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Research Article

Learning from Accidents: A Qualitative Analysis of Damage Data to Identify the Antecedents of Utility Strikes

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Abstract

Underground utilities (particularly electricity and gas) pose a significant hazard to workers during excavation works. Even with advanced digital instruments for utility detection, governing standards and strict compliance regulations, utility strikes continue to occur at an alarming rate. Therefore, analysing utility strikes and their antecedents is necessary to determine their causes as a first step towards preventing them. A dataset of 10 case studies related to 'dangerous occurrences' and 'lost time' categories in utility strikes were selected for analysis based on purposive sampling. Identification of the incidents' causes was performed by coding the excerpts of narrative within incident reports produced using the NVivo 12 software program. In total, 33 causes of incidents were identified and categorised into two thematic groups viz. worker or work related categories. The causes of incidents were then discussed, practical recommendations made and conclusions drawn. Finally, an innovative practical framework (based on pre-event, event and post-event phases) was developed to address the causes of incidents in utility strikes. Emergent findings provide a basis for firms and industries to augment the health and safety of workers employed on buried utility services projects.

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Highlights

- Root causes of buried utility service strike incidents were identified and categorised from case studies.
- Two main classifications for 33 causes of incidents in utility strikes (i.e. worker and work-related categories) were established.
- Strategies for mitigating the causes of incidents in utility strikes were recommended.
- A novel and pragmatic response training framework for addressing the causes of utility strike incidents was proposed.

1 Introduction

Utilities services consist of pipes and cables that provide essential water, gas, electricity, sewerage and telecommunications services for buildings and infrastructure (Apak et al., 2022). Any disruption to these critical infrastructure services has concomitant cost and health and safety implications (Wells et al., 2022). To envisage the scale of the issue, the UK alone reports that more than 4 million holes are excavated in roads each year (McMahon et al., 2005), with approximately 60,000 utility strikes occurring annually (ICE, 2017). This in contrast to the USA, which has 500,000 strikes equating to approximately one per minute every year (Talmaki and Kamat, 2012; Li et al., 2015). By analysing the 10,620 incidents, Li et al. (2015) concluded that approximately one injury occurred in every 16 incidents of service strikes, one fatality occurred in every 65 incidents and an average of approximately $61,200 (USD) in property damage was attributed to each utility strike. Overall expenses associated with utility strikes significantly exceed the documented property damage expenditures (Koschmann et al., 2022). These incidents can cause expensive delays to repairing or installing utility services and pose significant safety risks to workers (Metje et al., 2015). Gas explosion (Koschmann et al., 2022) or electrocution (Metje et al., 2015) are perhaps the most notable and prominent risks posed that could have fatal consequences (Makana et al., 2018). Examples of financial losses incurred include the economic loss due to service disruptions (Rose et al., 2007), the associated social costs attributed to utility outages valued at circa £5.5 billion a year (McMahon et al., 2006), and the increased life cycle costs of the utility infrastructure (Makana et al., 2018). Other impacts include highway closures for repairs (Khosa et al., 2022), down time for businesses and homes (Tierney, 2007), environmental damage (Douenne, 2020) and the requirement for emergency resources (Metje et al., 2015). For example, a utility strike incident at a major UK airport led to the runways being closed for several hours, contributing to major flight delays and disruption, yet the incident repair cost was only a few thousand pounds (Metje et al., 2015). Consequently, polemic debate within the global infrastructure sector on the incidents that arise through underground utility strikes is omnipresent (cf. Li et al., 2015; Metje et al., 2015; Makana et al., 2018) and therefore, requires renewed insights and perspectives to mitigate risks to health and safety posed.

A wide range of equipment and operational procedures are utilised in street works to repair, replace and maintain buried service infrastructure (Rogers et al., 2012). Often, access to existing buried pipes and cables is achieved through excavation from the surface using open trenches excavated by hand or using excavators (Makana et al., 2018). Consequently, a utility strike is a constant safety risk due to the techniques employed (Usag, 2021; Marschalko et al., 2023). Generic reasons for utility strikes during road projects are primarily caused by a combination of inadequate communication, poor coordination, insufficient knowledge of underground utility locations and human errors (Koschmann et al., 2022). A lack of coordination among agencies (i.e. contractual partners) also plays a critical role in the frequency of utility strikes (Waugh and Streib, 2006). Agencies that have deficient coordination procedures are more likely to experience these incidents due to unclear responsibilities (Piratla et al., 2024). Both highway agencies and utility companies agree that a strong contractual relationship and synergy of safety protocols can minimise conflicts and claims (Makana et al., 2018). Furthermore, improper excavation practices, such as failing to maintain sufficient clearance around the utilities can also contribute to the frequency of utility strikes (Yadav et al., 2022). Utility strikes are frequently attributed to incomplete, out-of-date and inaccurate utility location data (Anspach, 2010; Su et al., 2023) and the absence of information related to uncertainties/errors of utility location data (Beck et al., 2009; Li et al., 2015). Unawareness of the positional uncertainties leads to falsely instilled confidence in plant and equipment operators and workers (Talmaki et al., 2013) and potentially misleads operators into unintentional utility strikes during excavation and drilling activities. Moreover, the lack of standardised data exchange and management practices for utility information is a significant cause of utility strikes (Sarvari et al., 2024). Although various fundamental and generic factors have been recognised as primary causes of incidents in any project (such as safety climate and leadership), it is essential to first comprehend the antecedents, trends and finer nuances of utility strikes to establish a knowledge base for devising effective prevention methods (Makana et al., 2018; Koschmann et al., 2022).

Excavation teams and utility companies document utility strike incidents by collecting factual and objective data and local reports as part of their health and safety reporting protocols (Talmaki et al., 2014). At present, there is a limited analysis of these data and the review and comparison of any differences and/or similarities across the industry (Makana et al., 2018). Extant literature reveals a distinct lack of research on the cause and effect of buried service strike incidents, especially in the UK context (Edwards and Love, 2016; Makana et al., 2018; Al-Bayati and Panzer, 2020; Koschmann et al., 2022). Therefore, this study aims to identify and evaluate the main causes of buried utility strikes based on 10 fully detailed cases in UK highway incidents. Existing excavation practices are analysed to form: reliable conclusions on how to prevent future underground utility strikes; and develop a novel theoretical framework for preventing and dealing with them. Findings presented address an existing knowledge gap in extant literature and permits policymakers and other highway professionals to demand changes towards engendering a safer utility sector.

2 The Utilities Sector in the UK

The UK utilities industry is an essential element of the nation's infrastructure, comprising electricity, gas, telecommunications and water firms (Edwards and Love, 20216). This sector is defined by its emphasis on distribution, regulation and the provision of vital services that cater to residential and commercial needs. The sector's regulatory framework is principally managed by the Office of Gas and Electricity Markets (Ofgem), which guarantees equitable competition and consumer protection in the electricity and gas markets. The United Kingdom is presently experiencing an energy transition characterised by a movement towards renewable energy sources and the incorporation of digital technology. This shift is altering the energy sector and increasing the demand for experienced people adept at navigating this evolving market terrain (Soni et al., 2024). The energy market dynamics are shaped by multiple factors, such as supply and demand variations, regulatory modifications and the ongoing transition towards sustainability via renewable energy sources (Bogdanov et al., 2021). The emergence of renewable energy companies enhances the UK's sustainability initiatives, as these enterprises concentrate on innovative technology that facilitate the energy shift (Seyfang and Haxeltine, 2012). Nonetheless, despite the anticipated development and the influx of upcoming contract opportunities, there is an increasing sentiment among the sector's professional contractors and employers that the development process (e.g. excavations for maintenance and road project development) is advancing recklessly to reduce productivity costs (Edwards and Love, 2016). This economic-political context, along with anecdotal information from practitioners, provides additional rationale for this research.

The UK utilities sector encounters numerous issues related to the maintenance and growth of subterranean utilities, which considerably affect operational efficiency and service delivery (Gilchrist and Allouche, 2005). A significant challenge is unpredictable demand, which hampers planning and resource management, hindering utilities from establishing cost-effective solutions that correspond with business requirements (Edwards and Love, 2016). This uncertainty is intensified by privatisation, which modifies resource allocation and management tactics hence, affecting maintenance efforts and infrastructure growth (Tamosaitiene et al., 2021). Deregulation has altered the operational scene, producing competitive dynamics that require enhanced maintenance practices and novel methods for subsurface utilities development (Robinson, 2007). As competition escalates, utilities must use comprehensive asset management techniques to improve operational resilience and efficiently oversee substantial assets (Nadel and Herndon, 2014). This is essential as the sector contends with escalating expectations and regulatory challenges necessitating a reassessment of current maintenance techniques (Chan et al., 2023). Furthermore, a deficiency in advanced digital technological skills presents a substantial obstacle to efficient maintenance and development of utility infrastructure (Sarvari et al., 2022). Investing in technology (and associated skills needed to utilise such) is crucial for tackling these difficulties. By utilising new technologies, utilities can optimise their procedures and augment performance in administering subterranean utilities (Maree et al., 2021). Nonetheless, the legal system must adapt to address the investment requirements and constraints encountered by these utility companies and contractors, assuring their capability to sustain and enhance infrastructure effectively (Edwards and Love, 2016). To surmount these challenges, utility organisations (both companies and contractors) must invest in technology (e.g. maintenance and cable line design is facilitated by a comprehensive framework that encompasses utility mapping) and modify their regulatory frameworks to guarantee operational resilience and sustainability in their maintenance practices (Mirshekali et al., 2023). In congruence with the Industry 5.0 concept, technologies must be operated by fully trained and competent staff because the sector remains heavily reliant on labour - technology per se cannot yet complete utility works (Posillico and Edwards, 2024). A deficiency of trained staff obstructs utilities' capacity to implement essential upgrades and repairs, thereby impacting service reliability (Haider et al., 2016). The skills gap is further exacerbated by increasing environmental concerns (Omer, 2009), requiring adherence to more stringent rules and sustainability initiatives, hence complicating maintenance techniques (Tamosaitiene et al., 2021).

