

GIANG VAN NGUYEN^{1*}, DUNG QUANG NGUYEN², THANH NGOC LE²**LANDSLIDE SURVEY AT CAM MOUNTAIN (AN GIANG, VIETNAM)
BY SEISMIC REFRACTION AND GPR METHODS**

Cam Mountain in An Giang Province, Vietnam, is a granite peak that is severely fractured and eroded on its slopes and summit. Trees cover the top of the mountain and around the side of the mountain. The roads are the primary means of transportation for indigenous people and tourists daily. Recently, there has been a phenomenon of large-sized boulders rolling down from the top of the mountain, causing an accident and killing tourists. To investigate the internal causes of landslides on a 2.3 km road stretch, geophysical profiles using GPR and seismic refraction methods were conducted to clarify the current status of geological structures beneath the road surface. The refractive seismic data analysis revealed four distinct layers based on elastic wave propagation velocity. Velocity values range from 1000 to 3000 m/s for the 2 upper layers corresponding to the weathered, broken, and highly fractured rock layers and in the lower 2 layers from 3000 to more than 4500 m/s, respectively corresponding to less fractured rock on the depth of more than 50 m. According to GPR data, the structural cross-section to an average depth of 30 m is a more complex picture. Detected 6 layers with different degrees of fracture cracking and showing different structural zones. In a few places are the drainage creeks from the mountain. These places need to be monitored regularly to have a basis for predicting landslides and rockfalls in the area of Cam Mountain. Landslides occur in geological rocks which are of different ages: claystone, mudstone, siltstone, shale, or marlstone. The rock-falls occur in more compact rocks: metamorphic or igneous rocks.

Keywords: Landslides; rock-falls; seismic refraction; GPR; Cam Mountains; Vietnam

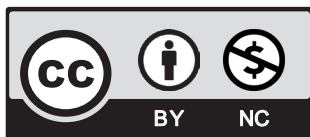
1. Introduction

Landslides are one of the most common types of natural hazards in the world. The characteristic of landslides is that they appear unexpectedly and with very different volumes, depths,

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ranges and frequencies because they come from many different causes [2]. According to many authors of the ground/rock mass movements and landslides monitoring, about half of all landslides are caused by ground slides, ca 10% of all landslides are caused by rock-falls and rolling rocks, ca 28% of landslides are caused by landslides of both soil and rock [6,22]. Most landslides are deep to very deep (surface of destruction at a depth 20 m and more) and considered extremely slow (movement rate <15 mm/year) but active, causing damage to infrastructure and residential houses and, to a lesser extent, in forests or on meadows [23,30]. Almost all landslides, earth flows, and complex mass movements of ground or rocks occurred in a geological setting composed of claystone, mudstone, siltstone, shale, marlstone, or rock of different ages, while rock-falls occurred in more compact rocks, composed of carbonate, metamorphic, volcanic, or igneous rocks [4,25]. Scientists worldwide have recommended measures in areas prone to landslides. It is necessary and crucial to establish a network of monitoring stations for factors that cause landslides [22]. Therefore, in each area where there has been a landslide, it is necessary to study and survey the geological structure characteristics, especially the shallow geological structure by a combination of geological, geophysical, and tectonic methods, etc., and drainage of groundwater [4,13,14,31]. Geological research methods include topography, geomorphology, tectonics, geodynamics, GIS, hydrogeology, and engineering geology to study geological features, fractures, faults, weathering, landslides, falling rock, and rolling stone. Carrying out geological surveys in the field, taking soil samples, and analysing samples in geological laboratories contribute to determining the causes and zoning of the risk of landslides [18,19]. Finally, measures to prevent and overcome landslides in the study area are proposed. The geological research methods for landslides include topography, geomorphology, tectonics, geodynamics, GIS, hydrogeology, and engineering geology. Understanding the geological features of rocks such as fractures, faults, weathering, landslides, falling rocks, and rolling stones, is of utmost importance. Geological surveys must be carried out in the field: taking soil samples and analysing samples in geological laboratories. It all contributes to determining the causes and zoning the risk of landslides [18,19]. In effect are the methods for preventing and overcoming landslides in the study area.

In Cam Mountain of An Giang Province, Vietnam, there have been frequent incidents of mass movement of rock and ground. This has been occurring along the road from Nui Cam to Chua Van Linh, which is a popular route for many locals and tourists. These landslides have caused large boulders to roll down from the top of the mountain, resulting in accidents and fatalities. To protect the road from these phenomena, engineering structures were built after obtaining information on the geological structure of the road base. Therefore, in the first stage of the works, it was proposed to perform non-destructive geophysical surveys to check the geological structures of the ground under the road. Geophysical surveys were carried out using seismic and GPR methods.

