EXTRACTION OF GEOTECHNICAL PARAMETERS FROM TRACES LEFT IN THE JUNE 14th 2008, IWATE-MIYAGI INLAND EARTHQUAKE

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ABSTRACT: A M7.2 earthquake occurred in the south inland of Iwate prefecture at 8:43 JST on June 14th, 2008. This earthquake was responsible for a remarkable number of landslides, while dwellings suffered little damage. These devastated areas are mostly found along the foot of Kurikoma Mountain, an active composite volcano belonging to Nasu volcanic belt. The terrain there shows clear traces of not only soil mass movements triggered by this earthquake but also those of the past events, indicating that the area has been suffering from frequent geotechnical disasters. To mitigate these hazards, extracting geotechnical key parameters to predict possible landslide hazards in these areas is crucial. Traces of two highly significant geotechnical disasters, namely a debris flow that buried Komanoyu hot spring inn and a landslide mass of about 70 million m^3 that induced tsunami in the reservoir of Aratozawa dam, were taken as sample examples for extracting key parameters.

Key Words: Iwate-Miyagi Earthquake, trace, debris flow, landslide-induced tsunami, estimating velocity, Depth-Averaged Material Point Method, geotechnical parameters

INTRODUCTION

An earthquake of JMA magnitude 7.2 struck a south border area between Iwate and Miyagi prefectures, northeast Japan, on June 14th, 2008. Its epicenter was located at 39°01.7'N 140°52.8'E, about 385 kilometers north-northeast of Tokyo. One of the most significant aspects of this earthquake was that a number of landslides were triggered while few dwellings collapsed. Fig. 1 shows a topography of the affected area with the peak of Kurikoma volcano at the upper-left margin of the laser scanned terrain. This LIDAR (Light Detection and Ranging) image of the terrain, which was obtained on June 15th, 2008, the next day of the earthquake, clearly shows that valley density above a certain elevation is relatively low while valleys below this elevation are eroding mountain slopes down to lower elevations. This feature suggests the presence of harder caprock (andesite) overlying relatively soft sediments of volcanic products (pumice tuff), and the terrain below this elevation shows clear traces of not only soil mass movements triggered by this earthquake but also those of the past events, indicating that the area has been suffering from frequent geotechnical disasters.

To deal with the repeated geotechnical/geological hazards in a rational manner, extracting important geotechnical key parameters to predict possible landslide hazards in these areas is crucial. Traces of two highly significant geotechnical disasters, namely a debris flow that buried Komanoyu hot spring inn and a landslide mass of about 70 million m^3 that induced tsunami in the reservoir of Aratozawa dam, were taken as sample examples for extracting key parameters. For the first example at

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Komanoyu hot spring inn, debris flow simulations were conducted changing values of key parameters for the Depth-Averaged Material Point Method (DAMPM) to obtain an optimal solution for realizing the debris velocities estimated from mud marks of the flow remaining along the gulch. For the second example of the 70 million m^3 landslide mass, the marks of tsunami surge were examined through a numerical simulation changing the velocity of the soil mass slipped into the reservoir of Aratozawa dam.

