# Landslide Investigation Using Transient Electromagnetic Method (TEM): A Case Study on Al-Ja'ydyya- Salhuob Landslide / Jordan

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**Abstract**
In this study, Transient Electromagnetic (TEM) geophysical method was used at Al-Ja'ydyya- Salhuob landslide located along Amman- Irbid - Jerash highway aiming at investigating the subsurface layering's, thicknesses and to map the subsurface failure detachments and internal structures of landslide. Seventeen TEM Soundings were conducted to cover the study area. The interpreted TEM models suggests three to four principle subsurface units that are prevailing in the study area: The upper surface unit with resistivity 50-100 Ohm . m and thickness is ranging from 15m - 25m correlates with colluvial deposits. The second subsurface unit is interpreted to be a Clayey marl and Chalky marl and it has a resistivity range of 8-15 Ohm . m and has thickness in the range of 2 - 4m. This conductive unit were mapped throughout the whole study area. It is expected that this layer has a very significance role for rock sliding and mass movement. The third subsurface resistive (>200 Ohm . m) unit is highly correlated with borehole logs and interpreted as a highly massive fractured limestone. The four subsurface unit is a very low resistivity unit. It was detected beneath the whole study area especially the northern Salhoub landslide. It is interpreted as a saturated fractured limestone unit or marl, chalky filling fractured limestone. The internal subsurface fractures and boundaries of landslides were delineated and were found to be coincident with surface outcropped fractures. The slippage failure surfaces were delineated and mapped and shown clearly in The 2-D E-W and NW-SE TEM models.
**Keywords:** Transient Electromagnetic (TEM), Al-Ja'ydyya- Salhuob Landslide, Jordan

## 1. Introduction

Landslides are considered as a worldwide, natural hazard, and may lead to loss of human life, property and infrastructures and then becomes as a natural disaster (Lutgens and Tarbuck, 2008). According to Montgomery (1993) Landslide is a general term of rapid mass movements, and they occur whenever the downward pull of gravity is overcomes the forces resisting flows. Land sliding can be taken place due to different factors such as: steepness of slope (Topography), water content, erosion and weathering, earthquakes triggering, quick clays, volcanic eruptions (Montgomery, 1993) and rainfall-induced landslides. Human activities such as highway road cut constructions and quarrying can also increase the risk of landslides. In Jordan, Many landslides have been occurred during the last fifty years, most of these landslides occur in a mountainous and hilly areas during intensive rainfall events (Masannat, 2014). They are also common along highway and route constructions where a large mass of rocks removed from the toe of mountain which will eventually influence on the stability of the area and rockslide will take place. Different types of landslides have been recorded along Amman - Jerash- Irbid highway in the end of sixties of the last century (Malkawi et al, 1996). In 1991/1992 winter season, Jordan witnessed an intensive rainfall and snowfall which had led in addition to other geological factor such as the strata dipping and topography to induce landslide along the under reconstruction Amman - Jerash- Irbid highway, and seven landslides have occurred along this route (Malkawi et al, 1996). This study will focus on the largest landslide occurred on this route which is known as Al-Juaydeya -Salhoub landslide.

Different geophysical methods have been used recently to investigate landslides. Hack (2000) discussed different geophysical techniques for analysis slope stability. High resolution seismic reflection method is rarely used for landslide characterization compared with other geophysical methods (e. g Bruno and Marillier, 2000; Bichler *et al.*, 2004; Ferrucci *et al.*, 2000; Bogoslovsky & Ogilvy, 1977). Seismic reflection using shear-wave were also performed (Bichler *et al.* 2004). Multi Analysis Shear Wave MASW integrated with Electrical Resistivity tomography (ERT) techniques were used to investigate an active Salhoub landslide (Al-Omari, 2014). Seismic refraction P-wave method were used for locate undisturbed bedrock beneath landslide (Mc Cann and Forster, 1990; Bievre G. et al. 2009; Crampin S. et al. 2006). The Generalized Reciprocal Method (GRM) – A seismic refraction technique were applied by several researchers to investigate the failure surface of large landslide (Mauritsch *et al.* 2000) , and were used for shallow landslides (Glade *et al.* 2005). Seismic tomography (ST) techniques were also used (e.g Méric *et al.*, 2005; Jongmans *et al.*, 2000). Electrical resistivity (ER) method is considered one of the most popular methods used for landslide investigations and it was performed in different worldwide geological environments (e.g. Havenith *et al.*, 2000; Wisen *et al.*, 2003; Demoulin *et al.*, 2003; Bichler *et al.* 2004; Caris and van Asch, 1991; Schmutz *et al.*, 2000; Lapenna *et al.*, 2005). Self Potential (SP) electrical method were used to detect the natural variations of potential difference arises from subsurface groundwater movements and weak zones (Lapenna *et al*. 2003; Patella, 1997). Electromagnetic methods (EM) were used recently by different researches for landslide investigation (e.g. Schmutz *et al*. 2000; Méric *et al.*, 2005; Bruno and Marillier, 2000; Mauritsh *et al*., 2000). Ground Penetration Radar (GPR) - an active Electromagnetic method were recently used for landslide investigation (e.g Roch et al 2005; Bichler *et al*. 2004; Barnhardt and Kayen, 2000; Jeannin *et al*. 2006). Gravimetric survey were used to investigate slope deformation (e.g. Blaha *et al*. 1998; Del Gaudio *et al*. 2000). A comprehensive review on the using of geophysical methods for landslide investigations can be found in (Jongmans *et al*, 2007).

