This is a peer-reviewed, author's accepted manuscript of the following research article: Michalis, P., & Sentenac, P. (2021). Subsurface condition assessment of critical dam infrastructure with non-invasive geophysical sensing. *Environmental Earth Sciences*, *80*(17), [556]. https://doi.org/10.1007/s12665-021-09841-x

Subsurface Condition Assessment of Critical Dam Infrastructure with Non-invasive Geophysical Sensing

Panagiotis Michalis[1,2] and Philippe Sentenac[2]

[1]School of Civil Engineering, National Technical University of Athens, Greece.

[2]Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow, UK

Abstract

Recent cases of dam failures indicate that the safe operation and proactive maintenance of infrastructure is of significant importance considering the growing number of ageing dams and the increase in intensity and frequency of extreme climatic events. The current procedures to assess the performance of dam infrastructure, usually based on geodetic and geotechnical instrumentation, do not provide repeatable and reliable information with regards to subsurface hazards that evolve within the body of earth-fill dams that could compromise the integrity of the structure. This increases the risk of failure with significant socio-economic impacts and long-term disruption on downstream communities. On the contrary, geophysical methods can provide advanced information about subsurface hazards and can therefore significantly assist to define the safety level of dam infrastructure. This will enable early remedial maintenance and repair actions to be carried out enhancing public safety and eventually reducing costs for asset owners.

This study presents for the first time the investigation of the condition of three reservoir dams in Scotland with the application of two complementary non-invasive geophysical methods coupled with visual inspection. Electromagnetic (EM) sensing was initially employed to provide an assessment of the upper soil layers of the crest and downstream shoulder of the dam. Electrical Resistivity Tomography (ERT) arrays were then installed on the crest to assess the subsurface conditions of the dam based on the resistivity signatures. The analysis of the geophysical models identified weak zones within the body of dams associated with high resistivity patterns associated with potential animal burrowing activity and fissuring on the crest of the dam. The electrical resistivity surveys revealed low resistivity zones influenced by seepage conditions inside the body of dams but also provided an indication of potential internal erosion areas. Finally the geophysical models provided an insight of the homogeneity of the fill material and determined the dam foundation characteristics. The geophysical results presented in this investigation provide important baseline measurements and key information about the current condition and on-going performance of dam infrastructure.

Keywords: dam monitoring, dam safety, geophysics, resistivity, electromagnetic sensing, seepage, internal erosion, non-invasive sensing.

[1]Corresponding author: pmichalis@mail.ntua.gr, ORCiD: https://orcid.org/0000-0002-2884-1050

1. Introduction

The current state of a significant number of dam infrastructure poses a major threat for the resilience and sustainability of downstream communities and infrastructure systems with significant socio-economic impact in case of a failure event. This has been particularly evident by the recent incidents of Oroville dam, US (2017), Whaley Bridge dam, UK (2019) and the Brumadinho dam disaster, Brazil (2019). The cascading effects of dam failures to other infrastructure systems also indicate the urgent need for a proactive approach to manage and mitigate natural but also human threats to infrastructure systems (Michalis et al., 2019 and 2020). The main reasons behind the current state of infrastructure lie (Pytharouli et al., 2019): (a) in the increasing age of these dams, (b) the current extreme climatic variability which is expected to cause major implications to structures as it has not been considered during their design phase and (c) that the existing models and prediction capabilities are not considered to be at advanced stage to reliable describe the long-term behavior of dams.

In the UK there exist more than 2600 dams in total (Tedd et al., 2000), with 530 categorised as 'large dams' (Roaf et al., 2009) having heights greater than 15 m, while worldwide the same number accounts for 58000 dams. Another major issue exists with thousands of smaller dams that are not subject to rigorous procedures related to the timely assessment and management of hazards during their lifetime. Condition assessment and monitoring of the long-term performance of dams is therefore critical to identify potential failure modes (Dunnicliff, 1993) and to contribute to improved understanding of current state of the structure ensuring their operation within safety limits (Michalis et al., 2016a). Early detection of deteriorating processes of dams is also important to assess their structural integrity and overall risk management (Seyed-Kolbadi et al., 2020).

Despite that dams are currently considered to be the most well-instrumented structures (Pytharouli et al., 2019) in many occasions major deterioration processes that occur inside their body are not reliably detected by conventional instrumentation, which increases risk of failure (Michalis et al., 2016b). This is considered a major issue for key hazards such as internal erosion and seepage mechanisms which are caused by the hydrostatic pressure induced by increased water level of the reservoir and by desiccation due to the high permeability of the soil allowing water to infiltrate inside the body of the dam. Other factors influencing the dam condition are the internal erosion processes, water level fluctuations, slope instability, creep mechanism, the effect of secondary consolidation, seismic activity and animal burrowing (Tedd et al., 1997, Michalis et al., 2016b).

The analysis of datasets deriving from geotechnical instrumentation installed within dams (e.g. piezometers, observation wells, pressure cells, inclinometers, extensometers) is used to assess most of the aforementioned internal processes (Kyrou et al., 2005; Guler et al., 2006; Rashidi and Haeri, 2017; Seyed-Kolbadi et al., 2020). The geotechnical instrumentation can provide an important insight of the hazards occurring inside the body of dams, however, the vast majority of these instruments are not delivering reliable data in the long-term. This is due to the fact that they are difficult to be accessed after construction due to their internal installation inside the body of dams and as a result cannot be maintained properly (Pytharouli et al., 2019). During the dam operation, major deformations also occur inside their body which has a prominent damaging effect on these installed instruments. The malfunctioning of geotechnical instruments is a well-known issue in the dam engineering community, which has led to false alarms and in some cases failed to provide early warnings about developing instabilities (Papachatzaki et al., 2009). Another major issue is that the majority of aged dams (> 100 years old) have not been equipped with modern and sophisticated instrumentation, as this did not exist at the time of their construction. Nowadays, installation of state-of-the-art instrumentation requires invasive and expensive intervention inside the vulnerable core of the dams and this is the main reason that is usually avoided by the asset owners.

The vast majority of the existing studies therefore focus on the deformations of dams analysing geodetic measurements (Dascal, 1987; Gikas and Sakellariou, 2008; Pytharouli and Stiros, 2009; Dounias et al., 2012; Michalis et al., 2016a; Gamse and Oberguggenberger, 2017; Scaioni et al., 2018; Zanganehasadabadi et al., 2019; Pytharouli et al., 2019). Studies based on the analysis of geodetic deformations have delivered key information about geometry changes of the body of the dam. However geodetic measurements do not provide a direct insight of the internal mechanisms that influence the dam behaviour but indicate a delayed deformation response of mature signs of degradation that occur inside the body of dams. The application of non-destructive monitoring techniques to enable a rapid assessment of such hazards, which cannot be identified at an early stage by the aforementioned instruments and existing conventional methods, is therefore considered of significant importance for optimised safety and proactive asset management of dams.

This investigation presents the application of non-invasive geophysical sensing applied for the first time at three specific aged earth-fill dams in Scotland (UK) coupled with visual inspection, without any geodetic and geotechnical constrains. The proposed sensing methods have the potential to be applied to assess in a non-invasive way the subsurface conditions and internal hazards inside the body of dams, offering key information in aged structures that are not equipped with internal instrumentation. In other cases they can also be used to couple and validate findings from internal instrumentation but also to provide key insights about the homogeneity of fill material and foundation characteristics in aged dams where these information in not available. The main objective of this study was to assess subsurface conditions and hazards but also to provide key insights about the homogeneity of fill material and foundation characteristics.

2. Geophysical methods employed in this study

Near surface geophysical methods offer a non-invasive alternative to complement the current subjective assessment procedure, which, in the majority of the cases, is mainly based on visual inspection and, when feasible, analysis of geodetic and/or geotechnical datasets. This investigation focused on the application of two complementary non-invasive methods which consisted of Electromagnetic (EM) sensing and Electrical Resistivity Tomography (ERT).

2.1. EM sensing method

EM Slingram profiling is a fast scanning, inexpensive and contactless method for evaluation of dams (Kirsch and Ernstson, 2006). EM has been employed for assessment of the top soil layers (< 3 m) beneath the surface of earth structures (Viganotti et al., 2013; Sentenac et al., 2013). The advantage of the method lies in the fact that the derived datasets are easy to process and accurate (Calum, 2017) and the technique is applied for a rapid assessment of anomalies and to map areas of interest that potentially require further investigation (Adamo et al., 2021).

