# DETAILED NEAR SURFACE GEOPHYSICAL SURVEY AT AN AREA STRICKEN BY THE 2016 KUMAMOTO EARTHQUAKES

*INAZAKI Tomio, Public Works Research Institute, Tsukuba, Japan*
*KISANUKI Hiroshi, Public Works Research Institute, Tsukuba, Japan*
*OGAHARA Takanori, Public Works Research Institute, Tsukuba, Japan*
*ONISHI Kyosuke, Public Works Research Institute, Tsukuba, Japan*

## Abstract

We conducted a detailed near surface geophysical survey at Mashiki Town, Kumamoto Prefecture, western Japan, where was severely damaged by the 2016 Kumamoto twin earthquakes of magnitudes 7.3 as the mainshock and 6.4 as a foreshock. The near surface survey comprised "Hybrid Surface Wave Survey" (HSWS), capacitively coupled resistivity (CCR) measurement using OhmMapper, and GPR measurements using Utility Scan DF or 350 HS tools. A total of 5 short survey lines were set to intersect a branched surface rupture, or placed in the downtown area of Mashiki Town. The purposes of the survey were to assess the usefulness of the above geophysical methods for the delineation of near-surface conditions of such earthen structures as levees and road embankments attacked by strong earthquakes, and to provide high-resolution subsurface profiles of the sites where surface structures were sporadically damaged. Notable results of our study were as follows. First, GPR successfully imaged detailed structures on the surficial zones form 2 m to in case to 5 m in depth. It was characteristic that a number of step-like sharp dislocations were identified around the surface rupture. Layered resistivity structures, concordant with inferred geological structure of the area, were imaged by CCR surveys up to 10 m in depth. HSWS, recently proposed by the authors, reconstructed S-wave structures up to 40 m in depth. In addition, HSWS records were processed through an ordinary seismic reflection data processing flow. As a result, reverse faulting structure was clearly imaged in concordance with the other near-surface survey results.

## Introduction

The 2016 Kumamoto earthquakes, which were featured as twin shallow earthquakes sequentially occurred on April 14 (foreshock) and 16 (mainshock) at 28 hour intervals, caused severe damage to housing in Mashiki Town, close to the epicenters of the earthquakes (JMA 2016). Twenty-seven percent of wooden houses built in the downtown Mashiki was judged as "completely collapsed" or "heavily damaged" by "one-by-one" visual inspection (Sugino, et al., 2016; NILIM, 2016). In addition, many authors reported that collapse of wooden houses concentrated in an irregular shaped "heavily damaged zone" of 500 m wide and 2 km long in the downtown (Kawase, et al., 2017; Moya, et al., 2017). It was also notable that the earthquakes generated 40 km long active faults along the Futagawa and Hinagu fault zones and a 4 km long branched surface rupture at the epicenter of the mainshock (Lin, et al., 2016; Shirahama et al., 2016). A number of topographic and seismological investigations were also carried out in and around Mashiki Town to try to explain the relationship between house damage and surface topographic features. Regretfully, they were too superficial, or too deep or too sparse to interpret the influence of near surface effects. MLIT (2017) conducted a dense near surface geophysical survey accompanied with geotechnical drilling in the heavily damaged zone. However, they misinterpreted the geophysical survey results due to adoption of inappropriate survey and processing parameters. We then carried out a detailed near surface geophysical survey to demonstrate usefulness of geophysical survey methods and importance of survey settings to obtain reliable geophysical sections of the near surfaces.

## Study Site and the Outline of Field Survey

### *Study Site*

The study site we conducted the detailed near surface geophysical survey was located in Mashiki Town, Kyushu Island, western Japan. **Figure 1** depicts survey lines and the surface ruptures associated with the 2016 Kumamoto earthquakes. A total of 5 short survey lines were set to intersect a branched surface rupture from the main ruptures which occurred along the known active fault named Futagawa fault. Both ruptures showed right-lateral strike slip displacements of about 50-100 cm with slight uplift of southern side. The surface ruptures were described by topographical field investigations (Shirahama et al., 2016; Sugito, et al., 2016) but also traced clearly from aerial photographs taken after the earthquakes. It is characteristic that both ruptures extend to divide a wedge-shaped lowland where Kiyama and Akitsu River flow through. Northern upland, on which downtown Mashiki develops, is formed by pyroclastic deposits flowed from Aso Volcano. Surface topography of the upland is even and incised by shallow gully, but slightly dips southwestward.

