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Analysis of landslide kinematics integrating weather and geotechnical monitoring data at Tan Son slow moving landslide in Ha Giang province

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ABSTRACT

Rainfall infiltration on the slope increases pore-water pressure in the soil/ rock mass and may cause landslides. Therefore, the precipitation, pore-water pressure and displacement show the kinematic variation of a landslide. In recent years, several approaches have been proposed to investigate the kinematic behavior. Among them, the combination of time series data and geotechnical model has demonstrated its effectiveness in stage classification of landslide kinematics. This paper aims to analyze and classify the stages of landslide kinematic variation with integrating weather and geotechnical monitoring data of Tan Son market landslides. The real-time monitoring station for Tan Son slow-moving landslides were equipped with fixed-in-place inclinometer probes and standard pore-water pressure sensors. The results show that landslide kinematics consist of three stages: stabilization, accumulation, and displacement. The displacement of the landslides was heterogeneous process. The velocity of the landslides significantly increased when the pore-water pressure ratio (r_u) at the sliding surfaces > 0.53. While it is almost impossible to notice any displacement when the ratio r_u < 0.45. During the displacement state, the trend of inverse velocity variation gradually decreases to near zero hour/mm. In addition, early warnings of landslide can be released based on the kinematic stages and changes in inverse velocity in this study.

Keywords: pore-water pressure, inverse velocity, displacement of slow-moving landslides, precipitation, Tan Son.

1. Introduction

The most rudimentary knowledge required for understanding landslide mechanisms and effects is that of kinematics. Most landslide technical literature proposes approach methods to measure precipitation, pore water pressure and displacement variation. These approaches can be divided into “physically based” and “phenomenologically based” models. The phenomenologically based approaches (Hong, 2005; Maugeri, 2006; Van Asch, 2007) aim to establish empirical correlations between displacements and their triggering factors or statistical relationships between the measured groundwater pressures and the weekly/ monthly rainfall, without explicitly taking into account the physical processes occurring in the slope. Because of the hydraulic and mechanical behavior of the soil, the physically based approaches try to

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*Corresponding author, Email: ducgeo@gmail.com reproduce the physical processes relating pore water pressure fluctuations to the rainfall regime (Calvello, 2007; Cascini, 2010; Palis, 2017; Vassallo, 2015). Relationship between pore-water pressure and displacement of a landslide is explained through statistical correlation relations (Sumio Matsuura, 2008; Wei-Li Liand, 2020; Md Rasel Sheikh, 2021). Therefore, the combination of landslide kinematic analyze results using geotechnical monitoring data and the validation geotechnical model result, to improve landslide forecasting, is a major focus of landslide research.

Rain infiltrates into the ground and forms ground-water, which flows through geological layer and is finally discharged into rivers. During this sequence of processes, the pressure of the water that fills the void spaces between soil particles and rock fissures rises when the amount of water infiltrating into the ground increases. A rise in pore water pressure causes a drop in effective stress, affecting the stability of a slope, and thus is a triggering factor of landslides. The relationship between precipitation, pore-water pressure and displacement of a landslide is the same as a cause-and-effect relationship. The response analysis of this relationship is necessary in the study of landslide kinematics. The persistent and long-term motion of slow-moving landslides provides an exceptional opportunity to investigate landslide processes and mechanisms. The landslide velocity is modulated by external forcing (such as precipitation, earthquakes, material supply and anthropogenic activity) (Pascal Lacroix, 2020). While the Global Climate Model well represents the observed average rainfall cycles, its coarse resolution limits its capability in reproducing extreme rainfall values (Hoang Cong H., 2022). Therefore, most of the landslide monitoring systems are installed at the slow-moving landslide (Allan, 2004).

Precipitation, pore water pressure and inclinometer are common monitoring methods at many different landslide sites (Baron, 2013). Nevertheless, detailed installation of rainfall-induced landslide warning systems for site-specific scale is still rare in Vietnam. The first landslide early warning system is installed in Hoa Binh province (2005). However, long-term maintenance of this monitoring system had been difficult, it was impossible to collect time series data. With the upgrade of storage and communication equipment in monitoring system, monitoring data was collected continuously with high temporal resolution provide significant opportunities in broadcasting warning information (Gian, 2017). In Xin Man, there were two landslide monitoring systems installed at Tan Son and Ban Diu villages in 2017 but the data of Tan Son station is longer and more complete than Ban Diu station. Until now, the Tan Son monitoring data is long enough to explore and find the relationship between precipitation, pore-water pressure and displacement of landslides.

The main objective of this study was to analyze continuously monitoring data on precipitation, pore-water pressure and displacement. Moreover, this study focuses the analysis at the times when the displacement or slope failure around the monitoring area is recorded. Therefore, we concentrated the following questions related to Tan Son slow-moving landslides:

- When will pore-water pressure variation become significant with affecting the displacement of Tan Son slow-moving landslide?
- How can determine the critical displacement stage and when the warning information will be issued?

2. Overview of the research site

Xin Man is a highland district in the western part of Ha Giang province. The district is characterized by strong dissection of topography, terraced slopes, many high mountains, and prone to landslides. The elevation varies from 140 to 2,400 m. Valleys are very deep, and characteristic V-sharps (Nguyen, 2016). This district covers an area of 582 km^2 and is currently considered to be one of the most prone landslide areas in Vietnam. Local people usually live on the slopes less than 2,100 m elevation, few of them are old deep-seated landslides. Due to the favorable conditions of terrain and water source, local residents often settle on these terrains, they also build terraced fields for rice. Therefore, most landslide occurring affect human's lives in this area.

The entire bedrock in the area is intrusive rocks of the Song Chay complex (γaD1sc), which is intensively weathered. The geotechnical properties of rock and soil express these are quite weak and highly vulnerable to landslides (Nguyen Ngoc T., 2015; Nguyen Q.H., 2017). We explored and recorded the seventy large landslides since 2015 (Fig. 1). The large landslides appear more in the Northwest region and less than in the southern region. Most of the large landslides are located in the terrain with elevation < 1,500 m, located along the main traffic routes in terrace fields, very few landslides appear in the area with thick vegetation cover. There are eleven slow-moving masses, the slide movement repeats many times, the range of the next slide is wider than the previous. They are all located on terraced fields and regularly affect agricultural production. The method of agriculture on the slopes of local people requires experiment about steep slope stability. Many large landslides are involved in the creation of steep slope and the pounding of water in the steep field. On the rice growing process, local people have to store water in terraced fields, which can reduce the factor of safe land.

