An Attempt for Velocity Estimation of Nebukawa Debris Flow Triggered by the Great Kanto Earthquake, 1923

Md. Aftabur RAHMAN[1], Takumi HASHIMOTO[2] and Kazuo KONAGAI[3],

[1]PhD Student, Graduate School of Urban Innovation, Yokohama National University
(79-1, Tokiwadai, Hodogaya-ku, Yokohama, 240-8501)
Email: rahman-aftabur-vb@ynu.jp
[2]Former Undergraduate Student, Graduate School of Urban Innovation, Yokohama National University
(79-1, Tokiwadai, Hodogaya-ku, Yokohama, 240-8501)
Email: hashimoto-takumi-mj@ynu.jp
[3]Professor, Graduate School of Urban Innovation, Yokohama National University
(79-1, Tokiwadai, Hodogaya-ku, Yokohama, 240-8501)
Email: konagai@ynu.ac.jp

A catastrophic debris avalanche that ensued from the 1923 Great Kanto Earthquake occurred near the rim of the Hakone crater, Kanagawa Prefecture; destroying Nebukawa town with loss of many lives. Its debris mass travelled along the Shiraito River; uprooting trees on both river walls, burying many houses, and pushed Nebukawa Railway Bridge to the sea. A simplified iterative approach is applied to this debris event for estimation of the velocity of debris slurry. Documented super-elevations of the flowing material along the bends of the flow path are used in this paper. An old topographical map is compared with the current terrain and real field data used as input parameter for the iterative procedure. Several stretches of the river channel are analyzed with the proposed approach and velocities of the debris flow are estimated for the chosen stretches.

***Key Words**: Great Kanto Earthquake, Nebukawa debris event, velocity, super-elevation, sloshing.*

1. INTRODUCTION

The Great Kanto earthquake of 1923 elicited a massive debris avalanche near the rim of the Hakone crater, Kanagawa Prefecture. There are many opinions about deaths caused by this sole event, which is referred to as “Shiraito-river debris flow”, because deaths were compiled for three major slope failures that took place on the heels of another in the same region. However, this debris mass is considered to have smashed 64 to 67 houses of Nebukawa town killing about 300 people of total 858 of Nebukawa town[1)]. A huge amount of soil mass was detached from mountainous area about 3.5 kilometers upstream of the Shiraito River, and turned into gigantic debris flows. The mass ran down the Valley of Shiraito River in a thick cloud of dust and rushed into the Nebukawa town with thunderous roar breaking and burying houses along the flow path[2)]. Debris mass swept away the Nebukawa steel deck railway bridge towards the sea, which deck fell down to the valley in the intense shake shortly before the debris surge.

The Nebukawa region, lying along the foot of Hakone Volcano, has long been an important point of traffic through Tokaido route connecting Tokyo with Osaka, and now we have the high-speed railway line, Tokaido-shinkansen, for the Tokaido route, which runs across the Shiraito River at an elevation lower than the Nebukawa steel railway bridge. All the more because of its importance, necessary measures are to be taken for this region referring to the past events. However, there is yet controversy as to where the real source was, how fast the debris mass ran the valley, etc., though there is the most dominant opinion developed by Kobayashi[2)].

Debris flow mitigation strategy includes identifying the mean flow velocity along the path, peak discharge, and flow volume etc[3)]. Furthermore, Velocity of flowing debris mass along the channel is of critical interest to the researchers and authorities concerned for mitigation of debris flows as it affects impact force, travel distance and erosion rate. Commonly, two approaches are used to estimate the debris flow velocity i.e. field investigation and experimental observation. Field investigation uses super-elevations of previous debris flow events and velocities are back calculated. However, velocity estimation is affected by several factors like bend and cross-sectional geometries, channel gradient etc.

Recent researches show the difficulties associated with estimation of debris flow velocity and influence of radius of curvature on the estimation of velocity[4]. A simplified methodology is proposed herein to estimate the debris flow velocity from sloshing period of flow along the curved path using field estimated super elevation of the previous debris event. Nebukawa debris flow area is chosen to validate the method of velocity estimation as detached mass traveled along curved channel of Shiraito River.