3 Methodology

Interpretivism (Posillico et al., 2021), inductive reasoning (Bortey et al., 2022) and thematic analysis (Roberts and Edwards, 2022) constitutes the core methodology adopted for this qualitative research which explores incident reports of buried utility strikes. Figure 1 delineates the iterative and linear process adopted and is split by two swim lanes to denote three activities within this process namely: 1) coding of the data; 2) methods employed; and 3) specifications. This process is performed via an: analysis of four sets of real-life case study data sourced from two sponsoring utility companies and classification of the cause of incidents.

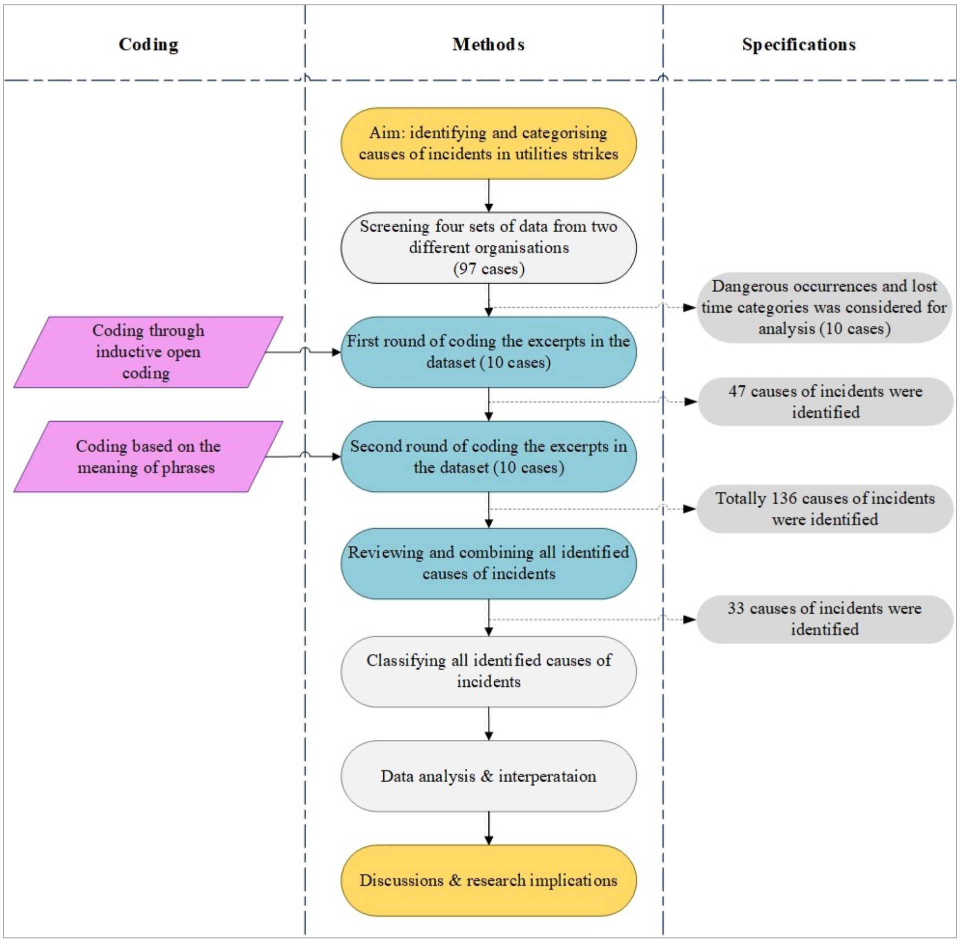


Figure 1: Research process framework.

The dataset was selected using purposive sampling to ensure only relevant data was collated and contained ‘dangerous occurrences’ and ‘lost time’ categories. The dataset was selected using purposive sampling to ensure only relevant data was collated and contained ‘dangerous occurrences’ and ‘lost time’ categories. This deliberate focus on serious incidents, defined as those resulting in significant harm, potential for fatality or mandatory reporting under health and safety protocols, was chosen to prioritise cases with comprehensive documentation, including detailed incident reports, witness statements, risk assessments, and site investigations prepared by senior safety advisors (Yin, 2018). Such incidents typically undergo thorough internal and regulatory scrutiny, yielding richer qualitative data on root causes compared to minor events or near-misses, which may lack equivalent investigative depth or completeness in organisational records (Hallowell et al., 2013; Makana et al., 2018). While this approach enhances the reliability of causal insights derived from the sampled cases, it may limit the capture of precursors evident in near-misses or minor incidents.

A total of 10 different cases were selected to mitigate researcher bias and increase the study’s outcome reliability. Cases were retrieved from the sponsoring organisations’ incident reports and consisted of: 1) textual documents in the form of a summary report and other supplementary documents (e.g. witness statements, risk assessment methods statement (RAMS) and email communication of staff) that extensively describe the incidents; and 2) site investigation reports prepared by senior safety advisors that include photographs of tools or machinery used or utility lines that are involved in the incident. Consequently, each case out of 10 representing ‘dangerous occurrences’ and ‘lost time’ accident occurrences serves as a unit of analysis and incorporates a variety of documents in different formats (i.e. text and image). The characteristics of the 10 utility strike case studies are presented in Table 1. These cases were selected because they were sufficient in terms of completeness of details and richness of qualitative data. Hallowell et al. (2013) and Yin (2018) proffer that the number of cases tend to span from a minimum of 4 to 10 when investigating complex contextual relationships; hence, justifying this sample size for the current study.

Table 1: Characteristics of the 10 utility strike case studies.

Case No.	Category	Utility type	Incident potential	Incident severity	Incident location	Incident duration	Weather condition	Nature of injury
1	Dangerous occurrence	Gas	Low	High (serious)	Site	≥ year	Cloudy	No
2	Dangerous occurrence	Gas	Low	Medium	Site	≤ week	Cloudy	No
3	Lost time	Water	Low	Medium	Site	≤ month	Clear	Yes
4	Lost time	Water	Low	Medium	Site	≥ 6 months	Clear	Yes
5	Lost time	Water	Low	High (serious)	Site	≤ week	Clear	Yes
6	Lost time	Water	Low	Medium	Offsite	≤ month	Clear	Yes
7	Dangerous occurrence	Electric	Low	High (serious)	Site	≥ month	Clear	No
8	Dangerous occurrence	Electric	Low	High (serious)	Site	≤ week	Clear	No
9	Lost time	Telecom	Low	Medium	Offsite	≥ month	Cloudy	Yes
10	Lost time	Telecom	Low	Medium	Site	≥ month	Clear	Yes

The process of identifying the causes of incidents commences with reviewing each document in the case to ensure familiarisation with the case. Therefore, each individual document contained in each case was reviewed at the first stage of data analysis to determine the related documents for further review. Post review of the 10 sample cases, relevant documents were selected (as per incident type and description) and added to each case to review and identify the cause of incidents. Identification of incidents causes was performed by coding the excerpts in the dataset via two iterations of coding, where on each round, a different approach was adopted to interpret and code the data. During the first round, the coding process was performed through inductive open coding (of phrases, words and sentences describing the causes of incidents in the incident reports and documents directly). During the second round, the coded area was not direct, consecutive or congregate but rather sporadic and patchy. This is because the meaning of the written text or semantics of the data were considered (which denotes the emphasis on causes of incidents). Following these two rounds, all the coded areas of incidents were reviewed, combined and classified. The computer assisted qualitative data analysis software (CAQDAS) called NVivo was used to identify the causes of incidents related to the utility strikes (Gardiner, 2022; Greig et al., 2023; Bayramova et al., 2024). NVivo was also used to perform analysis to: code emergent thematic excerpt in qualitative data; and converge the nodes (i.e. coded excerpts in qualitative data) into categories. To enhance coding reliability in this single-researcher analysis, an iterative process was employed involving multiple reviews of coded excerpts, node refinement, and convergence checks within NVivo to ensure internal consistency and semantic accuracy (Gardiner, 2022; Greig et al., 2023). While inter-rater reliability testing with additional coders was not conducted due to resource constraints and the interpretive nature of the study (prioritising depth over multiple perspectives) this approach mitigated potential bias through systematic familiarisation, inductive open coding, and thematic saturation across the cases (Yin, 2018).

4 Findings

A total of 33 causes were identified from the analysis and each identified cause was accordingly classified into its relevant category (i.e. worker and work) by scrutinising its characteristic(s), structure, semantics and the function they serve. According to Bayramova et al. (2024), classification of factors are beneficial for comprehending the conceptual characteristics of any given concept. This differentiation of function and structure enhances the efficiency, assimilation, use and implementation of the concept. Table 2 presents the classification of identified causes of incidents and their description based on the sampled dataset. The ‘category’ column describes the primary cluster of incidents as the main semantic characteristics of incident causes, whereas the ‘cause of incident’ column provides further granulation of the exact causes of incidents. The ‘description’ column elucidates upon the characteristics of the identified causes of incidents. Table 2 indicates that most of the causes are related to the work category (frequency (f) = 27 or 81.81% of total number of identified causes), followed by causes related to worker groups (f = 6 or 18.19% of total number of identified causes). Although the number of worker-related causes is lower than that of the work-related category, these causes are directly associated with workers and operators. Conversely, causes of the work-related category are related to different work and work procedure issues (i.e. management and control, equipment, safety culture and information). The categorisation was completed based on the root causes of incidents in sampling cases.

Table 2: Categorisation of causes of incidents in utility strikes.