After landslide analyzing about shape, slow-moving, material composition and characteristics of agricultural cultivation, we installed the monitoring equipments at Tan Son slow moving landslide (Figs. 2 and 3). The landslide is located on the terrace field, the slope angle varies from 25° to 30° degrees and their runing-out area will be able reach to many local houses. The landslide developed on igneous bedrock belonging to the Chay River complex, the largest igneous rock formation in Vietnam. The Chay River is divided into two main phases: the phase 1 consists mainly of porphyroid granite, medium to big- grained two-mica granite with gneissose texture; phase 2 is represented by medium grained two-mica granite, biotitegranite. Moreover, the upper part of the bedrock has been strongly weathered, whereas, at the bottom, the bedrock acts as an aquiclude. The thickness of the weathering layer is approximately from 1-3 m to 10-20 m including four levels: (1) fine sand layer with highly organic soils, (2) clayey sand, (3) poorly graded gravel with boulders, and (4) granitoid - gneiss rock with many cracks.

The Tan Son landslide began in July 2012 after one-week heavy rain. In August 2013, the landslide was still active again, causing serious damages to 5 houses, Tan Son market and provincial road No. 178. In the middle of the landslide body is the central market where local residents are crowded every weekend. On the surface, there are many huge gully erosions appear. In August 2016, there are some gully erosions creating holes with 1.5-2 m depth, 6 m diameter on average. This landslide is about 125 m wide, 150 m long, the depth of failure surface is 12.5 m, 122.270 m^3 volume, the main direction of movement is 75 degrees. There are many small houses and a market on the body landslide.

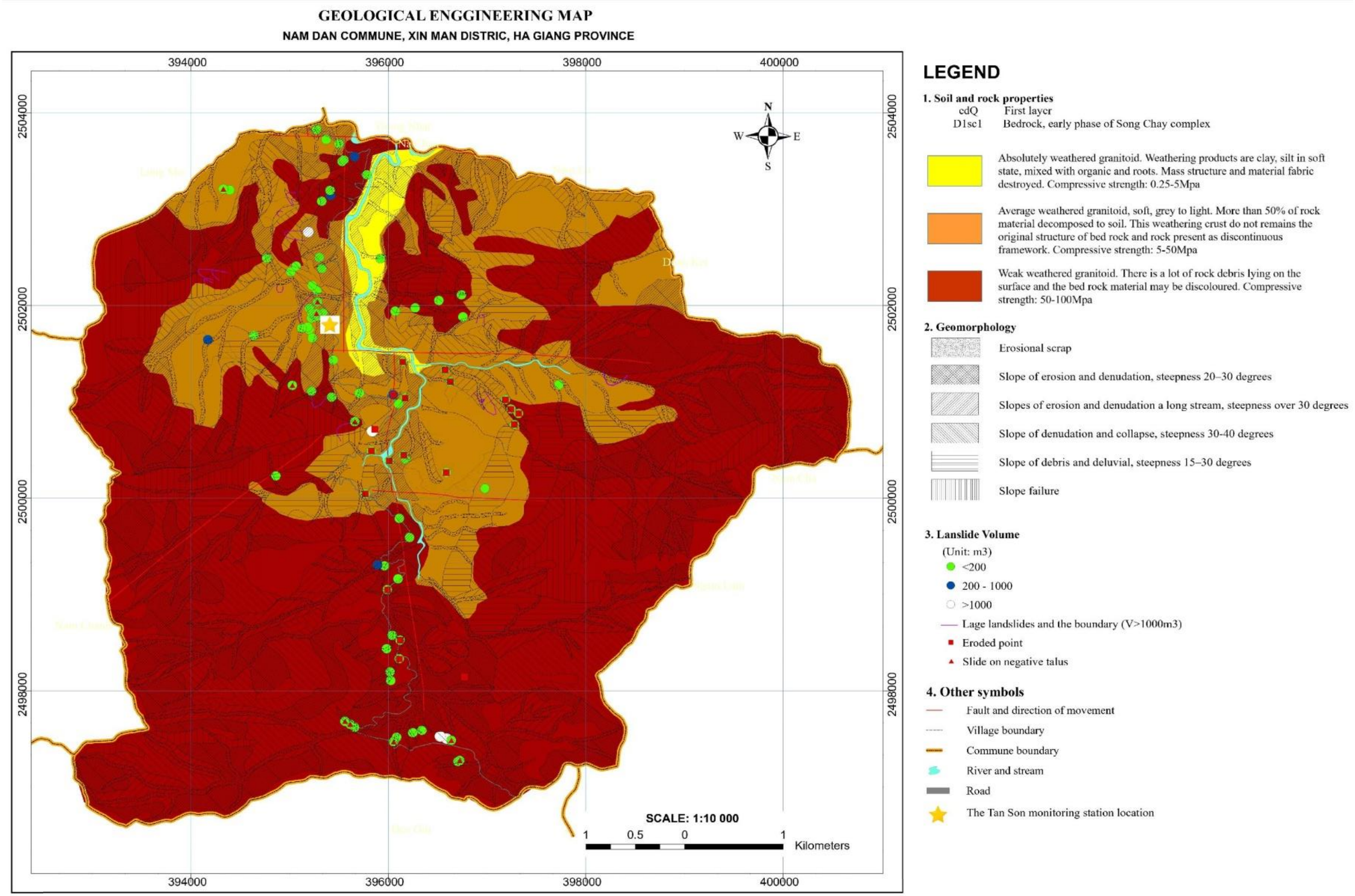

Figure 1. Geological engineering map in Nam Dan commune, Xin Man district, Ha Giang province (Nguyen Ngoc T. 2015)

