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Vertical Electrical Sounding (VES) investigation for road failure along Mekelle – Abi-Adi road segment, northern Ethiopia

Gebreslassie Mebrahtu*, Solomun Atsbaha and Berihu Abadi Berhe
School of Earth Sciences, College of Natural and Computational Sciences, P.O.Box 231, Mekelle University, Mekelle, Ethiopia (*gebreslassie.mebrahtu@mu.edu.et).

ABSTRACT

Roads constructed along the mountainous terrains of Ethiopia are susceptible to landslides mostly during rainy season. Mekelle – Abi Adi road is one of the economically important road corridors that connects many towns with Mekelle city. However, the asphalt road segment is heavily affected by quasi-translational type of landslide which hinders traffic flow of the area. Vertical electrical sounding (VES) method was applied to investigate subsurface geology of the road failure along Mekelle – Abi-Adi asphalt road, northern Ethiopia. The geo-electric section result revealed that the shallow subsurface geology of the site is characterized by four distinct geological formations, from top to bottom are: shale, shale-limestone intercalation, limestone and shale-gypsum units. The subgrade of the failed road section is shale unit which is overlain by jointed sandstone unit. The sandstone unit serves as a recharge zone to the bottom shale layer by percolating water via sub-base fill materials which in turn blocks vertical percolation and promote seepage force to the overlying soil mass. Hence, the road failure in the study area seems to be caused due to the development of pore water pressure in the shale layer which soaked water during heavy rainfall. The recommended remedial method for the road failure is re-designing of the affected route from chainage 48 km+850 m to 49 km+250 m towards the northwest of the study area and excavates the top 6 m shale unit.

Keywords: Road failure, Vertical electrical sounding, Landslide, northern Ethiopia.

1. INTRODUCTION

Road transport sector is one of the most powerful instruments used to promote economic growth and poverty reduction (Fan and Rao, 2003). Road networks in developing countries speed up the overall socio-economic development by providing vital communication links. However, construction and maintenance of road and highway networks in the developing countries are often problematic, and have resulted to economic setbacks (Okogbue and Aghamelu, 2010). Stability and durability of road depends on the traffic load and the strength of pavement layers (Kiehl and Briegleb, 2011). Geotechnical problems of a road could critically influence on the design, performance, lifespan, construction cost and maintenance of roads. For road alignment projects, geotechnical investigations are used to select and compare alternative routes for the road. An appropriate assessment of soil and rock characteristics is crucial in solving geological and

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geotechnical problems of roads. Pavement investigation generally consists of pavement materials testing as well as characterization of subgrade, sub base and base material through field and laboratory testing (Hearn, 2001; Dunganaa and Dubjurb, 2016).

In Ethiopia road transport is the dominant mode and accounts for 90-95% of motorized inter-urban and rural freight and passenger movements. However, because of its limited road network and related road failure problem, it remains one of the formidable challenges for Ethiopia in its endeavor towards socio-economic development and poverty reduction (ERA, 2008a). Ethiopia is a highly mountainous terrain with steep and rugged topography. Hence, in planning and designing of roads, detail geomorphological, geological, geotechnical, hydrogeological and geodynamic conditions should be conducted to select the ideal route and for design of appropriate treatment methods. Ethiopia is constructing massive roads and railways to connect the different parts of the country. Most of the roads constructed along the hilly and mountainous terrain are susceptible to failure mostly during rainy season (Ayalew, 1999; Ayenew and Barebieri, 2005). Therefore, there should be proper landslide hazard assessment and risk analysis prior to planning and construction. Over 700 landslide sites are recorded in Ethiopia mainly affecting roads, farmlands and houses (Woldearegay, 2013). Most of these failures are concentrated in the mountainous and rift escarpment of the country. The types of landslides experiencing along the roads include rock falls, rock slides, earth/debris slides and flows. Road failure is not caused primarily due to road usage, inadequate supervision, and poor construction materials but it is due to inadequate knowledge on the nature of subsurface geology on which the roads are built (Adiat et al., 2017).