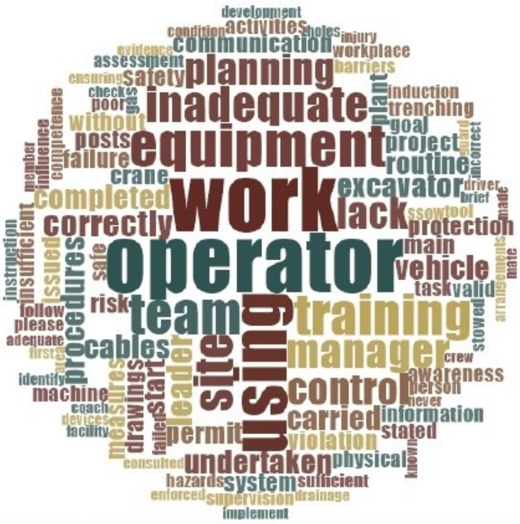
Code	Category	Cause of incident	Description	References				
				[1]	[2]	[3]	[4]	[5]
COI_1	Worker related causes	Operator/worker error in utilising plant, machinery and equipment.	It is often caused by a combination of human factors and inadequate system design. These errors can occur at various stages of operation, from perception and decision-making to execution.	✓		✓		
COI_2		Overlooking or neglecting basic safety by operator/worker (operators' overconfidence in their ability).	Operator overconfidence in their abilities can lead to overlooking or neglecting basic safety measures. This overconfidence often results in operators bypassing established safety protocols, assuming their experience or skill can compensate for the lack of adherence to safety guidelines.	✓	✓		✓	

COI$_{3}$		Operator/worker failure to identify the hazards.	This failure often stems from incomplete risk identification processes, inadequate use of available tools and human factors. Incomplete risk identification is a common issue in construction projects, often due to cognitive biases, lack of communication and insufficient stakeholder participation.	✓			✓	
COI$_{4}$		Ignoring the training provided by operators/workers (information, instruction and training).	Training is designed to enhance the error-free activity of operators by developing their readiness to perform tasks accurately. When operators disregard this training, it increases the likelihood of errors and accidents. This issue is compounded by the complexity of modern utility systems and the need for precise operations.	✓			✓	✓
COI$_{5}$		Unskilled, unqualified and inexperienced operator/worker for the work activity.	The lack of skill and experience can result in improper handling of equipment, misjudgement of safety protocols and failure to recognise potential hazards, which are critical in preventing utility strikes. Inexperienced operators are more prone to making errors that can lead to accidents, such as misjudging distances, failing to identify underground utilities and improper use of machinery.		✓	✓		
COI$_{6}$		Operators/workers who are unfamiliar with site layout and the site specific controls.	This issue arises when workers lack adequate knowledge of the underground infrastructure and the specific safety protocols required for the site. The lack of proper training and communication about site-specific conditions exacerbates this problem, making it a critical area for improvement in construction safety management.		✓		✓	
COI$_{7}$	Work related causes	Non-application of the agreed risk assessment method statement (RAMS) procedure by the team.	Teams may not follow procedures because they believe their actions are justified at the moment, leading to incidents. It may be resulting from a combination of human error, inadequate training and systemic issues.		✓			✓
COI$_{8}$		Inadequate leadership or supervision or particular operation on-site.	This issue often stems from toxic leadership styles, insufficient technical knowledge and a lack of effective communication and coordination among project stakeholders. These factors can lead to poor risk management and oversight, ultimately affecting project performance and safety.	✓	✓		✓	
COI$_{9}$		Failure to obtain work permission from the project's manager for certain duties.	This failure often results from inadequate contract management, poor communication and lack of coordination among stakeholders. Ineffective contract management can lead to misunderstandings about roles and responsibilities, resulting in unauthorised work being carried out without proper permission.		✓	✓		
COI$_{10}$		Objects falling from a height.	These incidents are often linked to falls from height (FFH). The literature highlights several factors contributing to such incidents, including risky activities, poor site conditions and individual (including low-security awareness and improper use of personal protective equipment) and organisational characteristics (such as lack of safety protocols and insufficient training).			✓		
COI$_{11}$		Imposed duress upon operators/workers to complete the task by the client.	Operators are often under significant pressure from clients to meet tight deadlines, which can lead to rushed work and an increased likelihood of errors. This pressure can lead to rushed work, overlooking safety protocols and ultimately, incidents involving buried utilities.	✓		✓		✓
COI$_{12}$		Excessive reliance on documentation (e.g. drawings), even in the face of conflicting evidence (knowledge-based error).	It particularly when conflicting evidence is present, can lead to knowledge-based errors. This issue arises when project teams depend heavily on existing documents, such as maps and records, without adequately verifying their accuracy against real-world conditions. Such reliance can result in misjudgements and errors during excavation, leading to accidental damage to buried utilities.	✓			✓	
COI$_{13}$		Irresponsibility of the site manager (knowledge-based error).	These errors often stem from inadequate knowledge management and insufficient safety awareness, leading to poor decision-making and oversight. This issue is compounded by the absence of systematic		✓			✓

		methods for capturing and utilising knowledge, which can prevent the recurrence of past mistakes.					
COI_{14}	Failure to appropriately deliver tasks to higher authorities on-site (planning).	This issue often arises from a lack of coordination and oversight, which are critical in managing complex utility work schedules and ensuring safety protocols are followed. The absence of effective task delegation and communication can result in mismanagement of resources and increased risk of incidents.	✓	✓	✓		✓
COI_{15}	Inappropriate workplace layout.	This issue arises when the physical arrangement of the worksite does not adequately support safe and efficient operations, leading to increased risk of striking underground utilities. The lack of proper layout planning can result in inadequate space for manoeuvring equipment, poor visibility of utility markings and insufficient access to necessary tools and information.	✓	✓	✓	✓	✓
COI_{16}	Human error - lapse and routine violation of instructions & regulations.	These errors often stem from a combination of individual and organisational factors, including inadequate training, lack of awareness and systemic issues within the organisation. Understanding these errors requires a comprehensive analysis of both the psychological and procedural aspects that contribute to such incidents.		✓	✓		
COI_{17}	Incorrect issue of licences & permits (routine violation).	This issue often arises from routine violations in the permit issuance process, where permits are granted without adequate coordination or adherence to safety protocols. For example, public road authorities often issue permits without coordinating with utility owners, leading to unplanned and overlapping utility activities.			✓		✓
COI_{18}	No or inadequate performance of maintenance tasks & routine testing and repairs of plant and machinery.	This issue arises from a combination of factors, including insufficient maintenance protocols, lack of enforcement of safety measures and inadequate communication among stakeholders. For instance, failure to conduct scheduled maintenance on equipment, such as mini-excavators, poses significant safety hazards.				✓	✓
COI_{19}	Unsuitable physical conditions and other influences that have a disadvantageous effect on human functioning (error enforcing conditions).	These conditions can exacerbate human errors, leading to accidents and disruptions. Inadequate identification of worksite hazards is a major factor in incident root causes in drilling operations.	✓	✓	✓	✓	✓
COI_{20}	Failure to adhere to a safe systems of work (SSoW).	This failure often stems from inadequate training, poor communication and non-compliance with established safety protocols.		✓		✓	
COI_{21}	Insufficient safety equipment, devices, personal protective equipment (PPE) for a specific task.	It often results from inadequate protection measures, leading to severe safety risks and operational disruptions. The lack of appropriate PPE and safety devices can exacerbate the likelihood of accidents, as workers are not adequately shielded from potential hazards.	✓		✓		✓
COI_{22}	Inadequate documentation or documentation control and emergency procedures in place for the specific task.	Proper documentation is crucial for identifying and managing utility conflicts, ensuring that all stakeholders have access to accurate and up-to-date information. The lack of standardised documentation practices and emergency procedures can exacerbate the risk of incidents during road construction projects.	✓	✓		✓	
COI_{23}	Inappropriate selection and use of plant, machinery or equipment for work.	This issue arises when the equipment used is not suitable for the specific task or environment, leading to increased risk of damaging buried utilities. The selection of appropriate machinery is crucial to prevent such incidents and ensure the safety and efficiency of road projects.		✓			✓
COI_{24}	Poor communication between organisation or team members.	This issue arises from various factors, including inadequate information sharing, misunderstandings and lack of clear communication channels. These communication failures can lead to errors in project execution.	✓	✓	✓	✓	✓
COI_{25}	Leadership failure to adequately manage and	Ineffective leadership can lead to poor risk management, inadequate stakeholder engagement	✓		✓		

	plan operational aspects of the work task.	and a lack of coherent project oversight, which are critical in preventing such incidents. These failures are often rooted in toxic leadership styles, insufficient leadership skills and a lack of technical knowledge, which collectively undermine project performance and safety.					
COI_{26}	Inappropriate or insufficient safety control measures designed or implemented.	The control measures are crucial for ensuring that construction activities do not inadvertently damage buried utilities such as cables and pipes. The lack of effective control measures often stems from inadequate planning, poor communication and insufficient adherence to safety protocols.		✓	✓		✓
COI_{27}	Insufficient organisation of the planning of works to be undertaken.	Effective management and coordination are crucial to mitigate the incidents. The lack of structured planning often results in uncoordinated utility activities. This issue is exacerbated in congested urban areas where multiple utility installations and maintenance activities occur simultaneously.	✓	✓			✓
COI_{28}	Insufficient quality or availability of procedures, guidelines, method statements, risk assessment and manuals (procedures).	This deficiency can lead to miscommunication, inadequate planning and increased risk of accidents during construction activities. The lack of standardised procedures and comprehensive guidelines often results in inconsistent practices across different projects.		✓	✓	✓	
COI_{29}	No or insufficient competence or awareness or experienced leaders & managers (information, instruction and training).	This issue is rooted in insufficient training and leadership development. Effective leadership involves not only technical expertise but also the ability to manage teams and communicate effectively, which are often lacking in current practices. This deficiency can lead to poor decision-making and inadequate risk management.			✓		✓
COI_{30}	Unclear operator/worker roles and responsibilities.	This issue arises when there is a lack of clarity regarding who is responsible for identifying, marking and managing buried utilities during construction. Such ambiguity can result in miscommunication, delays and ultimately, accidental damage to utility assets.		✓			✓
COI_{31}	Poor quality, condition and/or suitability of materials, plant, machinery and equipment.	These factors can lead to inefficiencies and errors during excavation and construction activities. Poorly maintained or unsuitable equipment can lead to inaccurate excavation, increasing the risk of utility strikes.	✓				✓
COI_{32}	Safety versus production, incentives or individual goals (incompatibility of goals).	This conflict is often exacerbated by differing priorities among stakeholders, leading to incidents that can have significant consequences. The challenge lies in balancing these competing goals to minimise utility strikes and their associated impacts.	✓			✓	
COI_{33}	Lack of availability, incorrect or complexity of buried utility drawings and other relevant information.	This issue arises from several factors, including the complexity of underground utility networks, inaccuracies in as-built records and the limitations of current utility location technologies.	✓	✓	✓	✓	✓

