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CHARACTERIZATION OF LANDSLIDES: A PRELIMINARY VERTICAL ELECTRICAL SOUNDING APPROACH

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ABSTRACT

Groundwater flow and accumulation within a landslide mainly govern its movement along the slip surface. Thus, a comprehensive understanding of the subsurface flow regime would be imperative in mapping the landslide body. Geoelectrical resistivity can be used to detect the significant changes in the ground caused by water flow and accumulation. A systematic vertical electrical sounding (VES) at selected locations would provide preliminary information on the subsurface nature of the landslide that can guide future surveys including 2-D electrical resistivity traversing. A VES survey using Schlumberger electrode configuration was carried out at the creep-type landslide that occurs on the southwestern part of the Uva Wellassa University, Sri Lanka. Four survey points were established for the preliminary VES survey, one at the toe area of the landslide, the other on the south-west boundary, and two points outside the landslide body. Each survey line spanned 200m in length. The data revealed the presence of partially dry and quartz-rich overburden and a clay-rich, water-bearing layer with an approximate thickness varying between 24 m -32 m with significantly low apparent resistivity around 30- 60 Ωm sitting on the partially weathered bed rock at a depth of approximately 30 m – 40 m. This was found to be the prominent character at all locations. Preliminary VES data indicate that the thickness of the clay-rich water-bearing layer increases toward south (uphill) while the quartz-rich overburden wedges in the same direction from the toe across the boundary to the adjacent ridge and up and over the ridge. This preliminary finding leads to understanding the general anatomy of the landslide and the surrounding undisturbed mass in terms of the number of layers, type of layers, their thicknesses, the presence of water and the depth to the bed rock as a first approximation.

Keywords: *Landslides, Electrical Resistivity Traversing, Vertical Electrical Sounding*

INTRODUCTION

Sri Lanka being a country in the tropics is exposed to heavy rainfalls regularly throughout the year. The mountainous terrain of the country together with the intense rainfall pattern triggers landslides every year. Nearly 20,000 square kilometers encompassing 10 districts were found prone to landslides (Bandara, 2005). Badulla being situated in a mountainous region is often beaten by landslides almost in all rainy seasons. Thus, it is imperative that effective mitigation measures and monitoring should be done based on thorough studies on landslides. Landslides are likely to generate changes in parameters of the ground such as groundwater flow and water pressure due to accumulation of groundwater. These changes can be used to map the landslide body in terms of groundwater flow and accumulation (Jongmans and Garambois, 2007). Geophysical methods seem to be an approach for such an exercise as they can be used to map the subsurface nature of a landslide and provide data over a volume rather than on a point or in one dimension (Everett, 2013; Kearey et al., 2001). Since Bogoslovsky and Ogilvy (1977) pioneered using geophysical techniques in landslide investigations, the approach has been increasingly used but with relatively little reference to landslide mitigation purposes focusing on dewatering the landslide body. The geophysical method to apply is decided based on its adequacy to solve the problem and on other controlling factors that should be thoroughly considered before any field experiment is designed (McCann and Forster, 1990). The presence of a geophysical contrast in terms of a geological, hydrological or mechanical boundary (e.g.: the limit of the sliding mass) is one key factor. The other is the nature of the geophysical method itself, namely the depth of penetration and the ability of the method to detect an anomaly (resolution). Usually the deeper-the penetration, the poorer-the resolution becomes, a characteristic trade-off expected in geophysical surveys.

Geophysical methods that can be and have been used to characterize the sub surface of land slide includes: Seismic reflection (Bruno and Marillier, 2000; Ferrucci et al., 2000; Bichler et al., 2004), Seismic refraction (Kearey et al., 2002), Seismic tomography (Méric et al., 2005), Electrical Resistivity method (Telford et al., 1990; Reynolds, 1997), Electromagnetic methods, Ground Penetrating Radar (GPR) (Bichler et al., 2004) and Gravimetric studies (Del Gaudio et al., 2000).

