Characterization of landslide and measurement of ground vibration period in the Salado-Paccha sector using GNSS equipment and refraction seismic testing

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Abstract. A landslide is a soils movement that depending on its level can be a very risky event, causing from material losses to human lives in some occasions. It can occur naturally or by anthropogenic means, the main causes are usually high intensity rainfall, soils with poor geomechanical characteristics, considerable seismic movements, erosion, lack of vegetation cover, among others. Paccha is a parish where there are several active landslides that put its inhabitants and their material goods at risk. As a result, this research analyzes one of them with UTM17s, 728845,38 E 9679536,46 N coordinates, located in the El Salado sector, for its study it is intended to characterize it, measuring its displacement and velocity through a monitoring of 36 days in 3 data collection campaigns with GNSS equipment using the RTK method, in addition a seismic refraction test is used to measure the period of vibration of the soil at the site. The results obtained indicate that the soil in the sector is clay and silt of high plasticity, the slip is extremely slow, semi-deep, with lateral propagation and rotational geometry. The displacement between points is 4,14 cm while the velocity is 0,43 m/year, finally the vibration period corresponds to a value of 0,13s and the shear wave velocity Vs is 178,85, which is categorized as a type E soil.

1 Introduction

A landslide is defined as the movement of unconsolidated materials, which occurs due to different instability factors that depending on their magnitude can cause serious problems, both economic, environmental, social and technical [1], in the most catastrophic occasions even death. According to the National Geology and Mining Service, landslides are defined as downslope movements of a soil or rock mass whose displacement occurs predominantly along a fault surface, or a thin zone with a shear deformation. Landslides can be caused by two factors: natural and anthropogenic or a combination of both. The first group includes the characteristics of the natural environment, such as climate, soils, type of rock, seismic events, etc. While anthropic factors constitute all those human activities that alter the natural conditions of the site, such as infrastructure development, earthworks, landfills, cuts or any productive activity that involves soil manipulation [2]. Geological processes gradually alter

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the structure of the geographic space, compared to human actions that modify the physical environment more rapidly over time. On the other hand, geodynamic processes such as volcanic eruptions and seismic activity influence the composition and stability of the soil, also molding and transforming the relief [3]. Due to the geographical location, Ecuador has constant volcanic and tectonic activity, in addition to considerable landslide risks [4]. On the other hand, there are meteorological and climatic conditions, for example, the El Niño and La Niña phenomena that result in floods, heavy rainfall and droughts [5], which produce changes in the stability of the terrain. Based on historical data, Azuay ranks third among the provinces with the highest number of landslides. Within the province of Azuay, the canton of Cuenca has the highest frequency of landslides, especially in the sectors of Nulti, Turi and Paccha, areas that for many years experienced latent threats, such as landslides and rock falls, which have endangered the lives of the population and the infrastructure of houses and roads. In Paccha specifically, landslides have occurred since 1957, whose intensity increased in 1993, an aspect that forced many of its inhabitants to abandon their homes [6]. Later, in 2005, after a seismic movement, a landslide occurred in the Nulti sector, a site very close to Paccha (Sánchez, 2008); currently, there are still complications in these areas. In the present study, a monitoring of a micro landslide located in the Paccha parish within the Cuenca County, Azuay province, was carried out by GNSS equipment using the RTK method, the information was collected in 3 campaigns belonging to the dates: October 28, November 11 and December 2 in the year 2022, i.e. in a period of 36 days. This with the objective of determining the position and velocity of the landslide, also by means of a series (including refraction seismic) in the study site it is intended to know the mechanical and physical characteristics of the soil, as well as the period of vibration of the same.

2 Study area

The study zone with UTM17s coordinates, 728845.38 E 9679536.46 N is a plot of land of approximately 25773 m^2 which has previously suffered landslides, it is located on the outskirts of the parish center of Paccha in the El Saldo sector. Fig. 1 below is a timeline of the area; the objective is to observe the behaviour of the terrain in past years.

