ERT-Based Leakage Tracing for Dam Safety and its Potential Sliding Surface

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ABSTRACT: Electrical resistivity tomography (ERT) has been efficiently applied to geological investigation, mining exploration, groundwater probing, and pollution prevention for years. In this paper, the on-site investigation was required to inspect the possible groundwater leakage through an earth dam during either its full-level storage period or empty storage period. A potential seepage belt could gradually develop along the residual permeable sandy/gravelly layer, an old abandoned river channel. A downhole ERT-based brine tracing technique was conducted on the slopes nearby a spillway and a dam levee widening. The brine seepage flow observation could rapidly reflect the possible direction and path of leakage flow developed in an earth dam in few hours. Monitoring the ERT distribution variations can effectively identify the leakage spatial path, accumulation zone, and its potential sliding surface on dam slopes.
Keywords: Electrical resistivity tomography, leakage, brine tracing, dam, potential sliding, seepage.

1. INTRODUCTION

Watertightness is one of key factors for planning dam engineering. The watertightness investigations cover the seepage conditions on not only an earth dam itself but also the dam foundations. Seepage is highly associated with permeability in geomaterials, geological structures, groundwater conditions, sinkholes, and mining pits (Hung, 1991). In general, sandstone and limestone are attributed to relatively high permeable geomaterials. A bedding plane could be regarded as a relatively high seepage channel when dipping to the downstream side. Fractured rocks nearby faults or fault belts, and rocks with tension cracks in anticline crests could lead to the leakage at dam foundations. Reserving water could impact on the original hydrogeological condition and promote groundwater to outflow into adjacent low water table watersheds.

A complete watertightness investigation, including the items of groundwater table and pressure, consists of geophysical inspection, geological investigation, borehole exploration, and piezometers (Hung, 1991). Electrical resistivity tomography (ERT in brief below), one of near-surface geophysical inspection techniques, has been used for groundwater flow or seepage investigations for years (Schuster and Krizek, 1978; TGS, 2011; Wightman, et al., 2003).

In this paper, the ERT method is applied to inspect the possible leakage through an earth dam in Taiwan. Modified from its traditional applications, an ERT-based brine tracing technique is introduced to efficiently identify the seepage trend of groundwater in potential sliding surface both nearby a spillway slope and on a dam widening slope.

2. OVERVIEW OF ELECTRICAL RESISTIVITY TOMOGRAPHY

The ERT inspection technique can trace geological layers, faults, groundwater pollutants, carves, mining, burial layers, or landslide mass. The principle of ERT is to develop an artificial potential field by probing one pair of current electrodes around a target zone (as shown in Figure 1). Two extra electrodes are used to measure the ground potential difference. The measured apparent resistivity image is usually displayed with a visible-light mode, which corresponds to the resistivity values varying from 2,000 to less than 1 ohm×m (Loke, 2000; Society of Exploration Geophysicists of Japan, 2014). The resistivity values for sediments composed of silt, sand, and rock are more than 5 ohm×m, corresponding to the pink, red, orange, yellow, or green zones. Water, pollutants, or metal form low resistivity-content zones, corresponding to the light blue and grey shades.

The on-site resistivity values are highly associated with mineral composition, grain size, mineral formation, water content, and ion concentration (Loke, 2000; Society of Exploration Geophysicists of Japan, 2014). Table 1 shows the typical resistivity value ranges for geomaterials and water. Rocks usually have relatively high resistivity values. Soils have a wide variety of resistivity ranges and vary with their water content. The resistivity response from fresh water usually overlaps the resistivity ranges of soils. However, sea water, as a better conduction medium, provides much lower resistivity values below the resistivity ranges for both soils and rocks. This implies that infusing brine, like a penetrant, into subsurface can be a potential method to trace groundwater flows when using ERT inspection.

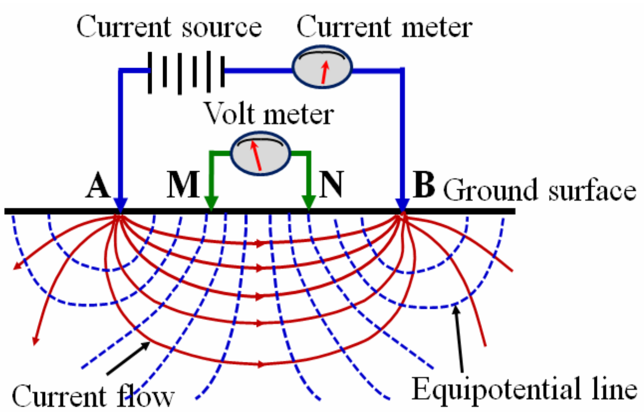


Figure 1 A schematic representation for ERT inspection

Table 1 Resistivity range of common rocks, soils, and waters (after Loke, 2000)

Material	Resistivity (ohm×m)
Rocks	
Granite	5×10^3–10^6
Slate	6×10^2–4×10^7
Marble	10^2–2.5×10^8
Sandstone	8–4×10^3
Shale	20–2×10^3
Limestone	50–4×10^2
Soils	
Clay	1–100
Sand (dry)	5×10^3–2×10^4
Sand (saturated)	2×10^2–10^3
Gravel (dry)	2×10^4–8×10^4
Gravel (saturated)	10^3–5×10^3
Alluvium	10–800
Waters	
Groundwater (fresh)	10–100
Sea Water	0.2

There are 4 commonly-used inspection types, including pole-pole array, pole-dipole array, dipole-dipole array, and Wenner-Schlumberger array (Loke, 2000; Society of Exploration Geophysicists of Japan, 2014). Each inspection type has different resolutions along the probing array direction and also expresses various inspection depth.

In practice, choosing ERT deployment is highly associated with subsurface characterization and environment (Loke, 2000; Society of Exploration Geophysicists of Japan, 2014). Inspection depth and resolution are in terms of electrode spacing and layout length. Furthermore, a trial and error process on sectional image is used to determine the optimal layout deployment. In general, the smaller electrode spacing is arranged, the higher image resolution and the shallower inspection depth are. Accordingly, the larger electrode spacing is used, the lower image resolution and deeper inspection depth are.

3. LEAKAGE TRACING CASES

3.1 Leakage throughout an earth dam

The reservoir located in southern Taiwan was constructed in 1953. Surrounding with scour-prone mudstone and silty sandstone, deposit rapidly piled up to 3 quarters of its design volume found in 1996. From 1997 to 2005, an improvement project was launched for dredging the reservoir sediments, re-constructing the spill and irrigation pipes through the earth dam, and dam mass improvement (Sinotech, 2010). Since 2006, several piezometers, water level gauges, water level wells, inclinometers, flow weirs, seismographs, and settlement points have been installed to monitor the dam conditions, including pore water pressure, water level, seepage condition, displacement, and surface conditions (Chiou, et al., 2010; Liming, 2014; Sinotech, 2010).

The 2,380-m long earth dam consists of one main dam (length 250 m) and two minor dams (right section length 300 m and left section length 1,830 m) (shown in Figure 2). The main dam is composed of concrete core, compact soils, and rockfill. Similar to the components in the main dam, the two minor dams are also constructed with compact soils and rockfill except clay core. The dam elevation is 42 m. The spill pipe intake and irrigation channel are also marked on Figure 2.

Figure 2 Top view photo of reservoir and dam (modified from Google Map)

The geological conditions along the earth dam is plotted in Figure 3. The clay core dam overlays a 10~20-m thick silty sand layer which overlaps a monocline consisting of overlayered pervious muddy sandstone and silty mudstone. The black dashed line also indicates the concrete core zone.

The annual monitoring report for dam safety shows: (1) the measured maximum settlement value less than tolerable settlement 10 mm/month; (2) the maximum lateral displacement less than 10 mm; and (3) eight leakage points found at the downstream side of the dam at positions of 0K+475 m~0K+825 m (Liming, 2014; Sinotech, 2010). The pervious geological condition and seepage findings promote the reservoir agency to engage in the positioning investigation of leakage on the dam mass.

