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THREE DIMENSIONAL COSEISMIC SURFACE TECTONIC DISPLACEMENT OF 2004 MID-NIIGATA PREFECTURE EARTHQUAKE

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Large earthquakes are often accompanied by ground displacements. The displacements are equally or even more responsible for the devastation than the strong ground motions. Study of terrain dynamics and landform changes, therefore, demand a priory focus, and Mid-Niigata Prefecture Earthquake of October 23rd, 2004 provided us with an opportunity to study the landform changes for a mountainous terrain. A method is proposed to convert Eulerian change in elevation to Lagrangian surface tectonic displacements. Application of the proposed method to low raised mountainous terrain, jolted by Mid-Niigata Prefecture Earthquake, showed promising accuracy and is well consistent with the field observations.

***Key words**: Mid-Niigata Prefecture Earthquake, Digital Elevation Model (DEM),Lagrangian surface tectonic displacement, rehabilitation*

1. INTRODUCTION

Although the ground shaking during an earthquake causes significant instant damages, strong earthquakes are all accompanied by the change in topologies which can trigger serious and long lasting geotechnical problems. Aftermaths of an earthquake are often more devastating than its immediate effect, especially in mountainous terrains. Large strains built up in soils and rocks along a dislocated fault can trigger post-earthquake disasters such as landslides and debris flows, which can last long causing serious problems for rehabilitations and land conservations.

Mid-Niigata Prefecture Earthquake (magnitude 6.8) of October 23rd, 2004 jolted low raised mountainous terrain of central Japan, having a well recognized active folding geological structure. Earthquakes in active folding structures have distinctive features and usually cause long lasting geotechnical rehabilitation problems. Following the history, Mid-Niigata Prefecture Earthquake triggered thousands of landslides. Other than landslides, large surface tectonic displacements were also observed in this earthquake which was responsible for the post-seismic flooding during heavy seasonal rains and many other problems for the rehabilitation works.

During an earthquake, stresses in the interior of the earth adjacent to the activated fault are redistributed leading to permanent deformation, which can be measured by comparing pre- and post-seismic geodetic observations. Due to the remoteness of disaster struck areas, usually high mountains, and due to its spatial extension, remote sensing technology, momentously developed in last few decades, has replaced other common approaches of landform measurement.

To study landform changes, Interferometric Synthetic Aperture Radar (InSAR) is one of the most advanced technologies that can measure elevation changes with high precision. However, thick vegetation and thousands of landslides have made fringe patterns too complicated for extracting pure elevation changes from the available C-band (5.405 GHz) InSAR interferogram. Furthermore, it gives the displacements only in the Eulerian frame of reference while, in reality, earthquake-induced ground deformations need to be dealt in Lagrangian description because soils and rocks are typically history-dependent materials. Therefore, the authors have obtained pre- and post-seismic digital elevation models (DEM hereafter) and proposed a method to convert changes in elevation in Eulerian description for DEM to Lagrangian displacements. Lastly, the moving average method was adopted to obtain the whole picture of landform changes.

2. LAGRANGIAN GROUND DISPLACEMENT

(1) Methodology

A method was originally proposed by Konagai et al. (2009)[1)] to evaluate Lagrangian components of surface tectonic displacement considering rigid body translation of three consecutive soil patches. The method has been improved incorporating rotations of soil patches about their planar axes. The criterion to filter out landslides and manmade changes has also been changed. The fundamental assumption that tectonic displacement varies gently in space holds for both the original and improved models.

Landforms herein are given as raster graphic images of pixels that contain elevation of the terrain, arranged at a fixed grid interval over the surface of the earth. It is assumed that there is a planar ground patch, *i*, immediately above a node *i*, and a soil particle *k* on this patch is exactly at the point where node *i* is projected (Figure 1).This patch with inclinations of θ_{x_1} and θ_{y_1} in *x* and *y* directions, respectively, moves to a new position, changing the inclinations to θ_{x_2} and θ_{y_2}. Referring to Figures 1, Eulerian change in elevation ($\Delta_{z,i}$), which is measured exactly above node *i*, is expressed in terms of the Lagrangian vector, $\{\Delta_{x,k} \quad \Delta_{y,k} \quad \Delta_{z,k}\}$, of the movement of the soil particle, *k*, on this patch as

$$\begin{bmatrix} -t_{x_2,i} & -t_{y_2,i} & 1 \end{bmatrix} \begin{Bmatrix} \Delta_{x,k} \\ \Delta_{y,k} \\ \Delta_{z,k} \end{Bmatrix} = \Delta_{z,i} \qquad (1)$$

where $t_{x_2,i} = \tan\theta_{x_2}$ and $t_{y_2,i} = \tan\theta_{y_2}$, i.e. direction tangents of the soil patch in its new position.