Figure 2 illustrates the causes of incidents in utility strikes from the case study data. The top of the figure presents frequently occurring keywords in a word cloud diagram. The bottom tabulates the top 25 keywords by count and weighted percentage (Bayramova et al., 2024). Cumulatively, the figure illustrates that keywords such as 'operator' (f = 24 or 2.12%) 'work' (f = 24 or 2.12%) 'equipment' (f = 16 or 1.42%) and 'team' (f = 15 or 1.33%) which suggests that most causes of incidents are related to these factors. The existence of keywords such as 'using' (f = 20 or 1.77%) 'inadequate' (f = 13 or 1.15%) and 'lack' (f = 11 or 0.97%) in causes of incidents in the word cloud represent the lack or wrong use of the safety materials and tools (e.g. instruments and standards) or devices. Furthermore, keywords such as 'team' (f = 15 or 1.33%) 'training' (f = 15 or 1.33%) 'site' (f = 14 or 1.24%) 'manager' (f = 12 or 1.06%) 'control' (f = 11 or 0.97%) and 'procedure' (f = 8 or 0.71%) depict generic safety management activities and approaches to improve safety. The most significant keywords in the word cloud that reflect the utility strikes case studies are 'cables' (f = 8 or 0.71%) and 'excavator' (f = 8 or 0.71%). This is because a mini excavator (circa ≤3 tonne rubber tracked 360° backacter excavator) and operator are frequently used to breakout the road or pavement surface using an hydraulic impact hammer and then excavate the soil below using a mass excavation bucket (Edwards et al., 2003). Other emerging keywords that have been presented in the word cloud are work 'permit' (*f* = 7 or 0.62%) and 'start' (*f* = 7 or 0.62%) that represent the importance of starting the activities in underground utilities related projects with a work permit to dig. The most commonly occurring cause of incidents in cases are on the topic of work procedure, management and control and equipment. These causes focalise on various levels of hardware and software issues, including: 1) equipment malfunction and usability problems (e.g. inappropriate machine or device for work); 2) unsuitable management and control (e.g. inappropriate or insufficient control measures); 3) inappropriate safety culture (e.g. failure to adhere to safe systems of work (SSoW)); and 4) lack of accurate and reliable information (e.g. unclear roles and responsibilities).



Word	Count	Weighted Percentage (%)	Similar Words
operator	24	2.12	`operating, operation, operational, operative, operatives, operatives', operator
work	24	2.12	work, worked, working
using	20	1.77	use, used, using
equipment	16	1.42	equipment
team	15	1.33	team
training	15	1.33	trained, training
site	14	1.24	site, sites
inadequate	13	1.15	inadequate
manager	12	1.06	management, manager
control	11	0.97	control, controls
lack	11	0.97	lack
planning	11	0.97	plan, planned, planning, plans
correctly	9	0.80	correct, correctly
leader	9	0.80	leader, leaders
cables	8	0.71	cable, cables
carried	8	0.71	carried, carry, carrying
completed	8	0.71	complete, completed
excavator	8	0.71	excavator
procedures	8	0.71	procedure, procedures
undertaken	8	0.71	undertaken
vehicle	8	0.71	vehicle, vehicles
permit	7	0.62	permit, permits
routine	7	0.62	routine
start	7	0.62	start, started, starting
communication	6	0.53	communicated, communication

Figure 2: Causes of incidents in utility strikes from the case study data.

Findings from these case studies provide essential insights into the crucial influence of worker actions and work-related factors on safety outcomes in utility strikes. Furthermore, it emphasises the significance of equipment-related issues, which are frequently linked to incidents which have a severe likelihood of major harm or fatality. The occurrence of keywords such as 'using,' 'inadequate' and 'lack' signifies that incorrect utilisation or insufficient safety protocols and equipment are significant factors in incidents. This underscores the imperative for robust safety protocols and the significance of compliance with established processes to mitigate risks. Moreover, the terms 'team' and 'training' underscore the significance of collaboration and sufficient training in safety management, indicating that team dynamics and readiness can profoundly affect the frequency of incidents. The incorporation of 'manager' and 'control' underscores the significance of management in executing efficient safety protocols and control mechanisms. The explicit reference to 'cables' and 'excavator' as pivotal keywords highlights how cable strikes involving machinery are commonplace. The significance of acquiring appropriate work permits prior to initiating underground utility projects, emphasises the necessity for regulatory adherence in safety protocols as illustrated by the phrases 'permit' and 'start.' Analysis reveals that the predominant causes of incidents pertain to operator/worker performance, work procedures, management practices and equipment usability.

Analysing the causes in the 'workers' and 'work' groups can help understand the intricate interrelation between the causes of incidents in utility strikes. The sequence of machine operations resulting in accidents underscores the interaction between human behaviours and equipment utilisation (Nguyen et al., 2024). Comprehending these interconnections is essential for formulating effective preventative methods. Worker-related causes frequently arise from operator errors, including inappropriate device usage and neglecting fundamental safety measures. Operators/workers may demonstrate overconfidence in their skills, resulting in an inability to recognise hazards and a disregard for their training (He et al., 2023). Moreover, untrained or novice operators may lack familiarity with the site configuration or particular controls hence, exacerbating the risk of accidents (Manca et al., 2013). The absence of familiarity may be intensified by insufficient communication among team members, resulting in misconceptions and harmful practices (Shachaf, 2008). Failure to implement established processes and insufficient leadership or supervision can substantially lead to accidents in the workplace. When teams neglect protocols or site managers fail to enforce safety measures, the probability of accidents escalates (Dekker et al., 2008). Furthermore, the inability to secure requisite work authorisations from project managers may result in illicit and hazardous activities (Zou et al., 2007). Physical hazards, such as falling objects, create considerable risks in utility works. These can be compounded by inadequate workplace design and insufficient safety equipment (Nadhim et al., 2016). Moreover, human errors, such as gaps in judgement and habitual breaches of safety protocols, can result in grave repercussions when coupled with hazardous working environments (Sarvari et al., 2024b). The relationship among these factors is clear; for example, an untrained operator may disregard instruction owing to overconfidence, resulting in the failure to implement safety protocols. This scenario might establish a cycle of neglect that is challenging to disrupt without proficient leadership and communication (He et al., 2023). Moreover, client pressure to expedite task completion may result in shortcuts that jeopardise safety, underscoring the tension between production objectives and safety regulations (Hashemian and Triantis, 2023).

Figure 3 illustrates the cause-and-effect relationships of the identified causes of incidents of utility strikes in UK road projects. In terms of causality of items, COI29 (no or insufficient competence or awareness or experienced leaders and managers (information, instruction and training) in the work-related group) and COI5 (unskilled, unqualified and inexperienced operator for the activity in the worker-related group) have the highest impact as measured by out-degree centrality (i.e. the number of direct outgoing causal connections to other causes). This network metric quantifies the extent to which a cause influences others in the directed graph constructed from the thematic analysis of case data, providing a descriptive ranking of relative impact within the sampled incidents (Bayramova et al., 2024). COI29 highlights the critical role of leadership. This deficiency is identified as having the highest impact on various worker and work-related issues, serving as a root cause for multiple other problems, including COI2, COI4, COI5, COI8, COI9, COI17, COI22, COI24, COI25, COI27 and COI32. COI29's influence manifests in COI2, where operators may overlook basic safety protocols due to overconfidence in their abilities. This overconfidence can stem from inadequate training and guidance, which are direct consequences of poor leadership and management practices (He et al., 2023). Similarly, COI4 illustrates how operators may ignore provided training, further exacerbating safety risks and operational inefficiencies (Nicolaidou et al., 2021). The lack of skilled and qualified personnel (as described in COI5) is another direct outcome of insufficient leadership, leading to unqualified individuals performing critical tasks (Sarvari et al., 2024a). Moreover, COI9 emphasises the failure to obtain necessary permissions from utility managers, which can be attributed to poor communication and organisational structure stemming from ineffective leadership (Suleiman, 2022). This lack of oversight can also lead to COI17, where incorrect issuance of licenses and permits to dig results in routine violations, highlighting the systemic failures in management practices (ibid). Inadequate documentation and emergency procedures, as noted in COI22, further illustrate the consequences of insufficient managerial competence, which can lead to chaotic responses in critical situations (Hashemian and Triantis, 2023). Additionally, COI24 points to poor communication among team members, a direct reflection of ineffective leadership and organisational culture (Sarvari et al., 2024a). Failures in management, planning and operational aspects outlined in COI25 and COI27 are also rooted in the incompetence of leaders, which can lead to disorganised work environments and increased risks (Nguyen et al., 2024). Finally, COI32 addresses the conflict between safety and production goals, where misaligned incentives and individual goals can further complicate safety management, again reflecting the overarching impact of inadequate leadership (ibid).