It is based on the measurement of induction of the primary electromagnetic field of the transmitting coil in the surrounding investigated medium. The primary field induces a secondary field whose intensity depends on the conductivity of the medium surrounding the transmitting coil. The depth to obtain the information on the conductivity of the medium depends on the frequency of the primary electromagnetic field or on the length of the transmitter coils. Instruments based on EM signals can provide a rapid, cost effective and contactless method to assess earth-fill structures (Sentenac et al., 2018). The CMD-2 from the company GF instruments (Czech Republic) that was used for the surveys, generates 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). Assuming that most of the soils are considered to be non-magnetic, the ratio between the secondary and primary EM fields provides a comparative reading of the soil conductivity (Reynolds, 1997). Soil conductivity can then be used to provide an indication of moisture levels of the upper soil layers of the dam. However, it remains challenging to derive conclusions about degradation processes based on EM results alone. This is the main reason that the EM method is usually complemented by other methods and datasets (e.g. ERT, visual inspections, and geotechnical instrumentation) to assess and validate internal hazards within the body of dams.

2.2. ERT sensing method

ERT is a geophysical method employed to assess subsurface conditions at significant depths (< 20 m) compared to EM profiling. It is based on the measurement of soil resistivity, 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). Electrical resistivity refers to a measure of how strongly a geologic material opposes the flow of an electrical current which is 'injected' into the subsurface. The Electrical resistivity can be determined by Ohm's law multiplied by a geometrical factor "K" based on the dimensions of the electrode array used such as the spacing between electrodes and the ratio of the spacing between electrodes to the spacing between the potential pair (McDowell et al. 2002, Reynolds 1997). The ERT technique has been employed in both laboratory and field conditions to assess the condition of embankments and dikes (Sentenac and Zielinski, 2009; Niederleithinger et al., 2012; Jones et al., 2014; Utili et al., 2017) based on the analysis of resistivity signatures attributed to soil moisture fluctuations and the detection of discontinuities (e.g. burrows, suffusion) within the body of earthen structures.

ERT is considered a rapid and cost effective method which has shown potential to be applied for the non-destructive detection of 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; Hunter and Powers, 2008, Sjödahl et al., 2009; Lin et al., 2013; Loperte et al., 2015; Olenchenko and Osipova, 2020). The method has shown a good performance in earth structures consisting of clay or silty sediments due to the excellent contact between the installed electrodes and the soil, and the high concentration of charged particles that facilitate electrolytic conduction through the soil (Sentenac et al., 2017).

3. Dam locations and main characteristics

The three reservoir dams that were investigated in this study are based in central Scotland, owned and operated by Scottish Water. As shown in Figure 1, Holl reservoir is located 52 km north of the city of Edinburgh, Mugdock reservoir at a distance of 13 km on the north side of Glasgow city, and Barcraigs reservoir on the south-west side and at a distance of 30 km from the city of Glasgow.

Figure 1: Location of Holl, Mugdock, and Barcraigs reservoirs in central Scotland.

All investigated dams have exceeded the age of 100 years and are considered to fall within the large dams category having a height more than 15 m based on ICOLD classification (ICOLD WRD, 2020). They are regulated under the Reservoirs Act (1975) and are categorised as 'large raised reservoirs', capable of holding more than 25000 m^3 above natural ground level. Details about the geometrical characteristics and other information regarding the core composition, but also the short and long-term behaviour of dams, were not available at the time of the geophysical survey. This aspect has also been highlighted by the asset owner who indicated that (Scottish Water, 2010, p.2): *There are no drawings or records of the original construction of Mugdock reservoir but it is thought that the embankment has a central puddle clay core flanked by selected fine-grained fill.* Another report by the Environment Agency highlighted that most embankment dams in Britain with age more than 70 years old were constructed to a traditional design with a central core of puddle clay (Charles et al., 2011). Based on the fact that the other two investigated dams (i.e. Holl and Barcraigs reservoir dams) are of similar, age, size and are located in the same geographical region, it is assumed that their composition also consists of a central puddle clay core.

3.1. Holl reservoir dam

Holl reservoir dam was constructed in 1901 and is located at an altitude of 200 m above mean sea level (AMLS). The reservoir is enclosed by an earth-fill embankment which is located on the south-east side of the area, as shown in Figure 2, with the treatment facility on the east side of the area and downstream of the embankment.

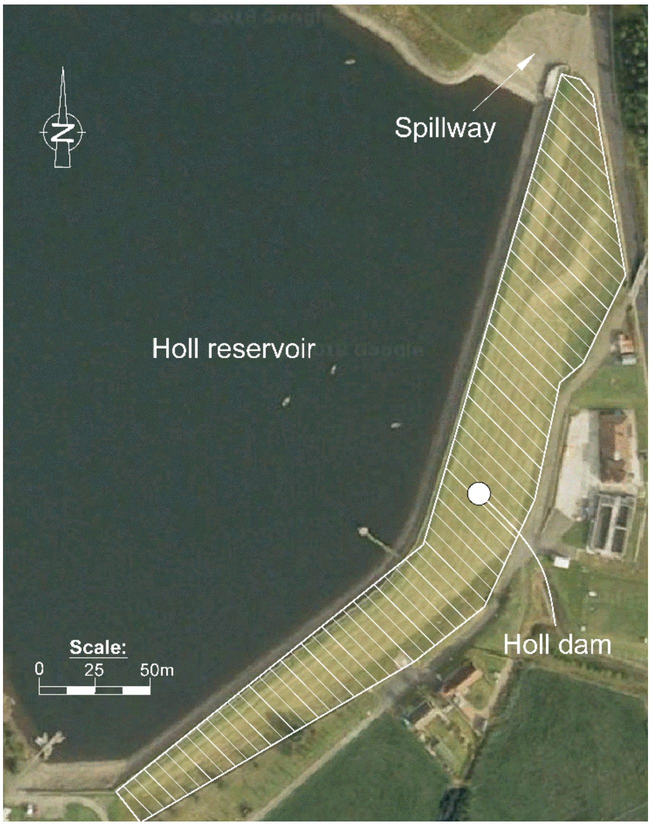

Figure 2: Holl reservoir with the earth-fill embankment and the spillway on the south-east and north-east sides of the area respectively.

The crest of the embankment has width and length of approximately 3 m and 415 m respectively. The downstream shoulder on the south-west side of the dam has a moderate slope which is gradually increased reaching the greatest values approximately at mid length of the embankment. On the south-east end and towards the spillway of the dam the downstream shoulder is composed of two different slopes with a plateau occuring between them.

The geology in the Holl reservoir area consists of Igneous bedrock with superficial deposits of Devensian – Diamicton till. Available borehole data at a distance of 1km from the dam area also indicated layers of till to a depth of 10m and mudstone and sandstone extending to 30m (BGS, 1998).

3.2. Mugdock reservoir dam

The Mugdock reservoir, shown in Figure 3, was constructed in 1859 and is presently one of the main feed reservoirs to Glasgow city. It is enclosed by an earth-fill dam with crest length of approximately 380 m at an altitude of 101 m AMSL. The upstream face of the dam is protected against deterioration and wave action with rip-rap. The maximum height of the dam from the foundation level is 21 m with the top water level at 97.07 m AMSL.

The geology in the Mugdock reservoir area consists of sedimentary bedrock with superficial layer of Devensian – Diamicton till. Available borehole data at a distance of 1km from the dam area also indicated layers of sandy boulder clay to a depth of 6m and mudstone and sandstone extending to 25m (BGS, 1976).

Figure 3: Mugdock reservoir enclosed by an earth-fill dam on south side with an overflow channel located on the south-west side of the area.

3.3. Barcraigs reservoir dam

The Barcraigs reservoir was constructed in 1916 and is enclosed on the south side by an earth-fill dam with crest length of approximately 400 m at an altitude of 151 m AMSL (see Figure 4). The spillway is located on the south-east side of the embankment while the upstream face of the dam is protected against deterioration and wave action with rip-rap. The downstream shoulder has a moderate slope which is gradually increased approximately at mid-length of the embankment where its maximum height is recorded.

The geology of the dam area consists of superficial layers of alluvium silt and clay sediments and Basaltic bedrock. Available borehole data at a distance of 3.5km from the dam area also indicated layers of stiff clay to a depth of 4m and basalt and sandstone bands extending to 50m (BGS, 2002).

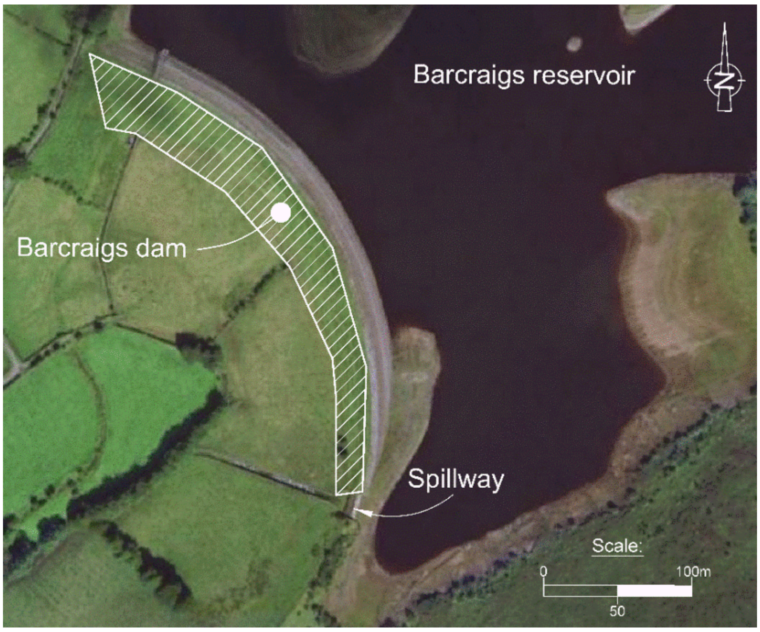

Figure 4: Barcraigs reservoir with the earth-fill embankment and the spillway on the south-west side of the area.