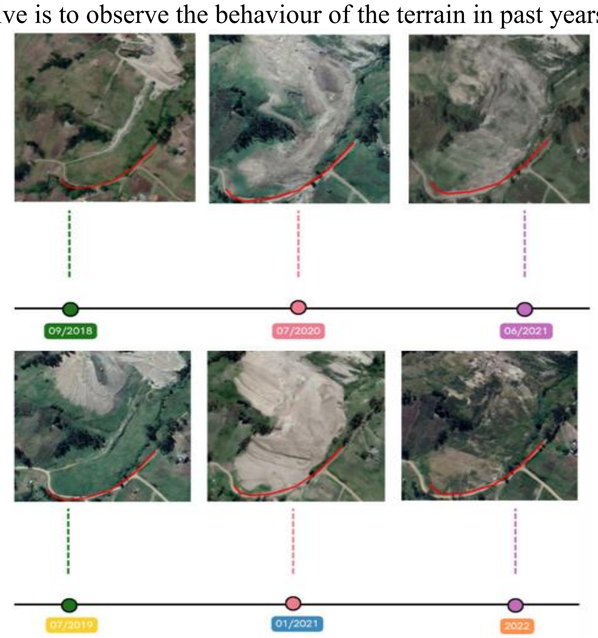

Fig. 1. Timeline of the landslide zone.

Fig. 1 shows that in 2018 and 2019 the landslide site remains normal, however, in 2020 there is already a movement of the terrain; at the beginning of 2021 an almost total reduction of the vegetation layer is observed but in the middle of the same year it is evident in the photograph that the terrain begins to regenerate, apparently the landslide at this date is relatively stable, finally in 2022 the vegetation layer is similar to that observed in 2018, indicating that possibly the speed of the landslide should have decreased.

The geomechanical characteristics of the soil belonging to the study area were measured with 7 SPT (standard penetration test) tests carried out in the sector and in neighbouring sites. Their information is conclusive as to the type of soil; high plasticity clay (CH) and high plasticity silt (MH) were obtained at the different sampling points. Of the 7 tests performed, 1 was carried out in the landslide zone, the rest in surrounding areas. The geomechanical parameters such as friction angle and cohesion are shown in Table 1.

Table 1. Geomechanical parameters of the study site

Depth [m]	θ (°)	c_u (kPa)
0,00-0,50	26,54	17,6
1,00-1,50	28,45	30,8
2,00-2,50	29,26	35,2
3,00-3,50	30,69	48,4
4,00-5,00	38,12	132
5,00-5,50	38,89	145,2
6,00-6,50	40,35	167,2

The values of the friction angle were obtained by averaging the results of the equations of Osaki [7], Dunham [8], Muromachi [9], while for cohesion the equation of Stroud [10] was used. Equations 1-4 belonging to the mentioned authors are shown below:

$$\emptyset = \sqrt{20 * N_{60}} + 15 \quad \text{(Osaki)} \quad (1) \qquad \emptyset = \sqrt{12 * N_{60}} + 25 \quad \text{(Dunham)} \quad (3)$$

$$\emptyset = 20 + 3.4\sqrt{N_{60}} \quad \text{(Muromachi)} \quad (2) \qquad Cu = K * Nspt \quad \text{(Stroud)} \quad (4)$$

In addition to the geomechanical characteristics, there are a series of relevant variables in a landslide, and their influence in the area studied is described below: the most important is precipitation because, depending on the intensity of the hydrological characteristics present in the area, there may be instability of the subsoil when a sufficient amount of water is brought in, as a result of the pressure exerted by the liquid in the pores and fissures of the soil. Likewise, rainfall and the formation of water currents on the surface (surface runoff) favor erosion processes. High rainfall in combination with an inauspicious soil type promotes the formation and acceleration of landslides [11]. Chacón Montero [12] states that the action of rain is the most regular activating agent, so controlling the entry of water into a slope that could be highly collapsible is fundamental to prevent possible landslides. Within the Paccha parish, the number of tributaries is considerable; however, in the landslide zone there is no watercourse that crosses within the studied area; the closest one is located a few meters away, so it could hardly have influenced the activation of the movement; however, we cannot rule out the possibility that during the winter season water crossings may be formed.

