

## Application of electrical imaging techniques for the investigation of natural dams: an example from the Thulagi Glacier Lake, Nepal

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### ABSTRACT

The Thulagi Glacier Lake in the Gorkha District of western Nepal was investigated by electrical resistivity tomography (ERT) to delineate buried glacier ice and permafrost zones within the dam. Data were processed using a 2-D inversion program and by finite-difference forward modelling. Interpretation of the processed electrical images indicates that the method can be used for detecting the buried ice and permafrost by virtue of their very high electrical resistivity values (>20,000 Ohm.m and >5,000 Ohm.m, respectively). The resistivity of permafrost seems to be strongly dependent on the material particle size: the finer the particle size the lower is the value of electrical resistivity. Water-saturated glacier sediments have values of electrical resistivity less than 3,000 Ohm.m. The ERT method was useful in mapping of buried glacier ice and permafrost as well as in differentiating other geological materials constituting the dam.

### INTRODUCTION

Geophysical data acquisition and processing techniques developed during the late 1980s provide the means of delineating subsurface targets of interest with a high degree of spatial resolution. Of particular usefulness is the subsurface imaging (SSI) or electrical resistivity tomography (ERT) technique that has found particular application within environmental, engineering, geohazard, and groundwater investigations. One specific application is the study of glaciers, glacier lakes, and natural earth dams.

There is an increasing demand for the methods of subsurface exploration. Several geophysical methods can be applied to study glaciers, glacier lakes, and natural dams. Reliable data acquisition, processing, and interpretation yield information that is useful for the assessment and monitoring of glacier environments. In Nepal, as hydropower resource evaluation and management and geohazard mapping become increasingly important, the requirements for detailed and specific subsurface information related to glaciers and glacier lakes are growing rapidly. Geophysical methods provide the means to map large areas of ground remotely and to obtain information on the in situ physical properties of the materials present.

The Thulagi Glacier Lake is situated in the northwestern part of the Gorkha District, western Nepal (Fig. 1). It is located on the upper reaches of the Dona Khola, one of the left tributaries of the Marsyangdi River. Plate 1 depicts a part of the glacier lake adjoining the dam. The Thulagi Glacier Lake is currently retreating at an average rate of about 50 m per year. The volume of lake is estimated at 30 million m<sup>3</sup> of water (DHM and BGR 1997). The fieldwork was carried

out during November 1996 as part of a larger international investigation under the Thulagi Glacier Lake Study Project carried out jointly by the Department of Hydrology and Meteorology, Ministry of Water Resources, His Majesty's Government of Nepal, and Federal Institute for Geosciences and Natural Resources (BGR), Hanover, Germany.

The area under investigation belongs geologically to the Higher Himalayan Crystallines comprising mainly gneiss and schist. The massif of Manaslu comprises a huge granitic complex (DHM and BGR 1997). The material that overlies the dead ice is thought to contain neo-glacial and supraglacial moraine, and glacio-fluvial and glacio-lacustrine deposits. The natural dam itself is made up of (?glacio-fluvial/lacustrine) silty to sandy gravel and fine sand and silt.

### GEOELECTRICAL METHODS APPLIED IN GLACIERS AND PERMAFROST ZONES

The history of application of geoelectrical methods to investigate permafrost zones and glaciers dates back to 1950s. The main problems solved by geoelectrical methods are detection of frozen and melting ground, and areas of massive ice accumulation. These methods have been used successfully for monitoring of permafrost and exploration of groundwater in such zones (Reynolds 1978; Bondarenko and Tarkhov 1980).

Electrical resistivity of frozen soils with interstitial ice has a complicated relationship with temperature, lithology, structure and texture, saturation, and concentration of ions in the pore fluid (Bondarenko and Tarkhov 1980). The favourable condition for the application of electrical resistivity method is where the frozen material forms a large

resistivity contrast with unfrozen material. Freezing free water in pore space of a material between  $-0.2$  and  $-2^{\circ}\text{C}$  increases resistivity of the material from 10 to 1,000 times (Bondarenko and Tarkhov 1980). The quantity of unfrozen water depends not only on the temperature but also on the structure and distribution of pore spaces. For fine-grained material, the quantity of residual unfrozen water is higher than in coarse-grained materials (Klushin 1968). The freezing process occurs over an extended temperature range rather than at a single value and it is likely that there will always be some residual unfrozen water at naturally occurring ambient temperatures (Keller and Frischknecht 1966). The electrical resistivity of permafrost zone is strongly dependent on particle size of the material: the resistivity for coarse-grained frozen material is higher than that of a fine-grained frozen material. The transition between ice-bonded permafrost and dead ice is not a sharp zone.