4. Dam survey results

The assessment that was carried out on all three dams initially consisted of visual inspections along the crest and downstream shoulder of the dams to identify potential warning signs of hazards on the surface of the structures. An EM survey was then carried out using a CMD unit from GF instruments targeting at a depth of 3 m below the surface of the dam, with main objective to act as a fast scanning method to assess the conductivity (or resistivity) distribution of the upper soil layers of the dam. Finally, based on the results obtained from the visual inspection and EM survey, the ERT surveys targeted at areas of interest to identify in more detail potential degradation processes occurring inside the body of dams. For the ERT measurements, the device ARES (GF Instruments, Czech Republic) was employed and the Schlumberger electrode arrays configuration was selected. Each ERT array had a total length of 96 m while the distance between the electrodes was 2 m on longitudinal profiles along the crest of the dams.

The obtained datasets from the EM survey were analysed using the OriginPro (OriginLab-USA) and Surfer (GoldenSoftware-USA) software programmes. The inverse 2D models of resistivity sections were compiled using the programme Res2Dinv (GEOTOMO Software - Malaysia) and results were collected using the 4th iteration of least squares method. Further analysis and visualization of the results was then carried out with Surfer software.

4.1. Holl dam survey results

The visual inspection carried out prior to geophysical survey identified animal activity on the east-side of the downstream shoulder of Holl dam, as presented in Figure 5 (a). This activity is related with the presence of mole animals, usually found in earth-fill dams, that develop micro-tunnels and, in many cases, extensive burrow systems which in the long-term can potentially affect the structural integrity of the embankment. On the north-east side of the dam soil fissuring along the crest was also observed as presented in Figure 5 (b). The EM survey was carried out covering the surface of the whole embankment area (see Figure 5 c) and was completed in two parts on the same day which was combined into one dataset producing the resistivity distribution recorded over the whole body of the dam.

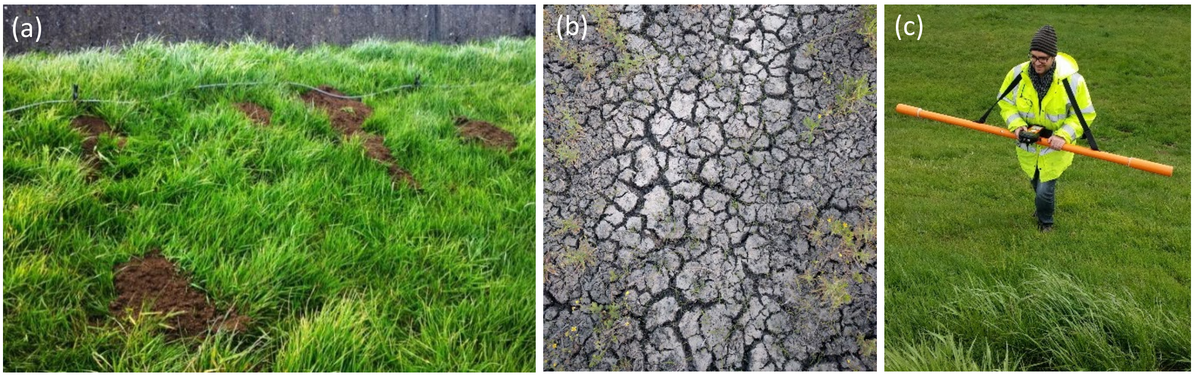

Figure 5: (a) Visual signs of excavated soil indicating the presence of mole-hills located in the upper part of the downstream shoulder of the embankment, (b) clay fissuring detected on the north-east side of the dam (c) EM survey carried out over the surface of Holl dam.

The two ERT arrays with length of 96 m and 2 m interval spacing of electrodes were then installed on the boundary between the south side of the crest and the downstream shoulder (see Figure 6) where the maximum slope was recorded. This location was selected to investigate the subsurface conditions over the maximum embankment height and the effect of the animal burrows which were mainly detected on the upper part of the downstream shoulder.

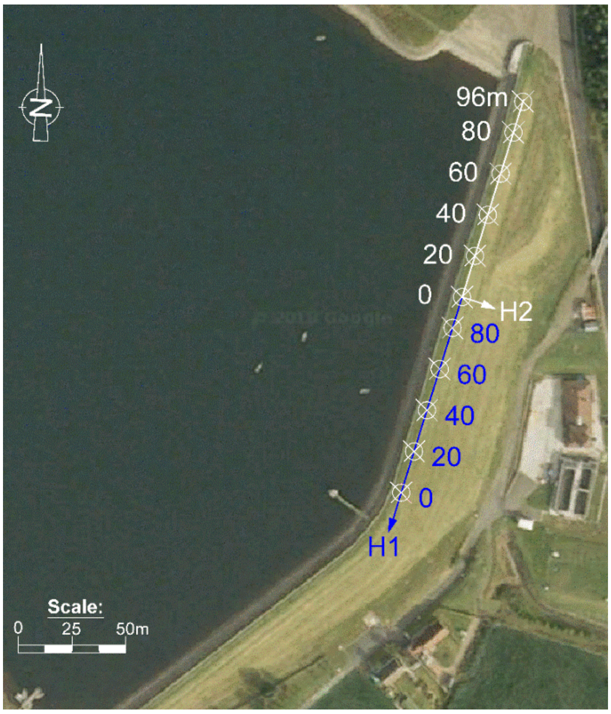

Figure 6: ERT arrays H1 and H2 with length of 96 m and electrode spacing intervals of 2 m on the north-east side of Holl dam.

The results obtained from the EM survey are presented in Figure 7 superimposed onto an aerial Google maps photo of the dam. The survey carried out revealed lower resistivity values, throughout the length of the crest of the embankment. The embankment at its maximum height (i.e. north-east side) also appears to be drier compared to the south-west side which is evident by the higher resistivity values. These higher range of resistivity values on the north-east side of the embankment are also influenced by the animal burrowing activity and fissuring on the dam surface which is agreement with the visual inspection findings (refer to Figure 5b)

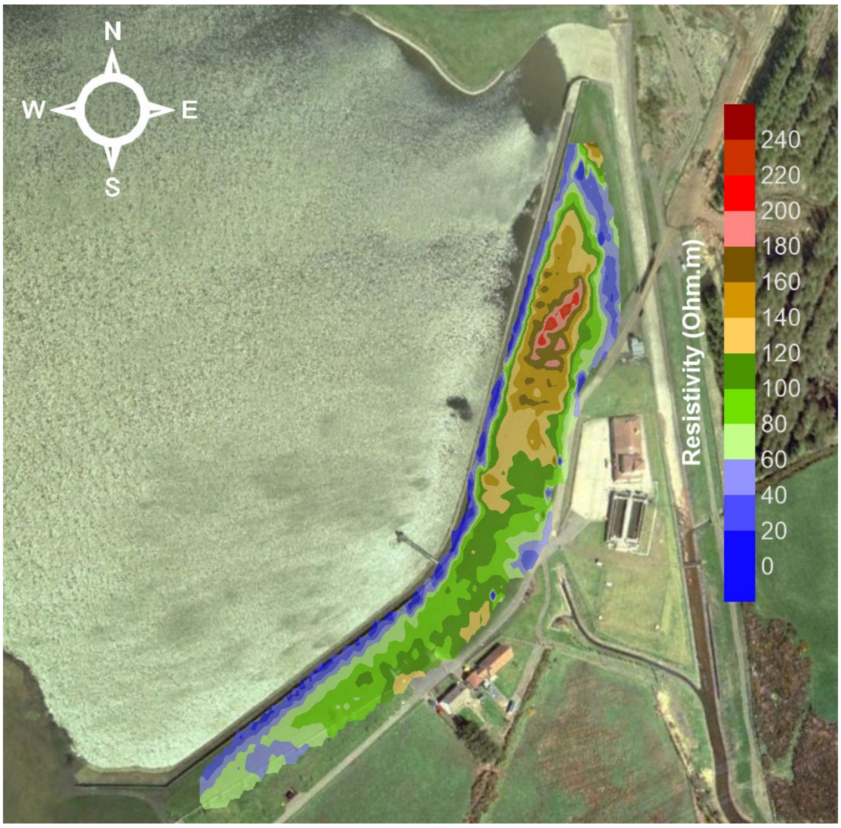

Figure 7: Higher resistivity areas are identified in the north-east side of the dam based on the EM survey carried out over the surface of the Holl dam.