Since landslides consist of a slip surface where most of the time ground water governs the movement, electrical resistivity can be used to detect the significant changes caused in resistivity in the landslide mass due to water flow and accumulation (Suzuki and Higashi, 2001). Electrical Resistivity Tomography is the advance method of modelling the subsurface of a landslide based on the water flow and accumulation. Landslide material can be highly disturbed by nature and could lead to difficulties in electrical current injection (Jongmans and Garambois, 2007) and further could affect the accuracy of the geophysical technique in use based on the signal-to-noise ratio. Thus, preliminary tests are important before designing a survey (Jongmans and Garambois, 2007). Therefore, prior to setting up a 2-D Electrical Resistivity Traversing (ERT) survey, a primary 1-DVertical Electrical Sounding (VES) can be done to get an approximate idea about the different layers with differing geophysical and geological properties and the bed rock formation at any selected point on the landslide body (Agnesi et al., 2005; Schmutz et al., 2000; Caris and van Asch Th, 1991). Based on the facts discussed above, A 1D preliminary VES survey with four survey points was designed to initiate the process of characterizing the Badulusirigama landslide in terms of electrical resistivity. This survey was expected to generate an approximation of the geology of the landslide body and the surrounding area in terms of number of layers present, their approximate thicknesses, the depth to the bedrock and the presence of groundwater.

The Badulusirigama landslide is being monitored by ground water level gauges, inclinometers, extensometers and a pipe strain gauge. A network of surface and subsurface drains has been constructed for the dewatering of the landslide. This particular site was selected with the future objective of comparing and contrasting the 2D ERT characterization of the landslide with the geotechnical measurements made through monitoring equipment and available borehole data.

METHODOLOGY

A desk study was carried out with the help of officials of the Badulla branch of National Building Research Organization to collect and collate existing data, aerial photographs, survey maps and monitoring reports on the selected site. Two visits were made to the selected site to demarcate the landslide margins and to assess its areal extent. After analyzing the nature of the site, a 1-D VES survey was carried out using the ABEM SAS 300 Terrameter following the Schlumberger array (Figure 1) in order to assess the response of the resistivity instrument and to clarify the nature of the soil profile and the bed rock formation of the site.

Four 1-D VES surveys were carried out covering a representative profile of the landslide from its center to the undisturbed stable ground (Figure 2). VES 01 was established in the toe area and VES 02 on the south west boundary of the landslide. The other two, VES 03 and VES 04 flanking the south-west boundary of the landslide on the undisturbed mass. Each survey line spanned 200 m in length. Current electrode spacing (AB/2) and potential electrode spacing (MN/2) followed are given in Table 1.

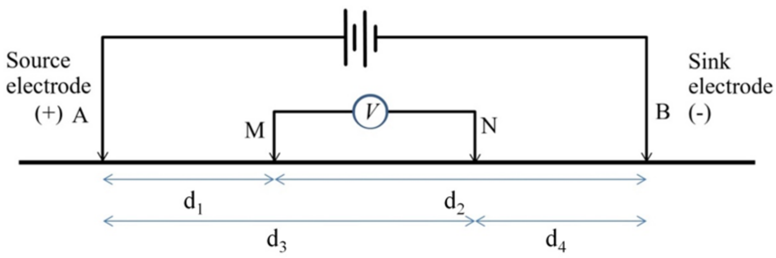

Fig.1.*Schlumberger Array setup (A & B: Current electrodes, M & N: Potential electrodes) (Rolia and Sutjiningsih, 2018)*

