Geophysical Assessment of Dam Infrastructure: the Mugdock Reservoir Dam Case Study

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Abstract. The safe operation and proper maintenance of dam infrastructure is critical taking into account social and economic impacts in case of a failure. Currently, the assessment of dam structures is based on geodetic and geotechnical monitoring instrumentation. However, the majority of these instruments do not provide repeatable and reliable information about the mechanisms occurring inside the body of dams that could compromise the integrity of the structure.

Geophysical methods can provide important information to define the safety level of dam infrastructure. Continuous dam monitoring would also enable early remedial maintenance and repair actions to be carried out improving public safety and reducing costs for dam owners, insurers and maintainers.

This study investigates for the first time the condition of Mugdock reservoir dam using two different non-destructive geophysical techniques. Electrical Resistivity Tomography (ERT) arrays were installed on the crest to assess the structural integrity of the dam based on the resistivity signatures. Electromagnetic (EM) sensing was then used as a complementary method to confirm the values obtained with the ERT for the upper soil layers of the dam crest.

The analysis of the results obtained from the electromagnetic survey indicated high resistivity superficial soil layers beneath the crest of the dam. The electrical resistivity surveys revealed low resistivity zones that could be influenced by seepage conditions inside the body of the dam.

The geophysical results presented in this report provide important baseline measurements which with the integration of future geophysical and geotechnical data will deliver key information about the on-going performance of dam infrastructure.

Keywords. dam monitoring, dam safety, geophysics, resistivity, electromagnetic sensing, seepage, internal erosion.

1 Introduction

Assessment of the post-construction performance of dam structures is important to ensure that operate within safety limits. In the UK there are more than 2600 dams in total (Tedd et al., 2000), of which 530 are categorised as ‘large dams’ (Roaf et al., 2009) based on ICOLD classification.

Future projections indicate that the frequency of extreme flooding across Europe is anticipated to double by 2050 (Jongman et al., 2014) with major implications for dam infrastructure. The hydrostatic pressure induced by flooding and the high permeability of the soil caused by desiccation can result in uncontrolled internal seepage inside the body of dams with destructive consequences. Other factors affecting the dam stability are the internal erosion, suffusion, reservoir level fluctuations, slope instability, creep mechanism, the effect of secondary consolidation, seismic activity (Tedd et al., 1997) and animal burrowing.

The maintenance and inspection of dams are therefore of increasing importance. Systematic monitoring of dam infrastructure can deliver key information providing early warning signs of an impending failure and a better understanding of the on-going performance of the structure (Michalis et al., 2016).

In many occasions internal erosion and seepage mechanisms within the body of dams are very difficult to be detected by conventional methods. The current practice to assess these mechanisms is based on geotechnical instrumentation. However, major issues exist with geotechnical instruments as they do not provide distributed, repeatable and reliable information in the long-term due to lack of maintenance as they are located inside the body of the dam. Geodetic measurements are also used to assess the deformations of the structure but they do not provide a direct insight of the internal mechanisms that influence the dam behaviour. The assessment and safety of dam infrastructure would be significantly improved with non-destructive techniques that would allow internal erosion and seepage characteristics to be detected.

This study presents the non-destructive assessment of an earth-fill dam using geophysical methods without any geodetic and geotechnical constrains. The applied monitoring techniques have the potential to provide information of internal erosion and seepage flow patterns inside the body of the dam.

2 Geophysical Methods

The two techniques that were employed in this study were Electromagnetic (EM) sensing and Electrical Resistivity Tomography (ERT).

Instruments based on EM signals can provide a rapid, cost effective and contactless method to assess earth-fill structures (Sentenac et al., 2012). EM sensors generate a fringing field between two electrodes at a constant frequency range penetrating the external medium which depends on the electrical and magnetic properties of soils (Michalis et al., 2015). The ratio between the secondary and primary EM fields provides a comparative reading of the apparent soil conductivity (Reynolds, 1997). Soil conductivity can then be used to provide the moisture levels of the soil layers of the dam and an indication of changes of pore water pressure potentially induced by various seepage flow conditions.