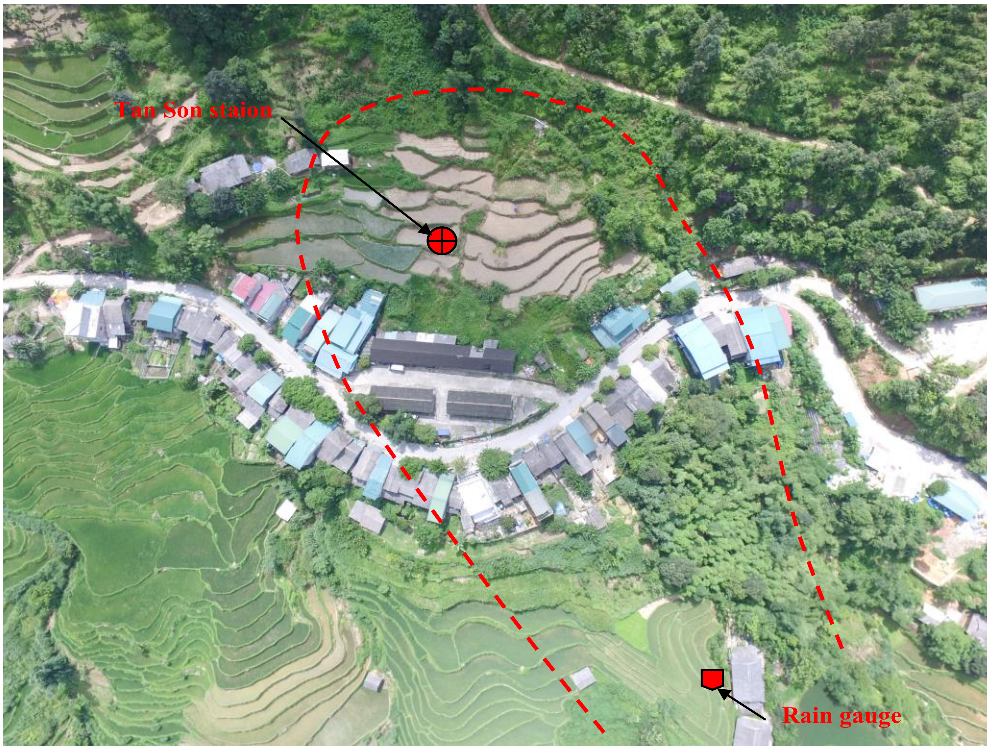

Figure 2. The Tan Son station on the slow-moving landslides in terrace fields in Xin Man district

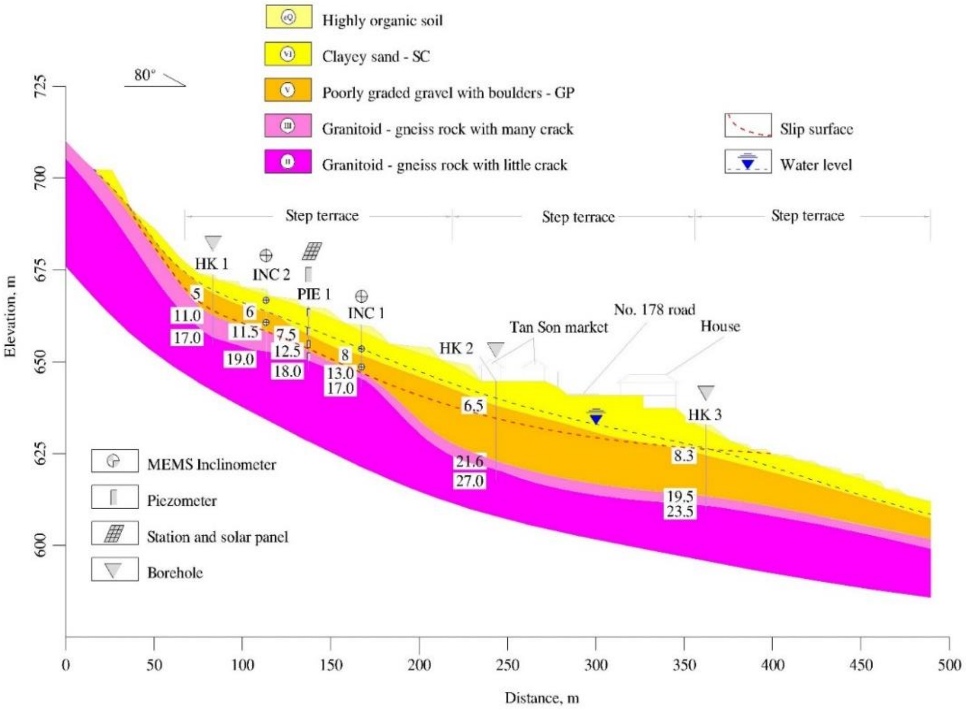

Figure 3. Geological longitudinal section of Tan Son slow-moving landslide

3. Materials and methods

3.1. Survey data

The depth of the geological strata is determined by the drilling method. Survey drilling work was carried out by XJ-1A machine, sampled by T6.86 sample tube. The samples taken are arranged in order from top to bottom according to the order of stratigraphy, recorded and described in the borehole cylinder. Samples are sealed in trays and then taken a photo to save the order of strata depth, each tray describes 5m of stratigraphic length. The image of the drilling sample allows easy recognition of the rolling rock or special stratigraphic changes, a preliminary assessment of the depth of the slip surface to install various types of monitoring sensors in the borehole.

The soil sample test results at the slip block location are used from the research results in the VINOGEO-SRV project. The samples were analyzed at the geotechnical laboratory to determine the physico-mechanical properties of the soil samples such as grain composition for soil classification, moisture content, density, alterberg limit, direct shear resistance. In soil classification, the soil classification system according to ASTM D-18 issued in 2011 is used for soil samples tested.

3.2. Monitoring sensors

The station system consists of sensor nodes, data logger, gateway, server and solar power arrangement (Gian Quoc Anh, 2017). Data packages received from the real-time monitoring stations are transmitted to the data center in an hour for a package. Finally, the data plots are saved at system storage and posted on the web site for access by the general public. The monitoring data is recorded from 3 main types of sensors: rain gauge, piezometer and inclinometer (Table 1).

Table. 1. Types of sensors and installation depths at slow-moving landslides

Sensor type	Sign	Borehole	Depth (m)
Piezometer – Geokon Model 4500S	TS_PIE1	BH1	1.5
	TS_PIE2	BH1	6.0
	TS_PIE3	BH1	10.5
	TS_PIE4	BH1	13
In-Place Inclinometer – Geokon MEMS Model 6155	TS_Inc1	ICL1	6.8
	TS_Inc2	ICL1	12.0
	TS_Inc3	ICL2	2.8
	TS_Inc4	IPI2	8

Rain gauge: The wireless iMETOS ECO D3 is a solar panel and battery powered data logger, designed to work in harsh conditions and in all climate zones. The system has a fully integrated UMTS/CDMA modem for direct communication with the FieldClimate platform. Data is regularly uploaded to FieldClimate platform where you can access it from any place at any time in real-time.

Piezometer: The Model 4500 Standard Piezometer is designed to measure fluid pressures such as ground water elevations and pore pressures when buried directly inside boreholes (90 mm diameter). The Model 4500AL is designed for low-pressure ranges with a heavy duty housing for pressures that exceed 3 MPa. Piezometer sensors are installed at depths: 1.5 m, 6.0 m, 10.5 m, 13.0 m at Tan Son station.

In-place inclinometer: The Model 6155 MEMS Horizontal In-Place Inclinometer consists of a string of MEMS (Micro-Electro-Mechanical Sensor) tilt sensors mounted on lengths of stainless-steel tubing, which are linked together by universal joints. The string of sensors is installed inside the casing with all the sensor cables passing to the surface where they are connected to data loggers. In the borehole, the lower sensor is installed in bedrock layer, the upper sensor is installed in soil layer. Inclinometer sensors are installed at depths: 6.8 m, 12.0 m, 2.8 m, 8.0 m at Tan Son station.

