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A Lab Study of Coupling Effects of Electromagnetic Induction on Underground Utilities

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Abstract

Electromagnetic induction is the most common technique used in the world for geophysical survey of underground utilities, in the planning stage, prior to construction/excavation and in the maintenance stage of projects. Despite its popularity and usefulness, its reliability and accuracy are nevertheless always questionable due to underground coupling effects amongst the very congested underground utilities. This work studies the disturbed electromagnetic field patterns caused by the coupling effect of neighbouring cables and metallic pipes via a series of validation experiments in PolyU's indoor underground utility laboratory. The study attempts to establish the 'fingerprints' of electromagnetic fields corresponding to different below ground conditions. In these experiments, 11 setups with 260 tests were designed to study the coupling effect between a cable and a pipe. The results show that the coupling effect is significant in the active detection of the cable but less significant in its passive detection. The experiment also compares the accuracies of cable and pipe detection at different induction frequencies with reference to the accuracy levels in the HK EMSD standard and PAS128:2014 British standard. This paper demonstrates the importance of coupling effects in the detection of underground utilities, which should be considered in future revision of standards.

Keywords: Electromagnetic induction, Pipe cable locating

1. Introduction

1.1 Research background

The invisible and congested world of underground utilities (UU) is often neglected to the general public, but UU are indispensable in modern living. Their growth is in line with the continuous development of cities and the ever-increasing demand for energy and a higher quality of life. The maintenance and rehabilitation of underground utilities have become difficult tasks due to the latter's complexity, age and neglect resulting from a commonly-held mindset of 'out of sight, out of mind'. These factors create a 'time bomb' effect and increase the risk of UU damage during excavation works.

According to the Highways Department in Hong Kong, there are about 47km of UU per kilometre of road, which is probably the greatest density in the world. More than 20 utility companies are continually developing the underground utilities network, which occupies the first few metres of underground space. In comparison with cities in other countries, the density of underground pipelines in Hong Kong's utility network is 3.5 times denser than that of Singapore, 24 times denser than that of England and 85 times denser than that of that of the United States (Olga Wong, 2014). It is probably due to the limited supply of habited land in the territory compared to the restricted development in country parks. Therefore, given its UU density and the problem of coupling effects caused by neighbouring utilities, Hong Kong, like other Asian compact cities and mega-cities, probably has one of the most challenging environments for near-surface geophysical survey.

There are about 400 UU accidents every year in Hong Kong (Olga Wong, 2014). This not only causes the loss of money or valuable water resources, but also results in casualties such as in the case of the Kaohsiung underground gas explosion in 2014 in Taiwan and the fatal Kwun Ling Lau landslide in 1994 in Hong Kong (Martin, 1994). The lack of visibility of UU and poor updating of records concerning them can affect the design, construction and maintenance stages of any construction project. Failures to identify the existence of UU can cause design faults and lead to construction delays.

In terms of construction, the bulk of UU construction rarely comply with the Hong Kong Highways Department's standards for underground arrangements within both footpaths and carriageways (Highways Department Standard Drawings, 2017). In the urban area, all utilities are laid in a complicated and chaotic manner under the footpaths and carriageways between buildings. Geophysical non-destructive utilities surveys are always required during the design, construction and maintenance stages of urban development and redevelopment projects in order to avoid damage to UU. There are several international specifications or standards in use. In 2003, the American Society of Civil Engineers (ASCE) published a Standard Guideline (ASCE 38-02) for the collection and depiction of existing subsurface utility data in the United States. The Standard Guideline stated four different quality levels for the underground utility detection. The quality levels rely on survey methods such as electromagnetic locators (EML) and Ground Penetrating Radar (GPR). (American Society of Civil Engineers, 2003). For accuracy, there are two ways of expression. One is reduction of location accuracy with increasing depth, while the other one requires an absolute value of accuracy without regard of depth. An example of the former is the British Standards Institution (BSI) published the PAS 128:2014 standard for specification of non-destructive underground utility detection, verification and location similar to ASCE 38-02. There are four quality levels for underground utility detection in the PAS 128:2014 standard. As a minimum, GPR or EML techniques are required for the quality levels QLB, detection (BSI, 2014). The second example (i.e. absolute value of accuracy) can be found in Hong Kong, which the Electrical and Mechanical Services Department of the HKSAR government (EMSD) published a code of practice for working close to electricity supply lines in accordance with the provisions of Section 15 of the Electricity Supply Lines (Protection) Regulation under the Electricity Ordinance (Cap.406). Most of the local underground utility detection undertaken for design, construction and maintenance works makes use of this code of practice as a standard. In the code of practice, only electromagnetic induction (EMI) methods are required for underground cable survey before excavation works. Consequently, EMI is the most commonly-used technology for locating underground utilities in Hong Kong (EMSD, 2005). However, unlike ASCE38-02 or BSI PAS128 (2014), which cover non-destructive surveys for all underground utilities, the EMSD standard concerns only with the main power supply live cables.

