# GEOTECHNICAL HAZARD FOR CIVIL INFRA-STRUCTURES IN THE OCTOBER 23, 2004 NIIGATA CHUETSU EARTHQUAKE, JAPAN

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**ABSTRACT**: A huge number of landslides induced by the Chuetsu earthquake caused a total of 233 segments of national and prefectural routes in Higashiyama mountain area to be closed to traffic, and total 61 village areas were completely isolated. Since railway and road facilities follow closely the motions of soil, damage to these facilities must be discussed in terms of soil deformations that they experienced. This report highlights cases of some tunnels.

**Key Words**: Chuetsu earthquake, landslides, active folding, tunnels

## INTRODUCTION

An intense earthquake of magnitude 6.8 jolted Mid Niigata Prefecture, central Japan at 17:56 JST on October 23, 2004. The hypocenter of the main shock was located at 37.3 N; 138.8E with depth of 13 km. The maximum intensity of 7 on the 7-grade Japanese intensity scale was reached.

The earthquake was followed by a series of strong aftershocks in rapid succession. The area suffered four seismic events of magnitude 6 or greater within 38 minutes after the main shock. The focal mechanisms of those major earthquakes are the reverse fault type with the compression axis oriented NW/SE, which is consistent to the historical solutions of major earthquakes in this area. Aftershocks are distributed along the northeast and southwest direction with a length of about 30km. The maximum acceleration of 1500 gal was recorded at Ojiya station, the nearest K-NET station to the hypo-center. This acceleration was much greater than that recorded during the 1995 Kobe earthquake.

The earthquake stopped the services of Shinkansen and regular railways, the Kanetsu and Hokuriku highways, and national routes along Uono and Shinano rivers. A Joetsu-Shinkansen high-speed train derailed for the first time since the Shinkansen railway network opened and started expanding nationwide. Uonuma tunnel of the Joetsu-Shinkansen suffered serious damage probably because the surrounding soil compressed the tunnel along its axis. An abundant number of landslides in the Higashiyama mountain area forced local authorities to suspend the operation of total 233 segments of several prefectural routes and the national route 249. As a result, a total number of 61 village areas were completely isolated. More road segments were blocked after the intense aftershocks including the one on October 27 (10:40am), in which the maximum intensity of 6-weak on JMA scale was recorded. Restoration of the damaged segments as well as further analysis for better measures for the upcoming snow-melting season, became a very difficult task due to fear of additional aftershocks in combination with heavy rain, an early sign of snow season in the area.

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Geotechnical hazards, such as landslides and tectonic compression, caused the majority of civil-infrastructure damage. Furthermore the local geology contributed to damage due to shaking. The first half of this paper describes the geological structure of the Higashiyama mountain area as the background for understanding the nature of these hazards. In the latter half, damage to tunnels will be highlighted, as they are indicative of the deformation of surrounding soil.

## GEOLOGICAL STRUCTURE AND LANDSLIDES IN THE AFFECTED AREA

Higashiyama mountain area is well known as one of the most landslide-prone zones in Japan. The map in Fig. 1 shows possible landslide locations in the southern part of the Higashiyama region as interpreted from aerial photographs taken before the earthquake (NIED [1]). The prevalence of NNE-SSW-trending folds characterizes this area. Stratified Pliocene rocks are found everywhere inclined or curved upward or downward. Since the up-folded rocks along anticlines were expanded and weakened, anticlines frequently have their crests eroded (Fig. 2). As a consequence, asymmetric ridges called cuesta, characterized by a steep cliff or escarpment on one side, and a gentle dip slope on the other, have formed. (The term "dip slope" is used here to denote the type of geomorphological setting where the rock joints are dipping along the slope.) Yamakoshi village, from which all inhabitants were evacuated, spreads over old landslide masses along the deeply eroded Higashiyama anticline.

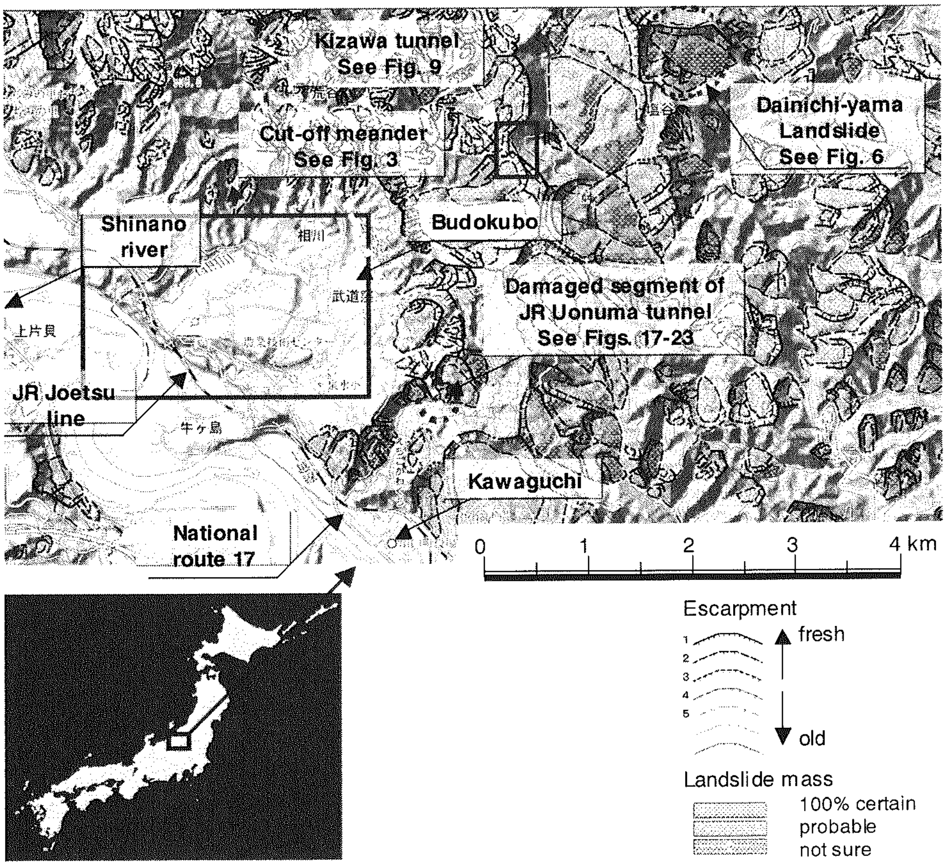



Fig. 1 Landslide map of Higashiyama mountain district.