Arranging three soil patches, i_1, i_2 and i_3, immediately next to each other in a triangular manner (Figure 2), and using the displacement of its center, $\{\Delta_{x,k} \quad \Delta_{y,k} \quad \Delta_{z,k}\}^T$, as the representative Lagrangian displacement vector of the triangle, the following set of solvable simultaneous equations is obtained.

$$\begin{Bmatrix} \Delta_{z,i_1} \\ \Delta_{z,i_2} \\ \Delta_{z,i_3} \end{Bmatrix} = \begin{bmatrix} -t_{x_2,i_1} & -t_{y_2,i_1} & 1 \\ -t_{x_2,i_2} & -t_{y_2,i_2} & 1 \\ -t_{x_2,i_3} & -t_{y_2,i_3} & 1 \end{bmatrix} \begin{Bmatrix} \Delta_{x,k} \\ \Delta_{y,k} \\ \Delta_{z,k} \end{Bmatrix} = T \begin{Bmatrix} \Delta_{x,k} \\ \Delta_{y,k} \\ \Delta_{z,k} \end{Bmatrix} \qquad (2)$$

Solving the above set of simultaneous equations (eq. 2) for all triangles within the target zone, Lagrangian components of displacement vectors $\{\Delta_{x,k} \quad \Delta_{y,k} \quad \Delta_{z,k}\}^T$ can be obtained for the entire target zone. The obtained Lagrangian displacement vectors show motion of the soil particles on the ground surface, which includes the effect of landslides and manmade changes. Therefore, to separate tectonic deformations from the entire Lagrangian displacements, landslides and large scale manmade changes are filtered out by limiting the Lagrangian vertical component of displacement below a threshold value. This threshold value is set so that the centre of moved plane remains within the projected boundary of the original plane. The following filtering criterion is used:

$\Delta_{z,k}$ > Threshold for Lagrangian vertical displacement

$$\Delta_{z,k} > \{t_{x_2,i} \quad t_{y_2,i} \quad 1\}\{\Delta_{x_{\lim}} \quad \Delta_{y_{\lim}} \quad \Delta_{z_{\lim}}\}^T \qquad (3)$$

where, $\Delta_{x_{\lim}}$ and $\Delta_{y_{\lim}}$ are half the planar dimensions of the soil patch in *x* and *y* direction, respectively. $\Delta_{z_{\lim}}$ is set to a constant value; e.g. while applying to the Mid-Niigata Prefecture Earthquake, this can be determined to be 1.36 meters from the maximum vertical tectonic displacement of the main shock in this earthquake[2)].

However, the obtained Lagrangian displacement components often show a remarkable scatter. Man-made changes during the time between two DEM's and presence of some non-surface objects on digital surface models might be most prominent among the possible causes. Therefore, the moving average method was used for overall features of displacements. Assuming that the scattered values follow the Gaussian distribution within a square window, the most frequent value (mode) is interpreted to be the real vector of the soil displacement for this area.

