NZGS SYMPOSIUM 2021
Good grounds for the future
24-26 March 2021 • Dunedin • New Zealand

Underground void detection by applying the electrical resistivity tomography (ERT) method for a limestone quarry in Northland, NZ

E.M. Sutter and N. Barounis
Cook Costello, Christchurch, New Zealand

ABSTRACT

Undetected cavities and large voids in rock can pose a significant problem to project progress or budgeting and are a potential health & safety concern. Often the problem arises from accidental detection during the project timeline which is less than ideal. Early detection of such features in areas where these have been reported can significantly decrease the risk to infrastructure, personnel, project timelines and budgets. Non-invasive geophysical techniques are excellent tools to detect cavities and voids on different scales and therefore help remediate negative effects caused by such features from the beginning of a project. Electrical resistivity tomography (ERT) is one geophysical method used for imaging underground cavities. The usefulness of this method is demonstrated with an example field study where this method has been used to detect extensive voiding under the working floor of a limestone quarry in New Zealand. An approximately 15,000 m^3 area was scanned to capture significant voids considered to be a threat to machinery and personnel. The findings were confirmed with the use of a total of 32 exploratory boreholes at a success rate of about 80 %. As a result of the non-invasive ERT measurements and the invasive bore testing, a hazard map of the quarry floor was produced. This study shows the effectiveness of combining geophysical methods with traditional geotechnical testing and aims to demonstrate best practice for design and construction in environments where voids and cavities pose a threat to infrastructure.

1 INTRODUCTION

Today's construction and engineering disciplines are increasingly confronted with hazards posed from undetected cavities in the ground because an increasing area of land will get developed to accommodate an increasing population, which may be in areas affected by past mining activities, in areas featuring karst (i.e. limestone), or areas that show underground erosion features related to seismic activity. Several construction hazards (e.g. health & safety, economic, feasibility) can result from these, often hidden, features. Although detection of voids and cavities may not be an inexpensive task, the risks these undetected features carry are often of far bigger concern. There are numerous, and some quite spectacular, cases of sinkhole openings caused by cavity roof or wall collapse reported from all over the world and in New Zealand. Where these features lead to subsidence or formation of a sinkhole in developed areas, this almost always leads to severe damage of infrastructure and, in some cases, fatalities. Detecting cavities and voids before they become a hazard, essentially means considerably reducing these risks.

For developments of any kind, the risk of subsidence or collapse from underground cavities and voids pose a safety concern. Furthermore, the related variation in subsurface bearing capacity has implications for foundation design (James, 2014). For a detailed discussion of hazards posed by undetected cavities and a review of the geophysical methods to detect these, the reader is referred to James (2014). This paper will discuss specifically the application of the electrical resistivity tomography (ERT) to detect large scale voids at the example of a limestone quarry in Northland, New Zealand.

2 DETECTING VOIDS AT WILSONVILLE LIMESTONE QUARRY – A CASE STUDY

2.1 Background Information

The Wilsonville Quarry is in Hikurangi just north of Whangarei. The quarry is operated since the early 20th century and supplies limestone aggregates to the cement works at Golden Bay's Portland works in Whangarei. At the time of the investigation in September 2018, the active mining area measured roughly 100,000 m^2. The deepest mining floor was at an elevation of 53 m RL. and covered an area of approximately 15,000 m^2.

The quarry uses blasting to mine the limestone and over time, drillings for deploying the explosives for this task had randomly encountered deep voids. These became more frequent with further progression to lower floor levels such as level 53 m. Increasing concern about health and safety of operating personnel and machinery has led to conducting the geophysical investigation presented in this paper.