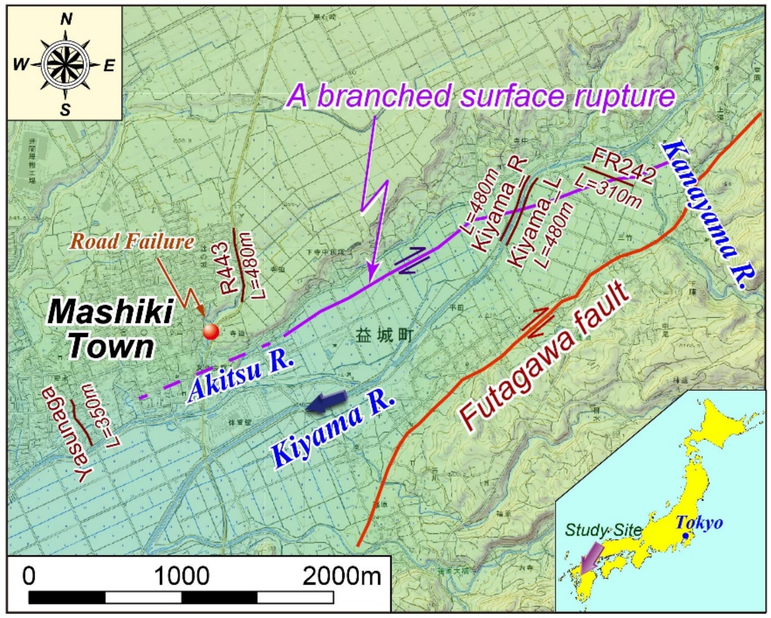


**Figure 1.** A map showing survey lines set to intersect a surface rupture and the Futagawa fault both associated with the 2016 Kumamoto earthquakes.

**Table 1.** Survey items and parameters employed for the detailed geophysical survey at the study site.

| Line / Parameters | FR242 | Kiyama_R | Kiyama_L | R443 | Yasunaga |
|---|---|---|---|---|---|
| Line Length | 310 m | 480 m | 480 m | 480 m | 340 m |
| *Employed Method* | | | | | |
| **Hybrid Surface Wave Survey** | | | | | |
| No. of Channel | 240 | 240 | 240 | 240 | 120 |
| Recording System | | | DAS-1 x2 | | |
| Geophone | | | GS-11D ($f_0$-4.5Hz) | | |
| Geophone Spacing | 1 m | 2 m | 2 m | 2 m | 2 m |
| Active survey # | 301 | 232 | 148 | 136 | 349 |
| Sampling Rate | | | 0.5 ms | | |
| Source | | | Extra-large Wooden Hammer | | |
| Shot Interval | 2 m | 4 m | 4 m | 4 m | 2 m |
| Passive survey # | 57 | 42 | 26 | 30 | 53 |
| Record Length | | | 32.8 sec | | |
| **Capacitively Coupled Resistivity Survey** | | | | | |
| Used Tool | | | OhmMapper | | |
| Dipole Length | | | 2.5/5.0/10.0 m | | |
| No. of Active Lines | 7 | 14 | 8 | 7 | 9 |
| **GPR Survey** | | | | | |
| Used Tool | | | Utility Scan DF/350 HS | | |
| No. of Scanned Lines | 13/8 | 0/17 | 0/14 | 15/8 | 5/14 |

### *Outline of the Field Survey*

As shown in **Fig. 1**, we deployed 2 survey lines along Kiyama River, and one along an embanked highway (R443), part of which was collapsed during the foreshock. We located Yasunaga line in the downtown to intersect an inferred extension of the branched rupture. FR242 line was located near the eastern end of the rupture. Employed methods were "Hybrid Surface Wave Survey" (HSWS), the authors originally proposed (Inazaki, et al., 2015), capacitively coupled resistivity (CCR) measurements using OhmMapper, and GPR measurements using Utility Scan DF or 350 HS tools. A total of 240 geophones were placed along a survey line at 1 or 2 m intervals. We used 2 set of seismograph (DAS-1) for HSWS. Sampling rates were 0.5 ms for active survey and 2 ms for passive survey. Dipole lengths were set to 2.5, 5, 10 m, and the electrode separations were from 0.5 to 3 in CCR measurements.