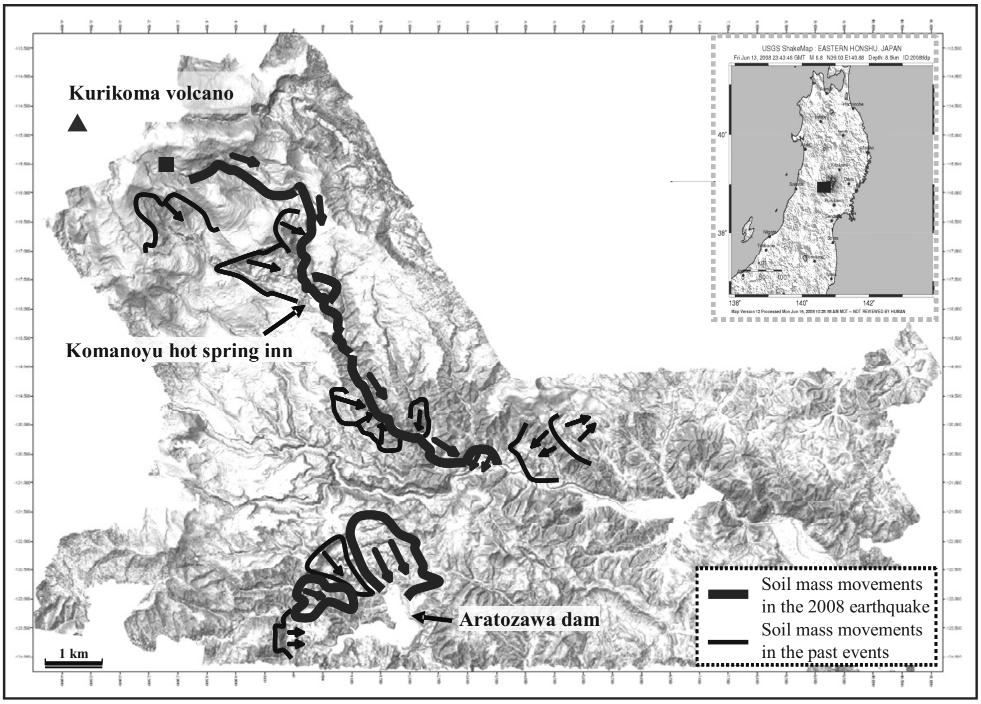


Fig. 1. Digital Elevation Model of the area affected by the 2008 Iwate-Miyagi Nairiku Earthquake: (DEM provided by Aero Asahi Co.)

DEBRIS FLOW WHICH HIT KOMANOYU HOT SPRING INN

Fig. 2 shows a path that the 1.5 million m^3 debris mass flowed down from its source right beneath the snow remaining around the eastern peak of Mt. Higashi-kurikoma (38.9584N 140.8061E), one of the peaks making up the Kurikoma volcano. A part of the mud flow of about a 0.5 million m^3 volume, whose path clogged with another landslide mass (38.9389N 140.8406E), surged up to "Komano-Yu" hot spring inn (38.9377N 140.8378E), where seven people were reportedly killed in soil and rubble.

The debris mass has left a mud-marked indication of superelevation at every curve along its path. Superelevation refers to the difference in surface elevation, or banking, of a debris flow as it travels around. Geological Survey Institute of Japan measured these superelevations at four major curves (see cross-sections {1} – {4} in Figs. 2 and 3).

Debris velocities were estimated from these superelevations, with the forced vortex equation which equates fluid pressure to centrifuge force (Johnson, 1984), as:

$$v = \sqrt{\frac{R_c g}{k}\frac{\Delta h}{b}} = \sqrt{\frac{R_c g}{k}\tan\theta} \quad (1)$$

where,

g: acceleration of gravity, Δh : the superelevation height (Fig. 3), R_c: the channel's radius of curvature

(Fig. 2), b: flow width (Fig. 3), $\theta(=\tan^{-1}(\Delta h/b))$: the banking angle (Fig. 3), and k: correction factor of viscous effects. This k, which is 1 for pure water flows, is often empirically set at 10 taking into account viscous features of debris flows. At the first curve (cross-section {1}), where the path takes a sudden and sharp turn in such a way that the flow seemingly surged straight up the gulch wall, the following equation of the energy conservation law was used instead of Eq. (1):

$$v=\sqrt{2g\Delta h} \tag{2}$$

Table 1 shows the estimating debris velocities at cross-sections {1} – {4}.

