12th Congress INTERPRAEVENT 2012 – Grenoble / France
Conference Proceedings
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DEVELOPMENT OF "HYPER KANAKO", A DEBRIS FLOW SIMULATION SYSTEM BASED ON LASER PROFILER DATA

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ABSTRACT

In Japan, wide-scale measurements for sabo work were conducted from 2008 to 2010 using laser profilers (LPs) with a standard data format. These LP data provide detailed topographic information on areas prone to sediment-related disasters. Widespread use of these data is thus expected in research on crisis management and sabo work. However, because there are no software applications for the LP data, they cannot be used effectively at present. In this paper, we used LP topographic data to improve the accuracy of KANAKO 2D, a debris flow simulator equipped with a graphical user interface (GUI). We sought a method by which the LP data could be used to easily produce appropriate landform data for simulation. We also concentrated on constructing a comprehensive debris flow simulation system based on a geographic information system (GIS) to enable visualization of the results. The use of accurate topographical data produced reasonable analytical results. We named the developed system "Hyper KANAKO" and demonstrated that it is a useful tool for debris flow prediction and sabo planning.

Keywords: Laser profilers (LPs), topographic information, KANAKO 2D, debris flow simulation, GIS, Hyper KANAKO

INTRODUCTION

Both the software and hardware for electronic information processing technology have advanced rapidly. In recent years, the Geographical Survey Institute and Sabo Offices in Japan have acquired large amounts of accurate laser profiler (LP) data, which provide detail digital topographic information. However, without software applications to handle these digital topographic data, only a few specialists or consultants with specialized systems can use these data. Therefore, these data are not used effectively or widely at present.

We used LP data to improve the accuracy of KANAKO 2D, a debris flow simulator equipped with a graphical user interface (GUI). We sought a method by which the standard LP data maintained for current sabo works could be used to easily produce appropriate landform data for simulation. The use of accurate topographical data produced reasonable analytical results. By including an efficient GUI and a geographic information system (GIS), KANAKO 2D will help users handle LP data and produce accurate debris flow simulations. The developed system is a useful tool for predicting debris flow, planning sabo dams, and managing existing sabo dams.

KANAKO 2D, A GUI EQUIPPED DEBRIS FLOW SIMULATOR

Numerical simulations of debris flow are useful for describing debris flow processes and determining the possible effects of sabo dams. Although various models have been developed, many existing

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debris flow numerical simulation systems lack efficient GUIs. In addition, most existing models have only limited applications. Consequently, users must apply different models or programs in different cases, which complicates debris flow simulation, even for trained professionals. To address these issues, we developed KANAKO 2D (Nakatani *et al.*, 2008), a general-purpose debris flow simulation system equipped with an efficient GUI. This system integrates and improves upon existing debris flow models, enabling users to simulate easily various sabo dam conditions and different types of movement for sediment transport.

1. Outline of KANAKO 2D

We developed our system using MS Visual Basic.NET (VB.NET). The developed software package has two parts, as shown in Fig. 1: a user interface, which manages the data input and display output, and a simulation model.

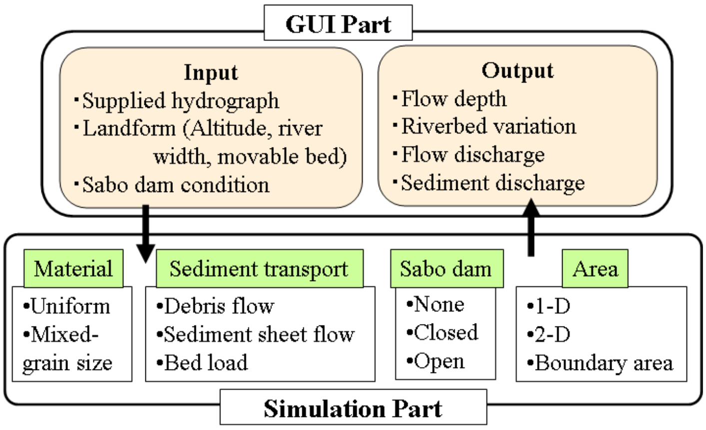

Fig. 1 Relationships of the main functions of the system

A GUI-equipped system allows information visualization and helps non-expert users to easily run numerical debris flow simulations. In a debris flow simulation, information visualization enables users to recognize debris flow simulation data, such as discharge, flow depth, and sedimentation thickness, as visual patterns and figures. It also allows users to browse many different types of information simultaneously and to gain an instinctive understanding of the data (Nakatani *et al.*, 2010).

