Application of a two-dimensional electrical tomography technique for investigating landslides along the Amman–Dead Sea highway, Jordan

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Abstract Electrical tomography geophysical surveys were conducted with the SYSCAL-R2 resistivity instrument at the location of instantaneous rock failure of a few 1,000s m^3 along the Amman–Dead Sea highway, Jordan, providing a ground image for investigating landslide sites which caused material damage and closed the road. This slide occurred along two major fault planes after heavy rainfall in a rock consisting of a succession of shale, marl and marly limestone layers which were folded, tilted and fractured. Three electrical tomography profiles were performed along the axis of the slope to assess the landslide risk in such potential unstable areas. The results obtained, based on two-dimensional inversion of field data, have allowed mapping of the shale zones at depths which are characterized by a lower resistivity value, and have demonstrated that the rupture was initiated at the contact between the shale mass (black colored) and the massive limestone (white, yellowish-brown colored).

Keywords Jordan · Landslide · Electrical tomography · Risk assessment

Introduction

The Hashemite Kingdom of Jordan (HKJ) is located on the northwestern edge of the Arabian Plate and includes an area of about 96,000 km^2. The landscape of the HKJ is a vast semi-desert or desert plateau in the east. To the west is a mountainous region rising to heights of 800 to more than 1,400 m above sea level, associated with the Wadi Araba Dead Sea Transform Fault (WADSTF) where 80% of the total population lives.

The east bank of the WADSTF is controlled by the regional tectonics of the horizontally, northward-moving Arabian Plate. Therefore, the compressed structures are folded with a higher intensity of deformation close to the transform fault and decrease eastwards, thus leading to deformational belts which represent potential zones of weakness, characterized by displacements and stress release represented by major landslides, joints, fractures, rock collapses, local earthquakes, rock movements and caverns. Rock fall and collapse of rock cut face are serious problems in road maintenance, and more detailed disaster mitigation is required in the HKJ where many roads are constructed in mountainous areas. The usual investigation method for estimating the danger of rock falls or rock cut-face collapse is by means of geological inspection. From these inspections, the danger of collapse is often empirically judged on the basis of crack conditions observed on the rock cut-face surface. Because of the empirical nature of this method, a conclusive investigation capability for detecting and locating potentially dangerous rock collapse sites is not always available. Therefore, the application of geophysical methods provides new means of rapid investigation of vast areas, producing data with increased accuracy from a larger number of sample points than is possible by the use of geologic engineering techniques (Bogoslovsky and Ogilvy 1977; Bogoslovsky and others 1977; Sasahara and others 1995; Jongmans and others 2000). As an additional advantage, the determination of the mechanical properties of the soils is not made on single samples of limited volume, but is rather based on measurements of large volumes of rocks directly involved in the processes occurring in the slope under investigation. Thus, the parameters measured automatically reflect the combined geologic and hydrologic characteristics, which sometimes cannot be identified separately. Moreover, geophysical measurements can be repeated any number of times without disturbing the environment.

A modern highway joining the capital city of the HKJ in the east with the Dead Sea region in the west was constructed 10 years ago under the supervision of the Ministry of Public Works and Housing. The highway is a dual

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carriage-way which passes across the western highlands of Jordan. It is a transport route of national importance, because it links the city of Amman with the Dead Sea, and leads to the Palestine borders (Fig. 1). Because of the rugged terrain in and around Al Adaseih village, the site has been excavated to various lengths, widths and depths in different directions.

During the winter season (November to February), a rock failure involving a few 1,000s m^3 occurred along the Amman–Dead Sea highway near Al Adaseih village (Fig. 1). Rock-failure phenomena occurred repeatedly after every heavy rainfall, fortunately causing only material damage. The road was closed, highlighting the risk of slope failures for transport systems. Most of the road slopes in the HKJ are discovered during construction works, which demonstrates the need for techniques to investigate potentially unstable cuttings. In Al Adaseih, the cut face is about 120 m high and dips at about 22°. At the main, active landslide site, the highway is trending in a NNW–SSE direction (Fig. 2). Field observations clearly show that the landslide is deep and was initiated at the contact between the massive limestone material and the black shale. The slide mass reaches a maximum thickness of about 20 m. All buildings and farms, which are located at the foot of the heap and close to the west side, are threatened by a landslide and this risk has to be assessed and addressed.