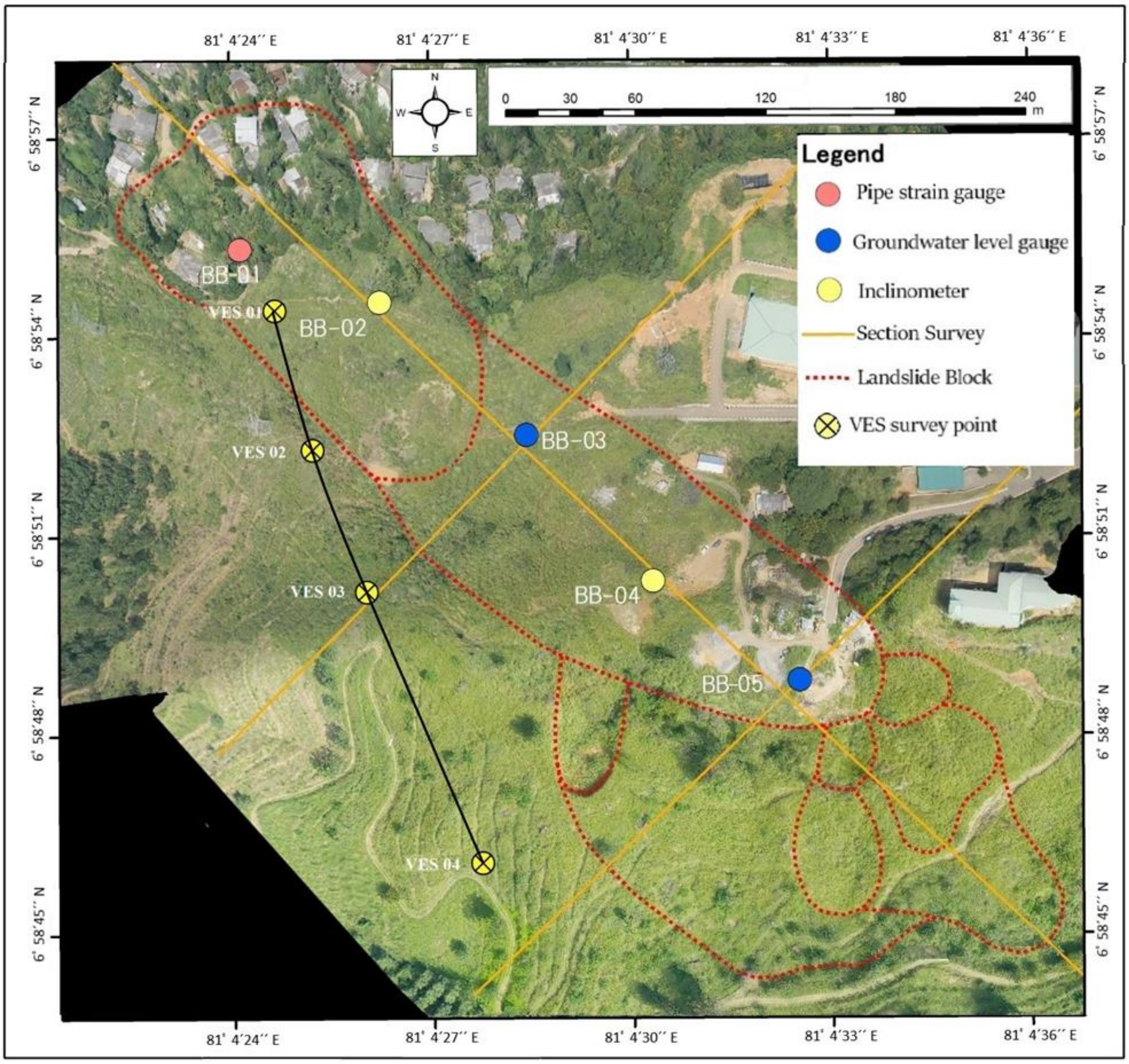

Fig. 2*. Landslide area shown on a drone image (Landslide Research & Risk Management Division, NBRO).*

Table 1: *Electrode Spacing,*

AB/2 (m)	1.5	2	3	3	5	7	10	10	15	20	30	40	50	50	70	100
MN/2 (m)	0.5	0.5	0.5	1	1	1	1	2.5	2.5	2.5	2.5	2.5	2.5	10	10	10

The potential difference (V) between M and N potential electrodes is given in equation (1) (AL-Menshed, 2018).

$$V = \frac{I\rho}{2\pi}\left(\frac{1}{d_1} - \frac{1}{d_2} - \frac{1}{d_3} + \frac{1}{d_4}\right) \quad (1)$$

where ρ is the apparent resistivity, I is the current, d_1, d_2, d_3 and d_4 are the distances between electrodes (Figure 1).