## Survey Results and Interpretation

**Figure 2** is a typical GPR depth section along the line crossing the surface rupture. Surficial structure up to 3m or more was imaged using GPR. With the aid of RTK-GNSS positioning system, we could precisely locate each GPR trace (usually 1 cm intervals) position within 1 cm in horizontal and 2 cm in vertical accuracies. As clearly depicted in **Fig. 2**, levee's surface significantly bent at the point where the survey line intersects the surface rupture. Moreover, a reflection (*ca*. 25 m) from the bottom of levee showed a flexural deformation. It indicated that the rupture was associated with hinge faulting of right (SSE) side along with right-lateral strike slip displacements. Because banking works were conducted recently (Ca. 60 years ago), the observed deformation in the levee body was presumed to be juvenile caused by active faulting associated with the earthquakes.

**Figure 3** compares other depth sections along the 480 m long Kiyama_R line. The top one is a resistivity section, imaging up to 15 m deep reconstructed from OhmMapper data (vertical exaggeration ratio is 2). As seen, a thin relatively high resistivity layer covered the surface underlain by thick relatively low resistivity layers. The middle section delineates an S-wave velocity structure derived from HSWS data (vertical to horizontal ratio is 1). Owing to the

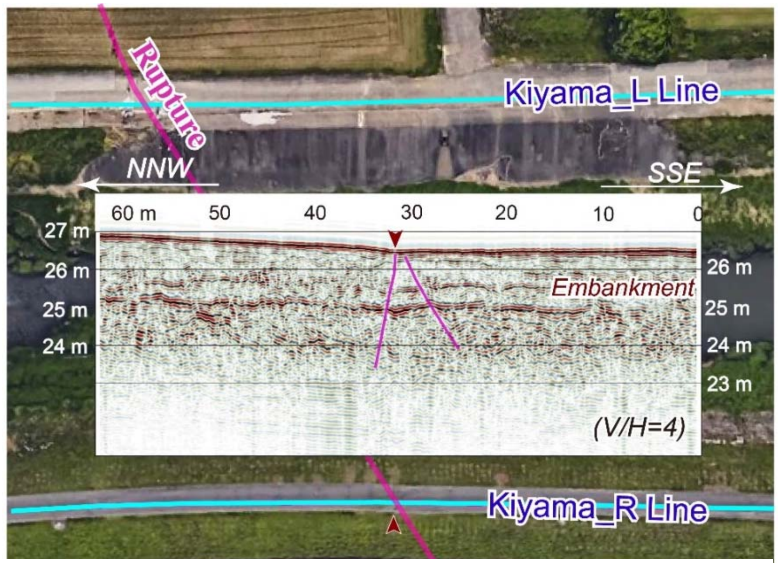


**Figure 2.** A part of GPR depth section along Kiyama_R line. Note that surface and the bottom of embankment are bending at a point (red triangle) where the line intersects the surface rupture.