Several geological, geophysical and geotechnical studies have been conducted on landslides in Jordan during the last three decades. Abedarhman (1998) investigated Al- Ja'ydyya landslide by interpretation of an old aerial photos, geotechnical and geological methods and concluded that the reason for mass movement in Al-Ja'ydyya landslide is the fracture rocks, tectonic setting and interpret the recent sliding as a reactivation of a pre-existing slide. Al-Kiliani (1996) conducted geotechnical, geophysical methods using Seismic Refraction (SR) and Vertical Electrical Sounding (VES) resistivity techniques at selected landslides in north Jordan, Al- Ja'ydyya landslide was one of them. The study concluded that Al-Ja'ydyya landslide is characterized by presence of one slippage surface and has safety factor of 0.978-1.23. El-Isa (1992) conducted a geophysical study using Seismic Refraction (SR) and VES resistivity at selected landslide along Amman-Irbid highway to investigate the subsurface conditions, stratification and rock types. Al-Omari (2014) conducted a geophysical study at Salhoub Landslide using Electrical Resistivity Tomography (ERT) and Multi channel Analysis Shear Wave (MASW) aiming at characterizing active Salhoub landslide region. He used the time-lapse ERT as a tool to monitoring the active landslide.

In this research paper, we applied Transient Electromagnetic method (TEM) calibrated with borehole logs to investigate Al-Ja'ydyya - Salhoub active landslide in order to: investigate the subsurface layering to depths of ten's meters, to investigate the layering thicknesses and to map the subsurface failure detachments and internal structures of landslide.

## 2. Study area

Al-Ja'ydyya –Salhoub active landslide study site is located along Amman - Jerash - Irbid route in the northern part of Jordan and within the coordinates [35°51'12.51" - 35°51'22.49" ]E, [32° 6' 49.38" - 32° 7' 5.13" ]N (Figure 1). According to (Massanat, 2014) The rockslide volume is estimated to be exceeded than 120.000 CM. The study area consists of two major landslides and they are separated by a distance of 340m (Figure. 1a and Figure. 1b). In this study they are named as the Northern landslide with dimension of (80m X 100m) and the southern landslide with dimension of (230m X 150m). They are located close to Al-Ja'ydyya village in the south and Salhoub Village in the north as shown in Figure 1a and Figure .1b. The study area characterized by the presence of rugged and hilly mountains and steep slope facing west to southwest and northwest topography. The slip surface where the soil and rock mass moved was linear and runs approximately in a plane parallel to the hillside (Dames and Moore, 1993) The elevation of the study area is ranging from 620masl in western part to more than 700masl in the eastern part of the landslide just through a horizontal distance of 280m.

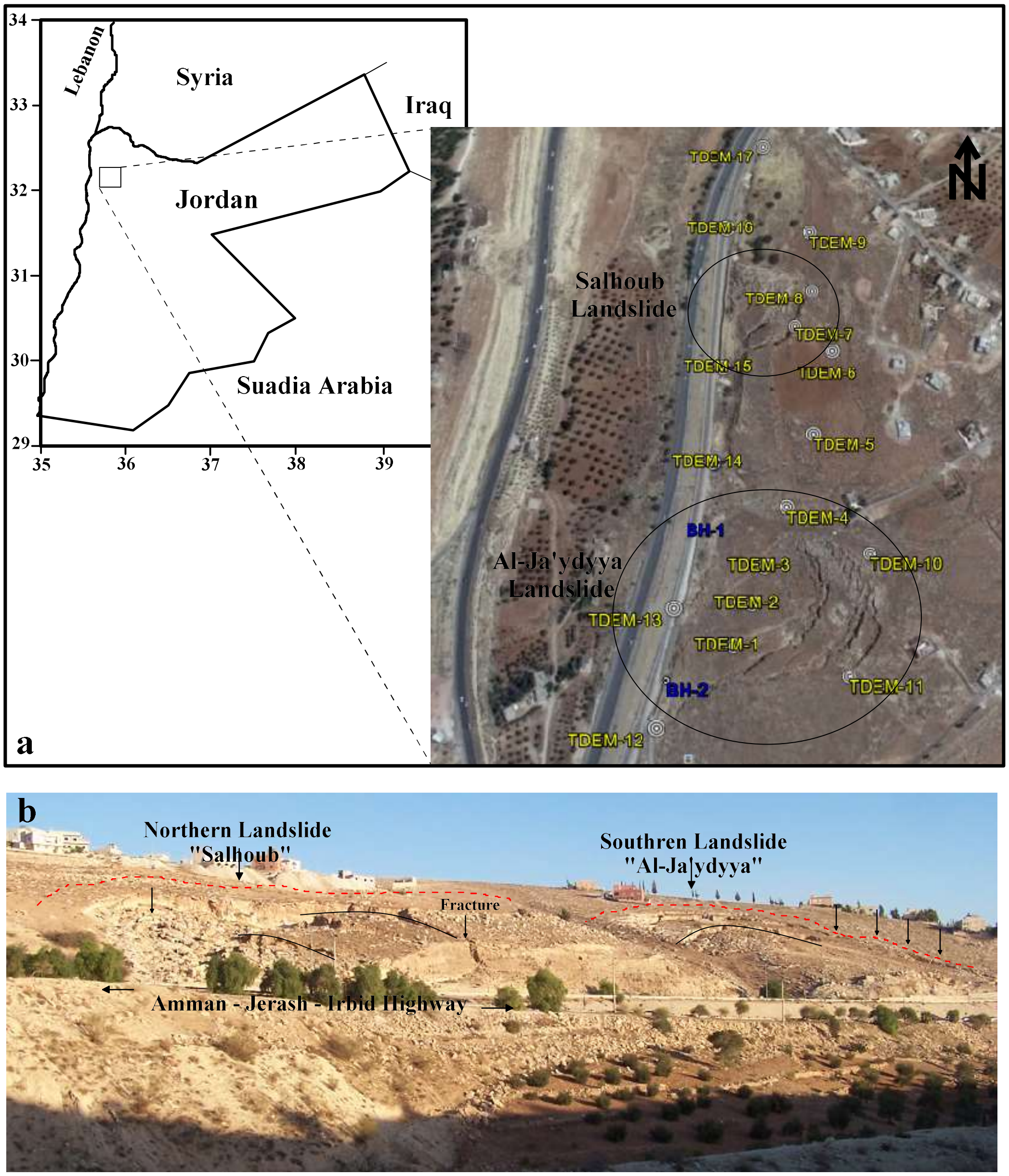


Figure 1. **a**. Location map of the study area showing TEM soundings, BH-1 and BH-2 locations and Salhoub – Al-Ja'ydyya landslides superimposed on Google earth map. **b**. Photo shows a general view of northern and southern landslides