2. SOURCE OF SHIRAITO-RIVER DEBRIS FLOW

Imamura[5], who surveyed the debris-mass affected area 50 days after the earthquake, reported that there are some suspicious scars on slopes of the outer rim of Hakone crater, which may have been the source(s) of this huge debris flow that ran about 6 km distance down in about 5 minutes. These scars were mostly on (1) the southern slope of Mt. Hijiri, and (2) the northern slope of Mt. Hoshi. In terms of size, those on the southern slope of Mt. Hijiri seem to be more plausible. However local people said that among those on the southern slope of Mt. Hijiri, eastern most Obora scar appeared after the debris flow event. Putting them together, Imamura concluded that the source of the debris flow was either the south to southwest scars of Mt. Hijiri or east scar of Mr. Shirogane.

Kobayashi[2] made an attempt to compare two topographical maps of the source area from different times of 1916 (Taisho 5) and 1970 (Showa 44). Kobayashi assumed that the decrease and increase in elevation are largely due to erosions and depositions respectively, and suggested that the Obora scar (**Fig. 1**), which is the largest in terms of the volume of the detached mass exceeding 10^6m^3, can be the most plausible as the source among others. This volume conforms to 1 to 3×10^6 m^3 volume estimated by Imamura[5]. Regarding the discrepancy between his opinion and the re-collection of the local people saying that the scar appeared after the debris flow event, Kobayashi explained that the scar at Obora is made up of two major hollows, and one of these two hollows may have appeared after the debris flow event.

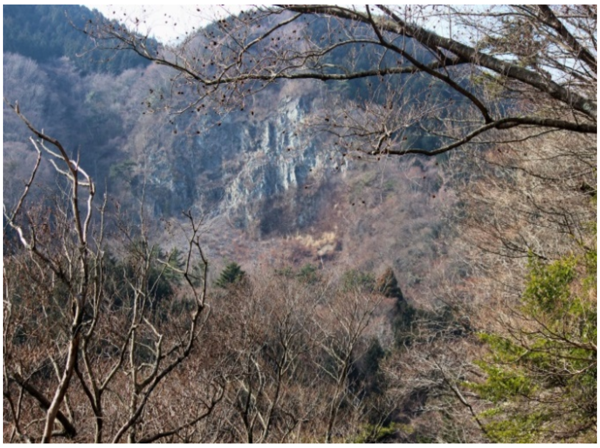

Fig. 1 Obora scar

With the help of highly advanced GIS tools, template matching of these two topographical maps was done in a more quantitative manner with reference to locations and elevations of Mt. Hoshi (814.6m a.s.l.), Mt. Hijiri (835.0m a.s.l.) and Mt. Shirogane (993.1m a.s.l.). The 1:50,000 scale map prepared in 1896 (Meiji 29) and the digital elevation model (DEM) of the target terrain prepared by the Geospatial Information Authority of Japan (GSI) on December 4th, 2008 were used herein as maps to compare. In the older map of 1896, the elevations of these peaks were 814.4m and 838m and 992.6m, respectively, and differ a little from those in the map of 2008. The error was probably attributed to the old way of measuring, called plane table measurement in which a drafting board on a tripod, an alidad, a pole and a tape line were used. However the distances among these peaks in the old map matched very well those in the new map, and the error in elevation is much less significant that in the drastic change in contour lines. Therefore geo-referencing of the scanned and digitized older map was done for the longitudes and latitudes of these reference (control) points.

Fig. 2 shows the obtained change in elevation in the source area of the Shiraito River debris flow. Though the accuracy is yet debatable, the change in volume was estimated to be -3.8×10^6 m^3 for the rectangular area shown in Fig. 2 with Obora scar in its middle, which volume conforms to 1 to 3×10^6 m^3 estimated by Imamura. However at the same time, **Fig. 2** shows that there are some suspicious dents remaining on mountain slopes and along river channels, indicating that there is a possibility that several debris masses from different sources joined together to be a large debris mass.