Geophysical methods help to delineate boundaries between residual soils, and weathered and fresh rock. It is also possible to locate anomalous foundation features like dykes, cavities, fault zones and buried river channels using these techniques (Reynolds, 1997; Fell et al., 2005; Chambers et al., 2006; Anderson et al., 2008).Vertical electrical sounding (VES) is used to explore subsurface lateral and vertical variations of resistivity (Telford et al., 1990; Nabighian and Macnae, 1991). Vertical electrical sounding is applied to an approximately horizontally layered to investigate vertical variation in formation resistivity. Resistivity of rocks and soils in the subsurface is largely dependent upon the amount of pore water present, its conductivity, and the manner of its distribution within the material (Fisseha and Mewa, 2016).

The research was carried out with the main objective of investigating subsurface geology and identifying factors which could be responsible for the failures of the Mekelle-Abi Adi road. Hence, vertical electrical resistivity (VES) method was employed to study subsurface geological condition of the road failure. The study area is located in the northern Ethiopia highlands bounded by geographic coordinates: 523,000m to 525,000m E and 1,509,500m to 1,510,500m N (UTM Zone: 37, Datum: Adindan) (Fig 1). The road is a major highway that links Mekelle town with most of the towns in the central zone of Tigray Region. The road failure happed after heavy rainfall in August 4, 2016. Significant landslide damage has occurred at a chainage distance of 48 km+850 m and resulted in a loss of the road base of 70-90 m in length and 2 m failure depth below the ground surface (Fig 1). Based on the site reconnaissance and ground monitoring, the failure type is quasi-translational movement which caused interruption of traffic along the road. The landslide largely extends towards the agricultural area found at the downslope of the road.

