Mapping coal fires using Normalized Difference Coal Fire Index (NDCFI): case study at Khanh Hoa coal mine, Vietnam

L. H. Trinh1, V. N. Nguyen2

1 Le Quy Don Technical University, Hanoi, Vietnam
2 Hanoi University of Mining and Geology, Hanoi, Vietnam

Abstract
Khanh Hoa coal mine (Thai Nguyen province) is one of the largest coal mines in the north of Vietnam. For many years, this area suffered from underground fires at coal mine waste dumps, seriously affecting production activities and the environment. This paper presents the results of classification of underground fire areas at Khanh Hoa coal mine using Normalized Diference Coal Fire Index (NDCFI). 03 Landsat 8 OLI_TIRS images taken on December 2, 2013, December 10, 2016, and December 3, 2019 were used to calculate NDCFI index, and then classify the underground fire areas by thresholding method. In the study, the land surface temperature was also calculated from Landsat 8 thermal infrared bands data, and then compared with the results of underground coal fire classification at Khanh Hoa coal mine. The obtained results showed that the NDCFI index can be used effectively in detecting and monitoring underground fire areas at coal mines. The use of the NDCFI index also has many advantages due to its calculation simplicity and rapidness compared to other methods for classifying underground coal fire areas.

Key words
coal fire, Khanh Hoa coal mine, Landsat data, NDCFI index, remote sensing

For citation
1. Introduction

Most types of coal have the ability to self-ignite under certain environmental conditions (endogenous combustion). The generation and accumulation of heat is the major direct cause of the spontaneous coal combustion [1]. Underground fires at coal mines produce many toxic gases, especially carbon monoxide (CO) and carbon dioxide (CO2). It is very difficult to extinguish underground coal fires. This is an extremely dangerous phenomenon in underground mining, seriously affecting the environment and causing damage to buildings and infrastructure [2, 3].

Underground coal fires occur in practically leading coal producing countries of the world, such as India, China, Venezuela, USA, RSA [4]. There were coal fires covering area up to several hundreds square kilometers, lasting for many years and still not extinguished [5]. In Vietnam, some underground coal fires were recorded in Quang Ninh coal basin (2009), at Nong Son coal mine (Quang Nam province, 2011) and Khanh Hoa coal mine (Thai Nguyen province, 2014).

Remote sensing data are widely used in the world in early detection and monitoring of underground fires at coal mines. Most of these studies use land surface temperature calculated from the thermal infrared data from Landsat and Aster satellite images to monitor underground coal fires [6–12]. These studies all showed that land surface temperatures in underground coal fire areas were much higher than in the surrounding area, even compared to urban areas characterized by impervious surfaces. Research of [13] at the Raniganj coalbelt (India) showed that the temperatures in the overburden dumps of open cast mines ranged 28 to 52 °C and within the mine 35 to 38 °C. Moreover, in some places temperature was found to be as high as 68 °C [15].

Due to low spatial resolution of the thermal infrared band data of Landsat and Aster images, some recent studies integrated Landsat 8 and Sentinel 2 images to detect underground fire areas in more details [10, 14].

Located in Southeast Asia, Vietnam is rich in mineral resources with 10 billion tons of anthracite coal, more than 200 billion tons of brown coal in the northern delta area [15]. In recent years, a number of studies on the application of remote sensing data in early detection and monitoring of underground coal fires in Vietnam were performed. Trinh and Zablotskii [11] used multi-temporal Landsat image data to monitor the change of land surface temperature at Khanh Hoa coal mine. The obtained results showed that the land surface temperature within coal mines and waste dumps was usually higher than 35 °C, while some areas had temperatures above 40 °C [11]. Landsat 8 image data and spatial analysis techniques were also used to predict underground fire locations at Khanh Hoa coal mine [12, 16]. Based on the analysis of the distribution of land surface temperatures calculated from Landsat satellite images, these studies enabled predicting fire locations, thereby providing information to help managers to promptly respond to underground fires at Khanh Hoa coal mines.

The use of land surface temperature data calculated from remote sensing images in monitoring of underground coal fires has the advantage of high accuracy of the results, but the calculation process is rather complicated. Band rationing method based on multi-spectral images with the advantages of simplicity in calculation and time-saving can be used effectively in classifying coal mining areas, including areas where underground fires occur [17]. Raju (2015) proposed using the Normalized Difference Coal Fire Index (NDCFI) to quickly map the areas where underground fires occur in the Jharia coalfield (India). In study [17], he observed that the spectral reflectance value of the pixels attributed to the fire exhibits maximum and minimum intensity response in band 8 (SWIR, 2.295 – 2.365 µm) and band 4 (SWIR, 1.600 – 1.700 µm) of Aster image, respectively. These spectral bands of the Aster images correspond to band 7 (SWIR2, 2.11 – 2.29 µm) and band 6 (SWIR1, 1.57 – 1.65 µm) of Landsat 8 OLI images. Thus, it is possible to use Landsat shortwave infrared bands to calculate NDCFI index for classification of underground coal fire areas.

