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Landslide monitoring by using ground-based millimeter wave radar system

T. Deguchi, T. Sugiyama, and M. Kishimoto
Nittetsu Mining Consultants Co., Ltd., Tokyo, Japan

ABSTRACT: The authors are currently developing ground-based radar system using millimeter wave. It is ultimately aimed to establish technologies that will allow us to monitor the slope stability and aging infrastructures. Our group has adopted 76 to 77 GHz band, which is internationally recognized as a collision prevention technology for automobiles. And this wave band is capable of transmitting radio waves approved by the regulatory authorities. In field tests, this radar was verified to detect targets remotely from a distance of about 1.6 km and to measure displacement with an accuracy of about 0.2 mm. In a long-term demonstration test conducted inside an open-pit mine, the radar-collected data clearly captured the precursor phenomena before the slope failure. The radar also successfully detected anomalies corresponding to consolidation subsidence of sediment deposited after the slope failure.

Keywords: ground-based radar; millimeter wave; slope failure; precursor phenomena

1 INTRODUCTION

The development of automobiles equipped with various sensors is underway for the purpose of automatic and safe driving of the vehicle. The millimeter wave radar, which is adopted as one of these in-vehicle sensors, has a longer target detection distance than a laser or infrared sensor. Moreover, it can be used regardless of day and night and has all-weather features that can be used without being affected by rain or snow.

The authors developed the slope stability monitoring system by applying the technology of millimeter wave radar to the steep rock slope inevitably formed inside the open pit mines. From the performance evaluation test of the radar, it was verified that the remote detection distance can be about 1.6 km and the displacement measurement accuracy can be 0.2 mm. In the long-term demonstration test, the precursor phenomenon of the slope failures actually occurred and the consolidation subsidence phenomenon of the deposited sediment were clearly detected.

2 OUTLINE OF MILLIMETER WAVE RADAR SYSTEM

For the purpose of monitoring the displacement amount of the slope with high accuracy, measuring methods using an extensometer or a tiltmeter have been applied conventionally. Recently, active utilization of GNSS (Global Navigation Satellite System) has advanced. However, these measurement methods are only capable of acquiring pointwise information at the site where these equipments are installed.

The monitoring system of the millimeter wave radar developed by the authors is installed at a certain distance away from the target (slope or infrastructure) and constructs observation routine by remote sensing technology. The radar device rotates in both the horizontal and vertical directions. The system can acquire 2-D images without contacting the target object while repeatedly transmitting and receiving millimeter waves when rotated on a stage installed on a base such as a tripod.

Figure 1. Appearance of ground-based millimeter wave radar.

Table 1. Specifications of millimeter radar device

Frequency	76.5 GHz
Wavelength	3.92 mm
Band width	1 GHz (adjustable)
Modulation	FM-CW
Radar system	Real aperture
Antenna type	Cassegrain (20 cm)
Antenna power	10 mW (10 dBm)
Antenna gain	40 dBi
Range resolution	0.30 m
Azimuth resolution	1.23 degree
A/D converter	16 bits
Weight	10 kg
Accuracy of displacement	less than 0.2 mm

In this system, the signal reflected on the slope and returned to the radar antenna is recorded as a complex number composed of intensity and phase. Since the information on the relative distance between the slope and the antenna is stored in the phase information, it is possible to measure the displacement amount of the slope by tracking the temporal change of the phase information recorded at the same antenna position. Such a technique is known as "interferometry" surveying methodology, and about one tenth to one twentieth of the wavelength is evaluated as a displacement measuring accuracy. Since this system transmits and receives radio waves in the millimeter wave band, displacement measurement capability of sub millimeter can be expected.

According to the Japanes Radio Law, the radar using millimeter waves in the 76 to 77 GHz band can be used without the radio station opening and statutory qualification acquisition under these conditions; (1) the antenna power is 10 dBm or less, 2) the bandwidth is 1 GHz or less, 3) the antenna gain is 40 dBi or less. As a result, it is possible to easily install a radar station that can freely transmit radio waves.