2. Natural and Geological Characteristics of the Study Area

The geophysical and geological survey was conducted on the road from Nui Cam to Chua Van Linh in Cam Mountain, which borders Cambodia (Fig. 1). Cam Mountain An Giang are isolated hills rising above the large alluvial plain of the Mekong River, located 250 km West of Ho-Chi-Minh City. Cam Mountains (Hills) are the last southeastern part of the hills running from Cambodia to Vietnam in the NW-SE direction. The ridges of the hills have the appearance of a plateau with an altitude of 350-450 m above sea level. However, the slopes of these hills are very steep (slope angle: 30-60°). Trees almost cover the top of the mountain and around the

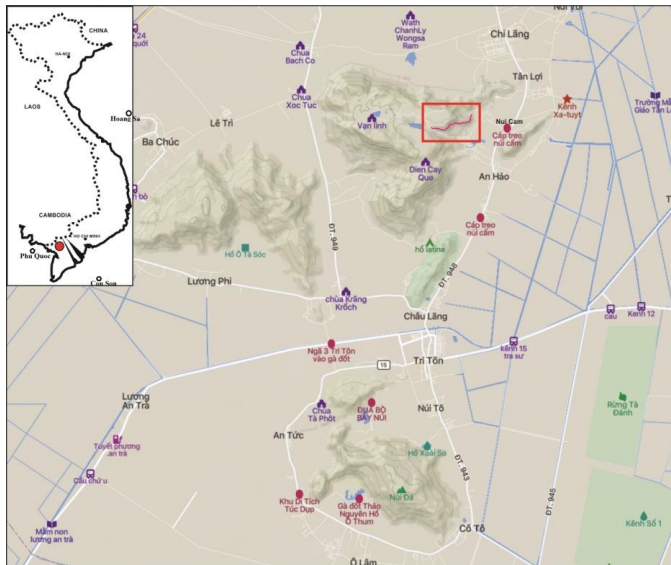


Fig. 1. Vietnam. Cam Mountain in An Giang Province.
 Research area – rectangle marked with a red line. A road from Nui Cam to Chua Van Linh is marked with a purple line

side of the mountain. On the eastern side of the mountain, there are roads for cars, motorbikes and rudimentary transportation and also the only way for indigenous people and tourists to travel daily [9,18]. The road from Nui Cam to Chua Van Linh (Figs. 2, 3) is particularly exposed to slope processes: landslides and rock falls. The frequent movements of rock masses occurring here after monsoon rains make it necessary to periodically repair the roadway. In many places, the carriageway of the road is built simply on a landslide.



Fig. 2. Vietnam. Cam Mountain in An Giang Province. Road from Nui Cam to Chua Van Linh. View from the SE(based on Google Earth)



Fig. 3. Vietnam. Cam Mountain in An Giang Province. Landslide on the north side of the road from Nui Camto Chua Van Linh

Geology of the study area

In South Vietnam, on the southwest of the Mekong River near the Cambodia border are isolated hills named Cam Mountains. These monadnocks are rising above the flat alluvial plain of the Mekong Delta. The core of the hills is composed of magma formations: volcanic rocks and granites (Fig. 4). The Hills protrude above the surrounding Pleistocene formations, which are covered with Holocene sediments. Undivided Quaternary sediments of proluvium, diluvium, and alluvium origin are found in the eastern study area, up to an altitude of approximately 100 metres above sea level, and along streams that flow through the hilly region. These near-surface sediments in the Mekong Delta are sands, gravels, pebbles and clays, sometimes mixed with rests of plants. The thickness of the cover formations is unknown [9,27]. On the ridge surfaces and the slopes of the hills, there are weathering covers: clays, gravels and their mixtures.

The exposed volcanic rock of the Upper Jurassic age is found on the western part of Cam Mountain. The main composition of this rock is andesite, which has a dark grey, blue-grey colour, sometimes mixed with green. The rock has a flow structure, sometimes with a nucleus filled with carbonates and secondary quartz. Secondary minerals in the rock are apatite and iron. The petrographic composition of the rock has a silicon oxide (SiO_2) content of 57-78%, and the alkalinity is moderate but often increases along the boundary in contact with the surrounding rocks [18]. Upper Jurassic granites are present on the eastern part of Cam Mountain. These are diorites and light granites containing a lot of muscovite, hornblende and biotite. Black biotite contains a lot of iron compounds. As a result of weathering, biotite will change into plinopit (yellow mica), which gives the rocks a yellowish or light brown colour. In the northwestern part

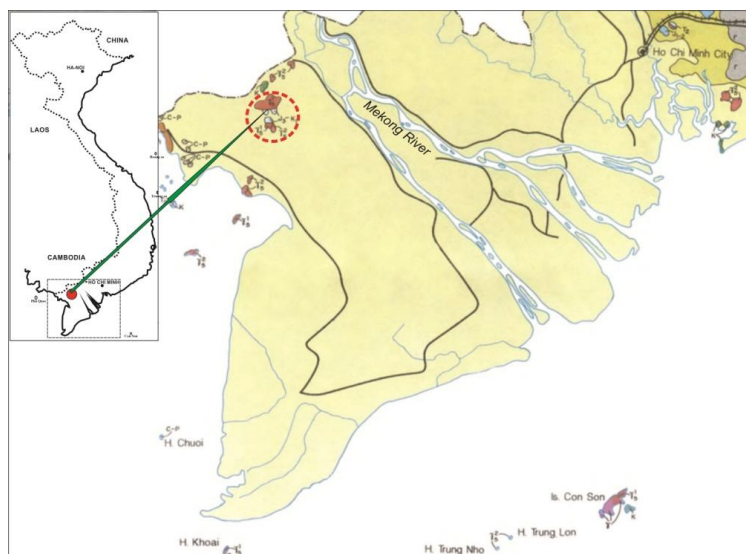


Fig. 4. Vietnam. Cam Mountain in An Giang Province. Granites are marked in brown

of Mount Cam, there are pink granites found in isolated locations. This intrusive rock complex Deo Ca is of Cretaceous age. The outcrops of pink rocks can be found on the eastern slopes of Mount Cam in a 700–800 metre wide belt [27].

