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THE DEVELOPMENT OF SUBSURFACE UTILITY ENGINEERING PRACTICES IN THAILAND

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ABSTRACT: This study investigates the development and practical implementation of subsurface utility engineering (SUE) in Thailand from 2003 to 2024. Using drawings from over 300 infrastructure projects and detailed field surveys across 21 locations, the research evaluates the accuracy of two primary detection technologies, ground penetrating radar (GPR) and electromagnetic pipe locators. Environmental conditions, especially soil moisture have significant impacts on detection performance. When applying a practical accuracy threshold of ±0.3 meters, the pipe locator achieved this standard at approximately 81% of the test sites, while GPR met the criterion at around 67%. The pipe locator also demonstrated a lower average error and greater consistency across varied soil conditions. These findings highlight the importance of selecting detection technologies based on site-specific characteristics and integrating both detection methods, supplemented with physical verification, to enhance utility mapping accuracy. While the results are based on a limited number of test locations, the study provides practical insights and supports the advancement of SUE implementation and quality control in Thailand.

Keywords: Subsurface Utility Engineering, Ground Penetrating Radar, Pipe Locator, Utility Detection

1. INTRODUCTION

Rapid infrastructure expansion below ground since World War II resulted in a global complexity of subsurface utility networks. Nearly 20 million miles of pipelines, cables, and wires have been installed [1]. The 20–50-year design life span of most utility systems now poses significant obstacles for present-day maintenance operations. The rapid growth of infrastructure and urbanization in Thailand has become a significant problem because of inconsistent documentation of the earliest utilities. Management of subsurface utilities presents a significant challenge, as water, sewage, electrical, and communication networks spanning hundreds of thousands of kilometers highlight the complexity and scale of these networks [2]. Underground utilities are complex in nature, with diverse types of materials including metallic, non-metallic, and optical fiber components serving various purposes [3].

The methods for locating underground utilities fail to satisfy contemporary needs in infrastructure construction. The monitoring systems and visual surveys typically diverge from actual positions by 15–30% [4]. According to recorded data, at least 104,000 US utility damage incidents occurred in a single year, while gas pipeline hits from third-party sources caused US$83 million in damages [5]. Tanoli et al. [3] reported that approximately 500,000 utility strike incidents are estimated to occur every year in the United States alone. Missing depth information, inaccurate available utility position data, and lack of visual guidance for utility locations have been identified as the major reasons for utility strikes during excavation operations [3]. The available data clearly demonstrates why better utility detection and mapping methods must be developed.

Recent research has further quantified the deficiencies in traditional utility records. Adebiyi et al. [6] conducted a comparative case study evaluating the completeness and positional accuracy of traditional utility records compared to Subsurface Utility Engineering (SUE) investigations for a highway reconstruction project in South Dakota. The analysis revealed significant under-documentation in the traditional records, with SUE investigations designating and mapping 160% more utility infrastructure across all asset types compared to One Call records. Positional accuracy metrics further exposed deficiencies in traditional mapping, with only 32% of utility footage analyzed aligned within 2 feet when comparing One Call records to SUE investigation data. Moreover, about 21% of utilities in One Call records deviated by over 20 feet compared to the SUE data [6]. These findings demonstrate the necessity of rigorous SUE practices to mitigate risks from inaccurate and incomplete utility data.

Ground Penetrating Radar (GPR) has emerged as a valuable technology in utility management by offering a non-destructive and efficient subsurface utilities investigation method [2]. The fundamental operating principle of GPR involves the transmission of electromagnetic pulses into the ground and the reception of the reflected signals, which have penetrated the subsurface and reflected with an amplitude that varies based on the dielectric properties of different materials [2]. However, there are several challenges in accurately locating outdoor subsurface utilities using utility locating devices. All those locators come with their own limitations, and their results can be restricted by several factors such as the geological condition of the site, characteristics of the surveyed utilities, accessibility of the surveyed utility, utility density in the surveyed area, and experience of the operator [7]. Conductive, clay, and rocky soils limit the reflection of microwave pulses due to their nature of signal scattering [7]. These environmental limitations are particularly relevant in tropical regions like Thailand, where high moisture content and clay-rich soils are common. Recent research in Eastern Thailand has demonstrated that machine learning approaches, particularly tree-based algorithms, can effectively predict soil moisture content from GPR histogram features, with boosted tree ensembles achieving cross-validation RMSE of 4.79 and R^2 of 0.708 across diverse soil conditions including coastal sandy, transitional mixed, and inland clayey soils [8].