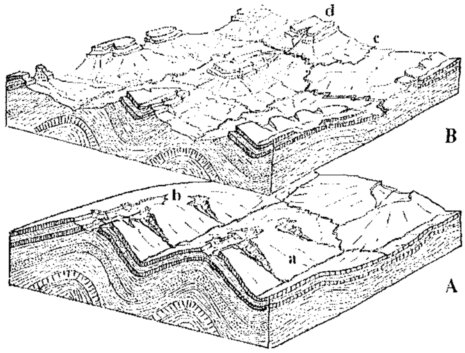



Fig. 2. (A) Early and (B) late stages of fold erosion (after Martonne E. de [2])

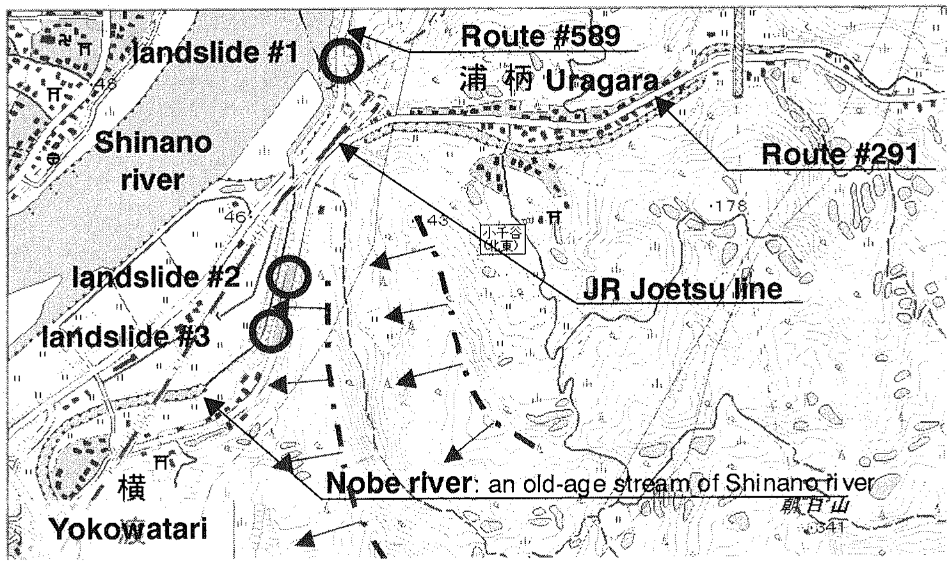
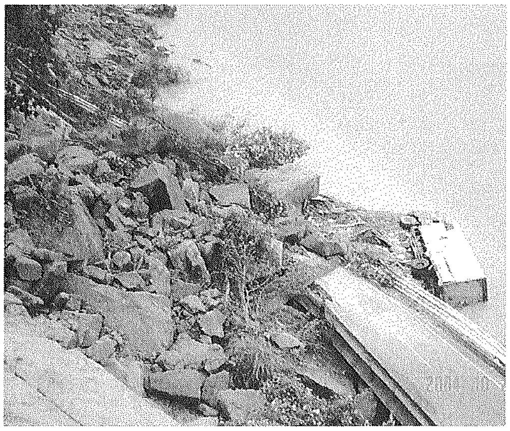
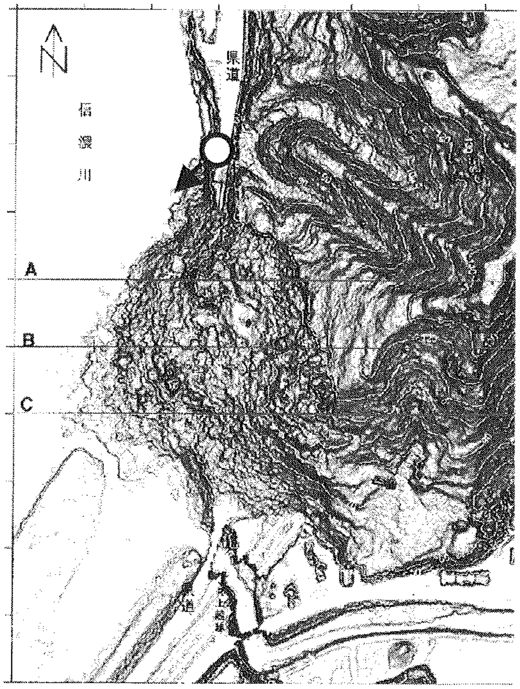



Fig. 3. Locations of surveyed landslides near Uragara and Yokowatari localities, Ojiya city: Arrows show gentle dip slopes of cuestas.

Shortly after the earthquake, a team of expert researchers of the Japan Geological Survey interpreted locations of landslides in the Higashiyama mountain district from aerial photographs (Sato, et al. [3]). They had found 1353 slides as of October 27. Various types of landslides occurred on both sides of cuestas of sedimentary rocks. A large-scale landslide can take place along a joint on a gentle dip slope of cuesta. In the Chuetsu earthquake, such kind of landslides included the Higashi-Takezawa landslide, in which a sedimentary rock mass slid down a 17 to 22 degrees-dipping joint of Shiroiwa (White rock) formation of sandy mudstone and dammed Imokawa River. A cliff failure of sandy mudstone of Shiroiwa formation at Myoken destroyed a segment of Prefecture Route 589 (Fig. 4, Landslide #1 in Fig. 3). The landslide mass was broken up into a number of large blocks, and buried three vehicles. Some part of the exposed surfaces of the broken rocks had a red-brown color, indicating that they had been air-corroded, while the greater part was bluish gray, indicative of corrosion-free surfaces of cracks formed during the landslide. The Shinano River, developing a little bend at Myoken, has been laterally eroding the rock of Shiroiwa formation, exposed on this cliff, over the centuries, increasing the probability of landslide.



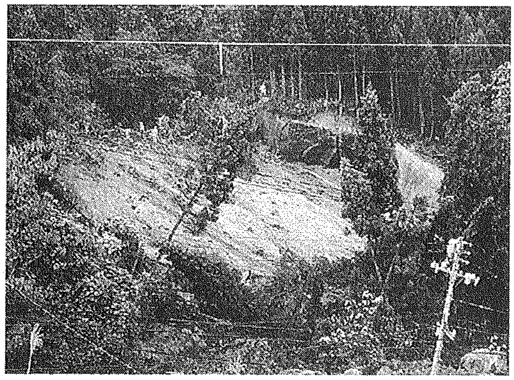




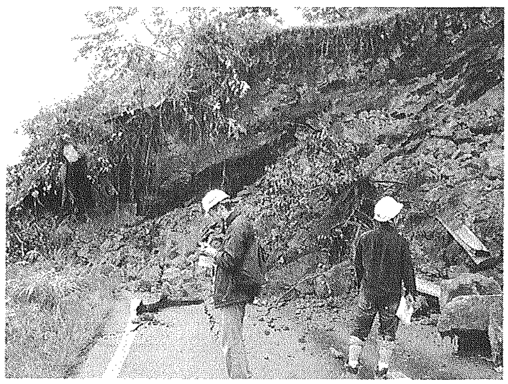
**Right:** Laser profiled topography of Myoken landslide area (Aero Asahi Co.) shows that the slide took place on a gentle dip slope of cuesta.

**Left:** Conveyed segment of National Route 291. Photo was taken at Point A in the map right.

Fig. 4. Landslide at Myoken (Landslide #1 in Fig. 6)



(a) Landslide #2 in Fig. 4



(b) Landslide #2 in Fig. 4

Fig. 5. Landslides at Yokowatari

Similar landslides are found at Yokowatari region, about 300-400 m south of the Myoken slide (Fig. 5, landslides #2 and #3 in Fig. 3). A poorly consolidated sandy mud rock plane slipped along its joint leading to Nobe River, and buckled upward as shown in Fig. 5(b). Nobe River at this location is an old-age stream of the Shinano River, and is considered to have eroded the toe of this dip slope. The landslide mass stopped the flow of Nobe river, and consequently, rice fields along the river were all flooded.