Data logger: The CR1000's module measures sensors, drives direct communications and telecommunications, reduces data, controls external devices, and stores data and programs in on-board, non-volatile storage. The electronics are RF shielded and glitch protected by the sealed, stainless-steel canister. The standard CR1000 had 2 MB of data/program storage.

3.3. Inverse velocity

Saito (1986) and Voight (1988) introduced instructions for processing observational data based on the inverse velocity to determine the displacement speed of the sliding block. As the strain rate increases, the velocity inverse will tend to gradually approach the time axis. Through the graph of the relationship between the inverse velocity and time, the intersection point between the time axis and the inverse velocity is considered the moment of instability of the sliding block. It has been shown that the inverse velocity of the sliding block usually displays a near-linear trend during the displacement acceleration period. Then, the linear regression method is used as a tool to estimate the slip time.

Just looking at the cumulative displacement chart will not identify the velocity of slope movement in short periods of time. Therefore, this study conducts an analysis of both the velocity variation and the inverse velocity of the landslide. However, inferring suitable linear trend lines and deducing reliable failure predictions from inverse velocity plots are processes that may be hampered by the noise present in the measurements. Data smoothing is therefore a very important phase of inverse velocity analyses.

When considering time series of short periods, the time interval is hours, the displacement data often changes rapidly and continuously, so it is difficult to determine the trend. It is necessary to use a tool to smooth this monitoring data. In this study, different filters are tested on velocity time series with loess regression function in R software. It is a non-parametric method where least squares regression is performed in localized subsets, which makes it a suitable candidate for smoothing any numerical vector. Loess regression used the polynomial function on a numerical vector to smoothen it. The size of the neighborhood can be controlled using the span argument, which ranges between 0 to 1 to control the degree of smoothing.

4. Monitoring Results

4.1. Precipitation

Looking at the rainfall graph, the amount can be divided by season. From October to May is the time of the dry season, from May to mid-June is the beginning of the rainy season with heavy rains, from mid-June to September is the time of the rainy season accompanied by rains with great intensity or lasting for many days (Fig. 4). The annual temperature change is also quite similar to the annual rainfall. The temperature increases from May to September, and decreases deeply in the rest of the year. The results of this study are similar to evaluation the performance of Global Satellite Mapping of Precipitation data in observing the sub-daily rainfall patterns in Vietnam and Representative Concentration Pathway scenarios (RCP4.5 and RCP8.5) (Pham T.T.H., 2021 & Nguyen Ngoc Bich P., 2022). The total annual rainfall in 2017 and 2020 is larger than the total annual rainfall in 2018 and 2019, which is related to the number of landslide events recorded in the Xin Man region. Precipitation and temperature are important factors used to correct for environmental noise for a time series of monitoring data.

In rainy season, the maximum

precipitation can rise up to 200 mm. There are many landslide events recorded in Xin Man district area that are related to heavy rains. Landslide events are recorded on dates: "2017-07-09", "2017-07-20", "2017-08-25", "2017-09-30", "2018-06-27", "2018-07-31", "2019-07-30", "2020-07-05", "2020-10-01". Landslide events often occur after heavy rains briefly. There are two types of rain that cause significant displacement of the slow-moving landslide: heavy rain and long-term rain. Observed for a long time, the temperature seems to have non-influence and non-relevant with the landslide events. However, temperature fluctuations cause the material to expand, forming fluctuations in the displacement data. Therefore, the temperature data are used to correct for noisy fluctuations for the displacement data. The main agricultural cultivation affect the surface of the terraces takes place in January to March. They only interfere with the piezometer sensors near ground surface. Therefore, this research does not use the data of the near surface piezometer.

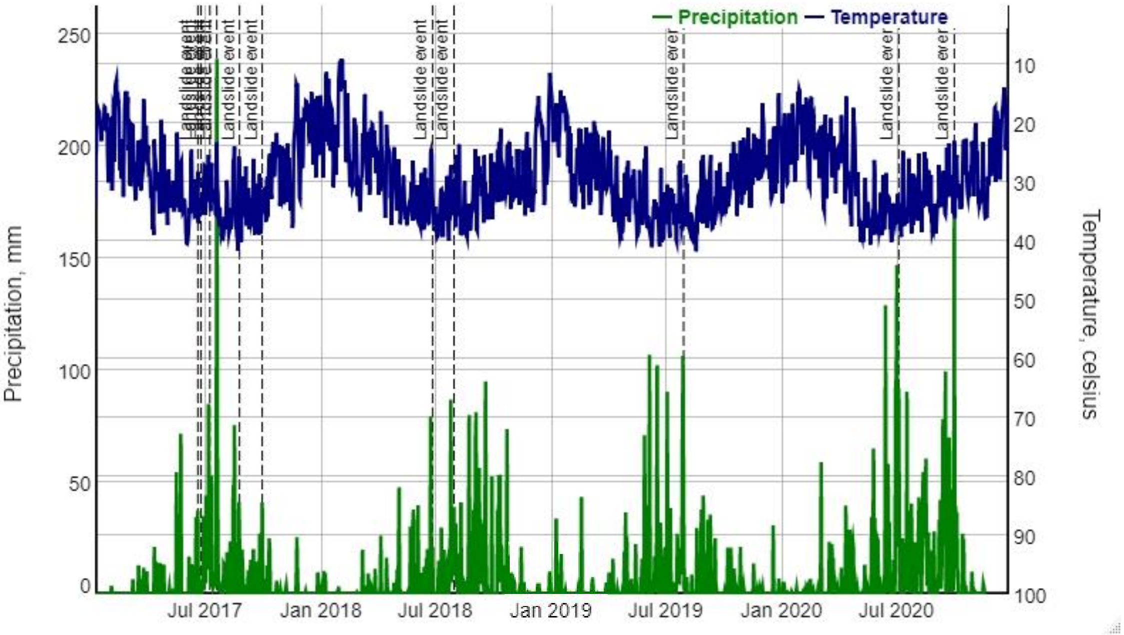

Figure 4. Monitoring data in rainfall and temperature in Xin Man from Jan. 2017 to Dec. 2020

4.2. Pore-water pressure

Figure 5 shows that the changing trend of pore water pressure at different depths in the landslide body is similar. These trends are cyclical in nature and highly dependent on rainfall. In both slow moving landslide, these trends can be divided into different periods. The degree of variation of pore water pressure between two seasons (dry season and rainy season) at Tan Son station is very clearly. However, when landslide events occur, the pore pressure at different depths has a more distinct variation. At the near landslide surface, the trend of pore water pressure change faster and larger than other locations above. In Tan Son landslide, the pore water pressure near the landslide surface at a depth of 13.0 m (TSPie4) showed quite coincident with the times of recorded landslide events.

