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Case study of debris flow disaster scenario caused by torrential rain on Kiyomizu-dera, Kyoto, Japan - using Hyper KANAKO system

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Abstract: This paper presents debris-flow numerical simulations using the Hyper KANAKO system, developed by the authors. The system uses the debris flow simulator KANAKO 2D equipped with a graphical user interface (GUI); hence, a user can easily produce appropriate landform data for simulations using standard laser profiler data, and visualize the results using a GIS. Hyper KANAKO was applied to the streams around Kiyomizu-dera in Kyoto, Japan. Kiyomizu-dera is a famous temple in Japan which is visited by numerous tourists throughout the year. We simulated a disaster scenario of debris flow caused by torrential rain. We set the hydrograph using rainfall intensity data, and set the landform data using information from the Geospatial Information Authority of Japan (GSI) and a digital elevation model (DEM). We evaluated different mesh sizes and also used a digital surface model (DSM) to consider the building heights. The simulation results showed that with small mesh size, the debris flow moved through the roads, which seems realistic for a disaster situation. When buildings were considered, the flow direction changed, and a 1-m flow depth, which was deeper than in other cases, appeared in the flow path. This may pose a dangerous situation for evacuations.

Keywords: Debris flow; Simulation; GIS; Hyper KANAKO system; Torrential rain; Kiyomizu-dera

Introduction

Debris flows can have great destructive force because of their high density and speed, and they often cause great losses in human life and to the economy. The amount of damage can be effectively reduced using numerical simulation models, which can describe the debris-flow process (e.g., Egashira et al. 1997; Takahashi 2007) and some graphical user interface (GUI) equipped tools have been

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proposed and widely applied in research field and also for practical use, such as FLO-2D (O' Brien et al. 1993) and KANAKO (Nakatani et al. 2008). Although some difference exist in detail, the essential of governing equations for debris flow simulations are almost common; such as continuity equations, momentum equation, and erosion/ deposition equation. The mentioned model and simulators above are based on difference method, and using grid scheme which calculation points are fixed. Recently, to consider the mechanisms of particle movement, Distinct Element Method (DEM) and Moving Particle Simulation (MPS) for debris flow simulation have been proposed (e.g., Fukawa et al. 2002; Jiang et al. 2013; Ishikawa et al. 2012). They can describe the effectivity in some characteristic phenomena, such as blockade process of open-type sabo dam with large rocks or woody debris in debris flow. However, debris flow simulation methods in DEM and in MPS still have temporal and spatial limitation. Therefore different method using grid scheme have advantage in debris flow simulation from the initiation in mountainous torrent to flooding and deposition process in urban area.

Presently, technical limitations existed so that the mesh size may be as large as tens of square meters for debris flow simulation. Thus far, planning and countermeasures for debris flow disasters did not consider the existence of building such as houses. These days, getting detail landform data such as 1×1 m^2 have become easier, accurate and smaller landform data can be used in debris flow simulation but few studies have considered the difference of the result between several mesh sizes. And in recent studies (Lin et al. 2011; Loup et al. 2012; Nakatani et al. 2013) showed that the existence of houses influences the flooding and deposition process, so that debris flow disasters can be evaluated more practically and more reasonable planning and countermeasures can be suggested by considering the influence of buildings.

This paper presents a case study of debris-flow numerical simulations using the Hyper KANAKO system (Nakatani et al. 2012), developed by the authors. The system uses the debris flow simulator KANAKO 2D (Nakatani et al. 2008), which is equipped with a graphical user interface (GUI); hence, a user can easily produce appropriate landform data for simulations using standard laser profiler (LP) data, and visualize the results using a geographical information system (GIS). We applied Hyper KANAKO system using Takahashi model and Finite Difference Method (FDM) using grid scheme, and considered the difference of mesh size and influence of the buildings in urban area.

