Review

Earthquake-induced soil displacements and their impact on rehabilitations

By Kazuo KONAGAI*1,
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Abstract: A large earthquake can trigger long lasting geotechnical problems, which pose serious issues on both rehabilitations and land conservations. Therefore one of what required of us is to deduce as much hidden signs as possible from observable changes of landforms. Though serious, damage caused by the October 23rd 2004, Mid-Niigata Prefecture Earthquake has given us a rare opportunity to study the landform changes in mountainous terrain hit by this earthquake. An attempt was made to convert changes in elevation in Eulerian description for images obtained from remote-sensing technologies to Lagrangian displacements, because Lagrangian displacements can directly describe behaviors of soils, which are typically history-dependent. This paper documents some big pictures of earthquake-inflicted landform changes obtained through this attempt.

Keywords: Mid-Niigata Prefecture Earthquake, active folding, digital elevation model, Lagrangian description of displacements, rehabilitation, land conservation

Introduction

In a large earthquake, not only intense shakes but also ground deformations can be equally or often more responsible for the devastation. Large strains built up in soils and rocks along a dislocated fault can also trigger post-earthquake disasters such as landslides and debris flows, which can last long causing serious problems for rehabilitations and land conservations. Therefore one of what required of us is to deduce as much hidden signs as possible from observable change of landforms.

An intense earthquake of magnitude 6.8 jolted central Japan at 17:56 JST on October 23rd, 2004. The hypocenter of the main shock was located at 37.29°N, 138.87°E, in mid Niigata Prefecture, at a depth of 13 km. The maximum acceleration of 1500 cm/s² was recorded at Ojiya K-net station which is about 10 km west of the epicenter.1) The main earthquake was followed by a series of strong aftershocks in rapid succession. These strong earthquakes had focal mechanisms of reverse fault type with the compression axes oriented WNW/ESE,2) which direction is almost normal to the NNE–SSW-trending geological folds of sedimentary rocks in the source region. 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 region is thus one of the most landslide-prone zones in Japan.

Some past earthquakes have shown that earthquakes in such active folding zones can trigger long-lasting geotechnical rehabilitation issues. The May 8th, 1847 Zenkoji Earthquake jolted the active folding mountain terrain west of Nagano, central Japan. Devastations were serious along the entire 50 km stretch of the surface fault rupture that appeared along the skirts of the active folding mountains. In 1884, 37 years after the earthquake, a crack near the southern summit of the Chausu-yama twin peaks (Elevation 730 m, Location: 37.294694°N, 138.875492°E near the southwestern end of the surface fault rupture) began to open wide, which was an early sign of a long-lasting landslide. An
800 meter-long soil mass on the mountain-side began to gradually change its shape, causing a small village on its toe to rise up remarkably. After heavy rains in 1930, the entire soil mass began to creep down the slope exhibiting thick, wet and sticky features, and the maximum speed of 93 m/year was reached in 1932–1934. The slope was finally stabilized in the 1970s with a tremendous amount of drainage works that were started in 1965.3) With all similar examples compiled in active folding zones, the quick stabilization of slopes in the Mid-Niigata mountainous terrain was considered to be a pressing need.

In addition to landslides, surface tectonic deformation is considered to have caused some problems for rehabilitating the affected areas. As will be discussed hereafter, the tectonic movements have caused the middle part of both the Shinano and Uono Rivers to be raised upward by about 0.5 to 1.5 meters. Probably due to this tectonic deformation, the upper stream reach of the Uono River was flooded in the heavy rain of June, 2005, about eight months after the earthquake. Therefore, the first and essential step for research to proceed and before any rational and scientific discussions on remedial measures take place, should be to separate soil deformations caused by the tectonic movement of the active folding zone from the overall soil deformations observed on the ground surface.

To deal with these problems in a scientific manner, a research program, “Earthquake damage in active-folding areas: creation of a comprehensive data archive and suggestions for its application to remedial measures for civil-infrastructure systems,” was set up getting the Special Coordination Funds for Promoting Science and Technology, Ministry of Education, Culture, Sports, Science and Technology (MEXT hereafter).4) This program was unique among many other MEXT-funded research programs in that an advisory panel was set up under the Japan Society of Civil Engineers including not only researchers but also experts from authorities such as Niigata Prefectural Government, Ministry of Land, Infrastructure, Transport and Tourism (MLIT) etc., all concerned about rehabilitation affairs. The idea was to facilitate real-time research information sharing among relevant organizations for rational rehabilitations.