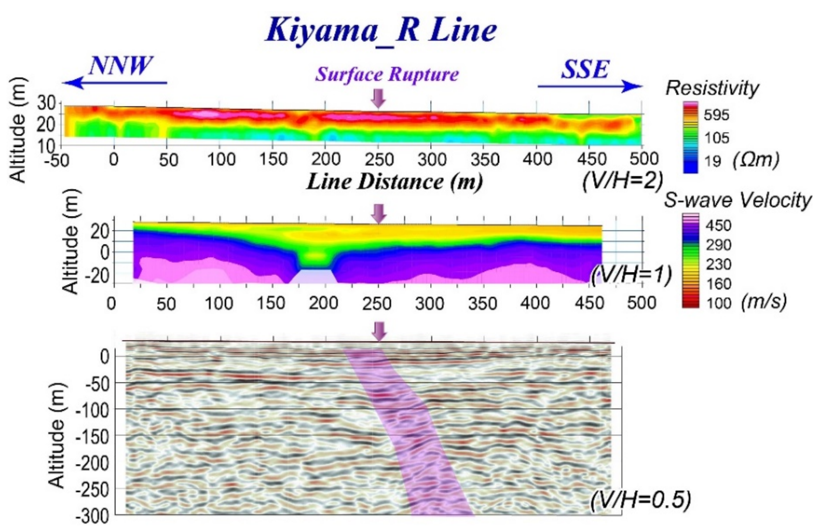


**Figure 3.** Depth sections along Kiyama_R line; Resistivity (top), S-wave velocity (middle), and a migrated P-wave seismic reflection depth section (bottom) reconstructed from HSWS records.

advantages of the HSWS method, we could reconstruct a velocity structure up to 50 m in depth. It is characteristic that a 50 m wide low velocity zone appeared at 200 m in line distance. This was interpreted as a buried meandering channel of old Kiyama River not as a low velocity zone associated with faulting, based on an aerial photogrammetric analysis.

Bottom is a migrated depth section reconstructed through P-wave seismic reflection processing for HSWS records. Owing to dense setting of geophones and shot points, we could obtain a high-resolution reflection section which successfully delineated a right side upthrown (reverse faulting) flexure structure showing cumulative displacements beneath the surface rupture. The reconstructed structure beneath the surface rupture strongly indicated that it was an active fault repeatedly dislocated the subsurface layers.

**Figure 4** is an S-wave velocity section along Yasunaga Line, placed in the "heavily damaged zone" in the downtown Mashiki. HSWS data processing enabled to provide relatively deep section compared with conventional active surface wave survey. We could image a layered structure up to 35 m deep. Note that thick low velocity layer appeared at the southern (right) part of the line, or the lowland around Akitsu River (**Fig. 1**). In contrast, heavily damaged houses were concentrated at the northern part (left side) of the line where the surface Vs was not so low. This strongly indicated that the surface Vs structure was not the primary cause of the house damage. It is possible that existence and types of foundations affected the seismic stability of wooden houses.

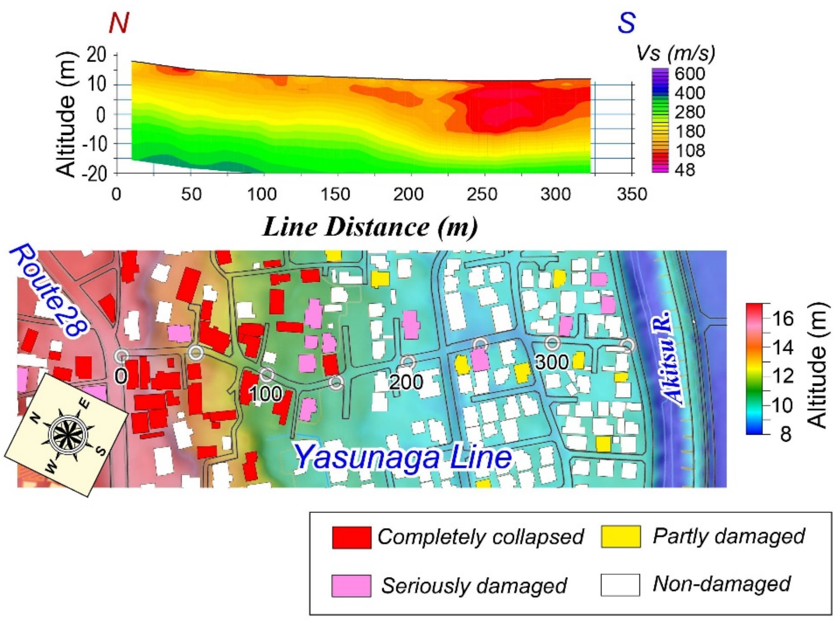


**Figure 4.** S-wave velocity structure (upper) and a survey line map (lower) of Yasunaga Line. Damage of each wooden house around the line was classified into 4 grade based on "street view" of Google Maps.