Given the worldwide use of these specifications and standards, the quality levels and accuracies suggested in many contracts and by the equipment manufacturers are seen as basic expectations for clients, but the actual site constraints, such as overlaid materials and interference from neighbouring utilities are not taken into account. For example, horizontal and vertical resolution limits are rarely mentioned and steel bars in concrete could mask the EM signal. This study aims to assesses such impacts, in particular coupling effects as a major source of uncertainty in electromagnetic studies of UU positioning. An example is illustrated in Fig. 1, where the induced electromagnetic fields from neighbouring utilities cross each other and cause interference.

The results of this present work provide a reference for users hoping to better understand the complexity of UU mapping using EML. It also provides information for future UU design and survey, such as minimum clearance distances between power supply live cables and utilities.

2. Background

2.1 Concepts of electromagnetic induction

With reference to Faraday's law, a current flows in a coil of wire if the magnetic field passing through the coil is changing (Knight, 2013). A magnetic field is induced with a direction perpendicular to the wire by an alternating current flowing along its length, or in the UU case, a metallic pipe. By applying Ampere's law, the magnetic field strength of a straight wire can be calculated by using the equation:

$$B = (\mu_0 I)/2\pi r \qquad (1)$$

where the constant μ_0 is permeability of free space, I is the current and r is radial distance from the straight wire.

An alternating current produces an alternating magnetic field oscillating with the frequency of the current. A magnetometer (i.e. Pipe and Cable Locator, PCL) can be used to detect the magnetic field from the wire when the frequencies match. In most parts of the world, the frequency of the alternating current for the power cable is 50/60Hz, which is at the lower end of the radio frequency band when compared with the range of mobile phone frequencies (900MHz and 1900MHz). This power frequency EMF complies with the International Commission on Non-ionizing Radiation Protection (ICNIRP) standard (1998) on continuous public exposure limits for electric and magnetic fields. Ideally, a single power cable can be located directly by a magnetometer (i.e. Pipe and Cable Locator, PCL) using passive mode, which detects the 50Hz frequency of the magnetic field. However, in reality, power cables are laid together or in bundles that spread in different directions and yield a flat response, which makes it difficult to distinguish individual cables. In order to locate and trace individual cables, it is necessary to induce an active signal, outside the 50/60Hz range, into the cable. A transmitter with a current generator is used to inject an electrical current at special user-selected frequencies into the targeted power cable. The AC voltage can be directly or indirectly induced into a target cable by the transmitter. The active method can also be applied to other metal conduits such as water or gas pipes.