By rearranging,

$$\rho = \frac{2\pi V}{I}\left(\frac{1}{d_1} - \frac{1}{d_2} - \frac{1}{d_3} + \frac{1}{d_4}\right)^{-1} \quad (2)$$

The geometrical factor (k) is given by,

$$k = 2\pi\left(\frac{1}{d_1} - \frac{1}{d_2} - \frac{1}{d_3} + \frac{1}{d_4}\right)^{-1} \quad (3)$$

And thus, the apparent resistivity is given by,

$$\rho = \frac{kV}{I} \quad (4)$$

where, V/I = R (resistance) (AL-Menshed, 2018)

The geometrical factor k was calculated using equation 3 and the distances (d_1,d_2,d_3 and d_4) between potential electrodes (AB) and current electrodes (MN). The apparent resistivity values were calculated from the measured resistance values and the geometrical factor values were calculated from the survey based on equation 4. The corresponding apparent resistivity curves were plotted on a logarithmic scale using the RESIST software (Vander Velpen and Sporry,1993) and Microsoft Excel.

The Root Mean Square (RMS) error was kept below 5 Ωm when plotting the resistivity curves from RESIST. The matched curves were used to determine the number of layers, their apparent resistivity values, layer thicknesses and depth to each layer.

RESULTS AND DISCUSSION

Preliminary VES data were collected at four survey points so that an approximation of the geology of both the landslide as well as the surrounding undisturbed mass could be compared. The resistance values recorded in the survey and the calculated corresponding apparent resistivity values based on equation 4 are given in Table 2. The relatively lower apparent resistivity values recorded at VES 01 (Figure 7) might be due to the presence of moisture in the overburden while the anomaly at a depth of 30 m - 40 m could be a quartzite boulder resting in the clay layer. The raw data of survey point VES 01 needs to be verified with data from an alternative location very close to VES 01 to confirm or to reject the presence of the anomaly detected at VES 01.

At VES 02 (Figure 3a) the presence of a thin layer with a thickness less than 7 m and with an apparent resistivity between approximately 350-1017 Ωm is detected. As per the surface indications and the apparent resistivity, this layer consists presumably of quartz-rich overburden. As indicated by the sudden and drastic drop of apparent resistivity, a thick water-bearing clay layer with an apparent resistivity of around 30.8 Ωm and a thickness of around 24 m is resting on the partially weathered bedrock (Figure 3a) (Palacky,1987). The bedrock is represented by the characteristic hike of the apparent resistivity values which maintain an angle close to 45º with the x axis of the apparent resistivity curve in Figure 3a. It bears an apparent resistivity value of around 507 Ωm. The depth to the lower boundary of this water bearing layer is around 31 m at the survey point VES 02.

Similar to the survey point VES 02, survey point VES 03 also indicates the presence of the same formation according to the corresponding apparent resistivity curve (Figure 4a). Beneath the thin (thickness< 9 m) resistive overburden the same thick water bearing clay layer can be observed with a thickness of around 30 m. And the depth to the bedrock is around 40 m.

Figure 5a shows how the similarities continue at VES 04 compared to VES 02 and VES 03. The presence of the three layers is evident and the indication of the bed rock at a depth of around 37 m is highlighted by the near 45º ascend of the curve. The characteristic thick water-bearing clay layer with a thickness of around 32 m lies beneath the identically thin (thickness< 6 m) resistive, overburden. The depth to the lower boundary of this water-bearing layer is around 37m at the survey point VES 04. The apparent resistivity curves of VES 02, VES 03 and VES 04 correlate to the approximated geological profiles shown in Figures 3b, 4b, and 5b respectively.

