Manning’s coefficient                    | 0.03 (s/m²)  |

Table 3 Simulation cases in Hiroshima.

| Case | 2D area landform data | Fluid phase density (kg/m³) |
|------|-----------------------|-----------------------------|
| 5    | DEM                   | 1,180                       |
| 6    | DSM                   | 1,180                       |

that the peak discharge of debris flow significantly affected the flooding and deposition in the residential area downstream of the dam. From the trial simulations, we confirmed that the debris flow developed by erosion was approximately 160 m³/s at the dam location when supplying water with a peak discharge of 45 m³/s from the upstream end. Therefore, we supplied discharge from upstream end in the trapezoid-shape hydrograph, setting with a peak discharge rate of 45 m³/s in a continuous time of 300 s (0–50 s increasing to peak from 0, 50–250 s peak continuing, and 250–300 s decreasing to 0 from peak). We set a shorter continuous time in Hiroshima assuming that the debris flow scenario occurred and developed from erosion, while in Kobe, we assumed the scenario from landslide and erosion.

From the field survey and reports, we set 0.1 m as the representative particle diameter. Because the finer materials were less than those in Kobe, we set the usual stony debris flow fluid density value of 1,180 kg/m³. We considered the two cases for Hiroshima listed in Table 3, and other parameters used in the simulation are listed in Table 2.

4. SIMULATION RESULTS

(1) Kobe City

Figure 12 and Figure 13 present the 2D-area simulation results for Kobe. Figure 12 presents the deposition thickness after the simulation, and Figure 13 presents the maximum height (flow depth + deposition thickness) during the simulation. In the 1D area, the same landform was set from DEM data in all cases. However, building height was expressed in the 2D area upstream close to the valley exit in Cases 3–4 compared to Cases 1–2. Therefore, significant deposition higher than 500 cm appeared upstream of the buildings close to the valley exit in Cases 3–4. In the Hyper KANAKO system, an integrated model incorporating the influences on 1D and 2D simulation areas was applied. Therefore, the riverbed elevation and flow depth in the boundary, 1D downstream and 2D upstream, influenced each area. Therefore, the deposition occurring in the 2D upstream influenced the riverbed variation in 1D downstream and the effect spread to the upstream side. Therefore, the sediment volume moving into the 2D area as the solid phase changed in each case. In cases with a fluid density of 1,180 kg/m³, Case 3 (3,800 m³), was smaller than that in Case 1, which was 6,600 m³. In cases with a fluid density of 1,400 kg/m³, Case 4 (5,000 m³) was smaller than Case 2 (7,000 m³). Here, the sediment volume included voids. In both fluid density values, DEM showed larger sediment movement to the 2D area. Furthermore, Cases 2 and 4 showed larger sediment movement with a higher fluid density value of 1,400 kg/m³ compared to those of Cases 1 and 3 with 1180 kg/m³. In Cases 2 and 4, because of the increase in sediment mobility from high fluid density, the difference between DEM and DSM was 1.3 times, which was smaller than 1.7 times between Cases 1 and 3.

In Cases 1–2 with DEM, the deposition and maximum height spread widely in the 2D area from the valley exit. In Case 1 with a density of 1180 kg/m³, the result showed higher than 500 cm around the valley exit. In Case 2 with a density 1400 kg/m³, the range showing higher than 500 cm was smaller than that in Case 1, but the range higher than 100 cm was larger than that in Case 1 to the downstream side. Therefore, the sediment moved down to the downstream side in Case 2 more than that in Case 1. In Case 3–4 with DSM, we can see higher deposition and maximum height on roads between buildings from the valley exit. The debris flow behavior in the 2018 disaster moving along the roads and part of the flow extending to the designated area, as shown in Figure 2, was better described in DSM cases than in DEM cases. Furthermore, the sediment moving along the road to the downstream was described in Case 4 with 1400 kg/m³ corresponding to the disaster situation.
Fig. 12 Simulation results, deposition at simulation end in Kobe (background ortho photo from GSI).