Frequencies between 50Hz and 480Hz are suitable for use in tracing underground utilities (ASCE 2002). Frequencies less than 1kHz are classified as low frequencies and frequencies greater than 1 kHz are classified as high frequencies. The frequency used depends upon the survey distance, depth of the buried asset and the signal strength involved. Electromagnetic waves with lower frequencies are able to travel longer distances, while those with higher frequencies yield stronger signals, and vice versa. When comparing lower and higher frequencies, an EM wave in the higher frequencies is easier to transmit by induction. Therefore EM waves of higher frequencies would be more easily induced into nearby utilities than those of lower frequencies. The higher frequency would couple with the electromagnetic fields generated by the nearby utilities. This produces the undesirable electromagnetic coupling effect during detection and affects the accuracy when locating individual utilities (Jeong and Abraham, 2004). The electromagnetic field shape, and as a result the detected signal, is distorted by nearby utility due to the coupling effect (Haddon, 2001). This leads to an inaccurate determination of alignment and depth for the target utility.

Table 1 provides a generic idea of the expected accuracy levels as suggested in PAS-128:2014. There are many other factors affecting accuracy as mentioned above, such as the distortion of the magnetic field in EMLs and the soil condition for GPR survey. Understanding the errors associated with EML technology is necessary for both clients and engineers or surveyors. The electromagnetic field shape is affected by neighbouring metallic objects due to induction and distortion. This coupling effect can seriously reduce accuracy when attempting to locate a pipeline. This study of the accuracy of EML technology and the impact of the coupling effect can therefore provide users with a better understanding and help setup a more realistic standard for utility detection by electromagnetic induction in the congested subsurface of modern cities. The aims of this work are to examine the coupling effect between an underground cable and pipe caused by electromagnetic induction methods during UU surveying and to 'fingerprint' the B-field in various active modes of underground utilities detection in order to improve the work procedure.

3. Experimental design and setup

A series of experiments on electromagnetic induction were conducted at the underground utility survey laboratory of PolyU in order to analyse the signal distribution B-field affected by the coupling effect between a power cable and a 50mm galvanized iron pipe. The independent variables included: 1) the horizontal separation distance between utilities (X), 2) the vertical distance or depth from ground surface (Y), and 3) the induction frequency (F) used (8kHz to 200kHz).

The detected location of the utilities (vertical and horizontal position) was determined by the peak signal strength value using the pipe and cable locator. Each value of peak signal strength, vertical position and horizontal position, was carefully measured and recorded to determine any deviation in the utilities alignment and depth when comparison with the actual position. The relationship between the above variables and the deviation in the vertical and the horizontal positions was explored using regression analysis, which studies the effects of horizontal distance between utilities, vertical distance between utilities and the different induction frequencies on horizontal and vertical accuracies, which are both negatively affected by the coupling effect.

3.1 Experimental setup

A single-phase 220V electric cable, which had a 2x2.5mm^2 signal core and earth cable, was used in the experiment. The cable was laid under the laboratory work platform and covered by soil (see soil properties in Table 2). A current and voltage meter was used to measure the current and voltage levels passing through the cable. One side of the cable was connected to a current and voltage meter that was controlled by the power source with a switch. The other side of the cable was connected to the light bulbs which were used to control the current. A fixed 50mm galvanized iron (GI) pipe was laid at 300mm depth below the working platform and covered with dry soil. The cable was laid at different horizontal separation distances (X) from the pipe and at various vertical positions/depths (Y).

Fig. 2 & 3 show the experimental setup. All data were detected on the chainage lines CH1, CH2 and CH3, which were at 1m intervals from each other. The end of the pipe was connected to a valve chamber at 1.5m distance from CH1. The electromagnetic field was either emitted from the live cable at 50Hz or induced by a transmitter through clamping round the cable with a split toroidal magnetic core. The split toroidal magnetic core carried a primary winding to magnetize the core with an AC signal of between 8kHz to 200kHz (F). The cable acted as a secondary transformer and induced an AC signal, as shown in Fig. 4.

For the passive detection, the magnetic field strength of the cable is calculated with reference to the Ampere's law equation (1) in Table 3:

3.2 Instrumentation

An RD8100 pipe and cable locator (Fig. 5) was used to determine the peak electromagnetic signal. The location of the cable was identified at the peak signal and the depth of the cable was measured by the locator with a twin aerial antenna. The location accuracy of the RD8100 locator as stated by the manufacturer is ±5% of depth and the depth measurement precision is ±3%, although the coupling effects of adjacent utilities are not considered. The magnetic field emitted by cables with a current of 1A to 5A can be detected at all designed depths because the B-field values in Table 3 are all above the stated threshold of 6E-15 Tesla. A current of 5A was selected for the experimental testing in order to maximize the response.