Electrical resistivity measurements made on polar ice (i.e. ice well below its pressure melting point) yield values up to three orders of magnitude lower than those found for temperate ice (Reynolds 1985). Whereas the electrical resistivity behaviour of polar ice is now reasonably understood (Reynolds and Paren 1984), that of temperate ice shows considerable variation for reasons that remain unclear (Reynolds 1985).

Electrical resistivity measurements by ERT conducted in the end moraine of the Tsho Rolpa Glacier Lake revealed the presence of dead ice (Oyo Corporation 1995; WECS and JICA 1996). Consequently, the ERT method has been recommended for monitoring the dead ice.

## DATA ACQUISITION AND PROCESSING

An ABEM Terrameter SAS300C was used for the measurement of electrical resistivity. The equipment is light and powerful for deep penetration. The minimum input impedance for the receiver is 10 MOhm. The range of resistance that can be measured is between 0 and 1.9 MOhm. Electrical imaging was carried out at seven profiles (two longitudinal and five transverse). The location of electrical profiles and soundings are presented in Fig. 2.

Electrical sounding was conducted by using the Schlumberger configuration. Electrical imaging was carried out by using the pole-pole arrangement, as it allows greater depth of penetration and is less affected by near-surface inhomogeneities such as eskers and water bodies. However, this arrangement has less vertical depth resolution than other electrode arrangements (Edwards 1977). The depth provided by the Schlumberger sounding is taken as a guide for depth information. For pole-pole arrangement, the electrode spacing was 5 m and the remote electrodes were kept fixed at one place for all profiles. Three electrodes were grounded at each station to secure good contact. The sequence of measurements to build up a pseudo-section along a profile is shown in Fig. 3.

Resistivity data measured along the profiles were processed by using the RES2DINV software (Loke 1996). This software is based on an algorithm that uses measured apparent resistivity data as the starting model (Barker 1992). It automatically generates a two-dimensional (2D) resistivity model for the measured data. The 2D model used by the inversion program consists of a number of rectangular blocks. The distribution of the size of the blocks is automatically generated by the program so that the number of blocks does not exceed the number of datum points. The depth of the bottom row of blocks is set to be approximately equal to the equivalent depth of investigation of the datum points with the largest electrode spacing. A finite difference forward modelling subroutine was used to calculate the apparent resistivity values, and a non-linear least-squares optimisation technique was applied for the inversion routine. The optimisation method basically tries to reduce the difference between calculated and measured apparent resistivity values by adjusting the resistivity of model blocks. The software has different options that help to modify processing parameters to suite the nature of data and geological problems to be solved.

## RESULTS

Initially, the image profiles were presented only as apparent resistivity pseudo-sections. Unprocessed sections merely show high electrical resistivity distribution in the subsurface of the dam. The depth to the high resistivity substratum was calculated by using vertical electrical sounding (VES). One of the representative sounding curves and corresponding calculated model is presented in Fig. 4. A visual inspection shows that all curves are of H-type. In all sounding curves, the topmost layer effect is from the unsaturated material, the intermediate is from partially saturated-fully saturated material, and the third layer effect is from the buried dead ice. The parameters (resistivity and thickness) calculated are presented in Table 1.

The electrical resistivity values for glaciers and permafrost given by Reynolds (1997) are as follows:

Glacier ice (temperate)	$2 \times 10^6 - 1.2 \times 10^8 \text{ Ohm.m}$
Glacier ice (polar)	$5 \times 10^4 - 3 \times 10^5 \text{ Ohm.m}$
Permafrost	$10^3 - >10^4 \text{ Ohm.m}$

The electrical resistivity of water in the Thulagi Glacier Lake was measured to be 110 Ohm.m at  $2^{\circ}\text{C}$ . It is generally understood that the electrical resistivity of water is influenced by the rock types and their chemical weathering. For the analysis of data in the present study, electrical properties measured in the Tsho Rolpa Glacier Lake are taken for comparison. The electrical conductivity of water in the Tsho Rolpa Glacier Lake was  $40 \mu\text{S/cm}$  at  $6^{\circ}\text{C}$  (WECS and JICA 1996). This conductivity is equivalent to 291 Ohm.m of resistivity at  $2^{\circ}\text{C}$ . In the Tsho Rolpa, similar measurements were conducted for waters derived from fossil ice and glacier ice which yielded resistivity values of 909 and 541 Ohm.m, respectively (temperature during measurement is