An ERT investigation line is chosen at distances of 0k+603 m~ 0k+783 m at the downstream side along the dam top, the most possible leakage position (Figures 2 and 3). The total investigation length is 180 meters. The inspection is conducted at both the high-level storage and low-level storage periods. The on-site images in the reservoir show that the water level and waters coverage have significant changes (Figure 4). If one carries out the ERT survey along the dam at the different storage levels, such variations on water head could likely lead to amplify the leakage effect on resistivity distribution and probably help investigators identify the leakage zone at the downstream side of the dam.

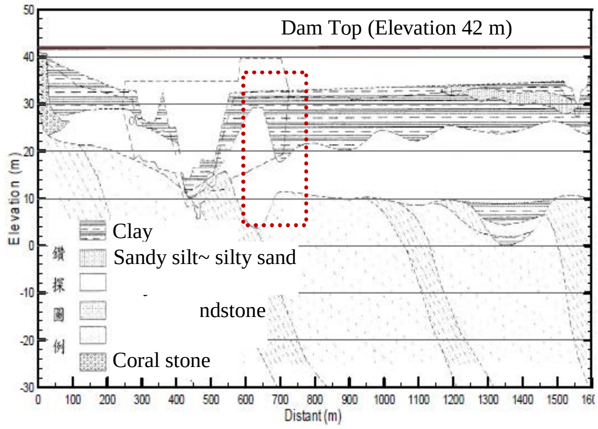


Figure 3 Geological profile along the dam mass (after Sinotech, 2010)

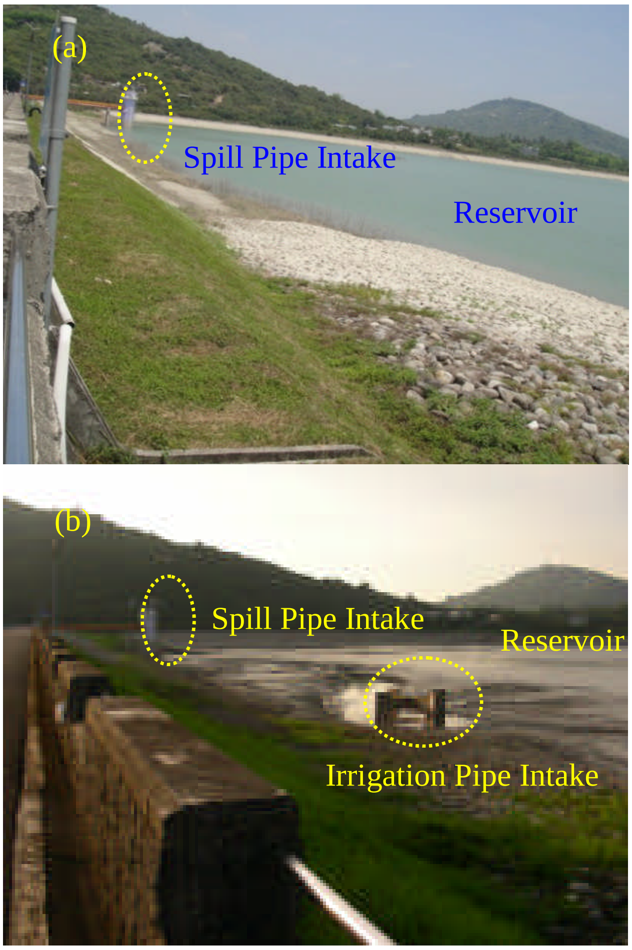


Figure 4 Field testing conditions: (a). full-level storage photo; (b). low-level storage photo

Figures 5(a) and 5(b) indicate the ERT inspection outcomes during the full-level and low-level storage periods, respectively. The estimated geological layers and groundwater table are labelled with black and white dashed lines, respectively. The relatively high resistivity contour zones, corresponding to the pink, red, orange, yellow, or green zones, indicate the sand or gravel layers. The relatively low resistivity contour zones, corresponding to the blue and grey shades, represent the silty sand and clay layers. The significant resistivity variation zone is found at the measurement positions of 30~70 m as shown in Figure 5(c). This pervious silty sand layer could be reasonably inferred as the potential leakage zone. In addition, an old landform sketch before the dam construction reveals that the meandering zone of the old river channel right overlaps this leakage zone.

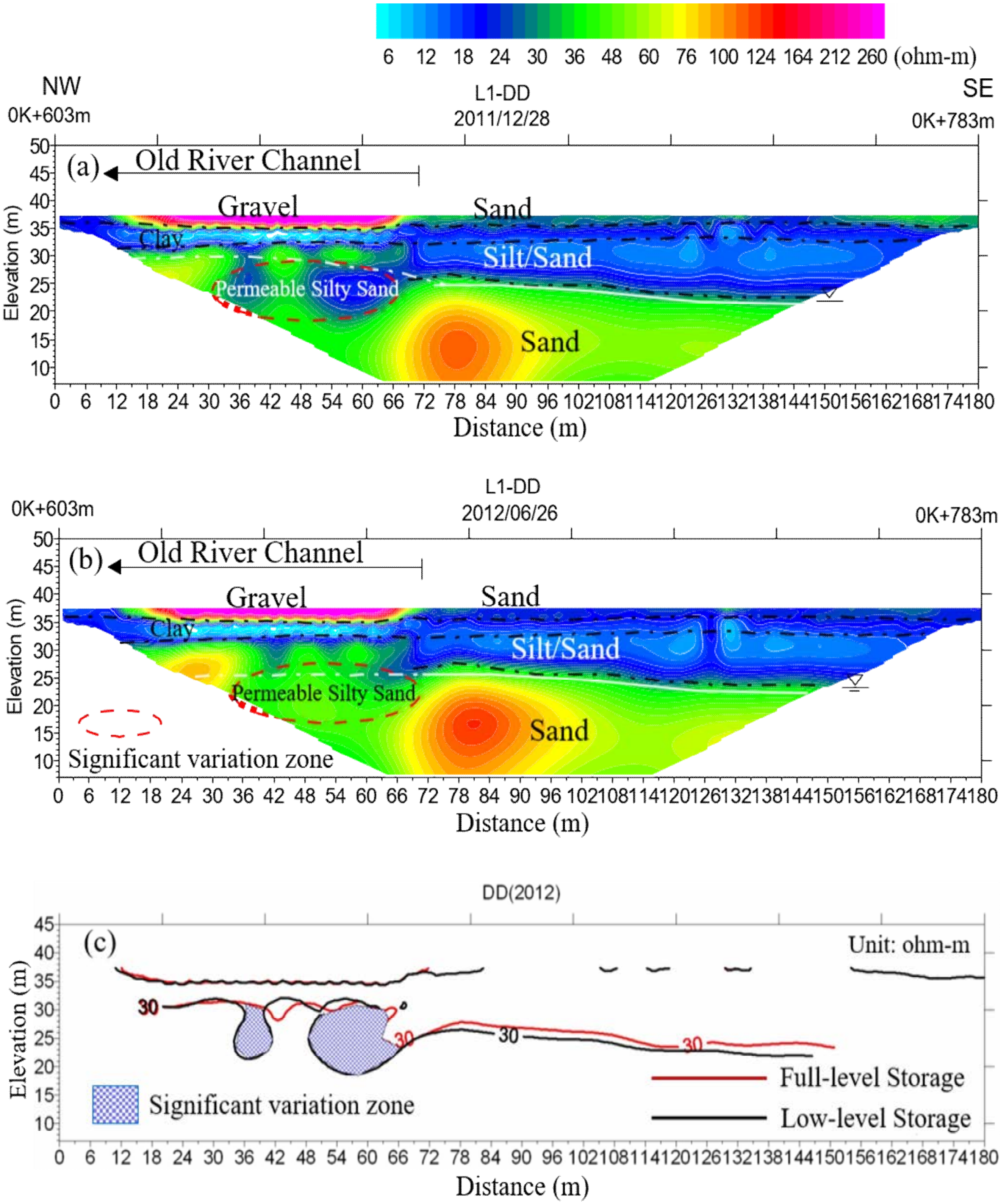


Figure 5 Electrical resistivity tomography images: (a). Full-level storage period; (b). low-level storage period; (c). resistivity variations

3.2 Detecting the potential sliding surface along a spillway

An off-stream reservoir in southwestern Taiwan was constructed during 1979~1987. The 1,535-m long earth dam, a height of 28 meters, is composed of selected impervious material core, compact impervious material, riprap cobble and rockfill, and downstream side gravel and sand filter. During the construction period, the dam engineers found that the main dam foundation crossed the old abandoned river channel. The soft ground could cause differential settlement, initiate extra seepage, and undermine the stability and safety on the main dam. In order to prevent from such damages, an extra ground improvement on the dam foundation led to postpone the time of completion more than 5 years.