Based on the findings of EM survey, the ERT investigation was focused on areas of interest where a higher range of resistivity values was detected. The inverse resistivity models obtained for ERT arrays H1 and H2 are presented in Figure 8. Lower resistivity soil matrix was detected throughout the cross section depicted in H1 and H2 models (ranging from 0 to 152 Ohm.m) down to a maximum depth of 15 m and 6 m respectively. In the H1 model minor resistivity anomalies (< 152 Ohm.m) are detected at the depth range 4 m – 7 m, potentially associated with animal burrowing activity and/or the presence of drier or coarser soil matrix. A high resistivity uniform signature (> 192 Ohm.m) is also detected at depth > 6 m throughout the H2 cross section, which indicates different fill material potentially associated with the presence of the dam foundation towards the spillway. The main findings of the dam assessment in Holl reservoir are also summarised in Table 1.

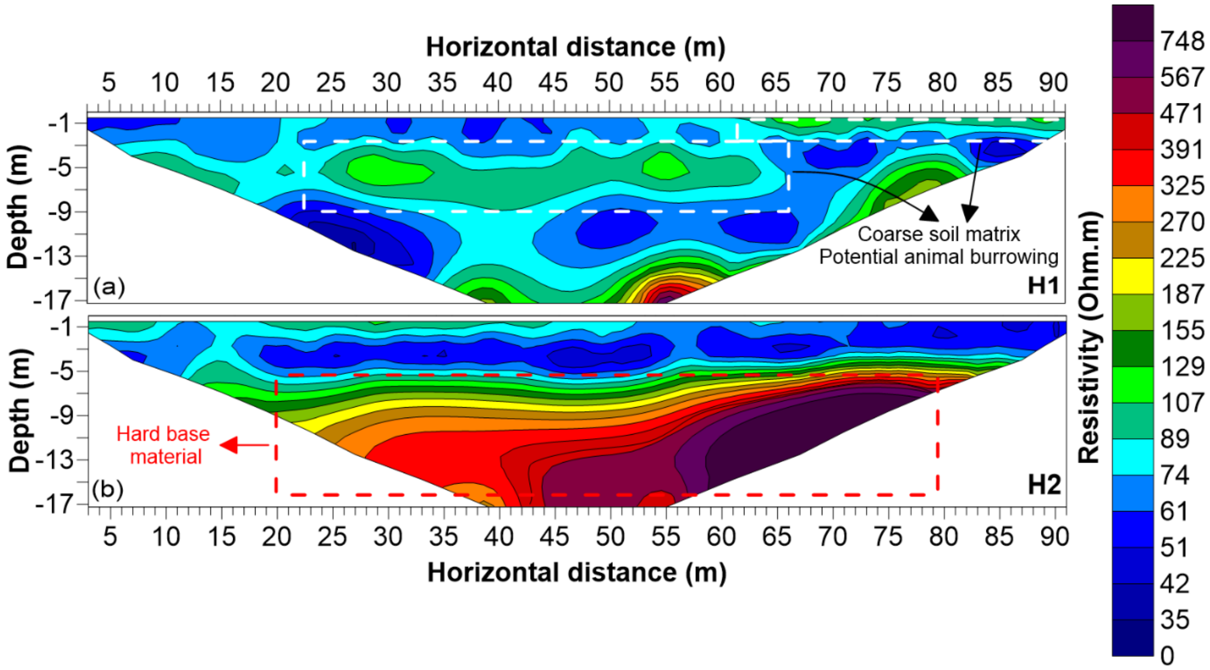

Figure 8: The ERT models for arrays **(a)** H1 revealed resistivity anomalies beneath the crest of the embankment at depth range 4-7m and for **(b)** H2 high resistivity signatures at depth > 6m.

Table 1: Summary of findings from the visual and geophysical assessment carried out in Holl reservoir dam.

Type of investigation	Depth	Summary of findings	Main reason(s)
Visual inspection	Surface	Clay fissuring	Temperature variations
Visual inspection	Surface	Soil deposits on the downstream face	Animal burrowing activity
Geophysical - EM	< 3 m	Higher resistivity signatures on the north-east side of the dam	Drier soil matrix in upper layers – Animal burrowing activity
Geophysical - ERT	< 7 m	Resistivity anomalies	Animal burrowing activity – and/or presence of drier/coarser soil matrix
Geophysical – ERT	> 8 m	High resistivity signatures	Presence of an hard base material (e.g. bedrock)

A visual correlation combining the findings of the visual inspection and the geophysical survey is also presented in Figure 9. The elevated resistivity areas at shallow depths are in agreement with the animal burrowing activity that was identified during the visual inspection. High resistivity patterns towards the north-east side of the embankment are potentially influenced by soil fissuring that was detected during the visual inspection.

Figure 9: Visual correlation of findings derived from visual inspection and geophysical assessment of Holl reservoir dam.

The complementary geophysical methods that were applied at Holl dam provided for the first time an insight of the subsurface conditions inside the body of the earth fill structure. Animal burrowing activity and signs of clay fissuring were initially identified by the visual inspection on the north-east side of the dam. These areas were in agreement with the higher resistivity patterns, potentially influenced by the presence of coarser soil matrix in the upper soil layers, based on the results obtained in both EM and ERT investigations. The non-invasive ERT investigation also revealed the presence of hard base material towards the spillway of the embankment which is evident by the high resistivity anomalies as presented in the analysed models.

4.2. Mugdock dam survey results

The visual inspection over the crest and the downstream shoulder of Mugdock dam was carried out during December 2015. The inspection did not reveal any significant findings and at the time of the survey the embankment had not encountered major deformations or slips. Animal activity was not evident at the time of the inspection while the crest and downstream face of Mugdock dam appeared to be in good condition with healthy short covering of grass.

The non-intrusive geophysical survey aimed at investigating the subsurface conditions beneath the crest of each dam. Primarily the EM survey targeted to assess the resistivity signatures over the crest and the downstream body of the embankment and detect anomalies in the upper soil layers. Three ERT arrays (M1, M2 and M3) were subsequently installed on the boundary between the south side of the crest and the downstream shoulder of Mugdock dam, as shown in Figure 10. All ERT arrays had a length of 96 m with 2 m interval spacing between electrodes, which enabled greater penetration depths providing a complete subsurface characterisation of the dam.

Figure 10: (a) Non-intrusive geophysical investigation with ERT arrays installed on the crest of Mugdock reservoir dam, (b) ERT arrays (M1, M2 and M3) with length of 96 m and electrode spacing intervals of 2 m covering part of the length of Mugdock dam.

Figure 11 presents the resistivity distribution obtained during the EM survey carried out over the crest and downstream shoulder of Mugdock dam. The results of the survey indicate resistivity layers > 120 Ohm.m throughout the body of the dam. Lower resistivity areas are evident on the south-side towards the toe of the dam. Significant anomalies in the soil resistivity (> 200 Ohm.m) on the south-east side are attributed to the interference of obstacles (e.g. concrete obstructions).

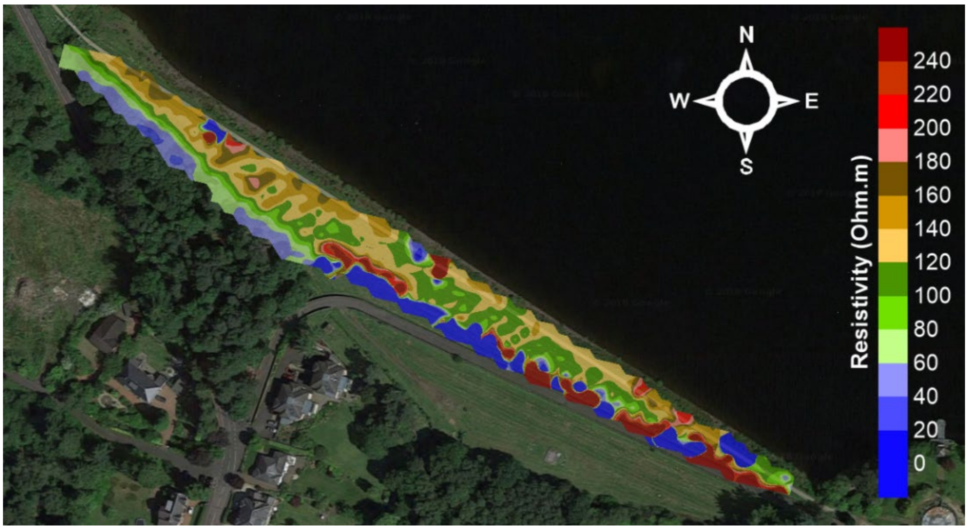

Figure 11: Resistivity values obtained during EM survey over the whole surface of Mugdock dam.