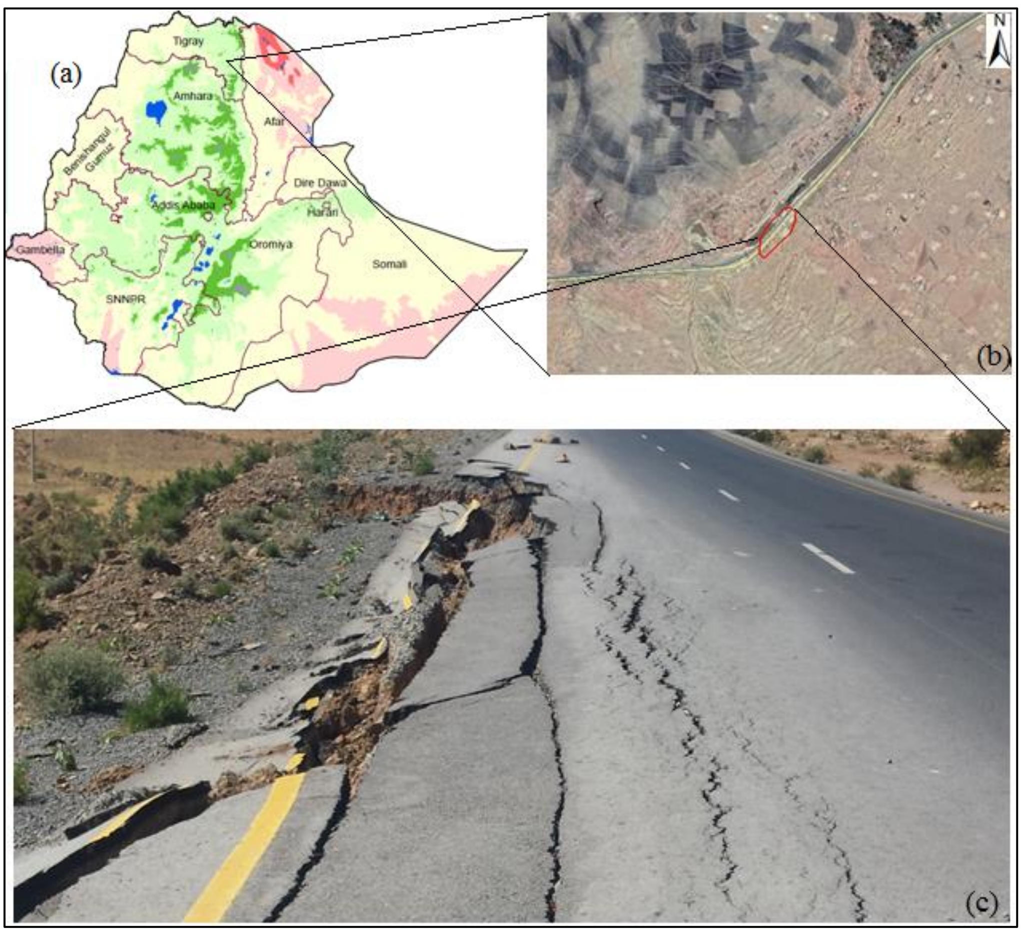

Figure 1. (a) Digital elevation map of Ethiopia (b) Google image of Mekelle – Abi-Adi road segment (c) road failure of the study area.

2. GEOLOGICAL SETTING

The regional geology of Northern Ethiopia is well studied by many scholars over the last decades at regional scale (Levitte, 1970; Beyth, 1972; Kazmin, 1972; Garland, 1980; Bosellini et al., 1997) and can be broadly divided into three major groups: Neoproterozoic Basement Complex, Paleozoic-Mesozoic sedimentary sequences and Cenozoic Trap Volcanic (Levitte, 1970). The Neoproterozoic basement complex of Mekelle area is the southern extension of the Arabian-Nubian Shield (ANS). The sedimentary deposition in Mekelle Outlier began around the Ordovician or Carboniferous and probably ended in Lower Cretaceous before the eruption of the Trap volcanics (Beyth, 1971). Sedimentary rocks are unconformably underlain by Neoproterozoic basement complex form a nearly circular Mekelle Outlier which covers 8000 km^2around Mekelle area and glacial rocks of Paleozoic age, overlain by Jurassic to Lower Cretaceous sandstone and limestone association (Beyth, 1972). The Mekelle basin is one of the well exposed basins in Ethiopia that constitutes nearly complete stratigraphic succession: from the lower (Adigrat) sandstone, through Antalo limestone to the Agula shale and Amba-Aradam formation (upper sandstone). At the top of the Mesozoic succession, there is detrital and mottled sandstone called Amba-Aradam sandstone (Mebrahtu et al., 2019) which consists of mudstone, siltstone and pebbly sandstone. After a major unconformity, the Mesozoic succession of northern Ethiopia is covered by a 2 km thick pile of flood basalt (Ukstins et al., 2002; Hagos et al., 2010). Flood basalts of Tertiary age unconformably overlie the sedimentary rocks which in places are intruded by a network of dolerite sills and dykes (Beyth, 1972; Bosellini et al., 1997). Four major sub-parallel WNW-ESE trending normal faults (Wukro, Mekelle, Chelekot and Fuicea Mariam) with steeply dipping fault planeexist in Mekelle Outlier (Beyth, 1971).

Mekelle – Abi-Adi road passes through different geological units and crosses Mekelle main fault. The geological units have variable engineering performance in supporting the pavement structure. The study area is characterized by three geological units namely: shale, shale-limestone intercalation and sandstone units (Fig 2). Shale and sandstone units cover large area as compared to shale-limestone intercalation unit. Shale unit is exposed in south and southeast part of the study area (Fig 2). Shale unit is overlain by thick Amba-Aradom sandstone. The thickness of shale unit, at the upslope, which caused failure of the road section, ranges 13 to 15 m.