A post-earthquake survey in 1999 indicated that the seepage volume and turbidity had significant changes in nearby wells. The post-event geological borehole exploration was conducted in the dam safety inspection and engineers started to design the waterstop grouting for mitigating the seepage through the dam (NCTU, 2005). The recordings in inclinometers and settlement points also revealed local deformation in the dam slope. A saturation condition was frequently found on the dam rockfill toe. All of these evidences implied that the seepage even piping (interior erosion) could exist in this dam.

Its accessary concrete spillway is located at the west minor dam as shown in Figure 6. Unfortunately, shallow sliding is frequently reported all the way around the spillway (NCTU, 2005). Figure 7 shows on-site slope failure images and temporary repair with plastic canvases preventing from more surface erosion. The shallow surface sliding removes more than 2-m deep top soils right beside the spillway culvert walls. The soil lose also spreads to the substrate soils under the spillway. Lack of substrate support leads to severe cracking on the spillway bottom. Substrate refill and retrofitting construction on the channel bottom are conducted for recovering the original function of the spillway.

Figure 6 Top view photo of reservoir and dam (modified from Google Map)

In order to know the possible sliding surface, the ERT-based brine tracing technique is introduced to this manner. Two borehole positions and two ERT investigation lines are also plotted in Figure 6. The borehole positions, including WH-1 and WH-2, are set at the dam-top roadside grass. A 56-m long ERT survey Line WH-1S is extended downward from borehole WH-1 and measures the sliding mass conditions directly (see Figures 6 and 7). Another 70-m long ERT survey Line WH-2S is extended from borehole WH-2 downward along the dam slope surface covered with bush and grass. Such an investigation pattern can not only provide the detailed geological information from the borehole samples but also transfer these two empty boreholes into the brine injection pipes for following ERT tracing.

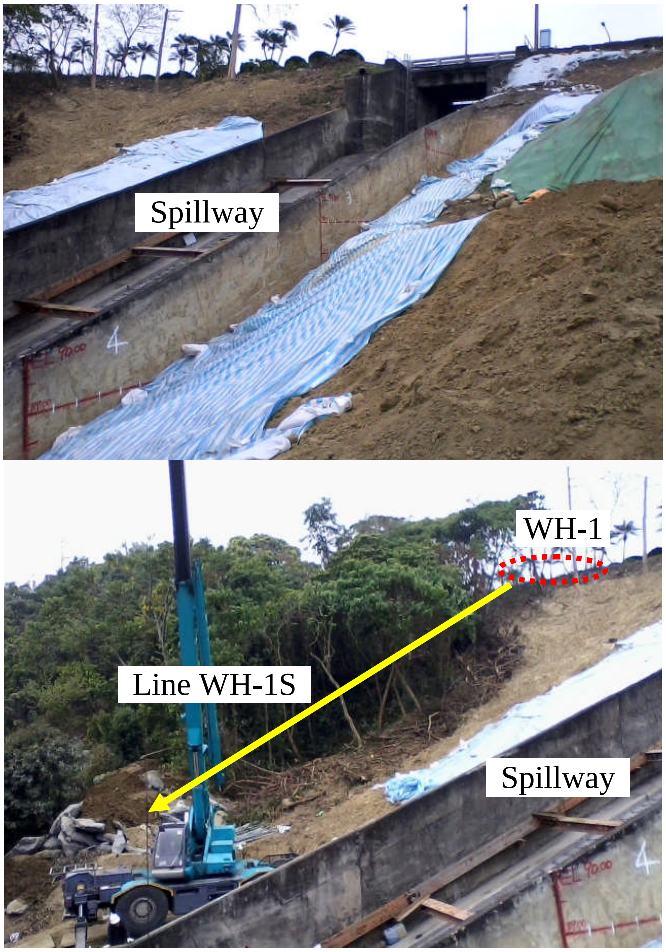


Figure 7 Slope sliding along the spillway structure

The around 19-m long geological column at borehole WH-1 is shown in Figure 8. The geomaterials in the dam mass from the ground surface are composed of top soil, weathering sandstone, loose sandstone, and loose sandstone with mudstone, in series.

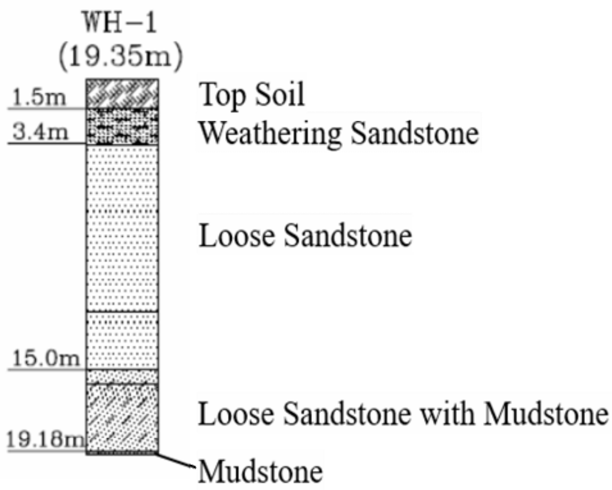


Figure 8 Geological column at borehole WH-1

The complicated 38-m deep column at borehole WH-2 is shown in Figure 9. The geomaterials in the borehole log from the ground surface to its exploration depth are, in sequence, composed of mudstone, loose sandstone with mudstone, loose sandstone, mudstone, loose sandstone/mudstone (interlayered), mudstone, loose sandstone with mudstone, loose sandstone, mudstone, loose sandstone, and mudstone. The permeable and impermeable layers alternatively occur throughout the dam mass from the ground surface.

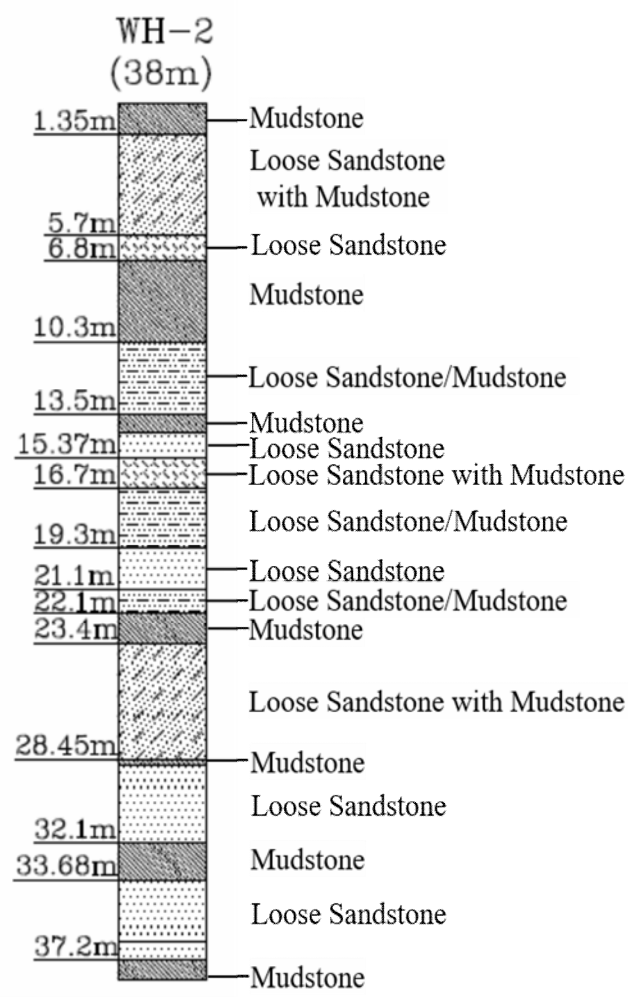


Figure 9 Geological column at borehole WH-2

Figure 10 shows the ERT-based brine tracing technique image at borehole WH-1. The brine water is continuously infused into the dam mass through the borehole PVC pipe from water tanks. The ERT instrument records the resistivity images before brine infusion and traces the resistivity variation images up to 840 minutes.