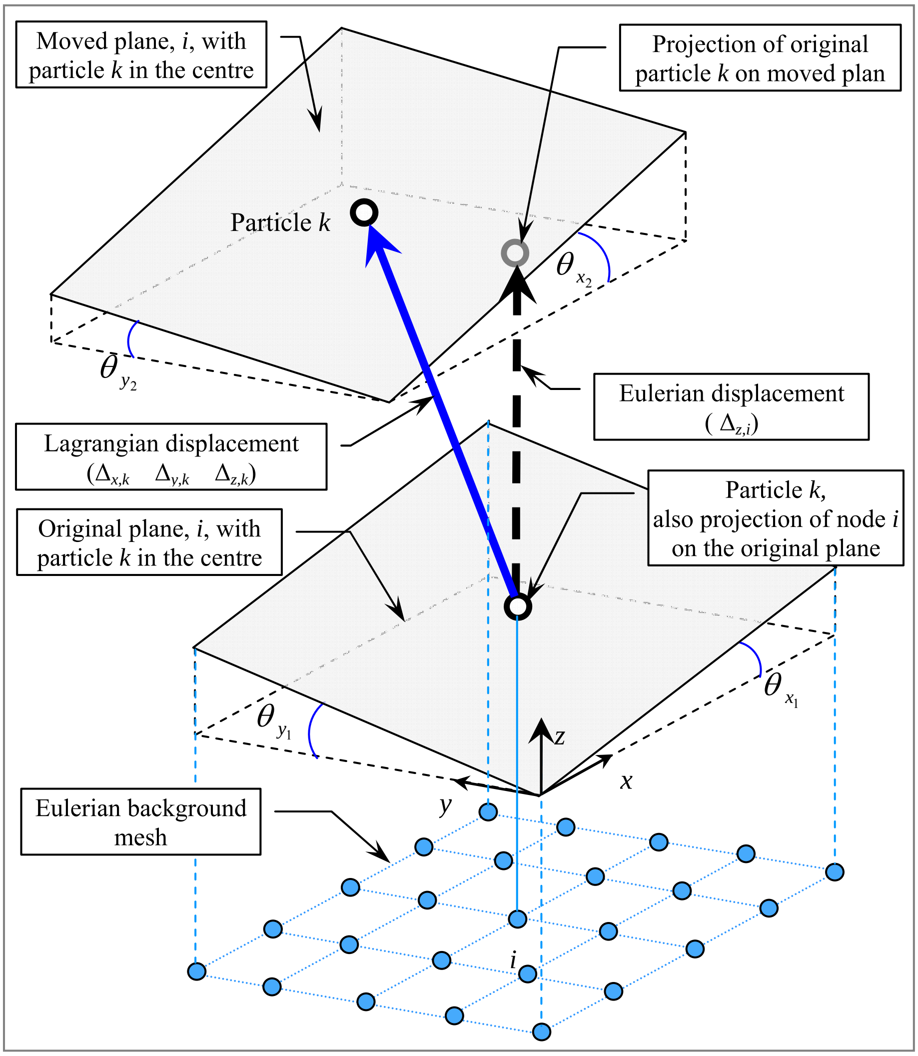

Fig. 1 Description of the method to convert Eulerian change in elevation to Lagrangian displacements

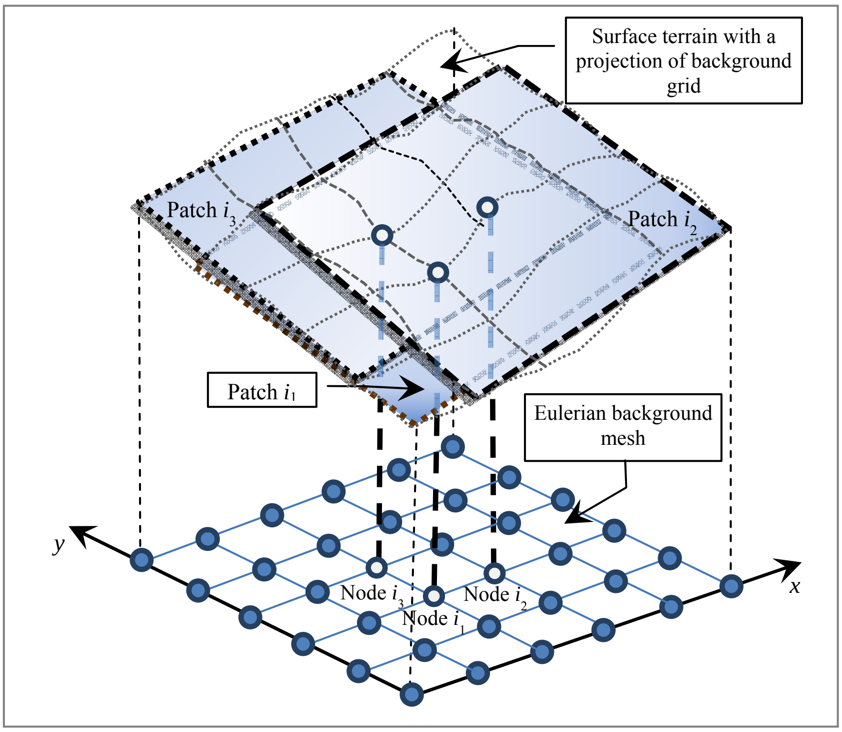

Fig. 2 Three consecutive soil patches arranged in a triangular pattern to solve a set of simultaneous equations for Lagrangian components of displacement.

Sweeping the entire zone with this square window, the whole picture of the deformation can be obtained. The size of the smoothening window has to be determined from its physical interpretation. The window size, to discuss the tectonic deformations, is desirable to be larger than the largest hidden landslide in the target area to minimize the effect of the hidden coherent landslides. At the same time, the size should not be too large to allow significant variation of the tectonic deformation within the smoothening window.

a) Ill Condition

To obtain a reliable solution, the condition of coefficient matrix T in the equation (2) is important. A system of equations is considered to be well-conditioned if a small change in the coefficient matrix or a small change in the right hand side results in a small change in the solution vector. This small change in the solution vector is namely important digits or tolerance of accuracy. The matrix condition can be determined as;

$$Cond(T) = a_{tol} / \varepsilon_{mach} \tag{4}$$

Where machine epsilon, ε_{mach}, gives an upper bound on the relative error due to rounding in floating point arithmetic.