Hyper KANAKO was applied to the streams around Kiyomizu-dera (34°59'41.78"N, 135°47' 6.11"E) in Kyoto, Japan. This site has been identified as one of several sediment disaster-prone areas for debris flows in Kyoto Prefecture. Torrential rains have recently increased in various parts of Japan, and because of the heavy rains, there have been increasing occurrences of severe sediment disasters, such as the Izu Oshima debris flow that occurred in 2013 (Ishikawa et al. 2014).

To assist with disaster prevention and management efforts, we simulated a disaster scenario of debris flow caused by torrential rain in this area. We set the hydrograph using rainfall intensity data and set the landform data using 10-m mesh digital elevation data provided by the Geospatial Information Authority of Japan (GSI). We also set 2-m mesh data from a digital elevation model (DEM), and used a digital surface model (DSM) to evaluate the differences between the mesh sizes and the influence of buildings on the debris flow.

1 Hyper KANAKO System

1.1 System outline

In the Hyper KANAKO system, the range of simulation targets is first chosen in a GIS, then the simulation is run by the user, and the results are returned to the GIS as an image. In running the simulation, the user performs the following steps.

(1) Search for the steepest gradient line along the valley using GIS and LP data.

(2) Create one-dimensional (1D) landform data from the LP data along the steepest gradient line.

(3) Create two-dimensional (2D) landform data suitable for KANAKO 2D using the LP data by setting the 1D downstream endpoint as a joint, as shown in Figure 1.

(4) Run the simulation on KANAKO 2D.

(5) Create the simulation result image and return it to the GIS.

(6) Register and manage the resultant image for each time in the GIS, as shown in Figure 2.

Figure 1 Setting landform in Hyper KANAKO (line shows the 1D area; square shows the 2D area).

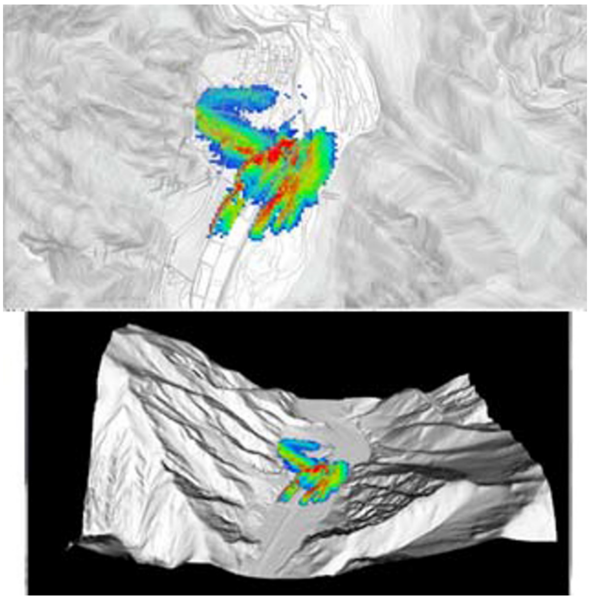

Figure 2 Results for Hyper KANAKO (above: in GIS; below: in 3D image).

1.2 Input data for setting landform

Hyper KANAKO can use LP data and digital elevation data provided by the GSI. The LP data are in the standard format for sabo works (dams constructed with the purpose of controlling debris flows) in Japan, and detailed 1-m mesh data are available for limited parts of Japan. The GSI elevation data have a wide field of application, and these data cover all of Japan. The system can use both LP data and GSI elevation data for one target area, and the data type that should be prioritized can be specified by the user. To use GSI elevation data in a 10-m mesh, a conversion tool which we developed (Nakatani et al. 2014a) can be applied.