The KANAKO 2D GUI system is easy for beginners to use because the required simulation datasets can be input using a mouse and viewed on a monitor. During simulations, users can view real-time images of debris flows, hydrographs, and the effects of sabo dams, as shown in Fig. 2. The GUI enables users without specialized training to identify better solutions effectively and to run debris flow simulations independently.

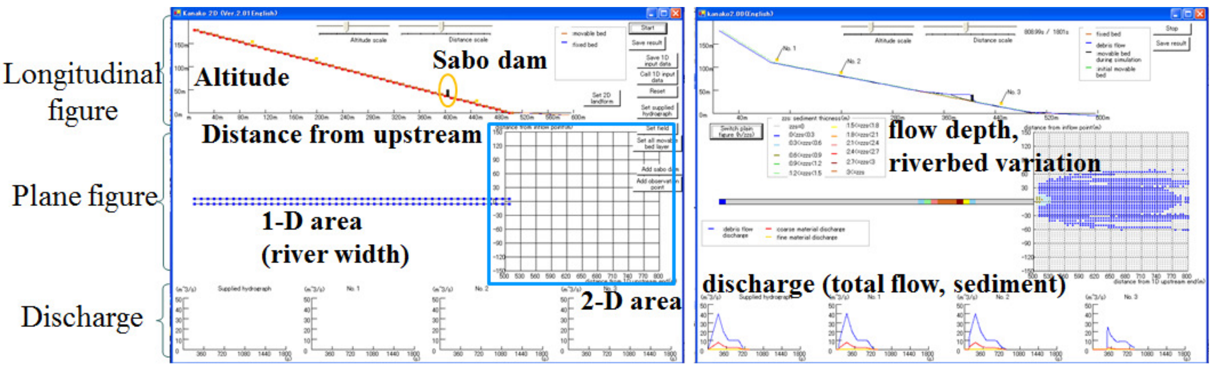

Fig. 2 An example of the input screen (left figure) and an output real-time animation screen (right figure) of KANAKO 2D

In KANAKO 2D, we applied and modified an integrated model (Wada *et al.*, 2008) so that we could obtain more accurate results in the boundary area between one-dimensional (1D) simulation areas, such as gullies, and two-dimensional (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 equations for momentum, continuation, riverbed deformation, erosion/deposition, and riverbed shearing stress are based on previous research (Takahashi & Nakagawa, 1991), as are the staggered scheme and arrangement of variables. 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:

$$\frac{\partial h}{\partial t}+\frac{\partial uh}{\partial x}+\frac{\partial vh}{\partial y}=i \quad (1)$$

The continuity equation for determining the debris flow of particles is

$$\frac{\partial Ch}{\partial t}+\frac{\partial Chu}{\partial x}+\frac{\partial Chv}{\partial y}=iC_* \quad (2)$$

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

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

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

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

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

$$\frac{\partial z}{\partial t}+i=0 \quad (5)$$

In equasions (1)–(5), h is the flow depth, u is the x-axis flow velocity, v is the y-axis direction flow velocity, C is the sediment concentration by volume in the debris flow, z is the bed elevation, t is time, i is the erosion/deposition velocity, g is the acceleration due to gravity, H is the flow elevation $H = h + z$, ρ is the interstitial fluid density, 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.

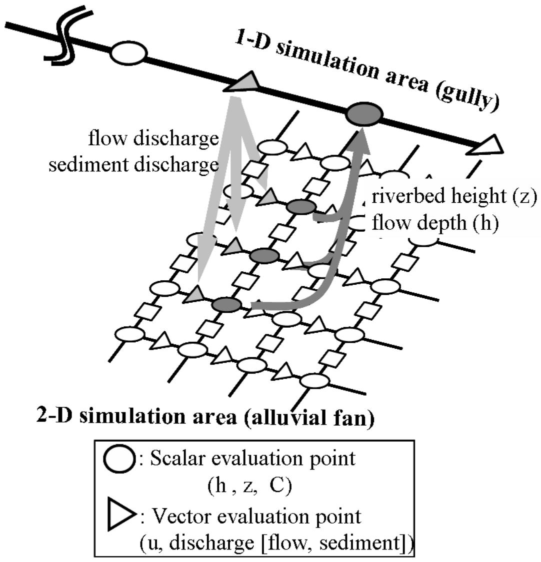

Fig. 3 Outline of the integrated model

Fig.3 presents an outline of the integrated model, which enables a continuous simulation of both 1D gully models and 2D alluvial fans models for each time step. The integrated model uses an explicit method. At time t, the calculated 1D downstream end-flow discharge and sediment discharge are applied as the 2D upstream inflow conditions, and the 2D upstream riverbed height and flow depth are calculated using the forward conditions. Then, at time $t + \Delta t$, the calculated riverbed height and flow depth are applied as the 1D downstream-end boundary condition. Therefore, the integrated model incorporates the mutual influences of the 1D and 2D simulations.