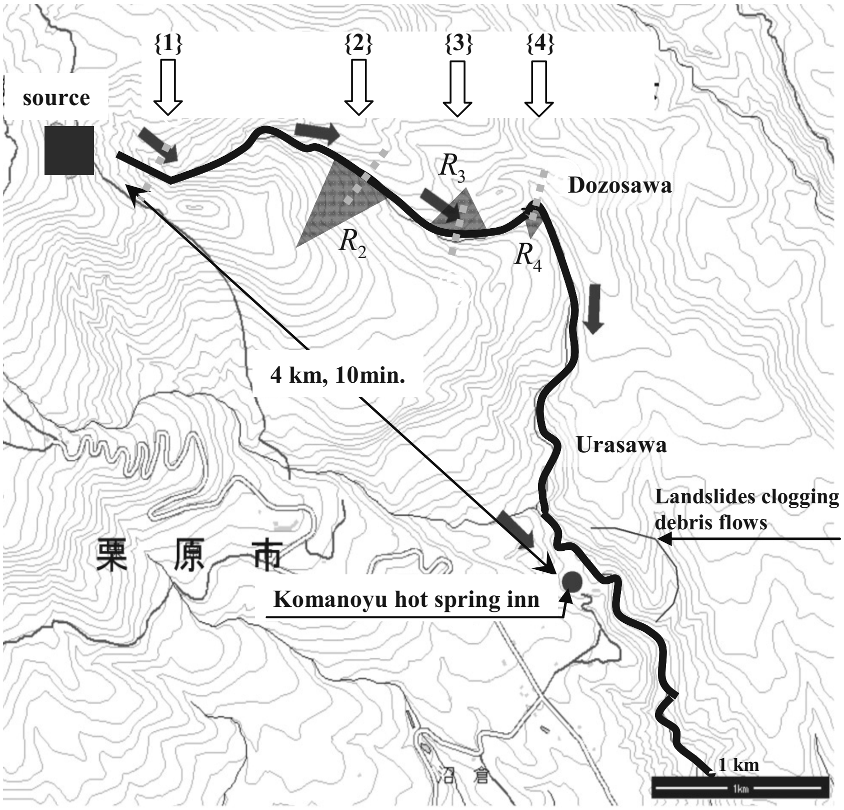


Fig. 2. Path of debris flow which hit Komanoyu hot spring inn

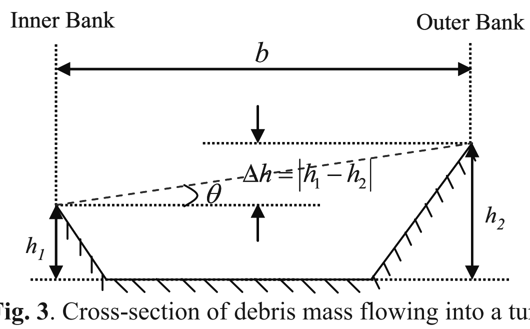


Fig. 3. Cross-section of debris mass flowing into a turn

Table 1. Estimating debris velocity

cross section	method	superelevation height Δh (m)	flow width b (m)	radius of curvature R_c (m)	debris velocity v (m/s)		
					k=1	k=10	average
{1}	Energy conservation law	59	-	-	34		
{2}	Johnson (1984)	23	115	730.4	37.9	12.0	24.9
{3}		36	90	230.2	30.1	9.5	19.8
{4}		40	100	140.7	23.5	7.4	15.5

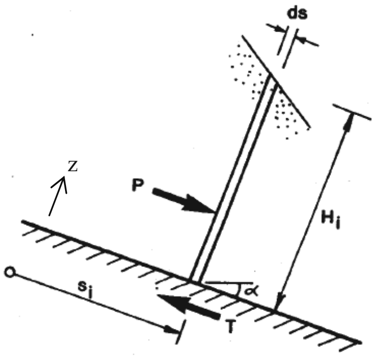


Fig. 4. Forces acting on a boundary block other than weight (Hungr, 1995)

Depth-Averaged Material Point Method (DAMPM) was used to simulate the debris flow. DAMPM is based on the concept to describe a debris mass as a cluster of upright material columns that move through cells of computational fixed Eulerian mesh (Konagai et al., 2002), and a simple semi-empirical model for describing equivalent fluid (Hungr, 1995) has been implemented for the material columns. The idea to describe material columns through a fixed computational grid is based on the scheme for the Material Point Method proposed by Sulsky et al. (1994). The advantage of this scheme is that it can represent large deformation and provide a Lagrangian description that is not subject to mesh tangling. In the DAMPM, governing equations are integrated along the z direction to ignore motions of particles within each column. Eventually, this procedure leads to both shallow water and consolidated elasto-plastic assumptions for liquefied and coherent debris mass flows, respectively.

A material column in the DAMPM is shown in Fig. 4. The net driving force acting on a boundary block between the columns consists of the tangential component of weight, the basal resisting force, *T,* and the tangential internal pressure resultant, *P*. The resultant pressure term, *P*, is described by the pseudo three-dimensional Drucker-Prager model whose yield surface is assumed to circumscribe the Mohr–Coulomb yield surface expressed in terms of the material cohesion, *c*, and the angle of internal friction, ϕ.

The basal resisting force is defined by the Voellmy bi-parametric model, owing to the fact that it gives the most consistent results with field measured data, as:

$$T = A\left\{\rho g h\left(\cos\alpha + \frac{a_c}{g}\right)(1 - r_u)\mu + \rho g \frac{\bar{v}^2}{\xi}\right\} \tag{3}$$

where *A*: the basal area, ρ : bulk unit density of the column, *g*: acceleration of gravity, *h*: height of the column, α : bed slope angle, a_c : centrifugal acceleration, dependent on the vertical curvature radius of the path, r_u : pore-pressure coefficient (ratio of pore pressure to the total normal stress at the base of the column), μ : the basal frictional coefficient, $\bar{v}$: local depth-averaged velocity, and ξ : turbulence coefficient that describes the thickness of the basal layer, dilatant flow, viscosity and turbulence.