If MATLAB is used for calculation, the machine epsilon of default data type (double precision) is obtained as $\varepsilon_{mach} = 2.2201 \times 10^{-16}$ with "eps" command. Setting the tolerance of calculation accuracy to any desired level, the condition of matrix T can be obtained by equation (4). All the sets of equations not fulfilling this criterion need to be filtered out to get a reliable solution. For the example case described in the following section, a_{tol} is set at 0.1.

(2) Application

a) Active folding zones and study area

Earthquakes in the active folding areas have distinctive features and usually cause long lasting geotechnical problems. In an active folding zone, the action of deep-seated forces has been shortening sedimentary rock layers causing folded geomorphic surfaces to appear and develop. Looking at a fold surface in profile (Figure 3) upslope and downslope flanks of the fold join together at anticlines and synclines, respectively. Since the up-folded rocks along anticlines have been expanded and cracked over centuries, anticlines frequently have their crests deeply eroded, with a number of debris deposits rimming the eroded hollows. Large-scale landslides are found even on gentle mountain sides dipping towards synclines because their toes are often deeply eroded by rivers. The active folding regions can be thus one of the most landslide-prone zones.

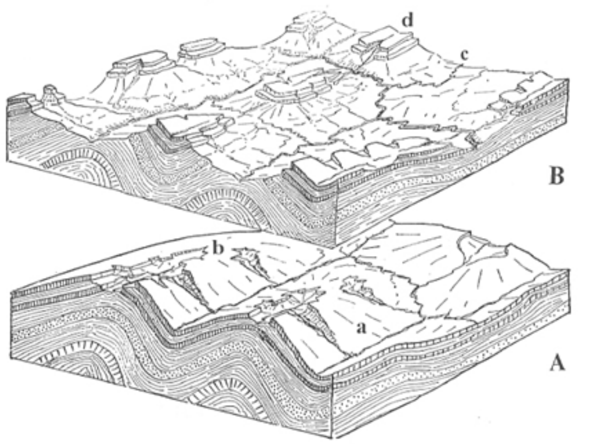

Fig. 3 Erosion of geological fold (Original figure from de Martonne, 1927). Erosion develops from A to B in such a way that syncline valley (a) and anticline ridge (b) in A to become anticline valley (d) and syncline ridge (c) in B, respectively.

Taking a look at the history, the May 8th, 1847 Zenkoji Earthquake (M=7.4) jolted the active folding mountain terrain west of Nagano, central Japan. Devastations were serious along the entire 50km stretch of the Nagano western basin-edge fault. The earthquake caused about 44,000 landslides to occur on the hanging wall side of the fault[3]. On March 15th, 1914, a M7.1 earthquake jolted a low-rising mountain terrain of Senboku, Akita, Japan. Though the intensities registered at major cities were not surprisingly large, the reported deaths of 84 among the total 94 were concentrated locally within the 10km x 10km Senboku area which had a folded geological structure. The magnitude 6.8 Mid-Niigata Prefecture Earthquake of October 23rd, 2004 jolted one of areas where active folding geological structure were most clearly recognized[4]. The hypocenter of the main shock was located at 37.29°N, 138.87°E at focal depth of 13 km. The main shock was followed by a large number of aftershocks with four being over M6. The focal mechanisms of these strong shocks, estimated by Hi-net and F-net[5], were reverse fault type that is concordant with pre-existing fold axis. This earthquake reportedly triggered and/or reactivated thousands of landslides. The economic loss due to these landslides was initially estimated at 8 billion US dollars, making this one of the costliest landslide events in history[6]. In addition to the landslides, large surface tectonic displacements were also observed in this earthquake which has caused some problems for rehabilitating the affected areas.

An 11 × 7.5 km active folding area of Yamakoshi mountainous terrain is selected as target zone to get the Lagrangian surface tectonic displacements from an available set of digital elevation models (DEMs) (Figure 4). The DEM for the pre-earthquake time (1975-1976) was obtained using stereoscopy while for the post-earthquake time (Oct. 24, 2004); it was obtained using the Laser Imaging Detection and Ranging technology (LIDAR)[7].

