# DETECTION OF LIQUEFACTION-INDUCED SAND BOILING BASED ON SATELLITE IMAGE

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**ABSTRACT:** By analyzing high-resolution satellite images, attempts were made to detect liquefaction-induced sand boiling caused by the 2011 off the Pacific Coast of Tohoku earthquake, Japan. As a result, effective detection of sand boiling on road pavements in the studied region could be made by executing a masking treatment on the satellite images using information on the location of roads. In addition to classification using training data, semi-automatic classification without any training data could be successfully applied on the satellite images, while referring to the spectrum data of actual boiled sands that were measured in the field and in the laboratory. .

**Key words:** Liquefaction, sand boiling, satellite image, spectral characteristics, 2011 off the Pacific Coast of Tohoku earthquake.

## INTRODUCTION

The March 11, 2011 off the Pacific Coast of Tohoku earthquake, Japan caused liquefaction of reclaimed and natural sandy soil deposits, inducing severe damage to housing lots, underground pipes and river dikes, among others. The number of the damaged sites was extensive, and they spread over a vast area. In the case with Kanto district, therefore, it took several months to complete the field surveys and to compile the list of liquefied sites (MLIT, 2011).

For undertaking prompt emergency actions in future large earthquake events, it is rather preferred to compile a preliminary list of liquefied sites in much shorter time. In doing so, satellite images are promising data for quick evaluation of liquefied sites, since they have a high potential of detecting sand boiling that is induced as a result of liquefaction (Matsuoka et al, 2001 among others).

In view of the above, by analyzing high-resolution satellite images, it was attempted in the current study to detect liquefaction-induced sand boiling caused by the 2011 off the Pacific Coast of Tohoku earthquake, Japan.

## SATELLITE IMAGE

The satellite images of GeoEye-1 taken on March 13, 2010 (i.e., about one year prior to the earthquake) and March 26, 2011 (in about two weeks after the March 11 earthquake) were employed in the present study. As summarized in Table 1, they are provided with high spatial and spectral resolution.

In order to reduce the possible seasonal effects on the spectral characteristics, satellite images taken during similar season were analyzed. It was also attempted to reduce the effects of atmospheric

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air by deducting the minimum value of the digital numbers from the original data.

## STUDIED REGION

While considering the availability of clear satellite images that were taken before and after the earthquake, we selected Itako and Kamisu cities in Ibaraki prefecture as the studied region. It has been reported that extensive liquefaction occurred in these cities during the 2011 off the Pacific Coast of Tohoku earthquake (MLIT, 2011; Tsukamoto et al., 2012, among others). Their location is shown in Figure 1.

## METHODOLOGY

### *Analysis of Satellite Images*

For the detection of sand boiling, two kinds of classification procedures were adopted; one is a simplified classification using the spectral characteristics of a pixel that corresponds to typical sand boiling as the training data, which was retrieved from the satellite image taken after the earthquake; and the other is a semi-automatic classification which referred to the spectrum data of actual boiled sands that were measured in the field and in the laboratory.

### *Field Investigations*

A spectrometer with a range of wave length from 325 to 1075 nm was used to evaluate the spectrum data of actual boiled sands with a thickness of 3 mm and those of asphalt road pavement in Hinode area, Itako city and Fukashiba area, Kamisu city under natural sunshine around the noon (i.e., in between 11am to 2pm) with a clear weather condition. For each of the investigated cases, three measurements were made, and their average values were employed for the analysis.

### *Laboratory Experiments*

By using the same spectrometer and the same boiled sands as employed for the field investigations, while using an artificial light source that simulates the sunshine condition, a series of measurements of the spectrum data was conducted in the laboratory to verify the possible effects of the following factors:
a. Thickness of boiled sands
b. Water content of boiled sands
c. Pavement material beneath boiled sands

## RESULTS AND DISCUSSIONS

Herein, results from the two kinds of analyses of the satellite images are presented. First, the simplified classification using training data of typical sand boiling for classification is discussed. Second, while referring to results from field investigations and laboratory experiments, applicability of the semi-automatic classification without any training data is verified.

### *Analysis of Satellite Images using Training Data of Typical Sand Boiling for Classification*

Figure 2 shows the results of preliminary analysis of satellite images conducted by Ishikawa and Sawada (2012) using the training data that corresponds to typical sand boiling. In the figure, the sites detected as boiled sand were colored in green. In general, the green colors concentrated into two areas, which correspond to Hinode area in Itako city, and Fukashiba and Horiwari area in Kamisu city. These results are consistent with the results from relevant field surveys (MLIT 2011; Tsukamoto et al., 2012, among others). Photo 1 shows typical sand boiling observed in these areas.