The induction field strength was 1 Tesla with 16 active frequencies (512Hz to 200kHz). The validation experimental tests were designed to operate at 8kHz, 33kHz, 65kHz, 131kHz and 200kHz, which match the most common frequencies used in site survey work.

3.3 Experimental procedure

The validation experimental tests were separated into two parts: passive mode and active mode.

The passive mode was only used to locate the live cable operating at 50Hz. The cable was laid with a variable separation distance (X) from the pipe and a variable depth (Y) at survey chainages

CH1, CH2 and CH3 (Fig. 2) taken in every 100mm along the chainage. The passive mode test was repeated by changing variables (X), (Y) and (F).

The active mode test was used to locate both the cable and the pipe. The TX-10 transmitter was connected to the clamp to induce an active signal operating at different frequencies. The active mode test was repeated by changing the three variables (X:350mm, 550mm, 750mm, and 950mm), (Y:150mm, 300mm and 450mm) and (F:8kHz, 33kHz, 65kHz,131kHz and 200kHz). The detected positions and depths for both passive and active modes of detection were compared with the actual position and depth in order to evaluate the coupling effect on the cable and the pipe (see Table 4 for a summary of the experiment setups carried out in different cable locations).

4. Data analysis

4.1 Baseline test without coupling effects of neighbouring pipe/cable

Baseline tests, free of coupling effects, were carried out individually on both the cable and pipe at a depth of 300mm. The results shown in Table 5 indicate that the horizontal deviation from the true location of the cable and pipe when measured by the PCL is ±50mm, which means that the accuracy standard of the HK EMSD and PAS128:2014 QL-B1 can be achieved even if only PCL is used while the specification requires multiple geophysical techniques. This means that the peak signal strength received by the PCL is satisfactorily closed to the actual horizontal position of the cable and pipe shown in Figs. 6, 7, and 8. Also, the baseline result shows that the PCL can achieve the accuracy stated in QL-B1, although the standard requires two detection technologies.

For the cable, the vertical accuracy using passive detection in the 50Hz power mode does not satisfy the requirements of HK EMSD and PAS128:2014. For the pipe, the horizontal detection accuracy is within the HK EMSD and PAS 128:2014 QL-B1 standards. Only the vertical accuracy of the 8kHz signal is outside the standard with a figure of 37% of detected depth, which is due to the low frequency signal's lack of resolution. The accuracy of the RD8100 when individually locating the cable or pipe satisfies the requirements of the PAS 128:2014 standard and the EMSD cable locating standard.

4.2 Test 1: Passive detection tests on the cable

Forty tests were carried out to locate the cable through passive detection. With reference to Table 6, the mean values of all the detected horizontal locations are within the accuracies stated for PAS128:2014 QL-B1 standard. When the separation between the cable and pipe increases, the detection accuracy of the horizontal location also increases, while the effect of the nearby pipe is decreased accordingly.

4.2.1 Horizontal accuracy

The maximum horizontal deviation when locating the cable through passive detection in all tests achieved the accuracies reported for QL-B2 in PAS128:2014. According to the test results, over 90% of the data are within the PAS128:2014 QL-B1 standard. The overall mean value of the deviation is about 50mm from the actual alignment. When the survey results are combined for the passive detection of the cable at depths of 150mm, 300mm and 450mm , the trendlines for the detected alignment of the cable are close to the actual alignment and fall within the PAS:2014 QL-B1 standard (Fig. 9). The HK EMSD standard can also be met when the separation is over 500mm. Comparison with the detected alignment for the cable at a depth of 150mm and 300mm, the deviations for the 450mm deep cable are larger than those. The effect occurred on passive detection while the cable was laid deeper and closer to the pipe (Fig. 10).