Figure 10 ERT-based brine tracing conducted at borehole WH-1

Figure 11 indicates the resistivity background image measured along survey Line WH-1S. The dotted and dashed lines represent the layer boundaries defined by both ERT and borehole sampling and borehole sampling only, respectively. The ERT background image consists with the findings at borehole WH-1. The top soil and weathering sandstone layers correspond to the light blue and green zones, scattering from the ground surface to depths of 3~5 m. The yellow, light green, and orange zones could indicate the sandstone, which overlays the sandstone with mudstone, a relatively low resistivity value zone.

Figure 12 represents the resistivity variation images (more than -5%) along survey Line WH-1S up to 840 minutes. The resistivity variations for brine tracing measure the resistivity differences between the background and the influence from brine transmission at specific moment. Infusing brine water could lead to the decrease of resistivity values in the dam slope when it seeps through more pervious layers. At the first 60 minutes, the intensive variations occur at the depths of 2 m on the dam slope around the injection borehole WH-1. Up to 240 minutes, the brine seepage flows downward along the permeable sandstone layer. A significant brine accumulation zone, marked as A, steeply seats upon a relatively impervious layer. In future, this would possibly develop as a potential sliding surface, about 3~5 meters deep, around the middle part of the dam slope when extreme rain occurs. After 14 hours, the brine water moves downward to the slope toe, labelled as B. This could be another potential sliding surface.

Figure 13 shows the resistivity background image measured along survey Line WH-2S. The dotted and dashed lines also represent the layer boundaries defined by both ERT and borehole sampling and borehole sampling only, respectively. The ERT background image also consists with the findings at borehole WH-2. The extremely low resistivity mudstone layer lays over the relatively high resistivity sandstone layer, corresponding to the yellow zones. Another mudstone layer overlays the sandstone interlayered with mudstone, which covers over a mudstone layer.

Figure 14 presents the resistivity variation images (more than -5%) along survey Line WH-2S up to 840 minutes. The resistivity variations for brine tracing indicate the resistivity differences between the background and the influence from brine transmission at specific moment. Within the first 240 minutes, the relatively high variations (-20% maximum) occur at the sandstone and mudstone interlayer, around at the elevations of 85~100 m and measurement positions of 15~30 m. As the infusion time increases, the resistivity variation range expands outward, but limited. However, when stopping injecting brine water into the dam mass (14 hours later), the expansion phenomenon on the resistivity variation image stops and vanishes synchronously. This possibly reveals that the brine water or groundwater is affected with near-borehole diffusion only. The coverage on resistivity variation depends upon continuous brine infusion. There is no significant direction or accumulation zone on the seepage or groundwater flow along investigation Line WH-2S installed on the dam slope. In fact, the dam slope is covered with broomy bushes and grass. There is no significant scour or sliding scars along survey Line WH-2S.

In brief, observing the brine seepage flow could rapidly reflect the possible groundwater or leakage flow path in specific geological layers and accumulation zone based on the ERT inspection technique. Tracing the brine path can also provide the potential sliding surface information on an earth dam mass in few hours.

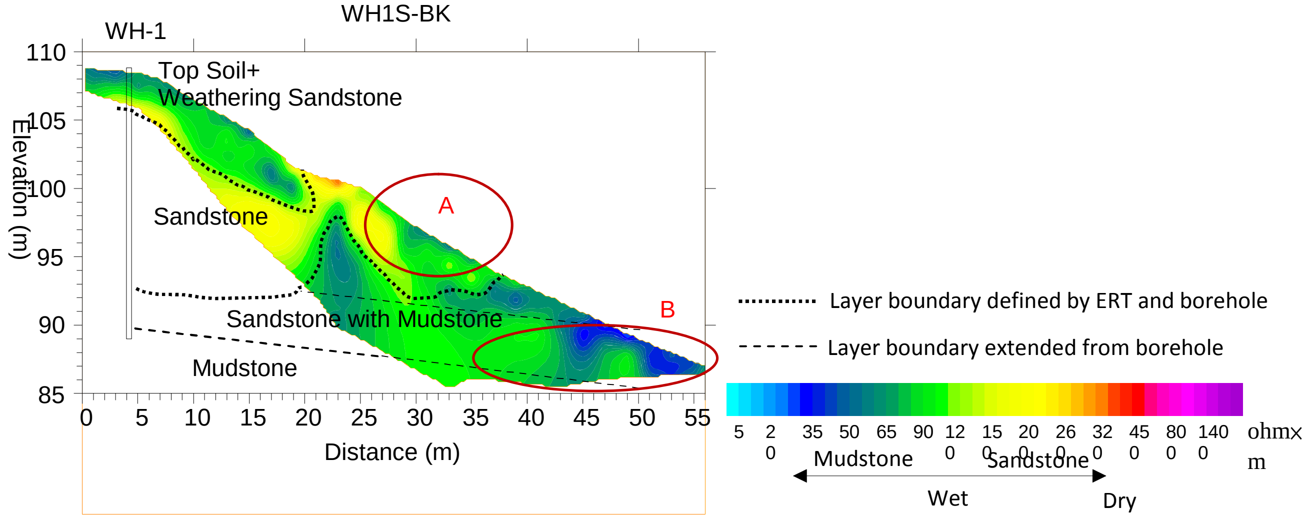
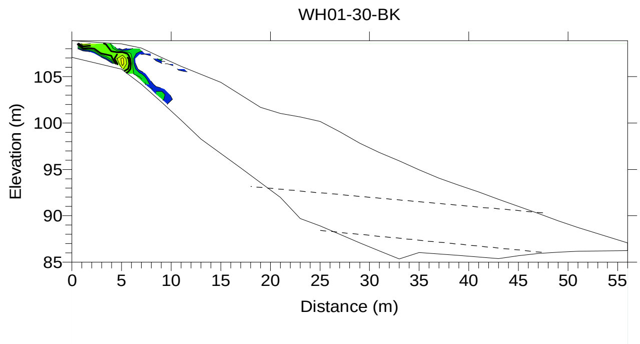
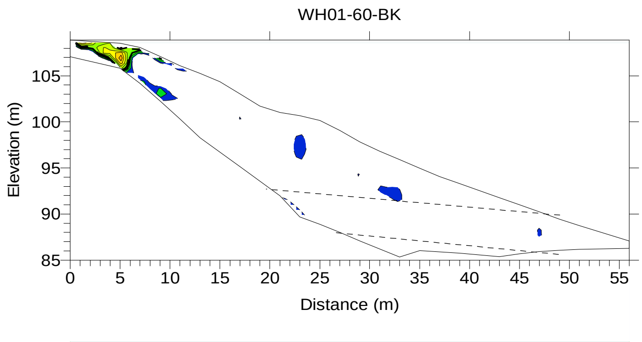


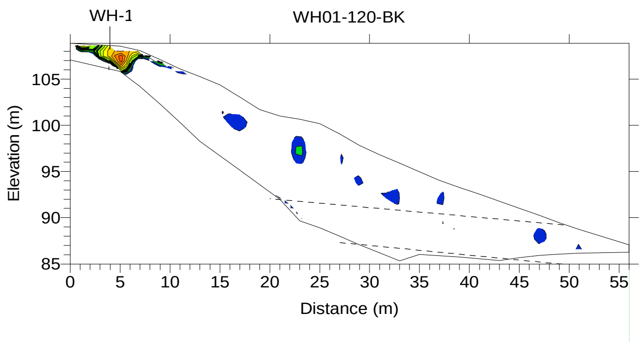
Figure 11 ERT background image along investigation Line WH-1S