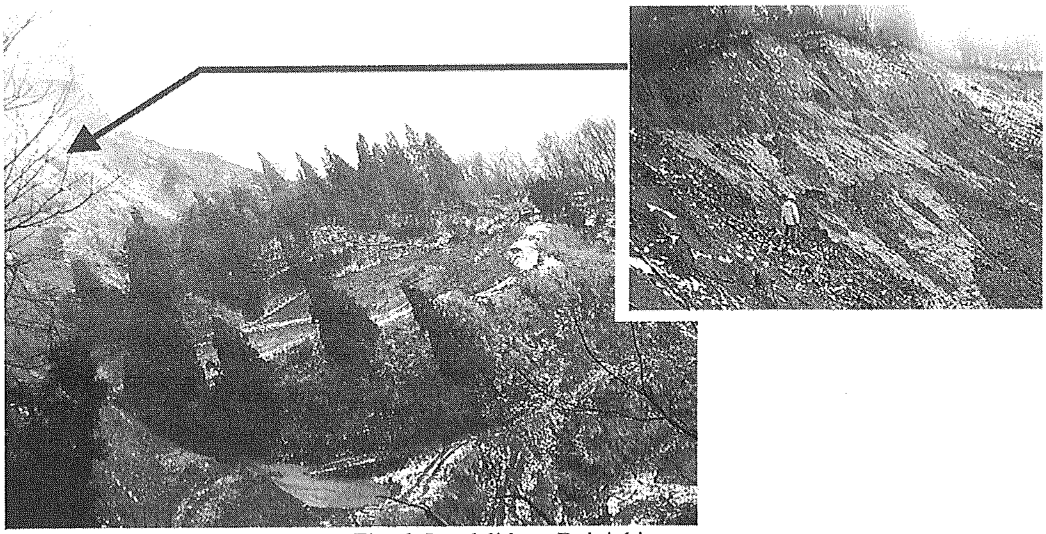


Fig. 6. Landslide at Dainichi-yama

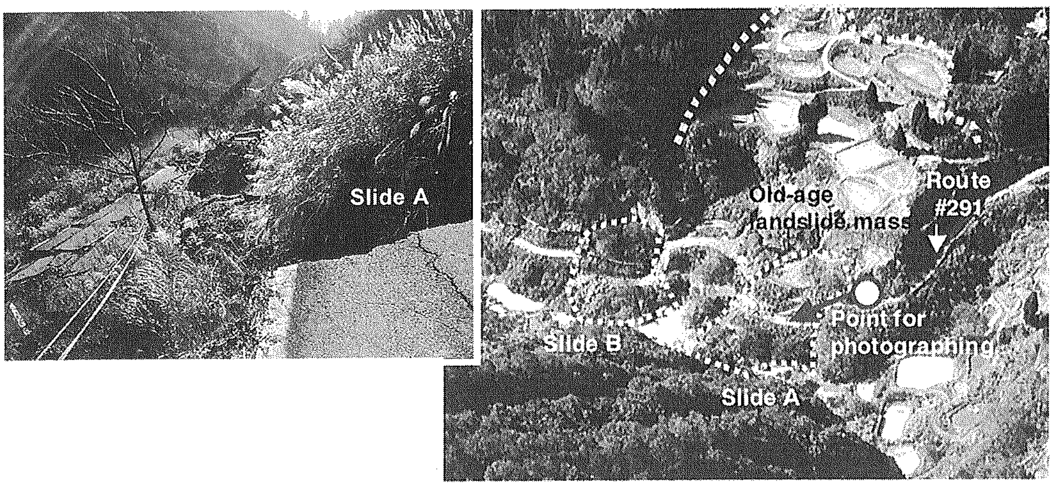
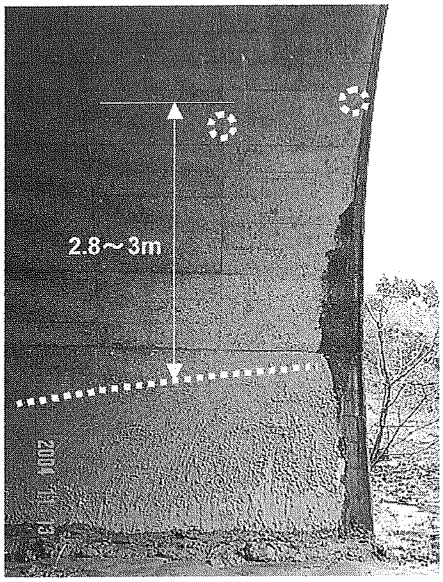



Fig. 7. Segment of National Route #291 carried down by a landslide at Nityono

Old landslide masses were reactivated in the earthquakes. The largest landslide (Fig. 6(a)) took place on the southeastern mountainside of a 400m-elevation peak near Dainichi-yama (see its location in Fig. 1). The escarpment shows stratified mud rock profile with sand rock films bedding in. The mud rock surface exposed on the escarpment was wet and shiny (Fig. 6(b)). The geological map of Ojiya District [4] suggests that the layers on the east wing of Toge Anticline dip 10 to 20 degrees southeast, and the landslide mass may have slipped along one of these bedding planes. Luckily, the landslide at Dainichi-yama caused no serious damage to civil-infrastructures just because it took place off major roads in mountains.

Some smaller-size slope failures took place near toes of large existing landslide masses, which toes had been gradually scoured by river streams. Fig. 7 shows a broken segment of National Route #291 carried down 20m towards Dodome River. The soil mass that failed seems to be the lower part of an old landslide mass whose 250 m wide and 300 m long surface was covered with some 10 carp ponds.

(a) Debris flow bed exposed by the tunnel mouth




(b) Mud spatters on the tunnel wall

Fig. 8. Debris flow by the northwestern mouth of Shiotani tunnel

A small debris flow took place near the northwestern mouth of Shiotani tunnel (Fig. 8(a)). Fig. 8(b) shows a part of the southern wall near the tunnel mouth. The remaining mud traces on the wall show that the 1.5m-thick debris flow hit the wall and spattered up on the tunnel wall by 2.8 to 3 m above its surface (broken line). Assuming that the entire kinematic energy is used up to increase the potential energy of mud droplets, these spatters suggest that the horizontal speed of the flow reached about 5.5 m/s. This velocity value is an estimation of the velocity at the edge of the flow profile. Judging from boulders and other suspended materials that were carried down (Fig. 8(a)), flow velocity of the mainstream may have been about twice as big as its velocity at the edges.

## LANDSLIDE AND TECTONIC COMPRESSION INDUCED DAMAGE TO TUNNELS

Past earthquakes revealed that underground facilities and/or foundations follow closely the motions of their surrounding soils. Therefore landslides and seismic faults are major causes of severe damage to underground structures. Crack patterns of Uonuma and Wanazu tunnels of the Joetsu-Shinkansen and the JR Joetsu line, respectively, suggest that the surrounding soils have compressed the tunnels in their axial directions. In general, most road tunnels in Higashiyama mountain district performed quite well suffering only minor cracking near their mouths. However the damage to Kizawa tunnel was serious.

***Kizawa Tunnel (Landslide induced damage)***

Kizawa tunnel skims the NW-SE trending branch of Futagoyama mountain ridge (Fig. 9). The area is covered thick with Ushigakubi formation of Pliocene age. The surface configuration shown in Figs. 9 and 10 indicates that Kizawa locality about 300 to 800m south of Mt. Futagoyama lies on an old landslide mass with its escarpment shown by line XX'. The south mouth of the tunnel is located a little below this escarpment. A depressed configuration is also found east to northeastern side along the Futagoyama ridge suggesting the presence of another landslide escarpment (line YY'). The North tunnel mouth is closer to this configuration.