The development of Subsurface Utility Engineering (SUE) practices in Thailand reflects both global technological evolution and unique local challenges. The current research examines this development through analysis of over 300 projects spanning two decades, documenting the progression from basic electromagnetic detection to integrated multiple-technology approaches. The investigation particularly focuses on quantifying accuracy improvements and establishing best practices for Thai urban environments, where high utility density and varied soil conditions create significant challenges for underground utility detection and mapping. Adebiyi et al. [6] noted that SUE investigations have been shown to reduce construction costs by at least 1.9% compared to traditional approaches, which rely on record drawings and site surveys of above-ground features to detect subsurface utilities.

Recent studies have demonstrated that human factors, particularly stakeholder behaviors, play a significantly more important role in damage prevention than previously believed [9]. Tanoli et al. [3] identified that "excavation practices not sufficient" was the biggest cause for utility strikes in the US, Canada, and the UK. Error in the available utility-location data or discrepancies between the location mentioned in records and the real-world location of a utility is one of the major causes for these incidents. However, overall uncertainty in utility location is the result of errors from utility records, utility detection equipment, Global Positioning System (GPS), and excavator and human factors, which require careful consideration to avoid utility damage during excavation [3]. The fast-growing utility infrastructure of Thailand will face implementation challenges that affect SUE programs due to workforce capabilities, communication problems, and procedural issues. SUE efforts require technological advances, effective stakeholder coordination, and regulatory structures with standardized procedures.

2. RESEARCH SIGNIFICANCE

This study provides critical empirical data on SUE technology performance in Thailand's specific environmental conditions. The research quantifies accurate differences between ground penetrating radar and electromagnetic pipe locators across varied soil types and moisture levels, establishing practical guidelines for technology selection. These findings enable optimization of utility detection strategies, reducing infrastructure damage risks and project costs. The work advances SUE implementation standards in Thailand and provides a comparative framework applicable to similar tropical environments with high soil moisture variability.

3. SUBSURFACE UTILITY ENGINEERING

Subsurface utility engineering implements a structured system to identify and manage underground utility risks by accurately detecting underground utilities and mapping their exact locations. Utility detection through SUE operates by electromagnetic induction where alternating electrical currents in conductors create magnetic fields which analysts use to determine utility types and positions [10]. SUE technology began in the 1970s and then progressed into extensive engineering procedures that merge several scientific approaches and methods [11].

SUE practices gained adoption across the world because they effectively control risks associated with underground infrastructure. Twenty-two states in the United States operate SUE programs for their highway projects. Virginia has mandatory SUE regulations for all their highway projects. The PAS 128 specification of the United Kingdom [12] includes SUE principles as a standard for underground utility detection systems. Australia established the AS 5488 standard [13] for similar purposes. Singapore together with Malaysia adopted SUE practices as part of their infrastructure development, but they follow different implementation protocols depending on regional conditions and requirements.

SUE implementation depends on quality levels which ascend from basic to advanced accuracy according to ASCE 38-02 [14] specifications. Quality Level D remains the most fundamental information source since it uses existing utility records together with verbal descriptions as its sole data source. The initial location information derived from existing records faces challenges because research indicates these records provide locations that may differ by 15–30% from actual positions. Quality Level C builds upon basic information by adding surface feature surveys that connect what is seen above ground, such as manholes and valve boxes, with database records to boost location accuracy.

The implementation of geophysical detection methods under Quality Level B (QL-B) marks a significant advancement in the subsurface utility engineering process. This phase, known as "Designating," utilizes modern technologies such as electromagnetic locators and ground penetrating radar (GPR) to enhance the identification and mapping of underground utilities. It builds upon previous levels by incorporating real-time field data for improved reliability.