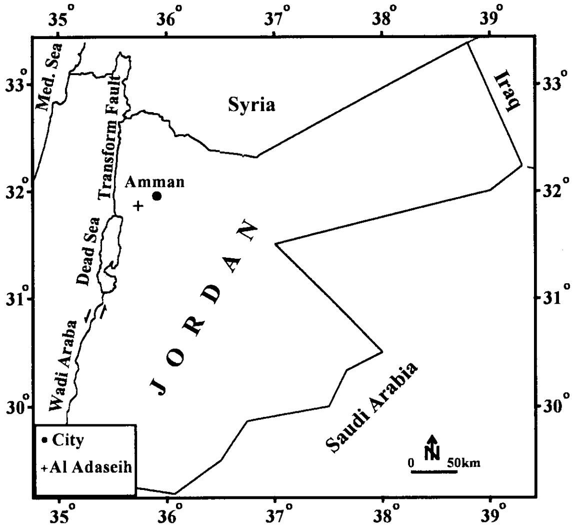

Fig. 1
Location map showing the Al Adaseih landslide site in Jordan

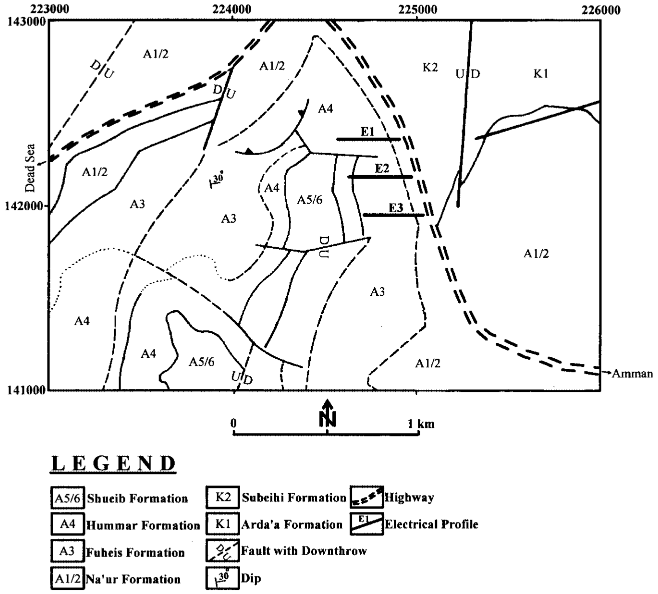

Fig. 2
Geological map of the study area (MacDonald 1965)

Geological setting

Throughout most of Jordan and during the Upper Cretaceous, the Tethys Ocean deposited carbonate facies of the Ajlun Group (Cenomanian-Turonian) which overlies disconformably the Kurnub Sandstone Group of the Lower Cretaceous (Abed 1982; Barjous 1995) and includes, in ascending order, the Na'ur Limestone, the Fuheis/Hummar/Shueib (undifferentiated), and the Wadi Es Sir Limestone formations (Table 1).

The rock mass in the study area is formed by a succession of shale, marl and marly limestone layers of Cenomanian age and dips gently (25–35°) to the ENE. These are equivalent, in the upward sequence, to the Fuheis/Hummar/Shueib formations of the Ajlun Group (Fig. 2). They are considered to be high landslide-risk units in Jordan (Batayneh and others 1999; Batayneh and Al-Zoubi 2000). The uppermost Wadi Es Sir formation of the Turonian and Belqa Group of bedrock outcrops on the surrounding hills, but is not exposed by highway excavations.

In central Jordan, and locally in the study area, the Fuheis/Hummar/Shueib formations are about 75 m thick and show broad lateral and vertical changes in lithology and thickness due to the facies changes. The depositional environment ranged from open marine to supratidal with some terrestrial sediment. This sequence forms a break in the morphological slope between the massive horizon, which forms the upper part of the Na'ur formation, and the overlying Wadi Es Sir formation. They are cut by two E–W trending major faults (Fig. 2). The slide occurred along these two faults, dipping towards the slope face and oriented at 22° from the slope trend. The rock mass is also cut by two major sets of steeply inclined and closely spaced fractures. These open joints weaken the rock mass by delimiting blocks, and play a major role in introducing water, particularly after heavy rainfalls, which dramatically reduces friction along discontinuities. An analysis of the main fracture sets is shown in the rose diagram of Fig. 3.

Figure 4 shows an E–W topography cross section through the Al Adaseih slide. This section was constructed by comparing the initial topography, deduced from the topographical map, and the topography after the landslides and excavation works.

Table 1
Geological sequence of the study area (Abed 1982; Barjous 1995)

Period	Epoch	Group	Formation
Upper Cretaceous	Paleocene–Mastrichtain	Belqa Group (B)	Muwaqqar (B3)
	Mastrichtain–Campanian		Amman (B2)
	Santonian–Coniacian		Wadi Umm Ghudran (B1)
	Turonian	Ajlun Group (A)	Wadi Es Sir (A7)
	Cenomanian		Shueib (A5/6)
			Hummar (A4)
			Fuheis (A3)
			Na'ur (A1/2)
Lower Cretaceous	Albian	Kurnub Hathira	Subeihi (K2)
	Aptian–Neocomian	Sandstone	Arda'a (K1)

Electrical prospecting

Two-dimensional inversion techniques are becoming increasingly common and often satisfactory to assess the resolution and determine the limitations of the data set, as shown by Dahlin (1996) and Dahlin and Loke (1998). Three electrical profiles (E1, E2 and E3, Fig. 2) spaced 200 m apart were measured along the axis of the landslide, i.e., along its direction of flow, using SYSCAL-R2 resistivity equipment (IRIS Instruments, France) with a Wenner configuration and 32 electrodes 2 m apart. The method is based on measuring the electrical potentials between one electrode pair while transmitting a direct current between another electrode pair.