The M1, M2 and M3 ERT models indicated elevated resistivity areas (> 107 Ohm.m) on the upper soil layers (< 3 m) of the dam, as presented in Figure 12. These results are in agreement with the resistivity range obtained from the EM survey. These high resistivity signatures are potentially related to drier/coarser soil matrix (e.g. gravel, clay, sand) and are not attributed to burrows, considering that animal activity was not observed on the crest and the downstream face of the dam during the visual inspection. The analysis of the results obtained from the three ERT arrays also revealed low resistivity signatures (< 24 Ohm.m) that are located beneath the upper soil layers. These resistivity areas are associated with saturation zones in clay sediments influenced by the seepage pattern inside the body of the dam. Higher resistivity signatures up to 748 Ohm.m are detected at depth > 10 m attributed to the presence of hard base material (e.g. bedrock foundation). The results obtained from the ERT models also provide useful information with regards to the fill material which for the layers beneath the upper soil surface of Mugdock dam is characterised as homogeneous, and is particularly evident in models M1 and M2. A summary of the main findings of the dam assessment in Mugdock reservoir is provided in Table 2.

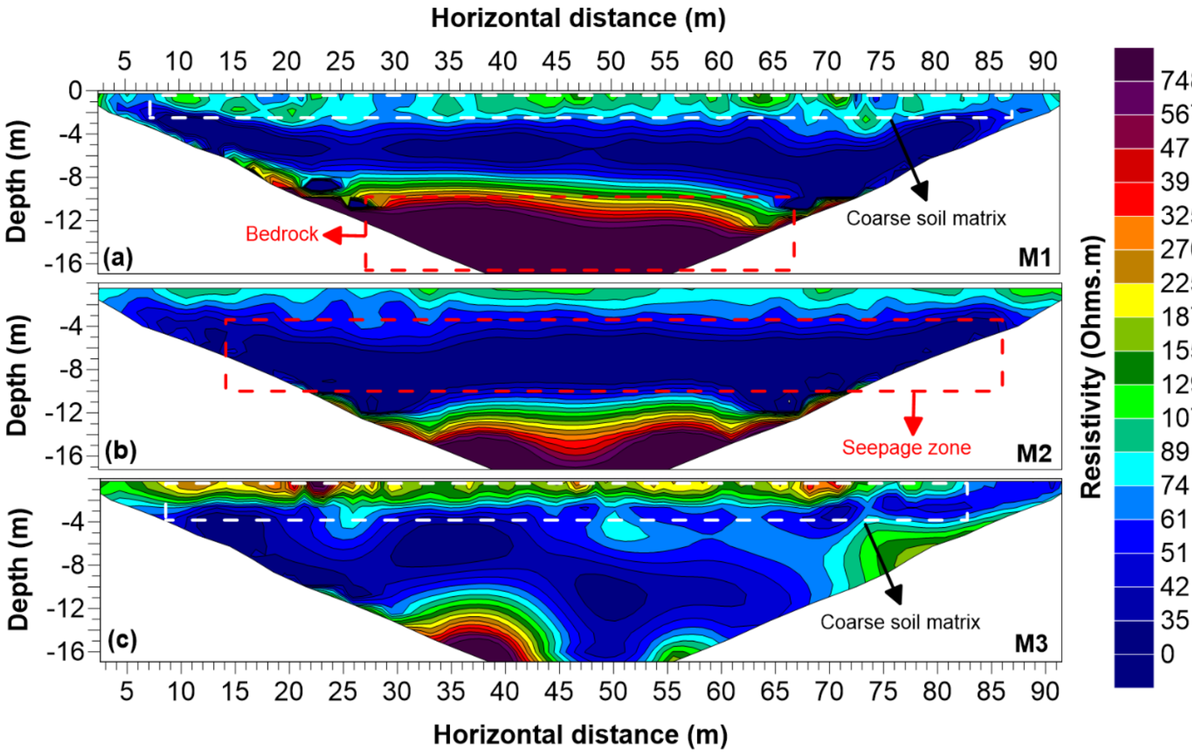

Figure 12: ERT models for arrays **(a)** M1, **(b)** M2 and **(c)** M3 indicated resistivity signatures potentially associated drier/coarser soil matrix in the upper soil layers, followed by zones influenced by seepage activity and hard base material.

Table 2: Summary of findings from the visual and geophysical assessment carried out in Mugdock reservoir dam.

Type of investigation	Depth	Summary of findings	Main reason(s)
Visual inspection	Surface	No significant findings	N/A
Geophysical - EM	< 3 m	Elevated resistivity signatures	Drier/coarser soil matrix in upper layers
Geophysical - ERT	> 3 m	Low resistivity signatures	High saturation zones potentially influenced by seepage pattern
Geophysical - ERT	> 12 m	High resistivity signatures	Presence of an obstruction (e.g. bedrock)

Figure 13 presents the visual correlation between the visual inspection and geophysical survey results. Uniform resistivity zones almost throughout the cross section indicate normal anticipated seepage activity inside the core of the dam considering that visual warning signs were not detected at the time of the survey.

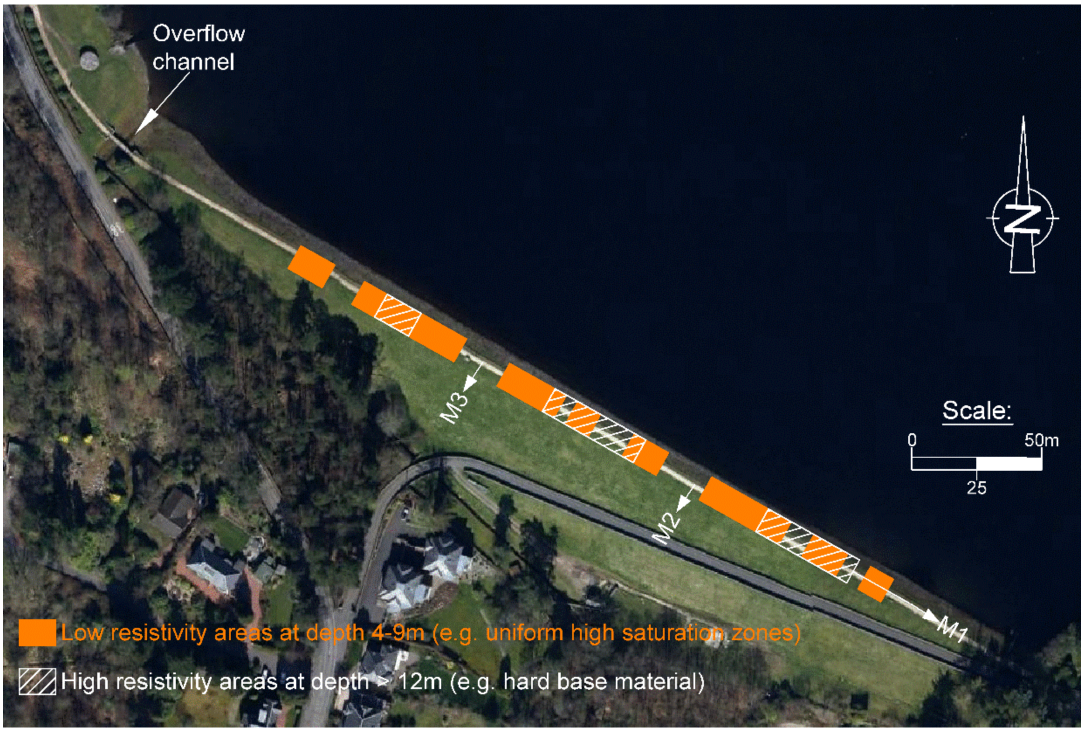

Figure 13: Visual correlation of findings derived from visual inspection and geophysical assessment of Mudgock reservoir dam.

In conclusion, the results of the survey carried out in Mugdock dam indicated elevated resistivity signatures in the upper soil layers due to the presence of drier and/or coarser soil composition. Uniform low resistivity areas were also detected at increased depth which highlight saturation zones influence by seepage patterns inside the body of dams. The presence of the foundation of the dam is also evident by the high resistivity values that were observed at increased depths.

4.3. Barcraigs dam survey results

A visual inspection over the crest and the downstream face of Barcraigs dam was carried out at the end of November 2015 during floods in the region. This month was provisionally in the top ten wettest months in Scotland on record with 242 mm of rainfall (Kendon et al., 2016). At the time of the survey the reservoir was at flood level while the spillway was under operation and was releasing water.

At the time of the inspection no significant settlements along the length of the crest were identified. Animal activity and burrows were observed in many areas mainly located on the upper part of the downstream face towards the crest. On an area located on the north-west side of the downstream face of the dam, soil deposits were detected, as shown in Figure 14 (a), without evidence of animal activity. This observation was accompanied with detection of wet patches and short reed vegetation that were observed in other areas on the downstream face of the dam. The aforementioned observations are potential signs of internal erosion, suffusion and seepage processes that usually occur inside the body and provide similar visual warnings on the downstream face of earth-fill dams. However, further investigation is required to identify whether these findings were associated with climatic conditions (e.g. extreme rainfall) or with seepage activity. Visual inspections also revealed areas with minor slope instabilities and circular slip surfaces, as presented in Figures 14 (a) and (b). It is noted that most of the slope instabilities were identified in areas towards the toe of the dam. A circular slip surface was observed towards the spillway on the south-east side of the dam which highlighted an area of interest for further investigation.

