Development of Landslide Monitoring System by Real-Time Kinematic Survey: Experimentation and Application in Mae Moh Mine, Thailand

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Keywords: GNSS, RTK, open-pit mine, landslide monitoring

SUMMARY

The global navigation satellite system (GNSS) using the real-time kinematic (RTK) positioning technique has been capable of monitoring centimeter deformation of ground movements. We have developed the RTK-GNSS landslide monitoring system (RTK-LANDMOS) for landslide movement monitoring and early warning in the Mae Moh lignite open-pit mine, the Electricity Generating Authority of Thailand (EGAT). The system continuously operates for 24 hours to analyze the effects of landslides induced by mining activities and slope's behavior through 10 monitoring stations distributed across the mine pit and dumping areas. Each station includes a built-in low-cost RTK GNSS receiver, data acquisition equipment, and a 4G long-term-evolution (4G LTE) communication device for data transmission. The built-in receiver running on solar energy with battery storage has a durable and hardy body designed to resist bumping objects in harsh environments. The RTK-LANDMOS efficiently manages real-time GNSS monitoring raw data transmitted to a central computer server from the on-site stations. The system will turn on the warning alarms and signals if the land movement exceeds tolerance criteria. Simultaneously, the notification message will be sent to all authorized participants via an online application, for instance, LINE® messenger.

Based on our experimental results, the RTK-LANDMOS provided reliable three-dimensional movements (North, East, Up), achievable as accurately as 5 centimeters or better, through data processing with additional outlier detection consideration. The system allowed the detection of land deformation and sent early-warning messages concerning the high risk of landslides. On November 22-27, 2021, the system significantly contributed to landslide management's effective preparation and mitigation phases during the concurrence of landslides in the upper north part of the west side dumping area. In the future, the RTK-LANDMOS will be considered a primary service supporting disaster management. Such an early warning system can reduce the possibility of injury, death, damage, and property loss from EGAT individuals and communities by immediately responding to landslide hazards in the Mae Moh mine area. After all, the RTK-LANDMOS ensures the safety of mining facilities and activities, resulting in the stability of the coal supply to power plants and strengthening Thailand's energy security and sustainability.

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1. INTRODUCTION

Mae Moh Mine is an open-pit lignite mine under the supervision of EGAT in the mountains of Lampang province in northern Thailand, located at the latitude and longitude of about 18°20′N and 99°43′E, respectively, considered as one of Southeast Asia's largest lignite coal mines. The mine is four kilometers wide and seven kilometers long, with a depth of 320 meters below the ground surface. It has a production capacity of about 16 million tons per year, supplying its largest coal-fired power plant in the country with a total contractual generating capacity of about 2,220 megawatts (MW). The mine supplies 4.4 tonnes of lignite daily to the power plant by removing overburdens (i.e., ecosystem, soil, and rock layers above coal seams) and transporting them to the west-side dumping area nearby the Mae Moh open pit mine for disposal. This dumping area is comparable to the open pit, with an average elevation of about 200 m above the surface. Surface mining by excavations and blastings triggering loss of soil structure may deteriorate the slope stabilities of the dumping and the pit areas. The massive structure deformation of the areas significantly impacts EGAT properties, mining activities, individuals, and nearby communities. A stability monitoring tool is necessary to warn against slope failure that may cause threaten EGAT individual's and communitie's safety and to support hazard mitigation preparations.

In recent years, GNSS technology has been widely used to monitor changes in the shape of the terrain surface. For example, Baryla and Paziewski (2014) used GNSS receivers combined with precise leveling to study the changes of KWD adamów open-pit mine in Poland. GNSS measurements were conducted in static mode and combined with leveling data using a least-squares adjustment to achieve positional accuracy at a millimeter level. This result showed the changing behavior in horizontal and vertical dimensions, corresponding to Chrzamowski and Wilkins (2006), which used GNSS for monitoring in Canada and southern Africa with millimeter-level accuracy. Similarly, Cina and Piras (2015) attempted to use a low-cost GNSS receiver and compared it with a high-quality GNSS receiver. They found that the low-cost GNSS receiver was comparable to the high-quality one at horizontal and vertical accuracies of 5 and 20 mm, respectively.

Bellone et al. (2016) and Malet et al. (2016) used low-cost GNSS receivers together with light detection and ranging (LiDAR) to study land deformation and monitor the large-scale landslide behavior of four mountainous areas of the Alps in French. The studies showed that the data obtained by installing six low-cost GNSS units in the high-risk areas could support the terrestrial LiDAR measurements to construct a digital elevation model (DEM) with centimeter-level accuracy. Furthermore, Notti et al. (2020) developed a system for monitoring the stability of the slope of the Madonna del Sasso sanctuary in Italy. The system consisted of low-cost GNSS units integrated with the warning system that displayed a graph with green, yellow, and red dots on the computer screen located in the office. Based on all mentioned studies, GNSS technology is one of the most appropriate positioning tools for stability monitoring.

This study aims to develop the RTK-LANDMOS to instantly detect landslides in the west-side dumping area and the Mae Moh open-pit mine. Sections 2 and 3 provide the principle concepts and the development methodology, respectively. Section 4 describes the experimental results and discussion, and the conclusion and further work are in Section 5.