On the other hand, the vegetation in the area is dominated by grass, although there is a small number of trees in the upper zone of the landslide, although this is not a determining factor in terms of landslide activation, but it is influential in terms of its stability. The grass, not having deep roots, does not generate efficient stability; the opposite is the case with trees, since their roots extend several meters below the surface, fixing the soil, which significantly increases stability; however, in this case, the number of trees is reduced, so there will not be a significant contribution. The importance of vegetation cover for landslide prevention is high; activities such as livestock, agriculture, deforestation, produce a considerable reduction of the vegetation layer, which generates a high probability of generating earth movements, this because there is no cohesive agent) [13]. Regarding topography, the study polygon presents slopes corresponding to a range between 7 to 13 percent, it is evident that there is a higher probability of earth movements in lands where the slopes are steep [11], however, there may be cases where the slopes are low and close to horizontality and landslides occur anyway because there are other variables involved in it.

Another factor to consider is seismicity, which is one of the most influential and determining factors for both activation and for areas that already have active landslides. Ecuador is one of the countries located in the Pacific Ring of Fire, which translates into a high probability of seismic activity causing vulnerability in various areas of the country. The entire territory of Paccha is located within a zone of medium seismic intensity according to IGM data (2012), so there is a latent risk that several sectors will suffer ground shaking. The vibrations produced in earthquakes can be strong enough to generate landslides of various magnitudes affecting extensive areas [14]. Another agent studied is erosion, although it is true that this is not an important factor compared to those mentioned above, but it should still be taken into account for an analysis. In this case, the study area has a moderate susceptibility to erosion, which translates into significant soil erosion and therefore loss of topsoil, reducing the stability of the terrain. Finally, geology and lithology are determining factors for the presence of landslides, since depending on the type of material and geological formations that make up the analysis zones, the ease with which the surface is degraded by the action of external factors such as weathering and weathering is determined. These conditions affect the behaviour of the soil mass, increasing the probability of landslides [11]. The study site is located within the "Biblián" geological formation, and the lithology of the area shows clays, sandstones and lavas.

3 Methodology

3.1 GNSS data collection

GNSS equipment was used to take monitoring points in the landslide in the study area, and using the RTK method, 3 campaigns were carried out on October 28, November 11 and December 2 in the year 2022, that is, in a period of 36 days; the method is briefly described below: The RTK (Real Time Kinematic) technique is a real-time kinematic method of relative positioning as a function of carrier phase that employs two or more receivers that simultaneously are tracking the same GPS satellites. This method is suitable if the line of sight of the propagation path is relatively unobstructed (case study). The base receiver is connected to a radio transmitter and remains stationary over a point of known location, on the other hand, there is a mobile receiver to which the base receiver measurements and coordinates are transmitted by radio waves. Software embedded in a receiver vehicle combines and processes the GPS measurements collected at the base and mobile receivers in order to obtain the Rover coordinates [15]. The expected positioning accuracy is in the order of 2 to 5 cm. For the calculation of distances between coordinates of the points obtained after processing, equation 5 is used; for the calculation of velocity, equation 6 is used where the assumption is made that it is a uniform motion. Only the points of the campaign belonging to October 28 and December 2 were considered. The time in years for the calculation of the velocity is 0.0986 years, obtained by dividing 36 days (data collection period) over 365 days (one year) so that the velocity takes units of m/year. The results of the campaigns are shown in the results section.

$$\sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2} \tag{5}$$

$$V = \frac{distance\ between\ points}{campaign\ time} \tag{6}$$

3.2 Refraction seismic method

In the field of applied geophysics there are methods known as seismic refraction and reflection. The objective of these is to measure the propagation time of seismic waves generated with the help of a hammer or by the detonation of explosives, which propagate vibrations in the ground that are measured by sensors (geophones) placed on a straight line of known distance between point A and point B called refraction line [16]. The importance of performing this test lies in that through a series of calculations and procedures it is possible to know very important parameters such as the speed of wave propagation and the vibration frequency in the sector, the latter with relevant characteristics since when the fundamental period of the site is close to the predominant period of the earthquake, harmonic amplification or resonance develops, resulting in a large horizontal acceleration of the ground surface [17]. The standardized methodology for the calculation of the fundamental period of vibration considering the profile of weighted shear velocities for a depth of 30 m where rock with a shear velocity of approximately 720 m/s and stiffness modulus of 500 Mpa is encountered, was formulated in the International Building Code 2009 [18]. Equation 7 is used to calculate the Vs30m (30 m depth weighted) wave.