4.2.2 Vertical accuracy

The results of the tests on vertical accuracy do not satisfy the EMSD and PAS128:2014 standards. The trend shows that the detection accuracy increases as the depth increases because the cable is located in a near-field region of the low frequency 50Hz electromagnetic field that surrounds it, as shown in Fig. 11. The near-field region causes ambiguities in the measurement of the cable's depth due to the high energy levels directed received by the antenna over a short distance. On the other hand, for the passive mode (locating the cable with 50/60Hz), the shorter the separation distance is, the higher the detection error becomes (Fig. 11).

It is obvious that the coupling effect negatively affects detection accuracy during passive detection. The horizontal accuracy stated in the HK EMSD requirements is achieved with a separation distance of over 750mm. However, only 22.7% of the overall vertical detection results is were within the HK EMSD and PAS128:2014 QL-B2 standard (±25% of detected depth). Moreover, 24% of the overall test results for the PCL used in passive mode do not reveal the depth of the cable, which cannot be determined accurately by passive detection due to the coupling effect. The results show that when coupling effects exist, passive detection is reliable only for the estimation of horizontal location. This is due to the coupling effect, the longer wavelengths and poorer resolution of the 50Hz electromagnetic field when compared with the shorter wavelengths used in other EML's active modes. It is to be expected that the difference in magnetic field strength received by the two antennas inside the PCL will be small. As a result, when the estimation of depth relies upon the comparison of the magnetic field strengths between the two antennas, a large error is created.

4.3 Test 2: Active detection test on the cable

A total of 110 detection tests were carried out in order to locate the cable through active detection. In active detection, the test result is only meaningful if the horizontal accuracy achieved is reasonably good. This is because the coupling effect occurs during detection of the horizontal location of the cable, which can shroud its true position.

Table 6 shows the effects of different high frequencies on the detection accuracy of horizontal cable location. The trend of detection accuracy is that deeper cable positions decrease detection accuracy as the separation distance decreases. Also, the detection accuracy increases as the separation distance increases except when the cable was at 300mm depth and separated horizontally from the pipe by 350mm. This exceptional case can be explained by the electromagnetic field shape estimated according to the decibel level detected by the equipment. The electromagnetic field for all frequencies of the cable were distorted to form an asymmetrical shape as figs. 12 (Estimated magnetic field shape on 33kHz). The peak signal strength was between the cable and pipe and manifested itself as a non-circular field shape resembling an ellipse when viewed on the vertical major axis. The detection deviation depended upon the separation distance in this case.

For high frequency induction (>1kHz) (Table 6), the detection accuracy was improved when the cable's separation distance was increased to 150mm and 300mm. When the cable was laid deeper than the pipe, the coupling effect became significant as the field shape was distorted by the shallower pipe. In the following sections, the results are analysed in terms of independent variables of separation distance (X), independent variables of cable depth (Y), and independent variables of frequency (F).

4.3.1 Independent variables of separation distance (X)

When the cable was laid at 150mm depth, shallower than the 300mm deep pipe, the test results for active detection showed that when separation distance was increased, the horizontal accuracy improved. When the cable was laid 350mm from the pipe, 60% of test results yielded a deviation greater than 500mm, which fails to satisfy the PAS128:2014 QL-B3 Standard. Almost 100% of the test results do not satisfy the PAS128:2014 QL-B2 standard. When the cable was laid furthest from the pipe at 950mm separation distance, the horizontal accuracy improved as 70% of the test results are within the horizontal accuracy suggested in the PAS128:2014 QL-B2 Standard. The mean deviation was also significantly improved from 519mm (X:350) to 188mm (X:950). Besides, all the peak signal strengths are to the left hand side of the cable, far away from the pipe (Fig.14 & Fig.15). The detection error increased when the cable was laid deeper. When cable at 300mm deep, 70% of the test results are within the horizontal accuracy suggested in the PAS128:2014 QL-B3 Standard. However, the cable at 300mm deep and only 40% of the test results are within the horizontal accuracy suggested in the PAS128:2014 QL-B2 standard. The detection accuracy is improved when the separation distance increases. The mean deviation values were improved from 444mm at a separation distance of 750mm (X: 750mm) to 275mm and 950mm separation (X: 950mm).