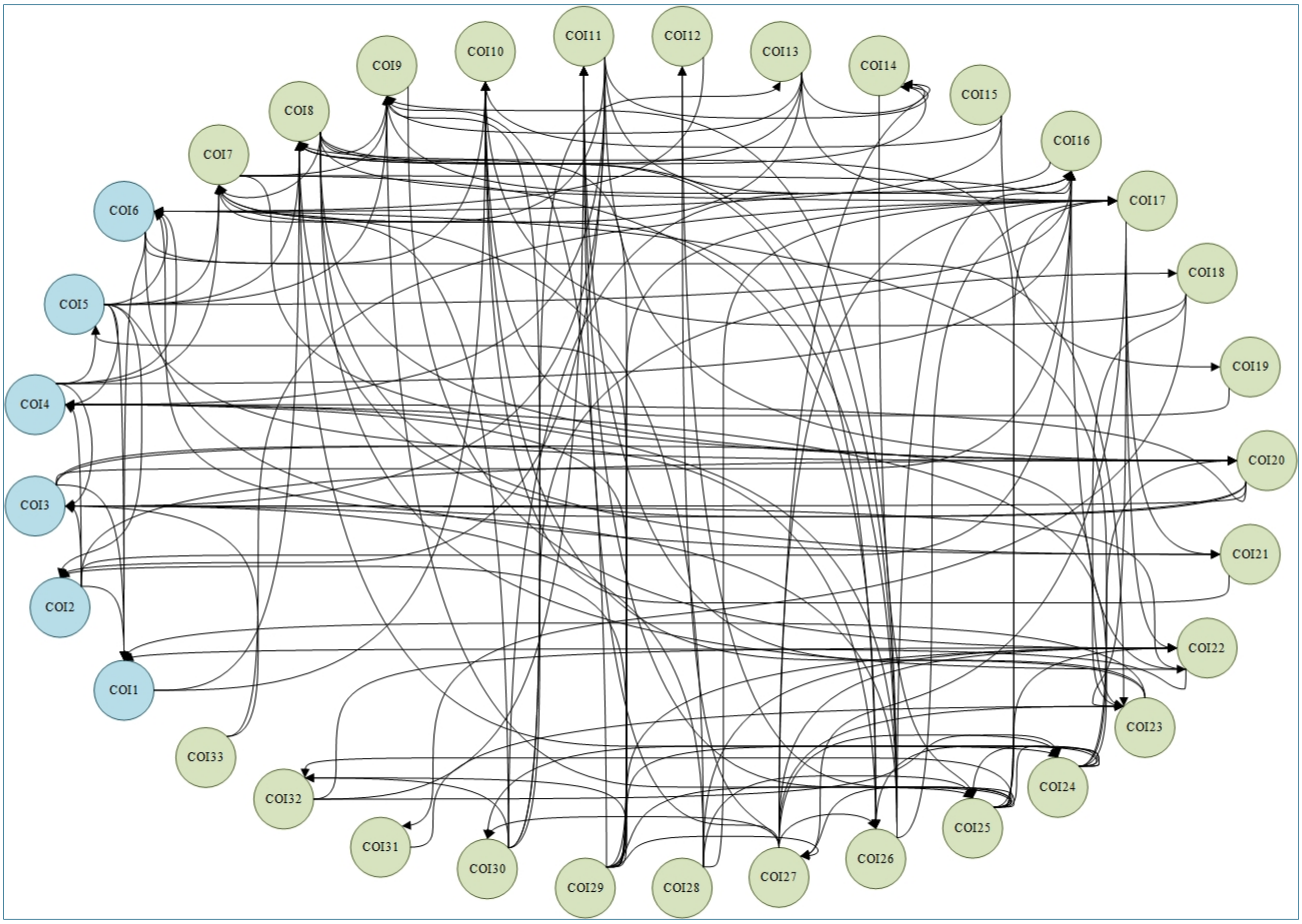


Figure 3: The cause-and-effect relationship of the causes of incidents in utility strikes.

Furthermore, 10 items (i.e. COI1, COI2, COI3, COI4, COI6, COI7, COI9, COI16, COI18 and COI20) can be considered as an effect of COI5 which underscores the critical role that operator/worker competency plays in workplace safety, particularly in utility environments. COI5 serves as a pivotal factor in the causality of workplace safety issues, with its effects manifesting in various operational errors and managerial failures. The implications of COI5 extend to a range of operator-related issues, which can be categorised as effects stemming from this unskilled operator/worker condition. For instance, operator/worker error in utilising devices (COI1) and overlooking basic safety protocols (COI2) are direct consequences of inadequate training and overconfidence, which are often prevalent among inexperienced workers (Liu et al., 2024). These errors can lead to significant safety breaches, emphasising the need for comprehensive training programs to mitigate risks associated with unqualified operators. Moreover, the irresponsibility of site managers (COI13) and failures in communication regarding task delegation (COI14) can intensify the risks posed by unskilled operators. These managerial oversights often stem from a lack of awareness or adherence to safety protocols which can be traced back to the foundational issues of operator training and safety culture within the organisation (Orikpete and Ewim, 2024). Human errors, such as lapses in following instructions (COI16) and non-application of procedures (COI7), further illustrate the cascading effects of COI5. These behaviours are often rooted in the inadequate performance of maintenance tasks (COI18) and failure to adhere to safe systems of work (COI20), which are critical for ensuring operational safety (Khalid et al., 2021). The relationship between COI5 and these various effects highlights the importance of implementing robust safety management systems that can effectively address the risks associated with unskilled operators. Such systems should focus on hazard identification, risk mitigation and fostering a strong safety culture to ensure compliance with safety regulations and enhance overall safety performance (Orikpete and Ewim, 2024). Other causes with high impact are COI25 (cause of 9 items), COI27 (cause of 9 items), COI8 (cause of 8 items), COI24 (cause of 8 items) and COI11 (cause of 7 items). While COI10 does not aggravate any items, COI9, COI12, COI14, COI19, COI21 and COI31 only impact upon one item, i. e., COI22, COI16, COI25, COI10, COI10 and COI23 respectively. These impact rankings are based on out-degree centrality in the causal network, a common approach in qualitative safety research for identifying influential factors through the frequency and directionality of coded causal links, without implying population-level statistical inference given the interpretive, case-based methodology (Nguyen et al., 2024; Bayramova et al., 2024).

In terms of being affected by the items, COI15, COI28, COI29 and COI33 cannot be attributed to any of the causes. However, COI16 (i.e. human error - lapse and routine violation of instructions and regulations) has the highest affectability and can be considered as an effect of 11 causes (i.e. COI2, COI3, COI4, COI5, COI7, COI11, COI12, COI20, COI22, COI26 and COI30). This highlights the complexity of human error in operational settings, particularly in high-stakes environments like excavation operations. COI16 encapsulates the notion that even well-trained individuals can make serious mistakes due to lapses in attention or routine violations of established protocols, which are often intensified by various underlying factors. For instance, COI2 highlights how an operator's overconfidence can lead to the neglect of basic safety measures. This overconfidence can result in operators overlooking essential safety protocols, thereby increasing the likelihood of accidents (He et al., 2023). As another example, the non-application of procedures by teams (COI7) also plays a crucial role in exacerbating human error. Teams' failure to adhere to established protocols compromises the integrity of operations, thereby increasing the potential for accidents (Sarvari et al., 2024b). Furthermore, the pressure placed on operators to complete tasks under duress (COI11), can lead to shortcuts and lapses in safety practices.

The cause-and-effect relationships depicted in Figure 3 employ directed links derived from iterative thematic coding, with node impact weighted descriptively via out-degree centrality to highlight frequent antecedent causes across the cases. This aligns with network-based approaches in construction safety analysis for prioritising root causes (Nguyen et al., 2024).

5 Discussions

Utility strikes in buried services during the excavation and construction of roadways may arise from multiple causes (Su et al., 2023) and accumulation of these causes could increase the potential severity of occurrences. Consequently, identifying and analysing the causes of utility strikes might facilitate their management and resolution, thereby reducing them. Figure 4 provides a taxonomy of root causes of incidents in utility strikes where worker and work-related issues are the primary causes of the incidents.

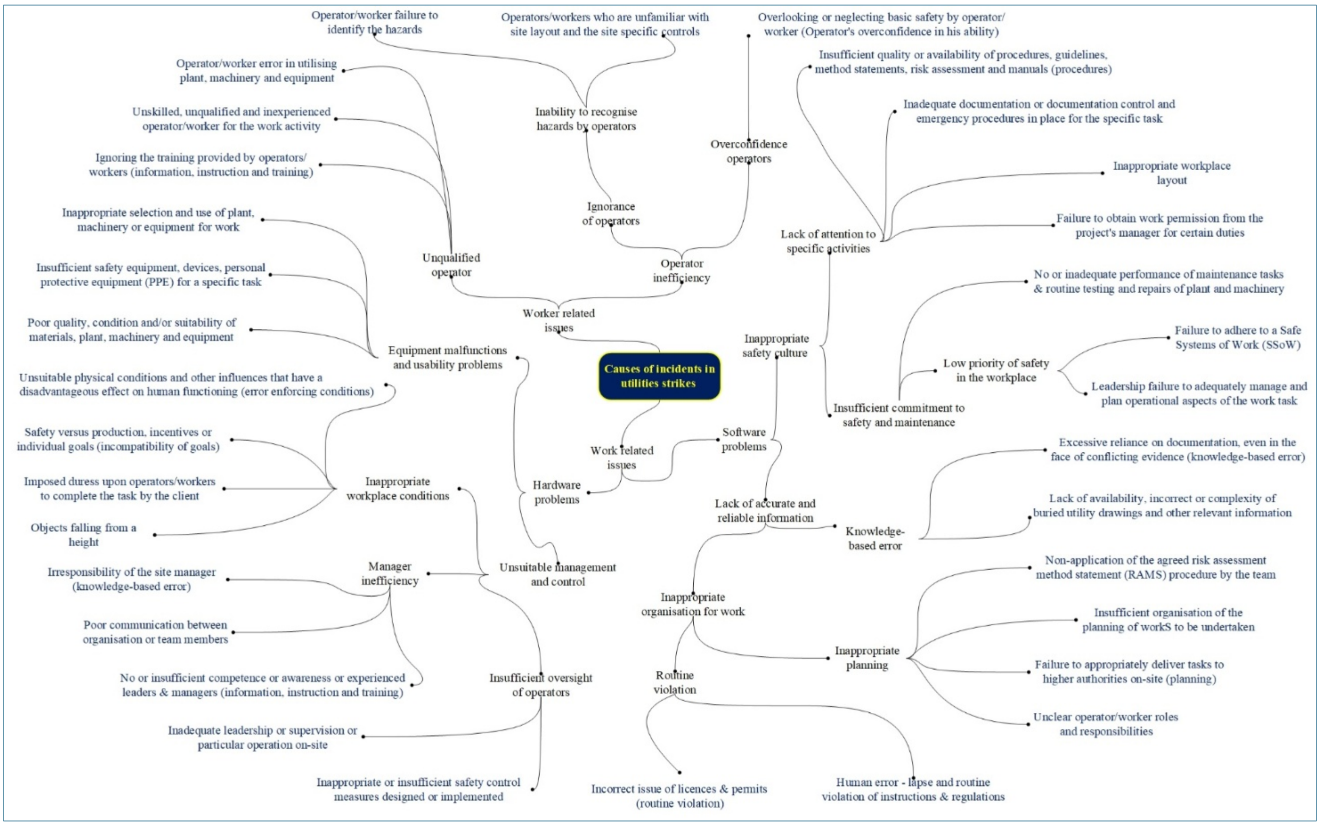


Figure 4: Taxonomy of root causes of incidents in utility strikes.