2. THE FUNDAMENTAL CONCEPTS

This research applies the concepts of RTK GNSS positioning and communication to the geographic information system (GIS) to develop a landslide monitoring system, i.e., the RTK-LANDMOS. The brief details are as follows.

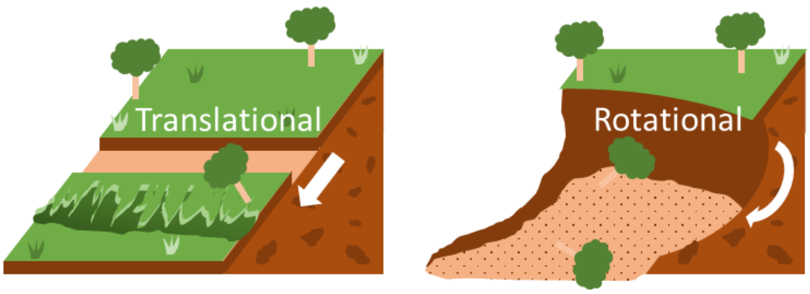


Figure 1 The characteristics of translational and rotational land movements.

2.1 Application of low-cost RTK GNSS in landslide monitoring

The behavior of land movement in the Mae Moh Mine is typically characterized by two types of movements, i.e., rotational slide and translational slide. The rotation is the movement along a curved rupture surface, whereas the translation is the movement along a plane, as shown in Figure 1. The speed of movement is generally low to medium rate. It usually takes at least 6 hours of movement, or the crack width is at least 30-100 cm before the failure happens. As the behavior mentioned, slow movement and measurable crack size, the idea of using RTK GNSS positioning was considered in this research. The low-cost RTK GNSS receiver was designed with the concept of easy assembling, installation, and mobilization. Besides, it should withstand the weather conditions of the Mae Moh Mine and be easy to maintain. We chose the SparkFun

GPS-RTK-SMA Breakout with the u-blox ZED-F9P module (www.sparkfun.com). It can receive multi-GNSS signals for RTK positioning, which provides an accuracy of about 1-5 cm. The solar cell panels were used for powering the receiver with the battery storage. The communication system also transmits the data to the office's computer server for position processing, then sends the movement status to the persons in charge of disaster management.

2.2 Wireless communication

Wireless communication is defined as the transmission of information between low-cost RTK-GNSS receivers in the monitoring areas and the data processing unit in the EGAT office. The land movement data were sent as full-duplex transmission, allowing simultaneous bidirectional communication. For instance, when the authorized user at the office sends commanding data (e.g., turning on/off warning lights at different risk levels) to the receiver unit, the receiver is still able to transmit the movement data back to the sender in the same transmission channel. Hence, the monitoring system can constantly transmit data to the data processing unit for real-time or near-real-time analysis. In case of an extreme movement and potential landslide, the system can instantly send a command to turn on a warning light installed in the receiver unit via a communication unit.

2.3 Geographic Information System

The low-cost RTK GNSS unit only provides accurate positioning information on the land movement, such as geodetic coordinates, times, the number of satellites, and position dilution of precision (PDOP). It cannot identify whether or not the quantity of movement is at high risk. It also can not graphically show the location of land movement and characterize its behaviors. Thus, we need a Geographic information system (GIS) because of its versatility in handling a large data set, providing an efficient environment for analysis and display of results. All relevant movement data are well-organized in a database and thus suitable for data queries and manipulations. This study integrates GIS with low-cost RTK GNSS units to support landslide disaster management decision-making.

3. THE METHODOLOGY

The RTK-LANDMOS consists of three main components, as shown in Figure 2: 1) ten low-cost RTK GNSS receivers, distributedly located in the high-risk areas of land movements, 2) the data processing unit, which manages the GIS data, processes GNSS data and analyzes all relevant data, and 3) the communication units, which receive and transmit data between the GNSS receivers and the data processing unit. This processing unit connects to CORS to obtain correction data. Figure 3 illustrates the RTK-LANDMOS development procedure; more details are in the following.

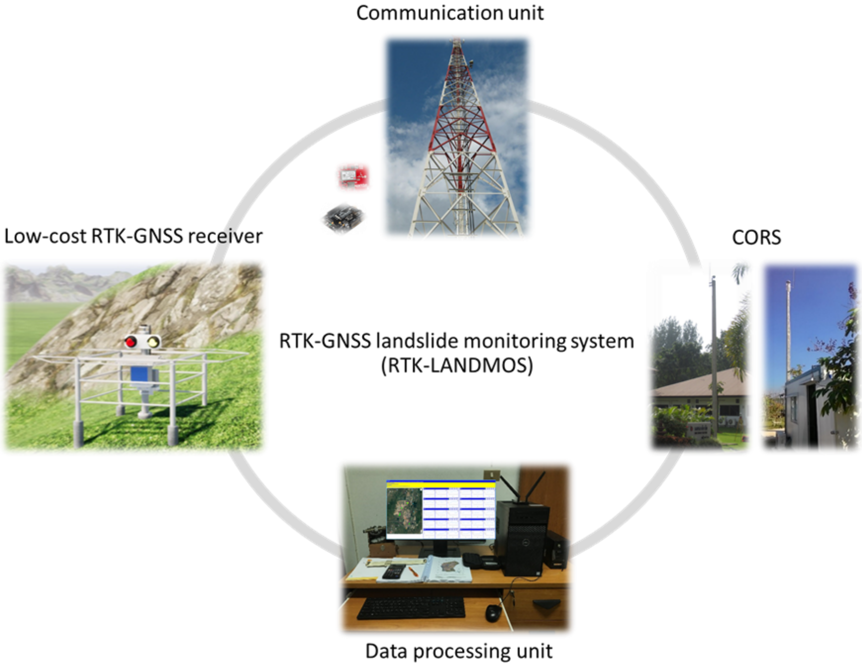


Figure 2 The architecture of the RTK GNSS landslide monitoring system, RTK-LANDMOS.