Figure 14: **(a)** Soil deposits on the west side of the downstream face of the dam. Slope instability on an areas located at **(b)** the toe of the dam and **(c)** towards the spillway.

An EM survey was initially carried out scanning the soil resistivity at 3 m depth below the crest and the downstream slope to detect any anomalies beneath the dam surface. Four ERT arrays (B1, B2, B3 and B4) were then installed on the boundary between the south side of the crest and the downstream face of the dam, as shown in Figure 15.

Figure 15: Non-intrusive ERT arrays (B1, B2, B3 and B4) 96m long with 2m electrode spacing covering the crest length of Barcraigs dam.

Figure 16 presents the resistivity distribution obtained during the EM survey carried out over the crest and the downstream face of Barcraigs dam. Low resistivity zones < 60 Ohm.m were detected throughout the downstream face of the dam, while in certain areas resistivity signatures < 40 Ohm.m are detected. These lower resistivity regions are in agreement with locations of wet patches obtained from the visual inspection. Towards the crest of the dam the obtained resistivity values are increased to more than 60 Ohm-m while the increased resistivity areas towards the spillway on the south-east side of the dam are potentially influenced by the presence of hard based material or obstructions (e.g. spillway).

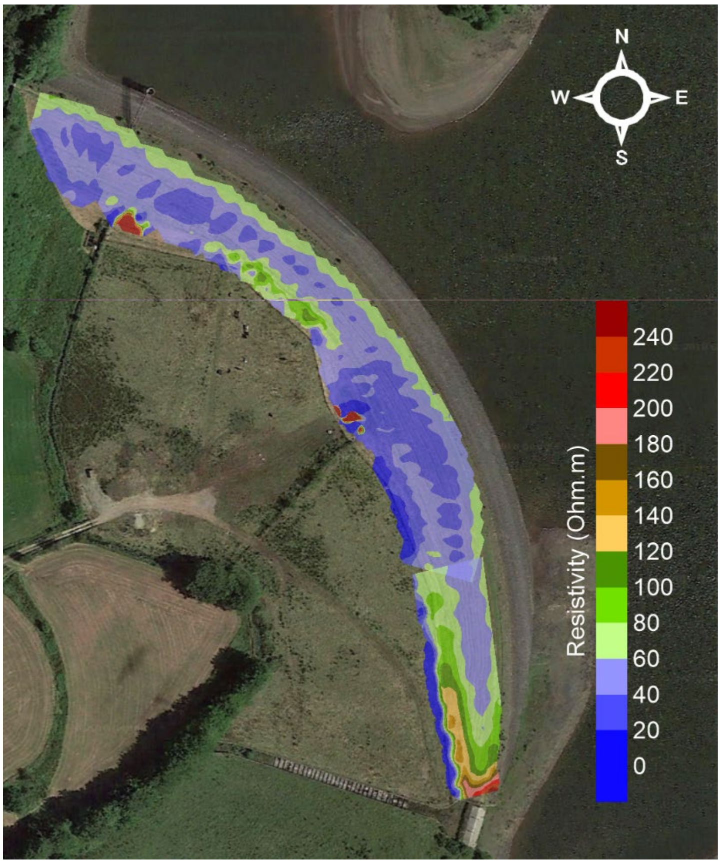

Figure 16: Resistivity distribution obtained during EM survey along the crest of Barcraigs dam.

The analysis of the ERT data obtained in Barcraigs dam revealed high resistivity areas (up to 478 Ohm.m) on the upper soil layers (< 2 m) of the embankment as shown in Figure 17. These high resistivity signatures are potentially related with the presence of drier/coarser soil matrix (e.g. gravel and/or sand sediment) and sand/air-filled 'pockets' caused by animal burrows. Low resistivity zones (< 24 Ohm.m) were identified beneath the crest which were particularly evident in models B1 and B3, as presented in Figures 17 (a) and (c) respectively. These areas indicate high saturation zones in clay sediments, potentially influenced by seepage paths inside the body of the dam. The horizontal distance of these zones also correspond to areas where signs of internal erosion and seepage were detected during the visual inspection on the downstream face of the dam (refer to Figure 14a). The different resistivity patterns that are detected throughout the cross sections in models B1 and B2 are attributed to variation in the fill material of the dam or to the presence of seepage activity in model B1. A saturation zone identified in model B4 at shallow depth (< 5 m) towards the spillway is potentially influencing the formation of the circular slip surface that was observed in the same area. A high resistivity region (> 660 Ohm.m) was detected in model B4 towards the spillway and is associated with the presence of hard base material (e.g. bedrock). The main findings of the dam assessment in Barcraigs reservoir are summarised in Table 3.

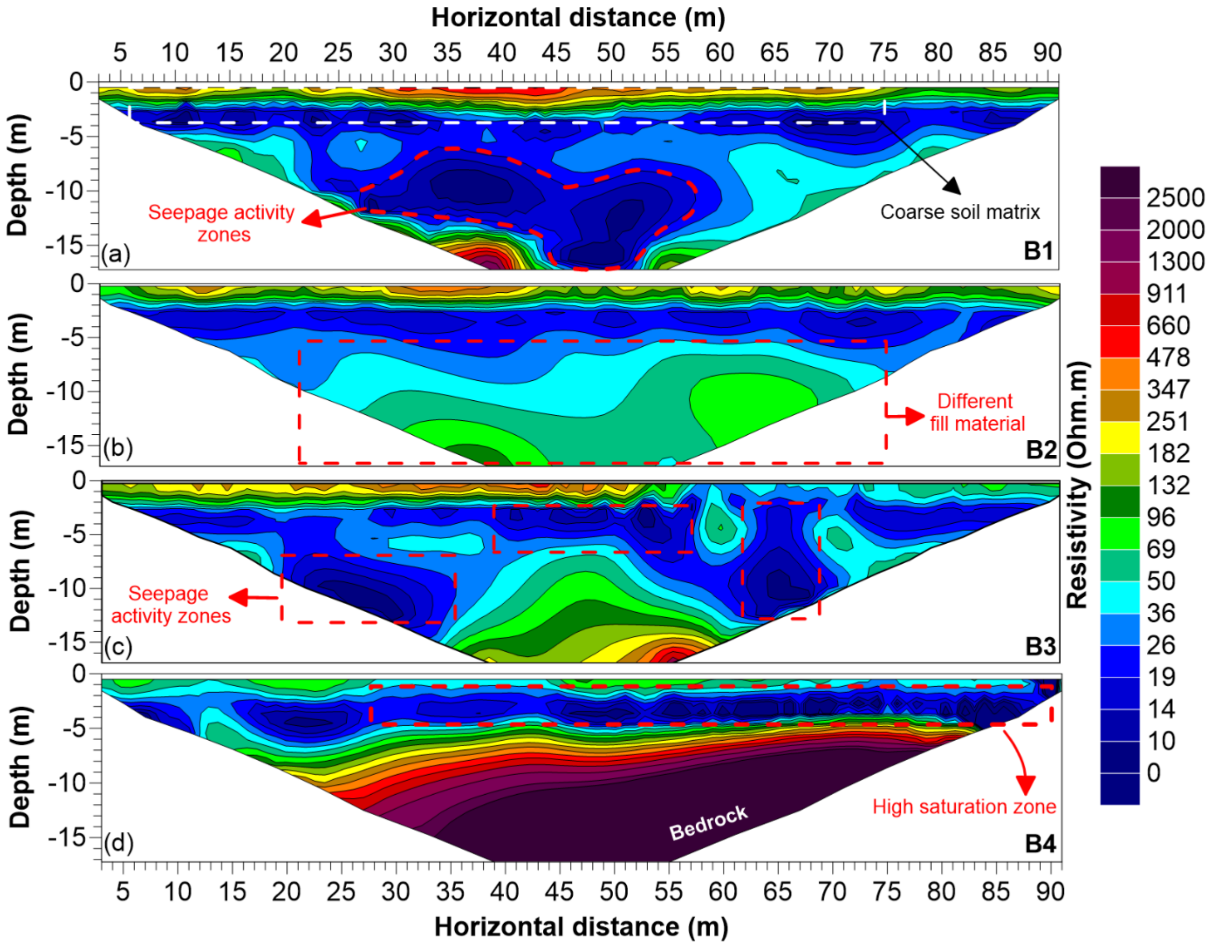

Figure 17: ERT model for arrays **(a)** B1, **(b)** B2, **(c)** B3 and **(d)** B4 revealed circular low resistivity signatures which are potential associated with seepage patterns inside the body of the dam and a higher resistivity anomaly which is related with the presence of bedrock.