To study landform changes, Interferometric Synthetic Aperture Radar (InSAR) is one of the most advanced technologies that can measure elevation changes with high precision.5) 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 from RADARSAT, a Canada’s commercial SAR satellite.6) Therefore, the author and core members of the program, have obtained digital elevation models (DEM hereafter) at 6 different times using stereoscopy for the pre-earthquake time of (1) 1975–1976 and Laser Imaging Detection and Ranging technology (LIDAR) and Interferometric Synthetic Aperture Radar (InSAR) for the post-earthquake times of (2) Oct. 24, 2004, (3) Oct. 28, 2007, (4) May 2005, (5) May 2006, and (6) May 2007.3) Landform changes due to the earthquake were first assessed. Then, changes in elevation in Eulerian description for DEM were converted to Lagrangian displacements, and lastly the moving average method was adopted to obtain the whole picture of landform changes.

Method to obtain Lagrangian soil displacements

Recent development of remote sensing technologies such as Laser Imaging Detection and Ranging technology (LIDAR) and Interferometric Synthetic Aperture Radar (InSAR) has enabled the acquisition of images of landforms and the changes in elevation with high precision. However, the methods allow us to detect displacements only in the Eulerian description, in which the description of motion is made in terms of the spatial coordinates which does not follow the motion of soil particles. Discussions of earthquake-inflicted geotechnical issues require more direct description of soil particle movements because soils are typically history-dependent materials.

Konagai et al.7) estimated Lagrangian components of tectonic displacement by assuming that tectonic displacement varies gently in space, and therefore three adjacent nodes of DEM would have the same Lagrangian displacements. If these three points undergo a rigid-body-translation movement, their Lagrangian components that represent the movement of the center of these triangles can be obtained by solving simultaneous equations for these three adjacent points (Fig. 1 and Eq. [2]).

In Fig. 1, the subscript, \( i \), for the Eulerian description of vertical displacement \( \Delta_{z,i} \), denotes the node number on the Eulerian coordinate system. Assuming that a small patch \( i \) of the ground surface with a particular node \( i \) mapped upon it is inclined in an East–West (\( x \)) and North–South (\( y \)) direction, \( \Delta_{z,i} \) is expressed in terms of the Lagrangian vector \( \{ \Delta_{x,k}, \Delta_{y,k}, \Delta_{z,k} \} \) of the movement of a particular soil particle, \( k \), on this patch as

\[
\Delta_{z,i} = \begin{bmatrix} t_{x,i} & t_{y,i} & 1 \end{bmatrix} \cdot \begin{bmatrix} \Delta_{x,k} \\ \Delta_{y,k} \\ \Delta_{z,k} \end{bmatrix}^T
\]
where $t_{x,i}$ and $t_{y,i}$ are direction tangents of the patch in $x$ and $y$ directions, respectively. Taking three
patches, $i_1$, $i_2$ and $i_3$, arranged immediately next to
one another in a triangle (Fig. 1), and assuming a
uniform Lagrangian displacement $\{ \Delta_{x,i} \Delta_{y,i} \Delta_{z,i} \}$
for these three patches, the following simultaneous
equations are to be satisfied:

$$\begin{bmatrix}
\Delta_{x,i_1} \\
\Delta_{y,i_1} \\
\Delta_{z,i_1}
\end{bmatrix}
= \begin{bmatrix}
t_{x,i_1} & t_{y,i_1} & 1 \\
t_{x,i_2} & t_{y,i_2} & 1 \\
t_{x,i_3} & t_{y,i_3} & 1
\end{bmatrix}
\begin{bmatrix}
\Delta_{x,k} \\
\Delta_{y,k} \\
\Delta_{z,k}
\end{bmatrix}$$