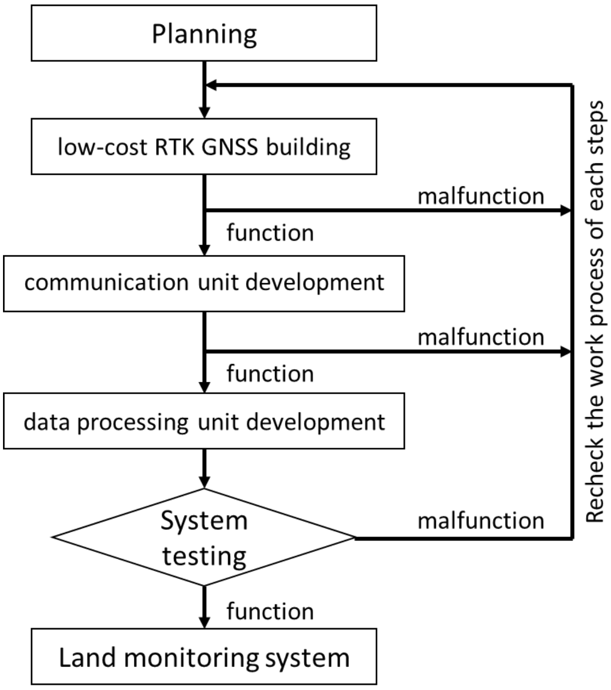


Figure 3 The procedure of the RTK-GNSS landslide monitoring system, RTK-LANDMOS.

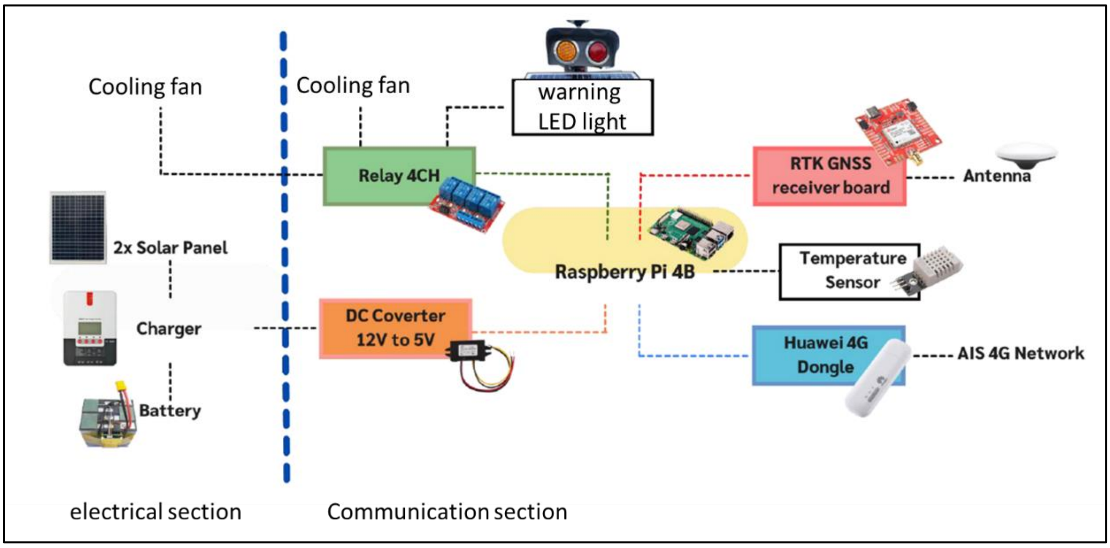


Figure 4 The components of the built-in low-cost RTK GNSS receiver units.

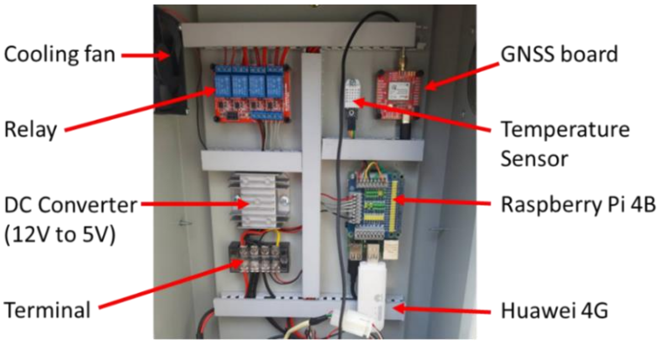


Figure 5 The example of electronic equipment in a waterproof sheet steel wall box.