The shale-limestone intercalation unit is exposed widely in south and southeastern part of the study area (Fig 2). Sandstone rock is outcropped in north, northwest and northeast parts of the

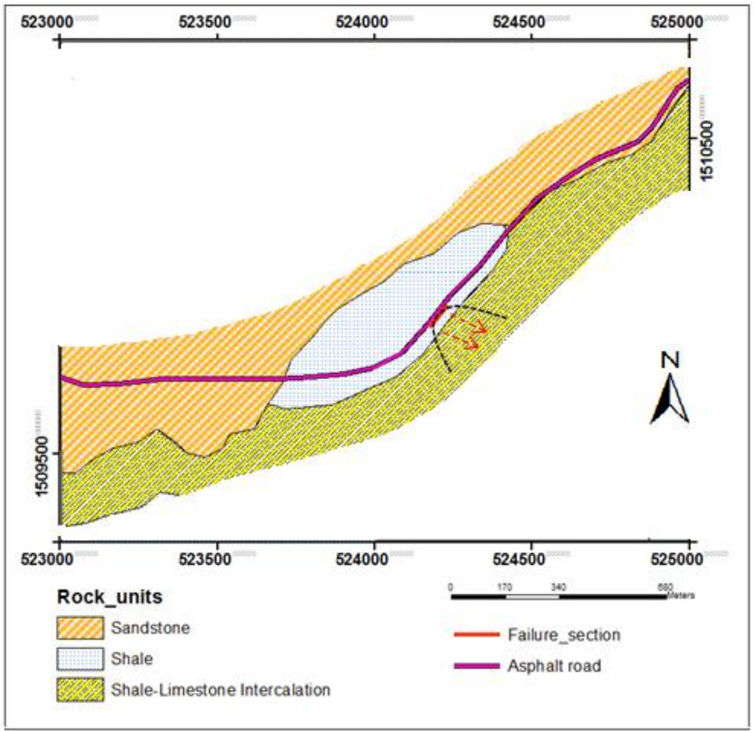

Figure 2. Geological map of the study area and its surrounding. The black dashed line indicates affected zone and dashed arrows show sliding direction of the landslide.

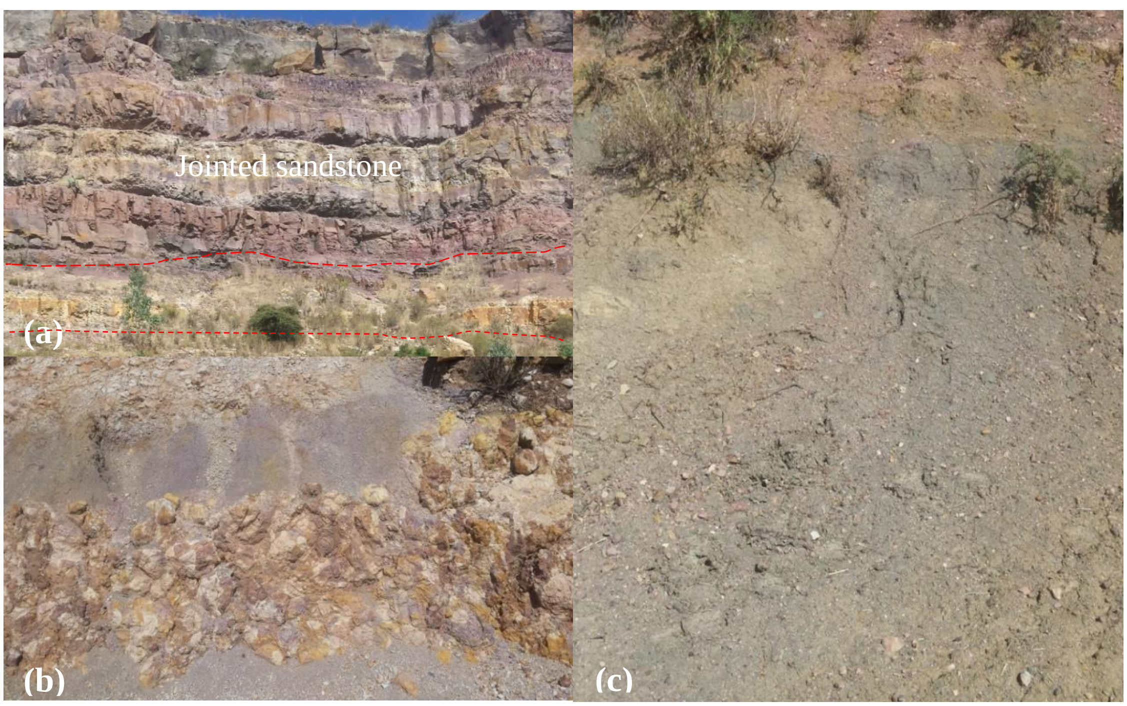

Figure 3. (a) Jointed sandstone unit exposed about 100 m away from the failure section located north west of the study area (b) highly weathered sandstone unit at the contact of the asphalt road failure (c) unconsolidated shale unit exposed along the slide section of the road.