The dry season lasts from November to May and has a total precipitation of about 20% per year (300-500 mm/year). Temperatures tend to increase and evaporate released water in the soil quickly. Some small rains with a precipitation less than 40 mm are not enough to make the pore-water pressure to change clearly. Pore water pressure refers to the pressure of groundwater held within soil or rock, in gaps between particles. The vertical pore water pressure distribution in aquifers can generally be assumed to be close to ground water pressure. Relationship between figure 4 and 5, pore-water pressure is influenced by the seasonal cycle.

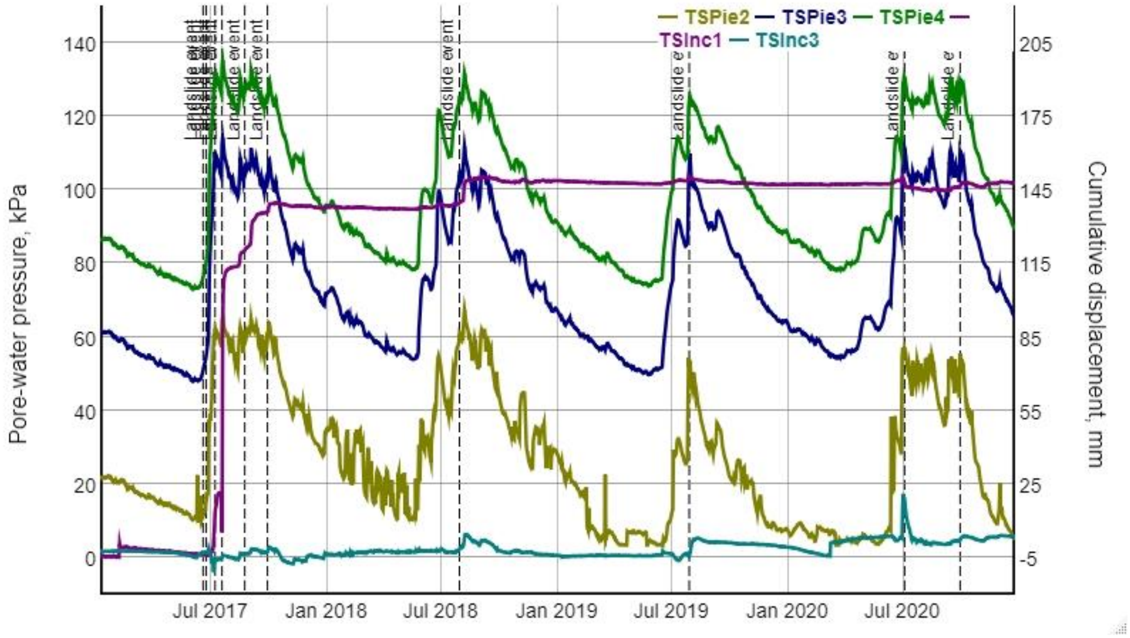

Figure 5. Monitoring data at Tan Son station from Jan 2017 to Dec 2020, relationship between pore-water pressure and cumulative displacement

Although the trend of pore water pressure evolution at different depths is similar, their values are different. Furthermore, the development of slope stability charts in particular necessitated a pore-water pressure definition. Therefore, the value of the pore-water pressure ratio (Ru ratio) is an advantage to use in the stability analysis. The Ru ratio is a simple way of describing pore-water conditions in a slope stability analysis. Generally, this threshold level is defined in terms of an excess pore water pressure ratio (r_u, where; Δu = excess pore water pressure; and = initial vertical effective stress). Although a single Ru ratio value can seldom, if ever, represent the actual field groundwater flow conditions but Ru ratio remains an option in SLOPE/W for legacy reasons. Seed and Booker (1977*)* originally proposed using a threshold level of about 0.6 for Ru ratio, but Japanese practice has recommended using a smaller threshold between 0.25 and 0.5 because of the uncertainty in predicting the magnitude of the generated excess pore water pressures (Iai et al., 1988; Japanese Geotechnical Society, 1998).

4.3. Landslide displacement

Displacements are determined by monitoring data occurred in the months of July, August, September and the beginning of October, the displacement is almost non-existent for the rest of the year. In general, the cumulative displacement tends to decrease in quantity and value from 2017 to 2020. At Tan Son station, on the cumulative displacement chart, there are four clear displacements in 2017, there is one large displacement in 2018 and 2019, there are two displacements in 2020.

Through the evolution of the cumulative displacement chart, the days had displacements recorded at the monitoring station from 2017 to 2020: "2017-07-09", "2017-07-20", "2017-08-25", "2017-09-30", "2018-06-27", "2018-07-31", "2019-07-30", "2020-07-05", "2020-10-01".

The trend of cumulative movement at Tan Son landslide is decreasing from 2017 to now. Therefore, short period significant shifts are used mainly at Tan Son landslide to compare with landslide events. The above observational results are also very similar to the external appearance of the landslide events. Moreover, the width of the gully erosion is widened over time.

5. Discussions

5.1. Kinematic characteristics of Tan Son slow-moving landslides

5.1.1. Long-term period

We propose a three-stage classification: stabilization stage, accumulation stage, displacement stage (Fig. 6). Once established, these may be performed automatically and with little input from monitoring data. This classification involves identifying onset of acceleration point and the setup of two different alarm levels, which would support the definition of the emergency plans.

Stabilization stage: The pore-water pressure ratio is less than 0.45, the time usually lasts from October to May next year. This stage does not record any effect, and can cause the displacement of the Tan Son landslides. Agricultural activities can only increase the noise to the piezometer sensors near the ground surface.

Accumulation stage: The pore-water pressure ratio increases continuously from 0.45 to 0.53, this time usually lasts from May to mid-June. This stage records the cumulative displacement value is very small and has not been affected to the stability of the landslides. The accumulation in the sliding mass kinetics here is represented by the pore water pressure ratio value at the most dangerous slip surface position.

Displacement stage: The pore-water pressure ratio increases over 0.53, this period usually lasts from mid-June to October. Besides, the inverse velocity decreases gradually and asymptotically close to the x-axis. From pore-water pressure ratio passed over 0.53 to the landslide events occurred, it was a process of accumulating and increasing rapidly.

The displacement cumulative shows that the number of displacement and the cumulative range of displacements tend to decrease, the more times in 2017 and less in the following years. Moreover, when looking carefully at the displacement stage, the number of times the pore water pressure ratio exceeded 0.53 in 2017 was also more than in the following years. At the beginning of the displacement stage, the increased rate of pore water pressure ratio in 2017 was also faster than in the following years and also recorded 2 landslide events occurring near the Tan Son landslide. Thus, the direct factor that reduces the number of landslide event occurrences is the decrease in the number of times the pore water pressure ratio exceeds 0.53. However, a number of other factors are not clear, so it should be noted that the rate of increase of pore water pressure ratio, agricultural production processes on the slope change the surface water flow, and the change of crops on the slopes.