Table 2: *Measured resistance values and calculated resistivity values.*

			VES 01		VES 02		VES 03		VES 04	
AB/2 (m)	MN/2 (m)	*k*	Resistance (ohm)	Apparent Resistivity (ohm m)	Resistance (ohm)	Apparent Resistivity (ohm m)	Resistance (ohm)	Apparent Resistivity (ohm m)	Resistance (ohm)	Apparent Resistivity (ohm m)
1.5	0.5	6.300	47.9000	301.7700	72.4000	456.1200	135.900	856.1700	66.8000	420.8400
2	0.5	11.800	26.0000	306.8000	35.9000	423.6200	79.600	939.2800	42.8000	505.0400
3	0.5	27.489	9.2100	253.1737	21.4000	588.2646	33.000	907.1370	20.7000	569.0223
3	1.0	12.566	20.7000	260.1162	58.7000	737.6242	65.100	818.0466	43.7000	549.1342
5	1.0	37.699	4.0800	153.8119	21.2000	799.2188	17.300	652.1927	13.4500	507.0516
7	1.0	75.398	0.9990	75.3226	10.1900	768.3056	6.920	521.7542	5.1900	391.3156
10	1.0	155.510	0.7770	120.8313	4.5000	699.7950	2.400	373.2240	1.6640	258.7686
10	2.5	58.905	2.2500	132.5363	10.0200	590.2281	7.220	425.2941	5.1400	302.7717
15	2.5	137.500	0.2860	39.3250	3.0300	416.6250	2.140	294.2500	1.0140	139.4250
20	2.5	247.500	0.3020	74.7450	1.0480	259.3800	0.845	209.1375	0.3280	81.1800
30	2.5	562.000	0.0950	53.3900	0.2530	142.1860	0.267	150.0540	0.0920	51.7040
40	2.5	1001.000	0.0345	34.5345	0.0800	80.0800	0.111	111.1110	0.0530	53.0530
50	2.5	1567.000	0.0148	23.1916	0.0432	67.6944	0.063	98.7210	0.0340	53.2780
50	10.0	377.000	0.0721	27.1817	0.1680	63.3360	0.244	91.9880	0.1300	49.0100
70	10.0	753.980	0.0080	6.0318	0.0946	71.3265	0.136	102.5413	0.0800	60.3184
100	10.0	1555.000	0.0160	24.8800	0.0632	98.2760	0.077	119.7350	0.0467	72.6185

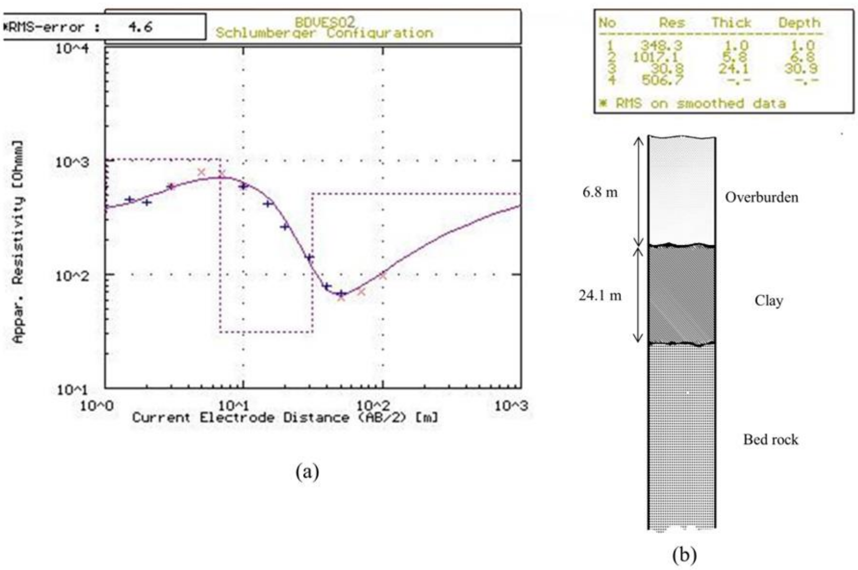

Fig.3. (a) *Curve matched from RESIST software for VES 02*, (b) *Geological profile for VES 02.*