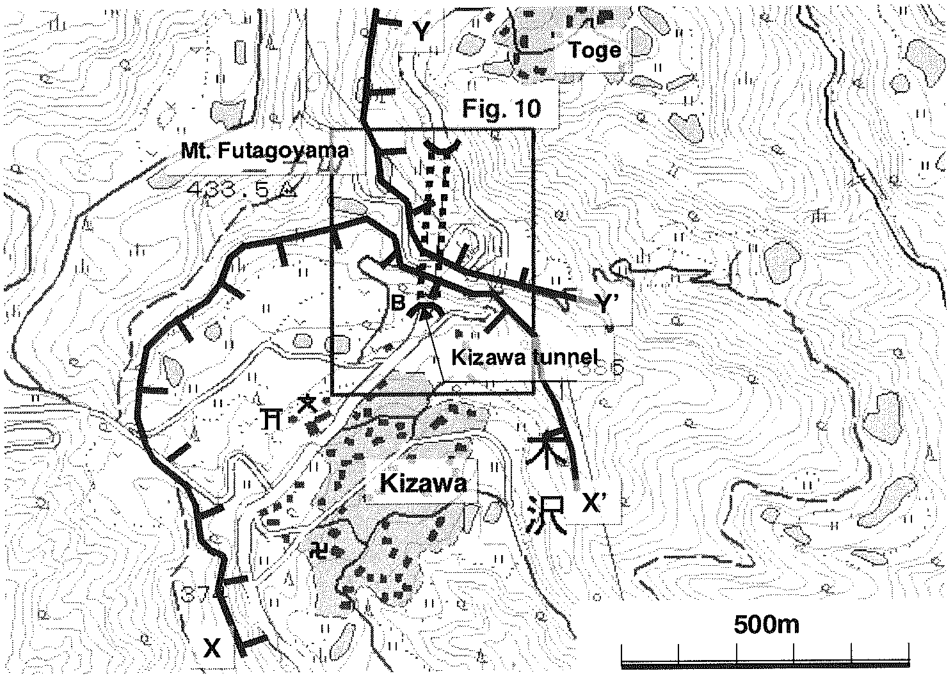



Fig. 9. Surface configuration in the vicinity of Kizawa tunnel

Fig. 11 shows the soil/rock profile along the tunnel. Though the rock layers forming this mountain show a normally stratified geological structure sloping about 18 degrees towards SW (Yanagisawa et al. [4]), a different image of structure appears when the rocks are described in terms of their strengths. The northern part of the tunnel crosses, at points P1 and P2, a severely cracked and/or weakened mud rock layer lying over a depressed surface of an almost intact mud rock.

The Northern 120m segment of Kizawa tunnel (Fig. 10) was laser-profiled. Fig. 12 shows that two pairs of major cracks, E1, E2, and W1, W2, go diagonally up through the tunnel (see Fig. 13). The cracks, E1 and E2 on the east wall (Figs. 12(a) and 13(a)), extend over the 45 to 83m distance from the north tunnel mouth, while W1 and W2 (Figs. 12(b) and 13(b)) over 38m to 88m distance on the west wall. Fig. 14 shows three cross-sections at 51, 55 and 59m points together with an intact cross section measured at 100m point. It is clear from this figure that the pairs of cracks on the wall became hinges for the upper half of the tunnel cross-section that was pushed 40 to 50 cm east and about 10 cm down.

This part of the tunnel passes 20 to 30 m to a mountainside sloping to the east, and the damage is considered to have been caused by the motion of the soil/rock surrounding the tunnel, which motion was not clear in appearance from outside. Some minor cracks found on the ground surface were mapped on Fig. 10. As we find more cracks hidden there, a clearer image of the landslide mass will emerge.

As has been mentioned, the northern part of the tunnel crosses at two locations, P1 and P2, a severely cracked and/or weakened mud rock layer (Fig. 11). The cracks E1, E2, W1 and W2 shown in Fig. 12 seem to have appeared in this weakened mud rock zone P1 near the north tunnel mouth. On the other hand, Cracks that appeared on the concrete lining (downward thin line arrows in Fig. 11) over some longer distance (100-180m) covering P2 zone, cut the tunnel axis upright and diagonally crosswise. This pattern of cracking seems to suggest that the tunnel was slightly bent towards the east-sloping mountainside. A lot of water reportedly came out of boreholes through the rock zones P1 and P2 before the tunnel construction. The soil profile along borehole #9 in Fig. 11 indicates that the underground water level is about identical to the upper surface of this weakened rock zone.

