
Practical guidelines for void surveying in New Zealand following the Canterbury earthquake sequence

R.A. Mellis & M. Finnemore

Southern Geophysical Limited, Christchurch, New Zealand.

ABSTRACT

The 2010 and 2011 Canterbury earthquake sequence caused widespread damage to housing and infrastructure, prompting the use of a wide variety of invasive and non-invasive damage assessment methods. Among these non-invasive methods, Ground Penetrating Radar (GPR) surveying was frequently utilised, particularly to detect voids at the slab-fill interface beneath concrete floor slabs. However, post surveying evaluations revealed that GPR surveys were often conducted or interpreted incorrectly, resulting in poor correlation between GPR data and subsequent invasive assessments.

This paper gives a brief overview of the practical capabilities and limitations of GPR for void detection beneath concrete slabs, drawing on experience from more than 200 void surveys undertaken by Southern Geophysical following the Canterbury earthquake sequence, and in house lab testing. Through case studies and data analysis, we clarify common sources of error, address widespread misconceptions, and propose practical guidelines for reliable GPR void surveying of concrete floor slabs in New Zealand.

1 INTRODUCTION

The damage to housing and infrastructure following the 2010 Canterbury earthquake sequence was significant and widespread (Kaiser et al., 2012; Potter et al., 2015), prompting those involved in damage assessment to adopt quick and cost-effective methods of assessing damage. This paper focusses on the use of Ground Penetrating Radar (GPR), often referred to as “concrete scanning”, to detect voids at the slab-fill interface beneath a concrete floor slab (Cassidy et al., 2011; Razak et al., 2015). GPR was widely adopted, primarily due to the speed of data capture and non-invasive nature of the method (Jol 2009). When utilised correctly, GPR is a quick and cost-effective method for surveying large areas, providing reliable results. When used incorrectly, results from a GPR survey can easily be misinterpreted, leading to inaccurate damage assessment results.

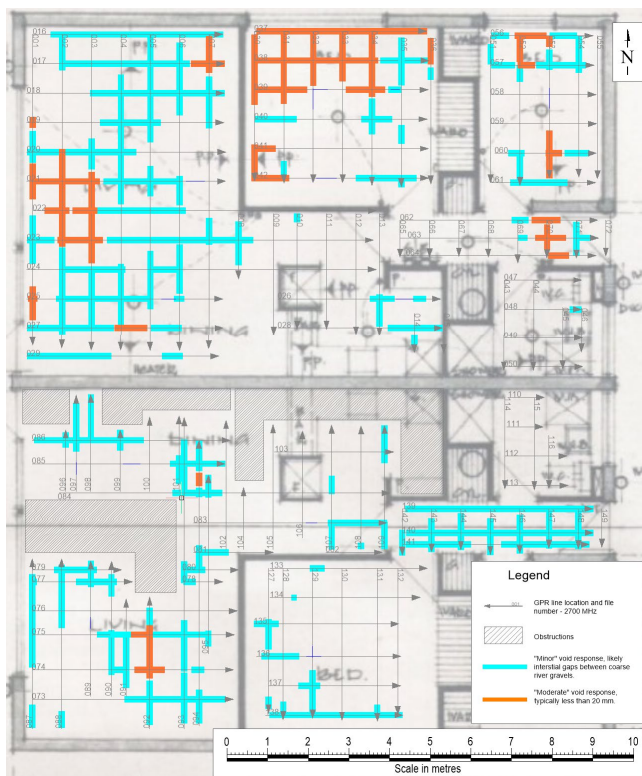


Figure 1: Site map showing the location and severity of voiding.

2 THE VOID RESPONSE

It is important to clearly define what a “void response” is, how it appears in the GPR survey results and how it differs from other responses. In very basic terms, a radar wave transmitted by a GPR system travels through a medium, in this case the concrete floor slab, and is reflected by changes in dielectric permittivity (K). Materials with a higher permittivity will reflect a positive polarity wave, such as water. Materials with a lower permittivity will reflect a negative polarity wave, such as air. As a void response at the slab-fill interface is a transition from concrete, with a permittivity of approximately 7, to air, with a permittivity of 1, a negative polarity response will be observed. This response is often referred to as a phase reversal anomaly (Nobes 2017 and 2018).