ERT is a geophysical technique that allows the electrical properties of a section of ground to be determined by measuring the drop in potential occurring due to an applied electrical current (Reynolds, 1997). The ERT technique has been employed in both laboratory and field conditions to assess the condition of embankments (Sentenac and Zielinski, 2009; Jones et al., 2014) but also to investigate internal mechanisms inside the body of dams (Johansson and Dahlin, 1996; Buselli and Lu, 2001; Panthulu et al., 2001; Sjödahl et al., 2005; Song et al., 2005; Sjödahl et al., 2009; Lin et al., 2013).

3 Mugdock Reservoir Dam

The Mugdock reservoir dam is located in central Scotland, UK at a distance of 13 km on the north side of Glasgow city (see Figure 1). The dam is owned and operated by Scottish Water and is presently one of the main feed reservoirs to Glasgow city.

Fig. 1 Location of Mugdock reservoir in central Scotland.

The dam is regulated under the current Reservoirs Act (1975) UK and is categorised as ‘large raised reservoir’ as it is capable of holding 2.200.000 m^3 of water above natural ground level. Mugdock dam, shown in Figure 2, was constructed in 1859 and it is operating since then. The crest length of the main dam is 380 m located on the south side of the reservoir at an altitude of 102 m above mean sea level (AMSL). The maximum height of the dam from the foundation level is 21 m with the top water level at 97.07 m AMSL. The upstream face of the dam is protected against deterioration and wave action with rip-rap.

Fig. 2 Mugdock reservoir enclosed by an earth-fill dam on the south side.

4 Survey areas

A visual assessment over the crest and the downstream face of the dam was carried out during October 2015 which was provisionally the driest October month since 2003, with 50% of average rainfall. The inspection did not reveal any significant findings and the earth-fill dam had not encountered major deformations or slips. Animal activity was also not evident at the time of the inspection while the crest and downstream face of Mugdock dam appear to be in good condition with healthy short covering of grass (see Figure 3).

Fig. 3 Views of the crest and the downstream face of Mugdock reservoir dam.

The non-intrusive geophysical surveys aimed at investigating the subsurface conditions beneath the dam crest. Primarily an EM survey was carried out using a CMD unit (GF instruments) scanning the soil conductivity at 3 m depth below the upstream and downstream sides of the dam crest to detect anomalies in the soil layers [see Figure 4(a)].

Fig. 4 Non-intrusive geophysical investigation using **(a)** an EM instrument and **(b)** ERT arrays installed on the crest of Mugdock reservoir dam.

ERT arrays were then installed on the crest of the Mugdock dam as shown in Figure 4(b). All ERT arrays had a length of 96 m with 2 m interval spacing between electrodes that enabled greater penetration depths providing a complete subsurface characterisation of the dam.

Three ERT arrays (M1, M2 and M3) were installed on the boundary between the south side of the crest and the downstream shoulder of Mugdock dam (see Figure 5). The ERT survey covered the whole length of the dam investigating also the subsurface conditions over its maximum height.

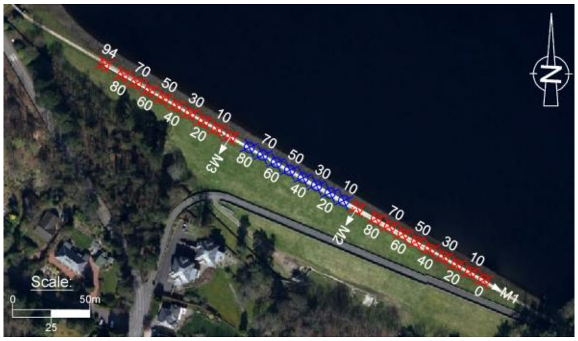

Fig. 5 Non-intrusive ERT arrays (M1, M2 and M3) 96 m long and 2 m electrode spacing covering the whole length of Mugdock dam.