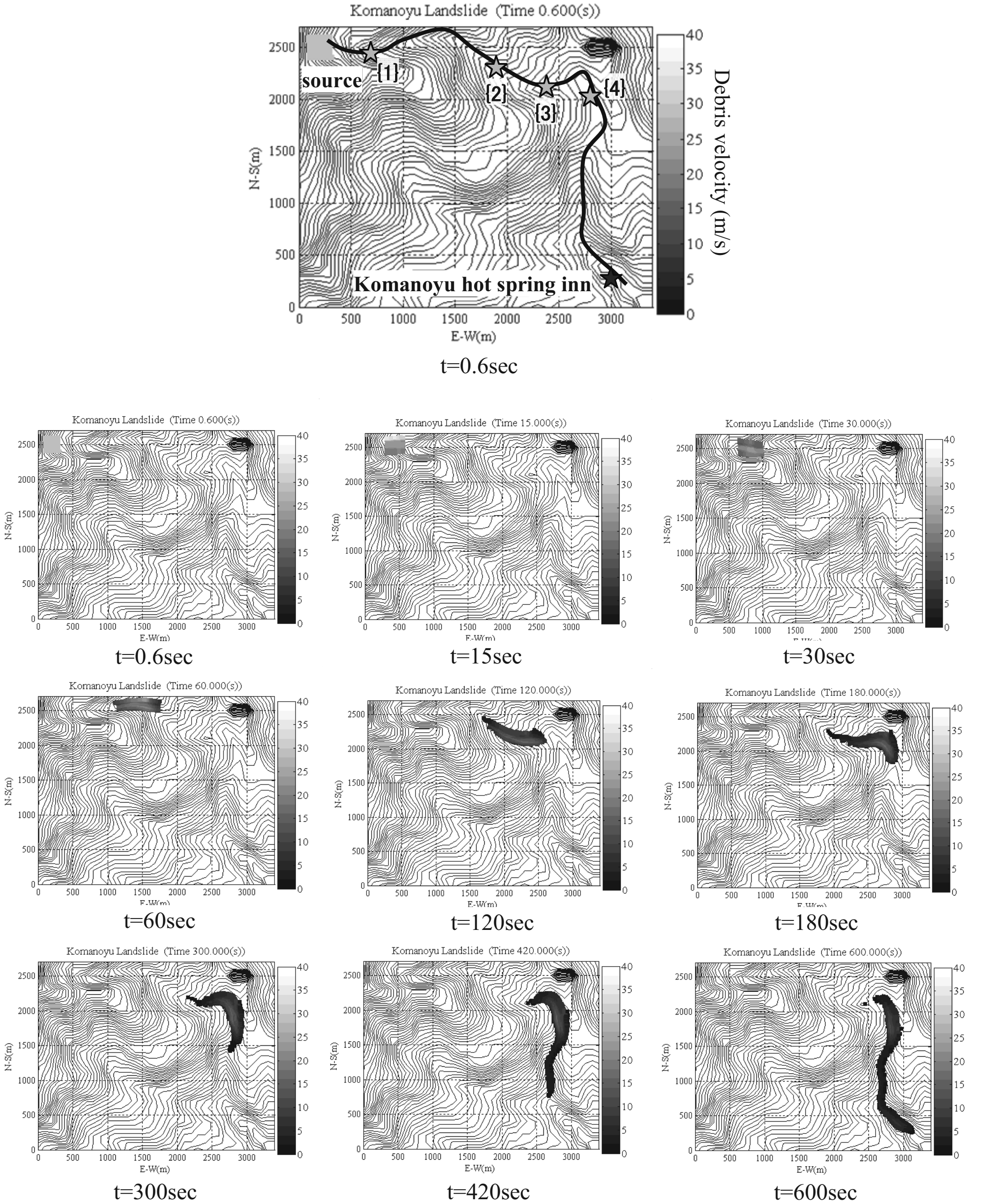


Fig. 5. Simulated debris flow

As a whole, the number of necessary Lagrangian parameters for the DAMPM simulation is seven as listed in Table 2. These seven parameters were then calibrated to adjust the simulated debris flow velocities to the velocities estimated from superelevations of the flow. Fig. 5 shows a simulated debris flow at t = 0.6, 15, 30, 60, 120, 180, 300, 420, 600s after the debris mass started flowing. It is said that the debris flow reached Komanoyu hot spring inn in ten minutes; this result was consistent with witness accounts.