The highest level of accuracy is achieved at Quality Level A (QL-A), referred to as "Locating." This involves physically exposing the utility using vacuum excavation or similar non-invasive techniques, enabling precise three-dimensional measurement and direct verification of utility characteristics. The SUE quality levels are summarized in Table 1.

Table 1 SUE quality levels and characteristics

Level	Definition	Data Sources	Methods
QL-D	Record-based information	Existing utility records, as-built drawings	Document research
QL-C	Surface feature correlation	QL-D + visible utility features	Site reconnaissance, survey of visible features
QL-B	Geophysical detection	QL-C + field detection data	Electromagnetic locators, GPR, magnetic methods
QL-A	Physical exposure	QL-B + direct observation	Vacuum excavation, test holes, direct measurement

The ability to select and effectively perform with detection technology relies on understanding fundamental principles together with environmental conditions. Radiodetection Ltd. [10] indicates that electromagnetic pipe and cable locators work within multiple frequency ranges from 512 Hz to 100 kHz. Lower frequencies achieve longer distances while higher frequencies enhance detection accuracy in difficult conditions. These detection systems use two methods to recognize magnetic fields that either naturally originate from utility conductors or through artificial stimulation. Ground penetrating radar functions through electromagnetic wave reflection from subsurface interfaces to develop utility images beneath the surface. It identifies both metallic and non-metallic utilities but its success depends on soil conditions [15], [16]. This is particularly evident in dense urban environments such as Mecca, where GPR was successfully used to detect complex subsurface utilities [17]. Additionally, GPR has demonstrated effectiveness in coastal environments for investigating shallow subsurface deposits, as evidenced by tsunami deposit identification studies in Indonesia that achieved high accuracy in distinguishing different sediment layers [18].

Environmental factors play a critical role in influencing the accuracy of detection systems. Soil conductivity together with moisture content and composition control signal transmission for electromagnetic and GPR systems in equal measure. According to Jung [11], the detection of buried utilities depends on three essential factors, utility material properties, burial depth, and environmental interference. Higher soil moisture levels along with clay substrates lead to reduced detection capability. Sandy dry conditions tend to enhance signal transmission. The number of utilities located in a specific area creates specific challenges for accurate detection since urban density hinders detection outcomes.

Modern subsurface utility engineering practices integrate multiple detection technologies as complementary systems to effectively address known challenges in underground utility mapping. Pressured pipes receive their best detection from acoustic methods whereas ferrous material detection leads to superior results with magnetic methods. Thermal imaging detection adds heat-generating utility to the comprehensive tools used for detection purposes. Current best practices in subsurface utility engineering combine multiple detection technologies under the support of well-developed quality management systems [19].

The financial advantages of correctly implementing subsurface utility engineering are extensively supported by research. A study conducted by Jung [20] involved 22 SUE and 8 non-SUE projects which produced benefit-cost ratios between 3.21 and 33.93. The strength of economic gains from SUE implementations shows a better relationship between how utility system complexity is compared to project expenses because site-specific quality selection outranks expense-based choices. The current research indicates that SUE projects with greater complexity generate more significant benefit-cost advantages which shows why comprehensive SUE methods succeed in difficult site conditions. Studies from the present day demonstrate that SUE deployment generates $11.39 in total savings per dollar invested in complex utility projects where utility relocations contribute roughly 40% of these benefits [21]

4. DEVELOPMENT OF SUE PRACTICES IN THAILAND

The development of SUE practices in Thailand followed three distinct stages that brought major improvements to both methods and technology. Recent development in SUE technology combines global trends with the specific challenges of Thailand's urban infrastructure and environmental context.

4.1 Initial Phase (2003-2008)

Introduction of SUE practices to Thailand started in 2003 through which basic implementation methods and limited technological systems prevailed. The main detection method of this period depended on electromagnetic tools, which received additional support from existing documentation alongside as-built drawings. During this time researchers undertook comprehensive surveys for oil and gas facilities that included extensive work for a service station network that has more than 250 sites throughout Thailand.