2. Problem of setting landform data for numerical simulations

When applying KANAKO 2D or other simulation systems 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 digital elevation model (DEM). However, special technology is required to select the intended area data from the DEM and convert it to a format suitable for the simulation system.

LASER PROFILER DATA FOR SABO WORK

In Japan, wide-scale measurement for sabo work was conducted from 2008 to 2010 using laser profilers (LPs) with a standard data format. These LP data provide detailed topographic information on areas prone to sediment-related disasters. The 3D topographical data in the LP database cover mountainous areas (about 55,000 km^2, 15% of Japan), and give accurate information in the Japan Profile for Geographic Information Standards (JPGIS) standard mesh size (1 × 1 m). Therefore, widespread use of these data is expected in research on crisis management and sabo work (Horiuchi, 2010).

However, the large amounts of LP data (for example, 10 GB for one mountain stream) take a long time to handle, and there are few software applications for the LP data. Therefore, these data are not used effectively at present.

STUDY AIM AND OUTLINE

As previously noted, the environment for running the debris flow simulation is prepared for each element. First an efficient GUI-equipped system is developed, and accurate LP data are acquired. However, running a simulation using LP data, and managing and applying the simulation result, require many working processes. No integrated system that can manage these processes has been developed.

We used LP topographic data to improve the accuracy of KANAKO 2D debris flow simulations. We focused on developing a method to easily produce appropriate landform data for the simulation using the standard LP data maintained for current sabo works. We also concentrated on constructing a comprehensive debris flow simulation system based on a GIS to enable visualization of the results. The use of accurate topographical data produced reasonable analytical results. This is a very useful tool for debris flow prediction and sabo planning. We call the system we developed “Hyper KANAKO.”

FEATURES OF HYPER KANAKO

1. Improved operability and visualization provided by the GIS

A GIS is the most appropriate tool for indicating or displaying objects with some geographic feature easily and clearly on a map. Users of Hyper KANAKO can easily set a range in the GIS using a mouse when preparing 1D and 2D topographic data. Because LP data, which are a source of topographic data, use the 3D coordinates of the plane rectangular coordinate system, plane coordinates are added to the topographic data in each dimension, in addition to elevation data. Geographic information is also added to the 2D topographic data in a world file format. This extension makes it possible to introduce a geographic concept into KANAKO 2D, which lacks such concepts.

The simulation results in the 2D range are output as a series of numbers for every mesh of topographic data. Hyper KANAKO can also output time-series images of the calculation results, such as a sedimentation depth, by changing the color according with the depth. Because a world file that responds based on geographic information from 2D topographic model information is attached to the time-series images, it is possible to check the simulation results on the GIS as soon as the calculation has ended. It is also easy to determine which buildings and areas would be flooded because the simulation results can be overlaid on other map data, such as a sabo base map.

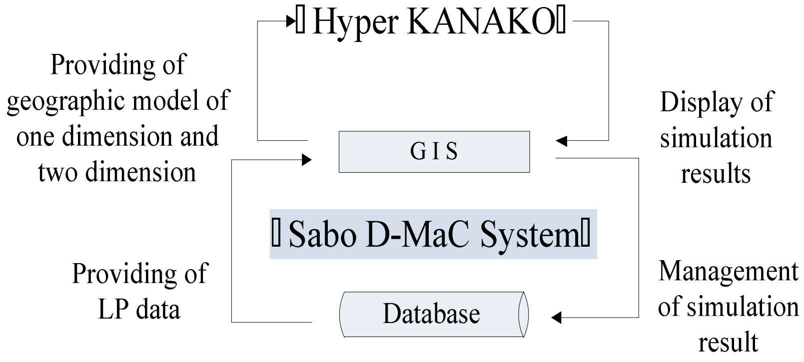

Fig. 4 Conceptual diagram of "Hyper KANAKO" combined with a GIS system

Fig. 4 shows a result from the combination of Hyper KANAKO with the Sabo D-MaC system (a sabo-related information management system), which was developed by the Sabo Frontier Foundation. This combined system can present a time-series 3D display by overlaying the images of the simulation results on the aerial view display function of the GIS system.