On the other hand, it could be also seen from Figure 2 that the results from the above analysis overestimated the occurrence of sand boiling. Though some structures and farms are colored in green, it has been confirmed by field investigation that no sand boiling was observed in-situ. Such overestimation was possibly caused by their spectral characteristics that were similar to those of boiled sands.

In order to reduce such overestimation, in the current study, a masking treatment on the satellite images was executed by using the information on the location of roads, as shown in Figure 3, which is provided through the service of "OpenStreetMap Japan" (OSMJP 2013). It was expected that the sand boiling on road pavements would have caused similar changes in the spectral characteristics of their satellite images. It should be noted that the information on the location of roads is not complete in the Fukashiba area, as can be seen in Figure 3, and thus this area could not be analyzed with sufficient accuracy in the subsequent analyses.

After the above masking treatment, as shown in Figure 4, the extensive sand boiling on the roads in Hinode area could be effectively detected. In addition, partial occurrence of sand boiling on the roads near JR Itako station could be also detected.

### *Field Investigations and Laboratory Experiments*

Figure 5 summarizes the spectrum data of boiled sands and asphalt pavements measured in the field investigations and laboratory experiments in terms of the relationships between the reflectance ratio and the wave length. For comparison, the data derived from the training data that corresponds to typical sand boiling on the satellite image are also shown. A reasonable agreement could be seen among the results from three different kinds of evaluations.

It was also verified in the laboratory experiments that the thickness of boiled sands did not affect their spectrum data, when they were under dry condition. When they were thicker than 1 mm, the pavement material beneath the boiled sands did not affect their spectrum data, either. On the other hand, as typically shown in Figure 6, it was revealed that the reflectance ratio was reduced with the increase in the water content of boiled sands, while the general shapes of the spectrum data were unchanged.

### *Analysis of Satellite Images using Semi-automatic Classification*

Figure 7 shows the results of satellite image analysis using semi-automatic classification. As the first step of the classification, a clustering treatment based on ISODATA method (Richar and Jia, 2005) without using any training data was applied on the satellite images, resulting into six categories as shown in Figure 8. As the second step, by referring to the characteristics of the spectrum data of actual boiled sands as also shown in Figure 7, the class #5 among the six categories was employed for the detection of boiled sands.

As the results from the above semi-automatic classification, successful detection of boiled sands in Hinode area and around JR Itako station could be made. The areas of boiled sands as shown in Figures 4 and 6 by using the two different kinds of classification matched to each other with a correspondence ratio of about 80 %.

## CONCLUSIONS

Liquefaction-induced sand boiling in the studied region could be detected based on the satellite images, which were taken with high resolution before and after the 2011 off the Pacific Coast of Tohoku earthquake, Japan.

Effective detection of sand boiling on road pavements could be made by executing a masking treatment on the satellite images using information on the location of roads.

In addition to classification using training data, semi-automatic classification without any training data could be successfully applied on the satellite images, while referring to the spectrum data of actual boiled sands that were measured in the field and in the laboratory.

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**Table 1** Characteristics of GeoEye-1 data

| Revisit days | Band number | Spatial resolution | Observation width | Band wave length |
|---|---|---|---|---|
| 11 | 4 | 1.64 m | 15 km | Blue: 450-510 nm<br>Green: 510-580 nm<br>Red: 655-690 nm<br>Near infrared: 780-920 nm |