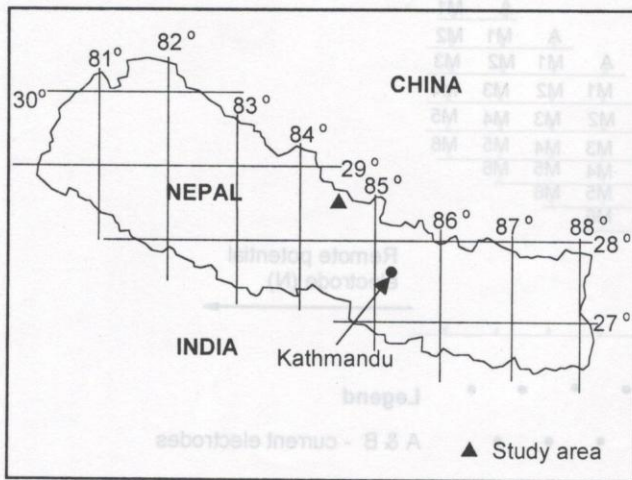


Fig. 1: Location of the study area

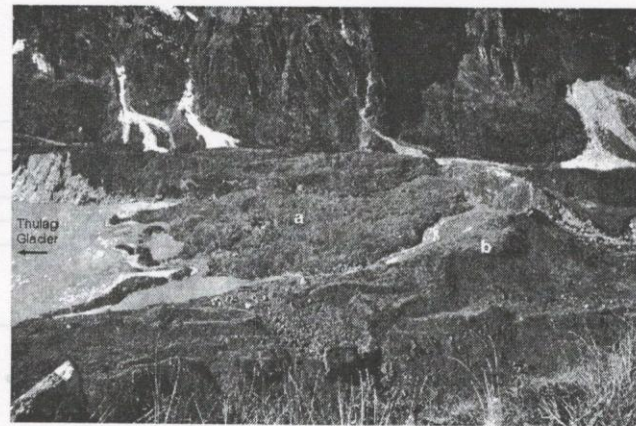


Plate 1: The ice-cored dam complex of the Thulagi Glacier Lake, Nepal, showing a: hummocky sand and gravel, and b: erosional ridges of silt and sand (after Richardson and Reynolds 2000)

