Preliminary report of geotechnical and structural damage along the surface rupture in Nishihara Village caused by the April 16th, 2016 Kumamoto earthquake

Takaaki IKEDA[1], Kazuo KONAGAI[2] and Takashi KIYOTA[3]

[1]Member of JSCE, Professor, Dept. of Civil and Environmental engineering, Nagaoka University of Technology
(1603-1, Kami-Tomioka, Nagaoka, Niigata 940-2188, Japan)
E-mail: ikeda@vos.nagaokaut.ac.jp
[2]Fellow of JSCE, Professor, Institute of Urban Innovation, Yokohama National University
(Tokiwadai 79-1, Hodogaya-ku, Yokohama 240-8501, Japan)
E-mail: konagai@ynu.ac.jpp
[3]Member of JSCE, Associate Professor, Institute of Industrial Science, The University of Tokyo
(4-6-1 Komaba, Meguro-ku, Tokyo 153-8505. Japan)
E-mail: kiyota@iis.u-tokyo.ac.jp

Key Facts
・ Hazard Type: Earthquake
・ Date of the disaster: April 16th, 2016
・ Location of the survey: Nishihara village, Kumamoto, Japan
・ Date of the field survey; April 16th to 17th, and April 22th to 25th, 2016
・ Survey tools: GPS receiver
・ Key findings:
 1) Various kinds of structural and geotechnical damage were observed along the surface rupture that appeared along the recognized trace of Futagawa fault in Nishihara village.
 2) Status of damage to road bridges has a wide variation, such as fractures of bearing devices and shifts of bridge girders, etc. though there was no report of bridge fall.
 3) Slope failures and road settlements were observed at many locations along Futagawa fault line. Ground displacements as well as strong ground motions along the fault rupture must have been responsible for the damage.

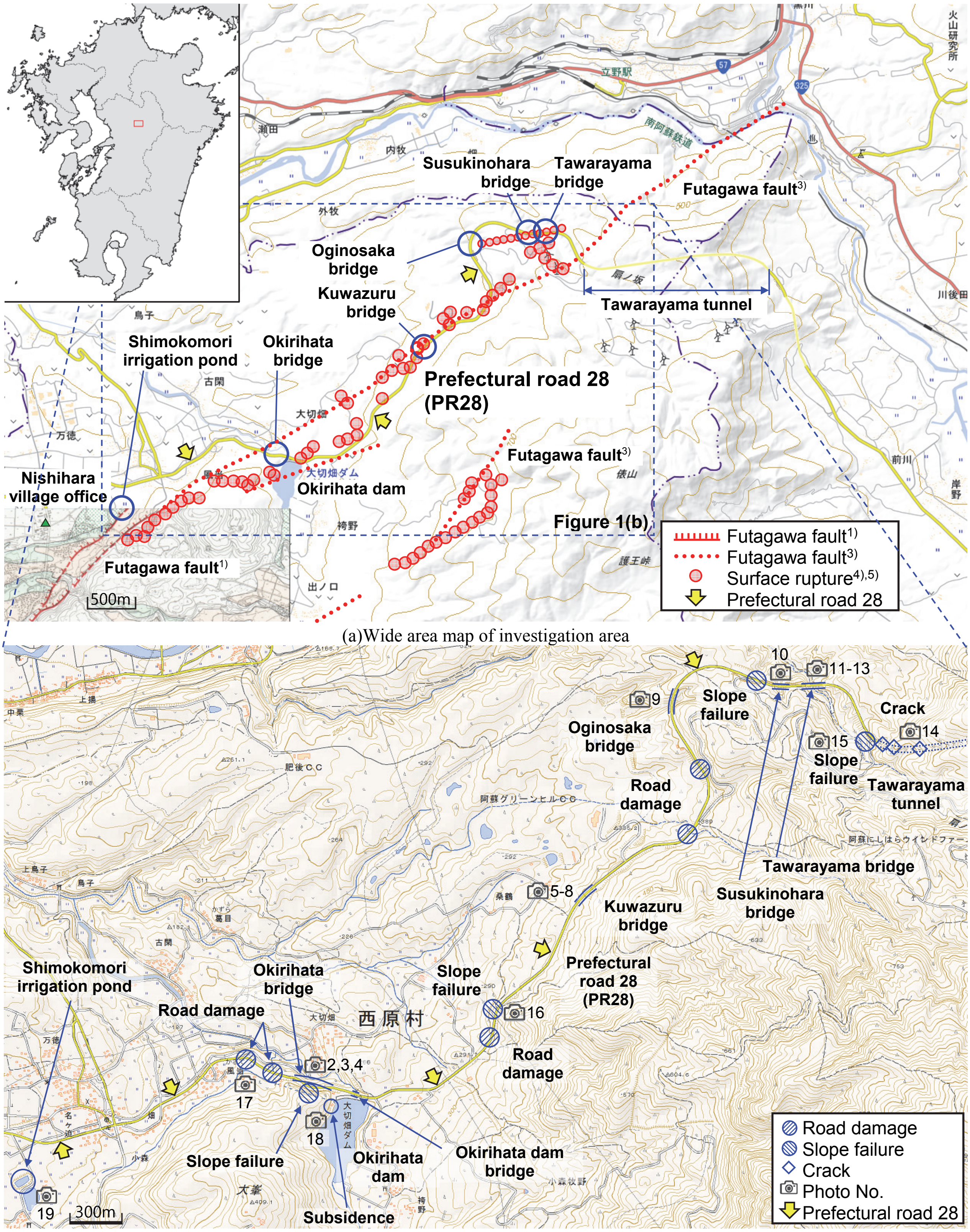
Key Words: *The 2016 Kumamoto earthquake, Surface rupture, Structural and Geotechnical damage, Prefectural road 28*