1.3 Simulation model

In Hyper KANAKO, the debris flow numerical simulation is based on the model presented in Takahashi et al. (2001) and Takahashi (2007), is the same as in KANAKO 2D, and includes equations for momentum, continuation, riverbed deformation, erosion/deposition, and riverbed shearing stress. Also, an integrated model (Wada et al. 2008) is applied, which incorporates the mutual influences of the 1D simulation areas such as gullies, and 2D simulation areas, such as alluvial fans. The basic 2D debris flow equations are shown below. The system applies the same equations used in 1D debris flow simulations, but includes y-axis directional terms. The effect of sabo dams can be simulated based on a model developed by Satofuka and Mizuyama (2005).

The continuity equation for the total volume of the debris flow is as follows:

$$\frac{\partial h}{\partial t}+\frac{\partial uh}{\partial x}+\frac{\partial vh}{\partial y}=s_T \tag{1}$$

The continuity equation for determining the debris flow of particles is

$$\frac{\partial Ch}{\partial t}+\frac{\partial Chu}{\partial x}+\frac{\partial Chv}{\partial y}=s_T C_* \tag{2}$$

The x-axis flow (main flow direction) is given by the following momentum equation:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-g\frac{\partial H}{\partial x}-\frac{\tau_x}{\rho h} \tag{3}$$

The y-axis flow (cross flow direction) also uses a momentum equation, as follows:

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-g\frac{\partial H}{\partial y}-\frac{\tau_y}{\rho h} \tag{4}$$

The equation for determining the change in the bed surface elevation is as follows:

$$\frac{\partial z}{\partial t}+s_T=0 \tag{5}$$

In Eqs. 1–5, *h* is the flow depth(m), *u* is the *x*-

axis flow velocity(m/s), v is the y-axis direction flow velocity(m/s), C is the volumetric sediment concentration in the debris flow, z is the bed elevation, t is time(s), s_T is the erosion/deposition velocity, g is the acceleration due to gravity(m/s^2), H is the flow elevation $H = h + z$ (m), ρ is the interstitial fluid density(kg/m^3), C^* is the sediment concentration by volume in the movable bed layer, and τ_x and τ_y are the riverbed shearing stresses in the x- and y-axis directions, respectively.

2 Kiyomizu-dera Study Site

Kiyomizu-dera is one of the most famous and celebrated temples of Japan, and it is visited by 4 millions of tourists throughout the year. Two streams have been placed on the list of sediment disaster-prone areas in Kyoto Prefecture, where debris flows may occur and cause damage. In this study, we selected the east stream close to Kiyomizu-dera for further study. In recent years, torrential rains have increased in various parts of Japan, and the heavy rains have resulted in more frequent occurrences of severe sediment disasters. In Kyoto Prefecture, a small debris flow occurred in 2012 in Kameoka City (Kyoto Prefecture 2012; Nakatani et al. 2014b); at that time the maximum observed rainfall was 90 mm/h.

We conducted a field survey of the study site to acquire detailed topography data and familiarize ourselves with the site conditions. The study site and stream is shown in Figure 3; on the left, the rectangle shows the field survey area, and on the right, the route and the point numbers (Numbers 1–10) are marked. Figure 4 shows the point locations. The elevations are presented in Table 1.

Table 1 Elevation of the points

Number	Elevation (m)
1	91
2	78
3	73
4	71
5	68
6	79
7	71
8	80
9	66
10	70

At point Number 3, there exists a small reservoir, 2 × 2 m in area, and 1.5 m in height. When a debris flow occurs, it is likely that it will flow into this reservoir. The building district is located at points Number 4, 5, 7, and 8, where the road is narrow; this configuration might cause deep debris flows because of the building structures. With regard to the elevations at points Number 5, 7, and 8, the lowest point occurs at location Number 5, and surrounding rainfall typically gathers there. Additionally, the main road that tourists use to visit Kiyomizu-dera is located at points Number 5, 7, and 8. If a debris flow were to occur and flow down this road, it might cause more severe damage than if it were to flow in other locations.