2.1.1 Geology and Hydrology

Basement rocks around the Wilsonville Quarry are formed by the Triassic-Jurassic age Waipapa Group greywacke. Overlaying these, are Tertiary sediments consisting of sandstones, coal measures, limestone and mudstones as depicted in Figure 1. The sedimentary deposits have a dip angle of about six degrees to the west and are at a higher elevation to the south of the quarry as compared to the north end. A survey bore northwest of the quarry revealed a Whangarei Limestone thickness of approximately 110 m and was described as highly fractured and karstified crystalline limestone (Williams & Miller, 2000). The middle and upper Kamo Coal Measures are about 30 m thick. They make up the unit underneath the limestone. During the 1920's and into the early 1930's coal mines have been operated in the Kamo Coal Measures until the mines got flooded with groundwater. From geological cross-sections in Mills (2012) it was estimated that at the floor levels existing during the geophysical investigation, the coal seams were expected to be located about 15 – 20 m below the RL 53 m floor level and gradually deepening in the east-west direction of the quarry. The area around the Wilsonville quarry is subject to geological faulting. Williams & Miller (2000) identified four major fault structures, one of which appears to cross the quarry in southwest-northeast direction. The displacement is described to be in vertical direction (thrust faults). Where it is not mined, the limestone is overlain by older mudstones that have been emplaced laterally through thrusting or gravitational sliding.

Wilsonville Quarry becomes flooded within a few hours after heavy rain events when left undrained. This is a consequence of the floor level being more than 30 m below the groundwater level (at RL 90 m in 2012).

Mills (2012) implied that recharge following heavy rainfall events is much more severe in terms of floor flooding than regular groundwater inflow, which is well managed by continuous pumping at the RL 53 m level. There is strong evidence for hydraulic flow between the surface, limestone and coal mines. Williams & Miller (2000) concluded that the main water bearing conduits in the limestone are fault controlled and that the flooding of the coal mines that led to their closure in the 1930's, likely was due to newly formed hydraulic connections through sinkholes in the overlying limestone formation.

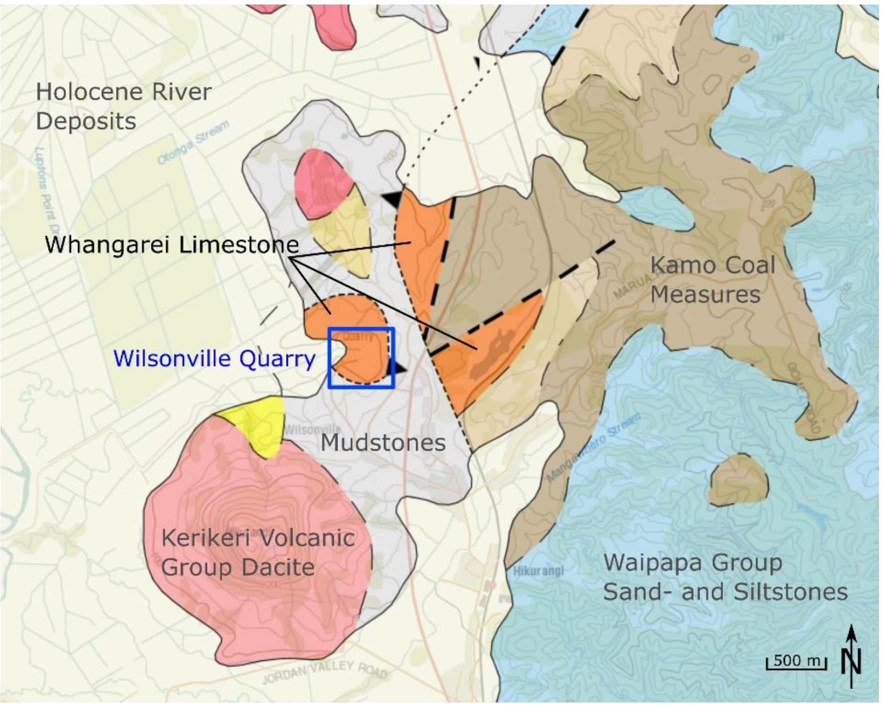

Figure 1: Geology in the vicinity of the Wilsonville Quarry (from http://data.gns.cri.nz/geology, accessed on 20.09.2018).

2.2 Geophysical Investigation at Wilsonville

2.2.1 Investigation Aims

Due to encountering several relatively deep cavities within the active mining area through explorational drilling, concerns were becoming apparent for the health and safety of mining personnel and machinery. The aim of the geophysical investigation was to determine:

- Whether there were any voids existing below the active quarry floor at RL 53 m.
- To what extent and where these features were located (i.e. mapping).
- Where possible, identify depth to coal seams.