5 Data Analysis and Results

5.1 EM survey

Figure 6 presents the soil conductivity obtained during the EM survey carried out on the upstream and downstream sides of the crest of Mugdock dam. The EM survey did not reveal significant anomalies and conductivity variations are attributed to the interference of obstacles (e.g. metal posts, small concrete areas around geodetic/geotechnical instrumentation). The top layer of the crest consists of soil material with average conductivity of 8 mS/m (resistivity of 125 Ohms.m) which is indicative of clay/sand/gravel soil matrix.

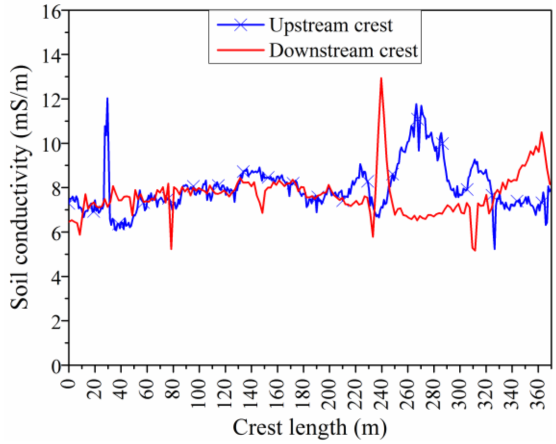

Fig. 6 Conductivity values obtained during EM survey along the upstream and downstream sides of the crest of Mugdock dam.

5.2 ERT survey

The inverse resistivity model for array M1 is presented in Figure 7. The 2-D model indicates resistivity areas up to 168 Ohms.m on the top soil layers (< 2 m) of the embankment. These signatures are potentially related with clay/sand/gravel soil matrix and are not attributed to burrows caused by animal activity. This is due to the fact that these results are in agreement with those obtained from the EM survey where the average resistivity was detected to be approximately 125 Ohms.m all over the crest of the embankment. Animal activity was also not evident on the crest and the downstream face of the dam at the time of the assessment.

Low resistivity anomalies (< 20 Ohms.m) are identified at the depth range 3 m – 8 m which are indicative of high saturation zones in clay sediments. High resistivity anomalies (> 2451 Ohms.m) are detected at depth > 12 m throughout the cross section which reach a maximum of 35000 Ohms.m at the horizontal distance between 35 m – 60 m. This elevated resistivity signature is likely associated with the presence of hard base material (e.g. bedrock, drain).

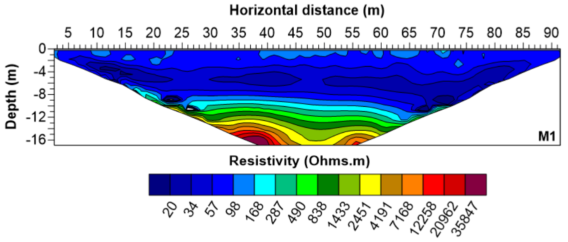

Fig. 7 ERT model for array M1 revealed low resistivity zones at depth range 3 m – 8 m and major resistivity anomalies at depth > 12 m.

Figure 8 presents the inverse resistivity model for array M2. The 2-D model indicates superficial resistivity areas up to 168 Ohms.m on the upper soil layers (< 2 m) of the embankment. Similarly to the previous model (M1), these signatures are potentially related with clay/sand/gravel soil matrix and are not attributed to burrows caused by animal activity.

Low resistivity zones (< 24 Ohms.m) are identified at the depth range between 5 m – 11 m which are associated with saturation zones in clay sediments potentially influenced by seepage conditions inside the body of the dam. High resistivity signatures (> 2451 Ohms.m) are detected at depth > 12 m which reach a maximum of 6687 Ohms.m at the horizontal distance between 35 m – 60 m and are related with the presence of hard base material (e.g. bedrock, drain).