Fig. 6 shows variations of debris velocity with respect to the distance from the source. Solid circle and triangle marks show debris velocities estimated from energy conservation laws and the superelevations of the flow with the correction factor k in Eq. (1) set at 10 respectively, while thick broken, solid, and thin dotted lines are respectively maximum, average, and minimum velocities of the simulated flow. Average velocities from the simulation are in good agreement with those estimated from the superelevations. The calibrated parameters were shown in Table 2.

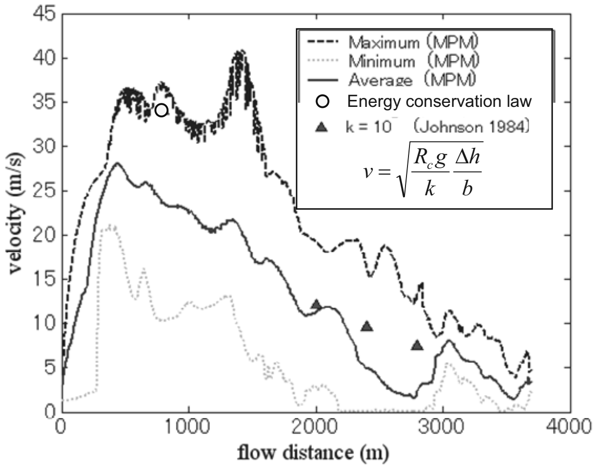


Fig. 6. Comparison of velocities from MPM simulation and those estimated from mud marks

Table. 2. Extracted geotechnical parameters at Komanoyu area

No.	Input Parameter	Symbol	Unit	Value
1	Density	ρ	kg/m^3	1600
2	Young's modulus	E	Pa	2.0*10^6
3	Poisson's ratio	ν	--	0.3
4	Angle of internal friction	ϕ	--	30
5	Basal friction	μ	--	0.075
6	Angle of dilatancy	ψ	deg	0
7	Turbulence coefficient	ξ	m/s^2	285

LANDSLIDE BEHIND THE RESERVOIR OF ARATOZAWA DAM

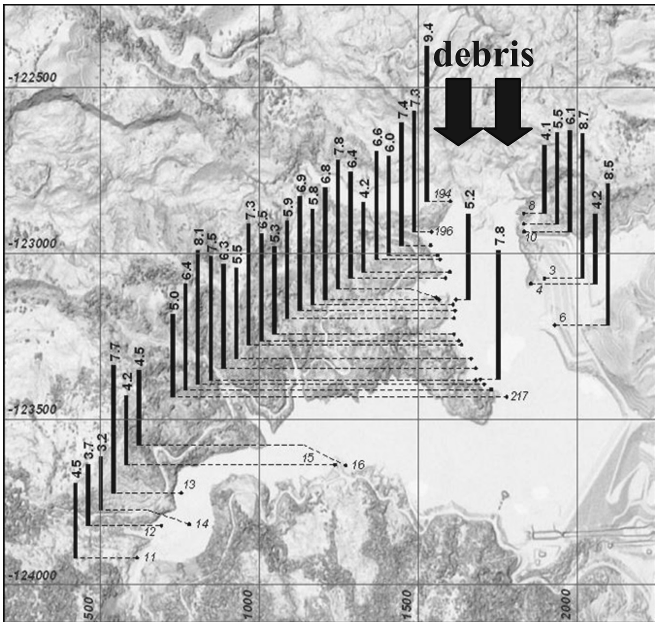
Fig. 7 shows a bird-eye's view of the Aratozawa landslide mass with an estimated volume of 70 million m^3. A part of the landslide mass of about 1.5 million m^3 has slipped into the reservoir of the dam, and caused a tsunami. This volume of debris, which is equivalent to about 2% of the total landslide mass, was calculated from both the changes in bathymetries before and after the earthquake, and the 2.4m increase in the water level of the reservoir from 268.5m to 270.9m (see Table 3). Due to this unusual tsunami surge, mud marks were remaining along the shores of the reservoir, indicating the tsunami inundation heights shown in Fig. 8. Based on the measured tsunami inundation heights, an attempt was made to estimate the velocity of the landslide mass slipped into the reservoir of the dam.