5.1 Worker Related Issues in Utility Strikes

Worker-related errors can occur at various stages of operation, from site perception and preparation to execution. These errors are often deviations from expected norms, influenced by technical risk assessments, psychological factors and systemic interactions (Sarvari et al., 2024b; Grams, 1998; Yemelyanov and Yemelyanov, 2017). Key examples include overlooking basic safety protocols due to operator overconfidence, incomplete risk identification from cognitive biases or inadequate communication, non-adherence to training leading to reduced spatial awareness and errors by unskilled or inexperienced operators in machinery use or hazard recognition (Talmaki and Kamat, 2014; Metje et al., 2015; Yang and Lu, 2023; Dishar and Altaie, 2024).

Figure 4 illustrates that one of the main causes of incidents in utility strikes can be attributed to the 'overlooking or neglecting basic safety by operatives (operators' overconfidence in their ability)'. Workers may not receive adequate training on the importance of safety practices, leading to a false sense of security in their abilities (Adams et al., 2024). They may fall into cognitive traps, where routine tasks are performed without full attention, increasing the likelihood of errors (Almeida and Binder, 2004). Moreover, a workplace culture that does not prioritise safety can reinforce overconfidence, as operators may not feel compelled to follow safety protocols (Gross et al., 2000).

Incomplete risk identification is a common issue in utility projects, often due to cognitive biases, lack of communication and insufficient stakeholder participation (Dicks and Molenaar, 2024). Workshops conducted during the design stage may overlook or under-assess certain risks, leading to incidents later in the project lifecycle (ibid). Moreover, focusing on generic hazard categories rather than specific sources can lead to an oversight of activities with low potential and severity (Jackson, 2020). Organisational failures, including management and leadership deficiencies, can inflame these issues because they often reflect the lack of comprehensive hazard identification (Pasman et al., 2018).

The lack of adherence to training can result in a lack of real-time spatial awareness, which is critical for preventing excavation-related utility strikes (Talmaki and Kamat, 2014). A significant portion of utility strikes is attributed to operators not following established rules and procedures, which are often covered in training sessions. This non-compliance can lead to frequent and costly incidents (Metje et al., 2015).

Unskilled operators often do not receive adequate training, which is crucial for understanding the complexities of utility tasks and safety protocols (Dishar and Altaie, 2024). The absence of formal qualifications can lead to a lack of understanding of the technical requirements necessary for safe operation (Skroumpelos, 2010). Inexperienced operators are more prone to making errors that can lead to accidents, such as misjudging distances or failing to identify underground utilities (Yang and Lu, 2023). Lack of experience can also result in improper use of machinery, increasing the likelihood of utility strikes (Tripathi et al., 2014).

5.2 Work Related Issues in Utility Strikes

Figure 4 illustrates that work and work procedure related errors include a range of hardware (e.g. equipment and management and control) and software (e.g. safety culture and information) factors. A combination of these factors can increase the severity or potential of accidents. For example, the lack of coherent leadership or oversight due to toxic leadership approaches can lead to inadequate risk management, increasing the likelihood of incidents such as utility strikes (James, 2022). Moreover, a lack of technical knowledge and leadership skills among project managers engenders poor decision-making and oversight, contributing to incidents on-site (Danial and Misnan, 2023; Farooq and Ihsan, 2022). The lack of clear guidelines and procedures for obtaining necessary permissions can magnify these issues, leading to conflicts and project delays (Hanák and Vítková, 2022). Site managers play a crucial role in ensuring safety and efficiency and their lack of knowledge or failure to apply it effectively can result in serious incidents. However, they often lack systematic methods for knowledge creation, capture, storage, sharing and reuse, which are essential for preventing repeated errors (Mohamed and Anumba, 2006). Leaders must possess both technical knowledge and soft skills to navigate complex utility environments (Danial and Misnan, 2023). Toxic leadership can create a weak risk management environment (James, 2022) and negatively alter project quality and delivery expectations, leading to operational failures (Muchiri and Mose, 2022). Regular inspections and adherence to safety standards are necessary to prevent such incidents (Lan, 2022). A lack of a robust quality assurance system can result in poor execution of road construction projects, further amplifying the risk of utility strikes.

In general, many factors negatively impact human functioning (often referred to as error enforcing conditions). For example, environmental and physical conditions (e.g. worksite hazards, fatigue and experience, time of day) can exacerbate human errors, leading to accidents and disruptions. Therefore, the interplay between environmental factors and human limitations is crucial in understanding these incidents (Tayab et al., 2020). Furthermore, latent errors within organisations, such as inadequate safety programs and lack of effective training, can create conditions that enforce errors (Gross et al., 2000). Research indicates that the failure to conduct scheduled maintenance on equipment (such as mini-excavators), poses significant safety hazards. This is often due to market pressures and internal company dynamics that deprioritise hands-on maintenance inspections in favour of virtual protocols, which are not effectively implemented on-site (Edwards and Love, 2016). A lack of routine maintenance can lead to the use of defective hardware, which is a known cause of accidents during repair and maintenance activities (Skroumpelos, 2010).

Failure to adhere to SSoW often stems from inadequate training, poor communication and non-compliance with established safety protocols. A lack of comprehensive training and awareness about safety codes and practices is a primary factor leading to non-compliance with SSoW (Das et al., 2024). Human error is a primary factor in the non-application of procedures, often due to oversight or misunderstanding of the protocols. Teams may not follow procedures because they believe their actions are justified at that moment, leading to incidents (Vaughen and Muschara, 2012). Metje et al. (2015) found that un-followed rules contributed to half of the utility strike incidents for a particular organisation, indicating a widespread non-compliance issue. Operators/workers are often under significant pressure and duress from clients to meet tight deadlines and low profit margins, leading to rushed work and an increased likelihood of errors. This pressure can result in operators bypassing safety checks and protocols to expedite the process (Metje et al., 2015). The competitive nature of the utility industry and internal company pressures can further exacerbate this situation. Companies may prioritise project completion over safety, leading to inadequate maintenance and inspection of equipment, which is crucial for safe excavation (Edwards and Love, 2016). Furthermore, many utility maps and records are outdated or inaccurate, leading to incorrect assumptions about the location of underground utilities (Metje et al., 2015). Workers may place undue trust in documentation, assuming it is comprehensive and accurate, which can lead to negligence in taking additional precautionary measures (Harper et al., 2001).

Many organisations collect data on utility strikes but do not openly share this information across the industry, perhaps given the commercial and in confidence nature of such data which could negatively impact company reputation. The downside of this decision is that mistakes are repeated by other companies and a general lack of learning from past incidents is inadvertently created within the sector (Metje et al., 2015). In utility projects, poor communication management, such as not clearly explaining project expectations and responsibilities, can lead to conflicts and errors (Afanyedor, 2021). Verbal communication errors (e.g. misunderstandings and hesitance in speaking up) are common in team settings and can contribute to safety incidents (Rabøl et al., 2011). Miscommunication during teamwork, especially between different staff groups or levels, can result in incorrect execution of tasks, increasing the risk of utility strikes (Rabøl et al., 2011). Any absence of systematic approaches for measuring and improving team integration and communication can hinder effective collaboration in road projects (Ibrahim et al., 2017). Poor leadership and communication styles in utility projects can amplify these issues (Okorie et al., 2016). A lack of communication can lead to overlapping schedules and unplanned utility cuts, increasing the risk of strikes (Chou et al., 2009). Without a centralised system to manage utility work schedules, fragmented planning occurs, where each utility company or contractor operates independently without considering the broader impact on road projects (Tseng et al., 2011). This issue is a higher risk in congested urban areas where multiple utility installations and maintenance activities occur simultaneously. A weak regulatory framework that does not enforce strict guidelines for utility coordination can contribute to organisational inefficiencies (Zhang, 2016).

The incompatibility of goals in road projects arises from the tension between safety and production, as well as political, social or individual objectives (Chen and Hu, 2013; Hysing, 2022). This conflict is negatively impacted by differing priorities among stakeholders, leading to incidents that can have significant health and safety consequences. Balancing these competing goals to minimise utility strikes and their associated impacts constitutes a major challenge. Safety protocols are often compromised in favour of production targets, leading to increased risk of utility strikes. For instance, the pressure to meet deadlines and tight profit margins can result in shortcuts that disregard safety measures, such as proper utility detection and excavation practices (Metje et al., 2015).Utilising excavators, which are more efficient but riskier than hand tools, is a common example of prioritising production over safety (ibid). Poor communication can engender conflicts, while strategies like compromise and collaboration can help align differing objectives and reduce the incidence of utility strikes (Afanyedor, 2021).