1. INTRODUCTION

On 14th April 2016, an inland crustal earthquake of Mw6.2 struck Kumamoto region of Kyushu Island. The earthquake generated strong ground motions near its source area. Seismic intensity 7 of the Japan Meteorological Agency (JMA hereafter) was recorded in Mashiki town in Kumamoto prefecture. Approximately 28 hours later of this Mw6.2 earthquake, an intense earthquake with Mw7.0 hit the affected areas, and JMA seismic intensity of 7 was observed again. The JMA named this series of earthquakes "The 2016 Kumamoto Earthquake".

It is considered from a CMT solution and aftershock distribution that the Mw7.0 earthquake and Mw6.2 earthquake were caused by ruptures of Futagawa and Hinagu faults, respectively. Surface ruptures appeared along the pre-recognized fault traces[1)]. Maximum right-lateral dislocation, about 2m, was observed at Dozono area in Mashiki town[2)].

The authors conducted a field survey in the affected area on 16-17th April and 22-24th April. This paper reports geotechnical and structural aspects of the damage observed along the surface rupture of Futagawa fault in Nishihara village. In this paper hereafter, the earthquakes of Mw7.0 and Mw6.2 are referred to as the mainshock and the foreshock, respectively.



(a)Wide area map of investigation area

(b)Detailed map of investigation area

Figure 1 Locations of geotechnical and structural damage along Prefectural Road 28. The base map on a scale of 1/25,000 is from the Geospatial Information Authority of Japan.[6)]

2. INVESTIGATION AREA

Figure 1 shows our survey locations in Nishihara village. Red broken lines and red dotted lines are the Futagawa fault traces shown in two published active fault maps[1), 3)]. Red-shaded circles are the locations of surface ruptures mapped by Geological Survey of Japan/AIST[4)] and Shirahama *et al.*[5)].

The Futagawa fault, which is considered to have been responsible for the mainshock, runs parallel to Prefectural Road 28 (PR28, hereafter) and not a small number of facilities were damaged along PR28. For the above reasons, we limited our survey to the swath along PR28.

3. DAMAGE TO ROAD STRUCTURE

Six bridges and a tunnel were found damaged along PR28. Blue-hatched circles in Figure 1 show locations of these investigated structures and slope failures. Table 1 shows the types and lengths of the investigated bridges.

(1) Okirihata bridge

Okirihata bridge is a gently curved 265m long 5-span continuous girder bridge, which runs EW direction and is convex northward. Photo 1 shows an aerial photograph of Okirihata area.