$$Vs30 = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{Vs_i}} \tag{7}$$

where *di* represents the depth of stratum *i* in meters, *n* the number of strata present in the 30 meters and *Vsi* the shear wave velocity of stratum *i*. Equation 7 is also used to obtain the global period, replacing the term *Vsi* by the period of each stratum, *Pi*. If it is necessary to obtain some other variable such as frequency, the same logical line is followed, that is replacing *Vsi* by the required variable, this can be done since equation 7 represents the weighted average.

For the refraction seismic tests carried out in the present investigation, two lines (one per test) of 36 meters each were made, with a total of 48 geophones (separated at 1.5 meters), the first line near the foot of the landslide, while the second one was drawn in the central zone, the test was based on the ASTM D5777 standard. For the processing and analysis of the data obtained, Geopsy software was used, the results are shown in the following section.

4 Results

4.1 GNSS data collection

After the 3 data collection campaigns and post processing, the coordinates of each point are obtained. Equations 5 and 6 shown in the previous section are used to calculate the distance and velocity, respectively, which are shown in Table 2.

Table 2. Velocity, displacement (distance) and coordinates in the study area

Point	Campaign 28/10/2022 N	Campaign 28/10/2022 E	Campaign 02/12/2022 N	Campaign 02/12/2022 E	Distance m N	Distance cm E	Velocity m/year
Base	9679274.89	729152.021	9679274.890	729152.021	0.000000	0	0
point 1	9679552.95	728772.239	9679552.952	728772.232	0.007071	0.71	0.08
point 2	9679547.72	728772.088	9679547.738	728772.077	0.017804	1.79	0.19
point 3	9679541.8	728772.157	9679541.863	728772.080	0.098234	9.83	1
point 4	9679533.31	728774.373	9679533.348	728774.312	0.073498	7.35	0.75
point 5	9679525.06	728776.212	9679525.039	728776.204	0.022472	2.25	0.23
point 6	9679520.24	728778.21	9679520.211	728778.220	0.029732	2.98	0.31
point 7	9679514.41	728779.776	9679514.414	728779.751	0.025000	2.5	0.26
point 8	9679498.51	728784.057	9679498.488	728784.098	0.047508	4.76	0.49
point 9	9679493.09	728787.601	9679493.100	728787.587	0.018439	1.85	0.19
point 10	9679562.92	728875.094	9679562.980	728875.035	0.085586	8.56	0.87
point 11	9679536.46	728845.409	9679536.468	728845.381	0.029411	2.95	0.3
Average						4.14	0.43

The average distance between points is approximately 4.14 cm, while the average velocity reaches a value of 0.43 m/year, using this data to characterize the landslide. Table 2 shows that point 12 belonging to the December 12 campaign does not present values, this is due to the fact that this point was removed by a resident of the sector as a result of his lack of knowledge about the study, therefore, for the analysis the point is discarded. The plot of the points belonging to the 3 campaigns is shown below in Fig. 2:

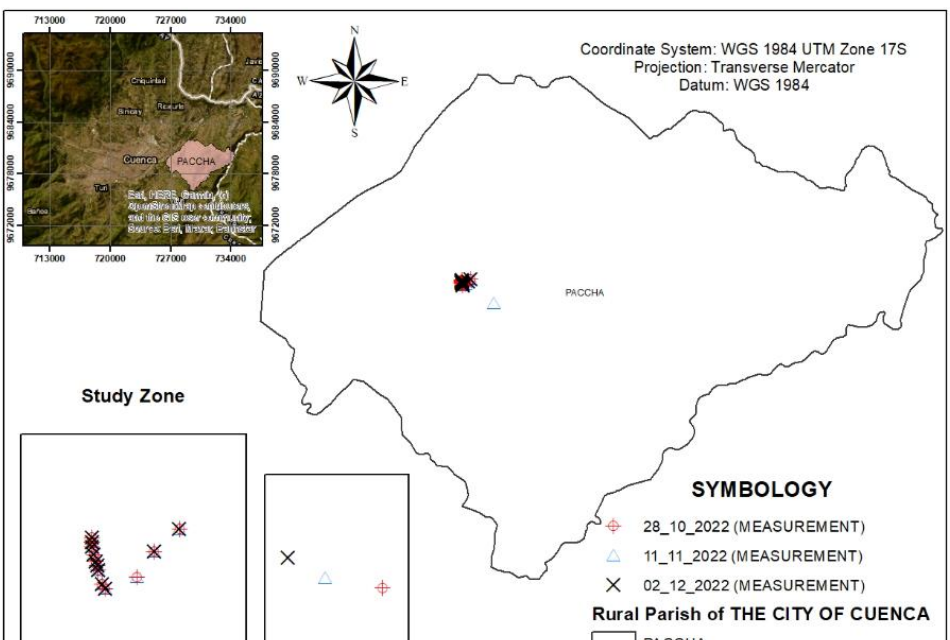

Fig. 2. Results of data collection in the campaigns

In the previous figure it can be seen that there is no noticeable displacement at first sight, when observing the lower left box the points remain practically in the same place, it is only when using the maximum zoom allowed by the software used for plotting where a slight offset between the points can be perceived, if we compare the values of the points belonging to the first and last campaign (table 2), they are very similar varying only in the decimal figures and not in a relevant way.

4.2 Refraction seismic

As described in the methodology section, the results obtained in the tests are presented in Tables 3 and 4 for the first and second seismic line (Ls-01 and Ls-02), respectively.

Table 3. Results line LS-01

	Frequency (Hz)	Period (s)	Velocity (m/s) Vs	ʎ (m)	Depth (di) (m)	di/Vsi	di/Pi
1P	27.194	0.036	92.011	3.35	1.68	0.018	46.56
2P	16.662	0.06	103.713	6.87	3.44	0.033	57.28
3P	12.095	0.082	124.115	9.99	5.00	0.040	60.93
4P	5.379	0.185	143.536	17.54	8.77	0.061	47.40
5P	4.017	0.248	196.957	42.22	21.11	0.107	85.13
6P	3.761	0.265	223.913	64.49	32.25	0.144	121.69
Σ					72.24	0.40	418.99

Table 4. Results line LS-02

	Frequency (Hz)	Period (s)	Velocity (m/s) Vs	ʎ (m)	Depth (di) (m)	di/Vsi	di/Pi
1P	33.13	0.03	111.06	3.35	1.68	0.015	55.53
2P	25.20	0.04	173.25	6.87	3.44	0.020	88.13
3P	20.57	0.05	205.56	9.99	5.00	0.024	104.09
4P	14.03	0.07	246.00	17.54	8.77	0.036	123.51
5P	8.71	0.11	367.69	42.22	21.11	0.057	185.19
6P	7.62	0.13	491.76	64.49	32.25	0.066	246.16
Σ					72.24	0.218	802.61

Equation 7 is used to calculate the value of V_{S30} and the overall period in each of the tests performed (Table 5):

Table 5. Vs30 and global soil period

	LS-01	LS-02	Average
V_{s30} (m/s) =	178.85	331.55	255.20
Period (s)=	0.17	0.09	0.13

With these values and resorting to the Ecuadorian construction standard (NEC) [19], the soil can be characterized, table 2 (from NEC 2015) of section 3. 2 (local geology) shows different properties that the soil must possess to classify it in the different profile types (A,B,C,D,E,F) being A the soil with better characteristics and F the most deficient, this from a geotechnical and structural point of view; one of the factors for the classification is the variable V_{S30} and the type of material of the area, table 6 shows an extract of the table used in the NEC to characterize the profiles:

Table 6. Excerpt table 2 section 3.2 NEC (2015): Classification of soil profiles

Profile Type	Description	Definition
D	Stiff soil profiles that meet the shear wave velocity criterion, or	360 m/s > Vs ≥ 180 m/s
	Rigid floor profiles meeting either of two conditions	50 > N ≥ 15.0 100 kPa > Su ≥ 50 kPa
E	Profile meeting the shear wave velocity criterion, or	Vs < 180 m/s
	Profile containing a total thickness H greater than 3 m of soft clays.	IP > 20 w ≥ 40% Su< 50 kPa