Table 3: Summary of findings from the visual and geophysical assessment carried out in Barcraigs reservoir dam.

Investigation	Depth	Summary of findings	Potential reason(s)
Visual inspection	Surface	Soil deposits on the downstream face	Typical sign of internal erosion/suffusion/seepage
Visual inspection	Surface	Wet patches and short reed vegetation on the downstream face	Typical sign of seepage activity
Visual inspection	Surface	Slope instabilities	Internal erosion and seepage that could trigger the formation of slip surfaces
Visual inspection / Geophysical - ERT	Surface / < 7 m	Animal activity on the upper downstream face / Higher resistivity values at depth < 2m	Resistivity values influenced by dry material or animal burrowing activity
Geophysical - EM	> 8 m	Low resistivity (< 40 Ohm.m) patches on the downstream face	High saturation zones due to seepage activity
Geophysical - ERT	5 - 15 m	Difference in the average resistivity values obtained between the models B1 and B2	Seepage activity in model B1 or non-uniform filling material between the two sections

Investigation	Depth	Summary of findings	Potential reason(s)
Geophysical - ERT	3 – 13 m	Circular low resistivity areas throughout the cross section	High saturation zones potentially influenced by seepage activity
Geophysical - ERT	< 7 m	Circular elevated resistivity zones at the horizontal distances between 58 – 62m and 69m - 76m.	Sand/air 'pockets' caused by suffusion and/or animal activity. Beneath these areas, high saturation zones were detected
Geophysical - ERT	< 5 m	Lower resistivity anomalies	High saturation zones potentially influencing the formation of slip surfaces

Figure 18 presents the visual correlation between findings obtained from the visual inspection and the geophysical surveys. It is pointed out that visual degradation signs along the downstream slope of the dam are in agreement with the location of low resistivity zones observed at depth 5-14m, potentially attributed to abnormal seepage activity inside the core of the dam.

Figure 18: Visual correlation of findings derived from visual inspection and geophysical assessment of Barcraigs reservoir dam.

The geophysical investigation in Barcraigs reservoir dam indicated areas of interest where potential signs of degradation were observed within the body and surface of the dam. The ERT models provided a low range of resistivity signatures and an insight of seepage and internal erosion signs which were agreement with the findings obtained by the visual inspection. Considering that the investigation was carried out after a period of intense rainfall and flooding, further geophysical monitoring and validation with long-term rainfall and reservoir water level datasets is necessary to identify whether the findings are attributed to weather effects (i.e. rainfall) or to seepage patterns inside the body of the dam, that will be mostly influenced by reservoir water level fluctuations. Potential air and sand-filled 'pockets' caused by suffusion or animal burrowing were also detected in the ERT models, highlighted by the circular elevated resistivity zones. High saturation zones with low resistivity areas towards the spillway of the embankment were also found to influence the formation of minor slip surface failure modes of the downstream slope of the dam.

5. Conclusions

The current state of ageing dams 'fuelled' by an increase in the frequency and intensity of climatic hazards are considered to be one of the main challenges for the growing infrastructure crisis.

This study demonstrated the complementary application of the EM and ERT geophysical methods which were coupled by visual inspection to assess the current condition of three Scottish dams with age over 100 years old. The geophysical investigation carried out in Holl dam revealed higher resistivity patterns on the north-east side of the embankment potentially attributed to the animal burrowing activity and fissuring on the dam surface and verified the extent of these hazards within the dam subsurface. The analysis of the geophysical datasets from Mugdock dam revealed high saturation zones located beneath the upper soil layers which indicate normal seepage activity that is anticipated to occur within the core of earth-fill dams. The results obtained from Barcraigs dam highlighted patterns of low resistivity signatures potentially influenced by seepage and internal erosion mechanisms or associated with extreme climatic events at the time of the survey. Finally, in all investigated dams it was successfully demonstrated that the applied geophysical methods can be employed to provide an indication of the homogeneity of the fill material inside their body and to obtain useful information about the depth and extent of their foundations.

This investigation provided for the first time important baseline geophysical measurements for three specific British dams and a key insight for a better understanding about their post-construction behaviour. The proposed methods have the potential to significantly benefit the condition assessment of aged dams by offering non-invasive key information about subsurface conditions related with moisture content, seepage activity and core fill patterns inside the body of dams. The proposed procedure can also be used to complement and validate datasets derived from existing dam instrumentation systems but their application can be particularly useful to aged dams that do not have a reliable geotechnical instrumentation system and their condition is mainly assessed based on visual inspections and on external deformation patterns. On the other hand, the application of geophysical methods and interpretation of their datasets can be challenging as it requires expert knowledge and a multidisciplinary approach to decode geophysical outcomes into key information about subsurface hazards inside the body of dams. Future research entails additional periodic geophysical surveys that will enable a time-lapse comparison of geophysical data sets and the integration of hydrological, geodetic and geotechnical analysis to quantify the impact of degradation hazards.

Funding:
The authors wish to acknowledge the financial support from the Engineering and Physical Sciences Research Council (EPSRC), Impact Acceleration Account (IAA) of the University of Strathclyde and Scottish Water (Grant No: RC8954B).

Acknowledgements:
The authors would like to thank three anonymous reviewers for providing valuable suggestions and comments.

Conflict of interest:
The authors have no conflicts of interest to declare that are relevant to the content of this article.

References

Adamo, N., Al-Ansari, N., Sissakian, V., Laue, J. and Knutsson, S., (2021) Geophysical Methods and their Applications in Dam Safety Monitoring. Journal of Earth Sciences and Geotechnical Engineering, 11(1), pp.291-345.

British Geological Survey (BGS) (1976). Geology of Britain viewer: Borehole scan BGS Reference: NS57SE234/3A. Accessed on 03/03/2021, available at: http://scans.bgs.ac.uk/sobi_scans/boreholes/925956/images/12341142.html

British Geological Survey (BGS) (1998). Geology of Britain viewer: Borehole scan BGS Reference: NO20SE314/1. Accessed on 03/03/2021, available at: http://scans.bgs.ac.uk/sobi_scans/boreholes/1013054/images/12308312.html

British Geological Survey (BGS) (2002). Geology of Britain viewer: Borehole scan BGS Reference: NS45NW21. Accessed on 03/03/2021, available at: http://scans.bgs.ac.uk/sobi_scans/boreholes/20057694/images/20057516.html

Buselli, G. and Lu, K. (2001) Groundwater contamination monitoring with multichannel electrical and electromagnetic methods. Journal of Applied Geophysics, 48, pp. 11–23. https://doi.org/10.1016/S0926-9851(01)00055-6

Calum, P. (2017) Geophysical methods for reservoir safety investigations. Environment Agency and British Dam Society Report, p.31.

Charles, J.A., Tedd, P., Warren, A. (2011) Lessons from historical dam incidents. Environment Agency Project: SC080046/R1. p. 167, ISBN: 978-1-84911-232-1

Dascal, O. (1987) Post-construction deformation of rockfill dams. Journal of Geotechnical Engineering, 113, pp. 46–59.

Dounias, G.T., Anastasopoulos, K. and Kountouris, A. (2012) Long-term behaviour of embankment dams: Seven Greek dams. Proceedings of the Institution of Civil Engineers - Geotechnical Engineering, 165(3), pp. 157–177. http://dx.doi.org/10.1680/geng.11.00052

Dunnicliff, J. (1993). Geotechnical Instrumentation for Monitoring Field Performance. New York: John Wiley & Sons, Inc.

Gamse, S. and Oberguggenberger, M. (2017) Assessment of long-term coordinate time series using hydrostatic-season-time model for rock-fill embankment dam. Structural Control and Health Monitoring, 24, e1859.

Gikas, V. and Sakellariou, M. (2008) Settlement analysis of the Mornos earth dam (Greece): Evidence from numerical modeling and geodetic monitoring. Engineering Structures, 30, pp. 3074–3081.

Guler, G., Kilic, H., Hosbas, G. and Ozaydin, K. (2006) Evaluation of the movements of the dam embankments by means of geodetic and geotechnical methods. Journal of Surveying Engineering, 132, pp. 31–39.

Hunter L.E. and Powers M.H. (2008) Geophysical Investigations of Earthen Dams: An Overview. Symposium on the Application of Geophysics to Engineering and Environmental Problems 2008. January 2008, 1083-1096. https://doi.org/10.4133/1.2963216

ICOLD WRD (International Commission on Large Dams World Register of Dams). (2020). World Register of Dams: General Synthesis. Accessed March 03, 2021 [https://www.icold-cigb.org/GB/world_register/general_synthesis.asp]

Johansson, S. and Dahlin, T. (1996) Seepage monitoring in an earth embankment dam by repeated resistivity measurements. European Journal of Engineering and Environmental Geophysics, 1(3), pp. 229–247.