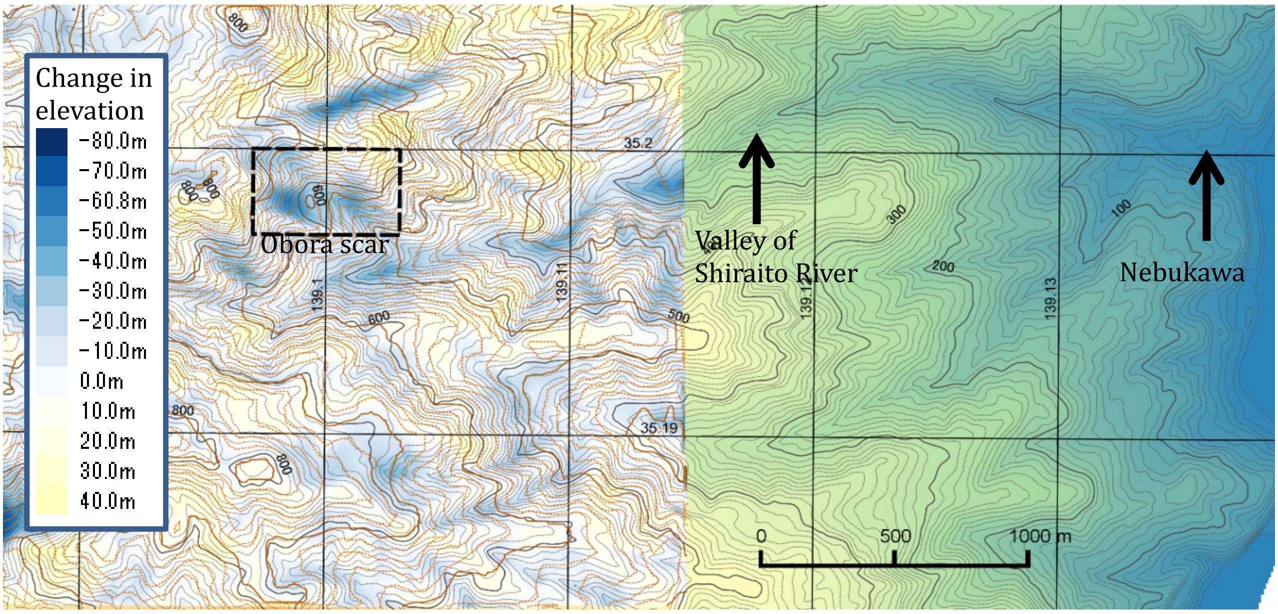

Fig.2 Change in elevation in the source area of the 1923 Shiraito River debris flow: Brown and black contour lines are for 1896 and 2008 terrains, respectively. The change in volume was estimated to be -3.8×10^6 m^3 for the rectangular area in this figure.

3. ESTIMATION OF DEBRIS FLOW VELOCITY

Rational estimation of velocity is crucial for any mitigation measures. A debris mass leaves mud marks along its flow path, and when it travels through a curved flume, height difference between mud marks on right and left river walls, referred to as "super-elevation" appears. Velocities are often estimated from the observed super-elevations using the following equation (1):

$$v = \sqrt{\frac{R_L}{k}\frac{g\,\Delta h}{b}} \quad (1)$$

where, R_L= radius of curvature of selected flume stretch, Δh= super-elevation, b= width of channel, g= acceleration due to gravity, k= correction factor for viscosity, and v = velocity of debris flow. Equation (1) assumes that flow is subcritical, the radius of curvature is equal for all stream lines, and every stream line's velocity is equal to the mean flow velocity. Correction factor k is introduced to account for the viscous nature of the flowing slurry and vertical sorting/ segregation of grains within the flowing slurry. Depending on what case history we use as an example, k value can vary largely. Van Dine[6] stated that k may vary from 1 to 5, while Chen[7] reported that k may be as high as 10. This large variation of k may also depend on the subjective manner of determining the radius of curvature.