By solving the above simultaneous equations for all
triangles within the target zone, soil displacement
elements $\{ \Delta_{x,k} \Delta_{y,k} \Delta_{z,k} \}^T$ are obtained for the
entire target zone. The obtained Lagrangian vectors
show soil particle motions on the ground surface,
whose motions can be greatly affected by landslides. To
separate tectonic deformations from the entire
Lagrangian displacements landslides were filtered out
by applying the following criteria.\(^7\)

1) Excluding large changes in elevations

$$\Delta_{x,i} > \text{threshold for Eulerian vertical}
\text{displacement}$$

$$= \begin{bmatrix} t_{x,i} & t_{y,i} & 1 \end{bmatrix} \begin{bmatrix}
\Delta_{x_{\text{lim}}} \\
\Delta_{y_{\text{lim}}} \\
\Delta_{z_{\text{lim}}}
\end{bmatrix}^T$$

with $\Delta_{x_{\text{lim}}}$, $\Delta_{y_{\text{lim}}}$ and $\Delta_{z_{\text{lim}}}$ set at 1.5, 1.5 and
2.0 m, respectively, and

2) Excluding large changes in slope inclinations:

$t_{x,i}$ and/or $t_{y,i}$ after the earthquake

$\geq \text{MAX (among direction tangents for all 8}
\text{nodes surrounding nodes } i \text{(see open circles}
\text{in Fig. 1}) \text{ before the earthquake)}$ \hspace{1cm} [3b]

t_{x,i}$ and/or $t_{y,i}$ after the earthquake

$\leq \text{MIN (among direction tangents for all 8}
\text{nodes surrounding nodes } i \text{(see open circles}
\text{in Fig. 1) before the earthquake)}$ \hspace{1cm} [3c]

Though the threshold for Eulerian vertical displacement
was set in such a way that the expected
maximum fault slip\(^8\) would be below the corresponding
threshold of Lagrangian displacement, the above
criteria are a mere expediency. Moreover, obtained
Lagrangian displacement components of remaining
points often showed remarkable scatters, partially
because there were a number of man-made changes of
landform over the 28 years interval between DEMs
prepared in 1976 and 2004. These changes include
creation of ponds for Koi-fish farm business (Fig. 2),
road widening, etc. Another important point to
remember is that digital surface models (DSMs)
created directly from LIDAR data contain non-
surface objects such as vegetation cover. They are
to be removed for obtaining bare-earth DEMs, but
some of these non-surface points can remain on the
obtained DEM even after filtering them out.\(^4\)

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. Sweeping the entire zone
with this square window, one can obtain the whole
picture of the deformation.

The window size is desirable to be larger
than the largest hidden landslide in the target area for the
discussion of tectonic deformations to minimize the
effect of the hidden coherent landslides, and was set
at 1 km, considering the half wavelength of the active
fold, because the largest landslide in this terrain
cannot be larger than the half wavelength of the
dominant fold. For discussing smaller scale soil
movements such as hidden coherent landslides, the
window size is to be minimized, and yet to be substantially larger than the abovementioned man-made changes.

Though the DEMs before and after the earthquake were carefully prepared, comparing DEMs from the two essentially different methods can cause some inevitable bias to be included in the result. Therefore for the target area discussed hereafter, the obtained elevation changes were compared with those at points of triangulations in order to verify the result (Fig. 3). There were total six triangulation points whose movements were not affected by landslides in the target zone. In this figure, open squares show Eulerian displacements directly obtained from DEMs, while open circles show the vertical components of Lagrangian displacements estimated through the process mentioned above. Between vertical components of soil displacement $\Delta z_k$, triangulation at the points of triangulation and Lagrangian expression of $\Delta z_k$, DEMs (open circles) obtained from the two DEMs, a linear regression analysis was carried to best-fit $b + \Delta z_k$, triangulation to $\Delta z_k$, DEMs, yielding

$$\Delta z_k, \text{DEM} = -0.033 + \Delta z_k, \text{triangulation}$$

with the standard deviation $\sigma = 0.34$ m. \[4\]

For the range of $\Delta z_k$, triangulation from 0.3 to 1.0 m, this $-0.033$ m bias is considered to be small enough to validate the process for converting Eulerian displacements $\Delta z_k$, DEMs to those in Lagrangian expression. Thus the present method is considered to allow for describing the entire view of tectonic displacements.