The first implementation phase faced difficulties due to imprecise utility network detection and shallow depth ranges in addition to heavy documentation dependency. During this period the employed methods created horizontal errors exceeding 1.0 meter when surveying areas with many utilities. The initial SUE projects set up a base that led to more developed SUE techniques but also revealed the requirement for improved detection strategies. During the initial phase, electromagnetic equipment served as the primary tools for underground utility detection, as shown in Fig. 1.

4.2 Development Phase (2009-2015)

This phase brought much progress through the adoption of innovative technologies and advanced methodologies into SUE practice. The SUE approach progressed through four main developments during this period, ground penetrating radar technology adoption, detection method combination, digital documentation system development, and GPS mapping system implementation.

The SUE practices moved outside of Thailand to include Cambodia together with the Lao PDR as part of cross-border infrastructure development projects. Southeast Asia became part of a regional expansion that allowed for the transfer of knowledge and standardization of practices throughout the area. The adoption of quality-level classification systems together with systematic documentation methods brought substantial improvements to project results. The second phase marked significant advancement with the introduction of ground penetrating radar technology, as illustrated in Fig. 2 (a).


(a) (b)

Fig.1 Radiodetection RD4000 electromagnetic locator: (a) receiver and (b) transmitter, used for metallic utility detection during early SUE development in Thailand.

4.3 Current Phase (2016-Present)

The present stage shows sophisticated SUE practices that employ combined methodologies and enhanced quality control systems. The present implementation of SUE utilizes multi-frequency GPR systems as presented in Fig.2 (b) alongside high-precision electromagnetic detectors, GPS mapping solutions, and digital data platforms, along with building information modeling (BIM) integration. Physical verification through water jet excavation was employed to provide ground truth data for accurate assessment.

Thailand requires a full system of laws and regulations to achieve systematic implementation of SUE practices. The Kingdom should adopt institutional approaches to benefit from established methods like those used by its neighboring country, Malaysia, including the National Underground Utility Database (NUUD) and mapping standards [22]. Malaysia provides a framework that combines international standard utility quality levels and defined stakeholder responsibilities along with centralized data management platforms that Thailand can adopt.

(a) (b)

Fig. 2 GPR systems used in SUE practices in Thailand: (a) MALA Easy Locator, a single-frequency system used during the development phase (2009–2015); (b) US Radar Quantum Imager, a multi-frequency system adopted in the current phase (2016–present).

5. CASE STUDY: ENVIRONMENTAL FACTORS AFFECTING UTILITY DETECTION ACCURACY IN THAILAND

A comprehensive field investigation was conducted to obtain empirical data on the performance of ground penetrating radar (GPR) and pipe locator technologies in Thailand. This section describes the study area and methodology employed.

5.1 Study Area

This research project examined 21 survey locations along natural gas pipeline routes in the eastern region of Thailand, specifically within Rayong and Chonburi provinces, as shown in Fig. 3. The selected pipeline segment represents a critical infrastructure component of Thailand's energy network, connecting the offshore natural gas facilities in the Gulf of Thailand to inland industrial areas. This pipeline corridor was chosen for its strategic importance and because it traverses through a variety of soil conditions with different physical and environmental characteristics, making it ideal for comparative analysis of detection technologies. The survey points were strategically distributed to encompass diverse geological settings, including coastal areas with sandy soil and inland regions with varied clay content. This provided a representative sample of the typical subsurface conditions encountered in Thai infrastructure projects.

5.2 Methodology

The research employed a systematic approach using three complementary detection methods. Physical verification through water jet excavation provided ground truth data for accuracy assessment, as shown in Fig. 4(a). The primary detection instruments utilized were a Radiodetection RD4000 electromagnetic pipe locator with a TX-3 transmitter (Fig. 4(b)) and a MALA Easy Locator Ground Penetrating Radar system (Fig. 4(c)). These non-destructive detection technologies represent the standard equipment used in SUE practice in Thailand during different developmental phases.

Both GPR and a pipe locator were used to detect underground pipes at each location. The horizontal and vertical coordinates obtained from utility detection through both methods were recorded. The actual utility position was verified through water jet excavation. The horizontal (ΔH) and vertical (ΔV) differences between the water jet and the other two methods were then compared. Soil samples were collected (Fig. 4(d)) at each location and laboratory tested for an evaluation of environmental factors that influence detection precision.