study area. It is characterized by vertically jointed fractures variegated color mainly reddish to whitish which forms high cliff reaches up to 60 m at the failed section. The sandstone at the lower section, which is close to asphalt road, is highly weathered and fractured (Fig 3), while the upper section is relatively less weathered. Hence, there are significant rockfalls and debris slide from the lower and upper slopes of sandstone rock which affects the road.

3. METHODOLOGY

3.1. Vertical Electrical Sounding

Vertical electrical sounding (VES) is used to explore subsurface lateral and vertical variations of resistivity (Telford et al., 1990; Nabighian and Macnae, 1991). Vertical electrical sounding (1D) is applied to approximately horizontally layered geological formations to investigate vertical variation of resistivity. The use of electrical resistivity measurements in studying mass movement is related to the fact that slope failure is closely related to the physical characteristics of the subsurface material. This is often reflected by resistivity contrast between the slide debris and the unaffected mass (Méric et al., 2005; Lapenna et al., 2005). Vertical Electrical Soundings has been used to study the behavior of electrical resistivity in areas affected by landslide and other similar failures (Jatto et al., 2012). Resistivity of rocks and soils in the subsurface is largely dependent upon the amount of pore water present, its conductivity, and the manner of its distribution within the material (Fisseha and Mewa, 2016).

In this study, Vertical Electrical Sounding (VES) data acquisition was employed using ABEM Terrameter SAS 1000 (ABEM, 1999, 2012) with Schlumberger electrode configuration at a maximum current electrode of AB/2 = 220 m. The vertical electrical sounding data is processed using IPI2win software and the maps are developed using Surfer and AutoCAD software. IPI2win software was used to produce the interpreted resistivity curves. Three profile lines were selected for the survey, in which all of the profiles are aligned parallel to the road axis with E-W orientation (Fig 4). The first two profiles are made very near to the road; they are positioned in opposite sides of the road. The third profile is at about 15m from the road, which is on the agricultural field found in the southern part of the site. VES data were collected at 21 sounding points all lying parallel to the road. The VES points are spaced at about 13 m, within a profile and were conducted with half current electrode spacing (AB/2) of 220 m. A measurement taken from the field provides reading of induced current, respective potential difference and calculated apparent resistivity of a point for predefined AB/2 and geometric factor.

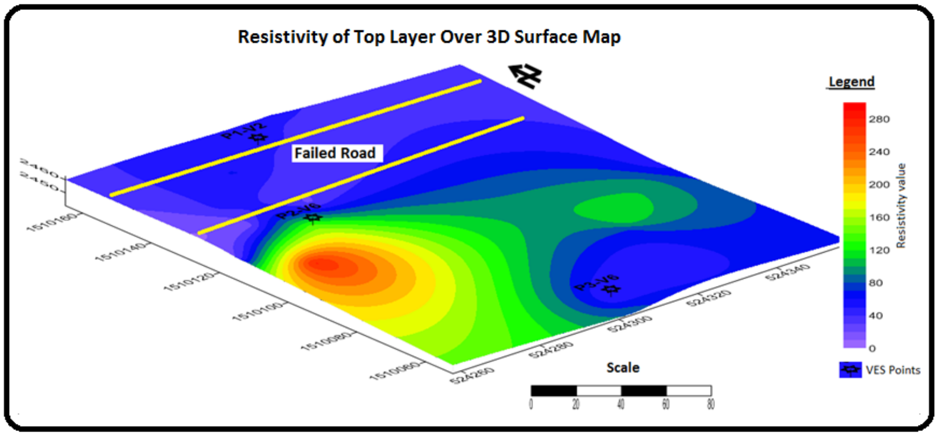

Figure 4. Vertical electrical sounding point locations in the study area.