## 3. Geology of the study area

The geological formations cropping out in the study area are of upper cretaceous age, and they can be summarized from oldest to recent as follow (Sawarieh and Barjous, 1993) and shown in Figure 2:

- **Na'ur Limestone Formation (NL):** This formation belongs to Cenomanian age and its lower part consists of dark greenish grey, bituminous marly limestone having nodular texture and fragments of gastropods and bivalves intercalated with glauconitic marl. It forms the base of Ajlun group, its thickness ranging between 180-200m. the remaining lower part consists of massive, nodular micritic and dolomitic limestone intercalated with marl and laminated mudstone. The upper part comprising of two prominent massive units nodular dolomitic limestone and limestone. The upper dolomitic limestone with chert nodules forms a prominent marker and its thickness reaches 22m. The depositional environment was a shallow-marine to deep marine, sub tidal of carbonate platform. Na'ur limestone (NL) formation is considered the principle geological formation where Al-Ja'ydyya -Salhoub landslides have occurred.

 

- **Fuhays Limestone (F)**: This formation is overlies Na'ur formation and forms a gentle slopes and has a total thickness of 80m. It consists mainly of marl intercalated with thin bedded of nodular limestone, marly limestone and dark shale.
- **Hummar Formation (H)**: This formation is overlies Fuhays limestone (F), its belongs to upper Cenomanian in age. It is comprising of massive marly limestone and micritic limestone overlain by limestone, dolomitic limestone intercalated with dolomite and thin beds of marly limestone and mudstone. It forms a prominent cliff due to its hardness relative the surroundings layers.
- **Shu'ayb Formation (S)**: This formation belongs to (Upper Cinemania to lower Turonian) in age with 60m thickness. It consists mainly of thin beds of chalky limestone and thin beds of dolomitic limestone intercalated with marl. It characterized by a gentle slopes morphology between the distinctive escarpments of Wad El-sir Limestone (WSL) and Hummar formations (H).
- **Wadi El-Sir Limestone Formation (WSL)**:This formation belongs to Turonian in age and has a total thickness ranged from 100m to 120m. It consists of massive well-bedded dolomitic limestone, carbonate litho-facies, fossilliferous horizons and dolomite.

The principle structures dominated in the study area is the northern extension of NE-SW trending deformed Wadi Sh'ayeb structure belt which comprising of an en echelon folds, monoclincal, flexture and faults (Figure. 2). The faults system associated with the principle structure are oriented NNE-SSE, SE-NE and E-W, and the latter exhibits a right strike-slip movements (Sawarieh and Barjous, 1993) . Figure 3 shows a schematic illustration of an East –West geological cross section along the Al'ajuyyda landslide.

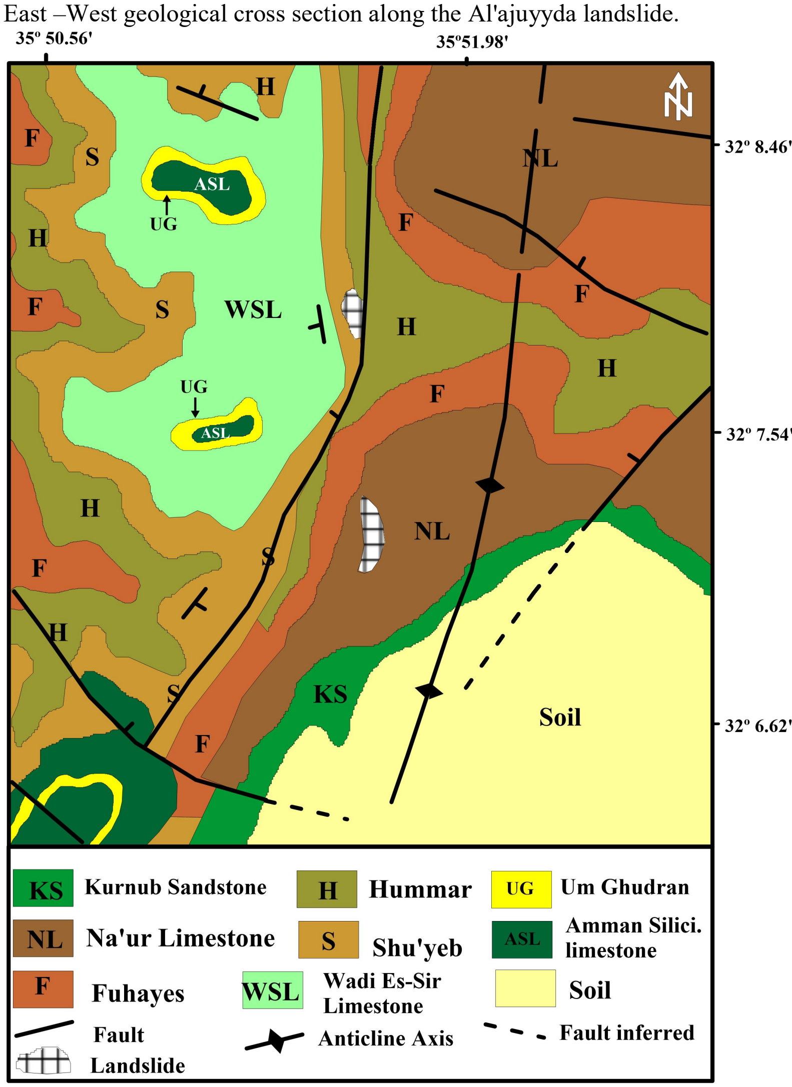


Figure 2. Geological map of the study area. (Modified after Sawarieh and Barjous, 1993)