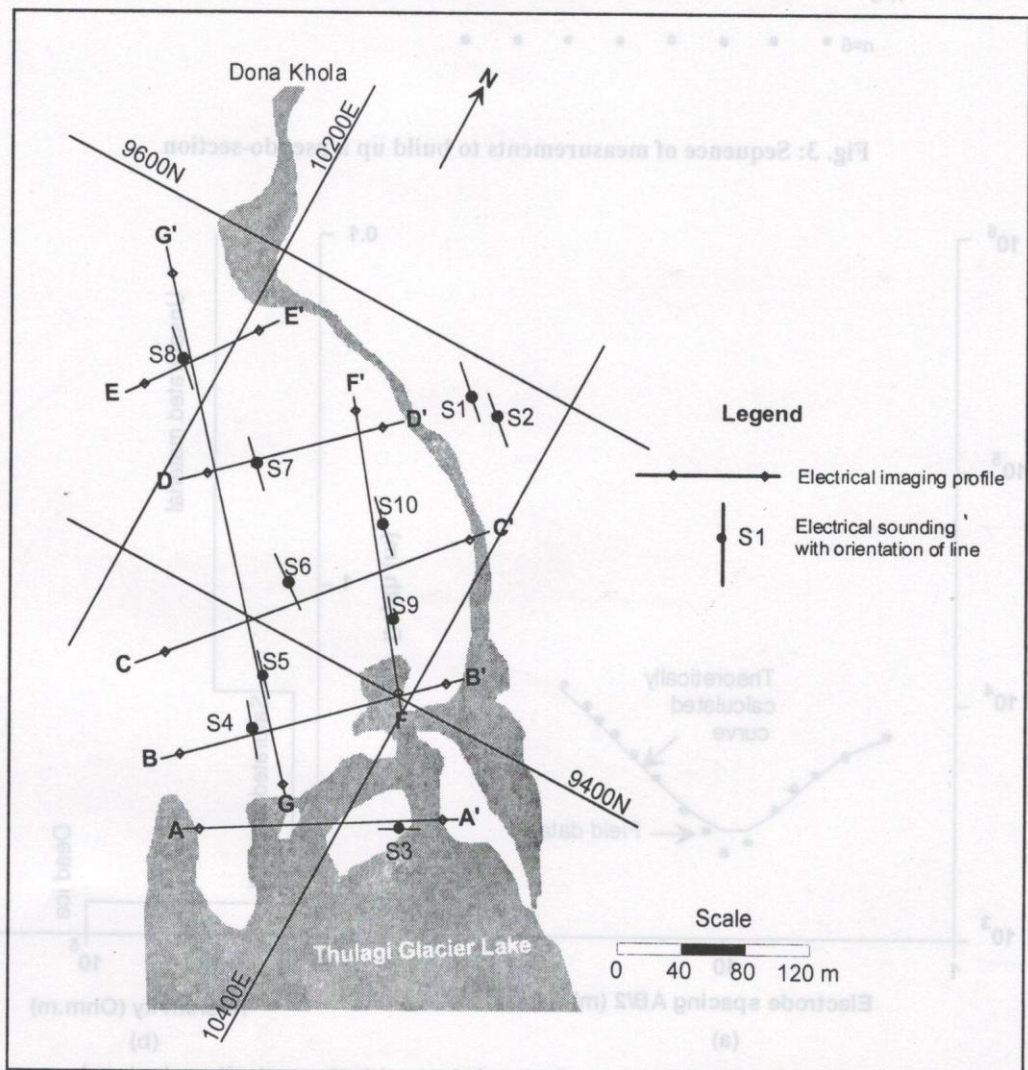


Fig. 2: Location of electrical image profiles and soundings

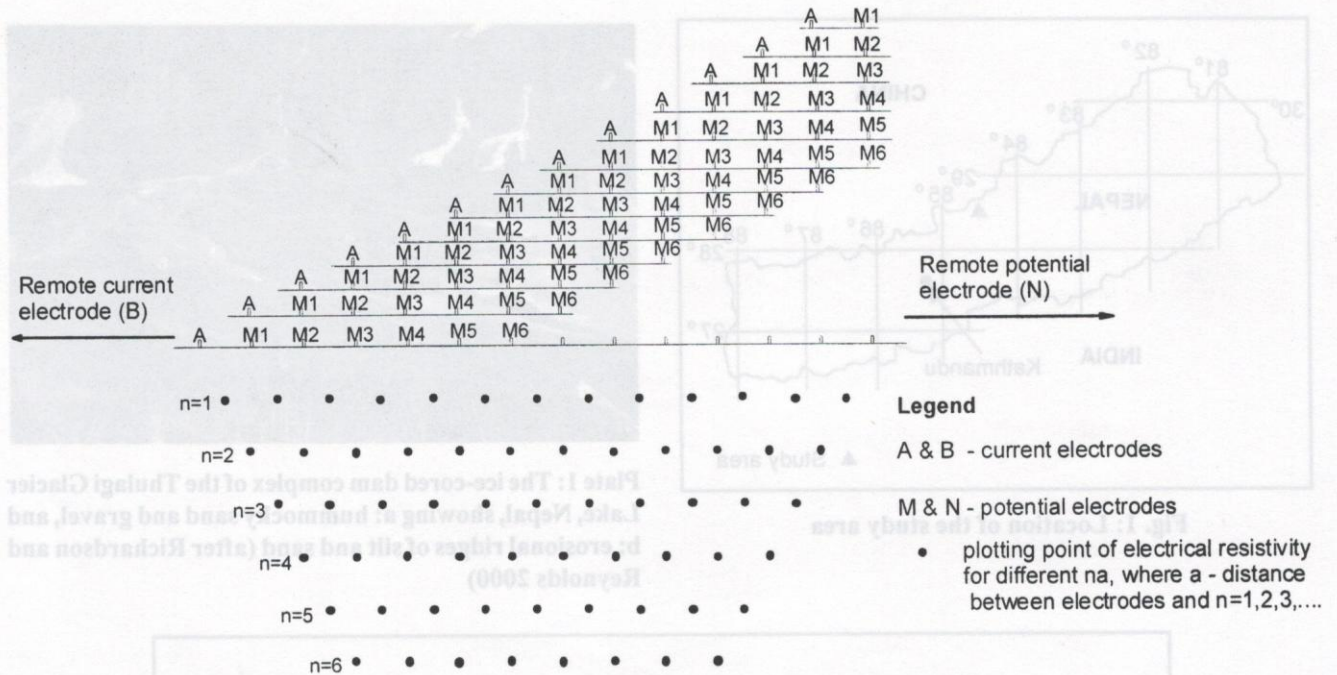


Fig. 3: Sequence of measurements to build up a pseudo-section

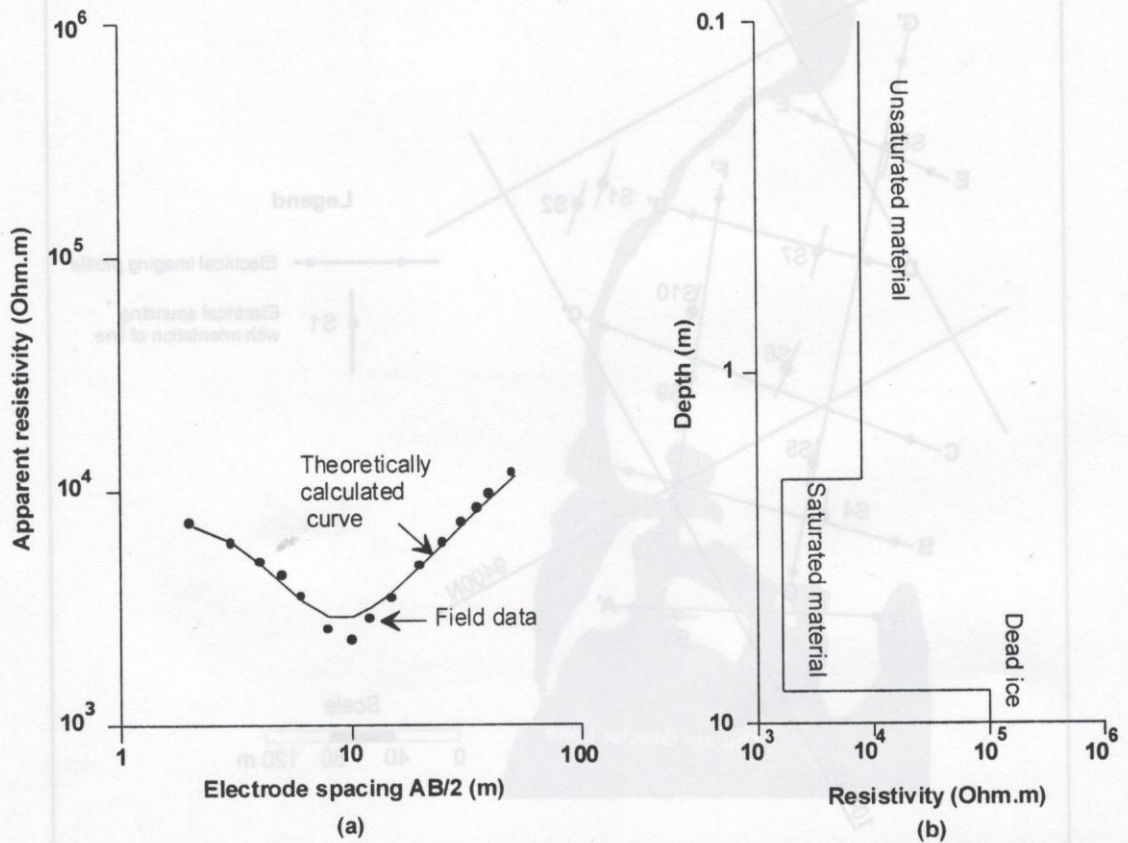


Fig. 4: Representative sounding curve, a: observed data with theoretically calculated curve and b: the interpreted model

**Table 1: Interpretation of VES data for layer parameters**

VES No.	$\rho_1$	$h_1$	$\rho_2$	$h_2$	$\rho_3$	$h_3$	$\rho_4$
2	3,000	4.5	1,250	39	50,000		
3	4,500	1	800	8	78,000		
4	11,500	2	3,800	6.5	25,000		
5	4,500	1	550	3.5	2,500	3.5	75,000
6	7,986	2	1,645	6.1	100,000		
7	5,500	1	1,350	8.5	75,000		
8	6,000	2	2,400	6	50,000		
9	6,000	1.5	1,300	12	23,000		
10	13,579	1	2,000	2	5,000	4	75,000

Note:  $\rho$  -electrical resistivity in Ohm.m,  $h$  -thickness in metres, VES No. 1 was not interpretable.

not mentioned). The lake water in the Thulagi has higher electrical conductivity than the lake water in the Tsho Rolpa. This suggests that the waters derived from the Thulagi Glacier and dead ice possess higher electrical conductivity than in the Tsho Rolpa. For the interpretation of electrical resistivity data in the Tsho Rolpa, following ranges were considered (WECS and JICA 1996):

- Unsaturated moraine (4–8) $\times 10^3$  Ohm.m
- Saturated moraine (2–4) $\times 10^3$  Ohm.m
- Dead ice  $10^5$  Ohm.m