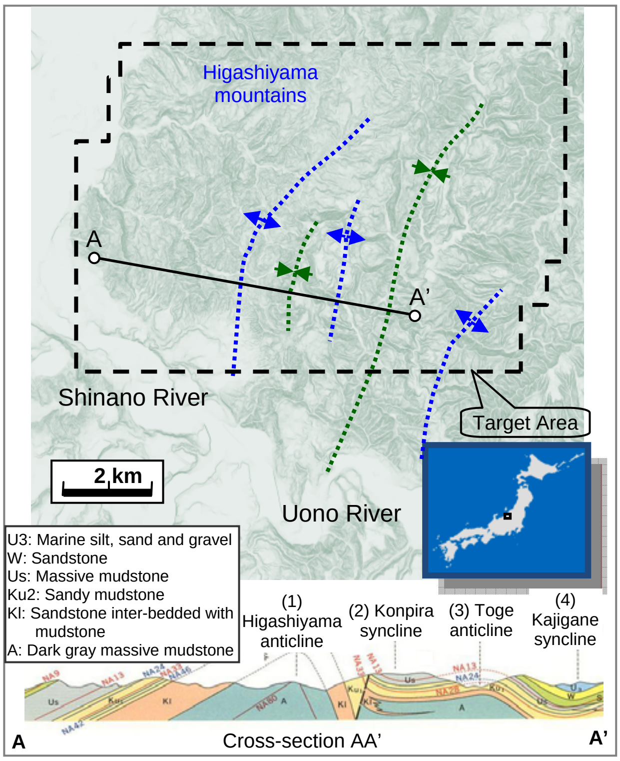

Fig. 4 Target zone on Zone VIII of the Japanese National Grid System

b) Results

First of all, large changes in elevation were filtered out by applying the filtering criteria. Distribution of the filtered points gives good correlation with the landslide map[8] (Figure 5). At the lower left corner of the target zone, Shinano River is located and much flatter topography is present (Figures 4 and 5). Large bunch of filtered points in this area is possibly due to ill-conditioned tangential matrices in the flat land.

Figure 6 shows the lateral components of surface tectonic displacements obtained through a 1400m x 1400m smoothening window. Shinano River Office of Hokuriku Regional Bureau has been measuring bench marks along Shinano and Uono Rivers. Lateral components of benchmarks' displacement during the earthquake are also plotted on the same figure and show a similar pattern to the surface tectonic displacements. There are two clusters of large lateral displacement. The largest one, a 1 to 2 km wide NNE-SSW belt concentrated around the Kajigane syncline, has appeared on the hanging wall side of the surface extension of the hidden fault rupture plane for the main shock (Figure 6). The two clusters of large lateral components of surface tectonic displacements are concordant with two thick clusters of landslides (Figure 5 and 6).

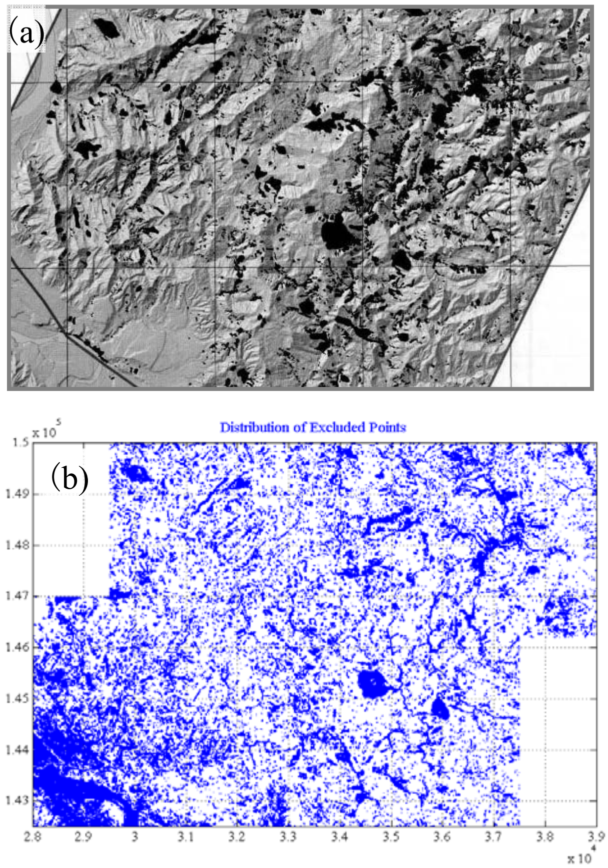

Fig. 5 a) Landslide map of the target zone and b) distribution of the filtered points for landslides and manmade changes

Figure 7 shows the vertical components of surface tectonic displacements obtained through a 1400m x 1400m smoothening window. There are two zones of large vertical displacement, which have been pushed up by 0.5 to 1.0 meters. The southwestern part of the target zone, location where Uono River joins Shinano River, shows most pronounced hump (Figure 7)

Area along the upper reach of this part of Uono River was flooded during the heavy rains of June 2005 and this was repeated again in July 2011. Vertical components of benchmarks' displacement during the earthquake (Figure 8) have shown that the area downstream of the Kajigane syncline has moved up.