Photo 2 shows a damaged support bearing at the western end of the bridge. At this end, the bridge girders moved north in the transverse direction. The rubber bearings were detached at their upper or lower ends, and the bridge girders fell off the bearings.

Photo 3 shows a damaged support bearing at the eastern end of the bridge. The bridge girders hit the curtain wall of the abutment. Furthermore the bridge girders shifted sideways in the transverse direction and the rubber bearings were detached from both their pedestals and the bridge girders.

Total 20 bridge-fall-prevention cables connect the girders to both abutments. 19 of these 20 were found intact. These cables might have helped to limit the motions of girders in the transverse direction too. Photo 4 is the lower end of Pier No. 2. There were many flexural cracks on the surface. These cracks may have been caused by the strong ground acceleration.

Table 1 Investigated bridges

Name	Type*	Length	Span
Okirihata bridge	Continuous girder bridge	265m	5
Okirihata dam bridge	-	35m	1
Kuwazuru bridge	Cable-stayed bridge	160m	2
Oginosaka bridge	Continuous girder bridge	128m	4
Susukinohara bridge	-	43m	1
Tawarayama bridge	Continuous girder bridge	140m	3

* - : unknown

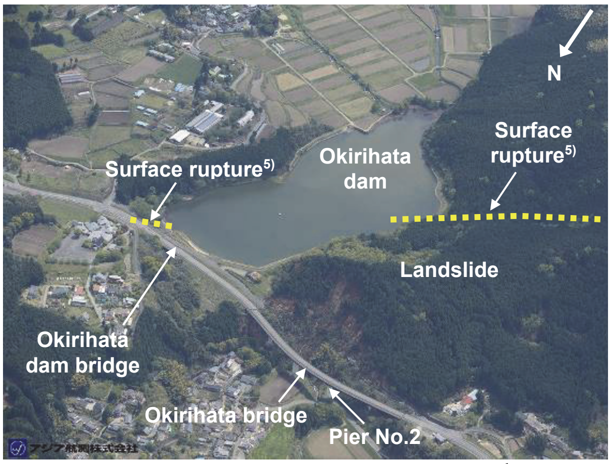


Photo 1 Aerial photograph of Okirihata area on 17th April 2016 (provided by Asia Air Survey Co., Ltd.).

Photo 2 Damaged support bearings at the western end of the Okirihata bridge. Bridge girders moved north in the transverse direction and fell down from their supports (32°50'33"N, 130°55'38"E).

Photo 3 Damaged support bearing at the eastern end of the Okirihata bridge. The bridge girders hit the curtain wall of the abutment and shifted sideways in the transverse direction (32°50'32"N, 130°55'47"E).

(2)Okirihata dam bridge

Okirihata dam bridge is located at the northeastern end of Okirihata dam (*see* Photo 1). Right-lateral ground offset appeared on the east side of the bridge. The bridge was thus compressed in its axial direction, however the damage to the bridge was not significant.

(3)Kuwazuru bridge

Kuwazuru bridge is a 160m long 2 span cable stayed bridge. The bridge is curved north. Photo 5 is the view of Kuwazuru brigde from south-west.

The bridge deck was pinned against the transverse beam of the X-shaped tower. The deck was detached from the tower and moved sideways to northwest. As the result, the entire deck moved apart from the southeastern incline column of the tower, and remained at rest getting much closer to the northwestern inclined column of the tower (*see* Photo 6).

The entire deck as a whole was found bent downward with its northeastern end touching the curtain wall of the northeastern abutment (Photo 7) while the other end was lifted up from the southwestern abutment as shown in Photo 8.

Surface ruptures showing right-lateral offset were found diagonally across the south-eastern approach of the bridge[6], suggesting that not only the intense ground shake but also the surface ruptures may also be responsible for the damage to Kuwazuru bridge.

(4)Oginosaka bridge

Photo 9 is a view of the Oginosaka bridge from its northern approach. The bridge is a 128m long 4 span continuous girder bridge. The bride is gently curved west. Rubber bearings support the bridge girders.

The bridge girders turned clockwise, which

Photo 4 Damaged bridge pier No.2 of Okirihata bridge. There were many flexural cracks on its south side (32°50’33”N, 130°55’41”E; provided by Mr. Takashi SATO).