3.1 The built-in low-cost RTK GNSS receiver units

In this study, each low-cost RTK GNSS receiver unit was built using a multi-band RTK GNSS board, SparkFun GPS-RTK-SMA Breakout, a circuit board that comes with u-blox's positioning chip, i.e., ZED-F9P module, as seen in Figure 5. This chip provides about 1-5 cm positional accuracy for RTK positioning based on the multi-GNSS signals from, for instance, GPS, GLONASS, Galileo, Beidou, and QZSS. The whole unit consists of several electronic components, most of which are available in Thailand, except for the SparkFun circuit board and a GNSS antenna. The electronic parts for building low-cost RTK GNSS units are durable and certified. In addition, the receiver units were designed to facilitate arrangements for repair, maintenance, and relocation in risk areas.

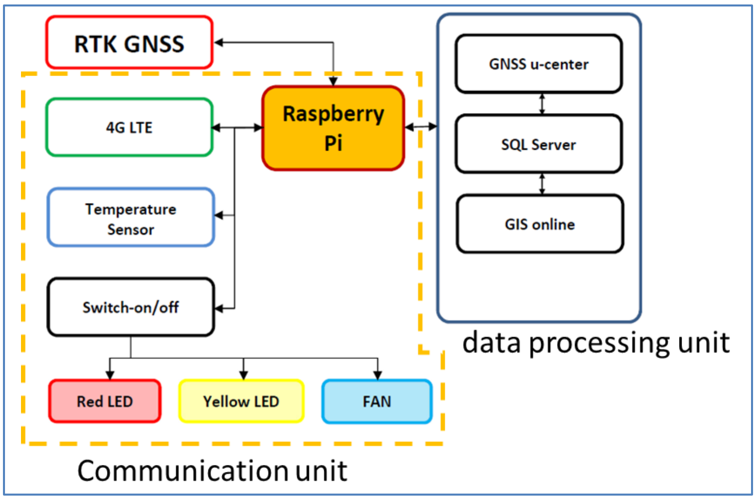


Figure 6 The diagram of the RTK-LANDMOS structure.

3.2 The communication units

The communication units provide receiving and transmitting sensors between the low-cost RTK GNSS receiver units located in risk areas and the data processing unit in the EGAT office using system controllers, e.g., Raspberry Pi controller boards (www.raspberrypi.com), as shown in Figures 5 and 6. The 4G LTE devices offer a secure and fast internet connection anywhere in Mae Moh Mine, providing ultimate performance for streaming data transfer. The communication units also include temperature sensors, switch-on/off-boards, and cooling fans.

Raspberry Pi is a series of small single-board computers. In this study, we use Raspberry Pi 4 Model B with an 8-gigabyte (GB) random access memory (RAM) because of its low cost, open design, modularity, benefits of flexibility, and variety in use. Such a mainboard system controller allows us to implement all electronic devices that best meet our positioning application requirements. The mainboard responds to temperature feedback to make decisions such as over-temp shutdown, fan speed control, and temperature compensation or temperature monitoring. Additionally, it can turn on/off a light-emitting diode (LED) warning light after receiving remote commands from the data processing unit.

3.3 The data processing unit

The data processing unit processes and analyzes the (National Marine Electronic Association or NMEA) data sent from the communication unit. The result expresses as a movement graph and the location of the receiver unit on a background orthophoto map. This processing unit, including additional outlier detection consideration, can instantly send command messages to low-cost RTK GNSS units and warning messages to the EGAT personnel in charge of disaster management in real-time or near-real-time. The main component of the processing unit is the GNSS u-center software for GNSS data processing (available at www.u-blox.com/en/product/u-center), connected to the continuously operating reference stations (CORS). These CORS provide RTK corrections, transmitted over the web in non-proprietary RTCM protocols, available 24 hours per day and 365 days a year. The results are stored and organized in a structured query language (SQL) server, which supports multi-communication simultaneously. As such, the server can manage several large-scale data sets of low-cost RTK GNSS units. Therefore, real-time or near-real-time data are usable for a GIS tool's warning system analysis. In addition, the processing unit contains the Thailand Geoid Model of 2017 (TGM2017) (Dumrongchai et al. 2021) for converting ellipsoidal heights to orthometric heights needed for local state plane coordinates.

Figure 7 shows the structure of the GIS online map server, including the web-based application, which entrusts data management and manipulation services. The GIS online map server is designed to support real-time data transferring between client and server using WebSocket protocol (www.ietf.org). It also provides a map service in which the orthophoto from satellite or aerial photo and digital surface model (DSM) can be imported as a background map. As a GIS database, the processed data from the u-center are stored in MySQL open source database (www.mysql.com) to respond to the map server's request. The web-based application, developed as a user interface, graphically provides spatial information on land movement behaviors with warning colors. Furthermore, the warning message will be promptly sent to all authorized participants in real-time via an online application, for instance, LINE® messenger, compatible with personal computers and smartphones.