Comparisons were made with processed image profiles in the dam of the Thulagi Lake (Fig. 5 and 6). These image profiles show different zones of very high and low electrical resistivity distribution. The electrical resistivity values of processed images are very close to the true electrical resistivity distribution in subsurface. Since the initial electrode spacing was 5 m, it was not possible to observe effects from dry and unsaturated materials occurring near the surface. Taking into consideration the data mentioned above, different ranges can be assigned to different types of material. These are as follows:

- Saturated materials <2,500 Ohm.m
- Partially saturated materials 2,000–4,000 Ohm.m (?)
- Lake water 110 Ohm.m (at 2°C)
- Ice bonded permafrost 5,000–3,0000 Ohm.m (?)
- Dead ice >20,000 Ohm.m
- (value deduced during modelling)

These ranges are approximate and may overlap with each other. Due to the non-uniform distribution of material within the end moraine, it is difficult to establish the exact border between resistivity values of fully saturated moraine and partially saturated moraine, and unsaturated and completely dry moraine. However, there is no ambiguity to recognise dead ice distribution in the subsurface by virtue of its exceptionally high resistivity to electric current flow. During

modelling, the resistivity value obtained for the model dead ice will largely depend on the surrounding materials of the dead ice. Large differences in the electrical resistivity between the dead ice and saturated or partially saturated material result in the underestimation of the model resistivity of the dead ice.