Fig. 13 Simulation results, maximum height (flow depth + deposition thickness) during the simulation in Kobe (background ortho photo from GSI).

(2) Hiroshima City

Figure 14 and Fig. 15 present the 2D-area simulation results for Hiroshima. Figure 14 presents the deposition thickness after the simulation, and Fig. 15 presents the maximum height (flow depth + deposition thickness) during the simulation. In the 1D
area, landform was set from DEM in both Cases 5 and 6. The moved sediment volume was 7700 m$^3$ in Case 5 with DEM and 6500 m$^3$ in Case 6 with DSM, including voids. The difference between Case 5 and Case 6 was 1.2 times, which was smaller than that in Kobe, and the influence of the deposition in the 2D upstream area to the 1D downstream area appeared to be smaller.

Because we set the scenario that culvert was blocked when debris flow occurred, the flow moved along the road from the valley exit. In particular, the concentration of the flow and significant deposition on roads a and b were described in Case 6 with DSM. Focusing on the upstream side around the valley exit, the range with deposition and maximum heights higher than 300 cm and 500 cm, respectively, were larger in Case 6 than those in Case 5. The location of damaged buildings and substantial deposition in the disaster corresponded to the Case 6 results, which showed higher values compared to those in the surrounding area. Furthermore, Case 6 showed a deposition and maximum height higher than 100 cm from road b to road c, as shown in Fig. 8 and Fig. 9. In Case 5, deposition and maximum height higher than 100 cm from road b to road c were expressed, but the surrounding areas of roads b and c were higher than

![Fig.14 Simulation results, deposition at simulation end in Hiroshima (background ortho photo provided by Hiroshima Prefecture captured after the disaster).](image1)

![Fig.15 Simulation results, maximum height (flow depth + deposition thickness) during the simulation in Hiroshima (background ortho photo provided by Hiroshima Prefecture captured after the disaster).](image2)
100 cm. Therefore, the concentration of the flow and deposition on roads b and c was not described in Case 5. Comparing deposition and the disaster situation of point d shown in Fig.8, the edge of the designated area, deposition, and maximum height, which are larger than 100 cm, are described in Case 6. In addition, within the north–east side from point e in the designated area as shown in Fig.8, the road to the north–south exists and deposition occurred on the road during disaster and shown in Case 6.

5. CONSIDERING DISASTER MITIGATION MEASURES

(1) Simulation usefulness for disaster mitigation measures

In Section 4, the debris flow behavior and the high-risk residential areas were shown from the simulation results based on real disasters and field situations. Applying DSM data in the alluvial fan area described the difference in elevation between the buildings and the road compared to DEM. Therefore, DSM simulations showed that the main flow of the debris flow concentrated and moved along the roads between buildings, which corresponded to the real disaster situation as compared to the simulations using DEM. Because the target debris flows have occurred in typical mountainous residential areas in Japan (Fig.1 and Fig.8 right, bird’s eye view), the risk of debris flow damage appears to be similarly high in other mountainous residential areas. If we can set high possibility scenarios of the disasters and apply DSM in residential areas, debris flow simulations for residential areas can provide useful information for evaluating the detailed level of risk in other areas.

For disaster mitigation works, governments provide structural measures, such as setting sabo dams, and some hazard maps and evacuation plans as nonstructural measures to residents. To conduct effective disaster management, measures with and without structures must be coordinated. However, at present, they are often considered separately, and information is provided separately. Employing the simulations, will make it easier to consider both scenarios together. Simulations can be used not only to consider disaster situations, but also to plan and evaluate effective structures. Therefore, they will also be able to show the detailed risk distribution in residential areas, considering the sediment trapping effect of the structures. Furthermore, it will be possible for residents to verify the disaster prevention measures provided by the government and to consider and propose other disaster prevention measures in the area positively.

