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A Blind test of nondestructive underground void detection by ground penetrating radar (GPR)

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Abstract

Blind test/experiment is widely adopted in various scientific disciplines like medicine drug testing/clinical trials//psychology, but not popular in nondestructive testing and evaluation (NDTE) nor near-surface geophysics (NSG). This paper introduces a blind test of nondestructive underground void detection in highway/pavement using ground penetrating radar (GPR). Purpose of which is to help the Highways Department (HyD) of the Government to evaluate the feasibility of large-scale and nationwide application, and examine the ability of appropriate service providers to carry out such works. In the past failure case of such NDTE/NSG based on lowest bid price, it is not easy to know which part(s) in SWIMS (S – service provider, i.e. people; W – work procedure; I – instrumentation; M – materials in the complex underground; S – specifications by client) fails, and how it/they fail(s). This work attempts to carry out the blind test by burying fit balls (as voids) under a site with reinforced concrete road and paving block by PolyU team A. The blind test about the void centroid, spread and cover depth was then carried out by PolyU team B without prior information given. Then with this baseline, a marking scheme, acceptance criteria and passing mark were set to test six local commercial service providers, determine their scores and evaluate the performance. A pass is a prerequisite of the award of a service contract of similar nature. In this first attempt of the blind test, results were not satisfactory and it is concluded that 'S–service provider' and 'W–work procedure' amongst SWIMS contributed to most part of the unsatisfactory performance.+

Keywords: blind test, ground penetrating radar, air-filled void.

1. Introduction

The unseen network of underground utilities is probably the most complex man-made networks in any city. These networks include water supply pipes, gas pipes, power cables; sewers and storm water drainage, telecommunication cables, street lighting, traffic lighting cables, etc. In comparison of the visible damages in bridges and roads, existence and aging problems of underground utilities are often neglected until it fails and causes problems like road collapse due to subsurface wash-out, water leakage and seepage to the road surface, etc [1-4]. In congested Asia cities with hilly terrain like Hong Kong, the water distribution networks always operate under high pressure, which constantly causes underground water leaks and seepage [5]. Main loss is attributed to aging underground pipe network in the city, causing un-noticed subsurface washout of subgrade soils and sub-base. It follows that underground void space grows, ultimately collapses the highways and pavements, and may cause casualties when these structures are subject to daily live load and its own weight could not be supported. NDTE/NSG detection of the existence of the unseen underground void is therefore required to avoid casualties due to sudden road subsidence. Underground void can be generalized in three types, namely air-filled voids, water-filled voids and mixture of air-water voids.

For detection of the above three types of voids, GPR is the most preferred NDTE/NSG method because of (1) adequate and detectable dielectric contrast amongst void, water and road/pavement materials, (2) high resolution of features and (3) efficient data acquisition compared to other methods like resistivity, seismic and others. For (1), water and overlaid road/pavement materials like voids (i.e. air space/water), concrete, asphalt or paving block, dielectric properties of the above exhibit large contrast detectable by GPR. For (2) resolution, high-frequency GPR (e.g. >600 MHz) offers a resolution up to centimeter level and is able to distinguish subsurface void from road/pavement materials. For example, if a 600 MHz antenna is used, resolution can be about 80 mm in optimal case based on an assumption of wave velocity 0.1 m/ns and a half-wavelength resolution criterion. For (3) efficient data acquisition, GPR is superior as its control units and antennae can be carried in a cart or towed by a vehicle traversing at highway speed. Such data acquisition cause only minimal traffic disruption and it does not require physical contact with the ground like other nondestructive road inspection methods, like falling weight deflectometer. GPR is therefore the best candidate for underground void detection in the busy urban city. In this study, only air-filled void is studied for the sake of fairness to test the service providers during the blind test. Fully or partially water-filled void was considered not suitable in blind test because water content can vary significantly in each test date for individual service provider, which creates doubt of fairness. A similar blind test by mainly GPR, as well as electromagnetic induction (EMI) and metal detectors (MD) was conducted to detect anti-personnel landmine in Japan in 2005 [6]. The test makes use of not only NDTE/NSG methods, but also statistical tools such as analysis of variance (ANOVA), confidence level, and probability of detection (POD) during the hunt of more 200 landmine surrogates.

Few previous laboratory experiments and numerical models were developed to study detection of water leak and associated road subsidence by GPR [7-17]. Its accuracy is improved by and highly dependent on advancing digital signal processing in detailed three-dimensional spatial underground model [18]. To study the problem, the first question is “How a void looks like in a GPR slice scans and radargrams?” An air-filled void in a GPR radargram can be qualified/suspected with the following four steps in sequence and by elimination.