3 THE VARIABLES

3.1 The GPR system

Most GPR systems are designed around a nominal signal frequency, with some GPR systems utilising multiple antenna or stepped frequencies for imaging at different depths and resolutions. Concrete scanning GPR systems are typically between 500 MHz and 3000 MHz, with frequencies greater than 1500 MHz considered “high frequency”. An appropriate GPR system and associated frequency must be selected for each survey.

Most GPR systems apply manual or automatic gains to the on-screen data which, when assessed live on site, can alter the apparent void response, leading to misinterpretation. Therefore, the raw data without additional gains needs to be exportable from a GPR system so it can undergo a standardised processing flow.

There are several variables that need to be accounted for when surveying a concrete floor slab with GPR. The main variables include 1) the GPR system used, its frequency and its output format, 2) slab construction, including thickness, materials used and in-slab steel reinforcement distribution, and 3) materials below the slab, including type of fill/grade (henceforth referred to as fill) and underfloor insulation. We will discuss each of these variables and what their impact is on the GPR survey results. While this paper focusses on the use of GPR with respect to scanning concrete floor slabs, many of the guidelines could be adapted to other applications of GPR.

With the variables described and their impact on the survey results established, we will propose a set of practical guidelines to follow when undertaking GPR void surveys on concrete floor slabs. The end goal being the production of a site map, showing the location and severity of voiding which, in our experience, is by far the most useful singular output for engineers, assessors and homeowners (Figure 1).

3.2 Slab construction

Concrete floor slabs come in a range of thicknesses; however, residential floor slabs are generally between 90 mm and 120 mm thick, and commercial floor slabs between 120 mm and 250 mm thick. The top of voids at the slab-fill interface are therefore most often 90 mm to 250 mm deep.

Concrete floor slabs are constructed using a range of materials, some of which will strongly influence the survey results. Typical material changes include concrete type/quality, steel reinforcement quantity and distribution, integrated heating pipes and, less frequently present but crucial to a survey's viability, steel fibre reinforcement.

3.3 Materials below the slab

Building practices have changed throughout the years, including the type of engineered fill and the addition of underfloor insulation. The type of fill present below the floor slab will impact the response at the slab-fill interface.

Expanded Polystyrene (EPS) is the most common type of underfloor insulation used below a concrete floor slab. EPS is composed of approximately 2% polystyrene and 98% air (reference). As EPS is 98% air, it appears in radargrams as a significant void response.

4 GUIDELINES FOR SURVEYING

To ensure the aforementioned variables are suitably accounted for, we propose the following guidelines when undertaking a GPR void survey on a concrete floor slab. These guidelines have been broken up into three stages to assist in developing an appropriate survey plan, using the correct GPR system, while also identifying circumstances where GPR is not the appropriate tool for the task early in the evaluation.

4.1 Prior to the survey

Key questions that should be asked and accounted for prior to surveying, if possible, are as follows:

Is polystyrene insulation present below the concrete floor slab? If so, we do not recommend undertaking a GPR survey in areas where underfloor insulation is present, as a continuous void response will be visible in the data in all insulated areas. It may be prudent to GPR survey only the areas where no underfloor insulation is present and undertake invasive investigations, such as drillhole inspection, throughout the remainder of the slab.

Are there coverings affixed to the top of the floor slab? Some floor coverings or underlays are backed or lined by a metal foil layer. These foils reflect 100 % of the radar waves and therefore need to be removed prior to GPR surveying. GPR surveying can typically be conducted without issue if tiles, carpet and/or underlay are fixed atop the concrete floor slab and no metal foil is present.