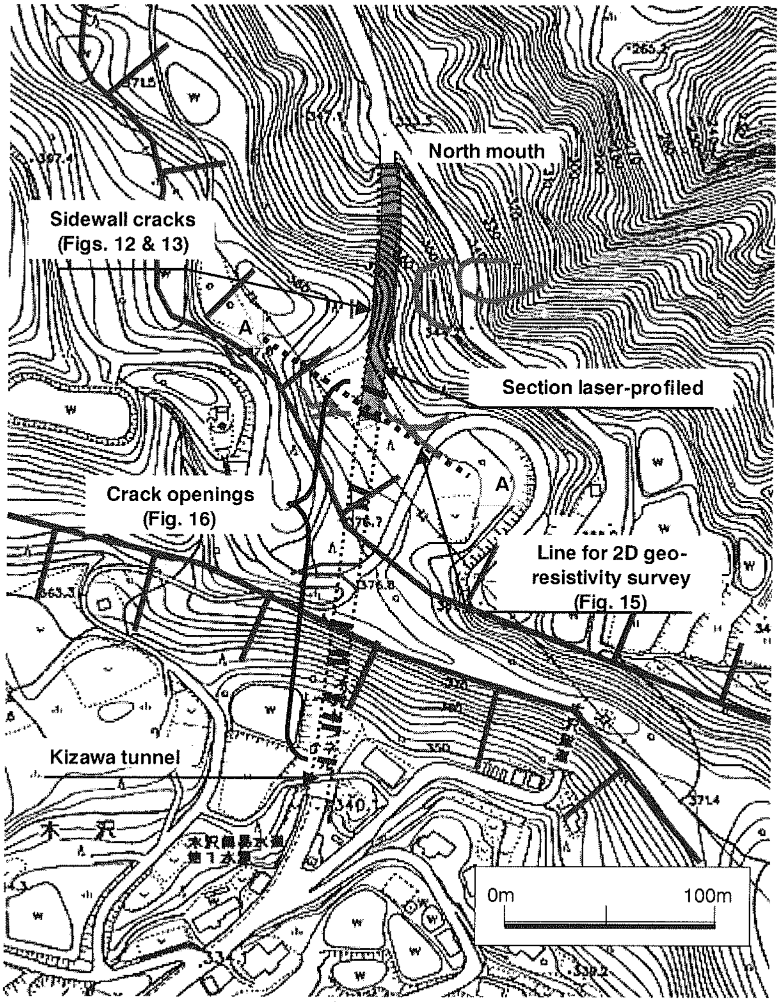



Fig. 10. Kizawa tunnel

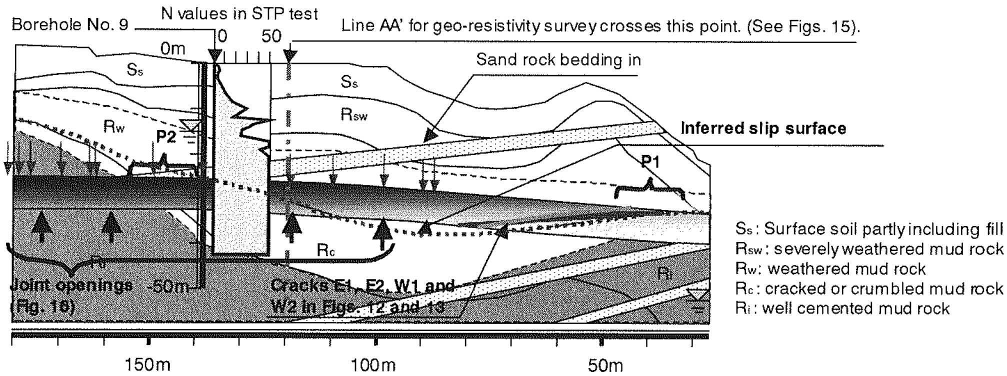



Fig. 11. Soil/rock profile along Kizawa tunnel: Downward thin arrows on the tunnel crown show locations of cracks cutting the tunnel axis upright and diagonally crosswise, while upward thick arrows show locations of joint openings (see Fig. 16).

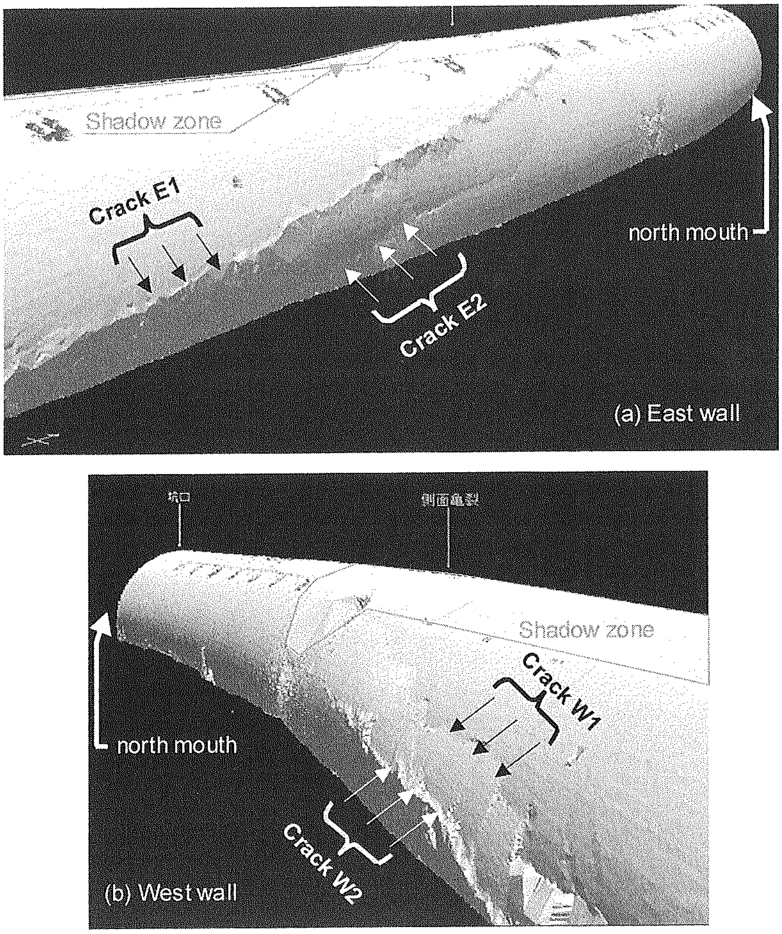
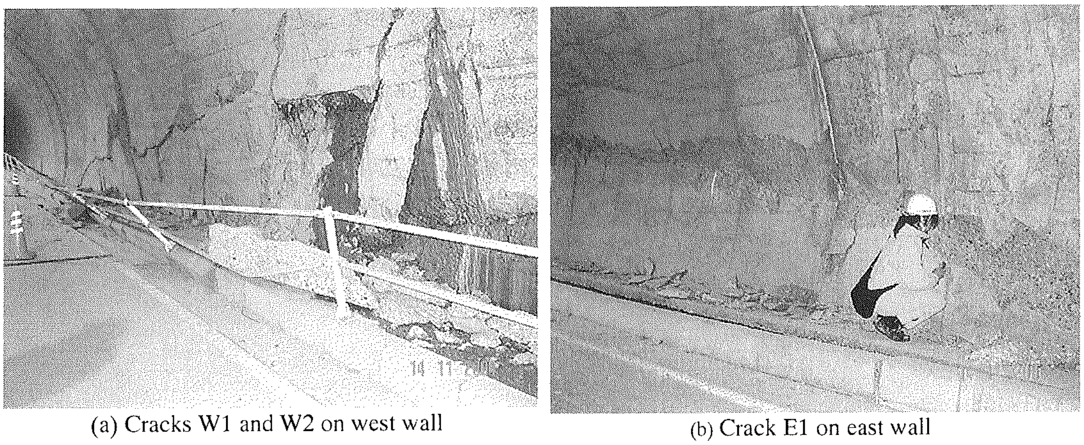



Fig. 12. Laser-profiled north segment of Kizawa tunnel: Laser-profiling was conducted after a steel frame was put up in the damaged section for protection of vehicles against possible danger. Therefore, there was a shadow zone where a laser beam did not reach.



(a) Cracks W1 and W2 on west wall (b) Crack E1 on east wall

Fig. 13. Cracks appeared on the north segment of Kizawa tunnel

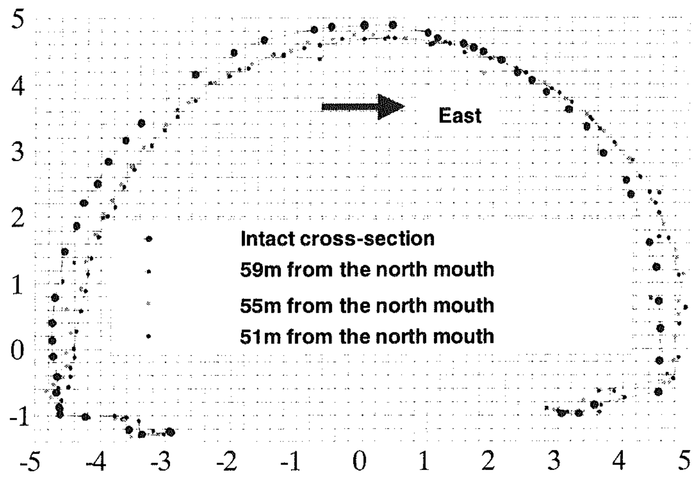



Fig. 14. Cross-sections of the cracked segment of Kizawa tunnel

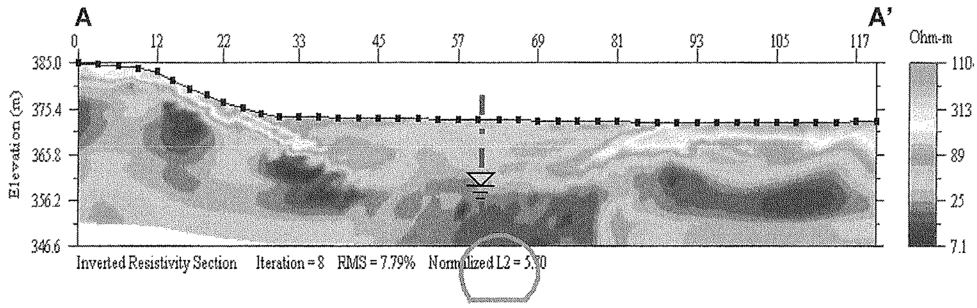
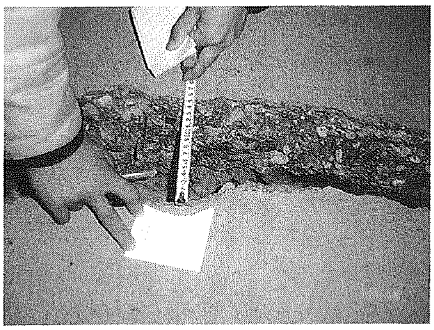