4. RESULTS AND DISCUSSION

Interpretation was made based on the integration of results from the vertical electrical sounding, geological traversing and secondary borehole log data from the two borehole wells drilled for drinking purpose.

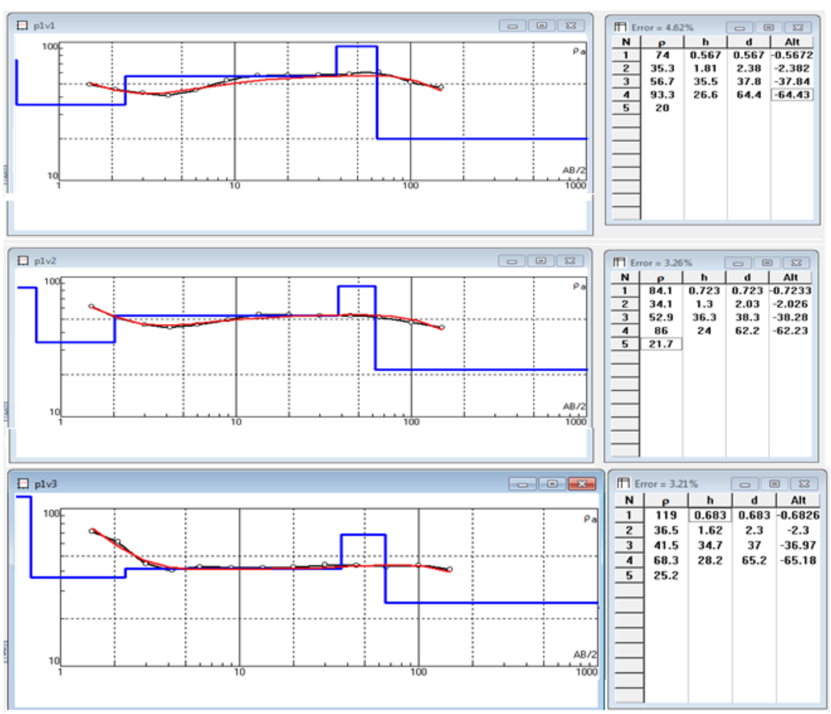

Figure 5. Interpreted VES curves of the three sounding points along the road failure.

4.1. Apparent resistivity sliced-stacked depth map

The apparent resistivity sliced-stacked depth map (Fig 6) was prepared from the vertical electrical sounding data at selected depths to understand subsurface geological variations in lateral and vertical directions at AB/2 = 3, 6, 10,and 20 m. The stacked plot shows that the subsurface comprises two distinct zones (1 and 2) of contrasting resistivity responses (Fig 6). Zone-1 covers an area with relatively low apparent resistivity value (<80 Ω.m) and Zone-2 is characterized by moderate to high apparent resistivity (100-190 Ω.m). The boundary between the two shallow zones with contrasting geo-electrical behavior trends in E-W direction. The developed sliced-stacked depth map shows that large part of eastern and south eastern part of the region at depths (AB/2 = 10 and 20 m) is characterized by relatively low resistivity responses (<80 Ω.m). However, at shallow depth (6 m), its low resistivity extends to north and north east. The entire subsurface tends to get relatively homogenous and low resistive at AB/2 = 20 m, except south west of the study area.