Fig. 7. Landslide mass behind the reservoir of Aratozawa dam
(Photo by Konagai, K., June 15, 2008)

Table 3. Dam lake elevations measured by Dam Management Office

Date	Elevation (m)	Remarks
06/14/08	268.5	Before Earthquake
06/14/08	270.9	After Earthquake, water level increased due to debris-inflow and possibly due to tectonic deformation
07/13/08	261.2 *	Reference elevation for measurements
07/25/08	259.1 *	Reference elevation for measurements

* The increased water level was lowered to be prepared for the rainy season.



No.	Point ID	Plane-rectangular coordinate system		Height
		X (m)	Y (m)	η (m)
1	194	1600.5	-122839.5	9.35
2	196	1540.5	-122934.5	7.25
3	197	1540.5	-122974.5	7.35
4	198	1560.5	-123004.5	5.95
5	199	1570.5	-123019.5	6.55
6	200	1600.5	-123054.5	4.15
7	201	1585.5	-123074.5	6.35
8	202	1555.5	-123129.5	7.75
9	203	1565.5	-123139.5	6.75
10	204	1620.5	-123139.5	5.15
11	205	1610.5	-123154.5	5.75
12	206	1615.5	-123169.5	6.85
13	207	1610.5	-123194.5	5.85
14	208	1610.5	-123244.5	5.25
15	209	1630.5	-123259.5	6.45
16	210	1635.5	-123274.5	7.25
17	211	1665.5	-123314.5	5.45
18	212	1680.5	-123344.5	6.25
19	213	1680.5	-123379.5	7.45
20	214	1695.5	-123379.5	7.75
21	215	1710.5	-123389.5	8.05
22	216	1730.5	-123409.5	6.35
23	217	1775.5	-123429.5	4.95
24	13	755.5	-123719.5	7.70
25	12	690.5	-123819.5	3.70
26	11	615.5	-123914.5	4.50
27	14	780.5	-123814.5	3.20
28	15	1240.5	-123634.5	4.20
29	16	1270.5	-123639.5	4.50
30	6	1930.5	-123214.5	8.50
31	3	1895.5	-123074.5	8.70
32	4	1855.5	-123089.5	4.20
33	10	1835.5	-122934.5	6.10
34	9	1830.5	-122909.5	5.50
35	8	1830.5	-122879.5	4.10

Fig. 8. Tsunami inundation heights
from lake elevation 268.5m on June 14th, 2008(before earthquake)

Numerical simulations of the tsunami surge were conducted based on the nonlinear long-wave theory. The governing equations for the tsunami surge with the effect of the reservoir bed uplifts are given on the Cartesian coordinates (*x, y*) as:

$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} - \frac{\partial \xi}{\partial t} = 0 \tag{4}$$

$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x}\left(\frac{M^2}{D}\right) + \frac{\partial}{\partial x}\left(\frac{MN}{D}\right) + gD\frac{\partial \eta}{\partial x} + f_B \frac{M\sqrt{M^2+N^2}}{D^2} = 0 \tag{5}$$

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial x}\left(\frac{MN}{D}\right) + \frac{\partial}{\partial y}\left(\frac{N^2}{D}\right) + gD\frac{\partial \eta}{\partial y} + f_B \frac{N\sqrt{M^2+N^2}}{D^2} = 0 \tag{6}$$

where,
M: flux in *x* direction (=*uD*, *u*: velocity in *x* direction), *N*: flux in *y* direction (=*vD, v*: velocity in *y* direction), *h*: initial depth of water, η: change in water level, *D*: total depth of water $(= h + \eta)$, ξ: reservoir bed's uplift, and f_B: frictional coefficient of reservoir bed ($= gn^2 / D^{1/3}$, *n*: Manning's coefficient).

Eq. (4) shows the mass conservation law including the effect of dam bed uplifts. Eqs. (5) and (6) describe motions in *x* and *y* directions, respectively. They have advection terms, hydro static pressure terms and frictional terms based upon Manning's formula for free surface flows.

To describe the effect of landslide-mass inflow, reservoir-bottom elements were lifted up one by one from the debris source end at the north of the reservoir to the end that the mass has reached (see Fig.9). Fig. 10 shows the change in the depths of the reservoir bed, which was obtained by subtracting bathymetry data in 1998 from that immediately after the earthquake (June - July, 2008). As the distance that the landslide mass reached was about 400m from the debris source end, the inflow velocity, *V*, of the landslide mass was obtained by dividing the distance of 400m by the time for the entire process of the reservoir bed's uplift.