Fig. 15. Spatial distribution of geo-resistivity across Kizawa tunnel



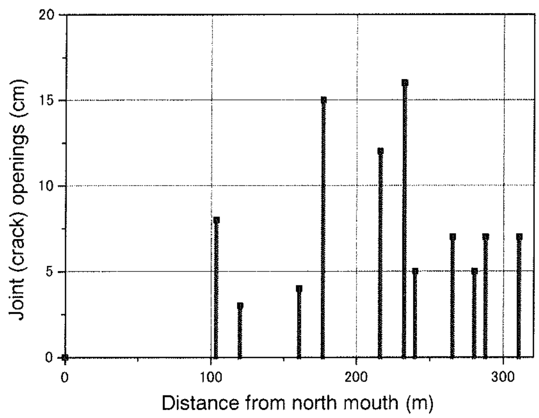



Fig. 16. Openings of the joints with respect to their distances from the north tunnel mouth

Near this borehole, a 123m-long line, A-A', was taken along a depressed ground surface for geo-resistivity measurement (see the broken line A-A' in Fig. 11). This line crosses in its middle over the tunnel at an angle of 60 degrees. The possible pattern of geo-resistivity distribution, obtained from an inverse analysis (Fig. 15), shows a shallow zone with high resistivity of about 300-2000 Ohm·m suggesting the presence of the original ground surface (0-36m and 72-123m). Low resistivity zones underlie this zone. In the middle of Line A-A' over the most depressed and flat configuration (26-90m), the surface soil deposit of about 15m-thickness is underlain by a lower resistivity zone (about 7-20 Ohm·m) whose upper surface is about identical to the underground water level in Borehole #9. This zone with an inclusion of the tunnel near the deepest bound of the geo-resistivity measurement (red circle in Fig. 15) is a little asymmetric. The presence of the tunnel may be affecting the underground water flow.

Expanded pavement joints were mostly found over a segment 100 to 305m from the north tunnel mouth, namely, southern two thirds of the tunnel. Fig. 16 shows the openings of the joints with respect to their distances from the north tunnel mouth. The figure says that the tunnel was expanded 89 cm axially. Figs. 9 and 10 suggest that the expansion of the tunnel axis may have caused partly by the motion of the surrounding soil near Escarpment XX'.

***JR Shinkan-sen Uonuma Tunnel (Tectonic compression induced damage)***

The shinkansen high-speed train line between Tokyo and Niigata passes through many mountain tunnels. The Uonuma tunnel is located just to the south of the main shock epicenter as shown in Fig. 17. Fig. 17 also shows the previously unknown Obirau fault and other faults.

The Uonuma tunnel, a 8625m long concrete tunnel, crosses the inferred Sarukurayama fault (see Figs. 17-18), which is located just above the epicenter and the damage to the Uonuma tunnel may hint a re-activation of a small segment of this inferred fault. The Sarukurayama fault stretches approximately 4km in the SSE/NNW direction from its southern end, just east of Kawaguchi town, to the Konpira mountains in north with its west side as a hanging wall.

As seen in Fig. 19, some landslides occurred above the tunnel damage location. Other researchers and also the authors research group have made field trips to different areas along the Sarukurayama fault, but no direct evidence, such as soil offsets and/or cracks indicating a fault-reactivation, was found.

Given the geological complexity of this zone, the tunnel was carefully constructed with its both sides first excavated large enough to permit the insertion of steel supports, which served later as foundations for cutting upper half of the tunnel. The tunnel was constructed through a squeezing rock zone, which extends 120 m to north of the segment damaged in this earthquake (See the abrupt change in geological formation in Fig. 20). At the damaged location, the tunnel is about 60-100 meter deep as interpreted from Fig. 20. Fig. 20 indicates an extreme amount of leakage (200 liter/min) during the construction time. The leakage may be related to the river flowing above the tunnel.

Cracks and a development photo of the damaged tunnel segment (Fig. 21(a)) between 195,060 and 195,080 m (distance measured from Tokyo station) are given in Figures 21 (b) and (c). Several cracks cut the tunnel diagonally from the south to the center of the damaged area. These diagonal cracks merge at their southern ends to form a thrust dislocation showing about 13 cm shortening of the lining at this point. At the center of the damaged segment, the concrete crown broke up into large pieces, and fell in onto the rails and their slabs. The spalled part of the tunnel crown in Fig. 21(c) exposes steel supports. In Figure 21(c), the south part of the damaged area is to the right and the central part to the left. The northern part of the damaged segment (195,113m -) has lighter damage and the rail foundation was not deformed as much as in the south part (see Figure 22(a)). However the center ditch along the rails shows a clear right-lateral shift of about 10-15cm where it is crossed by crack. NW-SE trending diagonal cracks were prevalent there (Fig. 22(b)).