This study presents the results of classification of underground fire areas at Khanh Hoa coal mine (Thai Nguyen province, northern Vietnam) based on Landsat 8 multi-temporal data using NDCFI index. 03 Landsat 8 images taken on December 2, 2013, December 10, 2016 and December 3, 2019 were used to calculate the NDCFI index, and then classify the underground coal fire areas using the thresholding method. In the study, we also compared the obtained results and the surface temperatures determined from the Landsat 8 data. This comparison allowed to demonstrate the effectiveness of the NDCFI index in classifying underground fire areas compared to the traditional method based on the land surface temperature measuring.

2. Materials and methodology

Study area

Thai Nguyen is the province with the second largest coal reserves in Vietnam (reserves about 15 million tons of fat coal, 90 million tons of coal) after Quang Ninh province. Khanh Hoa coal mine is the largest coal mine in Thai Nguyen province with mining area and waste dump covering more than 300 hectares; the annual coal extraction capacity exceeds 600 kt of coal. Underground fires at coal mines and waste dumps of Khanh Hoa coal mine proceed for a long time, seriously affecting the quality of living environment and production activities. Although many solutions were applied, so far the problem of underground fires at Khanh Hoa coal mine has not been completely solved. Geographical location of Khanh Hoa coal mine (Thai Nguyen province) is shown in Fig. 1.

Materials

In this study, multispectral cloud-free Landsat 8 OLI_TIRS images with spatial resolution of 30 m (multispectral bands) and 100 m (thermal infrared bands), taken on December 2, 2013, December 10, 2016, and December 3, 2019 in the Thai Nguyen province (northern Vietnam) were used for calculating NDCFI index. The Landsat 8 data present the L1C level product, downloaded from...
the United States Geological Survey website\(^1\). Landsat 8 image data used in this study are presented in Fig. 2, RGB = NIR:RED:GREEN.

### Methodology

After acquiring, the Landsat 8 data were subjected to atmospheric correction \([18]\) and geometric correction. The spectral reflectance values at short-wave infrared bands (band 6 and band 7) were used to calculate NDCFI index using the following formula \([17]\):

\[
NDCFI = \frac{\rho_{SWIR2} - \rho_{SWIR1}}{\rho_{SWIR2} + \rho_{SWIR1}}.
\]  

(1)

After calculating NDCFI index, thresholding method was applied to classify the underground coal fire areas. The threshold value was selected based on the NDCFI index analysis histogram.


In order to compare the results of the underground coal fire classification, we also calculated the land surface temperatures based on the Landsat 8 thermal infrared bands data. The split-window algorithm was used to calculate land surface temperatures from Landsat 8 data using the following formula \([19–21]\):

\[
T_s = T_{B10} + c_1(T_{B10} - T_{B11}) + c_2(T_{B10} - T_{B11})^2 + c_0 + (c_3 + c_4w)(1 - \varepsilon) + (c_5 + c_6w)\Delta \varepsilon,
\]

(2)

where: \(T_s\) – land surface temperature; \(T_{B10}, T_{B11}\) – brightness temperature of bands 10 and 11 of Landsat 8 imagery; \(w\) – atmospheric water vapor content (g/cm\(^2\)). The value of atmospheric water vapor content was calculated using formula proposed by Huazhong \([22]\); \(\varepsilon\) – mean emissivity; \(\Delta \varepsilon\) – emissivity difference; \(c_0\) to \(c_6\) – values of split-window coefficients \([23]\).

Flowchart (methodology) for the underground coal fire classification using NDCFI index calculated nased on Landsat 8 OLI_TIRS data is shown in Fig. 3.
3. Results and discussion

Figure 4 shows the NDCFI indices for Khanh Hoa coal mine (Thai Nguyen province) calculated based on Landsat 8 images taken on December 2, 2013, December 10, 2016 and December 3, 2019. On the NDCFI images, the Khanh Hoa coal mine is represented by bright pixels, differing from the surrounding area. The area within the Khanh Hoa coal mine and the waste dump, where the underground coal fire occurred, has the brightest color. This can be explained by the fact that the reflectance value of underground coal fire pixels at wavelength 2.11–2.29 µm (band 7 of Landsat 8 image) is much higher than at wavelength 1.57–1.65 µm (band 6 of Landsat 8 image). Meanwhile, the reflectance value of vegetation in band 7 is lower than in band 6 of Landsat 8 image, so vegetation is represented by dark pixels on the NDCFI index images. Built-up lands and bare lands are light gray on the NDCFI images because the difference in their spectral reflectance value in bands 6 and 7 of Landsat 8 image is not marked.