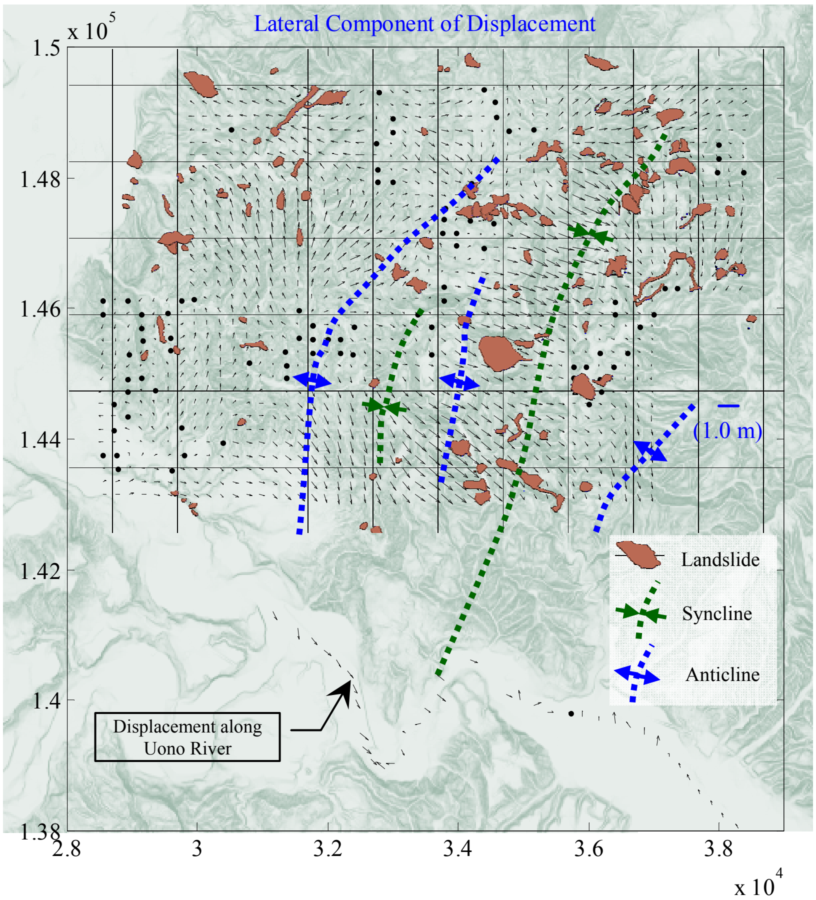

Fig. 6 Lateral components of surface tectonic displacement of the target zone on Zone VIII of the Japanese National Grid System.