How thick is the concrete floor slab being surveyed? This will dictate the frequency of GPR system used in the survey. Higher frequencies should be used to survey thinner concrete slabs and lower frequencies used to survey thicker concrete slabs. As a general guideline, 1.5 GHz to 3 GHz GPR systems are typically well suited to scanning 100 mm to 400 mm thick concrete floor slabs, which accounts for most residential and commercial floor slabs. The smaller wavelength of the higher frequency systems allows for higher resolution imaging between 40 mm and 400 mm depth, where the slab-fill interface and subsequent voiding is likely to be located. When scanning concrete slabs thicker than 400 mm, transitioning into lower frequency systems becomes necessary, the larger wavelength of the lower frequency systems will propagate deeper, allowing for a stronger signal to reflect off any voids.

What is the anticipated steel reinforcement size and distribution within the concrete floor slab? As steel reinforcement reflects 100 % of the radar waves incident on the steel, very tightly spaced steel reinforcement

or multiple offset layers of steel reinforcement can complicate surveying or make GPR surveying a non-viable method for identifying voids. The physical size of the GPR antenna can be the limiting factor when surveying concrete floor slabs with tightly spaced steel reinforcement. If an antenna is narrower than the bar spacing, most of the transmitted radar waves will penetrate below the steel reinforcing bars when the GPR is positioned between the bars. Consequently, if the antenna is wider than the bar spacing, a significant portion of the transmitted radar energy will be reflected regardless of the position of the GPR system. The antenna size is typically associated with the signal frequency, such that high frequency GPR systems typically have a narrower antenna and low frequency GPR systems have wider antenna; however, as there are many different antenna configurations which affect their size; therefore, we recommend identifying and accounting for the antenna width of each GPR system as needed. In practice, the size of the GPR system as a whole can be used as a general guideline as they are often manufactured to be as small as practicality allows given a particular antenna width.

4.2 Interpreting the data

Identifying voids within radargrams is typically done with visual analysis, assessing how “strong” the void response appears in the data. Comparing the void response to known, ground-truthed results serves as a helpful quality check. We recommend one additional step to ensure repeatability between surveys and technicians; compare the amplitude of the void response with “first arrival”, which will differ from one GPR system to the next. The “first arrival” is the radio wave travelling directly from the transmitter to the receiver antenna (Comite et al., 2016). This is done as follows:

Measure the amplitude of the first positive peak at first arrival, measure the amplitude of the first negative peak at the void, then express this as a percentage, i.e. the amplitude of the void response is 78% of first arrival. This analysis must be done using the raw GPR radargrams or radargrams with only a uniform gain applied. Non-uniform gains such as energy decay or the custom, often automatically generated, gain curves applied by the GPR system must be removed as they will alter this result.

In an ideal world and if all GPR systems, concrete floor slabs and sub-slab conditions were identical, it would be possible to consistently correlate void response amplitudes with an accurate void thickness repeatedly across all surveys. However, due to the number of variables impacting the amplitude of a void response, this is not possible. Instead, we recommend defining void responses using broader categories, such as “minor”, “moderate” or “significant” with estimated void thickness ranges associated with each, such as “typically 0 mm to 5 mm”, “typically 5 mm to 20 mm” and “typically 20 mm and greater” respectively.

When interpreting the data, five common variables should be considered and accounted for as they have the greatest impact on the amplitude of a void response:

1. Slab thickness. For a set gain, voids will be higher amplitude the closer they are to the surface, such that that void response will appear weaker below thicker floor slabs and vice versa.
2. Spacing and distribution of steel reinforcement within the concrete floor slab. Voids present below the steel will have a lower amplitude response due to the reduced radar pulse energy reaching and reflecting off the top of the void.
3. What fill type is present below the floor slab? This typically won't alter the approach to the GPR survey, it will however affect the results and subsequent interpretations. Engineered fill, such as AP40, in direct contact with the slab will result in a range of responses, from a very weak negative polarity response to a moderate positive polarity response, depending on moisture content and compaction. On the other hand, coarse river gravels used extensively prior to the Canterbury Earthquake Sequence, typically appear as a weak negative polarity response indicative of possible minor voiding due to the interstitial air gaps between gravel clasts.