### INTERPRETATION OF VES

An intermediate layer revealed by VES is saturated except at VES No. 4. The intermediate layer has resistivity values ranging from 550 to 2,500 Ohm.m (usually less than 2,000 Ohm.m). The analogy of electric current to groundwater flow can be used for the estimation of effective porosity. In a clay-poor matrix the surface mechanism of electric current transport is negligible in comparison with the transport through electrolytes in the interconnected pores. The effective porosity (mostly representing interconnected pores), which is responsible for the conduction of electric current of a saturated material, can be estimated by using the Humble formula which is simplified form of Archie's equation (Telford et al. 1976)

$$F = \rho_t / \rho_w = 0.62 / P^{2.15}$$

$$\text{or, } F = 0.81 / P^2$$

where  $\rho_t$  -saturated material resistivity,  $\rho_w$  -water resistivity,  $P$  -effective porosity and  $F$  -formation factor. The formation factor measured in the field is called the apparent formation factor.

The Humble formula is applicable for loose sand. This equation can also be applied for loose non-cemented and clay-poor granular formation similar to that of study area. Formation factor and effective porosity calculated by using the Humble formula are presented in Table 2. The resistivity of the formation water (water in pores) is assumed to be similar to the lake water (i.e., between 120 and 110 Ohm.m) corresponding to the temperature range of 0–2°C.