However, discussing displacements for particular locations will require careful attentions given the standard deviation of 0.34 m that may be a reflection of some local conditions.

**Tectonic displacements**

Target zone is an $11 \times 7$ km$^2$ active folding area of Yamakoshi mountain terrain (Fig. 4), and Fig. 5(a) shows horizontal components of surface
tectonic displacements extracted from the DEMs for the target zone. The target zone may be slightly too small for discussing the entire tectonic deformation that spreads beyond the boundaries of the zone. It was, however, fortunate that Shinano River Office, Hokuriku Regional Bureau of the Ministry of Land, Infrastructure and Transport (MLIT), has been measuring exact locations of bench marks along both the Shinano and Uono Rivers on regular basis. Lateral components of the bench marks’ displacements due to the earthquake were also plotted on Fig. 5(a). There is a NNE–SSW trending 1 to 2 km wide belt of large eastward movement to the west of and along the Kajigane syncline. This belt of lateral displacements seems to have appeared immediately west of the line of intersection between the ground surface and the straight extension of the hidden deep-dipping fault rupture plane for the major event of M6.8, whose geometry was estimated by Hikima and Koketsu. The second cluster of large lateral displacement vectors that has appeared near Uragara hamlet, 4 to 5 kilometers west of the Kajigane syncline, is near the projection on the ground surface of the hidden fault rupture plane for the first largest aftershock of M6.3, which took place at 18:03 JST, about 7 minutes after the main event. When the landslide-distribution map is superimposed on Fig. 5(a), it is noted that two clusters of landslides overlap the clusters of large lateral tectonic displacements.
Fig. 5. (a) Lateral and (b) vertical components of surface tectonic displacements of the target zone on the Japanese National Grid System, Zone VIII (see Appendix): Landslide distribution is shown in Fig. 5(a). A boxed area in Fig. 5(a) is Kizawa locality where Kizawa Tunnel skims Futagoyama Mountain ridge. Damage to Kizawa Tunnel will be discussed in the latter half of this paper.
Figure 5(b) shows vertical components of estimated tectonic displacements. It is notable that there are two areas in the target zone, which have been pushed up by 0.5 to 1.5 meters. The most remarkable hump spreads wide across the southwestern part of the target zone where the Uono River joins the Shinano River. The Uono River, after flowing straight west through a flat wide spread valley of Horinouchi, meets the sedimentary silty sand rock ridge of Cenozoic Era. The river then abruptly changes its direction, from SE–NW to NE–SW, along this rock ridge, making a sharp up-folded bend. Then it forces its way through the narrow and lowest points among the mountains making a sharp down-folded bend. On the geological map of this area, the approximately 2 km-long stretch of the Uono River between these two bends continues straight to both the Kajigane and the Kodaka synclines at its north and south ends, respectively, suggesting that this 2 km-long stretch of the river is a part of the large Kajigane syncline.

Areas along the upper reach of this part of the Uono River were flooded due to heavy rainfall of June 27th–28th, 2005, about 8 months after the earthquake (Fig. 6). Assuming that the same amount of water in the 2005 rain flowed down the Uono River as existed before the earthquake (ignoring the landform changes caused by the Mid-Niigata Prefecture Earthquake), possible water depths at all bench marks along the 57.5 km-long flooded zone (from bench marks No. 15 at 37.26642°N, 138.862209°E, to No. 72.5 at 37.25923°N, 138.899975°E) were estimated by using the Manning empirical equation (open circles in Fig. 7). For this estimation, precise dimensions for the river cross-sections and inclinations at all bench-marks before and after the earthquake were provided by the Shimano River Office, Hokuriku Regional Bureau of the Ministry of Land, Infrastructure and Transport (MLIT).

Solid circles in Fig. 7 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 No. 37.5, No. 52.5 and No. 62.5, while virtual water levels at these points do not reach the high water levels. This figure thus suggests that there was a cause-and-effect relation between the earthquake-induced tectonic deformation and the flooding of June, 2005.