For most underground investigation problems, there are usually several geophysical methods suitable to use. In the case of the Wilsonville quarry the Electrical Resistivity Tomography (ERT) method was most promising to successfully image and map voids and cavities at the scale of interest (i.e. > 2 m diameter, potentially > 3 m deep and at an unknown depth) and under the given surface conditions (e.g. standing surface water in several locations, undulating and rough surface). The method is briefly explained in the next section. For the given geology, it was considered that ERT methods could potentially delineate the cavity features better than any other geophysical methods available at the time of the project (i.e. magnetic and seismic).

2.2.2 Electrical Resistivity Tomography (ERT)

The ratio of measured potential gradient to injected current times the distance the current travels underground, is referred to as resistivity. It is an intrinsic ground property defining how easy a ground material can transport electrical current. Ground resistivity varies depending on several factors. For example, dense crystalline rock typically has a high resistivity, whereas a porous sediment would have a relatively lower resistivity and clay or organic material generally having a very low resistivity. Apart from porosity and compaction degree, resistivity also depends on pore fluid type and saturation, temperature, and clay content.

To measure the ground resistivity usually four steel rods are used together. Two of which serve as so-called current electrodes, where current gets injected through into the ground. The other two are the points between which the potential difference is measured (potential electrodes). The potential difference that is measured for one point in the ground is ultimately controlled by the resistance of the ground volume and the distance the current travels between electrodes (i.e. the resistivity). Figure 2 shows the principle of this.

Electrodes can be placed in different relation to each other (i.e. array types), which allows to investigate different targets in an optimal way. The further apart the electrodes are placed from each other, the deeper the current will travel and the more information from deeper parts of the ground is collected. In a modern 2D survey, typically several steel rods get placed in the ground on the surface and the instrument automatically cycles through a predefined sequence of electrode combinations always using four electrodes for one measurement. This allows scanning of a 2D section below the survey line in a reasonably short time.

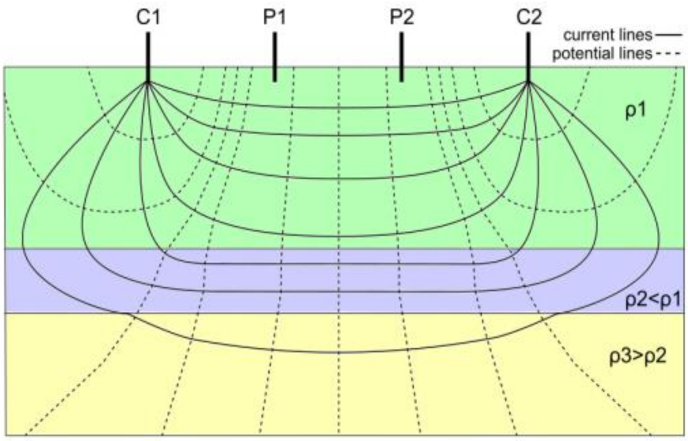

Figure 2: Principle of the Electrical Resistivity Tomography (ERT) method (from Sutter (2018)). Current gets injected through two steel rods (C1, C2) and the potential gradient is measured between two other steel rods (P1, P2). At geophysical boundaries, the current lines are bent and refracted. Hence different subsurface conditions excite different potential signals measured at the surface through potential electrodes.

Electrodes placed into hard crystalline rock can limit the ability of the equipment to transmit an electrical current and measure the electrical resistivity of the underground. This is due to the very high contact resistances between the host rock and the electrodes for such scenarios. The geophysical investigation at the quarry required pre-drilling the holes for the steel rods and used a bentonite-water mixture within these holes to lower the contact resistance to a point where current injection to the ground became possible.