The data were processed with the inversion algorithm, RES2DINV, version 3.41c proposed by Loke and Barker (1996) to obtain a resistivity section. The inversion routine used by the program RES2DINV is based on the smoothness constrained, least-squares method inversion algorithm (deGroot-Hedlin and Constable 1990; Sasaki 1992). The two-dimensional model used in this program divides the subsurface into a number of rectangular blocks (Loke and Barker 1996), and the resistivity of the blocks is adjusted in an iterative manner to minimize the difference between the measured and calculated apparent resistivity values. The latter are calculated by the finite-difference method of Dey and Morrison (1979).

The resulting image of electrical profile E1 (Fig. 5), with a penetration depth of about 11 m, shows that the resistivity at depth ranges between 3 and 40 Ωm, which are typical values inside shale sediments. Electrical surveys have distinguished the following three layers in the slope. The first, the upper layer (20–40 Ωm), is composed of comparatively dry landslide deposits, corresponding to the landslide body. The second layer, the main part of the landslide mass, is characterized by an increased moisture content and, consequently, by a reduced resistivity of 3–10 Ωm. The third, lower layer (15–30 Ωm) corresponds to undisturbed shaly rocks comprising the base of the landslide. High resistivities (over 300 Ωm) are measured close to the surface between surface locations 48–60 m at places where massive limestones are observed. These results show that resistivity can be used to locate massive limestone zones. In addition, a high resistivity spot (150 to 250 Ωm) is observed at the foot of the slope and results from the presence of a limestone boulder, as already evidenced by surface geology.

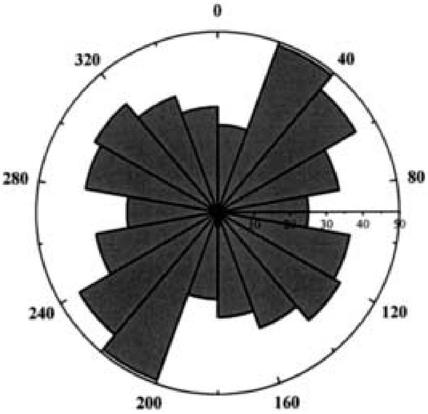

Fig. 3
Rose plot of strike orientation of fractures identified in the study area

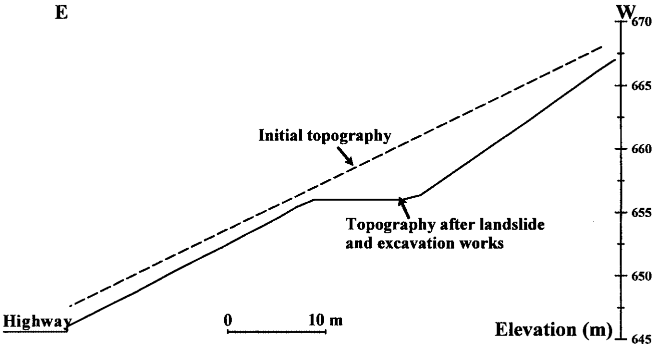

Fig. 4
Topographical cross section through the Al Adaseih slope. The initial topography was reconstructed from the topography map, and the topography after landslide and excavation works was geodetically surveyed

The model resistivity uncertainty (not shown) shows that the uncertainty percentage increases with depth, from less than 5% in the first two meters to 45% at a depth of 11 m. These values are low when compared to the resistivity variations resulting from shale and hard limestone.

The electrical profile E2 model section (Fig. 6) shows low resistivity values (4 to 40 Ωm), characterizing black shale between surface locations 24–60 m. Three layers are visible in the model section: the upper layer (20–40 Ωm) corresponding to the landslide body, the middle layer (4–10 Ωm) corresponding to the slip zone, and the lower