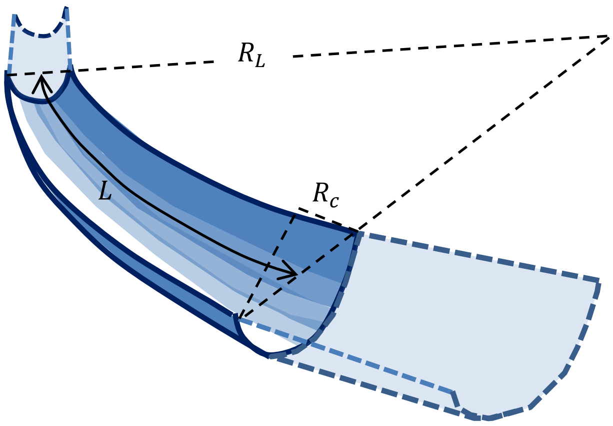

Fig. 3 Curved stretch of a flume connecting two straight channels at its both ends

To avoid the subjective way of determining the radius of curvature, the following assumptions are developed herein:

(1) The plan of the flume is approximated by an arc of radius R_L connecting two straight channels at its both ends (**Fig. 3**). This assumption indicates that a single square time history of centrifugal force is applied to the debris slurry through the arc section.
(2) The transverse cross-section of the flume is assumed to be a constant arc with radius R_c over its entire stretch.
(3) Viscous feature of the debris slurry is ignored.