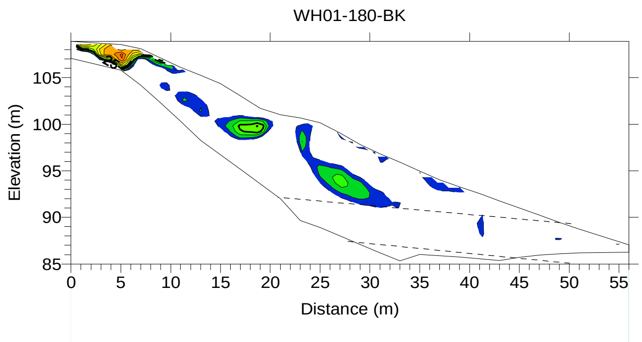
(a). ERT variation image after 30-min brine tracing



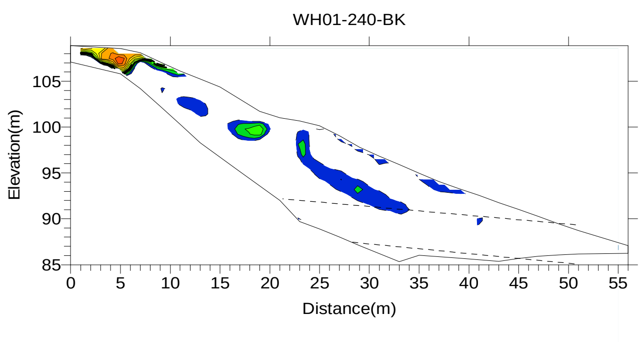
(b). ERT variation image after 60-min brine tracing



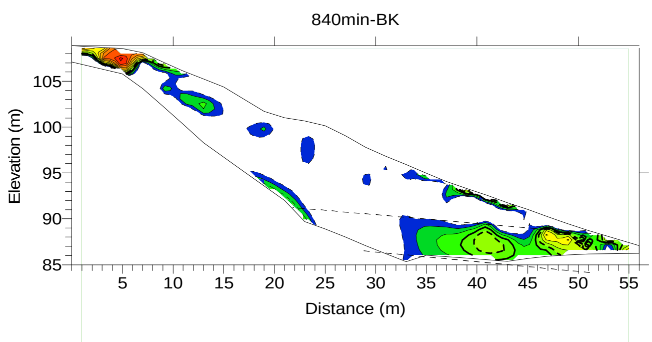
(c). ERT variation image after 120-min brine tracing



(d). ERT variation image after 180-min brine tracing



(e). ERT variation image after 240-min brine tracing



(f). ERT variation image after 840-min brine tracing

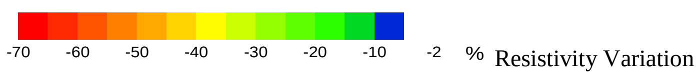


Figure 12 ERT-based seepage brine tracing image along investigation Line WH-1S (variation more than -5% only)

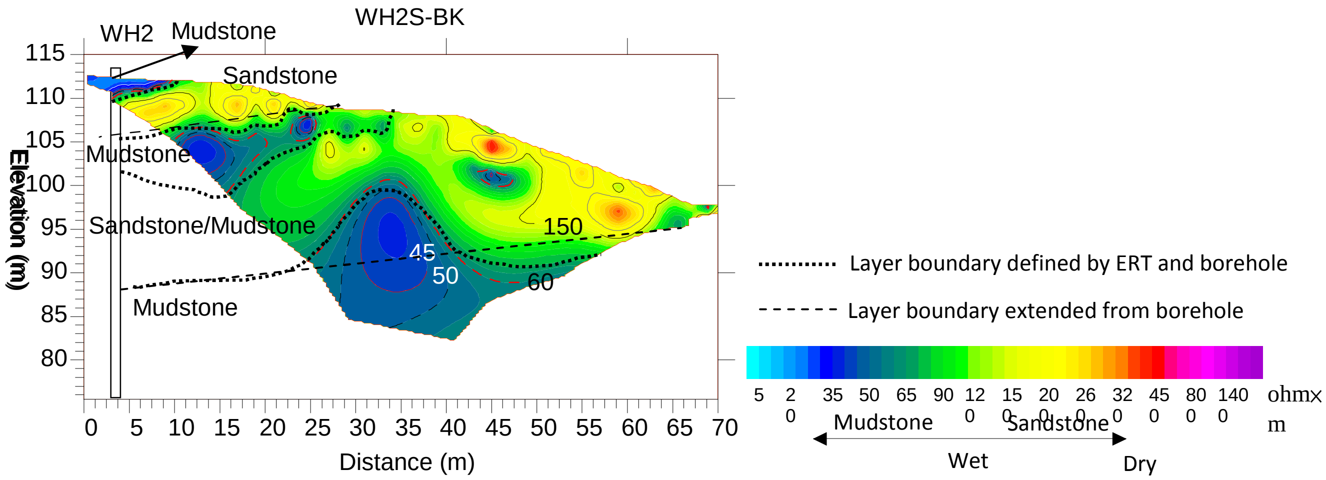
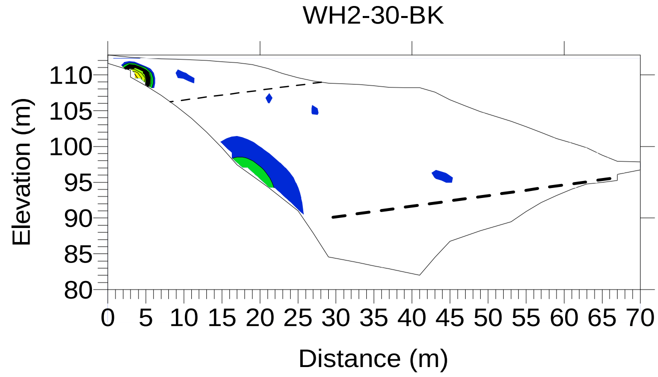
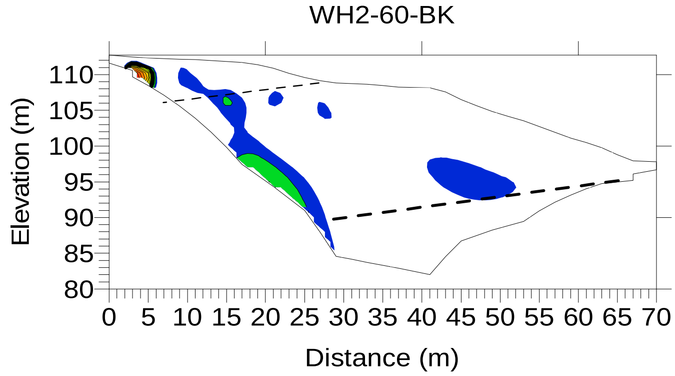


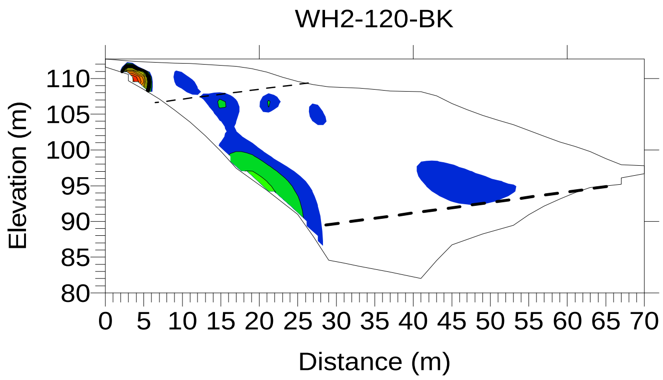
Figure 13 ERT background image along investigation Line WH-2S