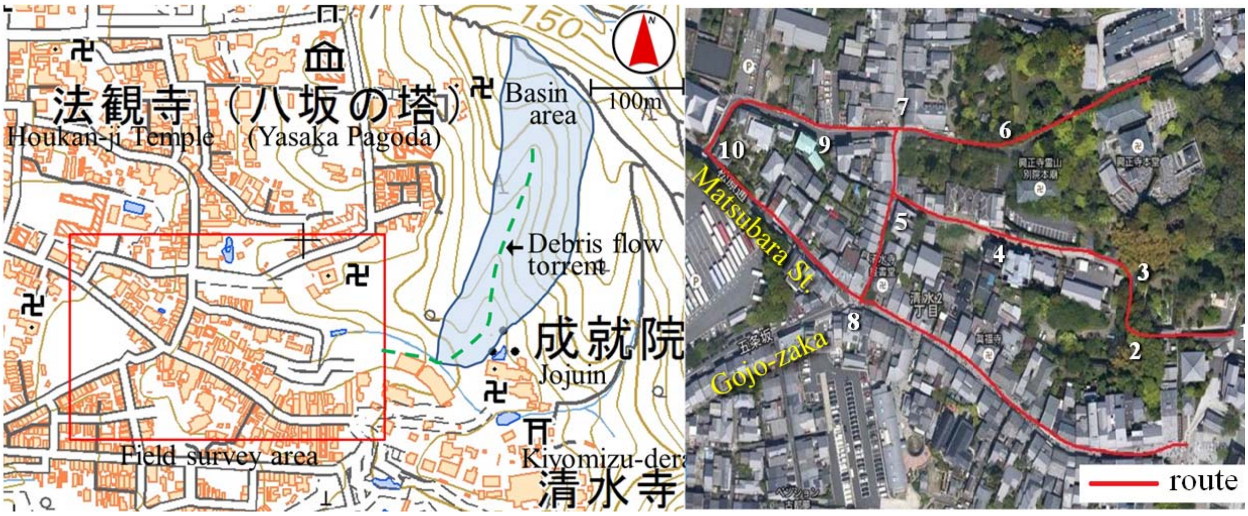

Figure 3 Locations of the debris flow torrent and Kiyomizu-dera (left: topographical map, rectangle shows the field survey area; right: route and point numbers in field survey).

Figure 4 Locations of sites Number 1–7, and entrance of Kiyomizu-dera.

3 Simulation Conditions

3.1 Supplied hydrograph

For a debris flow simulation, the user needs to set the hydrographic conditions. A debris flow is usually caused by heavy rainfall, so we assumed heavy rainfall conditions. The nearest rainfall observation station is the Kyoto Observation Point, and data for this point are available from the Japan Meteorological Agency. The one-hour rainfall intensity data for the largest five rainfall events at the Kyoto Observation Point are shown in Table 2. The maximum one-hour rainfall recorded in Japan is 153 mm/h.

We applied the rainfall intensity formula as a fair formula (PWRI 2003) using rainfall recorded on August 12, 2010.

We selected this rainfall event because it was large and occurred recently. We set the return period as 200 years for a large rainfall event. The calculated rainfall intensity was 148.4 mm/h, close to the record rainfall in Japan. In our simulations, we assumed the most severe rainfall condition to be 148.4 mm/h and applied it to the Rational formula (Aron and Kibler 1990), one of the simplest method formula to determine peak discharge from drainage basin runoff, as shown in Eq. 6:

$$Qp = 1/3.6 \times f \times i \times A \qquad (6)$$

where Qp is the peak discharge (m^3/s), f is the coefficient of runoff (here, 0.7 for mountainous streams), i is the rainfall intensity (mm/h), and A (km^2) is the basin area, which was 0.04 km^2 for the

Table 2 Top five hourly precipitation events recorded at the Kyoto Observation Point

Date	Hourly Precipitation (mm/h)
Aug. 26, 1980	88
Aug. 15, 1918	83.4
June. 28, 1941	80.9
Aug. 27, 1980	78.5
Aug. 12, 2010	76.9

study site. Peak discharge for water, not considering the sediment mixture, was calculated from Eq. 6 to be 1.15 m^3/s.