## Conclusions

We demonstrated that tuned near surface geophysical survey could delineate and characterize the near surface structure of a site where the 2016 Kumamoto earthquakes struck. Employed methods comprised Hybrid Surface Wave Survey, CCR measurement, and GPR survey. A total of 5 short survey lines were set in the site intersecting a branched surface rupture which occurred associated with the earthquakes. Notable results of our study were as follows. First, GPR aided by RTK-GNSS positioning system successfully imaged not only detailed structures on the surficial zones form 2 m to in case to 5 m in depth but also surface topographic displacements. A number of step-like sharp dislocations were identified around the surface rupture. Layered resistivity structures imaged by CCR surveys were concordant with inferred geological structure of the area, but it kinked around the rupture. HSWS reconstructed S-wave structures up to 50 m in depth, and identified similar bending structure around the rupture, indicating a southern side upthrown (reverse faulting) flexure structure. S-wave velocity section along a survey line placed in a heavily damaged zone delineated that low velocity layers extended around lowland part of the line. On the other hand, damaged houses concentrated at a hillslope where S-wave velocities were not so low. Thus, detailed geophysical surveys were helpful to understand relationship between surficial deformations or housing damage and geophysical properties of the near surface.

## Acknowledgements

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## References

Inazaki, T., and Kisanuki, H. (2015.09): Hybrid surface wave surveys along operational highways, *Proceedings of the 133rd SEGJ Conference*, 109-112. (*in Japanease with English Abstract*)

JMA (Japan Meteorological Agency), (2016): The 2016 Kumamoto Earthquake – Portal-: http://www.jma.go.jp/jma/en/2016_Kumamoto_Earthquake/2016_Kumamoto_Earthquake.html CMT solutions of the earthquake

Kawase, H., Matsushima, S., Nagashima, F., Bao Y. and Nakano, K., (2017): The cause of heavy damage concentration in downtown Mashiki inferred from observed data and field survey of the 2016 Kumamoto earthquake, *Earth, Planets and Space*, 69, 11p.

Lin, A., Satsukawa, M., Wang, Z., Mohammadi Asl, R., and Nakajima, F., (2016): Coseismic rupturing stopped by Aso volcano during the 2016 Mw 7.1 Kumamoto earthquake, Japan, *Science*, 354(6314), 869-874.

MLIT (Ministry of Land, Infrastracture, Transport and Tourism), (2017): Final report on safety measure of reconstruction works for downtown Mashiki from 2016 Kumamoto Earthquake disaster, 58p. (*in Japanease*) . http://www.mlit.go.jp/report/press/toshi08_hh_000034.html

Moya,L., Yamazaki, F., Liu, W. and Yamada, M. (2017): Detection of collapsed buildings due to the 2016 Kumamoto, Japan, earthquake from Lidar data, *Natural Hazards and Earth System Sciences*, https://doi.org/10.5194/nhess-2017-186

NILIM (National Institute for Land and Infrastructure Management), (2016): Quick report of the field survey on the building damage by the 2016 Kumamoto earthquake. *NILIM Technical Note*, No. 929.

Shirahama, Y., Yoshimi, M., Awata, Y., Maruyama, T., Azuma, T., Miyashita, Y., Mori, H., Imanishi, K., Takeda, N., Ochi, T., Otsubo, M., Asahina, D., and Miyakawa. A., (2016): Characteristics of the surface ruptures associated with the 2016 Kumamoto earthquake sequence, central Kyushu, Japan, *Earth, Planets and Space*, 69, 12p.

Sugino, M., Yamamuro, R., Kobayashi, S., Murase, S., Ohmura, S., and Hayashi, Y., (2016): Analyses of Building Damages in Mashiki Town in the 2016 Kumamoto Earthquake, *Journal of Japan Association for Earthquake Engineering*, 16, 69-83. (*in Japanese with English abstract*)

Sugito, N., Goto, H., Kumahara, Y., Tsutsumi, H., Nakata, T., Kagohara, K., Matsuta, N. and Yoshida, H., (2016): Surface fault ruptures associated with the 14 April foreshock (Mj 6.5) of the 2016 Kumamoto earthquake sequence, southwest Japan, *Earth, Planets and Space*, 69, 8p.