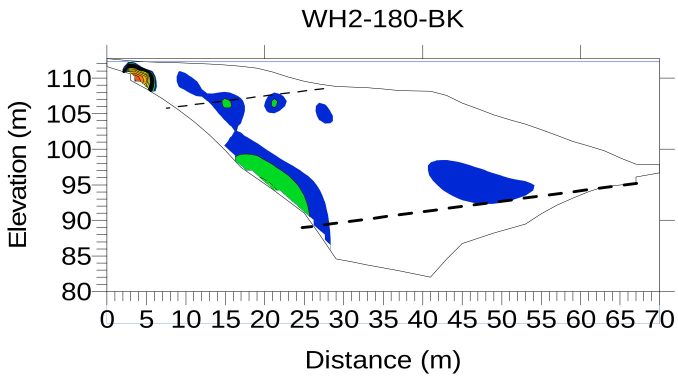
(a). ERT variation image after 30-min brine tracing



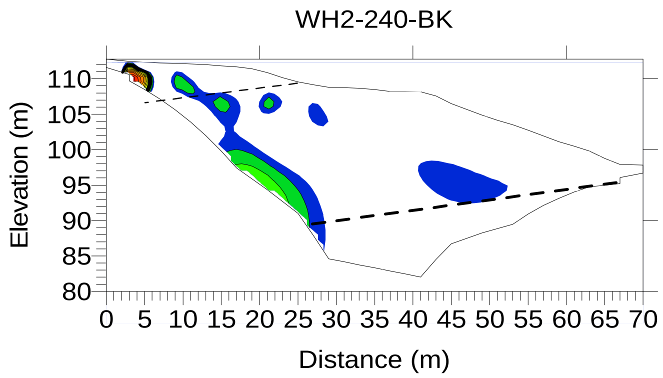
(b). ERT variation image after 60-min brine tracing



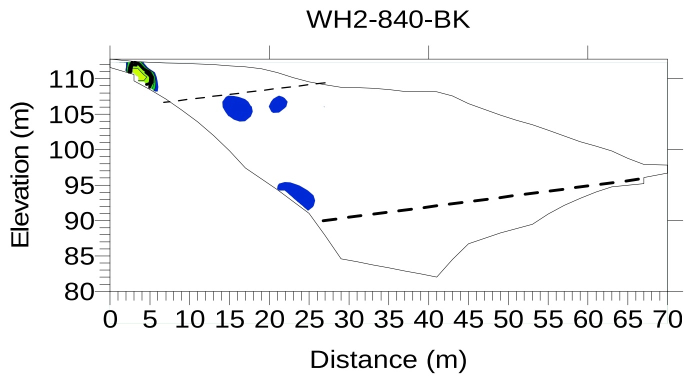
(c). ERT variation image after 120-min brine tracing



(d). ERT variation image after 180-min brine tracing



(e). ERT variation image after 240-min brine tracing



(f). ERT variation image after 840-min brine tracing

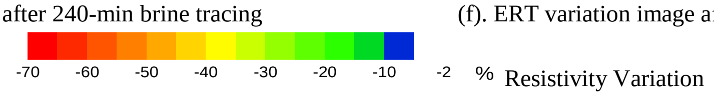


Figure 14 ERT-based seepage brine tracing image along investigation Line WH-2S (variation more than -5% only)

3.3 Brine tracing seepage in a dam levee widening mass

The accessary dam levee widening is designed for increasing the reservoir capacity described in section 3.2. Knowing the seepage conditions, including position and direction, can provide appropriate countermeasures for decreasing the seepage degree through the dam mass. In response to the engineering need, borehole exploration and ERT-based brine tracing technique are introduced to this seepage investigation at the dam levee widening slope.

The borehole position and two ERT survey lines are plotted in Figure 15. The borehole position is chosen at the downstream side slope adjacent to the dam levee top. A 56-m long survey Line WH-3H is set along the dam-top road and passes through borehole WH-3. Perpendicular to survey Line WH-3H, another ERT survey Line WH-3V is extended from borehole WH-3 downward along the dam slope surface. Using such an investigation pattern can not only identify the geological information from the borehole sample but also transfer the empty borehole into the brine injection pipe for ERT tracing.

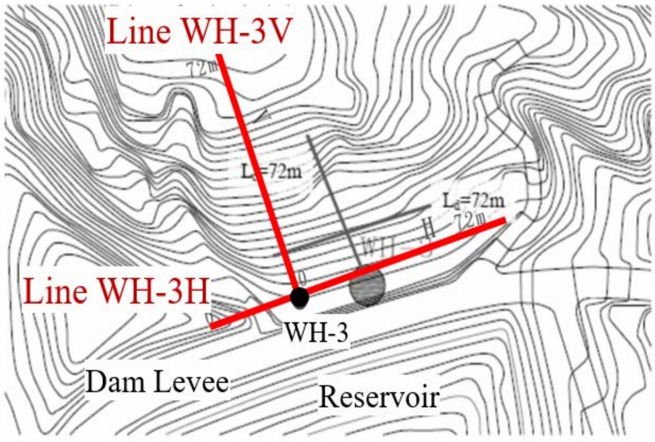


Figure 15 Borehole position and survey lines on a dam levee widening slope

The 30-m long geological column at borehole WH-3 is shown in Figure 16. The dam levee widening from the ground surface down to 30 m deep is composed of covering concrete, loose sandstone, loose sandstone/mudstone (interlayered), loose sandstone, mudstone, loose sandstone with mudstone, loose sandstone, loose sandstone with shale, mudstone and loose sandstone. The permeable and impermeable layers alternatively occur throughout the dam levee widening mass.

Figure 17 shows the on-site ERT-based brine tracing technique image at borehole WH-3. The brine water is continuously infused into the dam mass from the borehole pipe with water tanks. The ERT instrument records the resistivity images before brine infusion and traces the resistivity variation images for 400 minutes.

Figures 18 and 19 present the resistivity background and variation images, respectively, along Line WH-3H. The dotted and dashed lines represent the layer boundaries defined by both ERT and borehole sampling and borehole sampling only, respectively. The background image consists with the findings at borehole WH-3. Two loose sandstone layers correspond to the pink, red, orange, or yellow zones, scattering surface to depths of 2~3 m and depths of 6~13 m. In-between, the relatively low resistivity belt indicates the sandstone interlayered with mudstone. The resistivity variations for brine tracing measure the image difference between the background and brine infusing at specific moment (Figure 19). The resulting variations are still not significant after 300-min tracing. This indicates that the main seepage does not transmit along the horizontal direction, i.e., parallel to the dam levee top road.

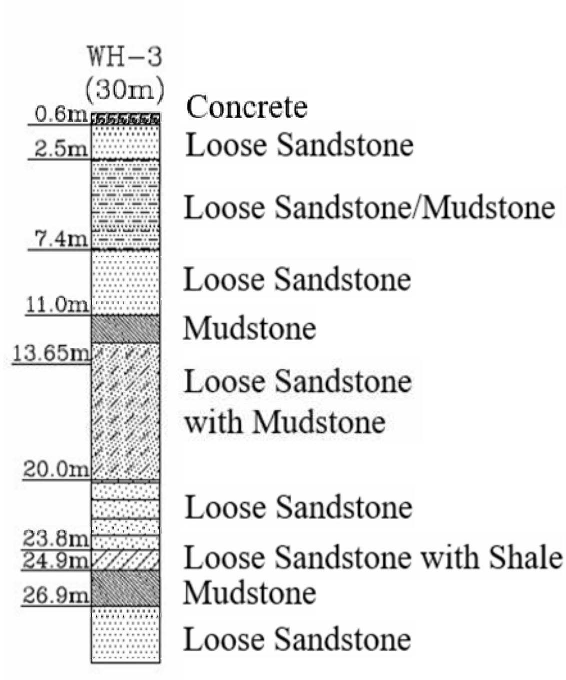


Figure 16 Geological column at borehole WH-3

Figure 17 ERT-based brine tracing conducted at borehole WH-3

Figures 20 and 21 also show the background and variation resistivity images, respectively, along survey Line WH-3V. The dotted and dashed lines represent the layer boundaries defined by both ERT and borehole sampling and borehole sampling only, respectively. The background image also consists with the findings at borehole WH-3. Similarly, two loose sandstone layers correspond to the pink, red, orange, or yellow zones, scattering surface to depths of 2~5 m and depths of 8~16 m, which overlays on mudstone. In-between, the relatively low resistivity belt indicates the sandstone interlayered with mudstone. The resistivity variations for brine tracing measure the image difference between the background and brine infusing at specific moment (Figure 21). In Figure 21, significant variation zones are identified on the pervious sandstone layer. The seepage moves downward to the slope toe in the SE-NW direction. The resistivity variations only exist within the pervious sandstone layer and no significant resistivity aberration is found in two mudstone layers as the infusion time increases. This indicates that the seepage or groundwater belongs to inter-stratum water flow and is almost sealed within two relatively impervious mudstone layers in this investigation coverage.