The Sabo D-MaC system is a GIS system that was developed to manage a variety of sabo-related electronic information as indicators of "geographic positional information." It is an intranet system that office staff can use with their own desktop PCs. The basic function of the Sabo D-MaC system is an integrated search function linking maps, databases, and folders. However, it is also an extension-type system that gives users the option to add systems, such as for (1) monitoring and observing data management, (2) managing project progress, and (3) analyzing 3D data. Typical 3D data analysis functions that are closely related to the functions of debris flow floods and sedimentation simulations are as follows:

1) a function to display longitudinal and cross-sectional profiles of any traverse line;

2) a function to display an aerial view of any range;

3) a function to search for the lowest riverbed line (longitudinal); and

4) a function to display a sedimentation area with any sedimentation gradient and to calculate the sedimentation volume.

For 3D data, LP data can be used for simulations and triangulated irregular network (TIN) data can be used for the sabo base maps.

The above 3D processing functions are used to execute tasks, such as setting a stream for simulation, visualizing the obtained results, and calculating a hydrograph based on the LADOF model (Satofuka *et al*., 2007), a debris flow simulation model for overtopping and failure of landslide dams (to be explained later). Here, we explain the operating method of the function for finding a sedimentation area with any sedimentation gradient and for calculating a sedimentation volume.

1.1 Searching for the lowest riverbed line

To search for the lowest riverbed line of the target stream, the upper and lower end points of the stream must be determined first to establish a search range. Then, an automatic search for the lowest coordinate is made on the circumference with 5 m radius around the base coordinate. This search process is performed recursively until the lowest riverbed line (longitudinal) of the stream is determined. To search for the lowest riverbed line of the target stream, we must first determine the upper and lower end points of the stream to establish a search range. Then, an automatic search for the lowest coordinate is made in a circumference with a 5 m radius around the base coordinate. This search process is performed recursively until the lowest riverbed line (longitudinal) of the stream is determined.

1.2 Setting the position and height of a dam and a sedimentation gradient

In addition, the position and height of the dam used to obtain a sedimentation area and sedimentation volume must be set. The sedimentation gradient of the sedimentation area must also be set. These settings are made on a graph (Figs. 5 and 6).