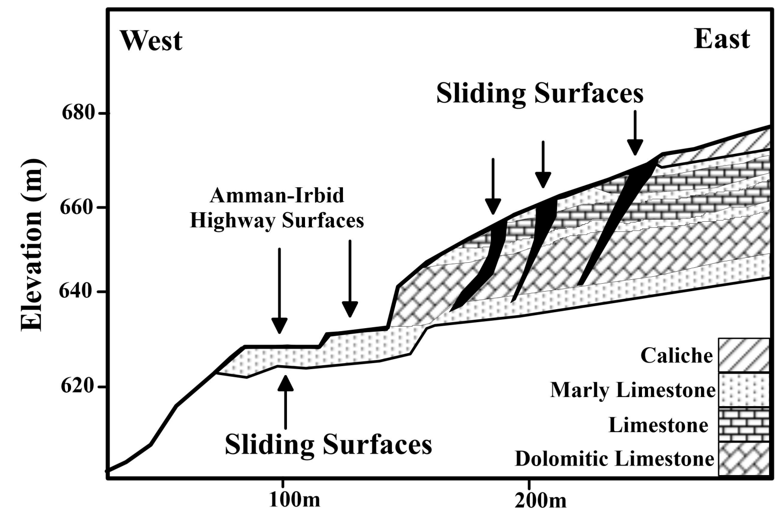


Figure 3. Illustration of an E-W geological cross section of Al'ajuyyda landslide (modified after Abderahman, 1998; Al-Omari, 2014)

## 4. Methods, Data Acquisition and Modeling

### 4.1 Transient Electromagnetic method (TEM)

Time domain Electromagnetic method (TDEM) or Transient Electromagnetic method (TEM) is proven to be a useful technique for near surface geophysical applications and shallow depths surveys (Fainberg *et al*., 1998). TEM data are less effected by lateral in-homogeneities (Helwig, 1994), and hence, it has better lateral and vertical resolution than other EM and electrical methods (Bruno and Marillier 2000; Méric *et al.* 2005).

In Transient Electromagnetic (TEM) method, a direct current (DC) is passed through undergrounded loop transmitter (Tx) to generate a primary magnetic field. After a discrete period of time, the applied direct current (DC) is switched off abruptly. An eddy currents will be generated in the subsurface conductor bodies or layers as a result of the sharp change of the primary field (Reynolds, 2011). The surface eddy currents will produce a second magnetic field. The surface eddy currents induced in a subsurface conductor start to diffuse inward outwards its center when the inducing field is removed and gradually dissipate by resistive heat loss and ohmic losses (Keary *et al*. 2002; Reynolds, 2011). This will cause a decaying of the secondary magnetic field at the earth surface (Sharma, 1997). The rate of change of these currents and of their respective magnetic field depends upon the size and shape of the conductor and on its electrical conductivity (Reynolds, 2011). The whole process of the stepwise excitation of the current loop is repeated many times and the data stacked for a given location (Reynolds, 2011). The resultant and superimposed primary and secondary magnetic fields can be measured used a another receiver coil (Tr) and can be separated and analyzed to provide information about the subsurface resistivity distribution. A detailed description of Transient electromagnetic method (TEM) and its applications can be found in many geophysical text books and published articles (e.g. Nabighian and Macnae 1991;Sharma, 1997; Reynolds, 2011; Keary *et al*.2002; Kirch, 2006).

## 5. Results

In this study, Seventeen Transient Electromagnetic (TEM) sounding points were carried out at Al-Ja'ydyya - Salhoub landslide site to cover the northern and southern landslide. Figure 1 shows the locations of TEM soundings locations. The Longitude, latitude, altitudes, and RMS for the modeled TEM soundings are summarized and listed in Table .1. The primary objective of transient electromagnetic (TEM) survey is to determine the subsurface stratigraphy based on differences in electrical resistivity distribution. The TDEM or TEM soundings were conducted along two major N-S profiles so that a different 2-dimensional electromagnetic resistivity - geological cross section models can be obtained. The size of electromagnetic square transmitter loop were varied between 25m * 25m to 50m*50m depending on the local topography and terrain conditions as well as the required depth penetration, with an estimated depth ranging from 80m to 150m below ground surface. The TEM field measurements were conducted using a TEM-FAST 48HPC system device. It consists of transmitter (Tx) – Receiver (Tr) unit control, 12-V battery, and two internal extra batteries, the system is managed by HP-IPAQ pocket. The system is attached by a TEM-RESEARCHER software and was used for processing, analysis and data interpretation. It enables to interpret the TEM data in a single 1-D curve and allows to construct a 2-Dimensional resistivity cross-section from multiple TEM measurements. The geological and litho-logical interpretation of the modeled TEM-resistivity values were carried out using the available geological information (Sawaria and Barjous, 1993) as well as a correlation with a certain borehole logs shown in Figure. 4 drilled previously in the study area for geotechnical and geological investigation (GEMT ,1993; Al-Omari, 2014). Figure .2a shows the results of correlation of TEM-12 model with Borehole log BH-2 and Figure .2b shows the results of correlation of TEM-13 and Borehole log BH-1. The total depth of each borehole is 20m (GEMT, 1993). Based on the correlations shown in Figure 4, It can be seen that there is a well coincident between the modeled TEM data and boreholes logs. The main electrical resistivity contrast can be seen in Figure 4a and Figure 4b is the contact between the slightly weathered, fractured massive limestone and the fractured limestone with massive chalky marl filling fractures at depth 20m. The resistivity at this contact is sharply decline from more than 120 Ohm.m to less than 15 Ohm.m. The correlation also exhibits a distinctive very low resistivity layer (<10 Ohm.m) found at depth 26m-28m (Figure 4), this layer is highly correlated to clayey marl layer in and to massive marl filling fractures in Figure 4. Moreover, this layer was delineated in most modeled TEM soundings in the investigated area. Beneath this layer a high resistivity layer (>200 Ohm.m) is highly correlated with moderately weathered, highly fractured massive limestone. This correlation allows to derive a general litho-resistivity relationship which can be used to interpret the other inverted TEM soundings in the investigated area and resistivity distribution at larger depths.