3 PERFORMANCE EVALUATION TEST

3.1 Evaluation test on the remote detection distance

Our radar system performs the absolute distance measurement to the target by the conventional FM-CW method. By giving the azimuth angle and the elevation/depression angle to the measured distance value, it is possible to give geographic information to a 2-D image and project it on a map.

Figure 2 shows the one example of the evaluation test about the remote detection distance performed inside the limestone open pit mine. The strong and weak reflection signals are displayed in white and black respectively. From

Figure 2, it is possible to understand the result of receiving a strong reflection signal from the slope which is about 1.6 km away.

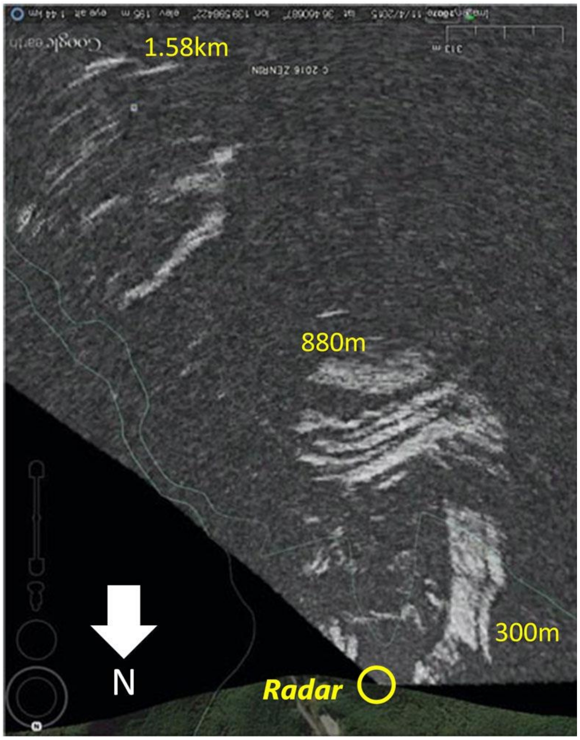

Figure 2. The power image acquired inside the limestone open pit mine.

3.2 Evaluation test on the displacement measuremant accuracy

Figure 3 shows the results of verifying the displacement measurement accuracy using a corner reflector (CR). The amount of displacement recorded by this radar system was graphed when moving CR horizontally by 0.3 mm in the direction toward the radar side. It was easily understood that the measurement record indicated by the red solid line properly had tracked the true movement of CR indicated by the black solid line. In addition, the blue solid line is a record that measured stable rock slope, the result that fluctuates around zero is appropriate. The 3σ value of measurement error was calculated as 0.2 mm for CR and 0.1 mm for the stable rock slope, and the results with displacement measurement capability at sub-millimeter were verified.

However, regarding as the long-term observation in the field, errors are liable to occur in displacement measurement results due to nonuniformity of the water vapor layer distributed in the atmosphere and its time variation. Moreover, attenuation of millimeter waves becomes large against heavy rain or snowfall, so it is necessary to consider that the SN ratio decreases.

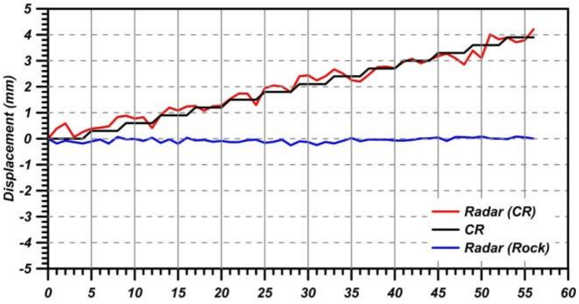

Figure 3. The result of evaluation test on the displacement accuracy by using the corner reflector.