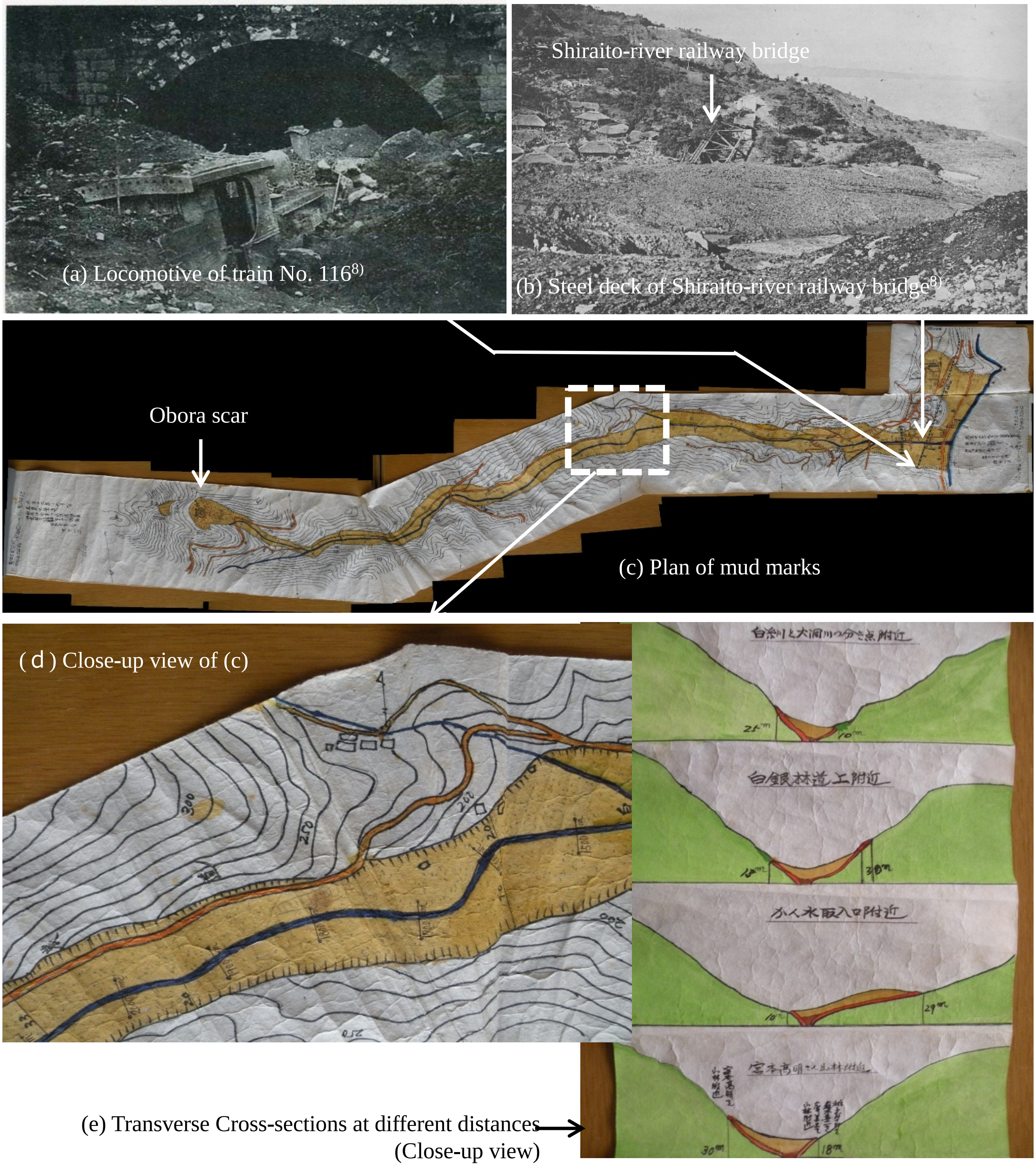

Fig. 4 Illustrations of mud marks along Shiraito River by Kazumasa Uchida (Kanagawa Prefectural Archives)

(4) Steady state flow is discussed. Other than this,

(5) All Lagrangian particles of the debris slurry that exist on a particular transverse cross-section of the flume at a certain time remain plane throughout the entire flowing process.

According to Assumptions 1 and 4, the maximum super-elevation appears at the lower end of the flume arc, and the time, T_0, for the flow to reach this super-elevation is assumed to be equal to a quarter of this sloshing period, $T_s/4$ (Assumption 5) for the average transverse cross-section with radius R_c.

$$T_0 = \frac{T_s}{4} = \frac{\pi}{2}\sqrt{\frac{R_c}{g}} \qquad (2)$$

Thus the following iterative procedure can be used to determine both the velocity and the radius of curvature:

Fig.5 DEM of current topography at Nebukawa debris flow area

(i) First, specify the target curved channel of length L_1

(ii) For this specified stretch of the channel, obtain the average radius of curvature $R_{L,1}$, and the average transverse cross-section with radius $R_{c,1}$ (Assumption 2),

(iii) Given the observed super-elevation Δh across the flow width b, and ignoring viscous features of the debris slurry (Assumption 3), obtain the initial estimate of flow velocity $v_{0,1}$ using Equation (1),

(iv) For the average transverse cross-section with radius $R_{c,1}$, obtain the time for the maximum super elevation to be reached, $T_{0,1}$,which time is equal to a quarter the sloshing period $T_{s,1}$ given by Equation (2).

(v) Multiplying initial constant (steady state) flow velocity $v_{0,1}$ by $T_{0,1}$, the entire stretch of the flume is updated to be L_2. For this updated stretch, the above mentioned procedures (i) through (iv) are repeated until sufficient and necessary convergence is reached.

Given a number of precedent field surveys and studies, Shiraito-River debris flow is competent for examining the proposed procedure. Other than that, Kazumasa Uchida, a 10 year old boy at the time of debris flow whose house was buried under the debris deposit, illustrated longitudinal and transverse profiles of the debris flow along the Shiraito River. His illustrations on scrolls of wrinkled Japanese paper are in storage at Kanagawa Prefectural Archives (**Fig. 4**). His illustrations were first digitized and geo-referenced to be overlaid on the current topographical map to extract necessary pieces of information (**Fig. 5**). Total 14 points (red points in **Fig. 5**) for the known exact locations were used for the geo-referencing using a spline function.

4. RESULT AND DISCUSSIONS

Velocities of this debris mass were calculated for three different bends of the river channel following the procedure given in the preceding section. Three stretches along the Shiraito River, 700-900m, 1700-1900m and 1900-2100m from the Obora scar, were chosen for this study. Super-elevations for these chosen stretches were measured from the illustration by Uchida. In reality, cross-sections differ from location to location even within a short stretch of the river channel. Therefore cross sections at a regular 100m interval were first obtained from the digital elevation model (DEM) of the current terrain of 2008, and corresponding arcs that best-fit the chosen cross-sections in the least square sense were calculated. Then, these cross sections were averaged to get the representative radius for the transverse cross-sections of the chosen channel stretch, which radius determines the sloshing period. **Fig.6** shows, in blue and red respectively, the real and equivalent cross-sections of Shiraito River channel at 700m, 800m and 900m distances from the Obora scar. Equivalent transverse cross-sections and their average cross-section are shown in **Fig. 7**.