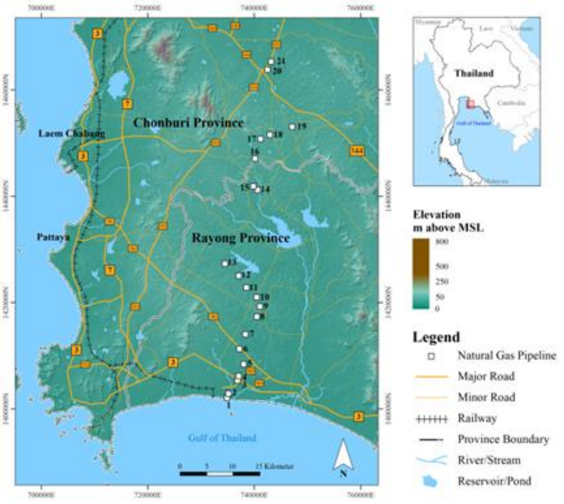


Fig.3 Study area shows a natural gas pipeline route through Rayong and Chonburi provinces.

The obtained soil samples were examined to determine their engineering properties. Standard gravimetric methods were employed to determine the sample moisture contents. Sieve analysis of particles helped identify their textural class. A laboratory performed soil classification following the Unified Soil Classification System (USCS) procedures to obtain standardized groupings. A set of tests based on Atterberg's limits determined the important properties related to soil plasticity. Standard penetration test (SPT) data collection provided information about soil density and compactness measurements at all locations.

Based on the laboratory test results, survey locations were categorized according to soil type (based on SPT-N value, soil consistency, and relative density) and soil moisture content (below 10% and above 10%). By establishing these classification categories, the environmental factors impacting detection precision can be evaluated. Each detection method obtained accuracy measurements by analyzing the absolute distance deviations between detected utility locations and their actual positions. Data measurement formed a foundation for the performance evaluation of detection systems under different environmental settings.


(a) (b)

(c) (d)

Fig. 4 SUE field operations: (a) water jetting for physical verification of pipeline location and depth; (b) utility detection using Radiodetection RD4000 electromagnetic locator; (c) GPR survey using MALA Easy Locator; (d) soil sampling at test location.

6. RESULTS AND DISCUSSION

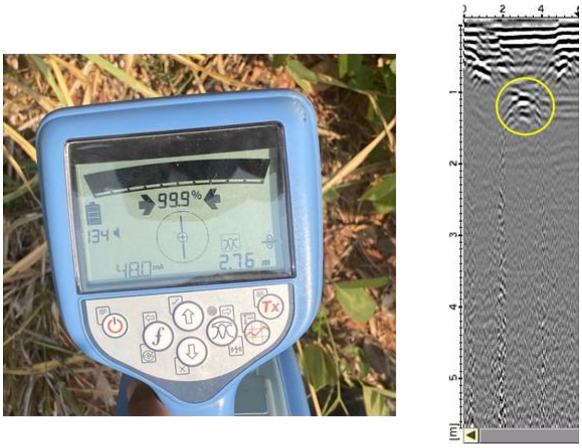
6.1 Comparative Analysis of Detection Technologies

Empirical analysis of underground pipeline detection technologies in Thailand yielded critical insights into their relative accuracy under varying environmental conditions. Table 2 summarizes the depth measurement errors for GPR and pipe locator methods at 21 survey locations.

The pipe locator demonstrated superior overall accuracy compared to GPR across the survey area. It provided more consistent results, with an average vertical error of 0.22 meters, compared to 0.30 meters for GPR. When applying a practical accuracy threshold of ±0.3 meters, the pipe locator met this criterion at approximately 81% of the test locations, whereas GPR achieved it at around 67%. These results suggest that the pipe locator is generally more reliable for subsurface utility detection under soil conditions in the study area. The example of the result obtained from both the pipe locator and the ground penetrating radar is presented in Fig. 5.