The rock types mentioned above are visible in natural and artificial outcrops exposures (outcrops) along the road from Nui Cam to Chua Van Linh (Fig. 2), running from the eastern foothills of Mount Cam (ca 100 m a.s.l.) to the plateau on its ridge (ca 450 m a.s.l.). The rocks appear to be severely fractured, crumbled, and weathered. The main fractures are in the SE–NW direction. The rock strata are inclined SW (Fig. 5).

The Cam Mountain area is southwest of the geological structure known as the Indochina Block. There is a system of shifting faults on the southwestern side of this block, close to the Mekong River. The Mekong Delta lies in a rift basin and is filled with Cenozoic sediments. To the south of this tectonic structure is a tectonic unit referred to as the Thai–Malaysian Fold System. The Cam Mountains area belongs to this tectonic unit. The rocks are heavily fractured and crushed due to the folding and faulting in the area. The rock layers are steep (60°), dipping towards SW, and fractured in different directions (Fig. 5). The results of the analysis of documents on remote sensing, geophysics, geological surveys, and measurements of tectonic fractures and deformations show that 2 main fracture systems have developed in the study area: NW–SE and NE–SW [9,18,27].

3. Methodology

To determine the geology of the eastern slope of Mount Cam, along the road from Nui Cam to Chua Van Linh, geological, seismic refraction and GPR surveys were carried out. Seismic and GPR cross-sections were carried out along the roadway, from the foot of the mountain to almost its ridge (Figs. 1, 2, 6, 7).



Fig. 5. Vietnam. Cam Mountain in An Giang Province.
 Granite rocks on the North side of the road from Nui Cam to Chua Van Linh

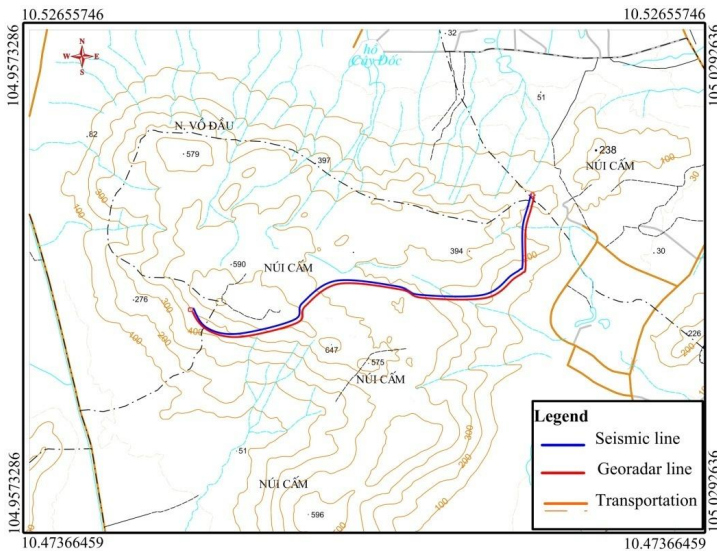


Fig. 6. The location of seismic refraction and GPR measurement line in Cam Mountain

The seismic refraction and GPR measuring lines with a total length of 2300 m are shown in Fig. 5 Present geophysical measurement line taken from east to west with the location of the first measurement point determined by GPS:

$$X = 10^{\circ}30'11.2''N; Y = 105^{\circ}00'56.6''E (109 \text{ m a.s.l.})$$

and the last measurement point is:

$X = 10^{\circ}29'58.2''N$; $Y = 105^{\circ}00'28.9''E$ (365 m a.s.l.).

The measurement results were shown in four sections of the road, 600 m each (Fig. 7).

The topography shows that in section 1 – there are very steep slopes, and there may be rock-falls; in section 2 – there may be two landslide zones; in section 3 – there may be one landslide zone; in section 4 – there may be one landslide zone (Fig. 7).

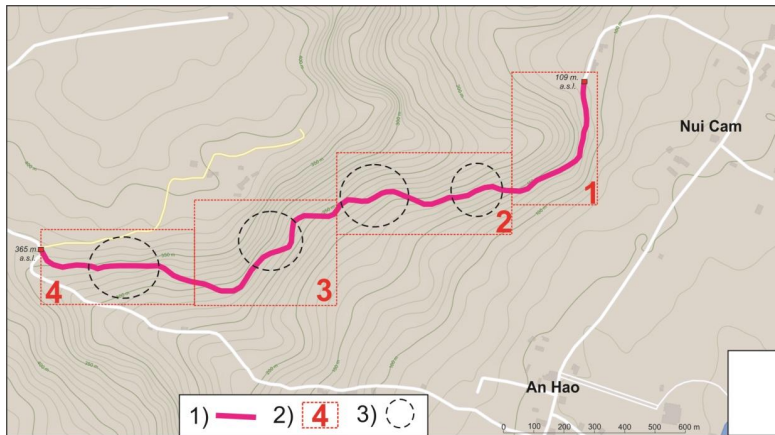


Fig. 7. Vietnam. Cam Mountain in An Giang Province. 1) a road from Nui Cam to Chua Van Linh; 2) road sections shown on seismic cross-sections and GPR cross-sections; 3) landslides

3.1. Seismic Refraction Method

For the research on the road from Nui Cam to Chua Van Linh, on the 2300 m long measuring distance, the Seismic Refraction method has been used with 24-channel Terraloc MK6 (Fig. 8) and ReflexW software to collect, process and interpret data.