For setting the debris flow hydrograph, we need to consider the sediment volume. We obtained a debris flow concentration of 30% by applying Eq. 7 from Takahashi et al. (2001):

$$Cd = \frac{\rho \tan\theta}{(\sigma - \rho)(\tan\phi - \tan\theta)} \qquad (7)$$

Then, we calculated the peak debris flow discharge using the method described in the Sabo Master Plan for Debris Flow Eq. 8 (NILIM Japan 2007):

$$Qsp = \frac{C_*}{C_* - Cd} Qp \qquad (8)$$

where Cd is the debris flow sediment concentration ($0.3 \leq Cd \leq 0.9C_*$), σ is the mass density of bed material (= 2650 kg/m^3), ρ is the mass density of the fluid phase (water and mud/silt) (= 1000 kg/m^3), Φ is the internal friction angle (= 35 deg.), $\tan\theta$ is the average gradient of the river bed (= 1/6), C^* is the concentration of the moveable bed (= 0.65), and Qsp is the debris flow peak discharge (m^3/s). The total debris flow peak discharge and sediment concentration were calculated to be 2.3 m^3/s and 30%, respectively. We presumed triangle shaped supplied hydrograph, and the debris flow duration time was set at 30 minutes. The supplied hydrograph is shown in Figure 5.

The supplied hydrograph applied here seems to be small. However, in flooding disaster research (e.g. Kreibich et al. 2009) showed that flow velocity smaller than 1 m/s may cause large damage on humans and buildings due to flow depth. Furthermore, debris flow holding higher density with sediment and rocks, the damage will be larger than flooding disaster. Therefore, the debris flow scenario as in Figure 5 can be dangerous.

3.2 Simulation cases and parameters

We simulated four scenarios of debris flow, as shown in Table 3. For the 10-m and 5-m mesh cases, Case 1 and Case 2, we set the landform data from GSI. For the 2-m mesh cases, Case 3 and Case 4, we acquired detailed DEM and DSM data for the study site. For Case 4, we used the DSM and considered the buildings located at the site; specifically, the set heights of the buildings were added to the ground elevation. For Cases 1–3, we did not consider the buildings.

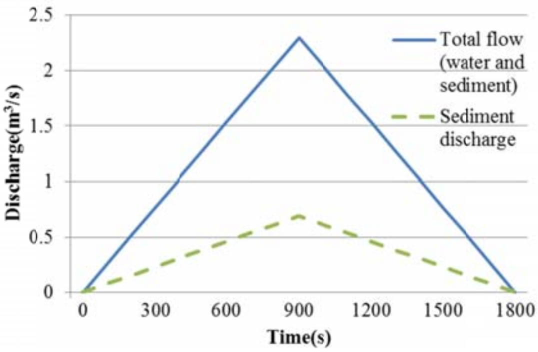

Figure 5 Supplied hydrograph from upstream.

As noted in Section 2, Hyper KANAKO is based on the model presented in Takahashi et al. (2001) and Takahashi (2007). Therefore, the erosion and deposition process is related to the difference between the equilibrium sediment concentration C_∞ and the actual sediment concentration C. The velocity of erosion/deposition s_T is calculated as follows.

If $C < C_\infty$, and $s_T > 0$, the erosion velocity is calculated from Eq. 9:

$$s_T = \delta_e \frac{C_\infty - C}{C_* - C_\infty} \frac{q}{d} \qquad (9)$$

where q is the unit sediment discharge (m^2/s), δ_e is the erosion coefficient and d is the particle diameter (m).

Table 3 Simulation cases for Kiyomizu-dera

Case	Mesh size in 2D area	2D area range *	Landform data
Case 1	10-m mesh	500 m × 500 m	GSI
Case 2	5-m mesh	500 m × 500 m	GSI
Case 3	2-m mesh	400 m × 400 m	DEM
Case 4	2-m mesh (consider buildings)	400 m × 400 m	DEM & DSM

Note: * flow direction × transverse direction.