4. Frequency of the GPR system. As the wavelength of a radar signal increases, the effect of a small void on the propagation of low frequency radio waves lessens, allowing the radio waves to 'skip' over smaller voids while high frequency radar is more strongly reflected (Annan 2003). The effect is that smaller voids will be less visible when using lower frequency systems, this needs to be accounted for.
5. Ceramic or other floor tiles bonded to the concrete floor slab. If the bonding agent, typically grout, does not entirely fill the area between the floor slab and attached tile, small voids will be present between the concrete floor slab and attached tiles. These voids will reflect some of the radar waves, reducing the amount of radar pulse energy reaching and reflecting off deeper voids below the concrete floor slab, thereby reducing the amplitude of the void response.

4.3 Ground truthing the results

While most variables in a GPR void survey should be accounted for by skilled GPR technicians, it is not possible to account for them all completely. The greater the number of variables, the higher the margin of error is likely to become. Therefore, we always recommend GPR void surveys are correlated with invasive investigations for the purpose of ground-truthing the results. Inspecting drill holes with a borescope camera is a reliable means of ground-truthing; however, drill hole inspection is often done incorrectly, therefore, we recommend the following approach:

1. Begin percussion drilling an appropriately sized hole for a borescope camera (18 mm diameter is sufficient for our borescope cameras), finish the hole with a dry core drill (or dry core drill the entire length of the hole). Be careful when drilling the base of the hole not to force the drill bit through too deep to minimise disruption to the fill. Try not to pierce the Damp Proof Membrane (DPM), if possible. Percussion drilling alone is not suitable for two reasons, 1) it will cause blow out on the underside of the slab, blocking the view of the camera, and 2) it will cause settlement of the fill at the immediate location of the hole, giving a potential false positive.
2. Heat a metal rod and insert down the hole to melt a clean hole through the DPM, or to melt the frayed edges of the DPM if pierced by the drill. This will improve camera visibility away from the hole.
3. Clean the hole with a vacuum and/or brushes to ensure camera visibility is good. Do not disturb the fill.
4. Take a video looking down the hole from above, show hole number/label in video.
5. Insert a side facing borescope camera down the hole. Record 360-degree video footage of all aspects of the sub-slab condition, paying special attention to angles that allow views away from the hole. Record the area between slab and DPM, DPM and fill, and any identified voids. We are most interested in identifying voids away from the immediate vicinity of the drill hole to avoid any disturbance drilling might have caused.
6. Measuring void thickness at the hole using a ruler or callipers introduces error as you may inadvertently position the ruler between large gravel clasts, or in a small depression caused by drilling. Instead, measure the void thickness using the borescope camera. Align the center of the camera with the base of the slab and take a measurement, move the borescope camera down until the center of the camera aligns with the top of the fill away from the immediate vicinity of the hole and take a second measurement. This will be the thickness of the void.

5 CONCLUSIONS

GPR can be a powerful, reliable and cost-effective tool when undertaking void identification surveys, if done correctly. The method relies on skilled interpretation of data while accounting for multiple variables; it is therefore crucial that the GPR operator has sufficient experience with GPR survey equipment and

understands the equipment and method limitations. It is also important to communicate to the client, typically a structural engineer, what the void survey will involve and discuss line spacing and the area to be surveyed before the survey commences.

Our proposed guidelines for void identification below concrete floor slabs can be summarised as follows:

Ask the right questions prior to undertaking a survey to ensure that GPR is an appropriate tool for the job. How large is the survey area? Is polystyrene underfloor insulation present? How much steel is in the slab? Is underfloor heating present? What coverings are currently fixed to the top of the slab?

Select the most appropriate GPR system for the thickness of the slab. Most residential and commercial concrete floor slabs can be surveyed with a high frequency GPR system, ranging from 1500 MHz to 3000 MHz. The footprint of the GPR matters, it typically mirrors the width of the transmitting antenna. If possible, use a GPR system with an antenna narrower than the steel reinforcing bar/mesh spacing.