**Shallow soil displacements and damage to tunnel**

The Mid-Niigata Prefecture Earthquake triggered and/or reactivated thousands of landslides, and 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. Several mountain hamlets have been rendered uninhabitable for the foreseeable future. Dimensions, topographical and geological features, etc. of the major 121 landslides were compiled through a thorough survey by the experts at the National Institute of Earth Science and Disaster Prevention for both academic and practical needs. However, one of serious worries of authorities in charge of reconstruction projects was that some hidden landslide masses could be reactivated in snow-melt season. As an example of these worries, a discussion for the reconstruction project of Kizawa Tunnel, a 300 m-long road tunnel follows.

Kizawa Tunnel skims the NW–SE trending branch of Futagoyama mountain ridge (Fig. 8) with its both north and south mouths located at 37.294864°N, 138.878088°E and 37.292688°N, 138.877916°E, respectively. The area is covered by the thick Ushigakubi formation of the Pliocene age. The surface configuration shown in Fig. 8 indicates that the Kizawa locality, about 300–800 m south of Mt. Futagoyama (elevation: 433.5 m; location: 37.117039°N, 138.152031°E), lies on the exposed planar slip surface of an old landslide with its scar shown by a thick broken line XX. The south end of the tunnel is located a little below this scar. A hollow-like configuration leading to a gulch is also found east to northeastern side along the Futagoyama ridge suggesting the presence of another old landslide scar (line YY). The north end of the tunnel comes out into this hollow. During the Mid-Niigata Prefecture Earthquake, the tunnel suffered a serious cracking. One of the most remarkable features of the damage was two parallel pairs of diagonal cracks of the concrete lining that appeared near the north mouth of the tunnel. A northern 120 m segment of the total 300-m-long tunnel was laser scanned. This laser-scanned image (Fig. 9) shows that cracks E1, E2, and W1, W2, run diagonally up through the east and west side walls of the tunnel. The cracks E1 and E2 on the east sidewalk extend over 45–83 m distance from the north tunnel mouth, while W1 and W2 appeared over 38–88 m distance on the west wall. Figure 9(c) shows a cross-section of the tunnel at 59 m from the north tunnel mouth. This figure shows
Fig. 6. Flooding of Uono River: (a) Flooded farm lands (data provided by the Hokuriku Regional Agricultural Administration Office, Ministry of Agriculture, Forestry and Fisheries, and Uonuma City), (b) flooded area near Benchmark No. 42.5 km (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).
that both E2 and W1 were folded inside the tunnel while E1 and W2 were folded backwards. These axially opposite pairs of zigzag folds just allowed the tunnel crown at this location to shift about 0.5 m sideways with respect to the invert, and there was no sign showing that the tunnel lining was sheared in a longitudinal direction along these cracks. To identify the cause of these cracks, borehole data near the cracked part of the tunnel were first gathered. In addition, two boreholes were drilled for in-situ geotechnical tests (Boreholes A and B in Fig. 8). An all-core 40-m-long boring was conducted at Borehole A, and hydro-geological properties of various soil/rock horizons were measured. The southern Borehole B was drilled to obtain both core samples and blow counts (SPT values) alternately at regular intervals of 0.5 m. All cores sampled from five boreholes (open circles in Fig. 8) indicated the presence of a thin and largely disturbed shear plane of siltstone (broken lines in Fig. 10). The shear plane with a dip of about 20–30 deg in the northwest interior of the mountain continues to its southeastern extension, dipping about 10 degrees south. This southeastern extension is roughly parallel with the intact bed stratum of sedimentary rock. The rock mass above this shear plane was generally disturbed as indicated by blow counts for Borehole B (Fig. 10). Kizawa Tunnel was thus considered to be obliquely intersected by this shear plane with its 40–80 m-long northern end segment and the remaining 220–260 m long southern part being embedded, respectively, in the lower intact and upper disturbed rock masses.