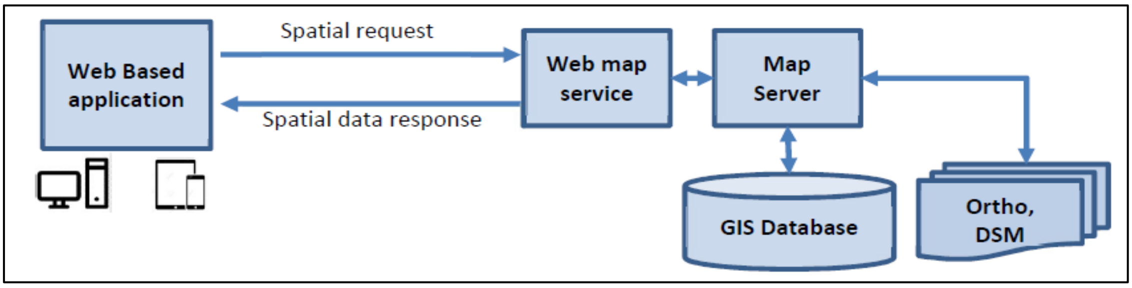


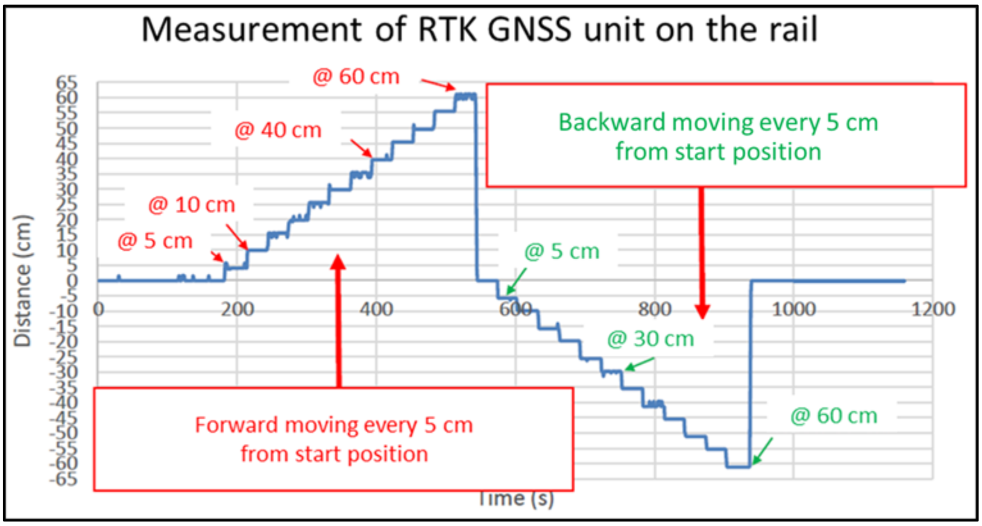
Figure 7 The GIS online map server structure.

4. RESULTS AND DISCUSSION

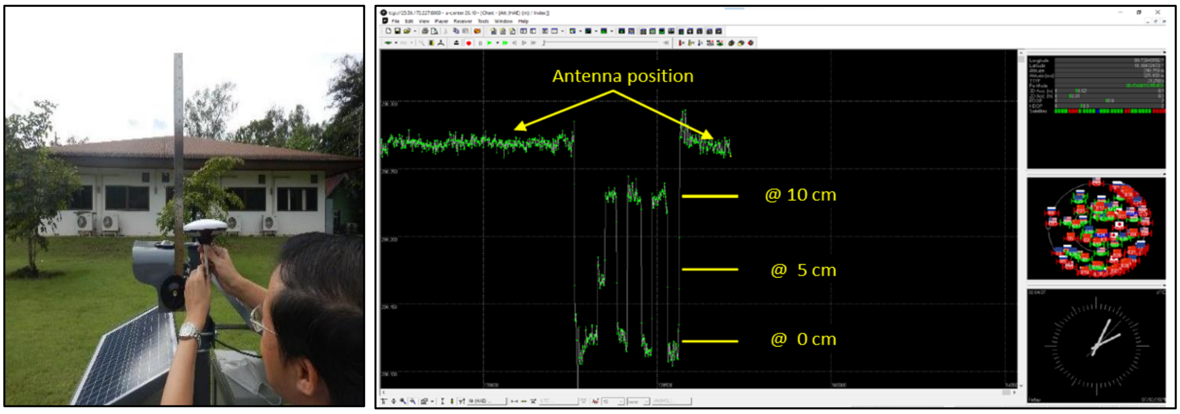
4.1 Experimental testing

We manufacture a linear rail for testing the operability and positioning accuracy of the RTK-LANDMOS with a measuring steel tape attached, as shown in Figure 8. This test aims to determine whether all low-cost RTK GNSS receiver units can work properly in any location of Mae Moh Mine. Each receiver unit is placed on the rail and can be accurately adjusted to determine horizontal and vertical displacements.

Figure 8 The low-cost RTK GNSS receiver unit on a linear rail obtaining correction data from the nearest CORS; either Trimble NetR9 or CHC P5E-Net CORS.