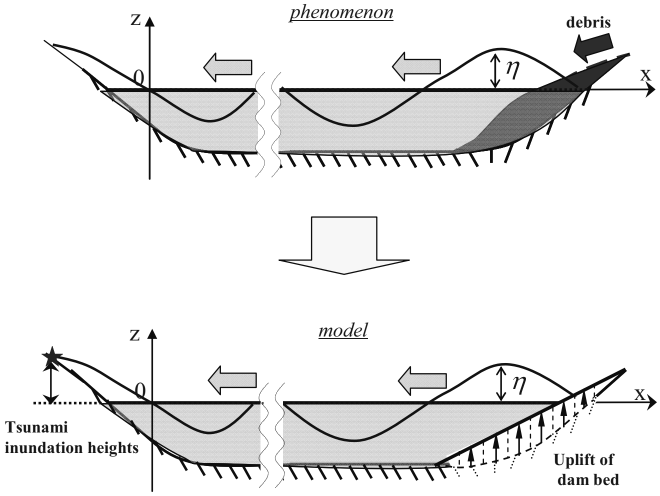


Fig. 9. Modeling of tsunami source

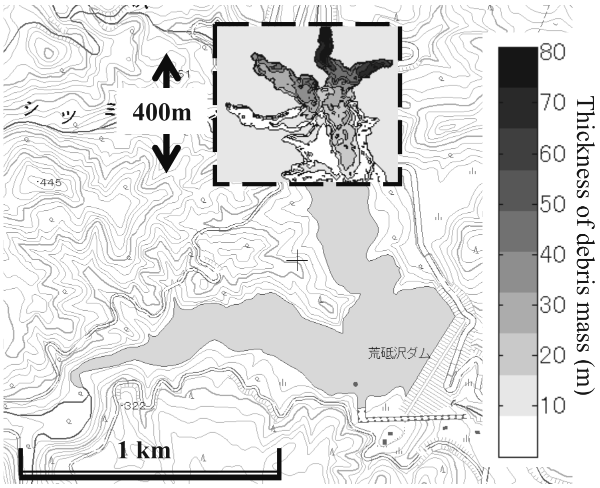


Fig. 10. Thickness of debris mass slipped into the reservoir (only in the dotted square)

Bars and lines in Fig. 11 are the measured and simulated tsunami inundation heights with respect to the measured points (see table of Fig. 8). The simulated heights are mostly affected by the debris inflow velocity V slipped into the reservoir and the reservoir's bed frictional coefficient f_B as shown in Eqs. (4) to (6). Gradually changing these key parameters, the result from the numerical simulation was accommodated to the optimum solution in a least square sense. The left side of Fig. 11 shows the effect of the inflow velocity on the simulated tsunami heights, while the right side shows the effects of reservoir bed friction. Simulated tsunami heights are highly susceptible to the landslide mass velocity while they are less sensitive to the reservoir bed friction. This tendency is particularly true near the source of the tsunami wave (open circles in Fig. 11). Through the least square optimization of the tsunami heights, the inflow velocity was estimated to be around 4.4m/s (see Fig. 12).

It is probably premature to deduce that the entire landslide mass had this velocity of 4.4m/s only from the abovementioned simulations for the tsunami caused by the 2% volume of the entire landslide mass. Moreover, hundreds of woods uprooted in this landslide event have drifted over the reservoir and thickly covered the water near the tsunami source. These driftwoods may have damped the tsunami wave particularly in the tsunami-source zone of the reservoir, and therefore yielded an under-estimation of the debris inflow velocity. However, it will be right in deducing that the lower bound of the inflow velocity was obtained from the tsunami inundation heights.