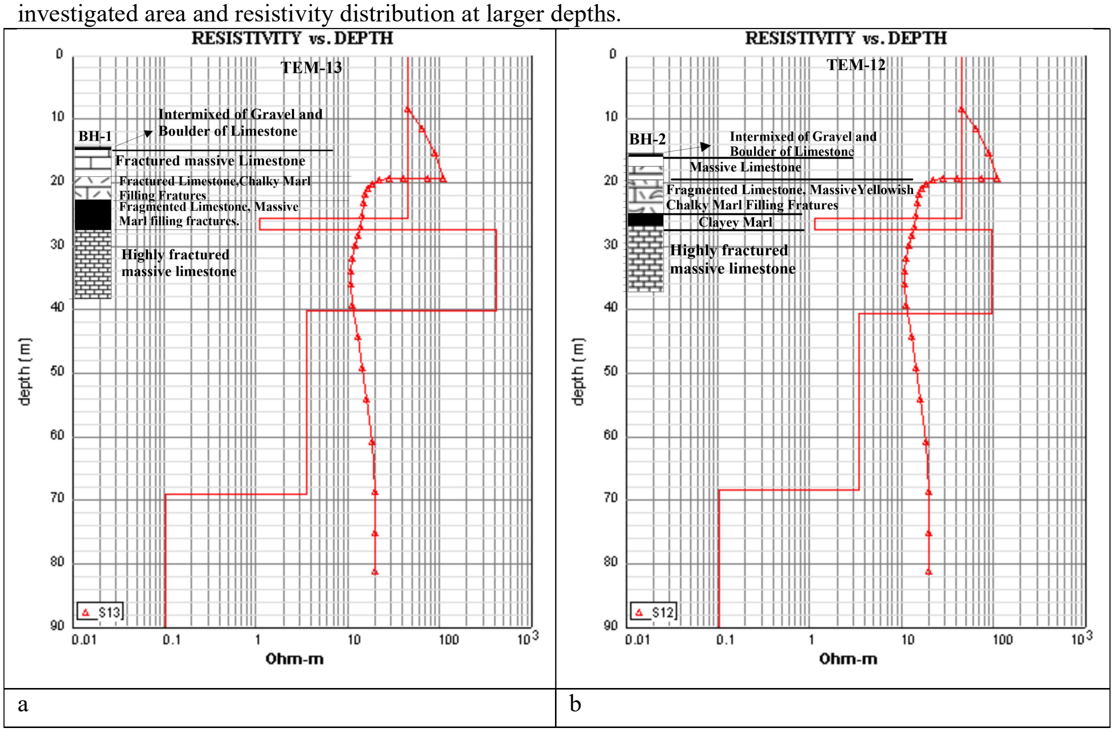


Figure 4. A. Correlation between TEM-13 and BH-1. B. Correlation between TEM-12 and BH-2 log

Table 1. Longitude, Latitude, Altitudes and RMS for the TEM soundings

| No. | Longitude | Latitude | Altitudes(m) | RMS |
|---|---|---|---|---|
| TEM-1 | 35° 51.277' | 32° 6.857' | 670 | 0.78 |
| TEM-2 | 35° 51.288' | 32° 6.879' | 675 | 0.71 |
| TEM-3 | 35° 51.295' | 32° 6.898' | 680 | 1.08 |
| TEM-4 | 35° 51.308' | 32° 6.929' | 670 | 0.28 |
| TEM-5 | 35° 51.325' | 32° 6.970' | 688 | 0.92 |
| TEM-6 | 35° 51.337' | 32° 7.018' | 695 | 0.44 |
| TEM-7 | 35° 51.314' | 32° 7.034' | 688 | 5.32 |
| TEM-8 | 35° 51.325' | 32° 7.056' | 690 | 3.04 |
| TEM-9 | 35° 51.324' | 32° 7.093' | 690 | 2.37 |
| TEM-10 | 35° 51.356' | 32° 6.905' | 705 | 1.55 |
| TEM-11 | 35° 51.343' | 32° 6.842' | 708 | 5.05 |
| TEM-12 | 35° 51.235' | 32° 6.817' | 658 | 6.73 |
| TEM-13 | 32° 6.876' | 32° 6.876' | 657 | 6.72 |
| TEM-14 | 35° 51.264' | 32° 6.954' | 653 | 1.69 |
| TEM-15 | 35° 51.269' | 32° 7.009' | 660 | 1.7 |

| | | | | |
|---|---|---|---|---|
| TEM-16 | 35° 51.270' | 32° 7.096' | 660 | 4.44 |
| TEM-17 | 35° 51.294' | 32° 7.151' | 663 | 1.4 |