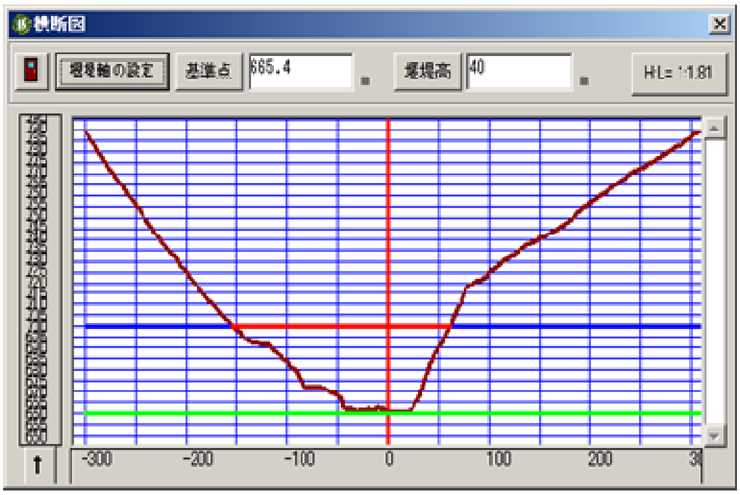

Fig. 5 Setting the dam height on a cross section

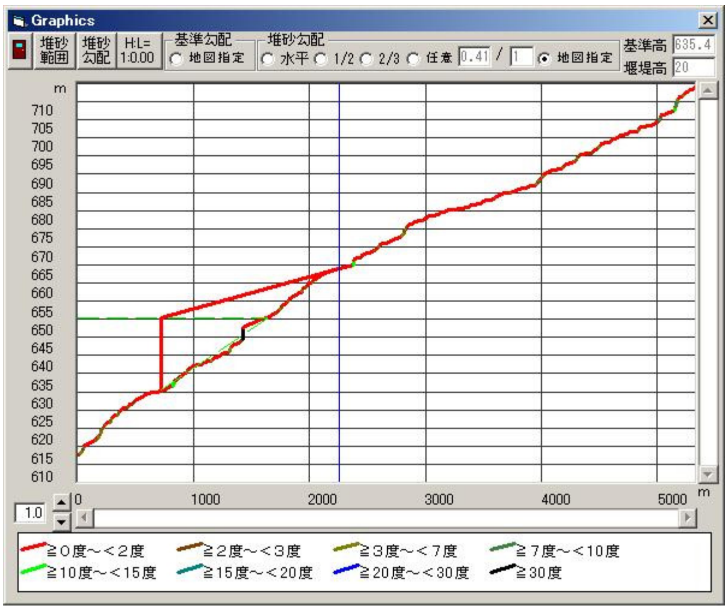

Fig. 6 Setting the sedimentation gradient on a longitudinal profile

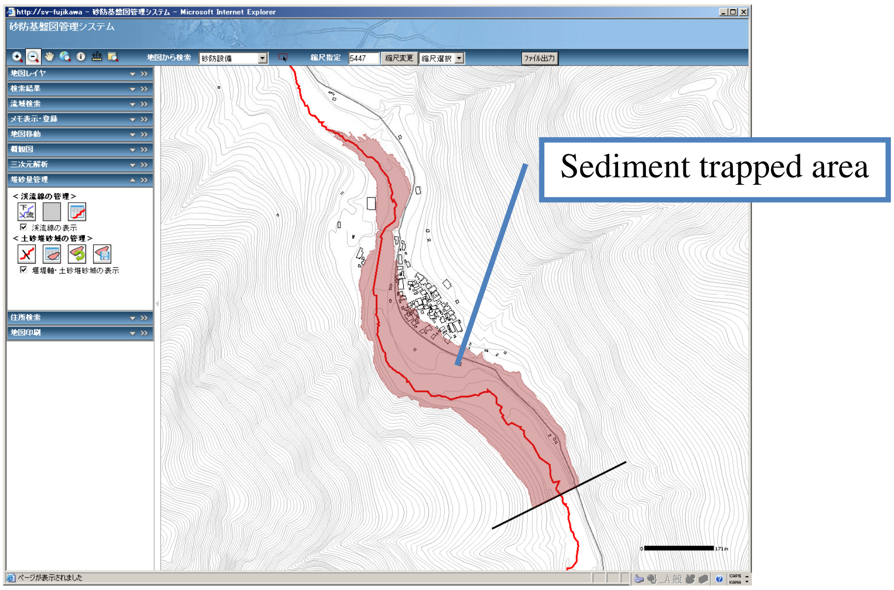

Fig. 7 Showing the area of trapped sediment on the "D-MaC" system

1.3 Calculating the sedimentation area and sedimentation volume

The sedimentation area and volume at a given gradient are calculated using LP data and a sedimentation plane equation that is obtained from setting the sedimentation gradient. The sedimentation area is evaluated by obtaining an elevation value on the plane coordinate from the grid-point coordinate of the LP data and a sedimentation plane equation and by comparing it with the elevation value of the LP data (Fig. 7). Example applications of this function are as follow:

1) planning the scale and layout of sabo dams;

2) calculating various quantities when a large-scale disaster occurs, such as when a landslide dam is formed; and

3) operating and maintaining existing sabo dams (asset management)

2. Using LP data to reduce the preparation time for topographic data

As shown in Fig. 8, a number of processes must be executed in a debris flow simulation, ranging from preparing the data and running the simulation, to saving the results. In particular, the process used to prepare 2D topographic data requires much time and labor.
Hyper KANAKO is equipped with a mechanism that allows for flexible data preparation in terms of the mesh number and mesh size of 2D topographic data, while significantly reducing the time and labor required to acquire and input data, by using LP data as the data source for the topographic model.
Flood simulations using the Sabo D-MaC system use binary-translated data from the 1-m mesh of the sabo LP data (Horiuchi & Iwanami, 2010). The algorithm for preparing 2D topographic data with an arbitrary mesh size from 1-m mesh data is as follows:

1) search for a mesh containing a coordinate whose elevation needs to be determined.
2) select three closely located points from the coordinates in the four corners.
3) obtain the elevation of a given coordinate from the rectangular plane equation.

In the binary translation, one file is created for each LP data acquisition task. Therefore, some file sizes may exceed 10 GB, but any coordinate can be searched and processed in the same length of time with the use of a random access function for the binary data.