Table 2 Summary of depth measurement errors for GPR vs. a pipe locator

Error Metric	GPR Error (m)	Pipe Locator Error (m)
Horizontal (mean ± σ)	0.34 ± 0.22	0.24 ± 0.17
Vertical (mean ± σ)	0.30 ± 0.26	0.22 ± 0.21
Horizontal (min - max)	0.00 - 0.80	0.00 - 0.70
Vertical (min - max)	0.04 - 0.96	0.02 - 0.89



(a) (b)

Fig. 5 The example of result obtained from pipe locator and GPR (a) The pipe locator screen shows the location and depth of the buried pipeline. (b) Identified abnormally from radargram presents the location and depth of underground pipeline.

Absolute vertical depth errors between the technologies are compared in Fig.6 through a mapping of survey location-specific measurements. Most of the recorded points are situated beneath the diagonal reference line demonstrating that the pipe locator produced lower errors than GPR measurements primarily in non-clay soil conditions. The visual display shows that the pipe locator performed better than GPR in measuring depth at most locations in the survey.

6.2 Environmental Factors Affecting Detection Accuracy

The study evaluated three environmental factors affecting detection performance through analysis of soil type, soil density, and soil moisture content. Detection performance was most impacted by the soil moisture content among all considered environmental factors.

The detection accuracy of equipment depended heavily on soil composition because performance showed distinct results between clay and sandy areas. The accuracy of the pipe locator increased to 0.21 meters in sandy or silty soils containing low clay contents when compared to a 0.33-meter vertical error. The pipe locator produced an average error of 0.26 meters in clay-rich areas, but GPR measured slightly better with a 0.22 meters error even though one location produced an outlier that influenced this comparison.

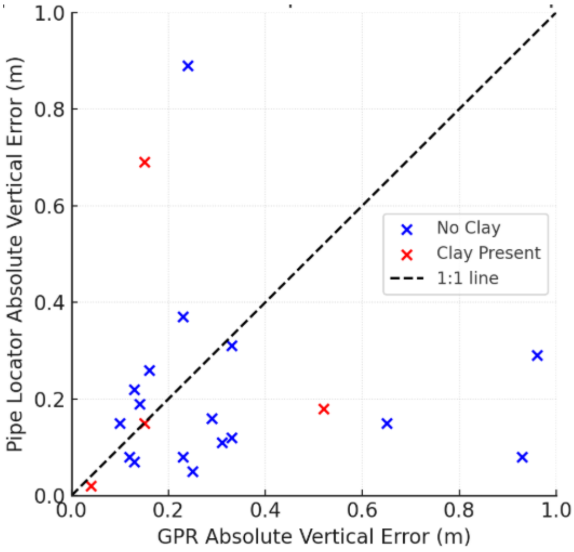


Fig. 6 Comparison of absolute vertical depth errors for GPR vs. pipe locator at surveyed locations. Points below the 1:1 dashed line indicate locations where the pipe locator demonstrated superior accuracy

Soil density, as measured by standard penetration test (SPT) results, showed some correlation with detection performance, though the relationship was not as strong as with soil type or moisture content. The analysis did not reveal a meaningful trend between SPT-N values and error magnitude for either technology, suggesting that while soil density may influence detection accuracy to some degree, it is not the dominant environmental factor.

A comparison of GPR and pipe locator detection accuracy shows a clear pattern through the data presented in Fig. 7's box plot regarding soil moisture levels. The research data separates into two categories based on moisture levels (≤10% and >10%) under both scanning technologies. GPR measurements display wider (taller box) error spreads along with larger variability when moisture exceeds 10%. The pipe locator produces consistent performance through its narrow error distribution which operates within all tested moisture ranges.

The pipe locator displays better overall accuracy and fewer outside readings when compared to GPR measurements as demonstrated in Fig. 7 through horizontal dotted lines indicating a ±0.3 meters practical accuracy threshold. The response of GPR measurement to moisture levels demonstrates increased sensitivity and some readings exceed threshold limits specifically in the region of high soil moisture. The graphical representation confirms that pipe locators maintain superior measurement stability across different soil moisture levels although GPR measurements suffer from environmental impacts.