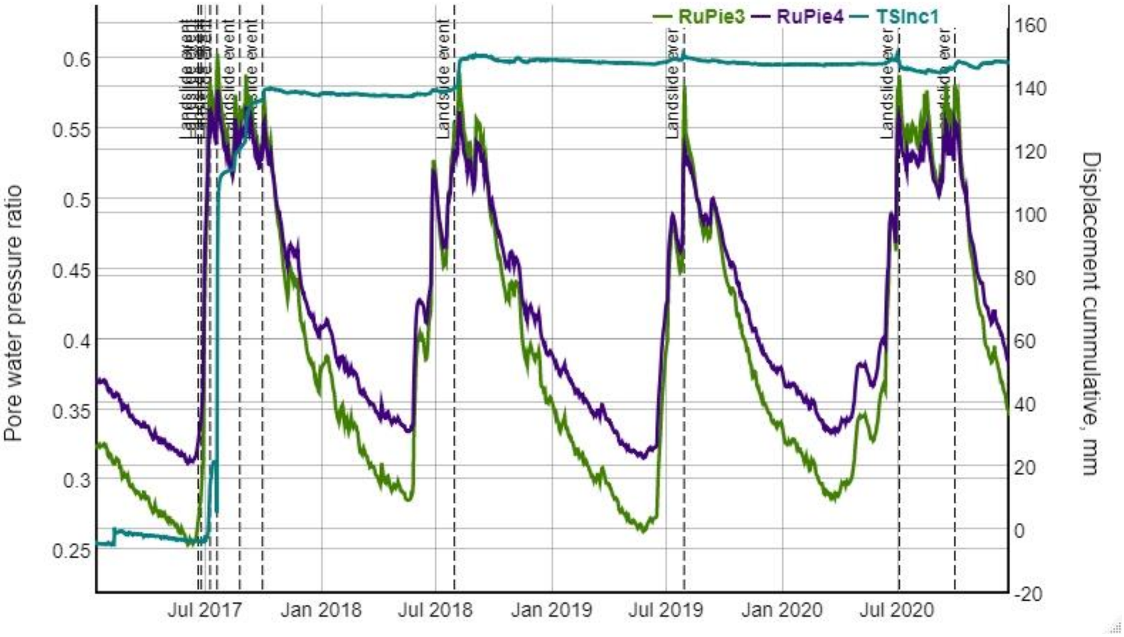

Figure 6. The states of landslide kinematic

5.1.2. *Short-term period*

The recorded landslide events around the monitoring station area are the times that need to be analyzed more clearly in the short time period. Accumulative displacement variation increases rapidly before the landslide events are recorded (Figs. 7). The pore water pressure ratio at the landslide surface is often superior at critical times, greater than the pore water pressure ratio values at other locations in the body of the landslides. Therefore, the pore water pressure ratio is calculated from the monitoring results of the sensors TSPie4 (Tan Son Sliding Block).

When considered for the short time periods before the landslide event occurs, an increase in pore water pressure ratio exceeding 0.53 is considered as the limit to signal multiple displacements determined by the inclinometer sensor. These displacements are much larger than the noise due to the environment and should be assumed to be the displacement of the landslides. At Tan Son landslide, the largest movement was recorded in 2017 and gradually decreased in the following years, the cumulative displacement from 2017 to 2019 is 148 mm.

Figures 7 show that the amount of cumulative displacement recorded by close monitoring for each landslide event varies widely. From 2017-07-04 to 2017-07-14, cumulative displacement is defined as 24.5 mm, but from 2018-07-22 to 2018-08-02, cumulative displacement is only 1.16 mm. Besides, the kinematic process of the slow-moving landslide is the cumulative displacement process. The cumulative displacement value may be small but as long as it will be larger. Thus, the cumulative displacement value depends on the kinematic characteristics of each landslide. It is difficult to use the cumulative displacement value to determine a common threshold for all landslides.