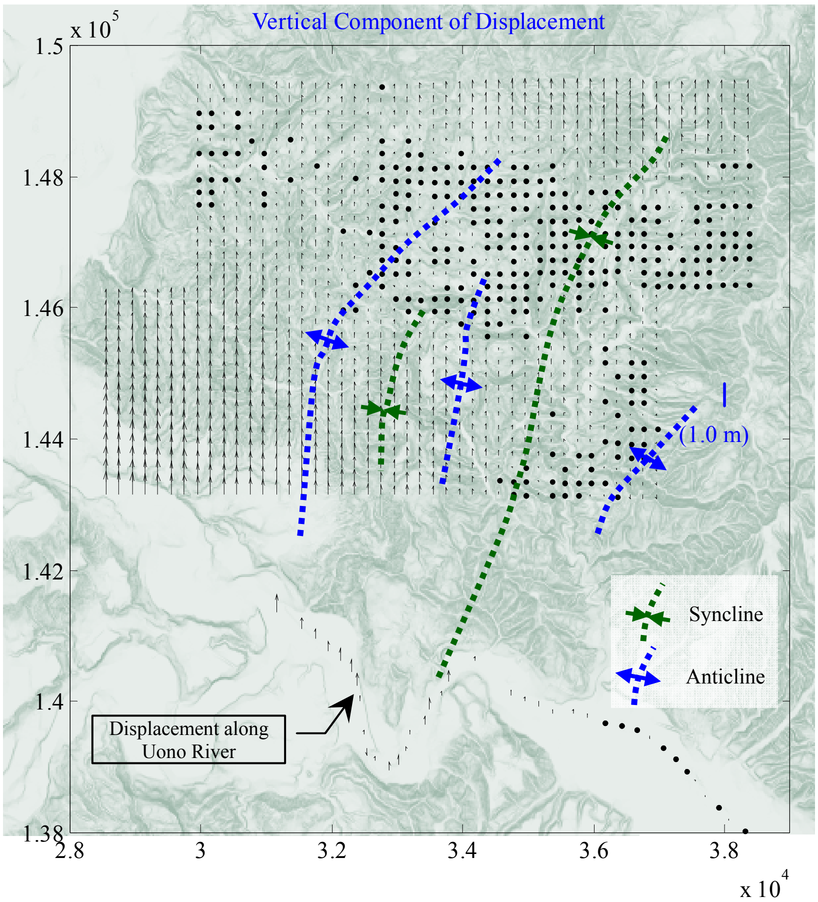

Fig. 7 Vertical components of surface tectonic displacement of the target zone on Zone VIII of the Japanese National Grid System

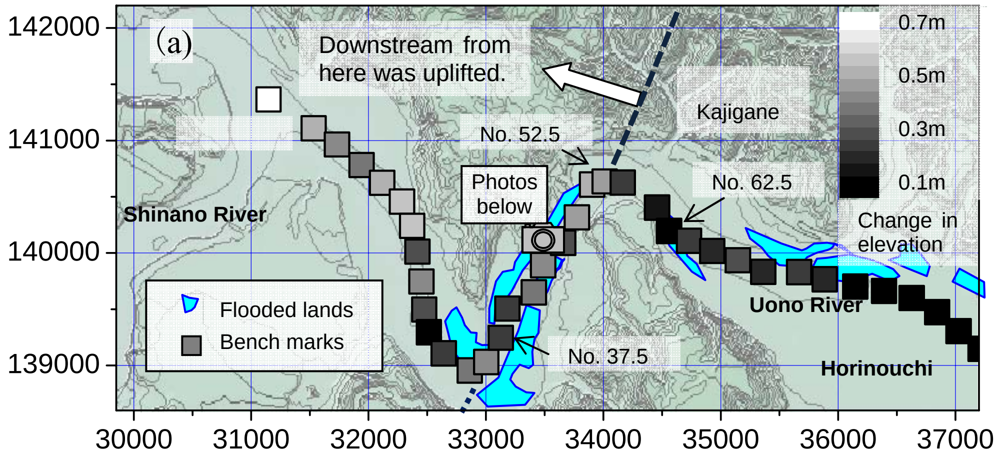

Fig. 8 Flooding along the upper reach of Uono River during the heavy rains of June, 2005 (a) Locations of flooded farm lands and change in elevations at benchmarks along Uono River on Zone VIII of the Japanese National Grid System (b) Flooded area near Benchmark No. 42.5km (Photo by Kotajima, S., 28th June, 2005) and (c) a photo at a later date from the same location (37.259828°N, 138.876801°E) as above (Photo by Konagai, K., 19th September, 2010). (d) Photo from the same location after the flooding of July 2011 (Photo by Konagai, K., 4th August, 2011)

Ignoring the crustal deformations caused by the Mid-Niigata Prefecture Earthquake and assuming same amount of water flowing down the Uono River in 2005 rains as existed before the earthquake, possible water depths at all bench marks along the 57.5km-long flooded zone were estimated by using the Manning empirical equation[9)] (Figure 9). For this estimation, precise dimensions for the river cross-sections and inclinations at all benchmarks before and after the earthquake were provided by the Shinano River Office, Hokuriku Regional Bureau of the Ministry of Land, Infrastructure and Transport (MLIT). Solid circles in Figure 9 show the actual water levels at all bench marks reached in the 2005 flood, while open circles show virtual water levels calculated for the Uono River as it existed before the earthquake. At almost all points, the virtual water levels (open circles) are lower than those (solid circles) reached in the 2005 real flood. Actual water levels were higher than the high water levels (HWL) at bench marks # 37.5, # 52.5 and # 62.5, while virtual water levels at these points do not reach the high water levels.

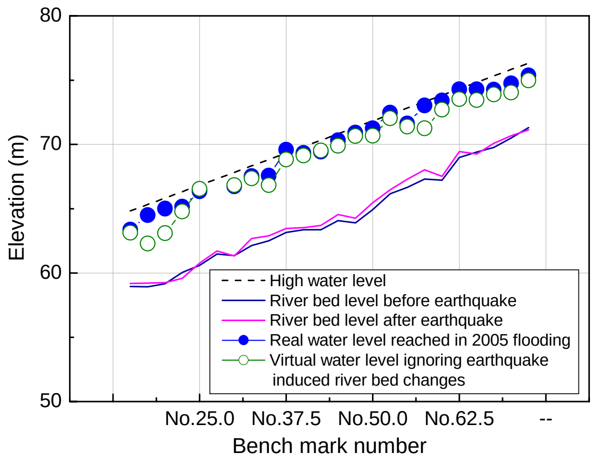

Fig. 9 Actual water level reached during the flood of 2005 and the virtual water level estimated from manning's formula along all the benchmarks of flooded length.