Photo 5 View of Kuwazuru bridge from south-west. The bridge deck moved sideways to northwest (32°51’04”N, 130°56’43”E).

Photo 6 Deck of Kuwazuru bridge detached from its tower: The deck moved apart from the southeastern incline column of the tower, and remained at rest getting much closer to the northwestern inclined tower column (32°51’05”N, 130°56’45”E).

Photo 7 Damage at the northeast end of the Kuwazuru bridge. The bridge deck hit the curtain wall of the abutment (32°51’07”N, 130°56’46”E).

movement differed from those of the other bridges. Displacement in the transverse direction was measured to be about 30cm at the north end of the bridge. At the south end, the bridge girders collided against their stoppers, which were designed to limit the transverse displacements of the girders.

Surface ruptures appeared near east of the bridge[5)] (*see* Figure 1(a)). Because the surface ruptures extend towards the bridge the damage to the bridge might have been affected by the fault rupturing.

(5)Susukinohara bridge

Photo 10 shows the damaged abutment at the western end of Susukinohara bridge, a simple beam pre-stressed concrete bridge of 43m long.

At the western end, the abutment was cracked seriously because the bridge girders collided against the curtain wall of the abutment. At the other end, also, the bridge girders collided and slid up against the abutment curtain wall by about 10 cm.

(6)Tawarayama bridge

Tawarayama bridge is a 140m long 3 span continuous girder bridge. This bridge was found to be the most seriously damaged among all surveyed. At its western end, the backfill soil of the abutment has sunken seriously. Photo 11 shows the damage to the western abutment pier. The curtain wall of the abutment has been hit by bridge girders and gotten dented. Rubber bearings had been deformed in the longitudinal direction. The valley-side soil at the toe of the abutment has sunken and the heads of thick pile foundations of the abutment were exposed. Cracks have developed upright through the abutment.

Photo 12 shows the bearing sheet of the damaged abutment at the east end of the bridge. The curtain wall of the abutment was pushed by bridge girders

Photo 8 Damaged support bearing and abutment pier at the southwest end of the Kuwazuru bridge. The bridge decks moved apart from their supports (32°51’03”N, 130°56’43”E).

Photo 9 Oginosaka bridge: The bridge girder turned clockwise (32°51’47”N, 130°57’06”E).

Photo 10 Damage to abutment at the west end of Susukinohara bridge. The bridge girders collided against the curtain wall of the abutment (32°51’47”N, 130°57’29”E).

Photo 11 Damage to the western abutment of the Tawarayama bridge. The valley-side soil at the toe of the abutment has sunken and the heads of thick pile foundations of the abutment were exposed. (32°51’48”N, 130°57’47”E).

and inclined outward. The backfill soil was pushed by the abutment and sunken seriously. At this end of the bridge, bridge girders shifted sideways in the transverse direction. Rubber bearings were detached from both the bearing sheet and girders. As the consequence, the girders fell down onto the bearing sheet. However anti-falling cables helped the ends of girders to stay on the bearing sheet.

The damage to the both abutments suggests that both abutments moved toward each other eventually pushing the girders. The steel girders were thus bent upwards, and their flanges were buckled as shown in Photo 13.

Surface ground ruptures were found diagonally crossing the bridge[6]. So it is thought that movement of both abutments were caused by the fault rupture induced right-lateral surface displacement.

(7) Tawarayama tunnel

Tawarayama tunnel was constructed by NATM method and completed in 2002. Its total length is 2,057m. We investigated its western 300m stretch. Diagonal cracks appeared on both sidewalls of lining concrete at the 45-50m distance from the western tunnel mouth (Photo 14). Large chunks of concrete came off the lining joint at the 100-120m and 250m distances from the western tunnel mouth. Photo 15 shows a damaged embankment of the western approach to the tunnel.

4. GEOTECHNICAL DAMAGE

Various kinds of damage to earthen structures and natural slopes were seen along the Prefectural Road 28. This chapter summarizes geotechnical aspects of damage observed in this survey.

(1) Roads

PR28 (yellow line in Figure 1(a)) was constructed

Photo 12 Bearing sheet of the damaged abutment at the east end of the Tawarayama bridge. The curtain wall of the abutment was pushed by bridge girders and inclined outward (32°51’47”N, 130°57’41”E).