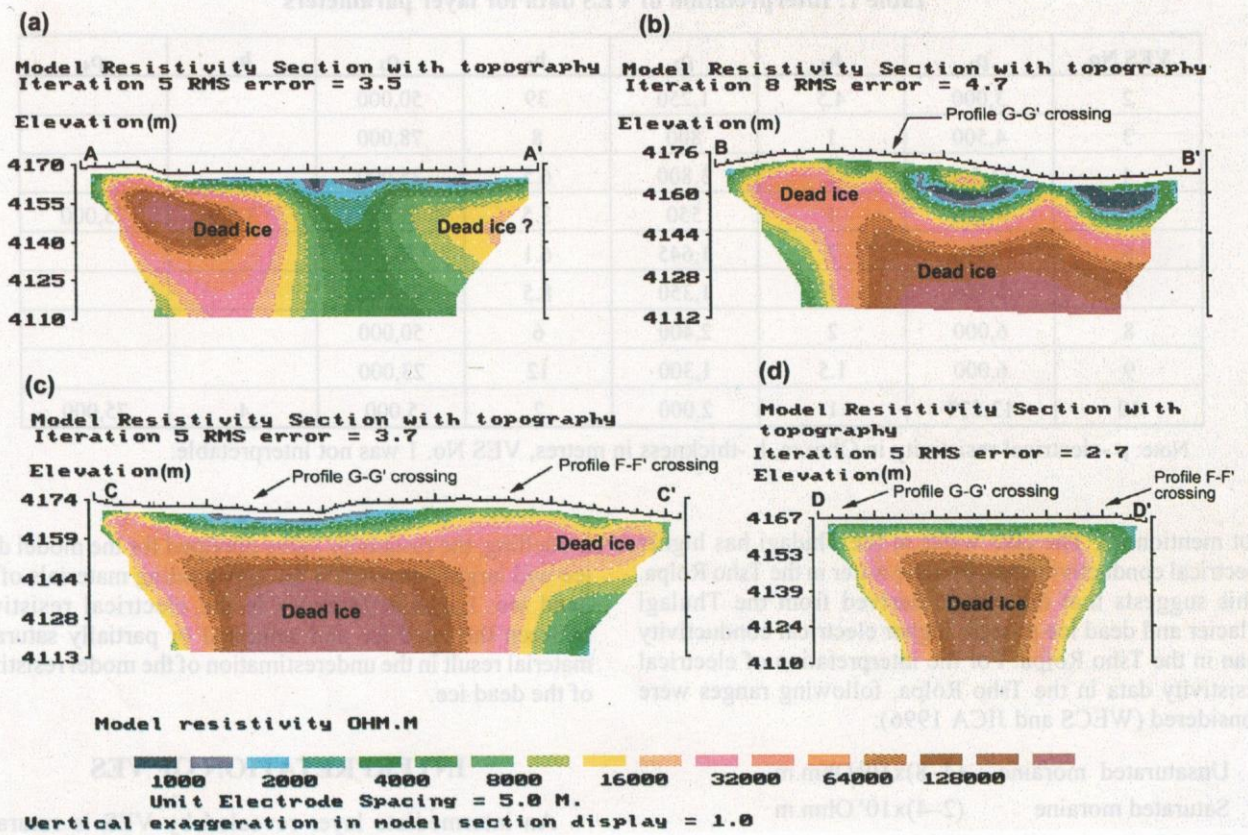


Fig. 5: Electrical images of profiles across the dam of the Thulagi Glacier Lake

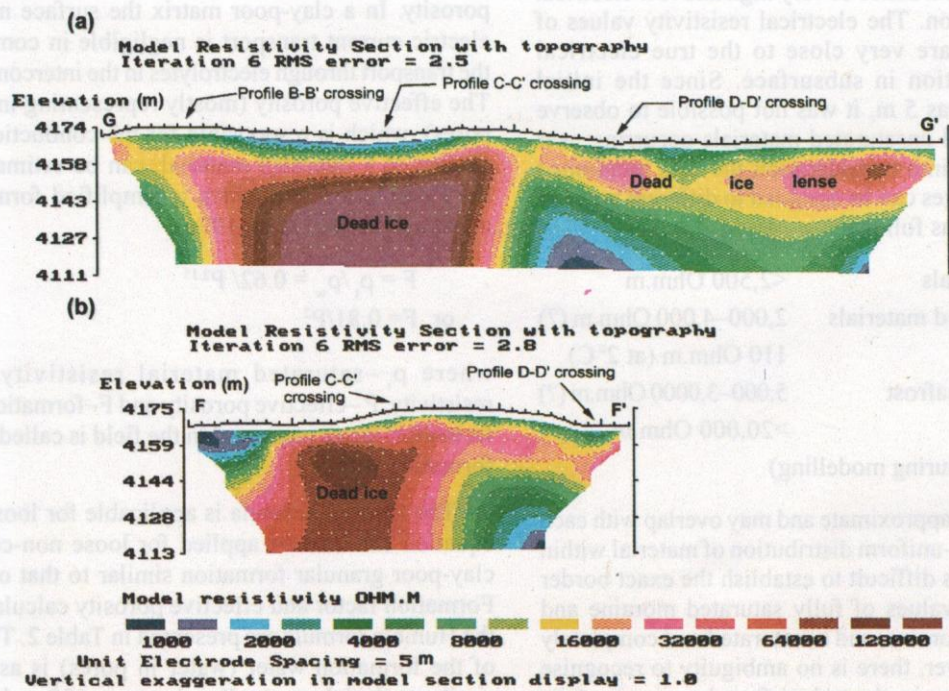


Fig. 6: Electrical images of profiles along the dam of the Thulagi Glacier Lake

**Table 2: Apparent formation factor and effective porosity in the study area**

VES No.	Resistivity of intermediate saturated layer Ohm.m	Apparent formation factor	Effective porosity %
2	1,250	10.4–11.4	27.9–26.6
3	800	6.6–7.3	35–33.3
5	550	4.6–5	41.9–40.2
5	2,500	20.8–22.7	19.7–18.8
6	1,645	14.9–13	24–23
7	1,340	11.2–12.2	26.9–25.7
8	2,400	20–21.8	20.1–19.2
9	1,300	10.8–11.8	27.3–26.2
10	2,000	16.6–18.2	22–21.1

The formation factor of 4.6 to 11 is characteristic for saturated (predominantly sand) material. A higher formation factor is due to the presence of gravel and boulders. Higher values of effective porosity are representative of medium- and fine-grained sands.

The above analysis indicates that the formation that covers the dead ice is not homogeneous. Different values of porosity obtained in different parts of the dam are the justification for the above interpretation.

### INTERPRETATION OF IMAGES

During the interpretation of image sections of permafrost zone, it is assumed that the higher the electrical resistivity values the more ice content in the subsurface. It is noteworthy that some of subdued resistivity effects that can be interpreted as the resistivity effect from permafrost can be due to the dissipation of currents in the nearest water body and/or ridge. The relatively short profile E-E' is thought to have been affected by such current dissipation in the surrounding ridge. For this reason, it is excluded from the present discussion.