In the office, the field data was edited for faulty points and then processed using geophysical inversion techniques. This essentially means that the field survey is simulated with a ground model until a sufficient fit is found between the field and modelled data (i.e. getting a small error between the data sets). The final model can be regarded as one possible representation of the subsurface resistivity distribution. There is, in theory, an infinite number of equally well matching models possible to obtain for a data set when using the inversion procedure. Therefore, the final geophysical inversion model should always be compared to known geology and borehole data, where available, to constrain the non-unique character of this technique. The Wilsonville Quarry investigation had a total of 32 exploratory boreholes of depths between 3 – 15 m bgl available to compare ERT data to. This comparison made the geological interpretation of the geophysical data set much more robust than the ERT data would have on its own.

2.2.3 Geophysical Data Acquisition

A total of 45 ERT profiles were acquired in five days and over two stages (June 2018 and September 2018) with a three-month break between stages due to inaccessibility of the RL 53 m level from heavy flooding during the first deployment. The profiles measured between 35 m and 115 m and reached depths of between 10 – 20 m bgl. Figure 3 gives an overview of the location and direction of the ERT profiles (blue lines) and the location of the exploratory boreholes (orange dots). The latest available aerial imagery base map was not (and still is not) representative of the mining status at the date of the geophysical survey. Therefore, the ERT profiles appear to be distorted on the surface, which is not the case.