The earthquake-induced change in the alignment of the road center-line was measured at every 8.8 m interval on assumption that the northern part of the tunnel embedded in the intact rock below the inferred shear plane did not move, and the measured displacements are shown in Fig. 8 at regular 17.6 m (8.8 m × 2) intervals. It should be noted that the greater part of the tunnel above the shear plane has shifted as a whole by about 0.5–1.2 m east to southeast. This also confirms that the entire rock mass above the shear plane slipped east to southeast gripping the southern part of the tunnel.

Referring back to past earthquakes, underground facilities and/or foundations closely follow the motions of their surrounding soils/rocks. Therefore, the problem at Kizawa was how large the shear plane

![Fig. 7. Actual water levels at all bench marks reached in the 2005 flood, and the virtual water levels for the Uono River as existed before the earthquake.](image-url)
had spread in the interior of the rock, and if the rock mass above the shear plane would move again in snow-melt seasons. Kizawa area, as shown by a square in Fig. 5(a), is within the NNE–SSW trending 1 to 2 km wide belt of large eastward tectonic movement to the west of and along the Kajigane syncline. Figure 11(a) is an enlarged view of this area showing that the entire area has shifted southeast. However, scaling down the window size for the moving-average method to a smaller square of 200 m × 200 m, a
different image of soil movements appears reflecting shallower soil deformations. Therefore, the image of shallower soil deformation (Fig. 11(b)) was obtained by subtracting tectonic displacements vectors viewed through the larger moving window of 1 km \( \times \) 1 km square from those through the smaller window of 200 m \( \times \) 200 m square. In Fig. 11(b), soil masses on almost all sides of Futagoyama Mountain show 0.5 to 1 m downslope movements.

Though these movements can infer the presence of coherent landslides, they are a mere indicator of hidden mass movements without clear-cut information of depths. Therefore, in light of this information, thorough surveys were necessary. At a later date in 2007, two irrigation wells (Well A and B in Fig. 8) in Kizawa area were found dislocated. Well A at 37.292201°N, 138.879062°E was dislocated about 0.15 m laterally at a depth of 34 m below the ground surface of altitude 356 m. In addition to this dislocation, its upper shaft has been inclined indicating that the ground surface at this location has shifted as a total of about 0.5 m sideways in southeast direction (see a vector at Well A in Fig. 8). Moreover, a well drilling company in charge of maintaining these wells reported that the pump for Well A was stuck in some deeper location when they tried to pull it up for treatment after the earthquake, indicating the presence of hidden shear plane(s)
beneath the confirmed depth of dislocation. Well B at 37.288443°N, 138.876143°E was dislocated at a depth of about 20 m below the ground surface of altitude 290 m. The direction of dislocation is unknown at this well because the well was a little too narrow for lifting a borehole camera into it for further details of the damage. These two dislocations of the wells and the diagonal cracks that appeared in Kizawa Tunnel make up a large triangle. This triangle infers a large hidden shear plane extending far beyond the south mouth of Kizawa Tunnel with the azimuth of its strike and dip angle being about 100° and 6°, respectively. This plane is almost parallel with the
exposed planar slip surface of an old landslide in Kizawa locality, and its azimuth and dip angle are not much different from those for the cutting plane inferred from the diagonal cracks that appeared in Kizawa Tunnel.

To check out the stability of the rock mass above this inferred shear plane, borehole packer tests were conducted beneath observed open-hole water levels in Borehole A (Fig. 8) using an inflatable packer to isolate the bottom-end section of the borehole. Figure 12 shows open-hole water levels and packer locations in chronological order. The first open-hole water level appeared about 5–6 m below the ground surface. This water seeped down when a drilling depth of 17–23 m was reached. The second open-hole water then appeared at a depth of about 25 m, approximately the same depth as the tunnel-crown level. This second water level was lowered when the drill went further down into a sandy soil-layer bedding in the intact mass of sedimentary rock.