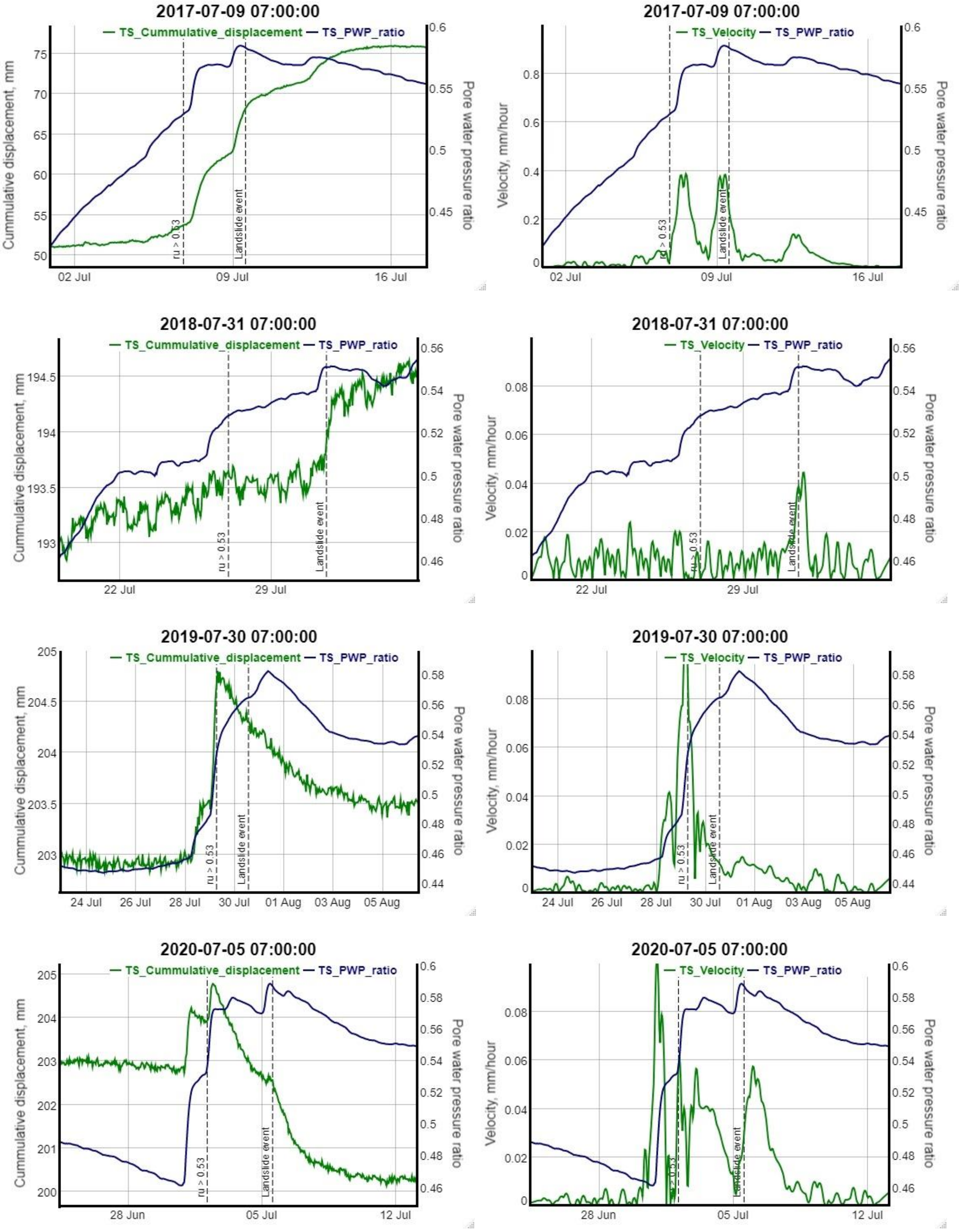

Figure 7. The variation of pore-water pressure over 0.53 at accumulation stage and displacement stage - Tan Son

Analyzing the kinematic characteristics of the sliding block by velocity (mm/h), Figures 7 showed that the speed of the sliding block increases more clearly than the noise caused by the environment. Only the velocity in July 2017 was the highest, most of the speed of the sliding block before the occurrence of the sliding event fluctuated quite similar and less than 0.1mm/h. From the moment the r_u passes 0.53 to the occurrence of the slip event, it is notable that sometimes the velocity exceeds 0.04mm/hr. These are the times when the monitoring system recognizes the movement of the sliding blocks most clearly and should also be considered the time to be warned in advance.

The problem needs to be clarified is how to estimate the time when the displacement appears obviously because the landslide velocity varies continuously. The landslide velocity increases rapidly when pore-water pressure ratio increases rapidly, it is noticeable when pore-water pressure ratio passes over 0.53. The pore-water pressure ratio and velocity variations take place at the same time, so the velocity is not significant in the landslide early warning. Velocity does not fully represent the kinematic characteristics of the slow-moving landslide at Xin Man. The limit of pore-water pressure ratio (r_u=0.53) determined through the monitoring results needs to be further validated by the geotechnical model to have a strong argument for the landslide early warning.

5.2. Prediction of the landslide occurrences based on monitoring data

The interpretation of monitoring data is one of the main points of emphasis when trying to predict the time of a geo-mechanical failure or to assess the probability of a slow-moving landslide. In the above analyses, both cumulative displacement and velocity have certain difficulties in identifying onset of acceleration points. The inverse velocity method demonstrated its effectiveness in anticipating the time of slow-moving landslides. The thresholds which separate the alarm levels would be established without needing a long period of neither reference historical data nor calibration on past failure events. The reliability and the applicability of the method can be decisively improved by time series data smoothing techniques. Therefore, this research uses the inverse velocity data to validate that the threshold is indeed meaningful for the warning that the displacement will occur.

As the velocity increases, the inverse velocity gradually reduces to zero (hour/mm). Figure 8 shows that when the pore water pressure ratio increases over 0.53, the inverse velocity reduced gradually under 25 hour/mm. From then until the landslide event occurs, the inverse velocity is always close to the x-axis. During this period, the reverse velocity value is always less than 25 hour/mm. Thus, the intersection between increasing pore water pressure ratio above 0.53 and reducing the inverse velocity value to less than 25 hours/mm is considered as the onset of accelerating point.

Pore water pressure sensors placed at different depths are subject to various types of errors due to environment and temperature. These errors need to be corrected by averaging or by suppressing error propagation. In this study, we are looking to find the threshold for each sensor position, so we have not conducted error correction for all sensors.

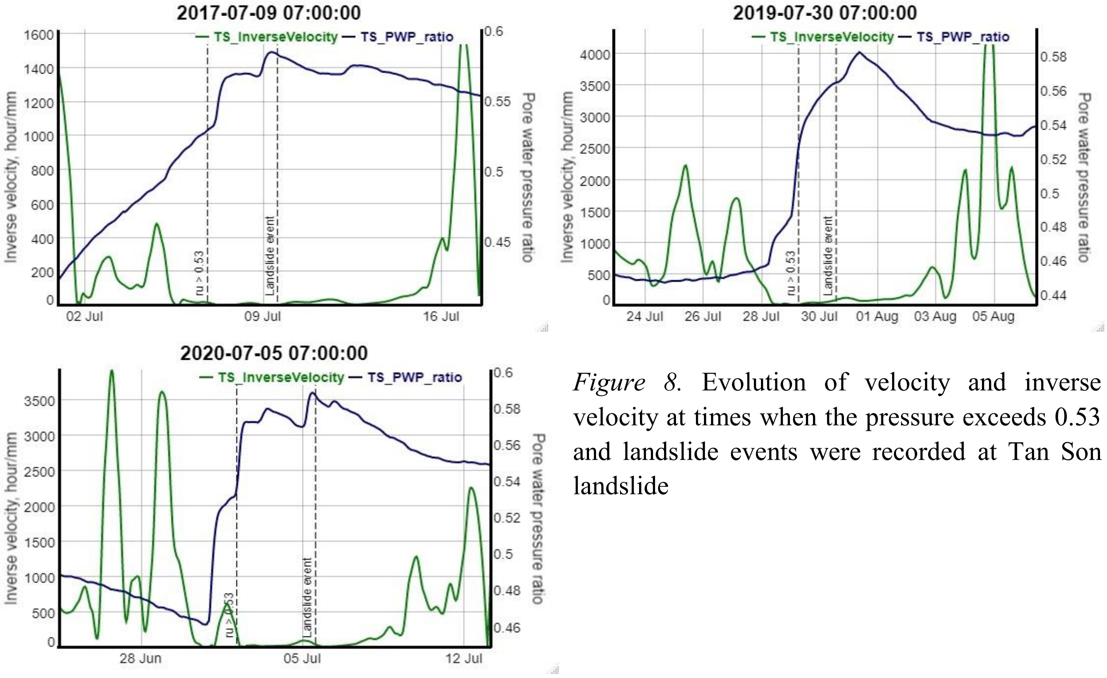

Figure 8. Evolution of velocity and inverse velocity at times when the pressure exceeds 0.53 and landslide events were recorded at Tan Son landslide

6. Conclusions

This study presents the kinematics of the Tan Son slow-moving landslides in terrace fields in Xin Man district, Northern Vietnam. Geotechnical monitoring data of precipitation, temperature, displacement and pore-water pressure is recorded for a long time (is recorded in the period from 1017 to 2020). The 9 landslide events are presented as clear evidence for analysis in short periods, which is the relationship for the kinematic characteristics of the slow-moving landslide.