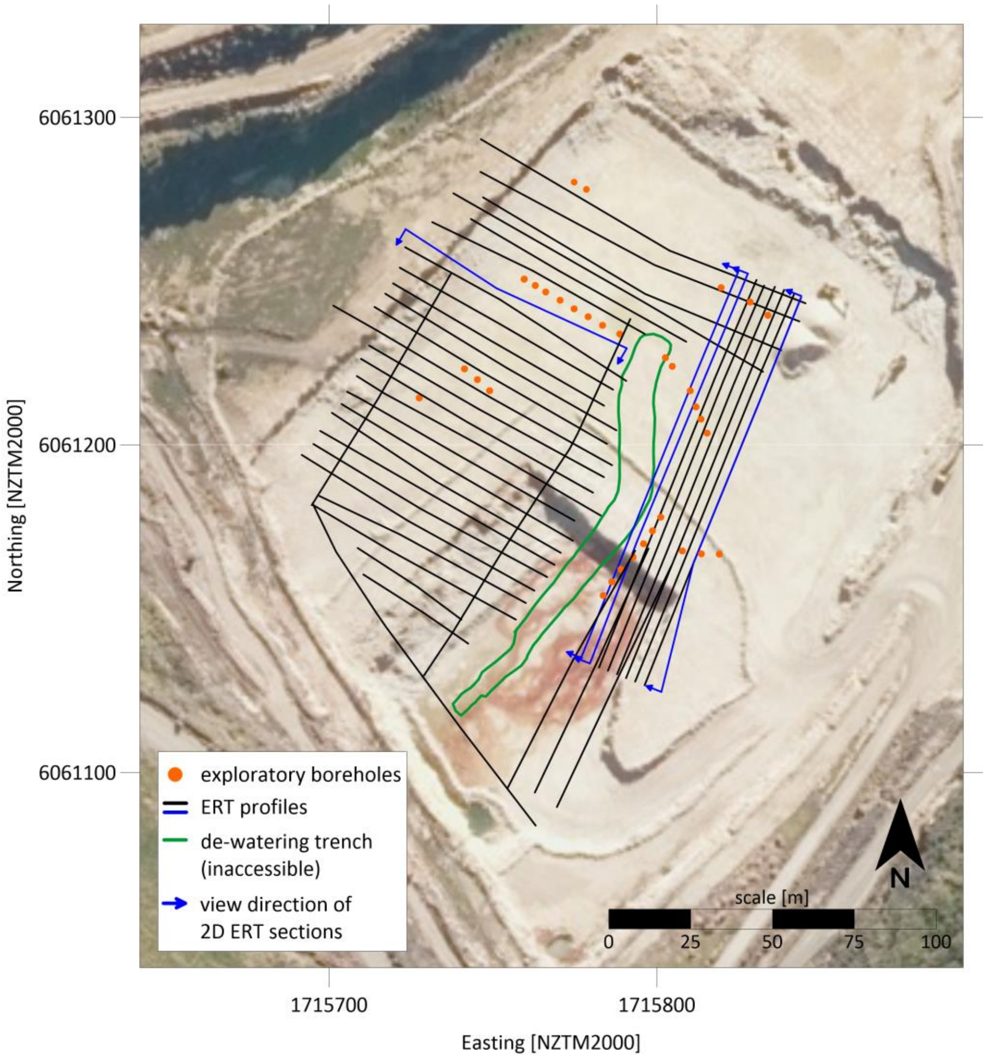

Figure 3: Survey map. Note that the latest background aerial imagery (LINZ Northland 0.4 m Rural Aerial Photos (2014-2016) was outdated and therefore not accurate of mining status at the date of the geophysical investigation.

All ERT profiles used a Dipole-Dipole type array to measure the resistivity distribution horizontally and with depth. The minimum spacing between electrodes was 5 m and therefore a vertical and horizontal resolution of only around 2.5 m could be achieved. A resistivity data error of 3 % was estimated from repeat and reciprocal measurements. GPS coordinates of electrode positions were taken with a variety of GPS equipment during the two stages of investigation. All of which had difficulties to obtain very accurate positioning (accuracy ranged between ~0.5-3 m) due to the > 30 m high quarry walls blocking satellite signals. The positioning of the boreholes based on the Stage 1 ERT data was determined using a handheld GPS device with an accuracy of ~5 m. Some of the mismatch between boreholes and ERT data can therefore potentially be attributed to the mismatch in GPS location between the two data sets.

2.2.4 Geophysical Data Discussion & Interpretation

A crystalline limestone of Tertiary age can be expected to have a resistivity of several hundreds to thousands of ohm meters (Ωm is the unit of resistivity). To detect voids, these features need to have a significantly different resistivity value compared to the host rock. With the groundwater table located above the 53 m RL and continuous pumping on that level, it could be expected that open spaces, such as voids and cracks, within the limestone would be filled with liquid or saturated debris, rather than air. This was important to determine the expected anomaly to look for in the geophysical data. Air-filled voids would have a much higher resistivity than limestone, whereas voids filled with liquids or saturated debris would have a relatively lower resistivity as compared to crystalline limestone.

Figure 4 shows three examples of ERT profiles acquired on the eastern side of the dewatering trench (marked blue in Figure 3 – Fig. 3: west to east = Fig. 4: top to bottom). The colours of the background images correspond to the resistivity models obtained along the profiles. Blue colours are indicating low resistivity values and yellow colours are relating to high resistivity values. Based on above expectations, the high resistive yellow areas were originally interpreted as limestone rock, whereas the blue low resistivity areas were interpreted as potential voids saturated with water or a mixture of water, clay and weathered rock.

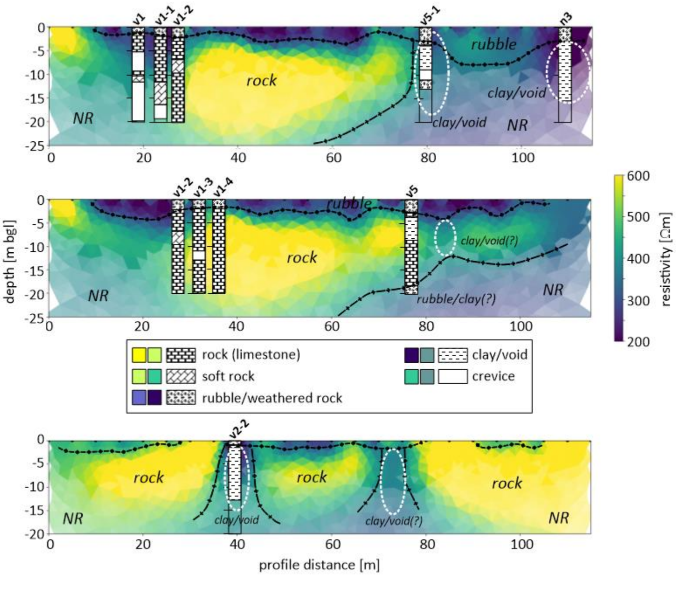

Figure 4: ERT models of three profiles on eastern side of trench (marked with blue lines in Figure 3). Borehole information and interpretations have been overlain on the ERT models. NR refers to "not resolved". The legend shows the borehole descriptions. The coloured squares relate to the resistivity colours generally related to that borehole unit.