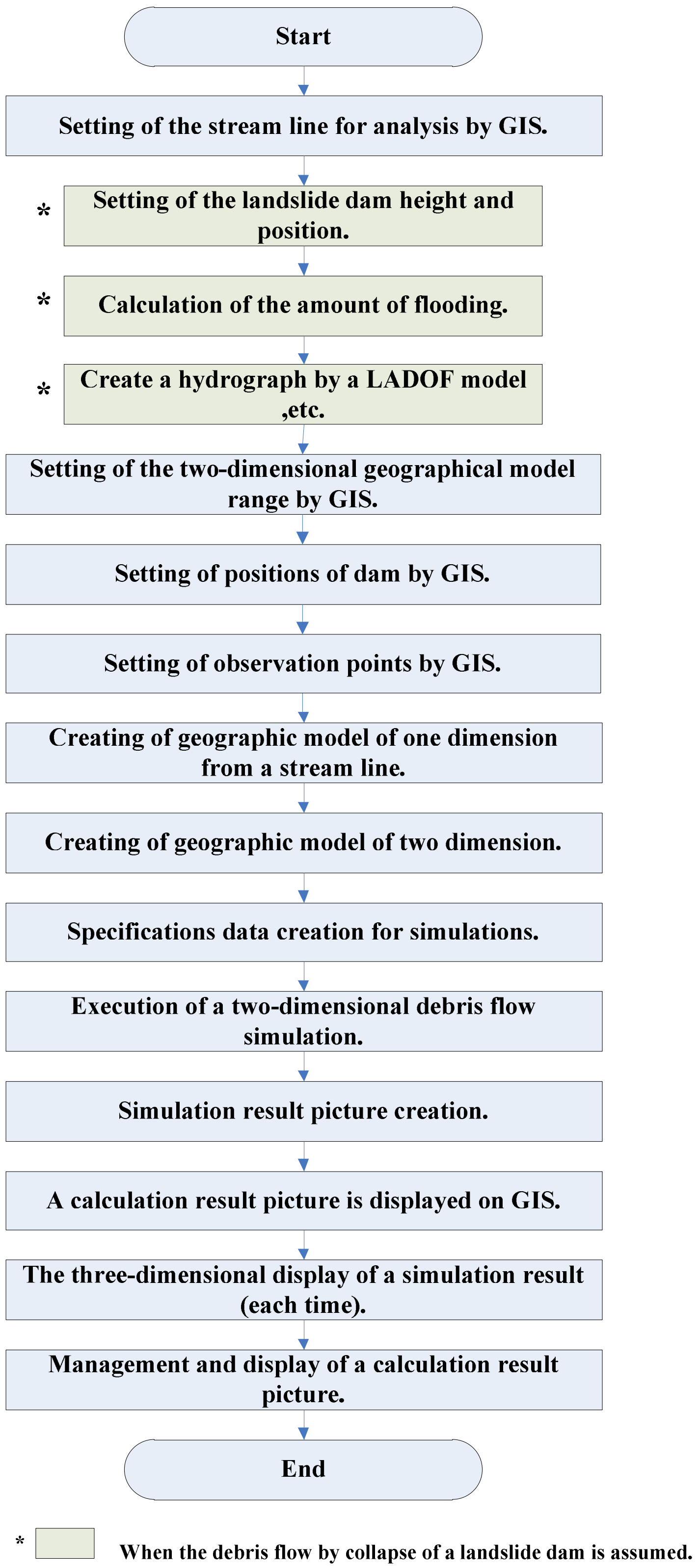

Fig. 8 Flow chart of a two-dimensional debris flow simulation

3. High-speed simulation

A simulation may require much time. Hyper KANAKO was developed as a high-speed program, using the C++ language instead of VB.NET. Hyper KANAKO can also perform a wide-range of analysis with no limitations on the mesh number of 2D topographic data and conduct analysis using detailed LP data. The main advantages of C++ are as follows:

1) flexibility for dynamic memory allocation;
2) high-speed access to arrays using a pointer;
3) a function to create a new class (huge file access class); and
4) the application of existing image processing technologies.

AN EXAMPLE APPLICATION OF HYPER KANAKO

An example application of Hyper KANAKO, showing the flow of simulation, is presented below. The data specification and calculation time of the example are given in Table 1.

Tab. 1 Data specifications used in the executed example

Item	Specification
Number of data in 1D domain	82 points, 5 m spacing
Mesh number of 2D data	150×150 meshes
Mesh size of 2D data	5 m
Calculation time	1,800 sec.
Output interval of calculation results	10 sec.