Fig. 8. Seismic equipment: a) Terraloc Mark-6 seismic probe, b) Geophones and connecting cable

The refraction method involves measuring the travel times of compression waves generated by an impulsive energy source at known points along the ground surface. The energy source is usually a small explosive charge, and the energy is detected, amplified, and recorded by special equipment designed for this purpose. The instant of the explosion or “zero-time” is recorded on the record of arriving pulses [24,32]. The raw data, therefore, consists of travel times and distances, and this time-distance information is then manipulated to convert it into the format of velocity variations with depth. The propagation of seismic energy through subsurface layers is described by essentially the same rules that govern the propagation of light rays through transparent media. The refraction or angular deviation that a light ray or seismic pulse undergoes when passing from one material to another depends upon the ratio of the transmission velocities of the two materials. The fundamental law that describes the refraction of light rays is Snell’s Law, and this, together with the phenomenon of “critical incidence”, is the physical foundation of seismic refraction surveys [12,21,33].

It is entirely adequate to assume that the critically refracted ray travels along the boundary between the two media at the higher of the two velocities. If the velocities of the layers increase with depth, a portion of the energy will eventually be refracted back to the surface where it can be detected. The refraction equations derivations make certain assumptions about the properties of subsurface layers. According to these assumptions, each layer in a given stratigraphic sequence has an isotropic velocity of propagation, and ray paths are composed of straight-line segments. Additionally, each layer has a higher propagation velocity than the one above it.

The seismic refraction method used to study this project has a vibration source generated by hammering with a weight of 5 kg. The geophones used for seismic refraction work are the vertical geophones SN-10V, with features that perfectly satisfy the recording of elastic oscillating waves in the frequency range of interest. The equipment is used in collecting refractive seismic data as Terraloc Mark6 manufactured by ABEM, Sweden (Fig. 8). This is a high-resolution, flexible seismic research system controlled by specialised software and can be installed on common laptops [1].

The observation system selected in construction is a full-linked system according to the general support method. The distance between the geophones is 5 m, calculated on the surface of the terrain. This distance is determined with a tape measure according to the specified linear azimuth. The general system of mutualistic method is a system of time-interval charting, where the forward chart corresponds to the forward burst point, and the reverse plot corresponds to the reverse burst point.

The procedure to perform field data collection for the seismic refraction method is carried out by: 1 – setting up each 115 m long gauge leg, according to the default configuration of the measuring and recording device along the topographic surface, including 24 geophones, every 6 m apart; 2 – for each of metre was arranging five wave points, including one wave point in the middle of the measuring stage, two wave points located nearly second measuring stage, two geophone tip (first and 24, on distance respectively 2.5 m and 60 m) and two points for near waves and two points for far waves [29]. After completing the first measurement section, the work was continued on the next (second) measurement section, in which the 24th (final) Geophone of the first stage was the first Geophone of the second section. In each section, the wave propagation process was repeated as in the first stage, including some repeated wave points (Fig. 9).

With such an arrangement, it is possible to record refracted waves coming from depths ranging from a few metres to as little as tens of metres, according to the geophone location model.

The seismic refraction method is based on the interpretation of the first arrivals in the seismic signals and assumes that the velocity increases with depth [24,28]. It is widely used in

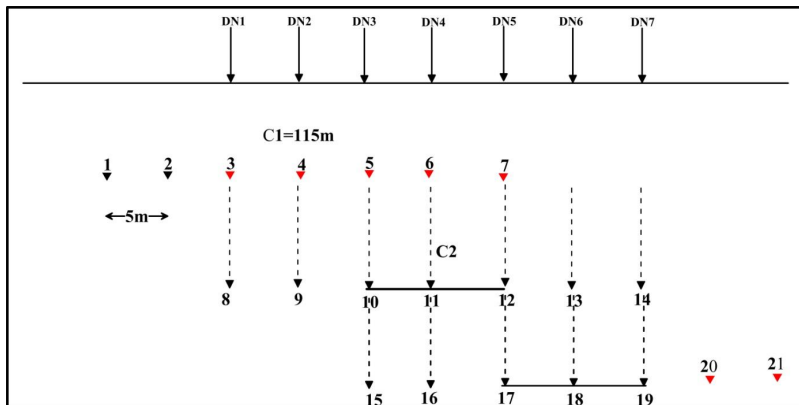


Fig. 9. The arrangement of wave-making points on 3 measuring stages

engineering geology for determining the depth of bedrock. For landslide investigation, the method has proved to be applicable, as both shear and compressional wave velocities are generally lower in the landslide body than in the unaffected ground [19,20]. Our case study is showing the use of seismic refraction for locating the undisturbed bedrock below landslides.

ReflexW software version 3.5 has been used to analyse the refractive seismic data [26]. The analysis method used is mainly a general method of GRM (Generalised Reciprocal Method) proposed by D. Palmer (1988-1990) [32].

3.2. Ground Penetrating Radar (GPR) Method

For the GPR research on the road from Nui Cam to Chua Van Linh, on the 2300 m long measuring distance, these radars Pulse EKKO 100A with two antennas: 100 and 50 MHz. (Fig. 10) and ReflexW software to process and interpret the data.