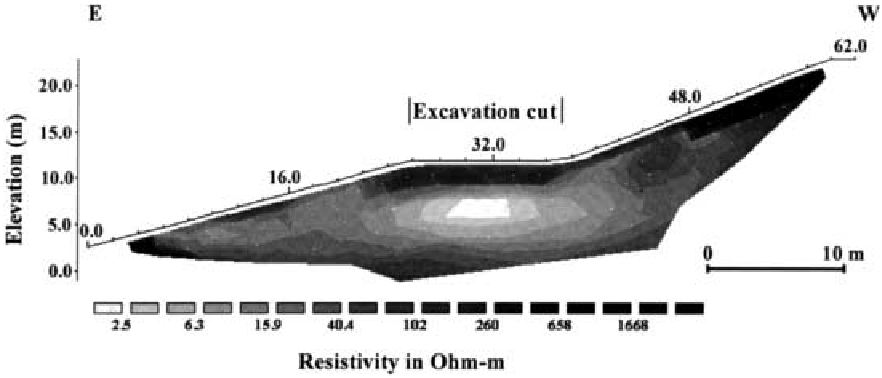

Fig. 5
Electrical tomography section E1 performed along the axis of the slope (for location, see Fig. 2)

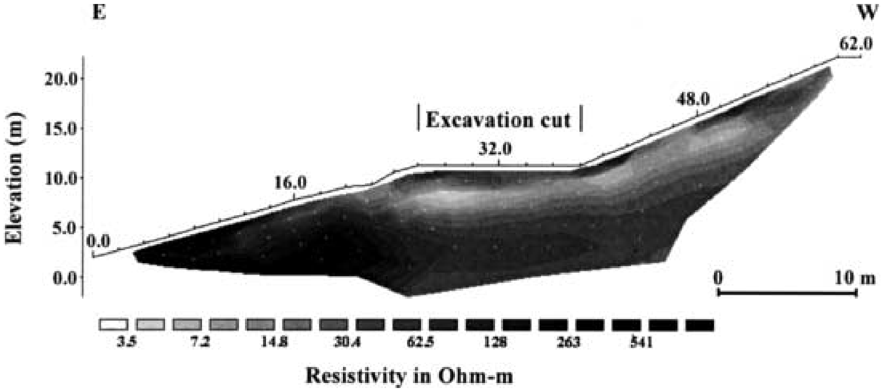

Fig. 6
Electrical tomography section E2 performed along the axis of the slope (for location, see Fig. 2)

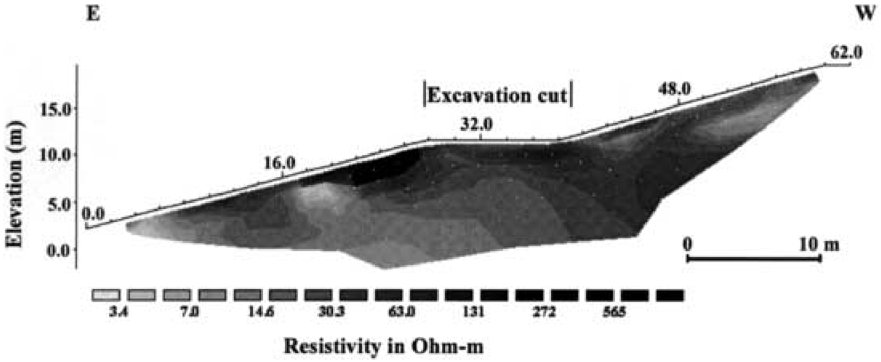

Fig. 7
Electrical tomography section E3 performed along the axis of the slope (for location, see Fig. 2)

layer (20–30 Ωm) corresponding to undisturbed shale comprising the base of the landslide. A high-resistivity zone (250 to 500 Ωm) is observed at the foot of the slope with a thickness of 8 m, and results from deep-routed zones of massive limestone. These results suggest that the landslide is active on the east side, and that the highway at the foot of the eastern slope is therefore more at risk for a future landslide.

Figure 7 shows the model section of electrical profile E3. The anomalies obtained show prominent, low-resistivity anomalies (4 to 40 Ωm) over most of the pseudosection characterizing black-shale sediments. The model section of electrical profile E3 shows a similar result to that obtained for electrical profiles E1 and E2 – three layers with different properties. The upper layer (20–40 Ωm), composed of comparatively dry landslide deposits, corresponds to the landslide body. The second layer, the main part of the landslide mass, is characterized by an increased moisture content and, consequently, by a reduced resistivity of 3–10 Ωm. The lower layer (15–30 Ωm) corresponds to undisturbed shaly rocks comprising the base of the landslide. A high resistivity spot, more than 200 Ωm, was observed between surface locations 20–27 m of the model section, and results from the presence of boulders of massive limestone.

Conclusions

The case history presented in this paper clearly illustrates that the electrical tomography technique is very helpful in studying landslides and assessing the risk. At the Al Adaseih site, the electrical tomography technique allowed two-dimensional images giving the resistivity distribution to 11 m depth along the landslide site. The geophysical images have shown that the shale sediments along the cut face have a thickness of more than 11 m. Furthermore, resistivity is a good physical parameter for distinguishing between the black shale and intact materials, which allowed the location of zones at risk for potential landslide. Combined with structural data, the electrical images were very helpful in delimiting the potentially unstable volume, and defining the measures for stabilizing the slope.

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