## 6. Discussion and Conclusion

The TEM's sounding measurements were interpreted separately as a 1-dimensional models with the aid of surface geological maps and calibrating with boreholes logs . In addition, two major electromagnetic profiles striking N-S and crossing Al-Ja'ydyya and Salhoub landslides were constructed using multiple 1-D TEM's as shown in Figure 5 and Figure 6. Furthermore, a NW-SE and two E-W 2-D electromagnetic profiles were constructed over both landslides and shown in Figure 7, Figure 8 and Figure 9 respectively. It was difficult to build a 3-D electromagnetic representation for the investigated area because the terrains and high elevation variability, therefore, and instead of that a different slices at different selected depths were constructed and shown in Figure 10. The 2-D TEM models suggest three to four subsurface units. The upper surface unit with resistivity 50-100 Ohm.m and thickness is ranging from 15m-25m correlates with colluvial deposits which consists of intermix of gravel and boulder of limestone and silty clay filling fractures and fracture massive limestone. This unit were detected throughout the whole investigated area and 2-D cross sections (Figure 5 -9). The second subsurface unit is interpreted to be a Clayey marl and Chalky marl and it has a resistivity range of 8-15 Ohm.m and has thickness in the range of 2-4m. It was extensively mapped throughout the whole investigated area (Figures 5 - 6 ), and it was clear beneath southern landslides Figure 10.a. The third subsurface resistive unit is highly correlated with borehole logs and interpreted as a highly massive fractured limestone. This subsurface unit is characterized by high resistivity values 200 - >400 Ohm.m and has variable thickness ranges from 10m to 30m as shown in the 2-D TEM model (Figures 5-10). This resistive unit appear in the 2-D TEM model (Figure 6) only beneath the southern landslide "Al-Jayadyya", whereas, this layer is not appeared under the Northern landslide 'Salhoub" as shown in Figure 6. TEM models shows that this unit is not laterally homogeneous and is highly faulted and influenced by the landslide boundaries (Figure 5 an 6). Moreover, a large lateral variations in resistivity is shown in Figure 6 and Figure 10 which may reflect a variations in litho-logical and geological facies between the northern and southern landslides. It is expected that the fractures of massive limestone were filled by marl, chalky marl which effect the resistivity to be decline to 20 Ohm.m beneath Salhoub landslide (Figure 5 and 6). A very low resistivity unit is shown beneath TEM-12, TEM-13 and TEM-14 at depth 70mbgl shown in Figure 6, and appear beneath the northern landslide Figure 7 and Figure 10.d, and it is interpreted as a saturated fractured limestone unit or a marl ,chalky filling fractured limestone. The internal subsurface fractures and boundaries of landslides were delineated and were found to be coincident with surface outcropped fractures (Figure 5 - 10). The slippage failure surfaces were delineated and mapped and shown clearly in The E-W and NW-SE TEM models (Figures 7- 9). By examining the slices in Figure 10, it can be concluded that a major fault structure striking WNW-ESE is delineated beneath TEM-4 as deduced from the large variations in resistivity values.

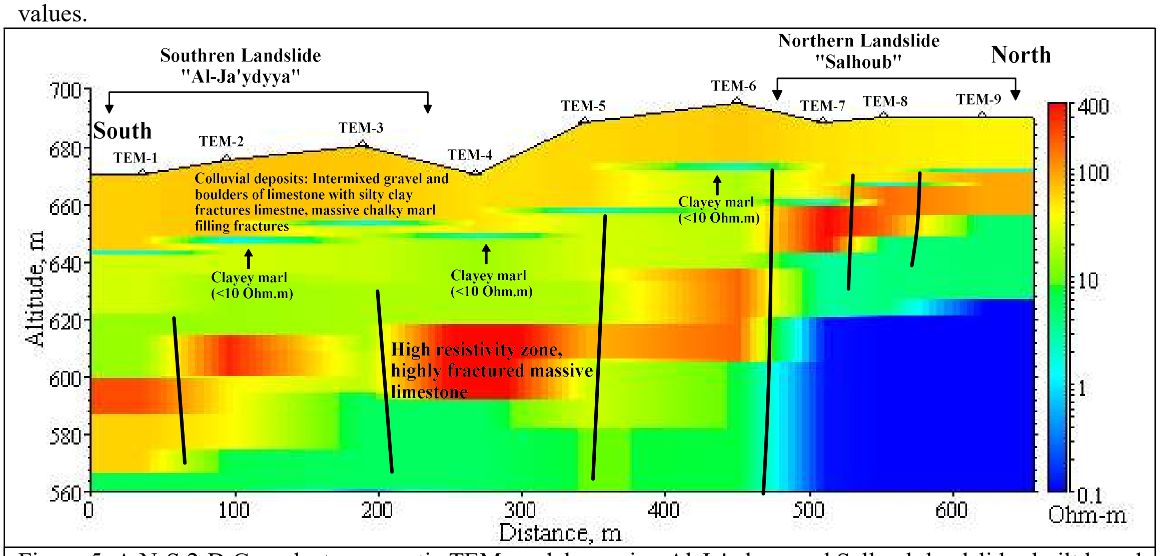


Figure 5. A N-S 2-D Geo-electromagnetic TEM model crossing Al-Ja'udyya and Salhoub landslides built based on multiple TEM sounding models. The model Shows the geological interpretation as correlated with borehole logs in Figure 4.