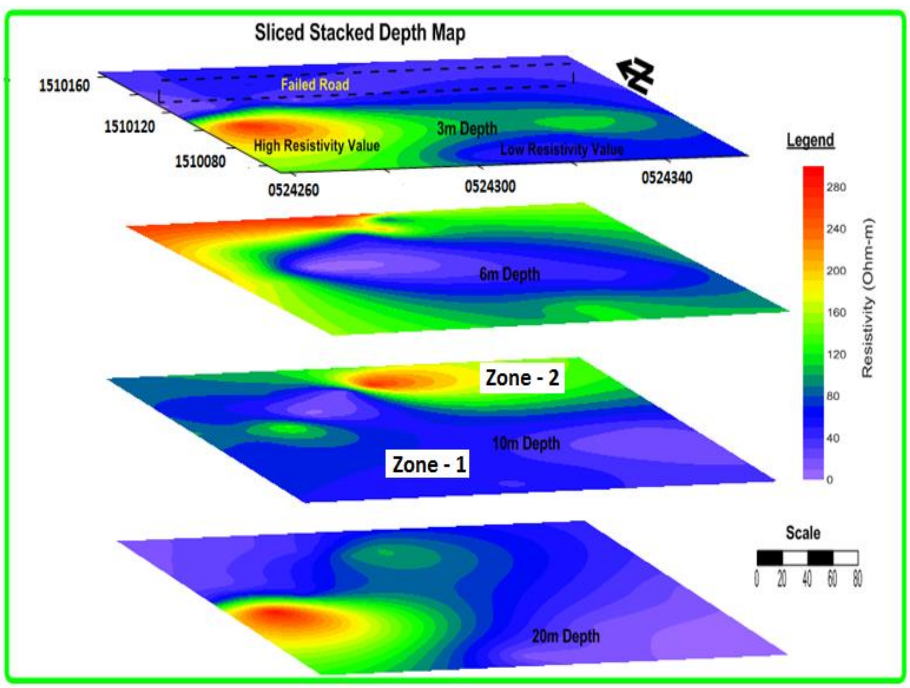

Figure 6. Apparent resistivity sliced-stacked depth map at various depth levels at half electrode separation (AB/2).

4.2. Pseudo-depth section map and Geo-electric map

The measured apparent resistivity values from sounding points along profile-1 were used to produce the pseudo-depth resistivity section map shown in figure 7(a). The resistivity value shows notable lateral (E-W) variation in geo-electric behavior of the shallow subsurface. Generally, the study area is characterized by low to medium resistivity layers throughout the depth. The low resistivity zone (<38 Ω.m) is confined to shallow depth (40 m) of north west where we have road failure and at greater electrode separation in the southwest of the study area (Fig 7a). The remaining vast part of the study area is covered by medium resistivity (>44 Ω.m) as we move away from the road failure towards northeast and southeast.