The situation is worse when the cable laid at a depth of 450mm, over 45% of the test results do not satisfy the PAS128:2014 QL-B3 Standard. The result shows that when the cable was laid deeper than the pipe, the coupling effect of the pipe becomes significant. The detection accuracy was not improved when the separation distance was increased to 950mm (Fig. 16) and all mean deviation values are over 400mm. Only 16% of the test results are within the horizontal accuracy suggested in the PAS128:2014 QL-B3 Standard. From the estimated electromagnetic field shapes, the peak signal strength was distorted towards the cable side at shorter separation distances, whereas the peak signal strength appeared between the centre of the cable and pipe when the separation was increased. There is no improvement of detection accuracy even up to 950mm separation.

4.3.2 Independent variables of cable depth (Y)

For the cable at 150mm depth, 70% of the test results comply with the PAS128:2014 QL-B3 standard for horizontal accuracy. With the cable at 300mm depth, almost 80% of the test results comply with the PAS128:2014 QL-B3 standard. For the cable at 450mm depth, about 50% of the test results comply with the PAS128:2014 QL-B3 standard (Fig. 17). It is obvious that the accuracy increases as the separation distance increases and the depth decreases. The error increases significantly when the cable is laid deeper than the pipe.

4.3.3 Independent variables of frequency (F)

The coupling effect is significant for the cable laid deeper than the pipe at 450mm depth, especially for the higher frequencies of 65 kHz to 200 kHz (Fig. 18). For 8kHz and 33kHz, only 25% of the detection test results do not satisfy the PAS128:2014 QL-B3 standard. For 65kHz to 200kHz, 50% of the detection test results do not satisfy the PAS128:2014 QL-B3 standard, while the overall mean values of horizontal deviation for this frequency range is 589mm, which results in a failure to locate the cable alignment. For all frequencies, the accuracy level is improved when the separation distance increases.

The result is better when the cable is laid shallower than the pipe at 150mm depth and at the same 300mm depth (Fig. 19 & Fig 20). Then 70% of the test results are within the accuracy suggested in the PAS128:2014 QL-B3 standard. However, when the HK EMSD standard is applied, only 11.8% of the test results complies, which is due to the coupling effect.

4.4 Fingerprinting the distorted B-field caused by the coupling effect on induction of high frequency electromagnetic waves to the cable

The electromagnetic field shapes of different frequencies were estimated from the detected electromagnetic signal strength in dB through the pipe and cable. The result shows that the estimated electromagnetic field shapes for each combination of the horizontal separation distance (X) and depth (Y) are similar for different frequencies.

For the cable at 150mm depth, the peak signal strength was distorted towards the cable side. The level of distortion of the electromagnetic field is reduced as the separation distance increases.

For the cable at the same 300mm depth as the pipe, the peak signal strength appears between the cable and pipe. Referring to the diagrams Fig. 12, the cable's electromagnetic field was distorted and formed a new shape. The peak signal strength was between the cable and pipe and its field shape resembles an ellipse when viewed on the vertical major axis. With a short separation distance, the deviation between the actual horizontal location and detected horizontal location is small and the horizontal detection accuracy are within the PAS128:2014 Ql-B1 standard. However, the coupling effect is revealed in the vertical accuracy as the depth of the cable cannot be estimated. Similar to the situation with the cable at 150mm depth, the level of distortion of the electromagnetic field is reduced as the separation distance increases (Figs. 14 & 15).

With the cable at a depth of 450mm, the peak signal strength was distorted towards the cable side at a short separation distance. The peak signal strength is shifted to the centre of the cable and pipe, and the level of distortion of the electromagnetic field is not improved as the separation distance increases (Fig 21).