Ground Penetrating Radar (GPR) is a geophysical method that applies the principles of electromagnetic waves at a very high-frequency range (from 1-2000 MHz and higher) to study geological structures [3,8]. The EM waves emitted by the Tx transmitter antenna spread through the ground, reflect off intermediate geological boundaries, and are then detected by the Rx receiver antenna. The boundaries of geological layers related to the structure's forming conditions define the intermediate boundary surfaces. It can be bedrock, different rocks/ground/soil layers, fissures/ cracks, voids, rock blocks, buried valleys and buried objects, for example, constructions or engineering infrastructure. The penetrating depth of the method mainly depends on the frequency of the transmitting and receiving antennas and on the nature of the rock/ground in the geological environment. The greater the frequency of the antennas, the more depth penetration is small, but the higher resolution [7,15]. Choosing the frequency of the antenna to collect data is also a problem that needs to be considered carefully to get better results. The frequency of antennas used to survey are 12.5, 25, 50, 100, 200, 400 and 800 MHz, with the depth of the survey of the ground from 1 m to 100 m [10,17,23]. The reflected signals are recorded continuously. When the wave is transmitting and encounters the boundary of rocks/ground layers (intermediate surface), which have two different types of electrical properties of a changing environment,



Fig. 10. GPR pulse Ekko 100A

can be calculated the ratio of reflection (R) and the transmission coefficient (T) by the average of the boundary conditions [7,28].

The result was Pulse EKKO 100A recorded as a radargram/echogram showing the structure of the ground by reflected waves. The time of return for EM waves is measured in nanoseconds (ns), and the penetration depth is measured in metres (m). Wave propagation velocity is expressed in metres/nanosecond (m/ns) [8,11,32]. The physical quantities used in GPR and their relationship with the environment are presented in TABLE 1.

TABLE 1

Formulas used in calculating the speed and length of EM waves and depth of GPR penetration

Electromagnetic wave propagation	The propagation of electromagnetic waves in a medium with low conductivity	Meaning
$v = \frac{\omega}{a}$	$v = \frac{c}{\sqrt{\epsilon_r \mu_r}}$	Wave speed depends only on ϵ_r , Where $\mu_r = 1$
$\lambda = \frac{2\pi}{a}$	$\lambda = \frac{1}{f\sqrt{\epsilon\mu}}$	Wavelength depends on speed
$\delta = \frac{1}{b}$	$\delta = \frac{2}{\sigma} \sqrt{\frac{\epsilon}{\mu}}$	The depth of the skin layer decreases when the conductivity increases
$B = 20\text{blog}_{10}(e)$	$B = 1636,01 * \sigma \sqrt{\frac{\mu_r}{\epsilon_r}}$	The attenuation does not depend on the frequency

Where c is the speed of light, ϵ_r is the electrical permeability, μ_r is the magnetic permeability, and it is approximately equal to 1 for most observed conditions in the geological environment, σ is the electrical conductivity, ω is the frequency, a and b are the characteristic quantities for the wave number.

GPR tests are conducted in a linear system (2D) from point A to point B. As a result, obtaining a GPR cross-section (A-B) is a picture that reflects the ground structure [28]. If we make several parallel GPR cross-sections, then the test results can also be presented in the 3D system.

4. Results

ReflexW software was used for interpretation of seismic refraction data [26]. In the following, the complete interpretation of seismic refraction data is described, including:

- 1 – import of the seismic data, 2 – picking the first onsets, 3 – putting together the travel times, 4 – assigning to specific layers and doing the layer inversion.

4.1. Refraction seismic results

The results of the research on the road from Nui Cam to Chua Van Linh (Fig. 7) are shown in four pictures: Figs. 11-14. The seismic refracted section is constructed for the 2300 m long measuring line along the road based on a series of data measured by clear waves with relatively high accuracy thanks to the source of the oscillation, although hammered, but directly on the rock. Based on the results of the analysis of seismic refraction data on the entire measuring line, we can see the picture of the current cross-section of the geological structure of this measuring line, including 4 layers (Figs. 11-14).

The first layer (1 in Figs. 11-14) has an average thickness of 5.5 m, with elastic wave velocity in the range of 1000-2000 m/s. This layer consists of rocks that have undergone intense weathering, resulting in strong cracks and spaces between them. The second layer (2 in Figs. 11-14) has a thickness of a few metres to 10 m, with elastic wave propagation velocity values ranging from 2000-3000 m/s. This layer corresponds to the medium fractured rock layer. The third layer (3 in Figs. 11-14) has a thickness of 5 to 15 m, with elastic wave propagation velocity values ranging from 3000 to 4500 m/s. This layer corresponds to a solid rock layer with very little cracking. The fourth layer (4 in Figs. 11-14) has the value of elastic wave propagation velocity >4500 m/s. This is a hard layer with a very high degree of monolithicity and very rare cracking.

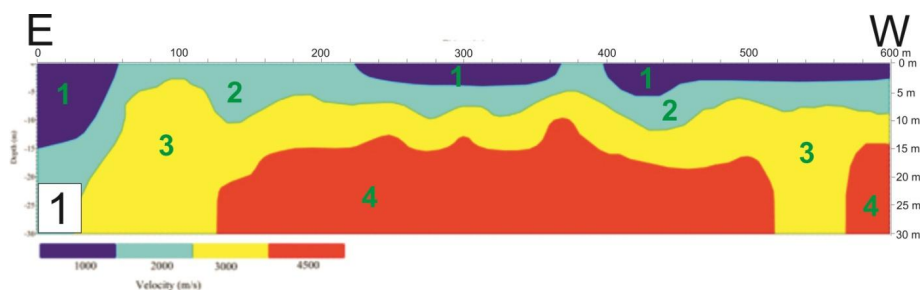


Fig. 11. Vietnam, Cam Mountain. Seismic cross-section 1

Seismic section 1 (Fig. 11) shows that on the 0-100 m section of the road, there is a large thickness of weathering cover and crushed rock (layers 1 and 2). In the 140-500 metre section,

layers 2 and 3 consist of cracked and crushed rocks from a depth of 2.5 metres to 15 metres. The rocks below a depth of 15 metres are naturally occurring and have slight fractures (referred to as layer 4). On the road section 520-580 m, the natural, hard rocks with a small number of cracks are below the depth of 30 m. There is probably a landslide zone in this place.