(2) Case study for measures through landuse

In general, sabo dams or check dams are used to prevent debris flows, and sediment occurring within the assumed debris flow scale can be trapped upstream of the dams. In Japan, large profile channel is prepared upstream of the dam. However, the channel downstream of the dam is often not adequately prepared. And it often becomes rather small and connected to roads or small drains. Therefore, though sediment can be trapped effectively upstream of the dam, some amount of the flow will move down from the dam and move along the roads. Recently, larger scale disasters compared to the assumed scale for disaster mitigation planning have occurred frequently, and some of the sediment might also move down from the dams.

Therefore, we considered a landuse method to mitigate the damage and let the debris flow move down safely in the residential area in conditions with or without dams in the upstream. This study aims to propose various ways to consider new disaster mitigation measures through landuse changes in residential areas based on the existing situation, instead of proposing just one best solution.

In order to consider safe landuse against debris flows in a residential area, we assumed to change the landform of the road from the valley exit as widening and extending to the Rokko River at a 10 m depth in Kobe. We applied the landform change in Case 4 (using DSM, fluid density of 1,400 kg/m³), which simulated the most life-like disaster situation. The target site is a residential area that spreads from the valley exit. In the disaster situation, some areas were relatively at low-risk for debris flow though located near the valley exit, as shown in Fig.1 right. Therefore, we assumed that there was space for transfer in neighboring areas. In addition, a road connecting to the Rokko River has already been constructed on the downstream side. Therefore, we proposed to extend the road to the upstream side and widen the existing road to consider the debris flows’ straight running characteristics.

The modified landform area is shown in Fig.16 left. The maximum change in width was 50 m near the valley exit and just upstream to the Rokko River. The center part of the road was set to approximately 25 m width. All the modified areas were lowered by 10 m from the original ground level.

In practice, the proposed landform change corresponds to the construction of a channel that works for debris flows to move down safely without causing damage to the residential area. Figure 16 center shows the simulation results of deposition thickness, and Fig.16 right shows the simulation results of the maximum height with the modified landform in Case 4. From landform changes, it is pos-
Considering countermeasures from land-use in Kobe Case 4, changing landform of the road existing from valley exit as widening and extending to Rokko River with 10 m depth (left: changed area; center: simulation results of deposition thickness; right: simulation results of maximum height).

Possible to reduce the damage because all the deposition and maximum height of the flow are within the channel works and do not show overflows.

On the other hand, the target Hiroshima Yanohigashi No.13 shows a different situation. Here, the upstream side of the high-risk designated area (northeast of e, shown in Fig.8 left) is almost entirely dangerous. The mountain is located on the northern side, and the residential area is located downstream of another debris flow torrent, called No.14, which exists on the southern side, as shown in Fig.8 right. In Kobe, the residential area spread to both sides of the high-risk designated area edge from the valley exit. Outside of the designated area seemed to be at relatively low risk except for the roads extending from the valley exit. However, in Yanohigashi No.13, almost the entire area is in danger, and there is no space for transferring in the neighboring safe area. In Yanohigashi No.13 upstream, buildings are located in a narrow area from the valley exit. On the upstream side of the high-risk designated area, almost all of the roads facing buildings showed deposition and maximum depth higher than 100 cm, which is located in a relatively high-risk area. In Yanohigashi No.13, the Yano River exists on the downstream side. However, in order to extend the road straight from the valley exit to the Yano River, building a new road through cutting the mountainside, which is large construction project, is required. It is difficult to utilize the original landuse in the residential areas to develop channel works by widening and extending roads. Therefore, the method proposed in Kobe is not suitable for Yanohigashi No.13.

(3) Issues in disaster mitigation measures through landuse

As one of the examples of countermeasures against debris flows through safe landuse, we proposed the construction of a channel by widening and extending existing roads in Kobe. The simulation was carried out and the effect was considered. Landuse changes need to be considered and discussed not only with the residents but also with the local government in several divisions, such as sabo or erosion controls, rivers, and roads. Therefore, to realize the proposed idea in actual situation, several issues still need to be resolved. However, setting sabo dams requires significant cost and time. With limited budget, it is difficult to set dams on all debris flow high-risk torrents, which exist in hundreds of thousands in Japan. On the other hand, nonstructures measures, such as warning and evacuation to avoid damage caused by disasters, are also difficult to implement because evacuation cannot be forced on residents. Therefore, considering a land-use method to mitigate the damage and allow the debris flow to move down safely in the residential area can become important but challenging measure to be realized. Considering the details, debris flow simulations can be an effective tool.