Photo 13 Buckled bridge girders of the Tawarayama bridge. A huge compressional force might be applied to the bridge girders (32°51’46”N, 130°57’37”E).

Photo 14 Damage of lining concrete at the Tawarayama tunnel. Diagonal cracks were appeared on the both side of lining concrete.

Photo 15 Slope failure at the western approach to the tunnel. (32°51’40”N, 130°57’48”E).

along scarps of the Futagawa fault by cut and fill. Many embankment sections suffered settlements of fill materials associated with cracks and offsets of pavement. The observed features of structural and geotechnical damage may have been affected by the strong ground motion and surface rupturing which appeared near damaged sites. Photos 15 and 16 show damage to embankment slopes. Photo 17 shows a damaged aqueduct embedded along the road. Joints in the aqueduct had become disconnected due to the uneven ground deformation, and huge amount of water was spouting out.

(2) Slope (Landslide)

A large landslide occurred south behind Okirihata bridge (Photo 1) Surface ruptures appeared in the mountain at south side of the landslide[5)]. The distance between the landslide and the surface ruptures were more than 200m. It is thus suggestive that the landslide was affected by the strong motion not fault rupturing.

(3) Okirihata dam

Okirihata dam is an earth-fill dam for agricultural irrigation originally constructed in 1865 during the Edo period. It was later greatly repaired in 1975. Photo 1 shows a bird-eye view of Okirihata dam.

The fact that some large facing stones of Okirihata dam have moved about 30cm off their original locations suggests that the dam has experienced strong ground motions. The crest of the dam has sunken (Photo 18) and its concrete spillway structure was cracked and deformed. No clear evidence of water leakage was visible.

(4) Shimokomori pond

Shimokomori pond is a small irrigation pond

Photo 16 Slope failure of an embankment for Prefectural Route 28 between the Okirihata bridge and the Kuwazuru bridge (32°50’44”N, 130°56’24”E).

Photo 17 Break of the aqueduct by the subsidence of the road (32°50’37”N, 130°55’25”E).

Photo 18 Subsidence of the embankment at the Okirihata dam. The concrete spillway was cracked and deformed but no clear evidence of water leakage was visible. (32°50’30”N, 130°55’49”E).

Photo 19 Damage of the Shimokomori pond. A small section of its north bank was breached in the earthquake and water flowed into the lower terrace of rice field (32°50’30”N, 130°55’14”E).

behind an earth-fill dam. A small section of its north bank was breached in the earthquake and water flowed into the lower terrace of rice field (Photo 19). Shimokomori pond is located on the extension of the recognized Futagawa fault trace. However, the relation between this breaching and the fault movement is not clear because the surface ground rupture died out before reaching this pond.

5. STRONG GROUND MOTION RECORD

Strong ground motions of mainshock and foreshock were recorded at Nishihara village office about 2.5km west of Okirihata bridge[7]. Figure 1 shows the location of Nishihara village office.

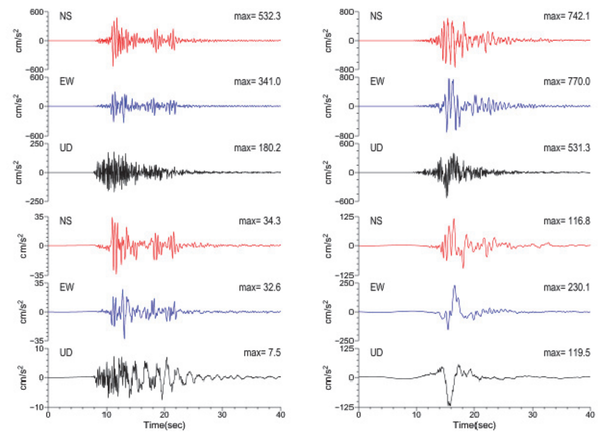
Table 2 shows three orthogonal components of the peak ground acceleration (PGA, cm/s^2) and peak ground velocity (PGV, cm/s). Time histories of the ground acceleration were Fourier-transformed and integrated in the frequency domain. Then the obtained spectra were bandpass-filtered (0.1-10.0Hz), and Fourier-inverse-transformed to get waveforms in the time domain. Figure 2 shows the acceleration and velocity waveforms of the mainshock and the foreshock. Durations of the mainshock and the foreshock were about the same with each other. However, the PGA and PGV of the mainshock were much greater than those of the foreshock. In particular, the velocity waveform of the mainshock shows a clear pulse with its predominant period of about 3.0s. The PGV of the EW component of the velocity was larger than 200cm/s. The clear pulse may be attributed to the strike-slip faulting of Futagawa fault.