- Step 1: eliminate continuous reflections observed in slice scans because these reflections are mostly likely underground utilities. Void manifests itself as local and discontinuous reflectors.
- Step 2: identify local, strong and discontinuous reflections in slice scans. These reflections shall manifest reverberation/ringing of the electromagnetic waves [19, 20]. The vertical start of this feature shall not exist at the ground/time zero in the radargrams and shall continue to be attenuated along with depth/time.
- Step 3: the reflection from the first reverberation/ringing should be out of phase compared to the direct wave, though this characteristic only appears when the void is adequately large compared to the wavelength so that the reflections at the top and bottom can be nicely separated. If the air void is small compared to the wavelength or partially water-filled, reverberations continue without clear out-of- phase top and bottom reflections.
- Step 4: the above two criteria are valid at the same coordinate at GPR traverses in both x-x and y-y grid directions.

Such void detection is unlike any typical engineering task, that it requires very high level of expertise on signal processing and interpretation. In addition, there are few concerns of implementation of such work. Firstly, it has to be carried out nondestructively and efficiently without too much disruption to the traffic. Secondly, daily and routine operation of the survey shall be undertaken by commercial service providers rather than touch-based research/consultancy by university as third party. Role of university shall be bound to pilot study of technical feasibility, and therefore we propose this blind test by setting up realistic marking scheme(s) and criteria acceptable by both HyD and service providers. The award of nationwide service contract is therefore based on two parts: (1) outcomes of such blind test which are reflections of technical competence level, as well as (2) bid price, but not only latter. To some extent, this measure excludes the ‘cow-boy’ service providers and guarantees a minimum level of technical competence. On August 2015, a consultancy project was agreed and setup between HyD and PolyU. It was agreed that PolyU is responsible of the following works:

- setup a 20 m x 10 m test site with various air-filled voids,
- carry out blind test. Result of which is used to benchmark and decide technical acceptance criteria in the blind test for local GPR service providers,
- analyse the findings from the blind test results and assist HyD to identify list of competent service provider(s) for the award of a subsequent 18-month service contract to the winner of the blind test,
- review the current applicability (both technology and commercialization) of GPR on void detection and suggest the procurement method.

2. Design of the test site

The test site (20 m long x 10 m wide) is at the Road lab located in Shek Mun, Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University in New Territories, Hong Kong. An overview of the site is shown in Figure 1. A site plan and a typical section are illustrated in Figure 2 and 3, respectively. There are eight voids are made of plastic fit balls, circular in shape and were blown up to its full size before installation. Details of the site setup are highlighted as follows:

(i) Diameters of all balls are in 1-m in diameter except ball 5 and 7 sized 0.62-m in diameter. The balls were laid with three different cover depths according to the as-built survey records, which are 1.5m (Ball 2, 4, 6 and 8), 0.62m (Ball 1), 0.60m (Ball 3), 0.37m (Ball 5) and 0.36m (Ball 7). Existence of Void 2 and 4 was not confirmed by GPR after later site test by PolyU because of signal absorption by reinforcement in concrete pavement, and very high moisture content of the soil (due to continuous heavy rain during soil backfill in January 2016), which affect the depth of

GPR signal penetration. Another possible reason is un-noticed burst of ball during and after the soil backfill. Therefore, these two voids were excluded in the blind test for service providers.

(ii) A bundle of three UPVC (diameter 50mm at a cover depth 0.85m) pipes and one DI pipe (diameter 200mm at a cover depth 0.66m) were buried to overlap the positions of void no. 3 and 5 and in the vicinity of void no. 1 and 7, as shown in Figure 1. Such setup was planned to disturb the signals of the voids, and test the ability of service providers to exclude these signals of utility from signals of voids.

(iii) After installation of the balls as voids (Figure 4), their lateral and top neigbourhood were covered by fine sand to avoid damage of the balls during backfill. Two types of highway and pavement were used: grade 30/20 concrete (100mm thick) with steel wire mesh and paving block (200 x 100 x 60mm thick).

(iv) The position and depth of the voids in the test site were surveyed jointly by PolyU and HyD with reference to local control framework established within the site area before backfill.

(v) The backfill soils were the same as the excavated soils from the test site. Boulders contained in the excavated soil were eliminated during the backfill.

(vi) Throughout the exercise of blind test by the six service providers, which took several weeks, PolyU repeated the GPR measurement on the traverses on top of the known void positions, so as to make sure that the voids made of fit ball remained to ensure fairness of the blind test.