The iterative procedure yielded the estimated velocities of 21.5, 28.5 and 16.7 m/sec at 700-900m, 1700-1900, and 1900-2100m respectively (**Table 1**). The obtained velocities are compared with those from a numerical simulation by Kobayashi[9] (**Fig. 8**), who used the following equation of motion by Kröner[10] for a moving mass subjected to frictional resistance and air resistance:

$$\frac{dv}{dt} = g\left(a - \frac{v^2}{\xi D_f}\right) \qquad (3)$$

where, $a = \sin\beta - \mu\cos\beta$, with $\beta =$ river-bed slope, $\mu =$ basal frictional coefficient, $\xi =$ turbulence coefficient after Voellmy (inversely proportional to drag coefficient), and $D_f =$ depth of flow. As can be seen in Equation (3), Kobayashi's estimation is based upon the Saint Venant hypotheses for a one-dimensional non-Newtonian flow with inclusion of an additional friction slope term. Meanwhile, the iterative procedure given herein takes into account of the sloshing nature of the slurry for a curved flume cross-section. Seeing the debris mass movement from different aspects, the obtained velocities (open square in **Fig. 8**) are 50 to 100% of those from those estimated by Kobayashi. The most

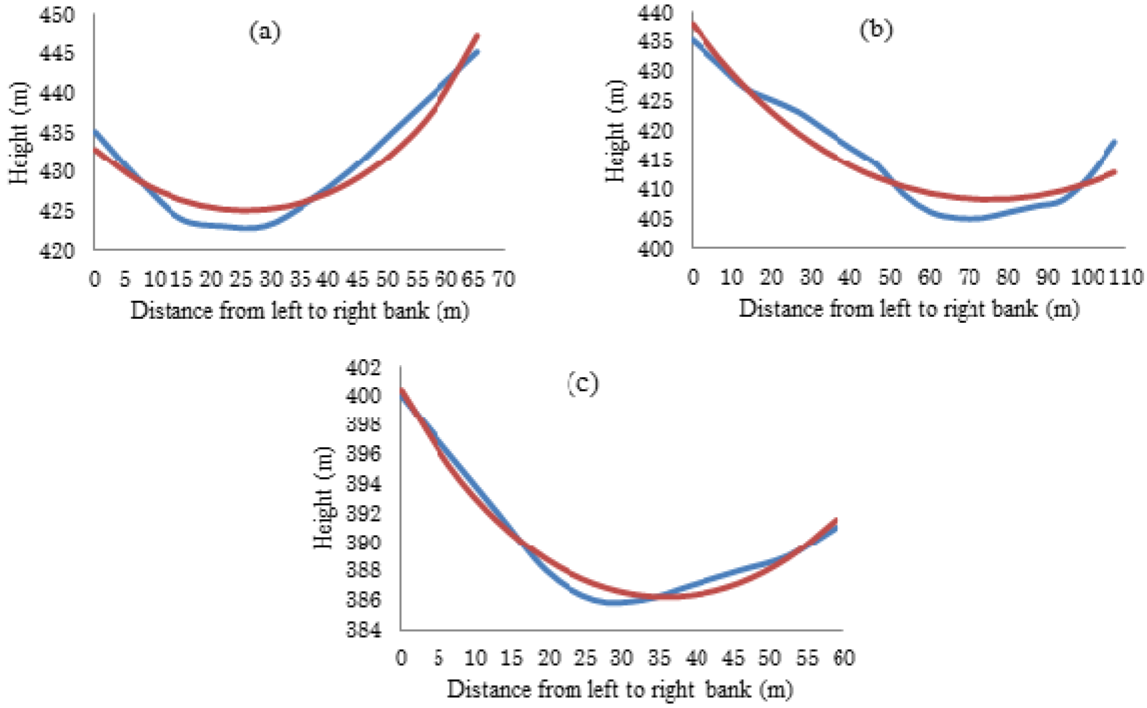

Fig.6 Transverse sections at (a) 700m, (b) 800m & (c) 900m from source area (Obora scar)