When interpreting the results, ensure that only uniform gain is applied, or use the raw data. Non-uniform gains will alter the results. Compare the amplitude of the void response with the amplitude of first arrival, it is the most reliable way to provide consistent results across all surveys, after accounting for the variables. Also compare the results with previous, ground truthed surveys to ensure consistency through time.

If voiding is identified, ground-truth the results with invasive investigations in key locations. Dry core drilling a hole through the slab and inspecting the sub-slab condition using a side facing borescope camera is a reliable way of ground truthing, avoiding false results typical of measuring voids directly at the hole location.

Finally, present the results in a clear and concise way. Ideally, produce a map showing the location and severity of voiding, including the survey line locations. The supplementary report should provide enough detail that the survey could be duplicated by a third party with the same result. Annotated example radargrams should be provided, showing the range of void responses and their interpretation. All radargrams from the survey should be provided to ensure full transparency and to allow for third party review.

6 CASE STUDIES & LABORATORY TESTING

To develop our recommended guidelines, we drew from extensive real world survey experience and in-house laboratory testing. This section outlines specific examples that demonstrate the capabilities of GPR when applied to concrete floor slab void surveys.

Three radargrams from three different surveys are presented as case studies to illustrate what the void response looks like in real world conditions and how it differs with changes in construction methods and materials (Figure 2). The void responses were ground truthed using borescope camera inspection of drill holes.

The amplitudes along each void (how bright they appear) do not directly correlate with the thickness of the void, unless the quantity and distribution of steel reinforcement and concrete slab thickness is taken into consideration. Such that, thinner parts of the void in Case Study 1 show a higher amplitude response than thicker parts of the void in case study two. The thicker slab in Case Study 2 used a more aggregate-rich concrete, which was identified when drilling and is visible as small internal reflections in the radargram. This and the additional slab thickness reduces the amount of radar energy reflecting off the top of the void. In contrast, the unreinforced slab in Case Study 3 shows the response from a 25 mm thick EPS insulation layer, which is less than 1/3 the thickness of the void in Case Study 2 yet results in a higher amplitude response due to the thinner concrete slab and lack of steel reinforcement above the EPS.