By means of the results shown in Table 5 and the values shown in Table 6, it is possible to classify the type of profile in the study area. Profile type D is discarded because it indicates the presence of stiff soils, despite the fact that the average V_{S30} (255.20 m/s obtained in Table 5) corresponds to values belonging to this type of profile (360 m/s > Vs ≥ 180 m/s). A more appropriate classification would be found within soil type E since the sector exposes soft clays, in this case the value of V_{S30} belonging to LS-01 (178.85 m/s) meets the criterion of Vs < 180 m/s exposed in table 6. For all that argued the profile that best fits the soil of the study sector is type E.

Other important graphs obtained with the processing of the information are those that show the relationship between the depth of the stratum versus the wave velocity VP and VS, Figs. 3 and 4 present these results of LS-01 and LS-02 respectively.

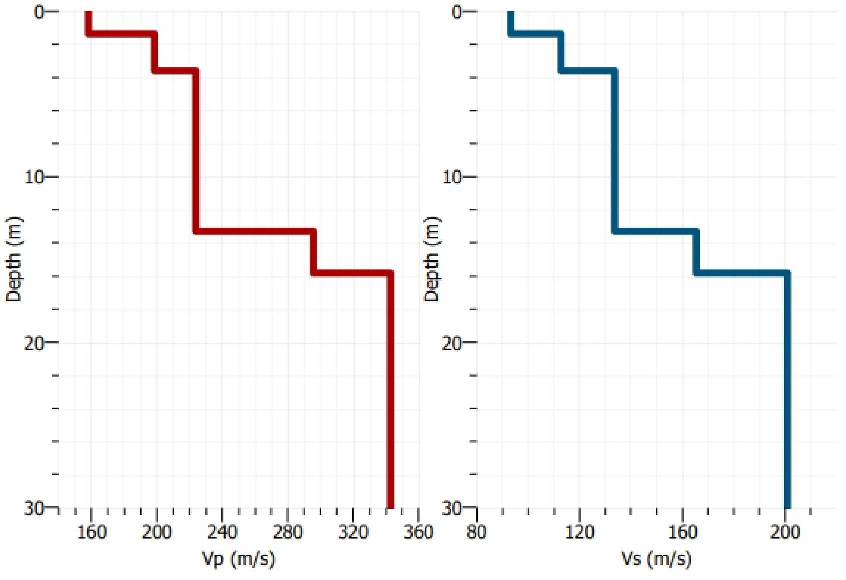

Fig. 3. Depth versus wave velocity Vp and Vs line LS-01

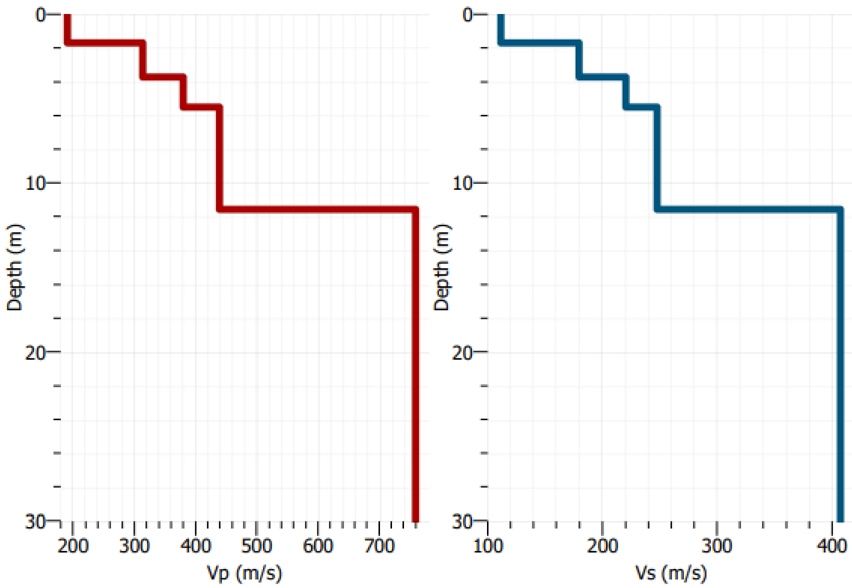

Fig. 4. Depth versus wave velocity Vp and Vs line LS-02

Both Fig. 3 and 4 show that the results obtained in Tables 3 and 4 are consistent with the graphs shown. It is indisputable that as the depth increases the wave velocity Vp and Vs also increase, this is mainly due to the fact that in deep strata the geomechanical characteristics are usually better, the soil is more consistent and consequently the velocity increases.

4.3 Characterization of slippage

Based on the above, it is possible to characterize the landslide. In the classification according to the velocity it is in the category of extremely slow since its value is less than 0.06 m/year. On the other hand, when cataloguing it by rupture depth it can be said that it is a semi-deep landslide in other words from 2 to 10 m [20]. With respect to the classification by movement, it can be argued that it is of lateral propagation, although it is true that [21] mentions that usually this type of category has slopes of 6 % while the value of this variable in the study zone presents slopes corresponding to a range between 7 to 13 % approximately, however, the difference between these values is not very large, so it can be classified within this category. Finally, when pigeonholed by its geometry, it is classified as a rotational landslide since it involves a semi-circular movement of the material in a curved plane, around an axis transverse to the slope, as can be seen in the satellite photographs in Fig. 1. In conclusion, the landslide is extremely slow, semi-deep, with lateral propagation and rotational geometry.

5 Conclusion