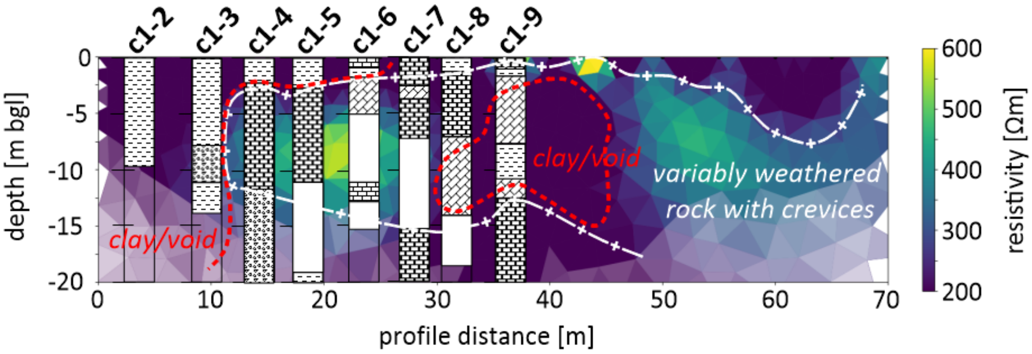

Figure 5: ERT inversion model (background) on western side of the trench (blue in Figure 3) with borehole information and interpretation overlain. Borehole classification legend is shown in Figure 4.

The exploratory boreholes were drilled after the ERT data were analysed and successfully targeted some of the indicated/interpreted voids (e.g. v1, v2-2, v5-1, n3). The ERT data interpretation originally only distinguished between "limestone rock" and "potential voids". With the drilling information this was later refined with the second stage ERT data completed. Areas of "rubble" where crystalline rock is broken up or weathered and may contain clay and/or water in the pore space were additionally identified, especially where low resistivity values were apparent close to the surface (i.e. surface weathering). Where the drillers encountered crevices in the hard or soft rock, this was assumed to be filled with the encountered saline mud as most areas on the ERT models that show larger crevices on the associated borehole logs, have a relatively lower resistivity than observed for other areas of rock. Saline mud present in crevices would lower the resistivity over the resolved ground volume and lead to this overall lowered resistivity.