If $C > C_\infty$ and $s_T < 0$, the deposition velocity is calculated from Eq. 10:

$$s_T = \delta_d \frac{C_\infty - C}{C_*} \frac{q}{h} \tag{10}$$

where δ_d is the deposition coefficient and h is the flow depth. The erosion and deposition coefficients were set as 0.007 and 0.05, respectively, which are typical values for debris flow simulations in Japan (Takahashi 2007). We applied 20cm, scores of centimeters diameters, from the field survey which also seems to be usual in Japan debris flow events. Other simulation parameters that were set are shown in Table 4. Manning's coefficient, which is used for calculating riverbed shearing stresses of debris flow, was set as 0.03, the typical value for the mountainous river.

For the 1D simulation area, the interval of the 1D calculation points was set as 5 m, the river width was set as 1 m, and we did not set unstable soil in the 1D area for all cases. Landform settings for the 1D and 2D areas are shown in Figure 6.

4 Simulation Results and Discussions

The 1D area downstream discharge result is shown in Figure 7. For the 1D area, the results are the same for all cases. The total flow discharge peak value is 1.31 m³/s, smaller than in the supplied hydrograph. The sediment discharge became smaller because the deposition occurred in a 1D mountain stream area, then the total flow discharge became smaller. However, the flow moves towards the downstream area containing sediment.

Table 4 Other parameters for the simulation

Parameters/Variables	Value	Unit
Simulation time	1800	s
Time step	0.01	s
Diameter of material	0.2	m
Mass density of bed material	2650	kg/m³
Mass density of fluid (water and mud, silt) phase	1000	kg/m³
Concentration of movable bed	0.65	
Internal friction angle	35	
Acceleration of gravity	9.8	
Coefficient of erosion rate	0.0007	deg.
Coefficient of deposition rate	0.05	m/s²
Manning's coefficient	0.03	s/m$^{1/3}$

The simulation results for the debris flow trace at 1800 s (after simulation), are shown in Figure 8; these results include data for the maximum flow depth and deposition thickness.

The results show that during the simulated debris flow, some of the flow would cover the ground of Kiyomizu-dera, whereas the majority of the flow would enter the downstream area where many souvenir shops are located. There are always numerous tourists visiting and sightseeing in this downstream area. When the mesh size was as large as 10 m for Case 1, the flooding area for the trace was larger than the areas for Cases 2, 3, and 4. Additionally, the flooding area was not located along the roadways, which is different from the situation during actual disaster cases such as the Izu Oshima and Kameoka debris flows. For the 5-m mesh and 2-m mesh results, there was not much difference between Cases 2 and 3 (these cases did