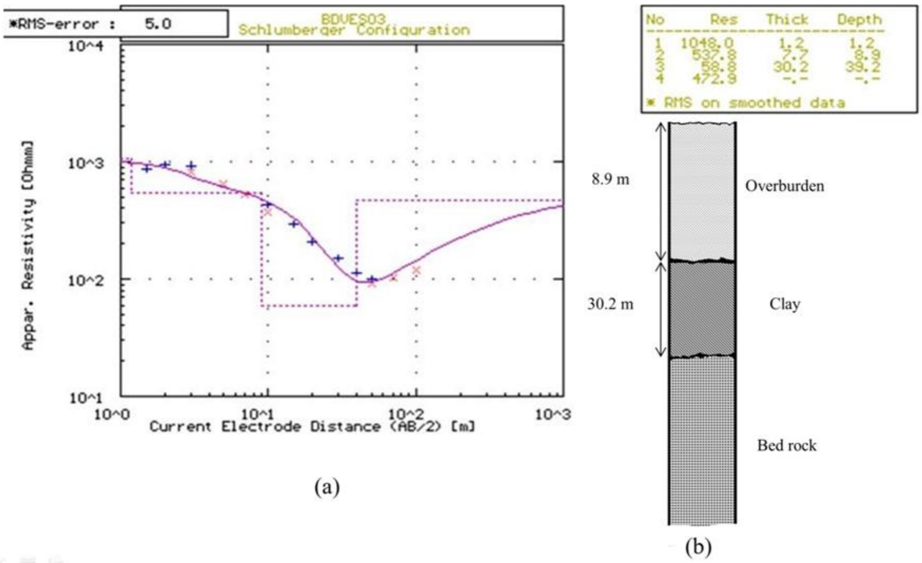

Fig. 4. (a) *Curve matched from RESIST software for VES 03*,(b) *Geological profile for VES 03.*

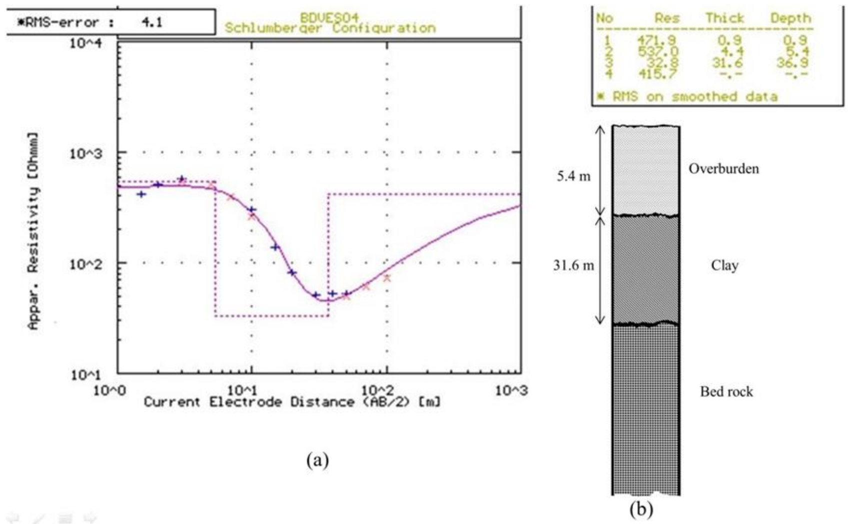

Fig. 5. (a) *Curve matched from RESIST software for VES 04*,(b) *Geological profile for VES 04*

Apparent resistivity values corresponding to different depth horizons provide a reasonable picture of the subsurface as a first approximation that can aid in configuring a more detailed 2-D ERT survey. Moreover, interpolation of the depth profiles gives a preliminary cross section of the landslide revealing its anatomy.

The characteristic thickening of the water bearing clay layer and the wedging of the quartzite- rich layer uphill is clearly evident in Figure 6. All three points, VES 02, VES 03, and VES 04 are characterized by a similar number of layers and their thicknesses (Figure 7).