The landslide kinematics is characterized by three stages of stabilization, accumulation, and displacement. The landslides were stable when the pore-water pressure ratio was less than 0.45. At the accumulated state, the ratio r_u ranged from 0.45 to 0.53. When this ratio increased over 0.53, the landslides began to move down. At the movement stage, the reverse velocity decreased below 25 h/mm and asymptotically near the x-axis. The stage classification involves the identification of the onset of accelerating point and the setting an alarm, which would support the definition of the emergency plans.

The variation of the pore-water pressure ratio near the slip surface of the slow-moving landslide is the most important factor that controls the safety factor. When the pore-water pressure ratio was higher than 0.53, the landslide displacement was well recorded by the inclinometer sensors. The value of 0.53 can be considered as an monitoring threshold for the Tan Son slow-moving landslides.

The factors of cumulative displacement and velocity rapidly changed and were influenced by environmental noise. It is difficult to establish a warning threshold based on displacement. The inverse velocity should be smoothed by the time data series smoothing tool. The result shows that the inverse velocity reduced below 25 hours/mm and asymptotically near the x-axis as the displacement sharply increases. This phenomenon could be clearly observed before the landslide events are recorded and when the pore water pressure ratio increased over 0.53. Combining the variation of the pore water pressure coefficient and the reverse velocity identify the onset of accelerating point. This time is considered as the critical threshold to set an alarm for the Tan Son landslide.

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References

Allan G., Tony M., Colin M., 2004. Monitoring and remediation of a slow moving landslide. ISSMGE, the proceedings of the 9th Australia New Zealand Conference on Geomechanics.

Baron I., Supper R., 2013. Application and reliability of techniques for landslide site investigation, monitoring and early warning outcomes from a questionnaire study. Nat. Hazards Earth Syst. Sci., 13, 3157-3168.

Calvello M., Cascini L., Sorbino G., 2007. A numerical procedure for predicting rainfall-induced movements of active landslides along pre-existing slip surfaces. International Journal for Numerical and analytical methods in geomechanics, 32(4), 327-351.

Cascini L., Calvello M., Grimaldi G., 2010. Groundwater modelling for the analysis of active slow-moving landslides. Journal of Geotechnical and Geoenvironmental Engineering (ASCE), 136(9), 1220-1230.

Gian Q.A., Tran D.T., Nguyen D.C., Nhu V.H., Bui T.D., 2017. Design and implementation of site-specific rainfall-induced landslide early warning and monitoring system: a case study at Nam Dan landslide (Vietnam), Geomatics, Natural Hazards and Risk, 8(2), 1978-1996.

Hoang-Cong H., Ngo-Duc T., Nguyen-Thi T., Trinh-Tuan L., Jing Xiang C., Tangang F., Jerasorn S., Phan-Van T., 2022. A high-resolution climate experiment over part of Vietnam and the Lower Mekong Basin: performance evaluation and projection for rainfall. Vietnam J. Earth Sci., 44(1), 92-108. https://doi.org/10.15625/2615-9783/16942.

Hong Y., Hiura H., Shino K., Sassa K., Fukuoka H., 2005. Quantitative assessment on the influence of heavy rainfall on the crystalline schist landslide by monitoring system -case study on Zentoku landslide, Japan. Landslides, 2(1), 31-41.

Nguyen Q.H., Lieu T.M., Thien H.D., Thinh T.V., Trung B.B., Kien N.C., Thuong N.V., 2016. Forecasting the landslide risk at Nam Dan commune, Xin Man, Ha Giang. Journal of Building Science and Technology, 4.

Nguyen Ngoc Bich P., Phan Van T., Trinh Tuan L., Tangang F., Cruz F., Santisirisomboon J., Juneng L., Xiang Chung J., Aldrian E., 2022. Projected future changes in drought characteristics over Southeast Asia. Vietnam J. Earth Sci., 44(1), 127-143.

Nguyen Ngoc T., Duong T.T., Dao M.D., Hoang H.Y., Pham Nguyen H.V., Tran T.L., 2015. Impact of engineering geology conditions on landslide and land subsidence in Nam Dan commune, Xin Man district, Ha Giang province. Report of Programme SRV-10/0026 Capacity building and technology transfer for mitigation of geo-hazards in Vietnam in the context of climate change.

Iai S., Koizumi K., Noda S., Tsuchida H., 1988. Large scale model tests and analysis of gravel drains. Proc., 9th World Conf. on Earthquake Engineering, Vol. III, Japan Association for Earthquake Disaster Prevention, Tokyo, Japan.

Japanese Geotechnical Society, 1998. Remedial measures against soil liquefaction, A.A. Balkema, Rotterdam, Netherlands.

Maugeri M., Motta E., Raciti E., 2006. Mathematical modelling of the landslide occurred at Gagliano Castelferrato (Italy). Natural Hazards and Earth System Sciences, 6, 133-143.

Pascal L., Alexander L.H., Grégory B., 2020. Life and death of slow-moving landslides. Nature Reviews Earth & Environment, 1, 404-419.

Pham T.T.H., Matsumoto J., Nodzu M.I., 2022. Evaluation of the Global Satellite Mapping of

Precipitation (GSMaP) data on sub-daily rainfall patterns in Vietnam. Vietnam J. Earth Sci., 44(1), 33-54.

Van Asch T., Van Beek L., Bogaard T., 2007. Problems in predicting the mobility of slow-moving landslides. Engineering Geology Journal, 91, 46-55.

Palis E., Lebourg T., Tric E., Malet J.P., Vidal M., 2017. Long-term monitoring of a large deep-seated landslide (La Clapiere, South-East French Alps): initial study. Landslides, 14(1), 155-170.

Saito M., 1969. Forecasting time of slope failure by tertiary creep. In: Proceedings of 7th International Conference on Soil Mechanics and Foundations Engineering, Montreal, Canada, Pergamon Press, Oxford, Great Britain, 667-683.

Seed H., Booker J., 1977. Stabilization of potentially liquefiable sand deposits using gravel drains. ASCE J. Geotech. Engrg. Div., 103(GT7), 757-768.

Sumio M., Shiho A., Takashi O., 2008. Relationship between rain and/or meltwater, pore-water pressure and displacement of a reactivated landslide. Engineering Geology, 101, 49-59.

Vassallo R., Grimaldi G.M., Di Maio C., 2015. Pore water pressures induced by historical rain series in a clayey landslide: 3D modeling. Landslides, 12(4), 731-744.

Voight B.A., 1988. Method for prediction of volcanic eruption. Nature, 332(10), 125-130.

Wei-Li L., 2020. Dynamics of pore water pressure at the soil-bedrock interface recorded during a rainfall-induced shallow landslide in a steep natural forested headwater catchment, Taiwan. Journal of Hydrology, 587, 125003.