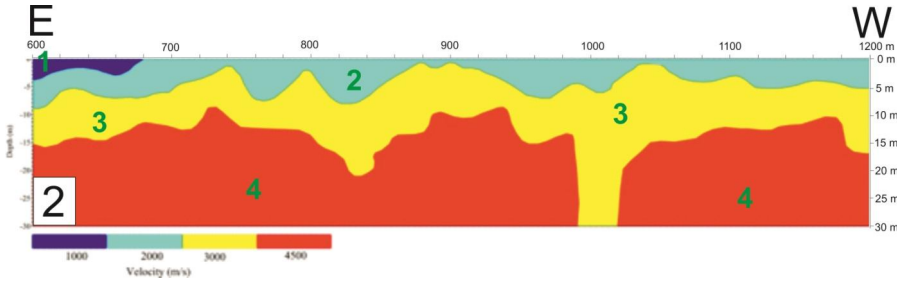


Fig. 12. Vietnam, Cam Mountain. Seismic cross-section 2

Seismic section 2 (Fig. 12) shows that on the 600-680 m section of the road, there is a small thickness of weathering cover and crushed rock (layers 1 and 2). In the section of 680-980 m, the cracked and crushed rocks (layers 2 and 3) are up to the depth of 15 m. The rocks beneath a depth of 15 metres are naturally slightly fractured (in layer 4). On the road section 980-1020 m, the natural, hard rocks with a small number of cracks are below the depth of 30 m. There is probably a landslide zone in the road section 1020-1200 m, the natural, hard rocks with a small number of cracks (layer 4) are at a depth ca 10-15 m.

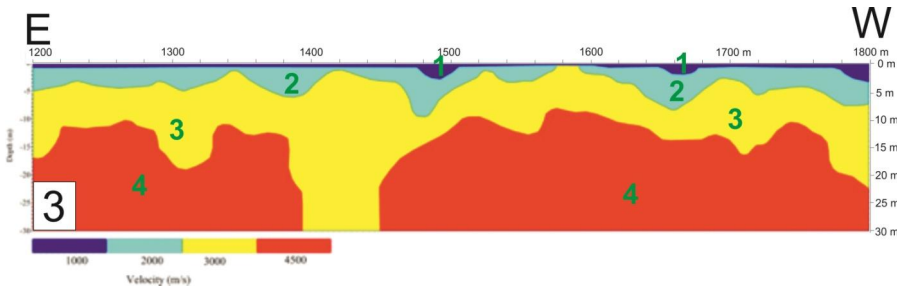


Fig. 13. Vietnam, Cam Mountain. Seismic cross-section 3

Seismic section 3 (Fig. 13) shows that the thickness of the weathering cover (layer 1) is minimal on the entire test section of the road (<1 m, locally 2.5 m). On the 1220-1380 m section, the natural, hard rocks with a small number of cracks (layer 4) are below the depth of 10-15 m. On the road section 1380-1460 m, the natural, hard rocks with a small number of cracks (layer 4) are below the depth of 30 m. There is probably a landslide zone in this place. On the 1460-1760 m section, the natural, hard rocks with a small number of cracks (layer 4) are below the depth of 10-15 m. At the end of the tested road section, the natural, hard rocks with a small number of cracks (layer 4) are below the depth of 22 m.

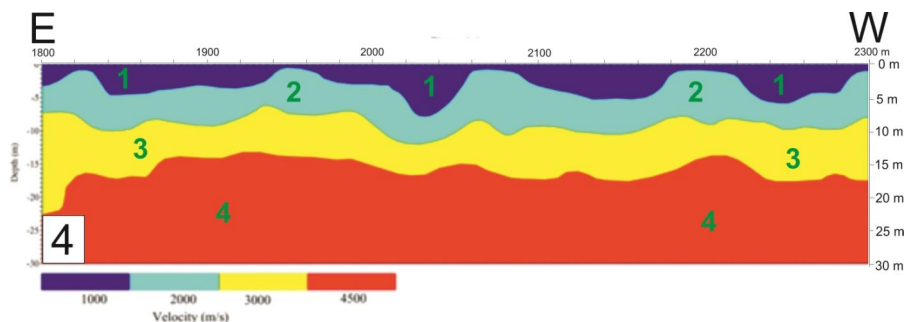


Fig. 14. Vietnam, Cam Mountain. Seismic cross-section 4

Seismic section 4 (Fig. 14) shows that all along the road, the thickness of the weathering cover (layer 1) ranges from 1-5 m. On the 1800-1820 m section, the natural, hard rocks with a small number of cracks (layer 4) are at a depth of 22 m. There is probably a landslide zone in this place. On the road section 1820-2300 m, the natural, hard rocks with a small number of cracks (layer 4) are below the depth of 15 m.