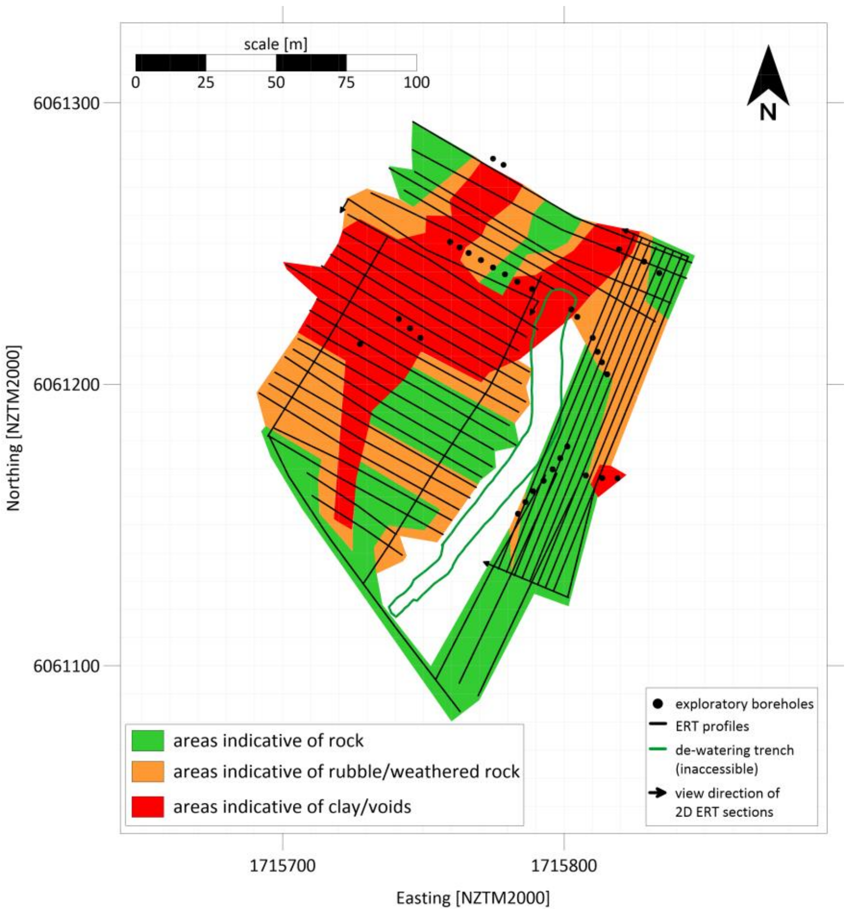

Figure 6: Area-wide hazard map for the 53 m RL at the quarry produced from the geophysical investigation.

However, as becomes apparent in Figure 5 (and partially also seen in Figure 4), the resolution of the ERT method at the used large electrode spacing was not able to identify such features (i.e. crevices) or thin layers (e.g. c1-4 to c1-9). This was a further factor (apart from likely GPS inaccuracies) for some discrepancy between boreholes and geophysical data and highlights an important consideration when using geophysical methods – the trade-off between resolution, possible area of coverage and associated survey cost.

2.2.5 Investigation Outcome

The goal of the geophysical investigation at the Wilsonville Quarry was to identify areas on the 53 m RL that were of concern to the health & safety of quarry personnel and machinery when working on that level (i.e. voids). Furthermore, the depth to the coal seams was also of interest. The latter was not encountered at the obtained depths of penetration with both, the ERT data and boreholes, and could therefore be assumed to be deeper than 20 m bgl. In order to provide the client with a tool to manage future mining at the 53 m RL, the geophysical models (informed by borehole data) were translated to a hazard map shown in Figure 6. Red areas are marking ground conditions of high concern (i.e. voids, eroded rock filled with saline mud, deeper than 10 m), orange areas were identified as areas where the rock conditions were starting to become a concern (i.e. rubble and weathered rock with clay in their matrix, potentially saturated, soft rock), and green areas marking portions of the ground where limestone rock was identified (low concern areas). This helped enabling the mining engineers to determine a safe plan for future blasting and mining the remaining limestone rock below that quarry level.

3 CONCLUSIONS

Using the geophysical data led to a good overview of the state of the limestone rock at the 53 m RL. The boreholes found to roughly match 80 % of what was predicted by the ERT data, which is a good match. It is important to use appropriate GPS gear with acceptable accuracy during the geophysical investigation and later to locate the identified anomalies and targets.

Considering the cost and effort of drilling boreholes, geophysical methods are valuable tools that can provide a cost-effective and broad overview of geological and hydrological variations in the underground. If they are combined with invasive testing, the geological interpretation of the geophysical models becomes more robust. If two or more different geophysical methods can be used at the same site, resolution and ambiguity issues of the geophysical methods can be further overcome.

ACKNOWLEDGEMENTS

The authors thank Golden Bay Cement for their permission to use the geophysical and borehole data of the case study.

REFERENCES

James, P. (2014). Feasibility assessment and informed survey design of cavity detection by forward geophysical modelling. Engineering Doctorate, University College London. 368p.

Mills, K. (2012). Site Visit Report and Assessment of Hazards at Wilsonville Quarry from Abandoned Coal Mines. SCT Report No WQNZ3755, 33p.

Sutter, E. (2018). Coastal Groundwater Dynamics – Investigation of Using Geoelectrical and Hydrochemical Tools for Saline Intrusion Monitoring. PhD Thesis, Victoria University of Wellington, 258 p.

Williams, P. W. and Miller, K. R. (2000). Hydrogeology of Wilsonville Quarry. Report prepared for Golden Bay Cement, June 2000.