Lapses and slips are unintentional errors that occur even among well-trained individuals (Sarvari et al., 2024b). These errors often result from momentary lapses in attention or memory, such as forgetting to close a valve or misreading instructions (Kletz, 2009). Such errors are not easily mitigated through additional training or punishment because they are often inherent to human cognitive processes (Kletz, 1999). In contrast, routine violations involve deliberate deviations from established procedures, often driven by social and motivational factors rather than a lack of knowledge (Reason et al., 1990). These violations can be exacerbated by organisational culture and practices that implicitly encourage or overlook such behaviour (Kletz, 2009). Organisational errors are essentially human errors at the managerial level, where systemic weaknesses are not addressed (Kletz, 2009). Inadequate identification of worksite hazards and insufficient leadership are significant contributors to human error because they create environments where errors are more likely to occur (Tayab et al., 2020). Errors are often linked to information-processing characteristics, while violations are influenced by social and motivational factors (Reason et al., 1990). While human error is a prevalent cause of incidents, it is crucial to recognise that these errors are often symptomatic of deeper organisational issues. Addressing these requires a holistic approach that includes improving organisational culture, enhancing training programs and redesigning work processes to minimise opportunities for error.

5.3 Strategies for Addressing the Causes of Incidents in Utility Strikes

A comprehensive understanding of the root causes of utility strikes is essential for developing effective strategies to prevent and mitigate future disruptions. By identifying these root causes, stakeholders can implement preventive measures significantly reducing the incidence of utility strikes (Afanyedor, 2021). Collaboration across sectors is crucial to developing comprehensive strategies to prevent utility strikes. Utility companies, construction firms and regulatory bodies must work together to create a unified approach that addresses the complexities of utility management and excavation practices (Metje et al., 2015). Regulatory compliance plays a vital role in this context, as adherence to local regulations regarding utility marking and excavation practices is critical for ensuring safety and preventing strikes (Ibrahim et al., 2017). Moreover, the implementation of safe excavation practices, including proper training and equipment use, is essential for minimising risks during utility activities (Tayab et al., 2020). Training and education for workers on utility identification and safe digging practices are vital components of a comprehensive prevention strategy (Afanyedor, 2021). By equipping workers with the necessary knowledge and skills, the likelihood of utility strikes can be significantly reduced. In summary, a thorough understanding of the causes of utility strikes, combined with the implementation of preventive measures, technological innovations, regulatory compliance and effective training, can inform strategies that significantly mitigate future disruptions.

Recent advancements in digital technologies offer promising avenues for enhancing underground utility detection and reducing strike risks. For instance, integrations of artificial intelligence (AI) with ground-penetrating radar (GPR), building information modelling (BIM) and augmented reality (AR) have been explored to improve visualisation and accuracy in utility mapping (Sarvari et al., 2022; Su et al., 2023;). These technologies facilitate real-time data processing and 3D reconstruction, potentially complementing traditional excavation practices (Maree et al., 2021). Furthermore, international studies highlight variations in prevention frameworks; for example, empirical investigations in Australia have examined underground utility strikes and associated prevention measures (Koschmann et al., 2022), while research in the USA emphasises root cause analysis for third-party damages (Al-Bayati and Panzer, 2020). Such comparative insights underscore the value of context-specific approaches, reinforcing the need for tailored strategies in the UK sector.

To effectively mitigate the causes of incidents related to utility strikes, a comprehensive approach involving proactive and reactive measures is essential. The research highlights a set of proactive and reactive measures in three primary stages (i.e. 1) pre-event; 2) event; and 3) post-event - refer to Figure 5). All provided measures have been extracted from the associated documents related to the case studies considered for this present research. Therefore, these stages will provide a practical framework to manage and mitigate the causes of incidents related to utility strikes. Measures presented in the pre-event stage cover the causes of incidents that are mostly related to the review of competencies, work permits and safety planning. The event stage measures cover the root causes of incidents associated with the site (e.g. monitoring and control and site handover briefing). Post-event measures focus on lessons learned from incidents, reliability reviews, policy and training updates and necessary alternatives. This phased framework distinguishes itself by synthesising empirical insights from realised incidents into a comprehensive prevention strategy, extending beyond traditional reactive measures to incorporate proactive and resilient elements tailored to utility strikes.

To facilitate practical implementation, the framework offers specific operational measures tailored to each phase. In the pre-event stage, organisations should conduct mandatory competency assessments for operators and managers, including verification of qualifications and site-specific briefings, alongside mandatory permit-to-dig processes with cross-verification of utility drawings (Makana et al., 2018; Metje et al., 2015). During the event stage, real-time measures include on-site supervision with mandatory pause-and-check protocols before excavation, deployment of cable location tools (e.g. CAT and Genny scanners) with documented scans, and team briefings for handover to ensure continuous monitoring (Edwards and Love, 2016). In the post-event stage, structured debriefs should be mandated, incorporating root cause analysis with updates to risk assessment methods statements (RAMS), training modules, and policy revisions, while sharing anonymised lessons across projects to foster organisational learning (Bayramova et al., 2024; Zhou et al., 2019). These operational details, directly informed by the analysed incidents, enable utility managers to integrate the framework into existing health and safety protocols, thereby enhancing prevention efficacy and reducing societal costs associated with disruptions.

To illustrate practical application of the framework (Figure 5), consider a synthesised example from the case studies involving an excavator strike on a buried electricity cable:

- **Pre-event**: Competency assessment identifies an inexperienced operator (addressing COI5); a permit-to-dig is issued only after verified utility scans and team briefing on outdated drawings (mitigating COI29 and information deficits).
- **Event**: On-site supervision enforces pause-and-check protocols upon encountering unexpected resistance, with immediate use of cable location tools and communication halt to reassess (countering COI1 and COI16 human errors).
- **Post-event**: A structured debrief conducts root cause analysis revealing leadership oversight; outcomes include updated training modules on spatial awareness and revised RAMS for similar sites, with lessons shared organisation-wide (promoting learning and addressing COI24 communication failures). This worked example demonstrates how the phased measures can interrupt causal pathways, preventing escalation and fostering resilience.

This comprehensive safety framework that incorporates both proactive (i.e. Safety I) and reactive measures (i.e. Safety II) across the event can significantly enhance workplace safety (cf. Sarvari et al., 2024a). This approach allows organisations to anticipate risks, respond effectively to incidents and learn from past events (via a feedback loop), thereby fostering a culture of continuous improvement. In the pre-event phase, proactive safety measures are crucial. Risk management techniques can be employed to identify potential risks and their root causes before they lead to incidents. A proactive strategy not only mitigates risks but also enhances overall workplace safety by addressing vulnerabilities in processes and systems (Benson et al., 2024). Additionally, the development of a portfolio of identification indicators of company safety enables organisations to assess safety levels and implement necessary measures proactively (Poghosyan et al., 2020). Leading indicators, which provide real-time data on safety activities, further support this phase by allowing organisations to monitor safety conditions and make informed decisions (Bayramova et al., 2024). During an event, reactive safety measures become essential. Implementing effective incident reporting systems allows for the documentation and analysis of safety incidents as they occur. These systems facilitate learning from past events, enabling organisations to adapt and improve their safety protocols in real-time (Cheng and Teizer, 2013). Moreover, near-miss reporting plays a vital role in this phase because it helps identify potential hazards before they escalate into serious incidents (Zhou et al., 2019). By fostering a culture that encourages reporting, organisations can gain insights into safety performance and enhance their response strategies. In the post-event phase, accident investigation and reporting are critical for identifying root causes and informing future safety measures (Thallapureddy, 2024). This reactive procedure not only helps prevent recurrence but also contributes to a deeper understanding of safety dynamics within the workplace. Insights gained can be integrated into the safety framework, ensuring that lessons learned translate into improved practices thus, creating the basis for a learning organisation. Overall, a structured safety framework that balances proactive and reactive measures across all phases of event management can lead to a more resilient safety culture. This practical framework describes an effective program, drawing on proactive and active measures, which limit utility strikes in road construction projects, improving safety and health in projects. This should be taken into consideration at the organisational level by businesses engaged in utility excavation works and at an industry level by practitioners concerned with utility services installation, repair and maintenance. This framework operationalises practical guidance for human, equipment, physical and socio-economic factors across the pre-event, event and post-event phases of utility strikes.