Thus, this figure helps us to develop a strong cause and effect relation between the surface tectonic displacements induced by the earthquake and flooding along the upper reach of Uono River.

(3) Accuracy of calculation

Fortunately, there are some triangulation points available within the target area, which can be used to check the accuracy of obtained surface tectonic displacements. There were only nine points within the target area which were not considered to be affected by the landslides. A promising level of accuracy is observed while comparing all the three components of obtained Lagrangian surface tectonic displacement to the triangulation data (Figure 9a). Figure 9(b) shows the accuracy of the vertical component of the obtained Lagrangian surface tectonic displacement and Eulerian displacement against the triangulation data.

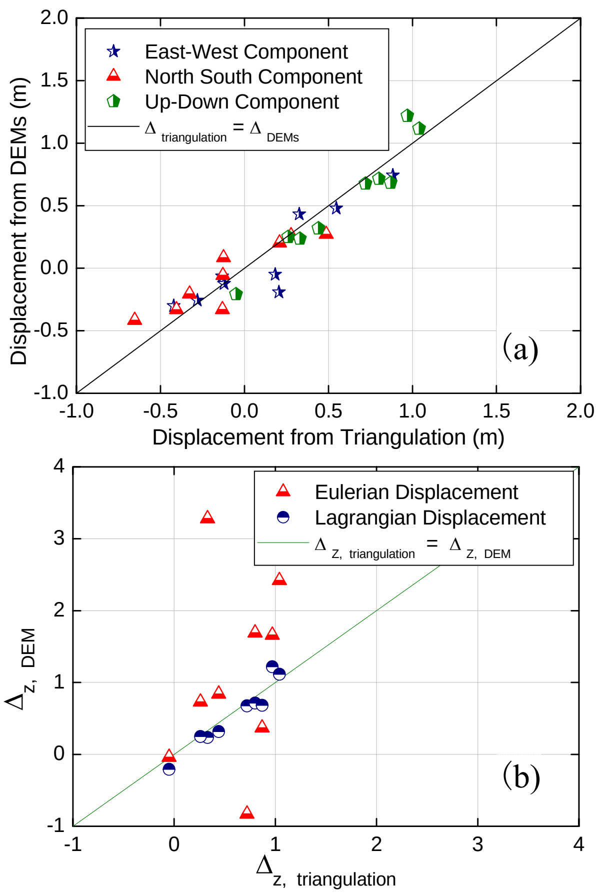

Fig. 9 Verification of the process for obtaining Lagrangian surface tectonic displacement a) Comparison of all the three components against the triangulation data b) comparison of the vertical component of Lagrangian and Eulerian displacement against the triangulation data

It can be easily deduced that the proposed method for the Lagrangian surface tectonic displacements gives real image of the actual ground displacement as compared to the Eulerian change in elevation, obtained directly from DEMs

3 CONCLUSIONS

Large earthquakes often cause long lasting geotechnical problems which need to be dealt rationally for proper rehabilitation tactics. Large strains built up in the soils and rocks along the dislocated faults develop permanent deformations and can trigger post earthquake disasters. Study of the terrain dynamics and landform changes, therefore, demands a narrow focus. Progressive development in the field of remote sensing enables us to detect sub-metric deformations; however, the obtained displacement is only in Eulerian frame of reference. A method is proposed to evaluate Lagrangian surface tectonic displacement from a set of pre- and post-seismic DEMs.

To minimize the scatter and for the smoothness of obtained results, landslides and manmade changes during the time between two DEMs are filtered out. A moving average method was then adopted to obtain Lagrangian components of surface tectonic displacement with a 1400m square smoothening window.

The lateral and vertical components of the surface tectonic displacement are well consistent with the field measurements/observations. Two clusters of large lateral displacement are consistent with two thick clusters of landslides and are located around the surface extension of the hidden fault rupture planes for the main shock and the largest aftershock. Vertical component of the displacement have shown uplifting of the southwestern part of the target area which is the confluence point for Shinano and Uono Rivers. Benchmarks' measurements along Uono River have shown similar trend. Flooding along the upper reach of the Uono River during post seismic heavy rains of June 2005 and July 2011 can be justified by this crustal uplifting. The obtained Lagrangian surface tectonic displacements have shown promising accuracy against the triangulation data.

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