A seismic survey along the road from Nui Camto Chua Van Linh (over a distance of 2300 m) indicates that natural hard rocks, slightly fractured (layer 4), may occur here at a depth of about 10-15 m below the road surface. Above them lie crushed, cracked and weathered rocks (layers 2 and 3). It was discovered that in certain sections of the road, natural rocks were found at depths exceeding 30 metres. In the seismic sections attached, these are road sections: 0-120 m and 520-580 m (Fig. 11), 980-1020 m (Fig. 12), 1380-1460 m (Fig. 13) and from 1760-1820 m (Figs. 13 and 14). The places where greater thicknesses of crushed rocks, as well as greater thicknesses of weathered covers, were detected, are probably landslide zones occurring under the road.

4.2. GPR results

GPR measurements were made along the road from Nui Cam to Chua Van Linh in Cam Mountain over a length of 2,300 m. The GPR data was analysed in the ReflexW program [26]. The results are presented in four sections (Figs. 15-18).

Analysis of GPR venograms/echograms from research on the road from Nui Cam to Chua Van Linh indicates that the following structural layers may occur along the roadway:

- 1 – concrete or asphalt layer of the roadway;
- 2 – a layer of road base (crushed stone, gravel),
- 3 – a weathered layer (weathered fragments of rocks mixed with clay),
- 4 – a layer of strong, weathered rocks,
- 5 – rock blocks and strongly cracked rocks, less weathered,
- 6 – hard, monolithic, poorly cracked rock.

The GPR cross-section 1 indicates a weathered layer extending to a depth of about 5 metres beneath the road, underlain by a layer of strongly weathered rocks (3 in Fig. 15). This layer occurs to a depth of about 5-20 m. Rock blocks and strong fractured but less weathered rocks (5 in Fig. 15) occur at a variable depth of 5-25 m, in places deeper. The top of the natural hard, monolithic, poorly fractured rocks (6 in Fig. 15) may occur at different depths: 10-15 m (see

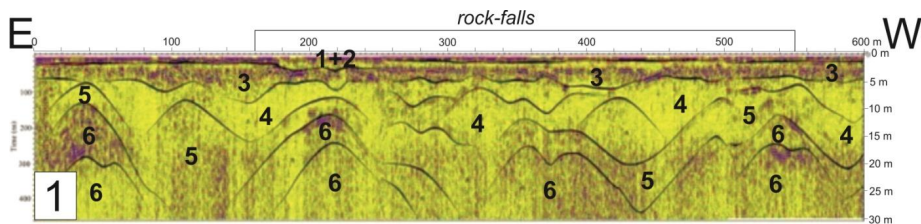


Fig. 15. Vietnam, Cam Mountain. GPR cross – section 1

distance: 20-70 m, 180-280 m, 340-440 m, 460-580 m). The zone of rock falls may be on the road section: 160-550 m. Landslide zones can occur along the following sections: 60-180 m, 260-340 m, 380-500 m and 560-600 m.

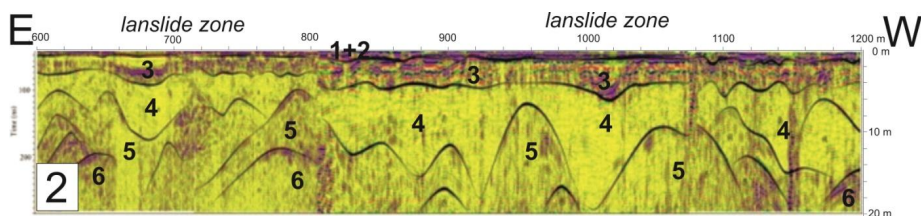


Fig. 16. Vietnam, Cam Mountain. GPR cross – section 2

The GPR cross-section 2 shows that there is a weathering layer under the road to a depth of about 5 m (3 in Fig. 16). Beneath it is a layer of strong, weathered rocks (4 in Fig. 16). This layer occurs to a depth of about 5-20 m. Rock blocks and strong fractured but less weathered rocks (5 in Fig. 16) occur at a variable depth of 5-20 m, in places deeper. Natural hard, monolithic, poorly fractured rocks (6 in Fig. 16) may occur at depths 12-15 m (on distance: 620-640 m, 750-820 m and 1180-1200 m). In the section of 840-1180 m, natural rocks occur below the depth of 20 m. Landslide zones can occur along the following sections: 640-720 m, 820-1100 m, and 1120-1200 m.

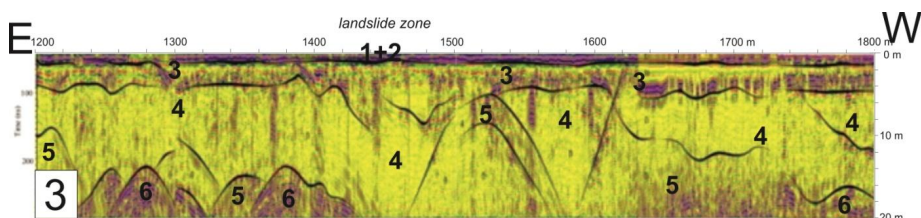


Fig. 17. Vietnam, Cam Mountain. GPR cross – section 3

The GPR cross-section 3, shows that there is a weathering layer under the road to a depth of about 5 m (3 in Fig. 17), but on section 1420-1500 m, it is on a depth up to 8-10 m. Beneath there

is a layer of strong, weathered rocks (4 in Fig. 17). This layer occurs to a depth of about 5->20 m. Rock blocks and strong fractured but less weathered rocks (5 in Fig. 17) occur at a variable depth of 10-15 m in places of 5 m (1480-1560 m). Natural hard, monolithic, poorly fractured rocks (6 in Fig. 17) may occur at depths 15 m (on distance: 1260-1420 m and 1750-1800 m). In the sections of 1440-1500 m and 1560-1720 m, natural rocks occur below the depth of 20 m. Landslide zones can occur along the following sections: 1220-1500 m, 1550-1620 and 1620-1800 m.