4.5 Test 3: Active detection test on the pipe

A total of 110 tests were carried out to attempt to locate the pipe through active detection. The data analysis was separated into two parts; namely horizontal accuracy and vertical accuracy.

4.5.1 Horizontal accuracy

Table 7 shows the results for the detected horizontal location of the pipe at different high frequencies. The results show that the detection accuracies from 8kHz to 200kHz are all within both the HK EMSD standard and PAS128:2014 QL-B1 standard. The mean deviation is between 0mm to 30mm, which means that the alignment of the 50mm GI pipe can be successfully located. There is no significant effect in any position resulting from the nearby cable.

From the Figs 22, 23 & 24, the trends for all high frequencies are close to the actual pipe alignment and the detection result satisfied the HK EMSD standard and PAS:128:2014 QL-B1 standard.

The results show that the depth of the cable causes only limited interference during the detection of the pipe's horizontal position (Figs. 25 & 26). For the case where the cable was laid 150mm deep, shallower than the 300mm deep pipe, the variation in the detection data is much larger due to the coupling effect. When the cable depth increases to 450mm, which is deeper than the pipe, the accuracy increases. In general, test results comply with the HK EMSD standard and are within the accuracy suggested in PAS128:2014 QL-B1 standard.

With reference to Fig. 26 there was no particular difference in horizontal accuracy noted between 8kHz to 200kHz.

4.5.2 Vertical accuracy

With reference to Table 7, of the tests aimed at detection of the pipe's depth, only the 8kHz result is insufficient to fulfil the HK EMSD standard and PAS128:2014 standard (Fig. 27). This shows that the 8kHz frequency's wavelength is too long to allow the PCL to calculate the depth of the pipe in a way similar to the discussion in section 4.2. The 33kHz frequency is the most suitable one for depth detection. Over 90% of the test results are within the HK EMSD standard and PAS128:2014 QL-B1.

For the frequencies of 65kHz, 131kHz and 200kHz, about 85% of the test results comply with the HK EMSD standard and are within the accuracy suggested in PAS128:2014 QL-B2. The trend shows that the detection accuracy increases with increasing depth of cable (Fig. 27). This phenomenon and the underlying reasons relating to coupling effects are the same as those discussed above for active detection.

For the Fig. 28, the trend shows that changes of separation distance do not affect the vertical accuracy. However, the cable's depth affects the accuracy of depth detection because the coupling effect is more significant for depth calculation for a shallower than a deeper utility.

Most of the depth detection data resulting from the induction of an 8kHz electromagnetic field overestimates the depth of the target utility. The variation between the test results and actual measurements for all frequencies is reduced as the cable depth increases (Fig. 29).

With reference to Table 7, for most of the combinations the vertical accuracy of the test results for the cable at 150mm and 300mm depth do not satisfy any standard. However, the situation is improved if the 8kHz frequency test results are neglected.

5 Summary of data analysis

5.1 Test 1: Passive mode on cable detection

Generally, when locating the cable by passive detection, the horizontal accuracy results are similar to the baseline test. All test results are within the accuracy suggested in the PAS128:2014 QL-B1 standard and most of them are comply with the HK EMSD standard. While it is commonly known that significant disturbance occurs during cable detection due to the coupling effect of neighbouring utilities, the disturbance was proven not to affect the horizontal accuracy at a low frequency such as 50Hz, but the vertical/depth estimation was largely inaccurate as a result of the long wavelength. Besides, if there is more than one cable (i.e. bundles) laid together, it is difficult to locate each cable individually as each produces the same frequency of electromagnetic field. In this case, active detection and connection to individual cables is required.

5. 2 Test 2: Active mode of cable detection

In comparison with the passive mode, the horizontal accuracy of results from active detection of cable location do not fulfil the HK EMSD standard. The results indicated that only when the separation distance increases is the horizontal accuracy improved, and the coupling effect is more significant when the cable is laid deeper than the pipe. As a result, the depth of the cable cannot be determined using the PCL due to the low accuracy of horizontal position estimation.