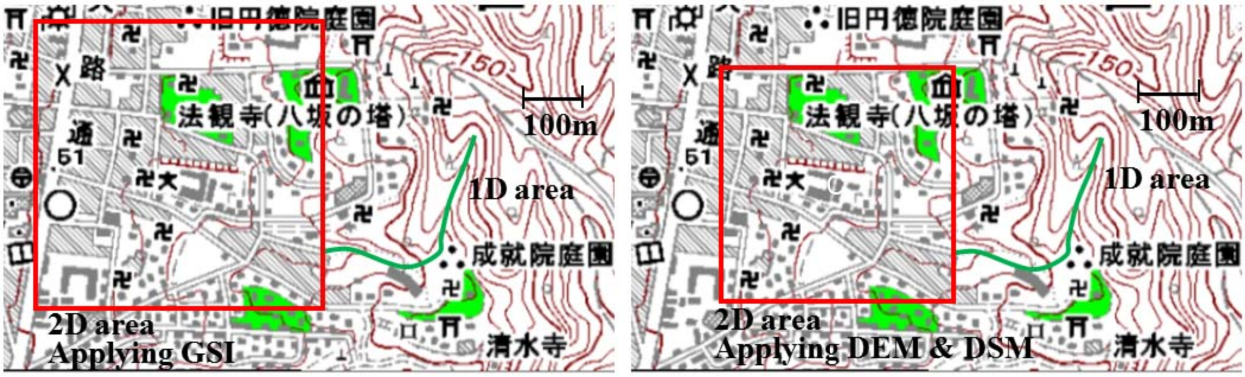

Figure 6 Simulation area applying GSI data (left: Case 1, Case 2) and applying DEM and DSM data (right: Case 3, Case 4).

not consider buildings). In both cases, the flow seemed to move down the street, except for the paths at locations Number 2 and 3, shown in Figure 3.

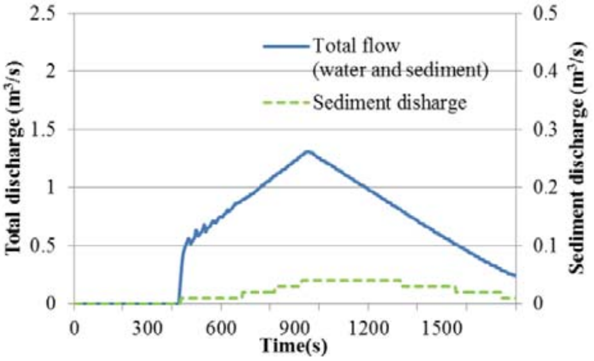

Figure 7 Simulation result of 1D area downstream discharge (all cases).

In Case 4, which used a small 2-m mesh and considered buildings, all of the flow occurred along the streets. Specifically, the runoff route was from Number 3 toward, subsequently, Number 4, 5, 7, and 9, as shown in Figure 3. Then, the flow changed direction toward the north, and finally toward the west. At locations Number 4, 5, and 7, which represent crowded buildings, the trace (shown here as the maximum flow depth) was greater than that in other simulation areas. The buildings appear to function as walls, and as the channel becomes narrower, the flow becomes deeper. At locations Number 5 and 7, the trace (flow depth) was greater than 1 m, indicating a scenario in which it would be difficult to safely move and evacuate people. However, Gojo-zaka and Matsubara Street, the other main streets in Kiyomizu-dera, appear to be safe for use in such a scenario.

In considering the results according to mesh size, smaller meshes such as the 5-m and 2-m meshes appear more likely to depict the real situation. This suggests that the mesh size must be the proper size for simulations aimed at identifying safe and dangerous areas, and pathways for evacuation. In other words, the mesh size must be small enough to represent the paths accurately.

With regard to comparisons of building conditions, in simulations that just considered the ground surface and not the buildings, the flow predictably moved downward from higher locations to lower locations. However, when building heights were considered, the flow direction did not always follow the ground elevation; therefore, buildings can have a large influence on the direction of debris flow.