The ERT results are summarised in two figures. The images across the dam (A-A', B-B', C-C', and D-D') are presented in Fig. 5 and those along the dam (F-F' and G-G') are presented in Fig. 6. The image profile A-A' indicates a melting zone in the middle of the profile where the major spillway of the lake is located, and it is due to the thermal effect of the running lake water. Dead ice is located towards the southwestern part. The resistivity effect in the northeastern part of the profile can be interpreted as the evidence of permafrost. However, the resistivity in this area may have been subdued due to the proximity of the water body on two sides and the surface feature indicates that there is a possibility of a dead ice body. Image profile B-B' indicates melting in the southwestern part of the profile. Very high electrical resistivity near the surface in the central part

of the profile is due to dry and unsaturated debris. There is saturated material at shallow depth in the central and northeastern parts of the profile. The hummocky terrain present at the southwestern part is justified by the presence of dead ice at shallow depth. The profile C-C' is located further downstream. The northeastern part of the profile shows a relatively low resistivity zone. This can be an indication of melting. Since this part of the profile is very close to the water body, current dissipation may have occurred. To confirm the evidence of melting, the profile needs to be continued across the water body. Profile D-D' (taken from further downstream) reveals a melting ice body from both sides. This is also confirmed by profile E-E'. Longitudinal imaging profiles G-G' and F-F' reveal that the lake is dammed by more than 100 m thick dead ice (along the profile) towards the southern part of the moraine. The thickness further decreases to about 70 m towards the northeastern part of the profile. A low resistivity zone found in depth at profile G-G' could be accumulation of saturated fine materials (silt and clay).

### CONCLUSIONS

This study reveals that surface electrical measurements are effective for the study of dead ice. They are also useful for monitoring the dams around glacier lakes.

Six imaging profiles through the dam of the Thulagi Glacier Lake indicate the presence of dead ice, ice-bonded permafrost, and melting zone in the subsurface. The melting of dead ice seems to be much intense near the spillway and in the north and northeastern parts of the dam. The hummocky nature of the dam surface is related to the occurrence of dead ice in the depth. Dead ice is covered by debris whose matrix is mostly medium to coarse-grained sands with gravel.

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### REFERENCES

- Barker, R., 1992, A simple algorithm for electrical imaging of the subsurface. *First Break*, v. 10(2), pp. 53-63.
- Bondarenko, V. M. and Tarkhov, A. G., 1980, *Enginernaya geologia i gidrogeologia*. In: Tarkhov, A. G. (ed.), *Elektrorazvedka, spravochnik geofizika*, Moskva: Nedra (in Russian), 518 p.
- DHM (Department of Hydrology and Meteorology, Ministry of Water Resources, His Majesty's Government of Nepal) and BGR (Federal Institute for Geosciences and Natural Resources), 1997, Thulagi Glacier Lake Study (unpublished), 24 p.
- Edwards, L., S., 1977, A modified pseudosection for resistivity and IP. *Geophysics*, v. 42(5), pp. 1020-1036.
- Keller, G., V. and Frischknecht, F., C., 1966, *Electrical methods in geophysical prospecting*. Pergamon Press, 517 p.
- Klushin, I., G., 1968, *Complekcirovannii primeneniia geofizicheskikh metodov dlya reshenia geologicheskikh zadach*. Izdatelstva Nedra, Leningradskoe Otdelenie, (in Russian), 311 p.
- Loke M. H., 1996, RES2DINV Ver.2.0, rapid 2D resistivity inversion using the least-squares method, distributed by IRIS INSTRUMENTS, 38 p.
- OYO Corporation, 1995, Electrical resistivity exploration at Tsho-Rolpa end moraine. Final Report. (unpublished), 20 p.
- Reynolds, J. M., 1978, Geophysical investigation of major Corneliussensbre end moraine. In: Fenwick, I. M. (ed.), *Okstinden Research Project Preliminary Report 1976*, University of Reading, pp. 17-30.
- Reynolds, J. M. and Parn, J. G., 1984, Electrical resistivity of ice from the Antarctic Peninsula. *Jour. of Glaciology*, v. 30(106), pp. 289-285.
- Reynolds, J. M., 1985, Dielectric behavior of firn and ice from the Antarctic Peninsula. *Jour. of Glaciology*, v. 31(109), pp. 253-262.
- Reynolds, J. M., 1997, *An Introduction to applied and environmental geophysics*. John Wiley & Sons, 796 p.
- Richardson, S. D. and Reynolds, J. M., 2000, Degradation of ice-cored moraine dams: implications for hazard development. In: Nakawo, M., Raymond, C. F. and Fountain, A. (eds.) *Debris-Covered Glaciers*. Proc. Seattle Workshop, September 2000. IAHS publication no. 264. (in press).
- Telford, W. M., Geldart, L. P., Sheriff, R. E., and Keys, D. A., 1976, *Applied geophysics*. Cambridge University Press, 860 p.
- WECS (Water and Energy Commission Secretariat) and JICA (Japan International Cooperation Agency), 1996, Report on the investigations of Tsho-Rolpa Glacier Lake, Rolwaling Valley, 35 p.

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