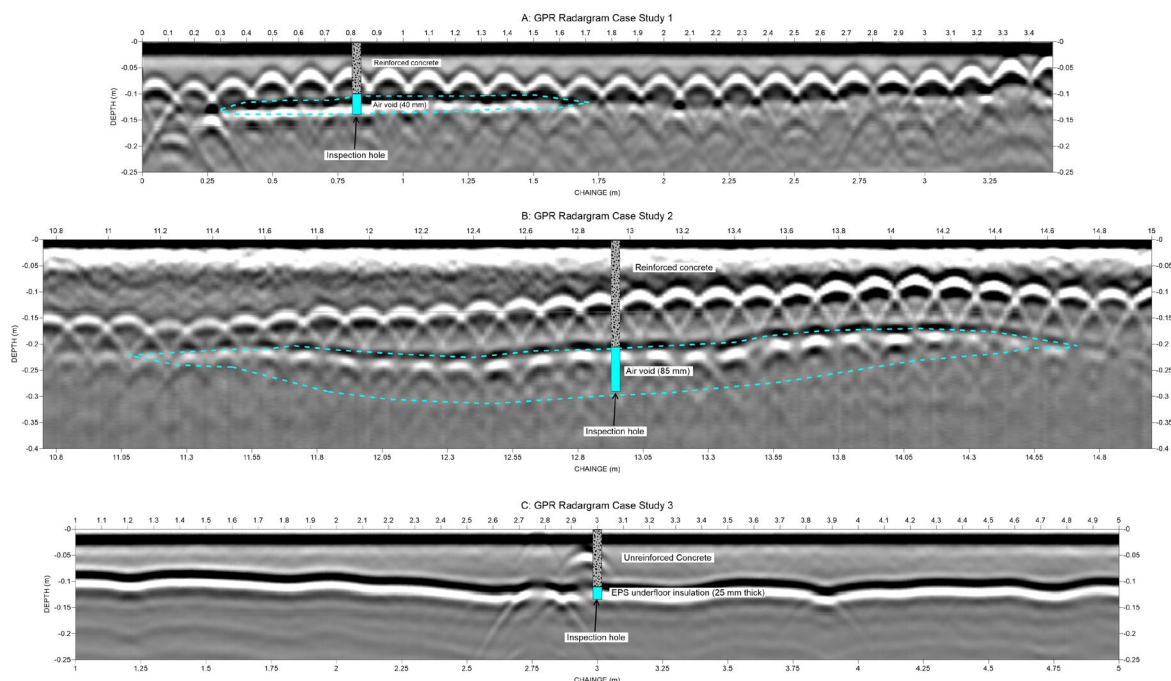


Figure 2: Case studies where a void response was encountered in three different scenarios. Reinforced residential concrete floor slab with 40 mm thick localised voiding (top). Reinforced commercial concrete floor slab with 80 mm thick tapering void (middle). Unreinforced residential concrete floor slab with EPS underfloor insulation present at the slab-fill interface.

An experiment was undertaken to demonstrate what a clear void response looks like in a GPR radargram, when emulating the construction of a standard residential floor (Figure 3). Additionally, we wanted to identify the limitations of correlating the void response with the actual thickness of voiding. This test consisted of using an EPS wedge to simulate a tapering void between a concrete slab and engineered fill. EPS is a viable material for this test as it consists of 98 % air. The thickness of the EPS wedge was varied between tests and the resulting radargrams from two setups have been provided. The radargrams were captured using a 1600 MHz GSSI StructureScan Mini concrete scanning GPR system.

Test Radargram 1 shows a clear negative polarity response at the top of the EPS wedge, slightly increasing in amplitude as the wedge thickness increases from 5 mm to 20 mm. Between 20 mm and 30 mm wedge thickness, the amplitude no longer increases as noticeably. Adjacent to the wedge is a weak negative polarity response from the dry AP40 fill where it contacts the concrete directly.

Test Radargram 2 also shows a clear negative polarity response at the top of the EPS wedge, the amplitude of this response fluctuates, and does not appear to noticeably increase in a consistent manner. Something to note is the overall thickness of the response is greater than that of the thinner EPS wedge; however, the thickness of the response does not increase proportional to the wedge and therefore cannot be reliably used to indicate void thickness. Adjacent to the wedge, we also see a weak negative polarity response from the dry AP40 fill where it contacts the concrete directly.

These results, coupled with the findings from ground truthed surveys, prompted us to recommend the “minor”, “moderate” and “significant” void categories and the associated void thickness estimates.