Based on the analysis of the NDCFI index histogram, threshold value was selected to classify the underground coal fires. In the study area in Khanh Hoa coal mine (Thai Nguyen province), the threshold value to classify underground coal fire areas / surrounding areas was −0.22. The image processing to select the threshold value was performed using ENVI 5.2 software.

The results of the underground coal fire classification at Khanh Hoa coal mine (Thai Nguyen province) based on the NDCFI index calculated from Landsat 8 satellite images dated December 2, 2013, December 10, 2016 and December 3, 2019 are shown in Figure 5, where the underground coal fire areas are painted red, while the surrounding areas are white. The underground coal fire areas classified based on the NDCFI index in 2013, 2016, and 2019 covered 103.68 ha, 98.01 ha, and 93.87 ha, respectively.

To compare the results of underground coal fire classification at Khanh Hoa coal mine by using NDCFI index, the land surface temperatures were also calculated from Landsat 8 images. The land surface temperatures in the study area calculated from the Landsat 8 satellite images of 2013, 2016, and 2019 are presented in Fig. 6. The lowest and highest land surface temperatures on
December 2, 2013, December 10, 2016, and December 3, 2019 were 21.02 °C and 38.82 °C, 20.95 °C and 38.51 °C, 19.86 °C and 38.92 °C, respectively. It can be seen that the difference between the highest and lowest land surface temperatures in the study area is not large. Areas of high land surface temperatures are locally distributed in Khanh Hoa coal mine area (shown by white pixels). The land surface temperatures in the inner city of Thai Nguyen are lower (about 30 to 35 °C), while the agricultural lands and forest areas have the lowest surface temperatures (less than 30 °C).

Figure 7 shows the land surface temperature spatial distribution maps for the area of Khanh Hoa coal mine location, which were obtained from Landsat 8 data. In this Figure, seven zones were identified with the following temperatures: below 20 °C, 20–23 °C, 23–26 °C, 26–29 °C, 29–32 °C, 32–35 °C, and above 35 °C. It can be seen that the land surface temperatures within the Khanh Hoa coal mine area was much higher than those in the surrounding areas, even compared to Thai Nguyen city, which was characterized by impervious surface. Areas with land surface temperatures higher than 35 °C were concentrated within Khanh Hoa coal mine (shown by red in Fig. 7).

The areas with land surface temperatures higher than 35 °C calculated from Landsat 8 images in December 2, 2013, December 10, 2016 and December 3, 2019 covered 101.16 ha, 96.60 ha, and 92.05 ha, respectively. Thus, it can be seen that the results of the underground coal fire classification using NDCFI index have very strong correlation with the high surface temperature areas, above 35 °C – the threshold temperature value for identifying underground coal fires [5]. The correlation coefficient between the NDCFI index and the land surface temperature on December 2, 2013, December 10, 2016, and December 3, 2019 reached 0.867, 0.807, and 0.862, respectively. The above findings show that NDCFI index can be effectively used in early detection and classification of underground coal fires. The use of NDCFI index for studying underground coal fires has advantages of its simplicity and rapidity compared to the method based on using land surface temperatures.
4. Conclusion

Underground coal fires are very dangerous phenomena in coal mining, greatly affecting the environment and production activities. Early detection of areas with high risk of underground fire is an urgent task; it is necessary to effectively respond to underground coal fires. This paper presents a solution for early detection and monitoring of areas with high risk of underground coal fire based on NDCFI index calculated from Landsat satellite data. The obtained results showed that NDCFI index has very high correlation with the land surface temperature. Areas with NDCFI values higher than −0.22 practically correspond to areas with land surface temperature above 35 °C. Applying NDCFI index allows providing timely information for managers to effectively respond to underground fires in coal mining sector.

References


Information about the authors

Le Hung Trinh – Lecturer, Le Quy Don Technical University, Hanoi, Vietnam; ORCID 0000-0002-2403-063X, Scopus ID 57035066200; e-mail trinhlehung@lqdtu.edu.vn

Viet Nghia Nguyen – Lecturer, Department of Mine Surveying, Hanoi University of Mining and Geology, Hanoi, Vietnam; ORCID 0000-0001-7010-8613, Scopus ID 57204141788; e-mail nguyenvietnghia@humg.edu.vn

Информация об авторах

Ле Хунг Чинь – преподаватель, Технический университет им. Ле Куи Дон, г. Ханой, Вьетнам; ORCID 0000-0002-2403-063X, Scopus ID 57035066200; e-mail trinhlehung@lqdtu.edu.vn

Вьет Нгиа Нгуен – преподаватель, кафедра маркшейдерского дела, Ханойский горно-геологический университет, г. Ханой, Вьетнам; ORCID 0000-0001-7010-8613, Scopus ID 57204141788; e-mail nguyenvietnghia@humg.edu.vn