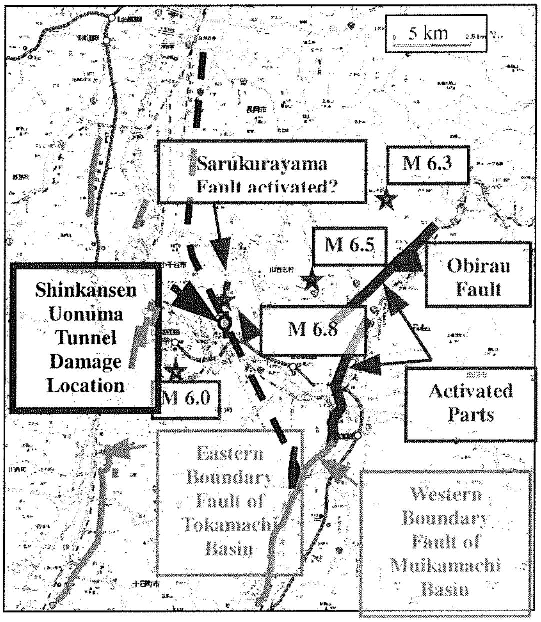



Fig. 17. Epicenters of main and after shocks and seismic faults

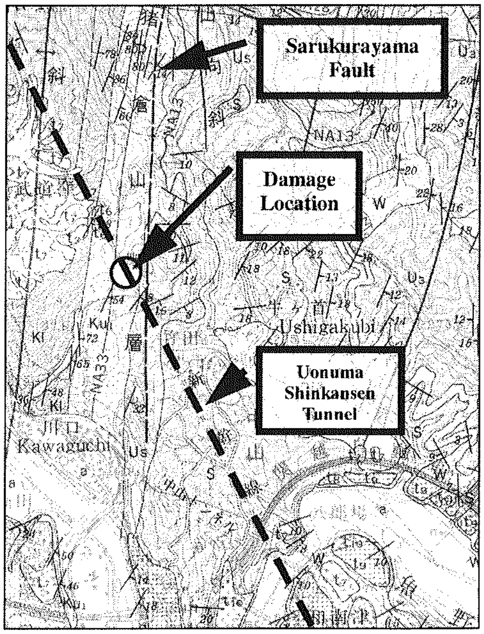



Fig. 18. Geological map with Uonuma tunnel

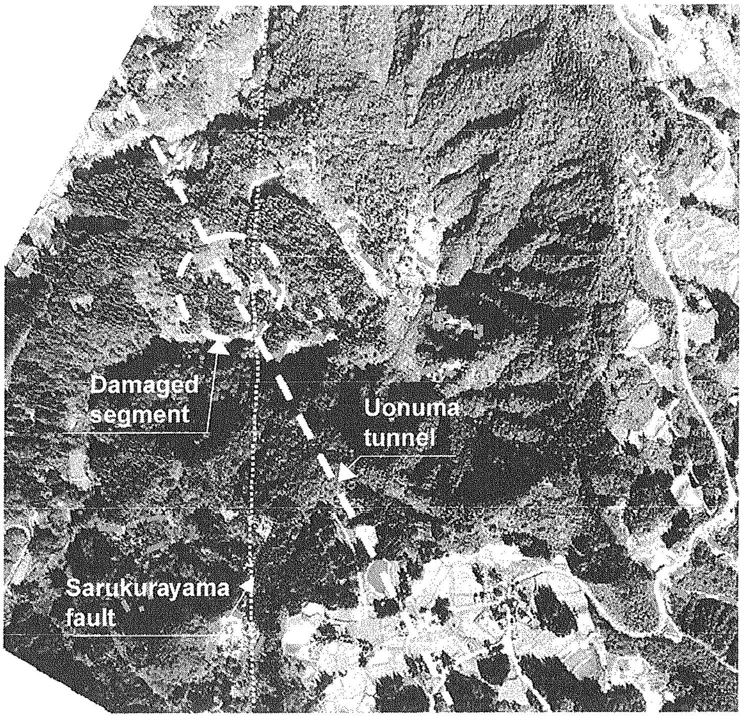



Fig. 19. Arial photograph of the area above the damaged segment of Uonuma tunnel

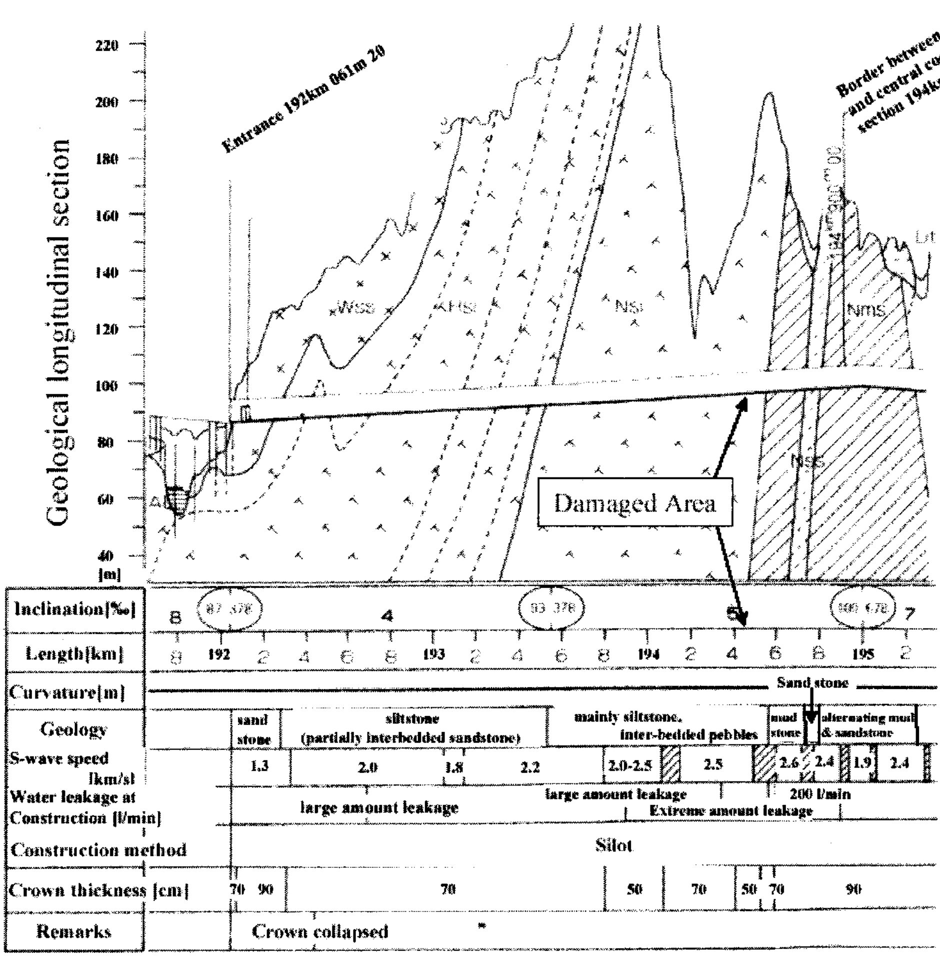
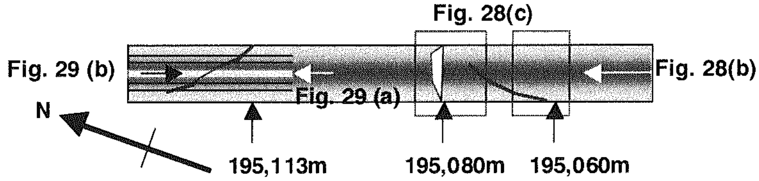
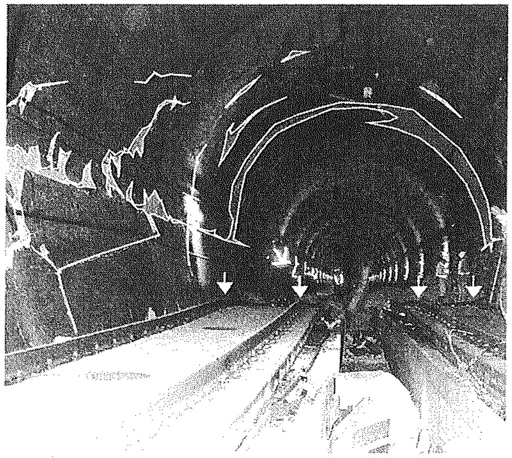