(a)

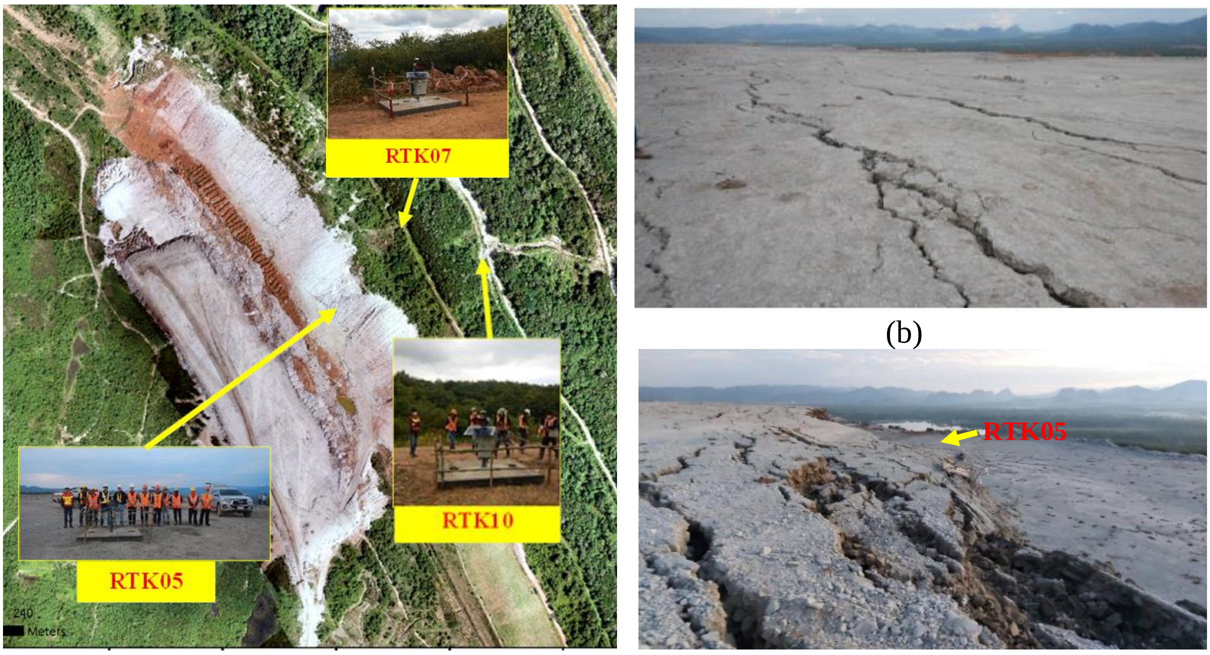


(b)

Figure 9 The field experiments: (a) horizontal and (b) vertical accuracy tests.

The RTK GNSS receiver unit was placed around the pit and dumping areas on the linear rail within 10 km of CORS. Currently, there are four CORS in Mae Moh Mine; one is Trimble NetR9, and the others are CHC P5E-Net, see Figure 8. Both types have high precision, usable for professional applications such as surveying, geodesy, and mapping. One of the CORS nearest to the receiver unit was chosen to transmit RTK differential data corrections. While the unit received the GNSS signals, it was moved along the rail in forward/backward directions every 25 seconds with a 5 cm increment/decrement from the middle or starting (0cm) position of the rail.

Figure 9 shows the RTK GNSS receiver unit's horizontal and vertical displacements determined over time. The forward plot is shaped like a stair with a 5cm step height, similar to the case of the backward direction, see Figure 9a. This result corresponds to a horizontal accuracy of a few centimeters that the receiver provides at short distances. For the vertical test, we unmounted the GNSS antenna from its position and slowly moved it along a ruler attached at 0cm, 5cm, 10cm, 0cm, 10cm, 0cm, 10cm, 0cm, and the antenna position, as shown in Figure 9b. Although the multipath effect could significantly cause a few centimeter errors while moving the antenna, the result revealed that vertical accuracy at a sub-decimeter level was achievable. In conclusion, the test results demonstrated that the low-cost RTK GNSS receiver units sufficiently provided the accuracy requirement of landslide displacement, i.e., 5cm or better in Mae Moh Mine, including waste dump areas.



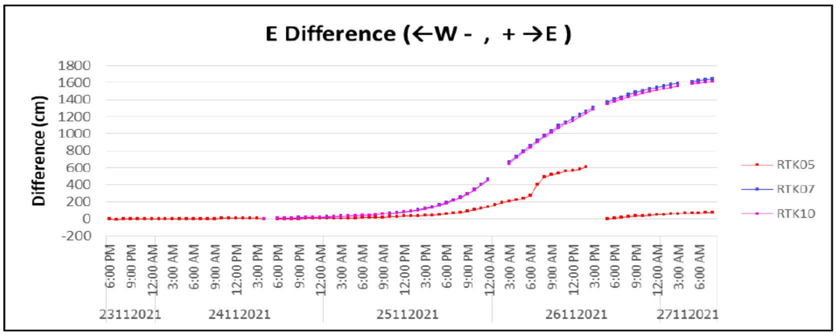
(b)

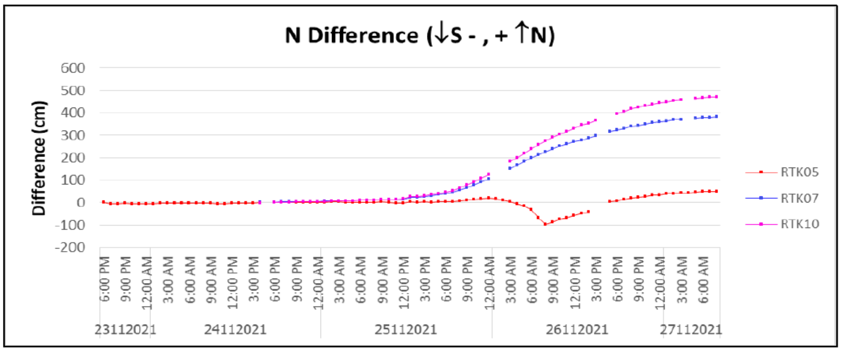
(a) (c)

Figure 10 (a) The test site in the west-side dumping area at landslide risk and three low-cost RTK GNSS receiver units (i.e., RTK05, RTK07, and RTK10); (b) the 250 m length of tensile cracks on November 22, 2021; (c) the landslide failure on November 26, 2021.