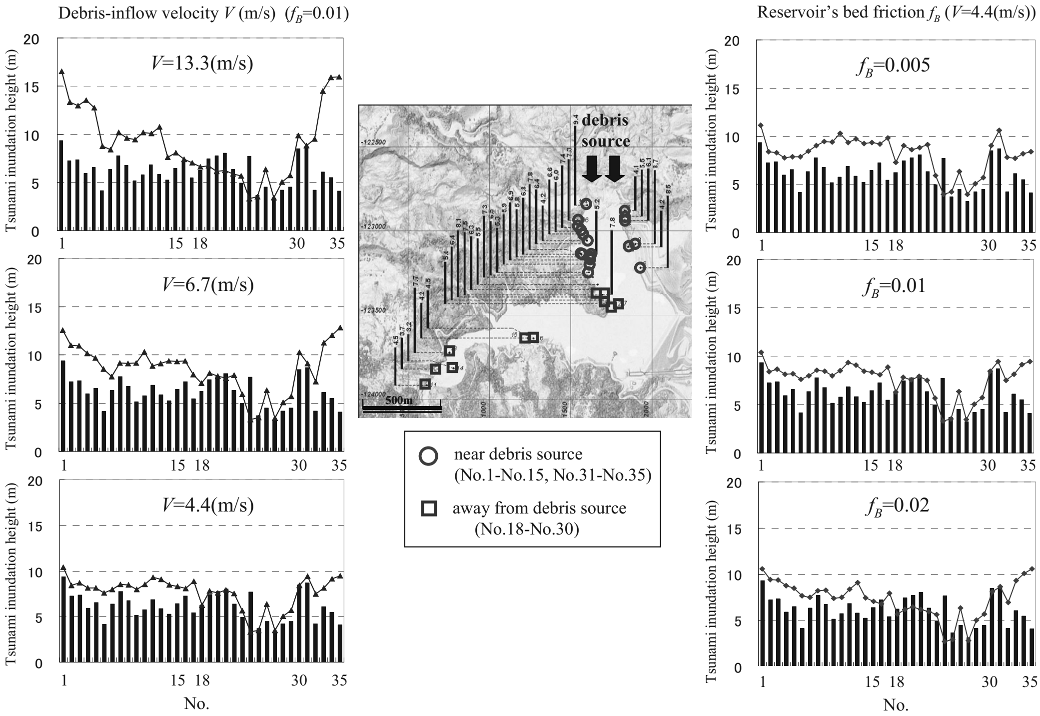


Fig. 11. Comparisons of measured and simulated results for tsunami inundation heights

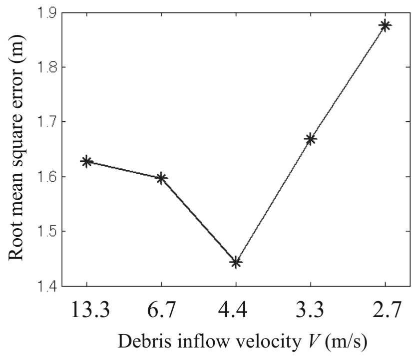


Fig. 12. Root mean square error between estimated and measured tsunami inundation heights

CONCLUSIONS

The Iwate-Miyagi inland earthquake was remarkable in that a number of landslides and debris flows were triggered despite dwellings with relatively little damage. The devastated areas are mostly found along the foot of Kurikoma Mountain, an active composite volcano. The terrain there shows clear traces of not only soil mass movements caused by this earthquake but also those of the past events, indicating that the area has been suffering from recurrent geotechnical disasters. In preparation for possible landslide hazards, extracting important geotechnical parameters will allow us to predict possible distances traveled by landslides and possible velocities of soil/rock masses. Traces of two highly significant geotechnical disasters, a debris flow that buried Komanoyu hot spring inn and a landslide mass of about 70 million m^3 that induced tsunami in the reservoir of Aratozawa dam, were taken as sample examples for extracting key parameters.

At Komanoyu area, debris velocities at four curves along the path were first estimated from superelevations of the flow. Then the debris flow was simulated by using the Depth-Averaged Material Point Method (DAMPM). DAMPM is based on the concept to describe a debris mass as a cluster of upright material columns that move through cells of computational fixed Eulerian mesh, allowing us to simulate large soil deformations which are not subject to mesh tangling. Gradually changing key parameters of DAMPM, the parameters that realize the best fit to the estimating velocities were obtained.

At Aratozawa dam, a part of a large landslide mass has slipped into the reservoir, and caused a tsunami. Given this unusual tsunami event, an attempt was made to estimate the velocity of the landslide mass from remaining tsunami inundation marks. Through the least square optimization of the tsunami heights by changing two key parameters for the simulation, namely the landslide mass inflow velocity and the friction of the reservoir's bed, the inflow velocity was estimated to be around 4.4m/s. Since hundreds of woods uprooted in this landslide event have drifted over the reservoir and thickly covered the water near the source, it will be right in deducing that the lower bound of the landslide mass velocity was obtained from the tsunami inundation heights.

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