However, one method cannot be applied to all residential areas. We need to consider the differences in the location, landforms, and characteristics of each residential area. The method to prepare channel works using roads was effective in Kobe, but it cannot be applied in Yanohigashi No.13. Therefore, in Yanohigashi, constructing sabo dams is high priority and evacuating to a safe area outside of the residential area is necessary for effective mitigation works.

6. CONCLUSIONS AND FUTURE WORK

In this study, we considered the debris flow disaster due to the heavy rain in July 2018 focusing on culverts and roads existing in residential areas. We set two targets in Kobe and Hiroshima damaged by debris flows, which are typical mountainous residential areas in Japan. We found that streams where debris flows occurred extending from the valley were concealed by culverts upstream of the residential area.
We also found that the culverts were blocked with sediment when debris flows occurred, and the flow including sediment moved down along the roads.

We also conducted numerical simulations to describe disaster situations, such as debris flow influence area and detailed risk distribution. For the simulation, we assumed that culverts located on the valley exit were blocked and debris flows moved down along the roads from the culverts’ locations. We applied two landform data, DEM and DSM, for simulations. For the usual stony debris flows in Japan, a fluid density value of 1,180 kg/m$^3$ could describe some of the fine sediment behaving as a fluid phase. However, in Kobe, we found that the flow contained a large amount of fine particles, so we also considered a higher fluid density value of 1,400 kg/m$^3$ and a debris flow scenario when most of the fine sediments behaved as a fluid phase. In the Kobe simulation results, the DSM cases with 1400 kg/m$^3$, the range showing higher than 500 cm was smaller, but the range showing higher than 100 cm was larger on the downstream side along the road and corresponded to the disaster situation. In the Hiroshima results, the DSM case showed higher values along the roads, indicating that flow concentrated on the roads and moved down, which described the disaster situation.

By applying simulations, we considered and proposed measures with safe landuse in residential areas instead of conventional measures such as sabo dams, evacuation, and warning. In Kobe, we proposed the construction of a channel by widening and extending the existing roads with a 10 m depth for safe landuse. Through the simulation, the proposed method of changing the landform was found useful to allow the debris flow to move down safely in the residential area. Because the land-use change needs to be considered by the residents and the local government in several divisions, it would be useful for residents to seriously consider the proposed method from showing the applied simulations. However, the method proposed in Kobe is not suitable for Yanohigashi No.13 in Hiroshima because of the different landforms and other conditions. Therefore, constructing sabo dams is high priority and evacuating to a safe area is necessary for effective mitigation.

When debris flows occur and move towards residential areas, culverts located in the valley exit seem to be blocked and often flow moves along the road. The roads that exist in mountainous residential areas are steep. Therefore, depending on the location of roads, buildings, and debris flow torrents, the flow may move along the roads from an unexpected location. Within and around the designated high-risk area for debris flows, we need to understand the location and direction of the roads extending from the valley exit, and realize the risk that flow might move along the roads. When considering the debris flow affected area and the detailed risk distribution, simulation can be a significantly useful tool. The application of DSM will describe the influence of roads in residential areas. In this study, we also aimed to provide information for considering disaster mitigation measures by applying simulations. Applying simulations will help residents not only evaluate the provided measures, but also consider other measures positively, and will enable them to play a major role in effective disaster mitigation works. In some conditions, modifying landuse such as extending or widening the roads and preparing the channels to make debris flow move down safely can be applied as effective measures.

For future work, it will be important not only to upgrade the simulation tools but also allow society stakeholders including residents, governments, and specialists to discuss and propose effective measures. By considering the different perspectives and discussing ideas and techniques, we may be able to find effective measures that will enable residents to play a major role in disaster mitigation works, including safe land use.

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