4.2 The experimental site in a landslide hazard area

The test site chosen to experiment with the integrated system of the RTK-LANDMOS was located in the upper north of the west-side dumping area, having landslide susceptibility. This dumping area's slope had dense trees that might obstruct the 4G mobile network. We urgently installed three RTK GNSS receiver units (i.e., RTK05, RTK07, and RTK10) in the area on November 22, 2021, after a few 250m-length tensile cracks appeared, as shown in Figure 10. The receiver units were temporarily mounted on 1.5m x 1.5m concrete platforms and located on different dump floors (each floor was approximately 15 -20 m high). Each platform had a 300 kg weight, enabling the receiver unit to be stable on the ground surface.





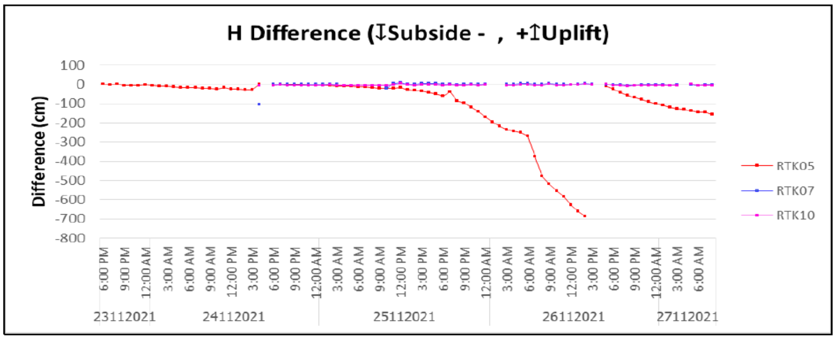
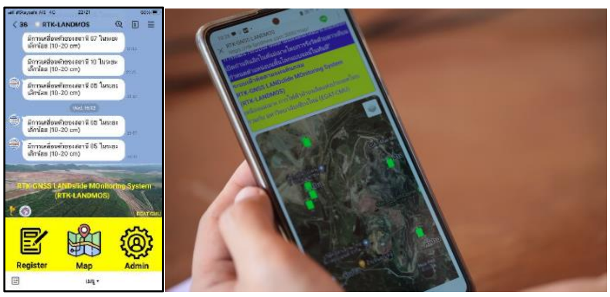


Figure 11 The land movement displacements during 23-27 November 2021.

The monitoring system continuously acquired the land movement data sets between 22 and 27 November 2021 with a 1Hz measuring rate. The transmission network was provided by a GSM model using a 4G telecommunication network. Some outliers were automatically detected and filtered out from NMEA data files using an additional outlier detector based on a least-square adjustment method. The filtered data (acquired from one second) were averaged using all data from the previous 15 minutes. Then, the averaged data were used to calculate daily displacement plots in North, East, and Up(or Height) directions every 15 minutes. This time frame has been selected based on the characteristics of land movements in Mae Moh Mine.

Figure 11 shows the displacement plots trend to change significantly with respect to time. It could be seen that the landslide failure started at 18.00 pm on November 25 and until 8.00 am on the next day. For instance, the RTK07 had the largest movement of 14 m in the East direction. In contrast, the RTK10 had the most significant movement of 4 m in the North direction, and the RTK05 quickly collapsed as much as 7 m (see Figure 10c). The easting and northing plots of the RTK05 were shifted by about 10 m because of its relocation at 15.00 o'clock on November 26, 2021. In addition, there were gaps in the plots due to no transmission data caused by the loss of 4G mobile network connectivity in the obstructed environments.

The results confirmed that the RTK-LANDMOS had sufficient accuracy and reliability for landslide monitoring. The RTK-LANDMOS continuously operated for 24 hours to monitor the movements. The system significantly contributed to landslide management's effective preparation and mitigation phases during the concurrence of landslides, e.g., emergency evacuation procedures, moving out of machinery, and area closure.



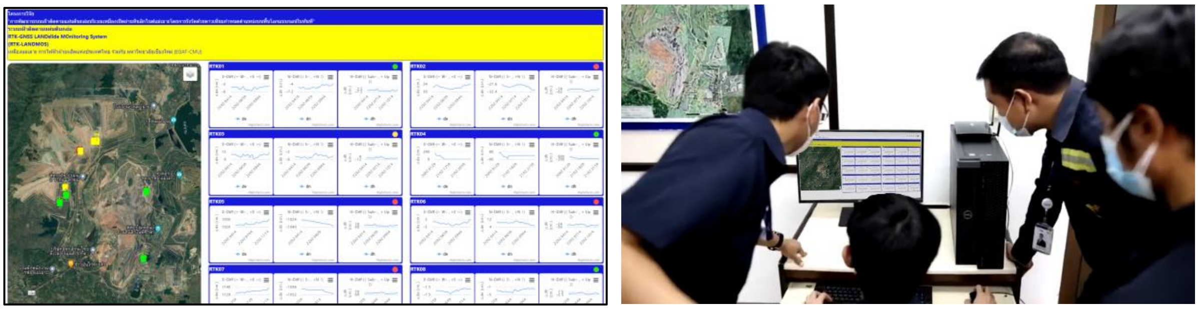


Figure 12 The RTK-LANDMOS provides notifications and land movement displacements on LINE® and Web applications.