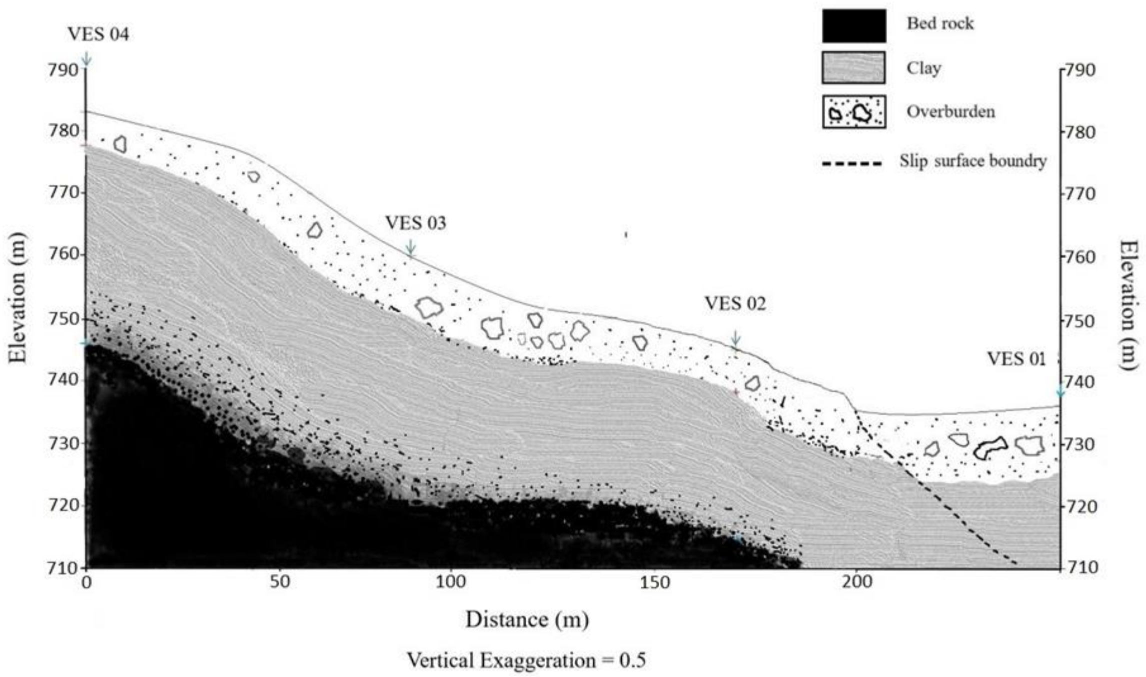

***Fig.6.** Interpreted geological profile along survey points VES 01,02,03 and 04.*

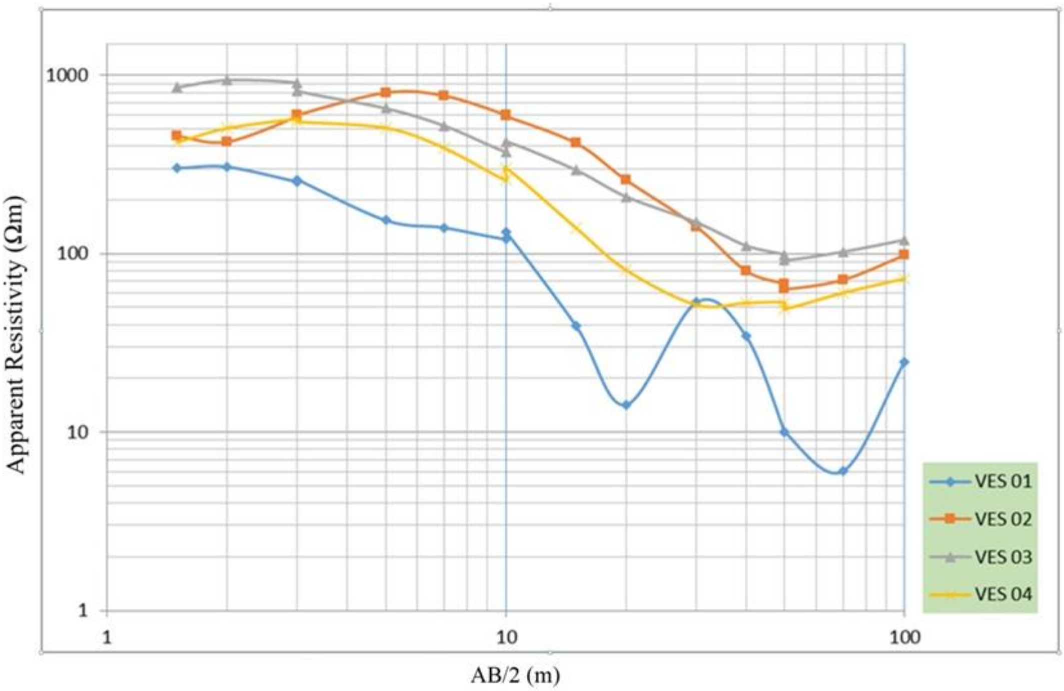

***Fig.7.** Apparent resistivity curves of the four VES points (Note that VES 01 curve deviates significantly from the rest suggesting possible presence of resistive quartzitic boulders at the toe region of the landslide)*

Partially dry and quartz-rich overburden and the clay-rich water bearing layer is a prominent character of all three locations. The clay-rich water bearing layer having a thickness over 25 m increases its thickness uphill while the quartz-rich overburden gradually thins out in the same direction. Apparent resistivity values derived for the survey point VES 01 may indicate the presence of highly weathered material and/or colluvium at the toe of the landslide.

A similar VES approach made by Agensi et al. (2005) with five VES surveys to evaluate a composite soil-rock landslide in Sicily, successfully revealed the bedrock formation and a shallow interface corresponding to a conductive layer which was found to be the slip surface with alternating conductive and resistive layers in between the slip surface and the bedrock. Another study by Caris and Van Asch Th (1991) was able to detect higher resistivity values on the stable mass and lower resistivity values on the disturbed landslide mass highlighting the presence of groundwater in the unstable mass.

The indication of the existence of the prominent water-bearing clay layer and depth to this layer is vital since frequently the water bearing layer contains the slip surface of the landslide and the presence of which could be cross-referenced with the geotechnical measurements (Jongmans and Garambois, 2007). Furthermore, knowing the presence and orientation of this water-bearing layer would be key in efficient and effective dewatering of the landslide body. Locations and dimensions for horizontal drains can be determined based on the geometry of the water bearing layer. Tracing the flow paths that feed this layer with groundwater can be useful in cutting off the water supply to the layer as well as in draining its water. Furthermore, based on this data, placing of monitoring equipment such as groundwater level gauges, inclinometers, at optimal locations and core sampling could be done effectively.