(vii) For construction details, local specifications in Highway drawings H1102B [21], H1103F [22], H6168, H6169, H6170 [23] and Section 11 Part 7 of General Specification for Civil Engineering Works (2006) [24] were followed in general.

There are three survey parameters about void detection by GPR, (1) coordinates of the centroid of void, (2) cover depth of void, and (3) void spread, as shown in Figure 3 and Table 1. Estimation of thickness of void is currently beyond the capability of GPR and data processing, so it was not measured in this Study. Figure 5 and 6 show two representative slice scans and two representative radargrams of the site. Firstly, the slice scans in Figure 5 show clearly the continuous reflection of the ductile iron pipe and the bundle of PVC pipes (white arrows), which must be excluded (i.e. step 1 in Section 1). Secondly, it also shows several locally strong but discontinuous reflections which are qualified for further void investigations in radargram in Figure 6 (i.e. step 2 in Section 1). Amongst these local strong reflections, void 1 and 3 were finally estimated as voids because they qualify all criteria listed in step 3 and 4 in Section 1.

3. PolyU's two-team approach and blind test for service providers

To ensure the appropriateness of the proposed technical acceptance criteria and marking scheme of void detection posed on the service providers, the PolyU team is sub-divided into two teams: Devil team A and Angel team B. Devil team A was responsible of the design, construction and as-built survey of the test site and records of the parameters of the voids described in Section 2. Angel team B carried out survey and produced reports estimating the centroid, spread and depth of voids. Results of which were assessed with the technical acceptance criteria in Section 4. The devil team A was led by the first author of this paper, with the help of a surveyor, a technician and an appointed contractor. The angel team B was led by the second and third author of this paper, and assisted by a group of postgraduate and undergraduate students. Before comparing the results of the blind test and answer, communication between the two teams was literally cut off to ensure that the survey carried by the Angel team B is truly a blind one.

After survey and presentation of results by the Angle team B, the devil team A and the angel team B, together with HyD, reconciled to review the accuracy of the blind test results, and establish benchmark such as a realistic marking scheme in Table 2 and 3, acceptance criteria and passing marks for assessment of service providers' performance. A realistic acceptance criteria was made based on the practical requirement on the position accuracy of void in view of road maintenance works. Finally, two acceptance criteria were devised and considered, where the more stringent criteria 1 (Figure 7a) defines the centroid of the void as strictly the CENTER point of the void, and the more relaxed criteria 2 (Figure 7b) defines the centroid of the void at any point within the PERIMETER of the void. PolyU Angel team B scored 67 and 88 out of 100 in acceptance criteria 1 and 2, respectively, as shown in Table 4. This score is a hybrid reflection of the strict/relaxed requirement of the two criteria, capability of latest commercially available technologies, ability of the best people in the city, human bias of the Angel team B, and site constraint (soil wetness, size of voids, etc.). The unscored 33 and 12 marks in the two marking schemes are probably a representation of the unreachable limit of the current technology and analytic ability of Angel team B at this particular site.

Then after careful consideration of the technological capability by local service providers and a practically acceptable range of accuracy for GPR survey results to be useful in real-life void detection, a much more strictly definition on centroid of void (i.e. center point of void), but a more relaxed passing score (50 out of 100) is adopted and agreed between PolyU and HyD. Service providers achieving score higher than or equal to 50 in the blind test is considered to be competent to carry out void survey by GPR in large scale. During the survey test in a day agreed by HyD and the service provider(s), they were allowed to work at the site in one full day (from 0930 am to 0530 pm). The following information was given:

- a layout plan
- coordinate(s) of local control point(s)
- marking scheme
- cover depth of void(s) are shallower than 3m.

- a blank form in Table 5 (Answer sheet filled by the service providers).

Service providers were required to submit the following information within 2 working days after the survey:

- filled checkbox in Table 5 (Answer sheet filled by the service providers),
- 2D radargram(s) (i.e. horizontal distance vs depth) indicating locations of void(s)
- raw data with header files
- GPR grid outline.

The two-day time frame is considered to be very tight but is required according to clients' perspective of HyD, given the requirement of GPR's rapid applications required in urban area. Survey results by PolyU's Angel team B and those by the service providers were compared. These reports and data were anonymous and handled firstly by HyD before reviewing by PolyU. To make sure that the intact shapes of the voids remain, therefore we carried out GPR survey on all voids once every week, during the few weeks of works carried out by Angel Team and the 6 service providers. It is found that the shape of the void did not change according to the results of radargrams' comparison. The soil was also carefully compacted by contractor and closely supervised by HyD officers, that the soil next to the laid fit ball was not disturbed, and therefore in all radargrams like the one in Figure 6, no sign of settlement next to the fit balls was found.