As previously mentioned, in general the Paccha area is prone to landslides, due to the poor soil characteristics in most of the sector, as well as the geological formations present in the area which exhibit instability, to this is added the anthropic factors that decrease the volume of the vegetation layer in the susceptible sites, not to mention the seismic and climatic factors that make this parish globally considered a focus of analysis for various investigations with the aim of preventing possible disasters. Punctually the studied area has already been victim of a considerable earth movement in previous years, so the objective of the present study is to characterize the landslide, as well as to measure the velocity, displacement and period of vibration of the soil, therefore, after taking data in three campaigns, the realization of the seismic refraction test and through all the compiled bibliography it is concluded that:

a) The landslide is extremely slow, semi-deep, with lateral propagation and rotational geometry.
b) The current velocity obtained is 0.43 m/year, but there is a possibility that in past years it could have been much higher.
c) The displacement found is approximately 4.14 cm measured from the campaign belonging to October 28, 2022 until December 2 of the same year. This value will probably decrease with the passage of time as the site will find stability, as long as no agent activates it again.
d) The calculated soil vibration period is approximately 0.13 seconds while the shear wave velocity Vs is 178.85 m/s which is classified as a type E soil according to the Ecuadorian Construction Standard NEC (2015).
e) The soil of the sector is clay and silt of high plasticity, the highest values of the friction angle of and cohesion are present in the depth of 6.00-6.50 meters with values of 40.35° and 167.2 kPa respectively, while in the depth of 0.00-0.50 meters the minimum values are exhibited, a friction angle of 26.54° and cohesion of 17.6 kPa, that is a soil with poor characteristics from a geomechanical and structural point of view.

Finally, based on the above, some recommendations are proposed, such as:

a) Maintain effective control of runoff in the area with the objective of avoiding saturation of the material in order to slow down possible increases in velocity.
b) Avoid all forms of construction both in the upper zone and at the foot of the landslide, as well as in sites adjacent to it, because as evidenced, the period of soil vibration at the site is very short, which would significantly affect the structures in the sector.
c) By planting vegetation, the volume of the vegetation layer should be increased, in addition to making use of a green belt in both the upper and lower zones, which will significantly increase the stability of the site.
d) It is plausible to incorporate the information presented in this document to the land use plan of the parish in order to improve it.

This project lays the groundwork for further analysis at the same site of interest, and presents future lines of research such as monitoring the sector during the first rainy season (March, April and May). In addition to studies focused on improving the geomechanical characteristics of the soil, and proposing possible solutions to the evident problem experienced by the site.

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