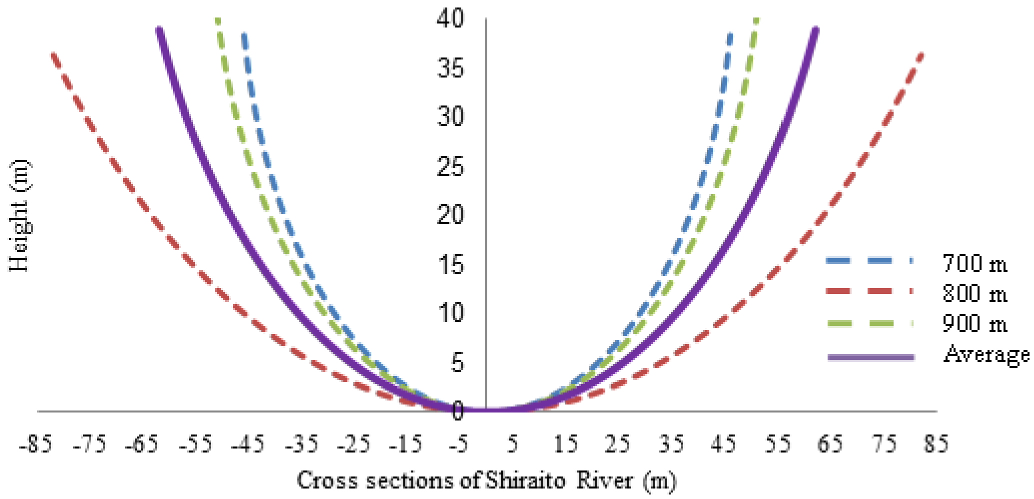

Fig.7 Average transverse section for 700-900m stretch

prevalent scenario of this debris mass flow, which is consistent to the pieces of verbal evidence from eye-witnesses including Mr. Kazumasa Uchida, says that the time for the debris mass to reach Nebukawa town was about 5 minutes, which time is about 1.6 times as large as what Kobayashi estimated (**Fig. 8**). Therefore the proposed iterative procedure yielded velocities closer to the well-accepted scenario in terms of results. However, the procedure is based upon an over-simplified debris flow dynamics ignoring turbulent nature of slurry, particle segregation processes in flowing slurries, etc. The possibility for utilizing the proposed iterative procedure is to be explored as we gather much more reliable information so that substantial accuracy is guaranteed in the general statistical sense.

Table-1 Velocity estimation at different sections of Shirato River

Distance from source are (m)	700-900	1700-1900	1900-2100
Radius of curvature of bend (m)	230.8	784.6	158.5
Radius of average cross section (m)	87.3	84.3	91.5
Sloshing period (sec)	18.75	21.86	19.20
Observed super-elevation (m)	17	12	21
Estimated velocity (m/sec)	21.5	28.5	16.7