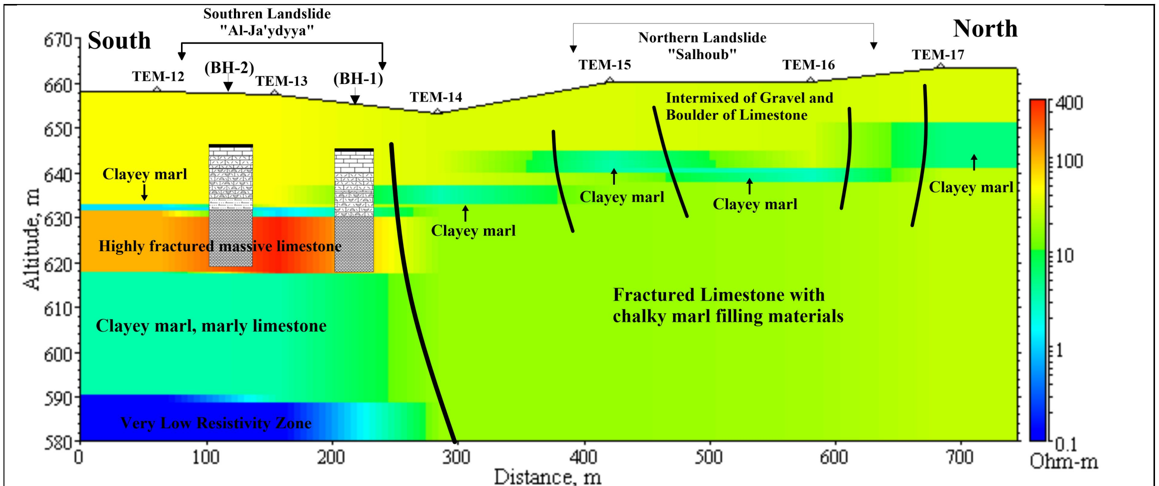


Figure 6. A N-S 2-D Geo-electromagnetic TEM model crossing Al-Ja'udyya and Salhoub landslides built based on multiple TEM sounding models. The model Shows the geological interpretation as correlated with borehole logs BH-1 and BH-2.

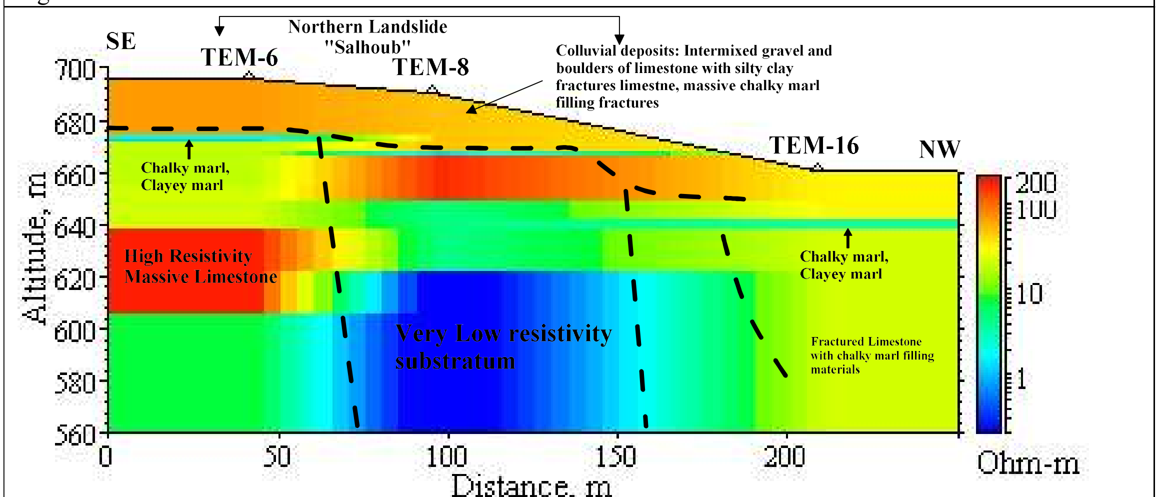


Figure 7. A NW-SE 2-D Geo-electromagnetic TEM model crossing Salhoub landslide built based on multiple sounding models (TEM-6, TEM-8 and TEM-16). The slippage failure surface is clearly shown.

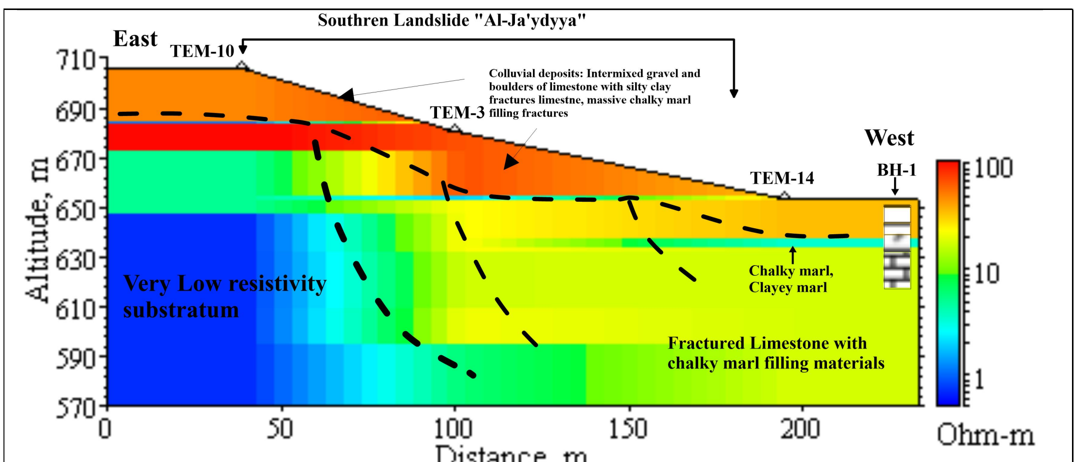


Figure 8. An East -West 2-D Geo-electromagnetic TEM model crossing Al-Ja'udyya landslide built based on multiple TEM sounding models (TEM-10, TEM-3 and TEM14). The model Shows the geological interpretation as correlated with BH-1. The slippage failure surface and its extension is

clearly shown.