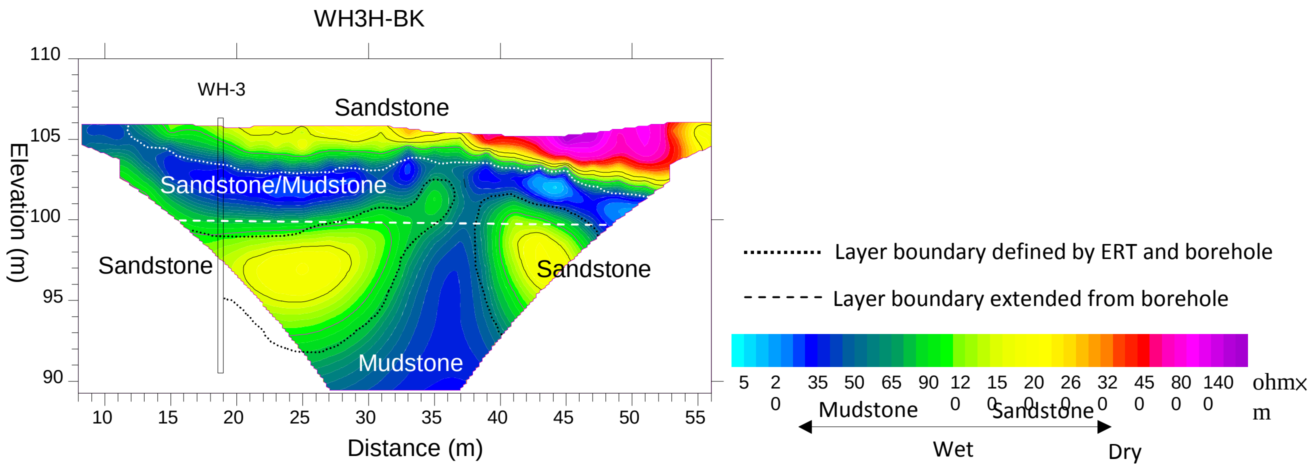
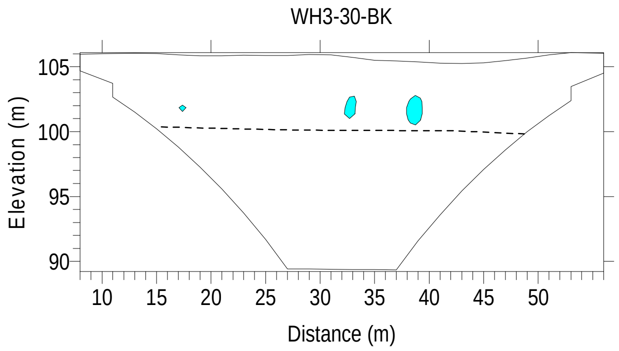
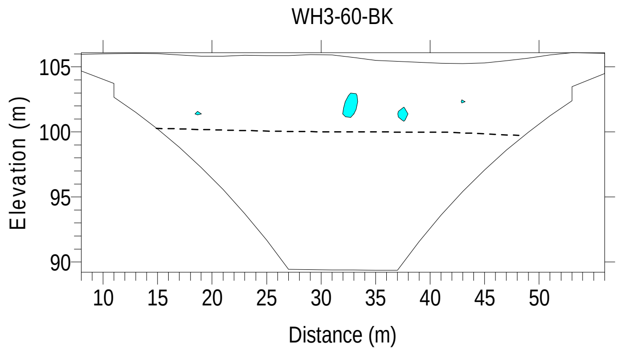


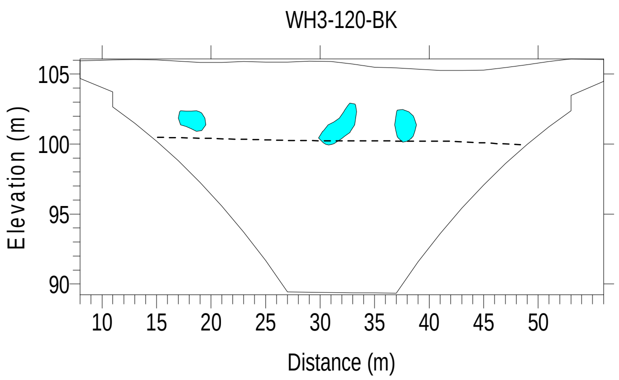
Figure 18 ERT background image along investigation Line WH-3H



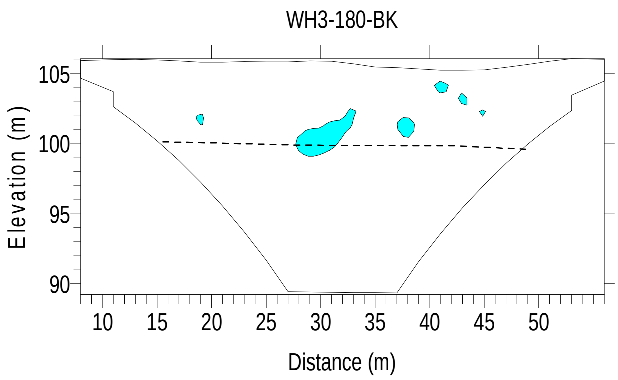
(a). ERT variation image after 30-min brine tracing



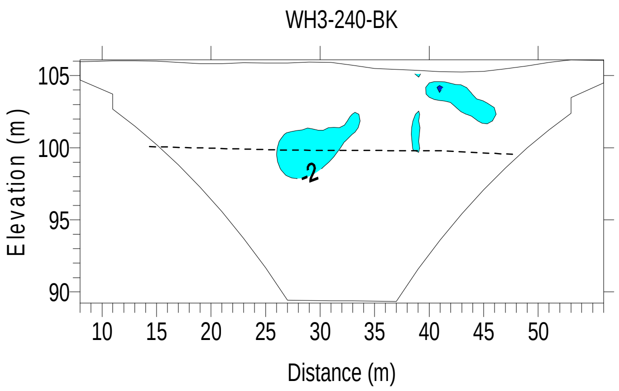
(b). ERT variation image after 60-min brine tracing



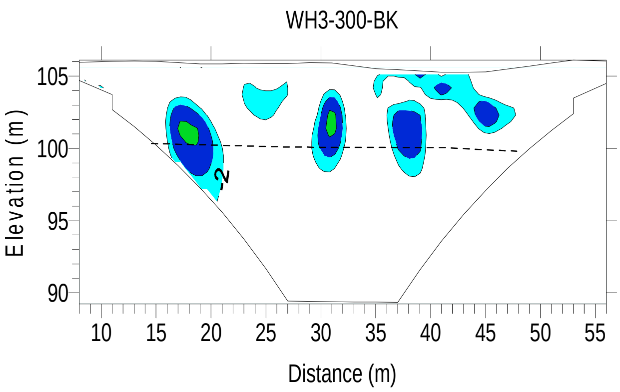
(c). ERT variation image after 120-min brine tracing