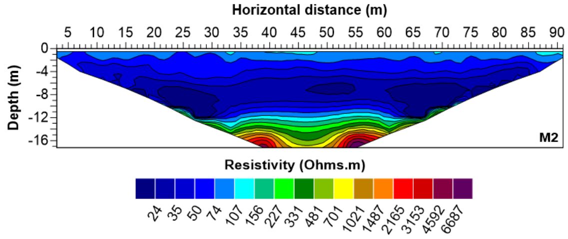

Fig. 8 ERT model for array M2 revealed low resistivity zones at the depth range 5 m – 11 m and high resistivity anomalies at depth > 12 m.

The inverse resistivity model at the maximum height of the dam is presented in array M3 (see Figure 9). The 2-D model indicates low resistivity soil layers (< 331 Ohms.m) extending down to a maximum depth of 2 m. Similarly to the results obtained from the previous models M1 and M2, these resistivity signatures are potentially related with the presence of superficial soil mixtures of gravel/sand/clay.

A uniform low resistivity area (< 74 Ohms.m) almost throughout the cross section indicates the presence of clay soil type. Lower resistivity zones (< 24 Ohms.m) are also identified below the superficial layers at depth range between 3 m – 12 m which are related with high saturation zones in clay sediments. The elevated resistivity anomaly (> 2165 Ohms.m) at the horizontal distance between 30 m – 45 m and at the depth range 12 m – 17 m indicates the presence of hard base material (e.g. bedrock) (see Figure 9).

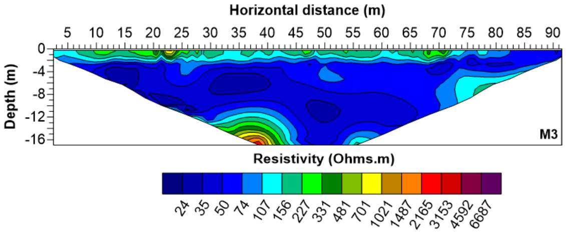

Fig. 9 ERT model for array M3 revealed high resistivity signatures in the upper soil layers of the dam (< 2 m) and low resistivity zones at the depth range 5 m – 11 m throughout the cross section.

6 Discussion and Conclusions

Dam safety is crucial taking into account that hydro-assets are facing extreme weather conditions due to climate change compromising their structural integrity. Systematic monitoring using geophysics is an important tool to assess the on-going performance of dams and define their safety levels.

This study aimed at assessing the Mugdock reservoir dam (> 150 years old) using two non-destructive geophysical methods. EM sensing was used to assess the top soil layers of the dam crest. ERT was then applied to investigate seepage conditions and other potential mechanisms inside the body of the dam.

The obtained resistivity models indicated elevated resistivity areas (up to 168 Ohms.m) on the upper soil layers (< 2 m) of the embankment. These results are in agreement with those obtained from the EM survey where the average resistivity was detected to be 125 Ohms.m throughout the crest of the embankment. These signatures are therefore potentially related with drier soil matrix of clay/sand/gravel mixtures. The analysis of the results obtained from the three ERT arrays revealed low resistivity signatures (< 24 Ohms.m) which are particularly evident in models M1 and M2. These resistivity areas are associated with high saturation clay zones potentially influenced by the seepage pattern which is expected to occur through the body of all earthen dams.

The geophysical investigation carried out did not reveal major anomalies inside the body of the dam. This study provided important baseline measurements that will enable a time-lapse comparison with additional geophysical periodic data to assess the on-going performance of dam infrastructure.

Future research entails the integration of hydrological and geological factors with future geophysical measurements and geotechnical data. This will enable to quantify the factors affecting the potential defects in the body of the dams including seepage and internal erosion mechanisms and will provide a better understanding of the post-construction behaviour of these structures.

Acknowledgments: The authors wish to acknowledge the financial support from Scottish Water, EPSRC and Impact Acceleration Account (IAA) from the University of Strathclyde.

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