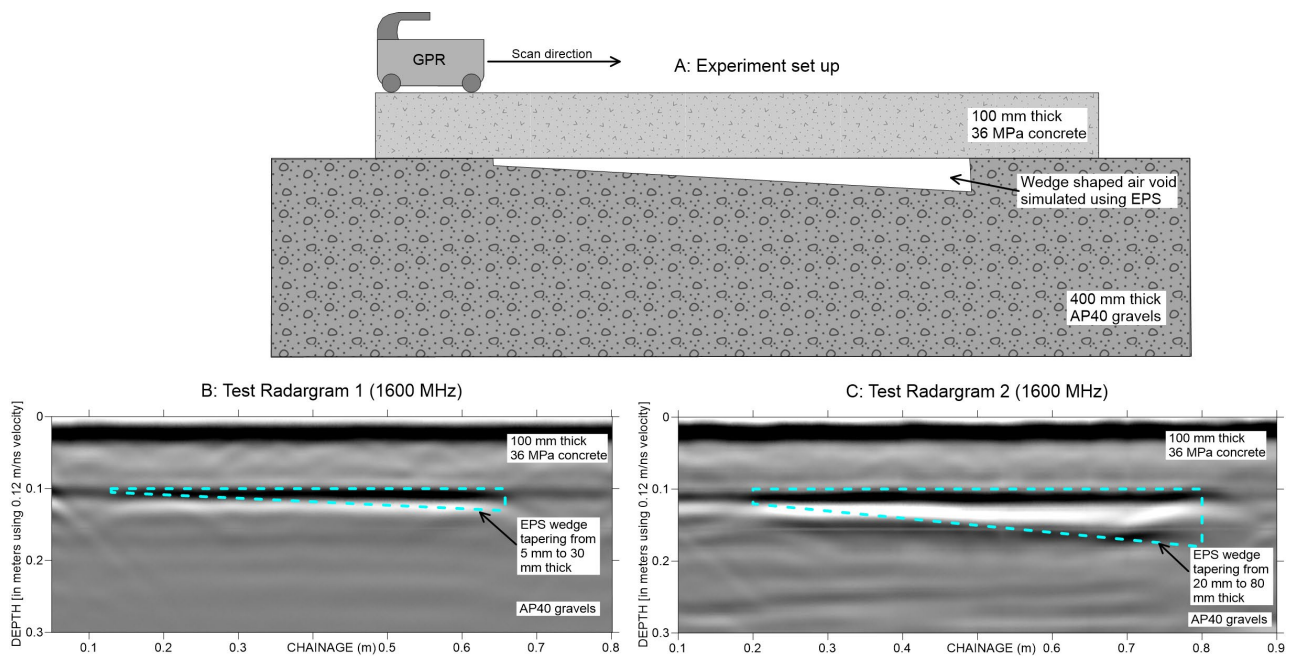


Figure 3: Experiment using EPS to simulate a void between a concrete floor slab and engineered fill. Experiment setup (A). Void test using 5 mm to 30 mm EPS (B). Void test using 20 mm to 80 mm EPS (C).

REFERENCES

- Annan P (2003). "Ground Penetrating Radar Principles, Procedures and Applications". *Sensors and Software*, 278pp.
- Cassidy NJ, Eddies R, Dods S (2011). "Void Detection Beneath Reinforced Concrete Sections: The Practical Application of Ground-Penetrating Radar and Ultrasonic Techniques". *Journal of Applied Geophysics*, **74**(4): 263-276. <https://doi.org/10.1016/j.jappgeo.2011.06.003>
- Comite D, Galli A, Lauro SE, Mattei E and Pettinelli E (2015). "Analysis of GPR Early-Time Signal Features for the Evaluation of Soil Permittivity through Numerical and Experimental Surveys". *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, **9**(1), 178-187. <https://doi.org/10.1109/JSTARS.2015.2466174>
- Kaiser A, Holden C, Beavan J, Beetham D, Benites R, Celentano A, ... and Zhao J (2012). "The Mw 6.2 Christchurch Earthquake of February 2011: Preliminary Report". *New Zealand Journal of Geology and Geophysics*, **55**(1), 67-90. <https://doi.org/10.1080/00288306.2011.641182>
- Jol HM, Ed. (2009). "Ground Penetrating Radar: Theory and Applications". ISBN 978-0-444-53348-7, Elsevier Science, Amsterdam, Netherlands, 544pp.
- Nobes DC (2017). "Ground Penetrating Radar Response from Voids: A Demonstration using a Simple Model". *Ndt & E International*, **91**: 47-53. <https://doi.org/10.1016/j.ndteint.2017.05.007>
- Nobes DC (2018). "Interpretation Pitfalls to Avoid in Void Interpretation from Ground-Penetrating Radar Imaging". *Interpretation*, **6**(4): SL21-SL28. <https://doi.org/10.1190/INT-2018-0049.1>
- Potter SH, Becker JS, Johnston DM and Rossiter KP (2015). "An Overview of the Impacts of the 2010-2011 Canterbury Earthquakes". *International Journal of Disaster Risk Reduction*, **14**: 6-14. <https://doi.org/10.1016/j.ijdr.2015.01.014>
- Razak NA, Senin SF and Hamid R (2015). "Detection of Sizes and Locations Air Voids in Reinforced Concrete Slab using Ground Penetrating Radar and Impact-Echo Methods". *Jurnal Teknologi (Sciences & Engineering)*, **74**(3): 63-67. <https://doi.org/10.11113/jt.v74.4553>