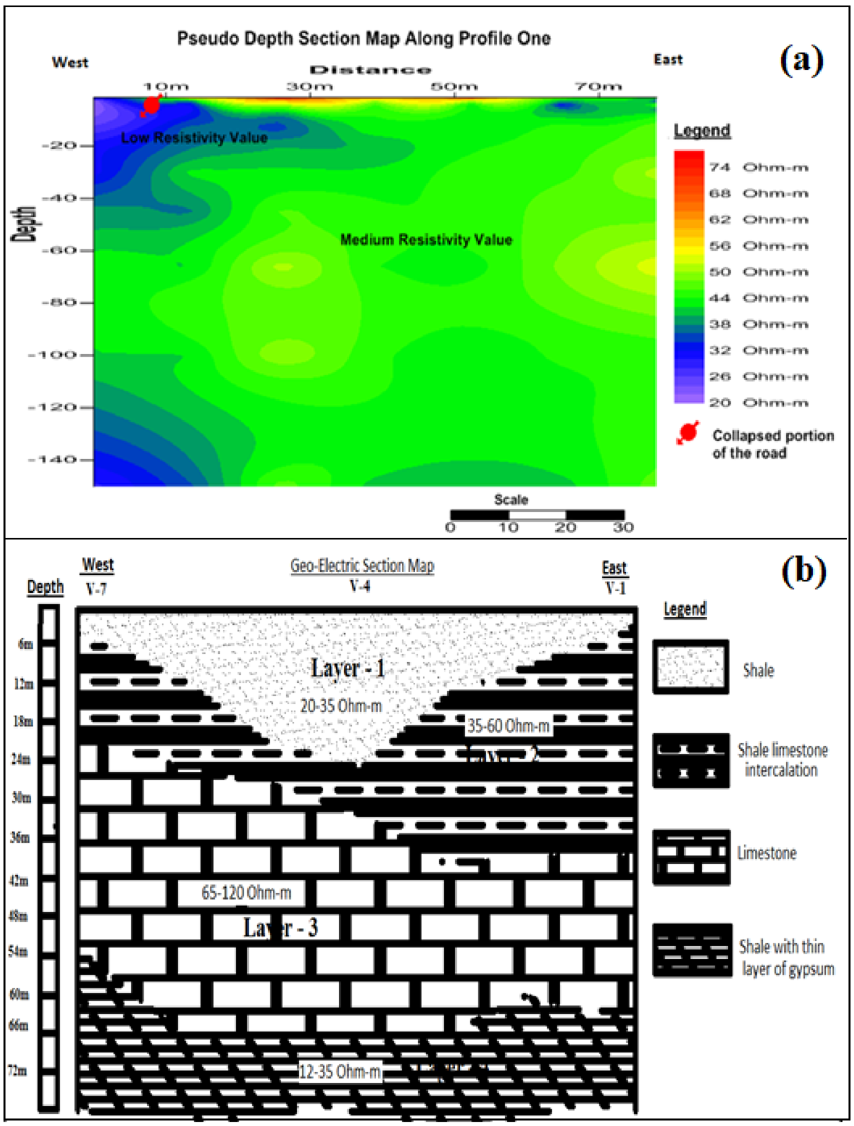

Figure 7. (a) Apparent resistivity pseudo-depth section map along profile 1 (b) geo-electric section map along the road failure.

The corresponding geo-electric section, shown in figure 7(b), displays four distinct geo-electric layers namely, shale, shale-limestone intercalation, limestone and shale-gypsum units.

There is very thin layer (few centimeters depth) at the top part of the road failure which is characterized by relatively higher resistivity value (>60 Ω.m). This is expected to be the response of asphalt concrete. The top layer with resistivity value (20-35 Ω.m) reflects response from shale unit which extends to a depth of 22 m at the center (V-4) and 6 m at the edges (V-1 and V-7). The underlying medium resistivity (35-60 Ω.m) horizon has maximum thickness of 33 m at the right edge and indicates the presence of shale-limestone intercalation unit. This is again underlain by another resistive formation (65-120 Ω.m), occupying the depth from 26 to 42 m, and attributed to a response from slightly weathered to massive limestone formation. The bottom layer with low resistivity value of 12-35 Ω.m,is attributed to shale with thin layer of gypsum. This layer starts at about 60 m and extends to larger depth. The resistivity of geological units increases with depth. However, its value drops at the fourth layer (shale-gypsum unit). This is due to the presence of thin layer of soluble gypsum which can weaken the strength of the rock unit.

5. CONCLUSIONS

The landslide in the road section has occurred after the heavy rainfall in August 4, 2016. The study used VES investigation method to understand subsurface geology of the road failure section. The subsurface geology of the failure section is grouped into four layers namely shale, shale-limestone, limestone and shale-gypsum units. The sliced stacked depth map and pseudo depth section map developed for the road site clearly demonstrates the vertical and horizontal apparent resistivity variation of the survey area. Field investigation showed that the sandstone rock at the upslope of failed road section is highly weathered and jointed which makes it highly pervious. Hence, it serves to recharge rainwater to down-slope impervious layer (shale unit). The shale layer at the lower section of the slope is impervious to hinder the vertical flow of water, which promotes development of pore water pressure and forced to disturb the overlying sub-base of the asphalt road and finally cause road failure. Hence, as a mitigation measure, 400 m length of the road route from chainage 48 km+850 m to 49 km+250 m should be re-designed by moving 15 m to the northwest of the asphalt road to offset the weak and expansive shale unit and excavate the top 6 m shale unit.

6. ACKNOWLEDGEMENTS

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7. CONFLICT OF INTEREST

No conflict of interest

8. REFERENCE

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