With reference to the published requirements for laying utilities underground in Hong Kong, a 300mm minimum clearance distance is required for power cables and an adequate separation between water mains and power cables and other services should be allowed (Planning & Lands Bureau (PLB), 2002 Chapter 7). But the real situation is more challenging than the 'ideal' stated in the published requirements, especially if am EML survey is considered. Considering the latter ideal clearance requirement and with reference to the estimated magnetic field shape, which summarize the results from active detection of the cable using different frequencies, most of the detection accuracies for tests with a 350mm separation distance do not satisfy any standard. Such unsatisfactory results are also produced even when the separation distance is increased to 950mm. These findings demonstrate that in practice, given the very congested underground environment, it is virtually impossible to make an accurate detection of an underground cable using a PCL.

5. 3 Test 3: Active mode of pipe detection

In terms of horizontal accuracy, all test results comply with the HK EMSD standard and are within the accuracy suggested in PAS128:2014 QL-B1 standard. The results also show that there is an improvement in horizontal accuracy when the cable is laid deeper than the pipe. This supports the findings that show the coupling effect on the cable is stronger when it is laid above the pipe. The best results are achieved when the induction frequency is 33kHz. However, detection of the pipe's depth using an induction frequency of 8kHz always fails and the detected depth is thus unreliable. Overall accuracy levels comply with the HK EMSD standard and are within the accuracy suggested in PAS128:2014 QL-B1 standard.

6. Limitations

There are several limitations to this study which should be noted:

1. The study of the coupling effect was only undertaken with a 220V, 5A single phase cable and 50mm diameter GI Pipe. The effect may be different for different voltages, currents, phases, sizes, materials and types of cable and pipe.
2. The soil condition was not taken into account in this experiment. Different types of soil and moisture content, and different instrumentation may affect the result.
3. Only 11 setups for chainages 1, 2 & 3 were carried out due to the size of the working platform.
4. The experiment only included testing up to 450mm depth.
5. The experiment was conducted indoors under constant temperature conditions.
6. The experiment only explored the effect of one nearby utility. In real situations the underground utilities are much more complex.

7. The cover of the working platform was fibre reinforced polymer boards. Other covering material such as concrete, bitumen or reinforced concrete will affect the result.

8. By using the clamping method for the active mode, only high frequencies were induced to the cable or pipe by the Tx-10 multifunction signal transmitter. Low and middle frequencies could not be tested using this experiment.

7. Conclusions

The electromagnetic field shapes were estimated as part of the investigation into the coupling effects' impact upon cable detection when using electromagnetic induction methods. The shapes of the electromagnetic fields were distorted, asymmetric and different from the well-known textbook symmetric B-field. Various electromagnetic fields were fingerprinted for different separation distances (X), cable depths (Y) and frequencies (F) of the EML. The fingerprinting of electromagnetic field shapes can help to estimate the impact of coupling effects on attempts to locate the position of underground cables. It will therefore improve the work procedures and understanding of the strengths and weaknesses of the technology in various scenarios.

The coupling effects between an underground cable and a pipe caused by electromagnetic induction methods during underground utility surveys were studied and their effects on utility location accuracies were assessed according to international UK/US and local HK standards. It is clear that the standards were drafted based on engineers' perception and expectation rather than a careful consideration of physics and actual complex site condition, namely coupling effects. In general, the coupling effect is more significant in a power cable than a metallic pipe and any other existing pipes, regardless of whether passive or active modes are used.

Requirements in some standards (e.g. HKEMSD) are too stringent requirement. For example, it should be accepted that the accuracy of UU detection will reduce with depth, as a general rule of thumb in energy decay noted by the BSI (2014). Variables such as overlaid materials like reinforcement mesh in concrete pavement and moisture content should be taken into account. This study serves as a benchmark, raising evidence of coupling effects in electromagnetic pipe locating, and further suggesting the importance of validation (in lab or in field) when such near-surface geophysical technologies are applied in civil engineering applications.

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