Jones, G., Sentenac P. and Zielinski M. (2014) Desiccation cracking detection using 2-D and 3-D electrical resistivity tomography:validation on a flood embankment. Journal of Applied Geophysics, 106, pp. 196-211. https://doi.org/10.1016/j.jappgeo.2014.04.018

Kendon, M., McCarthy, M., Jevrejeva, S. and Legg, T. (2016) State of the UK Climate 2015. Met Office, Exeter, UK.

Kirsch, R. and Ernstson, K. (2006) Groundwater Geophysics, Groundwater Geophysics, A Tool for Hydrogeology. doi: 10.1007/3-540-29387-6.

Kyrou, K., Penman, A. and Artemis, C. (2005) The first 30 years of Lefkara Dam. Proceedings of the ICE – Geotechnical Engineering, 158(2), pp. 113 –122.

Lin, C.P., Hung, Y.C. and Yu, Z.H. (2013) Investigation of abnormal seepages in an earth dam using resistivity tomography. Journal of GeoEngineering, 8(2), pp. 61-70.

Loperte, A., Soldovieri, F., and Lapenna, V. (2015) Monte Cotugno dam monitoring by the electrical resistivity tomography. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 8(11), 5346–5351.

McDowell, P.W., Barker, R.D., Butcher, A.P., Culshaw, M.G., Jackson, P.D., McCann, D.M., Skipp, B.O., Matthews, S.L., Arthur, J.C.R. (2002) Geophysics in engineering investigations. Geological Society Engineering Geology Special Publication, 19. Burlington House, London: The Geological Society of London

Michalis, P., Xu, Y. and Valyrakis, M. (2020) Current practices and future directions of monitoring systems for the assessment of geomorphological conditions at bridge infrastructure. River Flow 2020, Proceedings of the 10th Conference on Fluvial Hydraulics, Delft, Netherlands, 7-10 July, pp.1-6. ISBN 9781003110958.

Michalis, P., Konstantinidis, F. and Valyrakis, M. (2019) The road towards Civil Infrastructure 4.0 for proactive asset management of critical infrastructure systems. Proceedings of the 2nd International Conference on Natural Hazards & Infrastructure (ICONHIC), Chania, Greece, 23–26 June 2019, pp. 1-9.

Michalis, P., Pytharouli, S.I. and Raftopoulos, S. (2016)a Long-term deformation patterns of earth-fill dams based on geodetic monitoring data: the Pournari I dam case study. Proceedings of the 3rd Joint International Symposium on Deformation Monitoring (JISDM), Vienna, Austria, 30 March–1 April 2016, pp. 1-5.

Michalis, P., Sentenac, P. and Macbrayne, D. (2016)b Geophysical assessment of dam infrastructure: The Mugdock reservoir dam case study. Proceedings of the 3rd Joint International Symposium on Deformation Monitoring (JISDM), Vienna, Austria, 30 March–1 April 2016, pp. 1-6.

Michalis, P., Tarantino, A., Tachtatzis, C. and Judd, M.D. (2015) Wireless monitoring of scour and re-deposited sediment evolution at bridge foundations based on soil electromagnetic properties. Smart Materials and Structures, 24(12), pp. 1-15. https://doi.org/10.1088/0964-1726/24/12/125029

Niederleithinger, E., Weller, A., Lewis, R. (2012) Evaluation of geophysical techniques for dike inspection. Journal of Environmental & Engineering Geophysics, 17(4), pp. 185–195

Olenchenko, V.V. and Osipova, P.S. (2020) September. Electrical Resistivity Tomography of the Frozen Embankment Dam. In Engineering and Mining Geophysics 2020 (Vol. 2020, No. 1, pp. 1-8). European Association of Geoscientists & Engineers. https://doi.org/10.3997/2214-4609.202051007

Panthulu, T.V., Krishnaiah C. and Shirke J.M. (2001) Detection of seepage paths in earth dams using self-potential and electrical resistivity methods. Engineering Geology, 59, pp. 281–295.

Papachatzaki, Z.R., Anastasopoulos, K., Oikonomidis, C., Siachou, S. and Dounias, G. (2009) Experiences from the installation of geotechnical instruments in dams. Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering. 5-9 October, Alexandria, Egypt. doi:10.3233/978-1-60750-031-5-2121

Pytharouli, S., Michalis, P. and Raftopoulos, S. (2019) From Theory to Field Evidence: Observations on the Evolution of the Settlements of an Earthfill Dam, over Long Time Scales. Infrastructures 2019, 4(4), 65. doi:10.3390/infrastructures4040065

Pytharouli, S.I. and Stiros, S.C. (2009) Investigation of the parameters controlling crest settlement of a major earthfill dam based on the threshold correlation analysis. Journal of Applied Geodesy, 3, pp. 55–62.

Rashidi, M. and Haeri, S.M. (2017) Evaluation of the behavior of earth and rockfill dams during construction and first impounding using instrumentation data and numerical modelling. Journal of Rock Mechanic and Geotechnical Engineering, 9(4), pp. 709–725.

Reservoirs Act 1975 (1975) Elizabeth II. Chapter 23. Her Majesty's Stationery Office, London, UK.

Reynolds, J.M. (1997) An Introduction to Applied and Environmental Geophysics. John Wiley and Sons, Chichester.

Roaf, S., Crichton, D. and Nicol, F. (2009) Adapting Buildings and Cities for Climate change: a 21st Century survival guide. Elsevier Architectural Press, Oxford.

Scaioni, M., Marsella, M., Crosetto, M., Tornatore, V. and Wang, J. (2018) Geodetic and Remote-Sensing Sensors for Dam Deformation Monitoring. Sensors 2018, 18, 3682.

Scottish Water (2010) Mugdock and Craigmaddie Reservoirs, Glasgow. The Katrine Water Project – Milngavie Water Treatment Works. Accessed on 25/02/2021, available at: https://britishdams.org/2010conf/BDSvisit2010_Mugdoc_Craigmaddi_Reservoirs.pdf

Sentenac, P. and Zielinski, M. (2009) Clay fine fissuring monitoring using miniature geo-electrical resistivity arrays. Environmental Earth Sciences, 59(1), pp. 205-214.

Sentenac, P., Benes, V. and Keenan, H. (2018) Reservoir assessment using non-invasive geophysical techniques. Environmental Earth Sciences, 77, pp. 1-14, https://doi.org/10.1007/s12665-018-7463-x

Sentenac, P., Benes, V., Budinski, V., Keenan, H. and Baron, R. (2017) Post flooding damage assessment of earth dams and historical reservoirs using non-invasive geophysical techniques. Journal of Applied Geophysics, 146. pp. 138-148. https://doi.org/10.1016/j.jappgeo.2017.09.006

Sentenac, P., Jones, G., Zielinski, M. and Tarantino, A. (2013) An approach for the geophysical assessment of fissuring of estuary and river food embankments: validation against two case studies in England and Scotland. Environmental Earth Sciences, 69(6), pp. 1939–1949.

Seyed-Kolbadi, S., Hariri-Ardebili, M., Mirtaheri, M. and Pourkamali-Anaraki, F. (2020) Instrumented Health Monitoring of an Earth Dam. Infrastructures 2020, 5, 26.

Sjödahl, P., Dahlin, T. and Johansson, S. (2005) Using resistivity measurements for dam safety evaluation at Enemossen tailings dam in southern Sweden. Environmental Geology, 49, pp. 267–273.

Sjödahl, P., Dahlin, T. and Johansson, S. (2009) Embankment dam seepage evaluation from resistivity monitoring data. Near Surface Geophysics, 7(5-6), pp. 463-474.

Song, S.H., Song, Y.H. and Kwon, B.D. (2005) Application of hydrogeological and geophysical methods to delineate leakage pathways in an earth fill dam. Exploration Geophysics, 36, pp. 92–96.

Tedd, P., Charles, J.A., Holton, I.R. and Robertshaw, A.C. (1997) The effect of reservoir drawdown and long-term consolidation on the deformation of old embankment dams. Geotechnique, 47(1), pp. 33-48.

Tedd, P., Skinner, H.D. and Charles, J.A. (2000) Developments in the British national dams database. Proceedings of 11th British Dam Society Conference, London, pp. 181-189.

Utili, S., Castellanza, R., Galli, A., and Sentenac, P. (2017) Non-invasive portable geophysical tool to monitor water content in earthen long linear infrastructures. Procedia Engineering, 189, pp. 86-93. https://doi.org/10.1016/j.proeng.2017.05.015

Viganotti, M., Jackson, R., Krahn, H. and Dyer, M. (2013) Geometric and frequency EMI sounding of estuarine earthen flood defence embankments in Ireland using 1D inversion models. Journal of Applied Geophysics, 92, pp. 110–120. https://doi.org/10.1016/j.jappgeo.2013.03.001

Zanganehasadabadi, N., Pytharouli, S. and Michalis, P. (2019) Investigation of the relationship between rainfall and long-term settlements of an earthfill dam based on geodetic measurements. Proceedings of the 4th Joint International Symposium on Deformation Monitoring (JISDM), Athens, Greece, 15-17 May 2019, pp. 1-6.