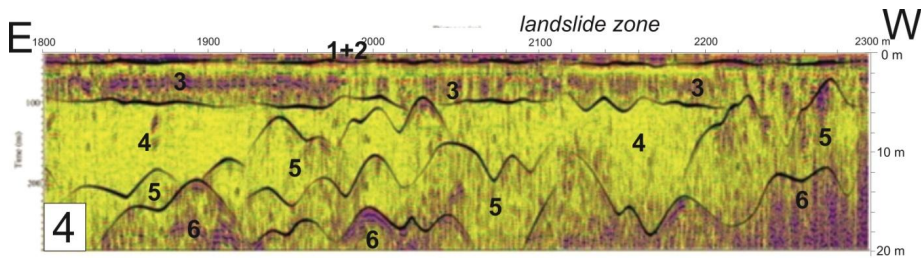


Fig. 18. Vietnam, Cam Mountain. GPR cross – section 4

GPR section 4 shows that under the road there is a layer of weathering to a depth of about 5 m (3 in Fig. 18), but only up to 2 m in the section of 2260-2290 m. Below it there is a layer of strong weathered rocks (4 in Fig. 18). This layer occurs to a depth of about 15 m. Rock blocks and strongly fractured, but less weathered rocks (5 in Fig. 18), occur at a variable depth, in places they are at 5 m (2020-2240 m and 2260-2290 m), and in the section 1990-2120 m are at a depth of about 8-10. Natural hard, monolithic, slightly fractured rocks (6 in Fig. 18), occur at a depth of 15 m (1840-2060 m and 2100-2300 m). At sections 1800-1840 m and 2050-2100 m, the natural rocks occur below the depth of 20 m. Landslide zones may occur on sections: 1800-1940 m and 2120-2200 m.

Georadar surveys show that the following rock layers occur under the roadway from Nui Cam to Chua Van Linh in Cam Mountain: weathered layer (layer 3), 2-5 m thick (on the road section: 1420-1500 m it can be 8-10 m thick); layer of strong weathered rocks (layer 4), the bottom of which may be at a depth of about 20 m (less than 20 m in places); layer of rock blocks and strongly fractured rocks, less weathered (layer 5), the top of this layer can be at various depths: 5-25 m, but in places it is on the depth higher than 25 m. In the section 1480-1560 the top of this layer is about 5 m deep; natural rocks, hard, monolithic, slightly fractured (layer 6), their top is at variable depths: 10-15 m, but in sections: 840-1180 m, 1440-1500 m, 1560-1720 m, the top of natural rocks is on the depth higher than 20 m.

The section of the road from 160 m to 550 m is the forecasted and most likely rock fall zone. Landslide zones are on sections of the road: 60-180 m, 260-340 m, 380-500 m, 560-720 m, 820-1100 m, 1120-1500 m, 1550-1620 m, 1620-1940 m and 2120-2200 m,

5. Conclusions

Our case study shows the use of seismic refraction to determine the location of the top of the natural bedrock of a landslide. We detected a strong change in wave propagation speed between

the landslide body (less than 1500 m/s) and the natural bedrock of the landslide (over 4500 m/s). In the study area, this boundary occurs at depths of 5 to 30 m. In the study area, four groups of rock layers with different wave propagation speeds were distinguished. On the road from Nui Cam to Chua Van Linh, four places were indicated where greater thicknesses of crushed rocks were detected, as well as greater thicknesses of weathered covers. These places were considered probable landslide zones occurring under the road.

GPR technology with 100 and 50 MHz low-frequency antennas was the right choice for the study to assess the current state of shallow geology in the Cam Mountain area. On a road with granite subsoil, GPR tests to a depth of 20-30 m are not unusual [23,34]. The GPR research allowed the detection of 6 groups of rock layers. A more accurate picture of the shallow geological structures under the road was obtained. The radar cross-sections showed quite clearly the anomalies associated with the critical zones. As a result of the research, nine places where landslide processes may arise have been shown.

The results of the seismic method and the GPR method are convergent and confirm that along the entire length of the examined road, natural rocks may be present at a depth of 10-15 m. In some places, they are deeper than 30 m. Landslide-prone places detected by seismic methods under the Nui Cam to Chua Van Linh road may be associated with deeper tectonic structures in the area. At this stage of research, it is difficult to explain this based on only one cross-sectional line. The GPR method is more adequate for the study of shallow geological structures. It indicates more places under the road that are susceptible to landslide processes (9 places), while the seismic method shows that there are only 5 such places.

The integration of the seismic refraction method with the georadar method provides information on the range of near-surface geological layers in the surveyed area. As a result, these two methods make it possible to determine the location of shallow geological structures, e.g. those conducive to the formation of landslides. Based on such research, it is possible to design engineering solutions that will contribute to reducing the effects of natural disasters. In the Mount Cam area of An Giang Province, Vietnam, on the road from Nui Cam to Chua Van Linh, geophysical surveys, in conjunction with other standard geological surveys, have identified structural sites that are prone to landslides. The tests performed are the basis for undertaking engineering projects aimed at the construction of structures preventing traffic hazards on the above-mentioned road [5,16].

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