(d). ERT variation image after 180-min brine tracing



(e). ERT variation image after 240-min brine tracing



(f). ERT variation image after 300-min brine tracing

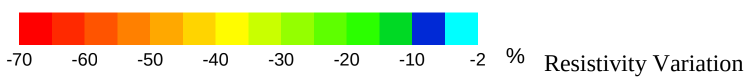


Figure 19 ERT-based seepage brine tracing image along investigation Line WH-3H (variation more than -2% only)

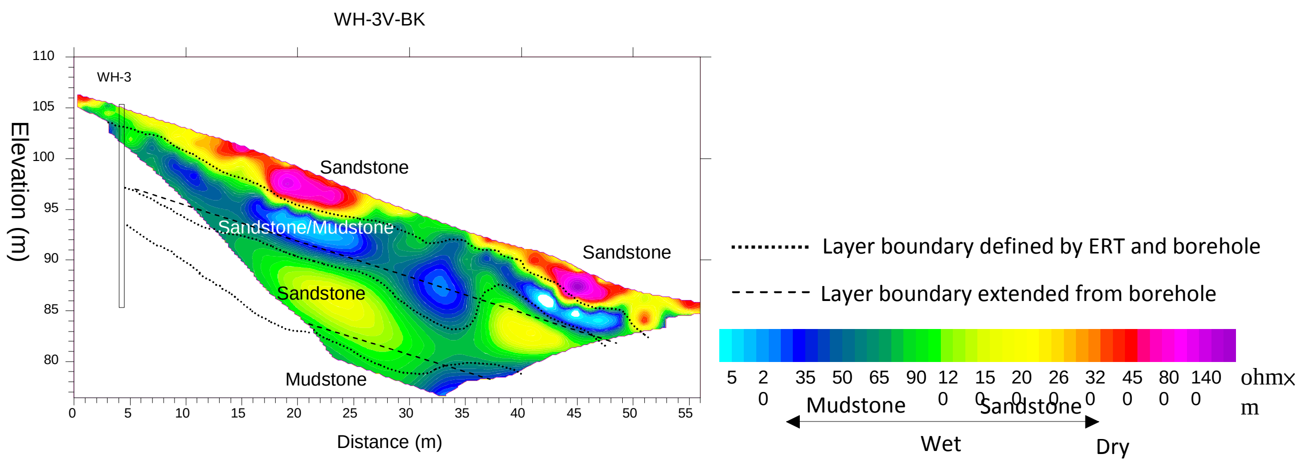
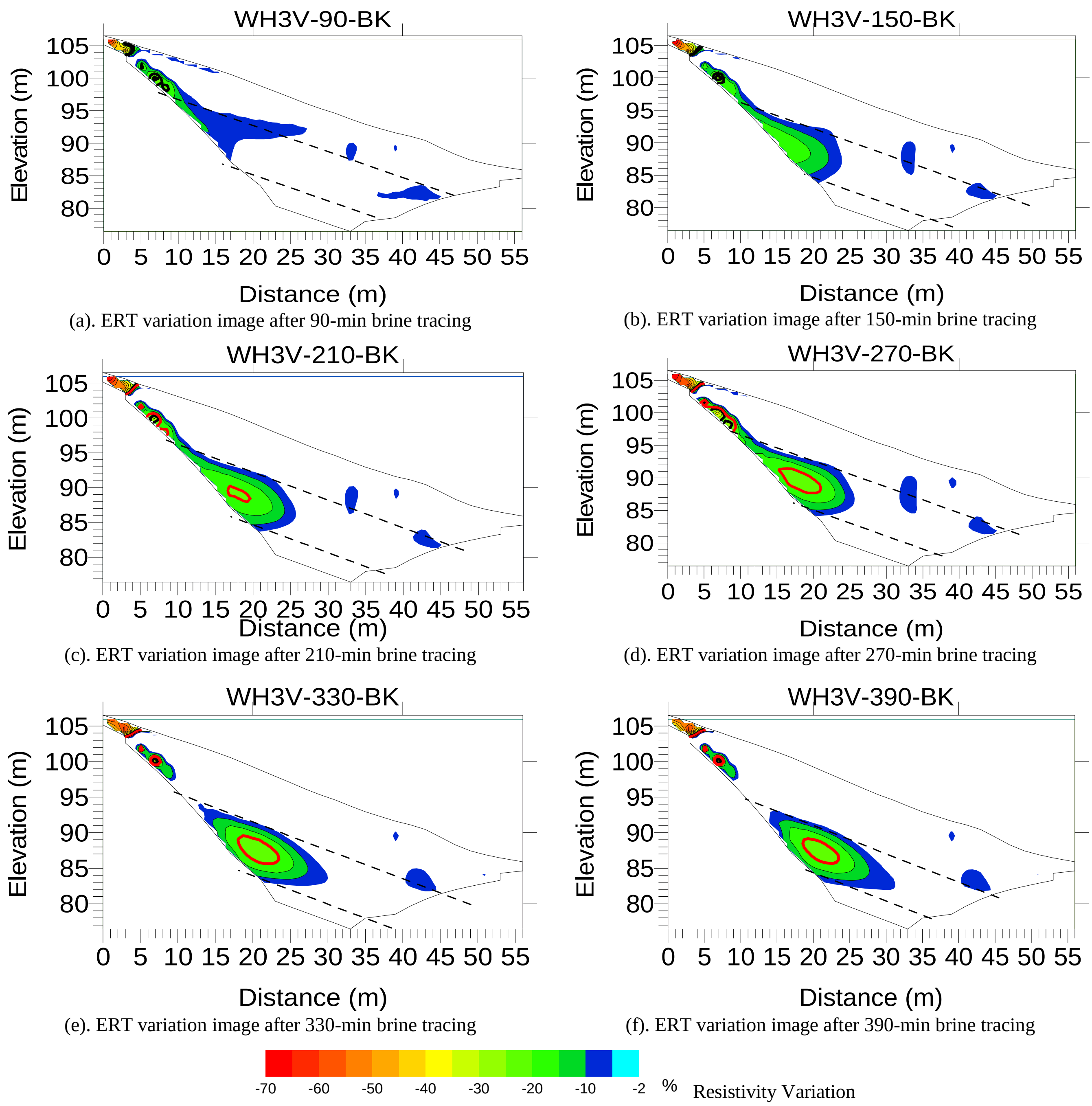


Figure 20 ERT background image along investigation Line WH-3V



(a). ERT variation image after 90-min brine tracing

(b). ERT variation image after 150-min brine tracing

(c). ERT variation image after 210-min brine tracing

(d). ERT variation image after 270-min brine tracing

(e). ERT variation image after 330-min brine tracing

(f). ERT variation image after 390-min brine tracing

Figure 21 ERT-based seepage brine tracing image along investigation Line WH-3V (variation more than -2% only)

4. CONCLUSIONS

The ERT-based leakage tracing technique is applied to investigate the potential seepage or groundwater flowing through earth dams in Taiwan. The conclusions are drawn as the followings:

1. Under the different reservoir levels, a high water-level storage in a dam provides a higher water head as a more intensive surcharge source. Significant variations on the resistivity space distribution are feasibly measured for tracing aberration leakage position on the dam mass.
2. The pervious silty sand is reasonably identified as the potential leakage section, which is located at the old river channel when constructing an earth dam. The previous river meandering causes deeper disturbance on the silty sand feature.
3. A downhole ERT-based brine tracing technique plays an active role to continuously detect the seepage flow path through the dam mass. Like a penetrant, the infused brine water will flow in the most possible leakage or groundwater path. Monitoring its ERT distribution variations can effectively identify the leakage spatial distribution and the major flow direction in an earth dam mass.
4. Using brine path tracing method, one can rapidly identify the accumulation zone of seepage in more permeable geological layers and its potential sliding surface on dam slopes in few hours. In future, dam engineers can use the ERT-based brine tracing technique to effectively sieve the possible leakage positions and take appropriate countermeasures preventing from further deterioration.

5. REFERENCES

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