After the bottom end of the borehole was isolated with the single packer, injecting water pressure was increased stepwise with each increment \( \Delta P \) set at about 20 kPa, and the resulting pressure \( P \) and flow rate \( Q \) were recorded when the flow had reached a quasi-steady-state condition. The data were recorded over a number of increasing and decreasing steps. The data from the injection test were used to determine the effective hydraulic conductivity \( k \) by means of the following equation as described in the Earth Manual:17)

\[
k = \frac{1}{2 \pi L a} \ln \left( \frac{2 L}{D} \right)
\]

where, \( L \) is the length of the isolated bottom end of the borehole, \( D \) the diameter of the borehole, and

\[
a = \frac{\Delta s}{\Delta Q}
\]

with \( \Delta s = \) increment of hydraulic head = \( \frac{\Delta P}{\rho g} \)

Injected water forces its way through a fractured rock mass, and the increment rate of the hydraulic pressure/height (Eq. [2]) decreases suddenly when the injection pressure exceeds a threshold as shown in Fig. 13. This pressure is referred to as the “critical injection pressure.” Figure 10 summarizes both hydraulic conductivities and critical injection pressures along Borehole A. It is noted that the critical injection pressures were 176 kPa for the borehole segments from 27 to 29 m in depth, immediately above the shear plane, and 241 kPa for the segment from 29 m to 31 m that includes the shear plane in it. Particularly, the flow rate for the segment from 29 m to 31 m did not relax back to zero when the imposed
injection pressure was removed. This indicated that when the injection pressure reached its critical value, the water suddenly forced its way into either the surrounding rock or the shear plane fracturing its bond. Thus, there was a concern that the rock mass above the shear plane would move when the open-hole water levels did increase by 24.1 m from the packer-isolated segments level. The Nagaoka Regional Development Bureau of the Niigata Prefectural Government drilled two Boreholes C and D (see Fig. 8) to monitor whether the open-hole water level would increase to that serious level, and whether the boreholes would exhibit signs of increasing inclination.\(^7\) An inclinometer was inserted along a notched casing fitted in the borehole, and inclinations were measured at a regular interval of 0.5 m. The records were compiled from 1st September 2005 until the end of 31st May 2006. The open-hole water levels for Boreholes C and D had been about 32 and 27 m below the ground surface levels with semiannual changes of \(\pm 2\) and \(\pm 1\) m, respectively. Water levels, reaching their peak values in snow-melting times (May) and immediately before snow times (December), were far below the critical levels, and inclinometer records did not show any sign of a possible rock-mass deformation. With these data compiled, the Nagaoka
Recent development of remote sensing technologies such as Laser Imaging Detection and Ranging Technology (LIDAR) and Interferometric Synthetic Aperture Radar (InSAR) has enabled the quick acquisition of precise images of landforms and the changes in elevation for areas devastated by a big earthquake. However, detected displacements are only in the Eulerian description, which does not directly describe behaviors of history-dependent soils and rocks. An attempt was made in areas affected by the October 23rd 2004, Mid-Niigata Prefecture Earthquake, to convert changes in elevation in Eulerian description for images obtained from remote-sensing technologies to Lagrangian displacements. DEMs of the mountain terrain before and after the earthquake were first obtained as raster graphic images with pixels arranged in a 2m x 2m square grid; each pixel has information of its elevation. Changes in elevation in Eulerian description for DEM were first converted to Lagrangian displacements, and then the moving average method was adopted to obtain the whole picture of landform changes.

To exclude the effect of shallow surface landslides, a 1 km x 1 km square window was used, and the large-scale ground deformation was first detected. For the horizontal components, there are two clusters of large displacements. The first cluster is a NNE-SSW trending 1 to 2 km wide belt of large eastward movement to the west of and along the Kajigane syncline. This belt of lateral displacements seems to have appeared on the hanging wall side of the line of intersection between the ground surface and the straight extension of the hidden deep-dipping fault rupture plane for the major event. The second cluster that has appeared near Uragara hamlet, 4 to 5 kilometers west of the Kajigane syncline, is seemingly near the projection on the ground surface of the hidden fault rupture plane for the first largest aftershock of M6.3, which took place about 7 minutes after the main event. It is noteworthy that two clusters of landslides overlap the clusters of large lateral tectonic displacements. For the vertical components, there are two humps in the analyzed zone, which have been raised upward by 0.5 to 1.5 m. The southern hump spreads wide across the area where the Uono River joins the Shinano River, and therefore could have been one of the causes of flooding that occurred about 8 months after the earthquake.