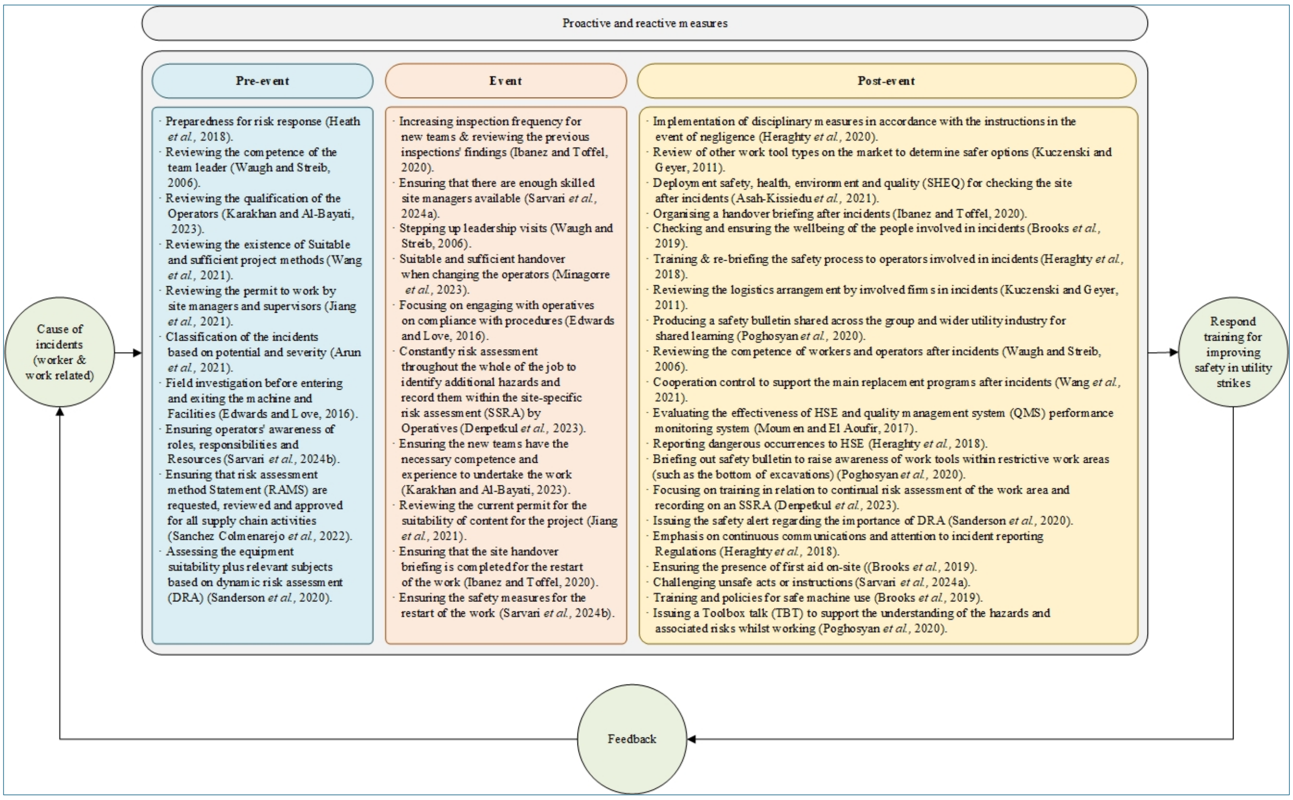


Figure 4: A phased framework (pre-event, event, post-event) for addressing the causes of incidents in utility strikes.

6 Theoretical and Practical Contributions

By employing a qualitative approach, the research analysed ten detailed case studies, which provided a rich context for understanding the complex array of interrelated causes of utility strikes. Specifically, a total of 33 causes were identified and classified into two main dichotomous categories viz.: worker-related causes; and work-related causes. This classification not only aids in understanding the diverse nature of utility strikes but also underlines the significance of addressing both human behaviour and systemic problems on site. Worker-related causes, such as lack of training or negligence, underscore the necessity for improved training programs and awareness activities. Conversely, work-related causes emphasise the significance of effective planning and risk assessment in construction and maintenance works in utility projects.

Theoretically, the study contributes to extant literature by categorising these causes of incidents into two primary categories. This classification enhances the comprehension of the interplay between human behaviour and operational systems in affecting safety outcomes. For instance, operator errors, such as neglecting basic safety protocols and failing to identify hazards, underscore the critical role of human factors in accident causation. Additionally, the research highlights the significance of compliance with SSoW and the repercussions of insufficient training and supervision, which are crucial in influencing safety culture within organisations. A comprehensive cause and effect analysis is also provided which elucidates the relationships between various factors leading to utility strikes. By mapping these relationships, the research provides a framework for understanding how different elements interact and contribute to incidents, thereby enriching contemporary knowledge of utility safety. A basis for future studies is therefore provided which should develop more robust safety management systems tailored to the unique challenges confronting utility works.

The development of the pre-event, event and post-event framework represents a novel contribution by operationalising an empirically grounded, phased approach to utility strike prevention that bridges Safety I (proactive risk anticipation) and Safety II (reactive learning and resilience) principles in the specific context of underground excavation works (Sarvari et al., 2024a; Bayramova et al., 2024). Unlike generic safety frameworks or technology-focused prevention models prevalent in the literature (e.g. machine guidance systems or best practice guidelines), this framework provides a structured, actionable pathway encompassing competency reviews and planning (pre-event), real-time monitoring and control (event), and post-incident learning with policy updates (post-event), directly informed by root causes identified in the case studies. This integration offers practical guidance for addressing human, equipment and socio-economic factors across the incident lifecycle, enhancing its applicability for organisational and industry-level adoption in the UK utilities sector.

Practically, the study provides actionable insights that can be utilised to mitigate the risks associated with utility strikes and have significant implications for incident prevention strategies. By identifying specific causes such as poor communication, inadequate leadership, and insufficient safety equipment, the research offers a roadmap for utility managers to implement targeted interventions. For example, enhancing communication among team members and ensuring that operators/workers are adequately trained and familiar with site layouts can significantly reduce the likelihood of incidents. Furthermore, the study emphasises the necessity of proper documentation and the availability of accurate utility drawings, which are essential for informed decision-making during utility activities. Insights gained from the case studies can inform the design of safety management systems that are adaptable to the diverse nature of utility projects, ultimately fostering a culture of safety within the industry. Emergent findings not only educate safety measures but also encourage a shift in organisational culture towards prioritising health and safety, thereby reducing the economic and social costs associated with utility accidents. Consequently, this study not only advances theoretical understanding of the causes of utility strikes but also provides actionable insights and strategies that can lead to improved safety practices in the UK utility sector. The enhanced operational guidance within the three-phase framework further strengthens its utility for practitioners, offering step-by-step measures (such as competency verification, real-time scanning protocols and post-incident debriefs) that can be readily embedded in site procedures to minimise strike risks and associated economic and societal impacts.

7 Limitations and Future Research Directions

The qualitative approach employed is a limitation which may introduce subjectivity and bias, potentially affecting the reliability and generalisability of the findings across different contexts beyond the 10 detailed cases analysed. A qualitative methodology allows for in-depth exploration of the incidents but it may not capture the full spectrum of factors influencing utility strikes, leading to an oversimplified understanding of the problem. Moreover, while the qualitative analysis of 10 detailed case studies can be valuable outcomes for the industry, the reliance on a limited sample size may restrict the generalisability of the findings, as the cases may not encompass the full spectrum of incidents across diverse utility environments. Additionally, the categorisation of the identified causes into 'worker' and 'work' categories are useful for organising the data, they may overlook the complex interplay between these factors. For example, this classification could mask the multifaceted nature of utility strikes, suggesting a need for more nuanced frameworks that consider the interactions between various causes.

Finally, the study's reliance on UK case studies may limit the applicability of the findings to other regions or industries with different safety cultures and practices. Additionally, while the manuscript references technological solutions, greater emphasis on emerging digital tools (such as AI-enhanced GPR and AR visualisation) could enrich future analyses (Su et al., 2023). Expanding the scope to include more international comparative studies on utility strike prevention frameworks would further enhance transferability beyond the UK context. Furthermore, the purposive selection of 'dangerous occurrences' and 'lost time' incidents, while providing detailed and reliable data for root cause analysis, excludes near-misses and minor events, which are valuable precursors for proactive prevention (Zhou et al., 2019). Future research should incorporate near-miss reporting to complement analyses of realised incidents and enable earlier intervention in causal pathways.

Future study should aim to expand investigations beyond UK highway incidents to include a wider array of case studies from diverse geographical areas and utility sector contexts. This approach would both confirm the established reasons of utility strikes and enable the formulation of more extensive preventative initiatives. Furthermore, utilising mixed-methods approaches that combine qualitative insights with quantitative data may strengthen the findings, offering a comprehensive perspective on the reasons leading to utility strikes. Investigating the causal linkages among the highlighted parameters is essential because it may provide significant insights into how various elements which interact and affect the incidence of utility strikes. For instance, utilising Bayesian modelling analysis could guide the formulation of focused interventions and risk mitigation strategies that successfully tackle the underlying causes of incidents. In addition, it is imperative to examine the factors contributing to the non-compliance with SSoW, since this underscores a critical deficiency in adherence to established safety measures. Future studies should focus on improving compliance with these methods to reduce hazards related to utility strikes. A significant domain for further investigation is operator errors, recognised as a primary contributor to utility strikes. This signifies an urgent necessity for enhanced training and awareness initiatives. Research may concentrate on assessing the efficacy of training interventions in mitigating these errors and improving overall safety performance. Moreover, examining the influence of leadership and oversight in mitigating utility strikes is essential, as insufficient leadership has been identified as a contributing factor. Consequently, subsequent research should investigate management techniques and their effects on safety results. Finally, it is crucial to address the causes of inadequate communication among team members because this problem highlights the need for the formulation of optimal communication techniques within utility teams to avert mishaps. By concentrating on these domains, researchers might enhance the overall comprehension of safety dynamics in utility projects. Additionally, the absence of formal inter-rater reliability testing in the NVivo coding process represents a limitation of the single-researcher interpretive approach. Future studies could incorporate multiple coders to strengthen validation of thematic identification and causal relationships.

8 Conclusions

Buried utility services strikes present serious safety and cost implications and it is important to prevent them from occurring during excavation works. The case studies identified the causes of strikes and indicated how they can be avoided in the future. This article analyses 10 sampling cases based on UK road projects to provide insights into the causes of incidents in these projects. A total of 33 causes of incidents were identified and categorised into two primary categories (i.e. worker and work). A key finding was that the worker related issues in underground utilities causes a significant number of strikes. More importantly, such issues can be prevented by training and controlling the qualifications before the activities. In many of the cases, the potential of these causes intensifies by the occurrence of work-related issues. Additionally, this study provides a practical framework for addressing the identified causes and offers a different perspective from many other previous works. Specifically, by exploring the causes of incidents and providing an innovative practical framework for improving safety in buried utility services the research elucidates upon practical prevention measures that could be implemented.

While literature is replete with generic types of causes of incidents (such as safety communication, safety climate, leadership and commitment), this study provides much needed granular detail of incident causes that are more specific and activity oriented. This finer nuanced perspective is imperative because it will yield actionable insights for site users. The long-term goal of this multi-step research is to create a knowledge repository that includes the causes of utility strikes and their related insights, which will require ongoing development and revision. This knowledge repository will provide a basis for organisations and industries in their pursuit of becoming continuous learning entities and therefore, lower the risk of (and magnitude of harm incurred from) utility strikes.

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Data Availability Statement

Data is subject to a non-disclosure agreement and is not available for wider dissemination or sharing.

Conflicts of Interest

The authors declare no conflict of interest.

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