Conducting preliminary 1D VES surveys on landslides are critical since it could provide the first insight into the subsurface anatomy of a landslide in terms of the number of layers, presence or absence of ground water and the depth to the bedrock. These preliminary information could be helpful in planning further 2D ERT surveys (Ex: to determine the number of electrodes and the electrode spacing needed for optimal resolution). Furthermore, deciding locations for bore holes for sampling and monitoring of the landslide could be done effectively with the understanding of the subsurface geology generated by these preliminary 1D VES surveys.

CONCLUSIONS

The study has revealed the most basic but essential data regarding the geology of the landslide itself as well as the undisturbed surrounding area. The three different layers with significant apparent resistivities and the presence of the less resistive water-bearing clay layer is clearly evident in the interpretation as well as in figures 3, 4 and 5.

Based on the data collected and interpretations made in this study it is apparent that 1-D VES surveys are able to detect the subsurface of a landslide with reference to the characteristic electrical resistivity values that different layers hold. Presence of groundwater in the landslide body further pronounces the contrast between layers during VES surveys due to the changes made by water to the resistivity of the layers in a landslide.

In the early stages of landslide investigation where no or little data regarding the site is at hand, 1-D VES surveys are capable of giving an insight into some basic but essential details such as the number of layers and groundwater levels at selected points of the landslide. Thus, it provides an initial platform for future characterization surveys and finally mitigation activities.

Furthermore, due to the limitations of 1-D VES surveys in terms of degrading resolution with depth and interference by earth materials, geotechnical measurements, observations made by core logging and bore holes and groundwater level gauge readings could be used to validate the interpretations made based on 1-D VES and other geophysical surveys.

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