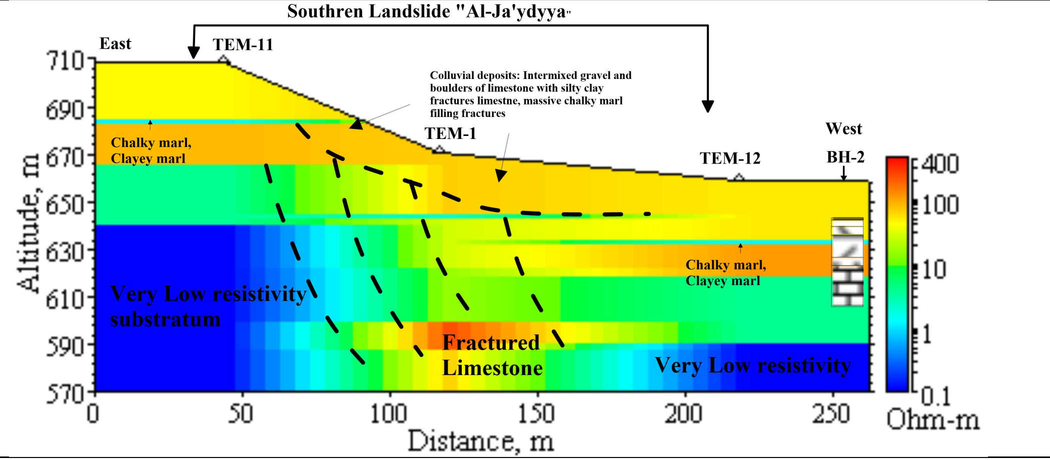


Figure 9. An East -West 2-D Geo-electromagnetic TEM model crossing Al-Ja'udyya landslide built based on multiple sounding models (TEM-11, TEM-1 and TEM12). The model Shows the geological interpretation as correlated with BH-2. The slippage failure surface and its extension is clearly shown.

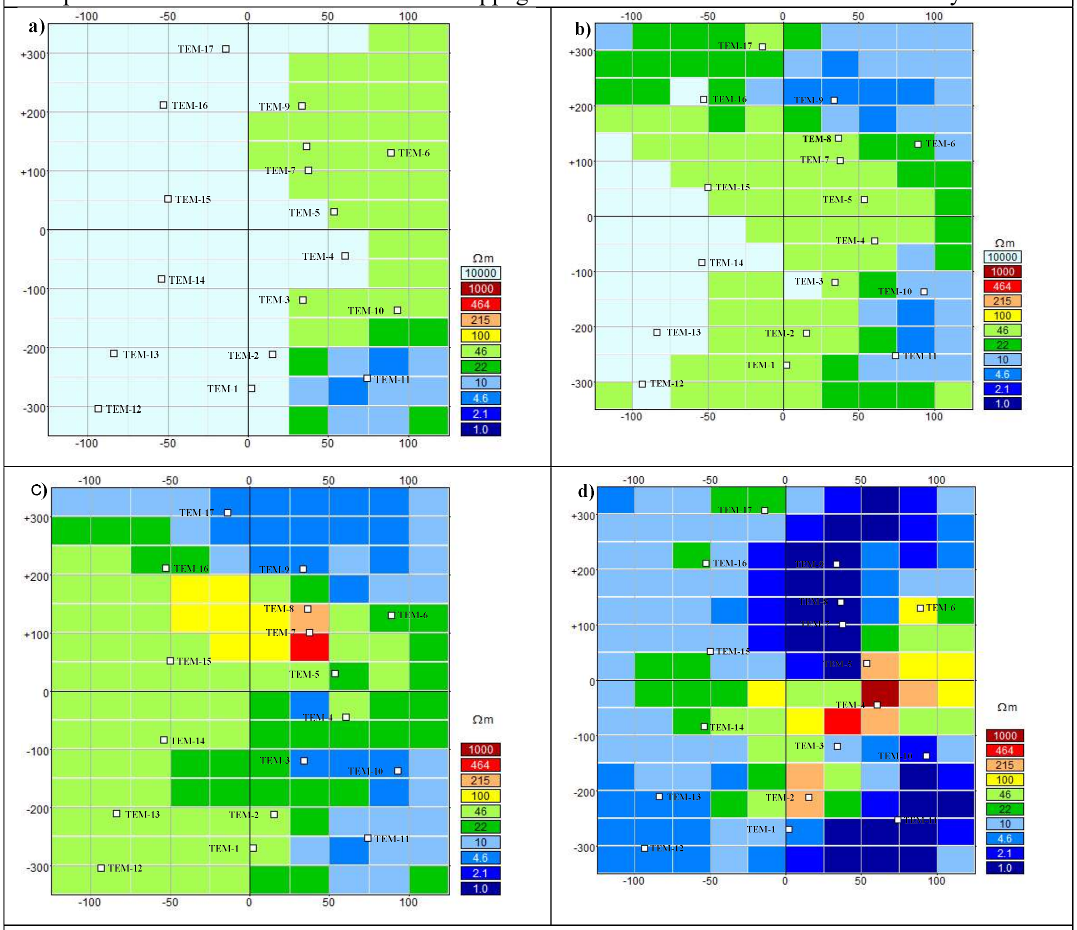


Figure 10.Geo-electromagnetic Slices at different depths a) 20mbgs, b) 40mbgs, c)55mbgs and d) 100mbgs. The slices were built based on multiple TEM's soundings, The light blue cells in Figure 10.a and Figure 10.b with 10.000 Ohm.m indicates for no data since the investigated area is characterized by high topography variations. A major structure striking WNW-ESE between the northern and southern landslide can be delineated beneath TEM-4 at all slices.

## 7. Conclusion

This case study of application of Transient Electromagnetic (TEM) method for investigating and characterization of Al-Ja'udyya and Salhoub landslides along Amman-Jerash - Irbid highway proved to be a reliable, efficient and provide valuable information about landslide. The method was used to investigate the subsurface resistivity – lithology relationship, internal structures and landslide fractures boundaries. Moreover, the slippage failure surface where the rock mass has occurred and its extensions beneath landslides were mapped. The TEM modeling results were calibrated and correlated with borehole logs to derive a litho-resistivity relationship. High correlations and coincident between the TEM model results and borehole logs were found especially in delineating the contact between subsurface units and their lithological constituents. The lithology-resistivity relationship were then used to interpret the other TEM soundings in the investigated area as well as the resistivity values at larger depths.

## 8. Acknowledgment

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