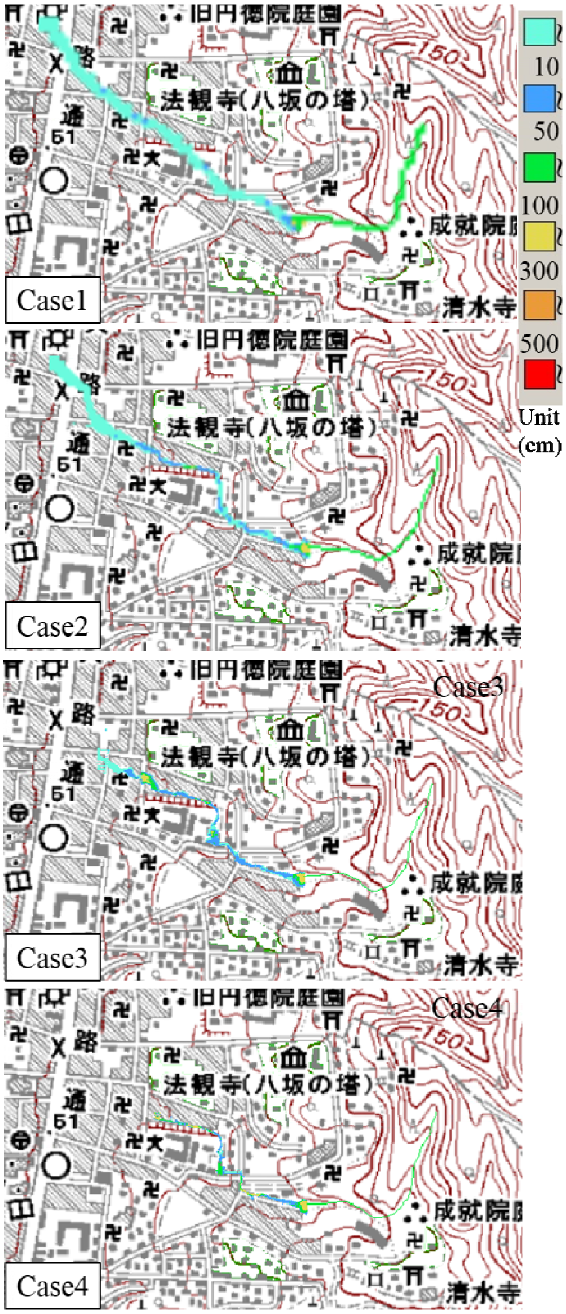

Figure 8 Simulation results for debris flow trace (maximum flow depth and deposition thickness).

5 Conclusions

This paper presents debris-flow numerical simulations using the Hyper KANAKO system. The system was applied to a stream around Kiyomizu-dera in Kyoto, Japan, an area that was identified as a sediment disaster-prone area for debris flow in Kyoto Prefecture. We modeled a disaster scenario for debris flow caused by torrential rain. To do so, we set the hydrograph using rainfall intensity data, and set the landform data using GSI and DEM information. We evaluated different mesh sizes and also used a DSM to consider building heights. The results showed that during the simulated debris flow, some of the flow would cover the ground of Kiyomizu-dera, and the majority of the flow would enter into the downstream area where many souvenir shops are located, and numerous tourists are always present. The smaller mesh-size cases, which were used to determine the paths at the study site, were able to simulate debris flows through the roads, which is a realistic scenario during a disaster situation. When buildings were considered, the flow direction changed, and deep flows appeared in some parts of the flow path; these areas may be dangerous during an evacuation.

Regarding to the previous model KANAKO 2D, GUI equipped debris flow simulation system enabled users to simulate easily various debris flow scenarios without specialized trainings. Besides, when applying KANAKO 2D or other simulation systems (e.g. Takahashi et al. (2001)) to actual landform conditions, users need to set the landform data as an initial condition. A simple way is to create data from a topographical map, either by hand or numerically. However, this method can be problematic because the work may take much time and the landform data may be inaccurate. Achieving exact simulation results requires using detailed three-dimensional (3D) topographical data, such as from a DEM and LPs. Special technology is required to select the intended area data from the DEM and convert it to a format suitable for the simulation system.

Hyper KANAKO system is superior to KANAKO 2D for the landform setting with 3D topographical data and for setting different mesh size easily. Furthermore, GIS-related system enable user to see and consider the simulation results easily and clearly on maps and on aerial photographs. Using DSM will also enable user to see the differences of houses existing conditions. However, not enough data were available to thoroughly assess the influence of buildings during debris flow disasters.

For more advanced studies, we need to work toward the following objectives to obtain highly accurate simulation results:

(1) Identify the proper mesh size for various scales of debris flow and for different landforms.

(2) Acquire detailed information on the influence of buildings at different scales of debris flow and for different types of debris flow, such as stony debris flows and mud flows.

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