Figure 3(a) shows the obtained acceleration response spectra for the foreshock and mainshock assuming the damping factor of 0.05 and seismic regional coefficient c_z of 0.85. Broken line in each figure shows the seismic design spectrum of the Level 2 earthquake ground motion for the ground classification II[8]. The response spectrum for the foreshock is generally smaller than the seismic design spectrum except for the period range of about 0.2 to 0.5 s. On the other hand, the response spectrum of the mainshock exceeds the seismic design spectra over a wide range of period. Figure 3(b) shows pseudo velocity response spectra. The response spectrum of lateral motion for the mainshock has clearly two predominant periods of about 0.8 s and about 3.0 s.

This indicates that the damaged road bridges may have experienced considerably large seismic loads exceeding the design load.

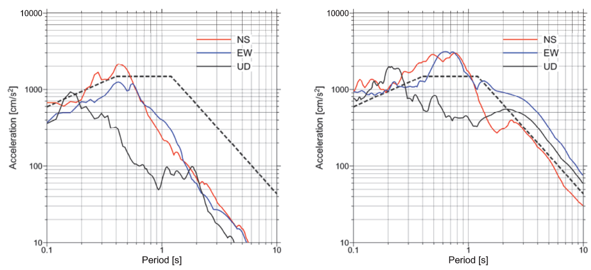
Table 2 PGAs and PGVs of the observation records at Nishihara village office.

		Component		
		NS	EW	UD
Mainshock	PGA(cm/s^2)	742.1	770.0	531.3
(Mw7.0)	PGV(cm/s)	116.8	230.1	119.5
Foreshock	PGA(cm/s^2)	532.3	341.0	180.2
(Mw6.2)	PGV(cm/s)	34.3	32.6	7.5



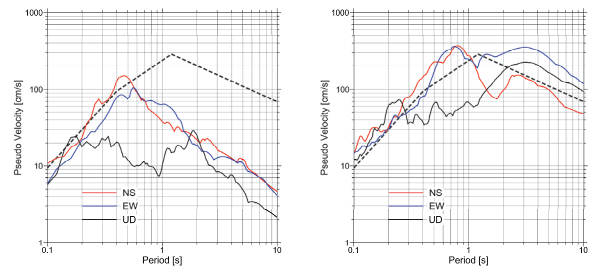
Foreshock(Mw6.2) Mainshock(Mw7.0)

Figure 2 Waveforms of strong ground motion at Nishihara village office during mainshock and foreshock.



Foreshock(Mw6.2) Mainshock(Mw7.0)

(a) Acceleration response spectra



Foreshock(Mw6.2) Mainshock(Mw7.0)

(b) Pseudo velocity response spectra

Figure 3 Response spectra of ground motion at Nishihara village office with damping factor 0.05. Broken lines indicate seismic design spectrum that was considering seismic regional coefficient (c_z=0.85) on the ground of Class II for level 2 ground motion for a crustal earthquake (Specifications for highway bridges).

6. SUMMARY

Many kinds of damage to earthen, concrete and steel structures were found along Prefectural Route 28 in Nishihara village, which route was constructed along the scar of Futagawa fault system activated in the main shock of the Kumamoto Earthquake of 2016. One of the noteworthy features of the main shock observed at Nishihara village office, was that the time history of the ground velocity exhibited a large and clear pulse with its predominant period of about 3.0s. Moreover, surface ruptures were observed at many locations along Futagawa fault trace. Therefore, not only the intense ground motion but also large ground deformations built up along the fault trace may have been equally responsible for the damage to road bridges and a tunnel along PR28. The foreshock with Mw6.2 occurred two days before the mainshock. However, it seems to have had less significant effects on damage to these facilities.

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