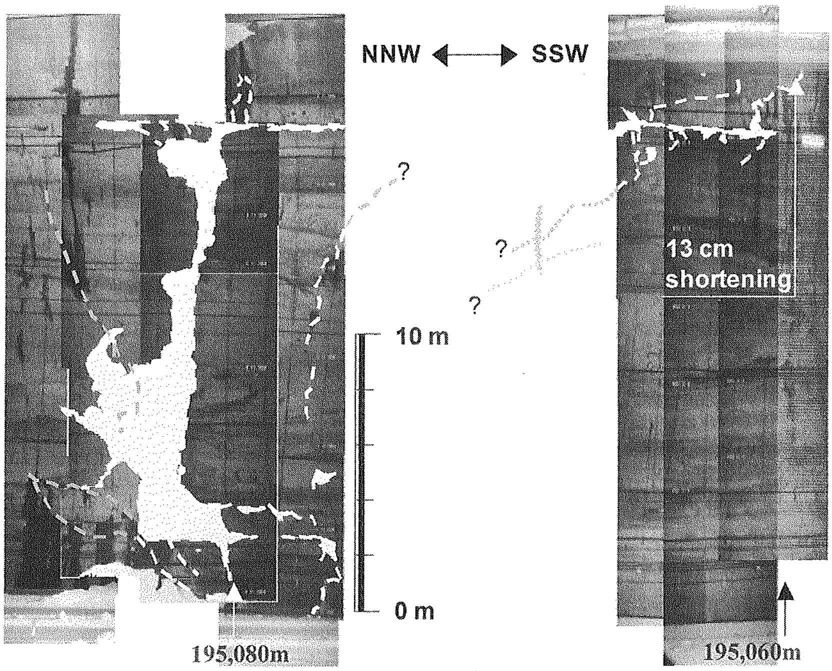

**Fig. 20**. Geological profile along the southern construction section of Uonuma tunnel (Japan Railway Construction Corporation [5])




(**a**) Damaged segment of Uonuma tunnel. Boxes correspond to location of photos in c) and d)



(**b**) Southern part of the damaged tunnel segment (from south to north)




(**c**) Development of cracks

**Fig. 21**. Cracks in the southern part of the damaged segment of Uonuma tunnel (195,060-195,080 m)

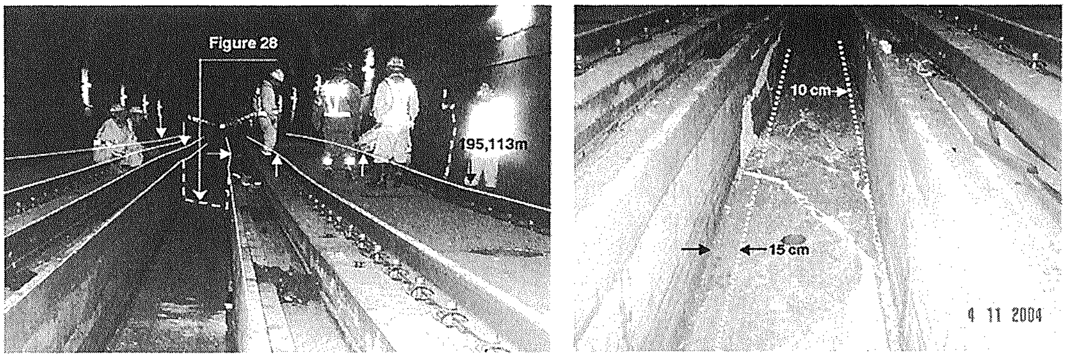



Fig. 22. Diagonal cracks on the tunnel slab showing right-lateral offset

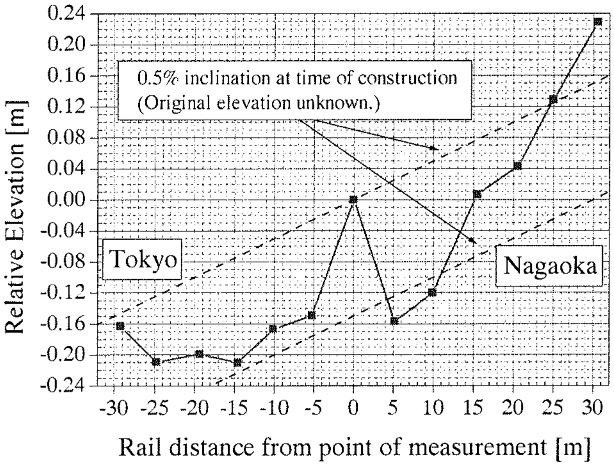



Fig. 23 Relative elevation of the down-traffic rail (origin = 195,070m from Tokyo)

Figure 23 shows the relative elevation of the rail measured with the help of laser range-meter, which was put on the high point in the damaged area about 10 meters south of downfallen concrete block (white arrows in Figure 21(b)). Buckling deformation of the rail slabs is clear from the figure. Between 0 and 5 meters there was a maximum vertical difference of 18cm compared to the 2 cm difference due to the 5% inclination at the time of construction.

Due to the tunnel depth at the damage location, the shallow landslides above the tunnel could have nothing to do with the damage. Most likely the tunnel was damaged due to a minor slip on a possible small fault segment crossing the tunnel and/or the overall horizontal compression due to movements of a nearby fault. This should have been responsible for the apparent shear plane failure pattern as shown in Figure 21(a).

## CONCLUDING REMARKS

Since underground facilities such as tunnels follow closely the motion of their surrounding soils, landslides and/or seismic faults can be major causes of their devastation. The October 23, 2004, Chuetsu Earthquake, followed by intense aftershocks in rapid succession, was responsible for a huge number of landslides. Shortly after the earthquake, researchers at the Japan Geological Survey quickly interpreted locations of total 1353 landslides in the Higashiyama mountain district from aerial photographs (Sato, et al., 2004), and there ought to be even more, which could not be detected from the photographs.

Most road tunnels in Higashiyama mountain district did not suffer any fatal cracking because most tunnels, excluding their mouths, were embedded in rather stable sedimentary rocks. No clear traces of landslides were seemingly found on soils surrounding Kizawa tunnel. However, cracks on the northern segment of Kizawa tunnel showed that the upper part of this segment was pushed about 10 cm down and 40 to 50 cm aside towards the mountainside steeply sloping east. Since the ring structure of the concrete lining sustains the surrounding soil pressure, this crack pattern seems a little serious.

It is expected that some landslides will probably be reactivated in the upcoming snow-melting time, and will cause some hidden problems to emerge. In restoring the destroyed road network, routs must be chosen carefully avoiding locations of high risk. For this, studying geological structures through a thorough investigation of the landslides that occurred in the affected district will certainly provide a good perspective. Cracks appeared on tunnel walls and road pavements are viewed as good strain gages showing how the surrounding soil were or are being deformed. Long-term observations of strain-buildup in the soil will be necessary at some key locations.

The cracks in the JR Uonuma tunnel for the Joetsu Shinkansen rapid trains showed a shear plane failure pattern indicating that the tunnel experienced axial compression. Most likely the tunnel was damaged due to a minor slip on a possible small fault segment crossing the tunnel and/or the overall horizontal compression due to movements of a nearby fault. Similar damage was found in the Wanazu Tunnel of the JR Joetsu line. Small fault segments in weak sedimentary rocks are often difficult to find in advance, and the damage to tunnels in the Chuetsu Earthquake poses us a difficult problem for constructing a tunnel through an active folding zone.

## ACKNOWLEDGEMENT

The authors' survey was a part of the reconnaissance by the Japan Society of Civil Engineers. The authors are grateful for all helps that JSCE has provided. The members are also grateful to Mr. Masaru Honda and Mr. Tomonari Kondo at the Division of Public Works, Niigata, Prefecture, and Mr. Mitsuru Shimizu, Stractural Technology Center, JR East, for providing the authors with necessary pieces of information about tunnels in Higashiyama mountain district and the JR Shinkan-sen Uonuma Tunnel.

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