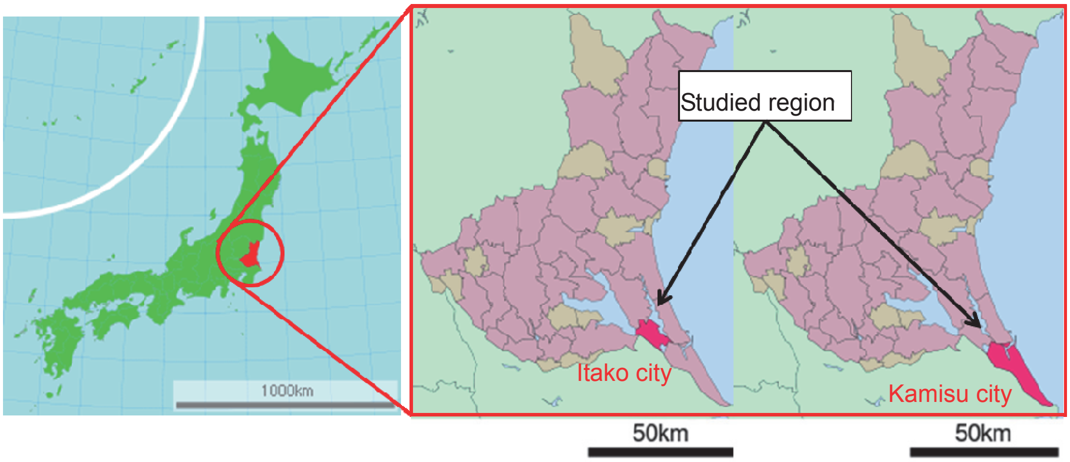


**Figure 1** Studied region

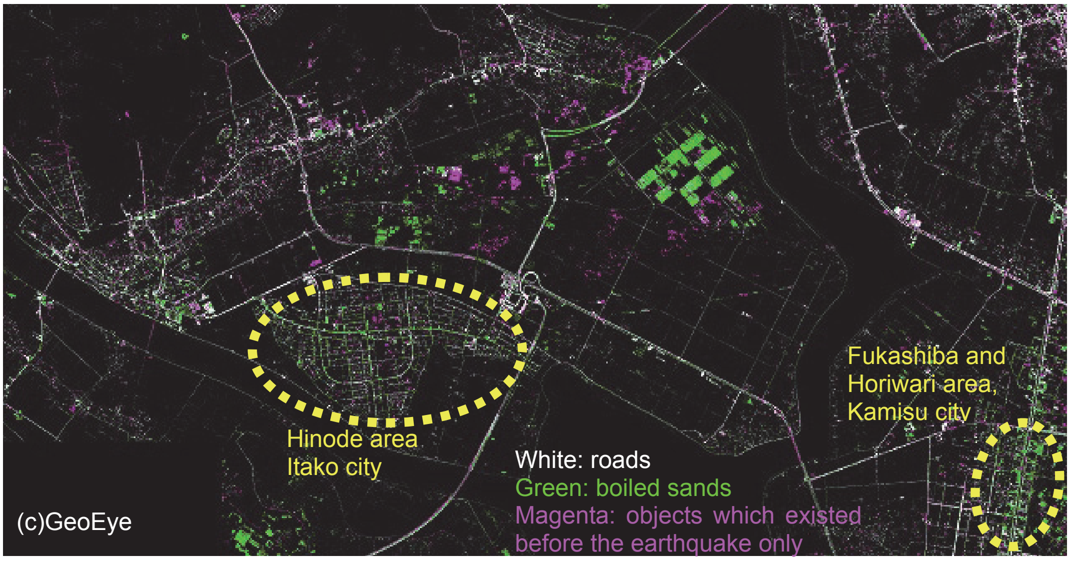


**Figure 2** Result from preliminary analysis (Ishikawa and Sawada, 2012)



**Photo 1** Sand boiling observed in a) Hinode area, Itako city and b) Fukashiba area, Kamisu city

**Figure 3** Location of roads in the studied area (based on OpenStreetMap)

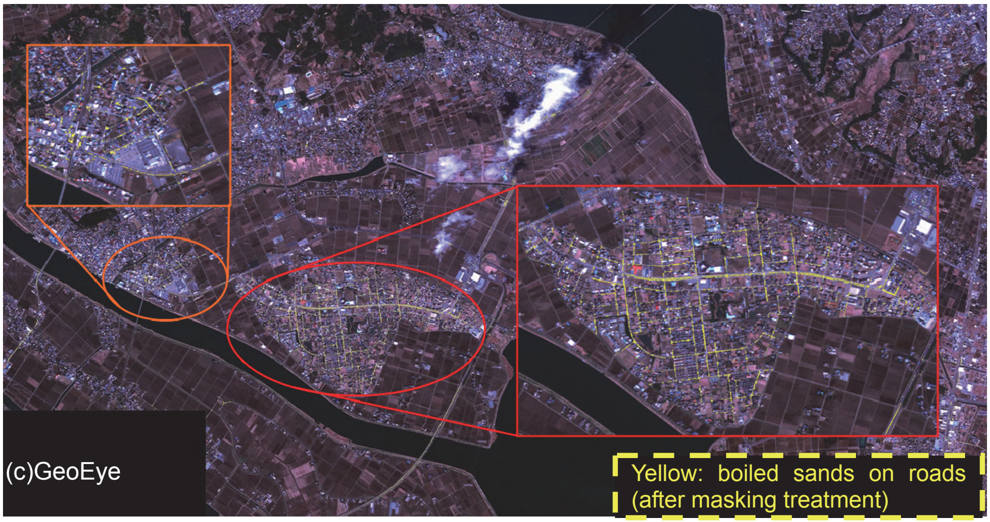