4 CASE STUDY OF SLOPE FAILURE DETECTION

Small-scale slope failure occurred in the field test conducted inside the open pit mine for about 7 months in Japan. A radar device was installed on a hill 350 m away from the slope. In this observation, the rotation range in the horizontal direction was set to 72 degrees and the rotation range in the vertical direction was to 18 degrees. Approximately 25 minutes was required for one data acquisition, and about 60 images per day was recorded.

The photographs in Figure 4 show the slope before and after the slope failure occurred. The 3-D image in Figure 5 (a) displays the displacement measurement results recorded over the course of about one month before the slope failure. The green shading in the figure indicates no change, warm colors indicate displacement toward the radar, and cold colors indicate displacement away from the radar. Warm color and cold color anomalies are clearly detected in pairs in the frame surrounded by the solid black line. No slope failure has yet occurred at this stage, so the precursor phenomena might be captured. The average displacement velocity was approximately 4 mm/day.

(a) before slope failure

(b) after slope failure

Figure 4. Pictures before and after slope failure.

From this measurement result we infer that as the surface layer gradually moved toward the bottom of the slope, the volume at the lower part increased, which was detected by the system anomalously as displacement toward the radar. Likewise the system anomalously detected the decrease in the volume of the upper part as displacement away from the radar. The cumulative displacement of the precursor phenomena exceeded 30 mm, though it might have been undetectable by the naked eye without careful observation.

A displacement amount that occurring as a precursor phenomenon is difficult to verify quantitatively. The verification data itself is impossible to acquire, as nobody can know the location and time of a slope failure in advance. Conversely, we can conclude that only such a radar system capable of visualizing the minute surface displacement in space-time coordinates can reach such a result.

Figure 5 (b) shows the results of the displacement measurements taken for about 2 weeks after the slope failure occurrence due to the landslides. We can also detect an anomaly in which warm and cold colors are paired, in the area framed by the black broken line. This anomaly falls somewhat below the place where the slope failure occurred. The accumulated sediment is most likely displaced in the subsiding direction with time in the initial stage immediately following the slope failure. We can therefore infer that the consolidation subsidence of the accumulated sediment is measured.

In Figure 6, the plan view of the area where the precursor phenomenon of the slope collapse was detected in Figure 5 (a) was enlarged and displayed. This is a diagram showing the cumulative amount of displacement until the slope collapse every 5 days. It is possible to easily recognize the appearance of warm color anomalies extending from the center of each image over time. In addition, a cold-colored anomaly gradually expanding on the east side (corresponding to the upper part of the slope) is captured clearly.

5 SUMMARY

Our group has developed a ground-based radar system with the aim of constructing a technology to monitor minute displacements of mining slopes and infrastructure buildings by remote sensing techniques. The verification test described in this paper, along with a number of other tests repeatedly performed, have confirmed that high-precision minute deformation measurements can be continued over an extended period of time. Most persuasively of all, our system has clearly visualized the precursor phenomena of an actual slope failure and the behavior of the ground surface presumed as consolidation subsidence of sediment in space-time coordinates.

In future work we will consider a method of correcting the phase delay due to water vapor. We also plan to develop a function to issue slope failure alerts in advance by applying techniques to detect tertiary creep. This may make it possible to update to a system that can objectively evaluate the risk of slope failure.

Finally, in this paper, we do not clearly indicate the place and the timing of the field examination. Regarding this point, for the convenience of confidentiality obligation, we would like you to understand unavoidable steps.