The image of shallower soil deformation was obtained for Kizawa locality by subtracting tectonic displacements vectors viewed through the larger moving window of 1 km x 1 km square from those through the smaller window of 200 m x 200 m square. The image showed that soil masses on almost all sides of Futagoyama Mountain have slid 0.5 to 1 m down. In this Kizawa locality, Kizawa Tunnel was seriously damaged with two parallel pairs of diagonal cracks appearing on its east and west concrete walls. Two parallel cracks on the west-side wall were folded inside and backward, while the other two on the eastside were folded backward and inside, respectively. This axially opposite pattern of zigzag folds allowed the tunnel crown to shift sideways about 0.5 m with respect to the invert. Two irrigation wells in Kizawa locality were also dislocated. Directions of these shear deformations were consistent with the Lagrangian displacement vectors obtained for shallower soils, and thus infer a large shear plane hidden beneath Kizawa locality.

The method proposed herein was proven to be useful for coherent mass movements in mountain terrains. However, the obtained images are a mere indicator of hidden mass movements without clear-cut information of depths. Therefore it is necessary for this method to be combined with the other investigations so that causes of landform changes will be rationally discussed in a comprehensive manner. More case-histories are to be analyzed for more advanced use of the method for disaster preventions and land conservations.

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Appendix: Geographic Reference System

The World Geographic Reference System is used to describe particular locations though DEMs for Mid-Niigata region were all prepared on the Japanese National Grid System because the Japanese Geological Survey uses it. The Japanese National Grid System divides Japan into a set of 19 zones assigned with Greek numerals from I to XIX in principle in a row-by-row pattern starting from the zone at the southwest corner. Exceptions (from XIV to XIX) are for isolated islands. The surveyed area of Yamakoshi mountain terrain is included in Zone VIII with its southwest corner located at 138.5°E, 36.0°N.

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Profile

Kazuo Konagai, born in 1952, received his BE, M.Eng. and PhD degrees from the University of Tokyo in 1975, 1977, and 1981, respectively. His PhD research was concerned with the ground tremor caused by high-speed trains. At the end of his PhD studies, he continued his research at the Nagaoka University of Technology for two years as a Research Assistant before taking up a research and teaching post as an associate professor at the same university in 1981. Konagai then joined the Department of Fundamental Engineering in the Institute of Industrial Science (IIS) at the University of Tokyo in 1987, and was promoted to professor at IIS, the University of Tokyo, in 1998. His primary research interests include soil dynamics, seismic waves, dynamic soil-pile interaction and hazard analysis. Much of his current research work is in the area of long-lasting post-earthquake geo-hazard issues; many of them are caused by earthquake-induced landform changes, specifically the integration of findings through field surveys with analyses of imageries from Laser Imaging Detection and Ranging technology (LIDAR) etc. He made 140 reconnaissance trips to areas devastated by 41 domestic and overseas earthquakes. They include the Mid-Niigata Prefecture Earthquake of October 23rd 2004, Japan, the Kashmir Earthquake of October 9th, 2005, Pakistan, the Wenchuan Earthquake of May 14th 2008, China, and the most recently the Off the Pacific Coast of Tohoku Earthquake of March 11th 2011.

He wrote 74 original papers including 10 and 34 published in the journals/special technical publications of the American Society of Civil Engineers (ASCE) and international journals respectively, 54 papers for international conferences/symposiums, 40 reconnaissance reports, a book and 10 book chapters. He won the best paper award of 1994, Journal of Structural Mechanics and Earthquake Engineering, from the Japan Society of Civil Engineers (JSCE).

He served as the Vice President of the Japan Association for Earthquake Engineering (JAEE) in 2007 and 2008, the President of Engineers without Borders, Japan (EWBJ) in years after 2006 before 2009. Konagai was a Research Scientist in the Department of Civil Engineering at the University of Houston (UH), USA, in 1985, a guest professor in the Department of Geotechnical Engineering at the Norwegian Institute of Technology (NTH), Norway, in 1995 and 1996, and has been also guest professors at the Bangladesh University of Engineering and Technology (BUET), Bangladesh, and the Dalian University of Technology (DUT), China, since 2001 and 2002, respectively.