**Figure 4** Result from analysis using training data of typical sand boiling for classification

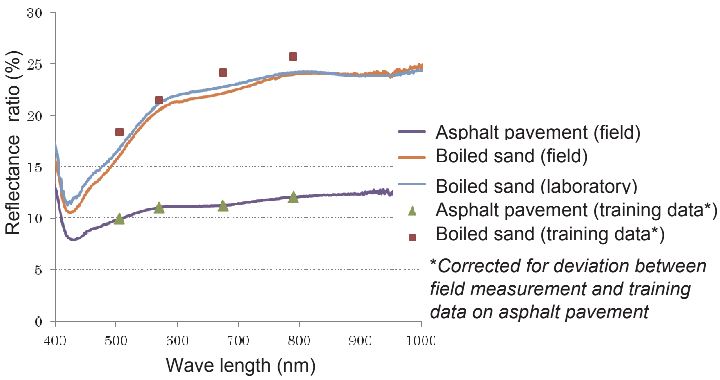


**Figure 5** Spectrum data of boiled sand and asphalt pavement

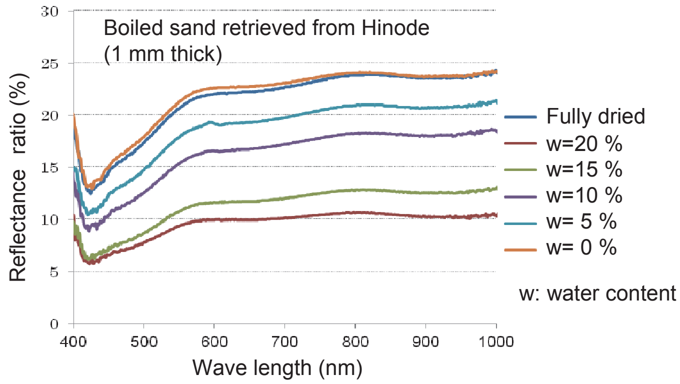


**Figure 6** Spectrum data of boiled sands at different water contents

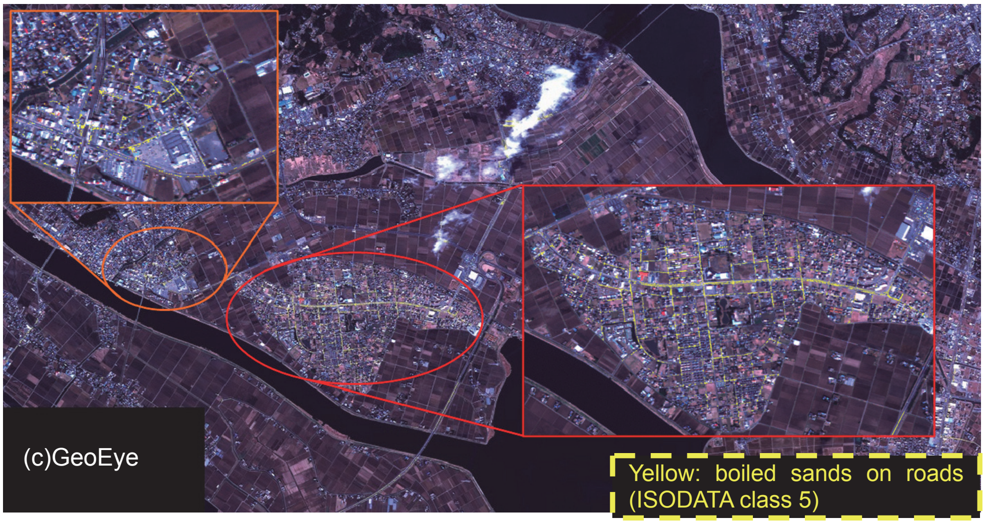


**Figure 7** Result from analysis using semi-automatic classification

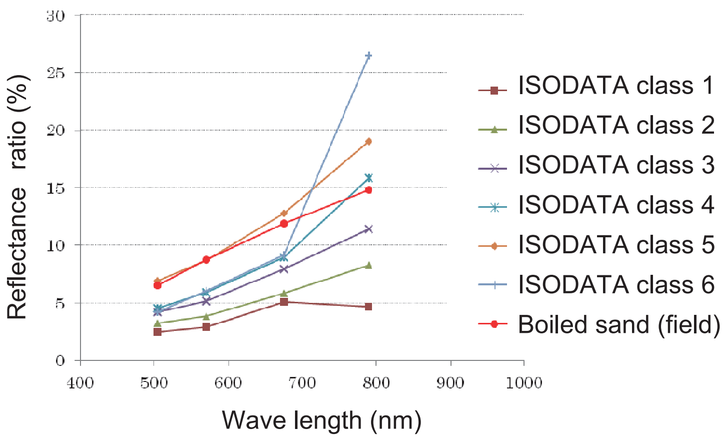


**Figure 8** Result from clustering treatment based on ISODATA method