The remaining RTK GNSS units were installed until early January 2022. All units were distributedly over Mae Moh Mine, especially the west-side dumping area. The system's work process was examined and found to work perfectly. Each unit's movement results and status can be accessed via the LINE® and Web applications on either the smartphone or the personal computer, as shown in Figure 11. After all, the RTK-LANDMOS, as an early warning system, can reduce the possibility of injury, death, damage, and property loss from EGAT individuals and communities by immediately responding to landslide hazards in vulnerable areas of Mae Moh Mine.

5. CONCLUSION AND FUTURE WORK

We have developed the RTK GNSS landslide monitoring system (RTK-LANDMOS) for landslide movement monitoring and early warning in the Mae Moh lignite open-pit mine. The RTK-LANDMOS comprises ten low-cost RTK GNSS receiver units, ten integrated 4G LTE communication units, and one processing unit. The system continuously operates for 24 hours to analyze the effects of landslides induced by mining activities and slope's behavior through 10 monitoring stations distributed across the mine pit and dumping areas. The RTK-LANDMOS efficiently manages real-time GNSS monitoring raw data transmitted to a central computer server from the on-site stations. The system will turn on the warning LED light if the land movement exceeds tolerance criteria. Simultaneously, the warning message will be sent to all authorized participants via an online application, for instance, LINE® messenger. The experimental test indicates that the system provides a positioning accuracy of 5cm or better, sufficient for detecting landslides in the Mae Moh area. On November 22-27, 2021, the system significantly contributed to landslide management's effective preparation and mitigation phases during the concurrence of landslides in the upper north part of the west side dumping area.

Such an early warning system can reduce the possibility of injury, death, damage, and property loss from EGAT individuals and communities by immediately responding to landslide hazards in the Mae Moh mine area. EGAT has recently decided to increase more than 50 low-cost RTK GNSS receiver units, together with a new development of the RTK-LANDMOS. In 2025, at least 100 receiver units will be ready to operate over Mae Moh Mine to provide continuous and accurate positioning 24/7. The new version of the RTK-LANDMOS will be considered a primary service supporting disaster management. After all, the RTK-LANDMOS ensures the safety of mining facilities and activities, resulting in the stability of the coal supply to power plants and strengthening Thailand's energy security and sustainability.

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BIOGRAPHICAL NOTES

Dr.Puttipol Dumrongchai is the head of this research and an Associate Professor at the Department of Civil Engineering, Chiang Mai University. He received his B.Eng. from Chulalongkorn University and an MS in Spatial Information Science and Engineering from the University of Maine, US. He continued his Ph.D. at Ohio State University, US., where he obtained his Ph.D. in Geodetic Science and Surveying. Assoc. Prof. Dr. Dumrongchai's current interests involve Local Geoid Determination, Terrestrial and Airborne Gravimetry, Physical Geodesy, Inertial Navigation Systems, and Geodetic/GNSS Applications. In 2015-201, he was appointed as the head of the Development Project of the Thailand Geoid Model, joined by the Royal Thai Survey Department, Royal Thai Armed Forces Headquarters.

Dr. Chawis Srimanee is a lecturer at the Department of Geography, Chiang Mai University. He received his B.S. (Geography), M.S. (Geoinformatics), and D.Eng (Surveying) from Chiang Mai University. The interesting area of research involved Physical Geodesy, Airborne Gravimetry, Geoinformatics, Physical Geography, Database Design, and Web development. Dr. Srimanee also has a long-term experience in advanced digital photogrammetry using LiDAR and multiple cameras.

Boonyarit Keawaram is the head of Mine Survey Section, Mae Moh Mine, the Electricity Generating Authority of Thailand. He obtained B. Eng, Survey Engineering, Kasetsart University and M. Eng, Civil Engineering, Chiang Mai University, Thailand. Boonyarit has currently been in charge of all mine survey works in Mae Moh Mine. He is a specialist in mine surveying and has long-term experiences in a long-range terrestrial laser scanner, LiDAR, unmanned aerial vehicle, and GNSS.

Thanatepol Boonprakob is the head deputy of Mine Survey Section, Mae Moh Mine, the Electricity Generating Authority of Thailand. He obtained B.Eng, Survey Engineering, Kasetsart University and M.Eng, Civil Engineering, Chiang Mai University, Thailand. Thanatepol has currently been in charge of coal volume computations in Mae Moh Mine. He is a specialist in mine surveying and has experiences in a long-range terrestrial laser scanner, LiDAR, unmanned aerial vehicle, and GNSS.

Teeradon Thongkam received B. Eng, Survey Engineering, Chulalongkorn University, Thailand. Teeradon is a survey engineer of the Mine Survey Section, Mae Moh Mine, responsible for overburden and coal volume measurements using a long-range terrestrial laser scanner and unmanned aerial vehicle integration method. He also is a specialist in GNSS.

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