6 ACKNOWLEDGEMENTS

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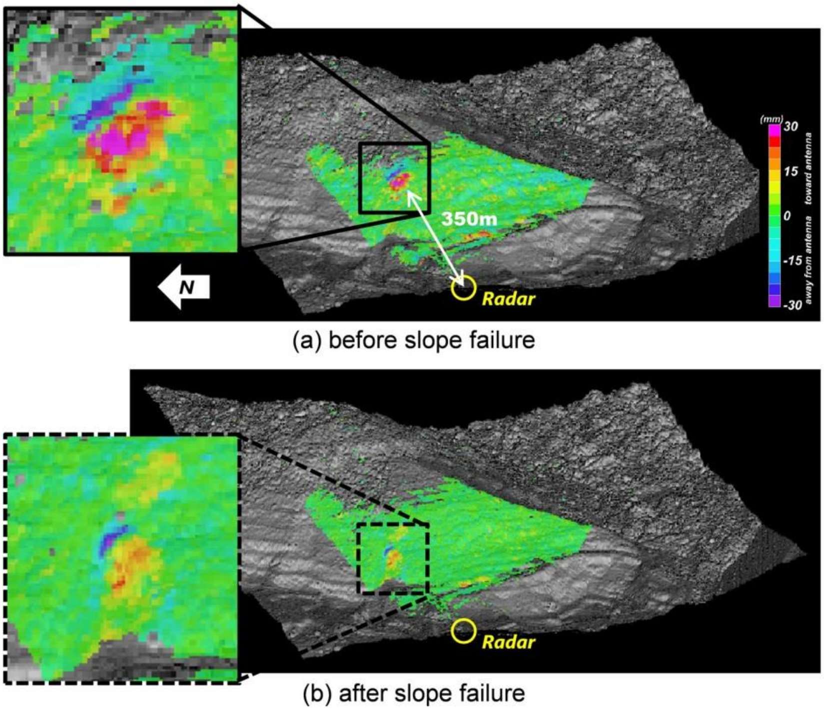

Figure 5. Three-dimensional displacement map before and after slope failure.

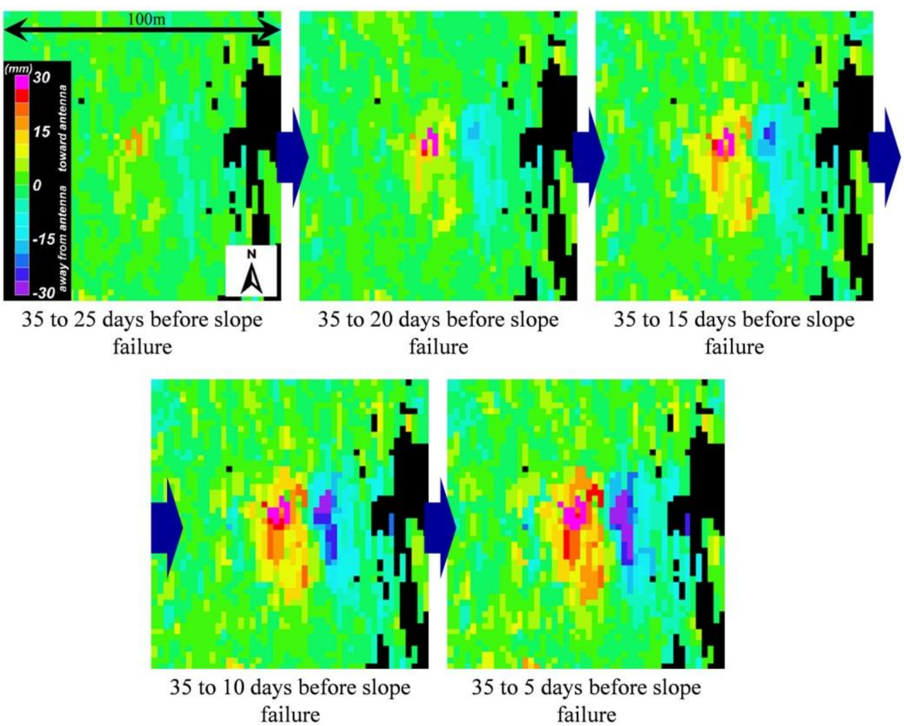

Figure 6. Three-dimensional displacement map before and after slope failure.