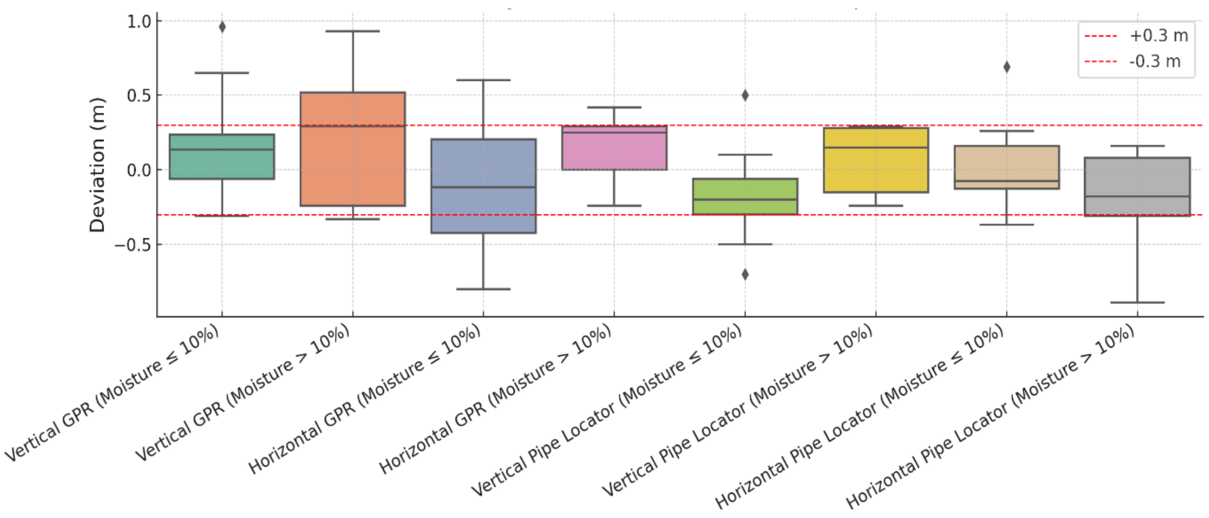


Fig. 7 Horizontal and vertical deviation of GPR and pipe locator vs. soil moisture content

The obtained results deliver essential guidelines regarding SUE methodology usage in Thailand's professional practices. Selection of detection technologies for site-specific environmental conditions should begin with the use of a pipe locator for metallic utilities and high moisture/clay sites while GPR serves as a complementary or alternative method for situations where electromagnetic methods are inadequate. The most reliable utility mapping for critical infrastructure projects requires the combined use of GPR with water jet excavation for physical verification.

7. CONCLUSIONS

Over the past two decades, the development of subsurface utility engineering practices in Thailand has significantly advanced underground utility detection and management. Based on field data from 21 test locations, this study finds that:

(i) The pipe locator demonstrated more consistent accuracy than GPR, with a mean vertical error of 0.22 meters, and met the ±0.3-meter accuracy threshold at 81% of test sites, compared to 67% for GPR.

(ii) Soil moisture was identified as the most influential environmental factor, particularly affecting GPR performance, which declined sharply in high-moisture conditions.

(iii) Soil type also influenced detection accuracy, with the pipe locator performing better in sandy or silty soils, while GPR showed slightly better accuracy in clay-rich soils.

(iv) While soil density parameters (based on SPT-N values, consistency, and relative density) showed some influence on detection performance, this relationship was not as pronounced as the effects observed from soil moisture content and soil type.

For effective field application, it is recommended to use pipe locators for detecting metallic utilities, particularly in environments with high moisture contents or clay soils. Ground penetrating radar (GPR) should be applied for identifying non-metallic utilities or used as a complementary tool alongside other methods. In critical infrastructure projects, combining both detection technologies with physical verification ensures the highest accuracy. Ultimately, the selection of detection methods should be guided by the specific environmental conditions present at each site.

It is important to note that these findings are based on a limited sample size (21 locations). Further testing across a wider range of sites is necessary to validate and generalize these conclusions for broader application in Thailand.

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