4. Technical acceptance criteria for local service providers based on Angle team B's results

The general acceptance criteria of void detection by NDTE/NSG (including GPR) were designed with reference to the rationale of an international standard (Institute of Structural Engineer (ISE) and a local experience by Hong Kong Accreditation Services (HKAS):

- an international standard of underground utility (UU) detection under a framework of Quality Level (QL) B1P/B2P (relative error compared to depth and absolute error, whichever is greater) in Specification for underground utility detection, verification and location ICE PAS-128: 2014 (Institute of Structural Engineer, 2014) [25]. This Quality levels B1 and B2 of this standard take into account of the physical principle of energy attenuation, that the accuracy would be reduced along with cover depth. The same rationale is followed in this study.

- Hong Kong Accreditation Services (HKAS) (2015), Building Diagnostic Testing - Infrared Thermography for Detection of Debonds of External Wall (HCM/2014/01) [26].

For this Study and with reference of the above basis, the acceptance criteria after the blind test by the Angel team B is shown in Table 2 and graphically presented in Figure 7. According to ICE PAS 128 (2014) [25], acceptance criteria can be assessed based on relative errors compared to actual cover depth or absolute error, whichever is greater (Table 2). Marking scheme based on these criteria is summarized in Table 3. In particular, the mechanism of score deduction was introduced to avoid excessive blind guess of voids by the service providers.

5. Comment on the results based on SWIMS

A graphical representation of void distribution by PolyU Angel team B and two examples of the six service providers are shown in Figure 8. As discussed in Section 3, acceptance criteria were devised. The more stringent criteria 1 defines the centroid of the void as strictly the CENTER point of the void, and the more relaxed criteria 2 defines the centroid of the void at any point within the PERIMETER of the void. Performance of six service providers in the blind test is in general unsatisfactory, though the actual results and scores are not publishable. Two observations of the unsatisfactory performance were suggested:

(1) According to the submitted radargrams by service providers, it is generally observed that the basic skills of de-noise, signal filtering and applying gain functions are insufficient (e.g. dewow, time zero correction, background removal and automatic gain control). It is obvious that most service providers tend to identify voids only at the most disturbed area without following steps of interpretation suggested in Section 1.

(2) Most service providers do not observe the mechanism of score deduction in the marking scheme, that attempt of identifying unsure voids should be avoided.

The outcomes (performance of PolyU's Angel team) of the project prove that GPR is useful in underground void detection. The work also attempts to study the reason behind SWIMS through conducting a blind test by service providers, and rewarding those who pass with a service contract of void survey. Amongst different factors in SWIMS, The factors '**I**nstrument' and '**S**pecifications' are excluded. It is because for the factor '**I**nstrument', all service providers make use of cutting edge commercially available technologies and instruments. For the factor '**S**pecifications', the blind test, the PolyU two-team design, the marking schemes and the technical acceptance criteria are considered to be realistic and fair to the service providers. PolyU's Angel team B proved that a moderate score 67 and a high score 88 can be achieved in both stringent and relaxed acceptance criteria, respectively. This unscored part (33 and 12) therefore corresponds to the limitation of '**I**nstrument' and '**M**aterials' in the complex underground which poses certain effect of uncertainty, under the hypothesis that the PolyU's Angel team B did everything perfectly. To exclude the reason of '**M**aterials' in the complex underground and make the test truly an ability test on service providers, a more relax passing score was adopted (i.e. 50) for the blind test. So by elimination of the five factors within SWIMS, the only two attributing factors to the unsatisfactory performance are the ability of service provider **'S'** and work procedure '**W'** (i.e. data collection, signal processing and imaging as a collective reason).

6. Conclusion

In sales document and research papers of NDTE/NSG, sample data and findings are mostly about the '√' cases, but the bitter reality during implementation of such technologies tells that the 'X' cases overwhelm the '√' cases. It is never clear that the reason(s) of these 'X' cases is/are because of one or a combination of the following five factors (SWIMS)

- **S**ervice provider, or simply, the people?
- **W**ork procedure?
- **I**nstrument?
- **M**aterials in the complex underground?
- **S**pecifications?

The major contribution of this work clarifies which part of the **SWIMS** contributes to the unsuccessful underground void survey using GPR in a well-designed blind test. The outcome and conclusion in this study therefore paves the way and setup a model/work flow on how other large-scale nationwide NDTE or NSG technologies can be commercialized to solve any particular engineering problem.

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