1. Setting the 1D stream

The target 1D stream is set by specifying its upper and lower end points on the GIS and then using the automatic lowest riverbed line drawing function of the Sabo D-MaC system. Fig. 9 shows the results. Structures on the 1D stream and observation points can also be set in the GIS in the same way.

2. Setting the 2D topographic data preparation range

A 2D topographic data preparation range is set in the GIS in the same way as for a 1D stream. In our system, the point connecting a 1D stream and a 2D topographic model is placed at the lower end of the 1D stream. If specifying the number of horizontal and vertical meshes and the mesh size, the corresponding frame will be displayed in the GIS. The range can be set by moving the frame from side to side or up and down. The results are shown in Fig. 10.

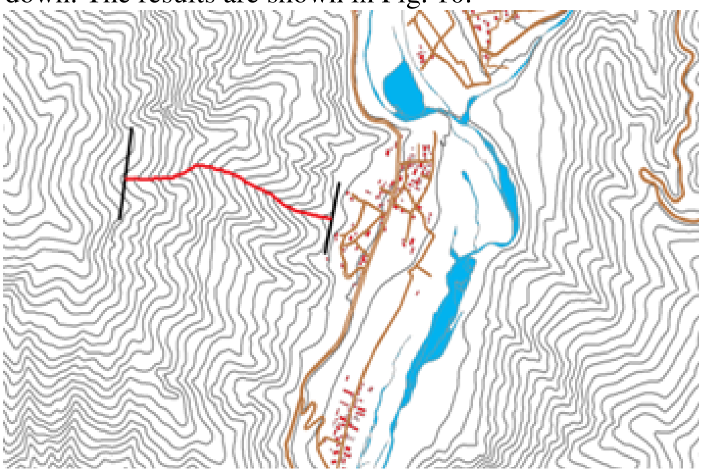

Fig. 9 Setting the one-dimensional stream

Fig. 10 Setting the two-dimensional terrain area

3. Executing a simulation

The debris flow simulation is started by clicking an execution button after completing the above processes. The parameters of a hydrograph or soil constants can be changed from the allocated Excel sheet. The simulation results are output as both numerical and image data at specified time intervals. The image data can be displayed by the GIS because it has geographical coordinates. A 3D display (aerial view) is also possible by using the Sabo D-MaC system. Figs. 11 and 12 show outputs of the results. Table 2 lists the processing time and specifications of the computer that performed the calculation using the data given in Table 1.

Tab. 2 Computer specifications and simulation run time

Item	Specification
OS	Windows 7 Professional 64 bit
CPU	Intel Core i7 2.8 GHz
Main memory	8Gb
Display adapter	NVIDIA Ge Force GTS 240 512M
Simulation preparation	ca. 4 min.
Simulation run	ca. 6 min.
Display of results	ca. 2 min.

COMBINING HYPER KANAKO WITH THE LADOF MODEL FOR LANDSLIDE DAM OVERTOPPING AND FAILURE PREDICTION

Hyper KANAKO is equipped with a mechanism to create parameter files for calculations using Excel or text editor software. Therefore, the system can use data calculated externally, such as hydrograph data calculated by the LADOF model, in combination with the Sabo D-MaC system. This combination makes it possible to perform a debris flow simulation triggered by overtopping and the failure of a landslide dam with ease and with high accuracy.

The LADOF model, which was developed to analyze the transition from debris flow to collective bed-load-type flow, is a 1D calculation model based on a two-layer flow model that analyzes a flow layer by dividing it into two layers. The model calculates overtopping and failure processes of a landslide dam by introducing a bank erosion velocity equation to a two-layer flow model, based on the concept that the bank erosion velocity equation is proportional to the first power of the flow velocity. For calculation, the LADOF model requires data that include a topographic model, ponding area, and ponding volume. Because the Sabo D-MaC system has functions to calculate the ponding area and volume automatically if the scale of the landslide dam is given, it is possible to calculate a hydrograph and sediment concentration at a given position in the event of dam failure if Hyper KANAKO is combined with those calculation functions.