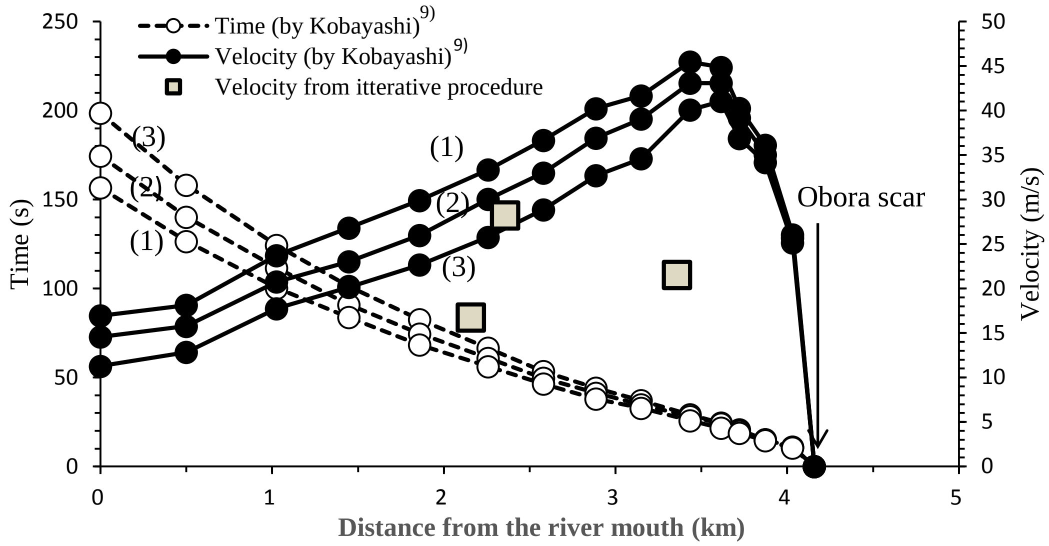

Fig. 8 Estimated velocities and travel times of debris mass from Obora scar: (1) $\mu = 0.08$, $D_f\xi = 12000\ m^2/s^2$, (2) $\mu = 0.08$, $D_f\xi = 10000\ m^2/s^2$, and (3) $\mu = 0.08$, $D_f\xi = 8000\ m^2/s^2$.

5. CONCLUSION

This paper described a simple iterative procedure to estimate debris flow velocity along a curved channel. The average cross-section is first obtained for the selected stretch of a curved channel, and is approximated as a downward arc Then the time for the flowing slurry to reach its peak super-elevation is approximated to be a quarter of the sloshing period for the approximated cross-section, and is multiplied by the initial value of the flow velocity to update the stretch of the curved channel. This procedure is repeated till a sufficient convergence of the solution is reached. Nebukawa debris flow triggered by the Great Kanto Earthquake of 1923 was chosen to estimate the velocity of this event using the proposed simplified procedure. As the results, the obtained velocities at different three locations were 50 to 100% of those estimated by Kobayashi's simulation, which simulation was based upon a different aspect of the debris flow dynamics, namely, the Saint Venant hypotheses for a one-dimensional non-Newtonian flow with inclusion of an additional friction slope term. The proposed iterative procedure thus yielded velocities closer to the well-accepted scenario which is consistent to the pieces of verbal evidence from eye-witnesses. However, the procedure is based upon an over-simplified debris flow dynamics ignoring turbulent nature of slurry, particle segregation processes in flowing slurries, etc. The possibility for utilizing the proposed iterative procedure is to be explored as we gather much more reliable information so that substantial accuracy is guaranteed in the general statistical sense.

ACKNOWLEDGMENT: This paper summarizes some of the outcomes of the Research Project ''Detection of Lagrangian displacements of terrains along an active fault and their implementation for land conservation'', No. 23246087 (Project leader: Kazuo Konagai, 3rd author of this paper), Ministry of Education, Culture, Sports, Science and Technology.

REFERENCES

1) Nishisaka K.: The great earthquake fire and activities of police in Kanagawa prefecture, History of Odawara City, 1966 (In Japanese).
2) Kobayashi Y.: A catastrophic debris flow at Nebukawa in the Great Kanto Earthquake of 1923, Earthquake Ser. 2, Vol. 32, pp. 57-73, 1979 (in Japanese).
3) Han Z., Chen G., Li Y., Xu L., Zheng L. and Zhang Y.: A new approach for analyzing the velocity distribution of debris flow at typical cross sections, Nat Hazards, June, 2014.
4) Prochaska A.B., Santi P.M., Higgins J.D. and Cannon S.H. : A study of methods to estimate debris flow velocity, Landslides, Vol. 5(4), pp. 431-444, 2008.
5) Imamura A.: Mud flow in Nebukawa, Report of the Imperial Earthquake Investigation Committee, 100, B, 85-86, 1925 (in Japanese).
6) VanDine DF: Debris flow control structures for forest engineering, British Columbia Ministry of Forests Research Program, Working paper, 08/1996.
7) Chen C-L: Comprehensive review of debris flow modeling concepts in Japan, In: Costa JE, Wieczorek GF (eds) Reviews in Engineering Geology, Vol. VII, Debris flow/avalanches: process, recognition, and mitigation. The Geological Society of America, Boulder, CO, pp. 13-29, 1987.
8) JNR Report of the damage to railway facilities, The Ministry of Railways, 1927.
9) Kobayashi Y.: A catastrophic debris avalanche induced by the 1923 Great Kanto Earthquake, Natural Disaster Science, Vol. 7(2), pp. 1-9, 1985.
10) Krörner H. J,: Reichweite und Geschwindigkeit von Bergstürzen und Fliecssschneelawinen, Rock Mechanics, 8, 225-2S6, 1976.