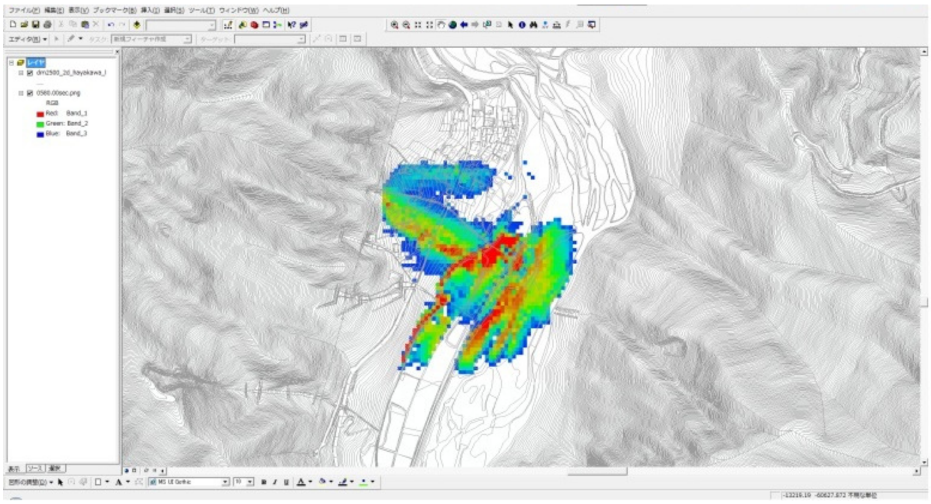

Fig. 11 Showing the simulation result in a GIS

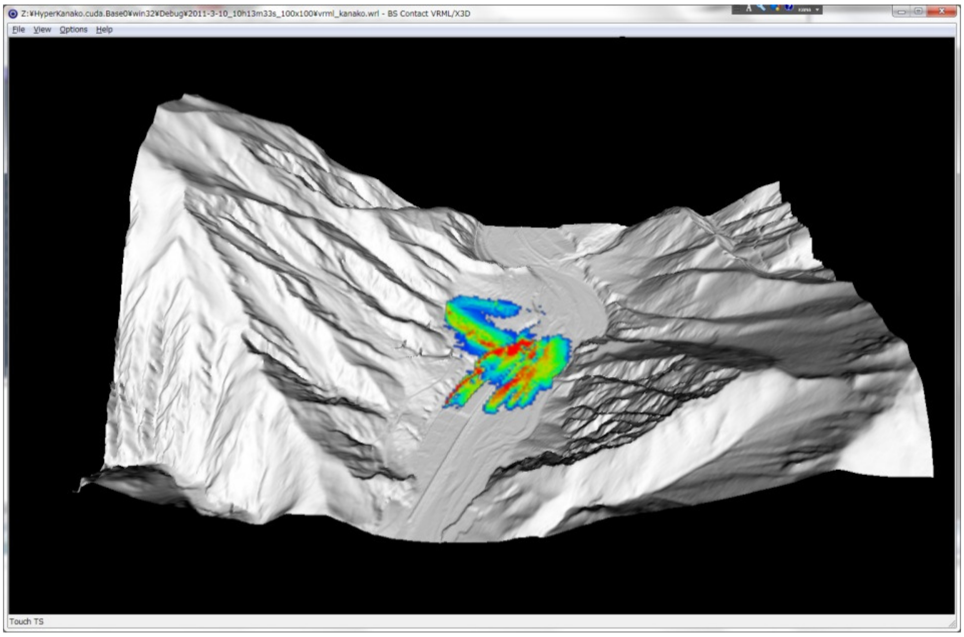

Fig. 12 Showing the simulation result on a 3D image

CHALLENGES AND CONCLUSION

The calculation can become even faster if we utilize the parallel calculation function of a powerful computer hardware because simulations in the 2D range are mostly matrix calculations. It may be possible to process 2D topographic data in 150×150 meshes at a speed much faster than the time given in Table 2 (for example, about 1/10 of that time). However, there are restrictions on the computer hardware or operating systems that can use this function. Hence, the program distributed normally is running calculation on software. The operability of the function for saving the simulation results can also be further improved by designing this function to suit specific needs.

Hyper KANAKO was developed for use with the Sabo D-MaC system. However, for users who do not have the Sabo D-MaC system, we are planning to offer a dedicated notebook computer as a mobile version that incorporates the functions of Hyper KANAKO and the Sabo D-MaC system as a package.

We will also produce and distribute a "tool" containing only a 2D debris flow flood simulation function so that ordinary users can make use of Hyper KANAKO by combining it with a free GIS or other software. We are also considering organizing a "Hyper KANAKO Study Group" consisting of those who purchase this tool. The study group would promote education regarding Hyper KANAKO use, the exchange of information among users, and meetings to discuss system improvement.

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