Sustainable Approach to the Replacement of Water Mains: Environmental, Social and Economic Considerations

Bert Ediale Young, Rafiu Deji Seidu, A. Kelani, Herbert Robinson, Obas John Ebohon, and Upeksha Madanayake

Abstract Water mains in many areas of London and some parts of the Thames Valley are still thus the oldest and in need of replacement. The mains have been susceptible to corrosion, leaks and subsequent breakage, causing water wastage, continuous maintenance cost, social and environmental impact because of disruptions to water supply to local communities, road congestion and damage to the road infrastructure. The aim of this study is to examine the factors, which determines the methods adopted for the replacement of water mains and the economic, environmental, and social considerations that underpins the decision-making process. The research method adopted is a mixture of quantitative and qualitative approaches using surveys and interviews. These trenchless techniques are preferred due to lower cost, speed and productivity. Directional drilling was selected due to its cost, speed and productivity but also because it is the most customer driven method to ensure a constant supply of water. There is a need for a sustainable procurement approach incorporating social and environmental factors which affects productivity such as ground conditions, unknown utilities, the impact of water disruption on residents/schools and delays

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due to obtaining road access permits. Involvement of Local authorities in the design and accessibility discussion can help speed up the process and increase productivity.

Keywords Water mains · Replacement methods · Environmental · Social and economic factors · Sustainability

1 Introduction

Despite major investment over the past decades within the UK's water industry, water mains in many areas of London and some parts of the Thames Valley are still thus the oldest and in need of replacement [21]. Historically water mains installed in the twentieth century were made from cast and ductile iron which were expected to hold a life expectancy of 50–100 years of trouble-free services [17]. Unfortunately, the mains have been susceptible to corrosion, leaks and subsequent breakage causing overall water wastage, continuous maintenance cost, disruptions of water distribution to local communities, road congestion and damage to road infrastructure [21]. Ofwat (2016), the water industry watchdog annual report highlighted 20% of water lost is occurring before it reaches homes and there is no sign of it declining. For example, Thames Water the biggest water company in the UK was reported as the leakiest, with 20,500 L escaping everyday per kilometre of main [9]. A Thames Water spokesman highlighted difficulties in the rehabilitation of water mains within London and argued that "Large scale mains replacements are disruptive, especially with two-thirds of our network running under the busiest and hardest to reach roads in London [9].

With many thousands of miles of water mains still to be replaced in the UK, it is anticipated that the costs of infrastructure renewal will be high with significant disruption to customers, households, road users and other stakeholders. Since the early 1990's the construction industry has been increasingly pressured and challenged to improve its efficiency and effectiveness. The focus of this research is on the replacement of water mains. Considerations will be given to the current methods used to replace water mains such as trenching/ open cut (OC) method, trenchless water main replacement technology, and the factors which are considered when selecting the most efficient and cost-effective methods of rehabilitation. There is also a need to balance social, economic and environmental factors to ensure sustainable procurement (see Fig. 1) for illustration.

In determining the most appropriate method, it will be crucial to consider the associated costs involved in replacing water mains, as well as social and environmental factors such as service disruption to customers and road users, accessibility, and other challenges/ restrictions. Hence, the aim of this research is to examine the factors, which determine the methods adopted for the replacement of water mains and the role of environmental and social considerations.

Fig. 1 Balance of sustainable procurement [5, p. 11]

2 Literature Review

2.1 Structure of the Water Industry

The UK has regional statutory water and wastewater companies responsible for public water supply and wastewater networks in the entire country. For example, Thames Water is responsible for providing water in the Greater London and the Thames Valley. Thames is the largest water and wastewater company in the UK and every day it treats and supplies 9.5 million customers with treated drinking water and removes and treats wastewater from 14.9 million customers [21]. All the regional water companies are regulated by the Water Services Regulation Authority ("Ofwat"), the Environment Agency and the Drinking Water Inspectorate ("DWI").

1. Ofwat is the economic regulator for all appointed water and wastewater companies and water-only companies in England and Wales. Ofwat is responsible for price control in a process known as Periodic Review ("PR") [21].
2. The Environment Agency (EA) seeks to maintain and improve the quality of 'raw' water in England and Wales and is responsible for issuing water companies with abstraction licences and discharge consents [21].
3. The DWI regulates all appointed water companies in England and Wales. It acts on behalf of the Secretary of State for the Department of Environment, Food and Rural Affairs ("Defra") and undertakes technical audits of water suppliers to examine all aspects of water quality, treatment and monitoring [21].

In an attempt to improve the delivery of water in the UK, water companies forge partnerships with major contractors and subcontractors. For example, in April 2017, steps were taken by Thames Water to launch the largest alliance in the water sector named Eight20. The partners involved are Thames Water and two designs and built joint ventures; made up of Costain, Atkins, IBM; and Skanska, MWH and Balfour

Beatty (SMB). The aim is for the alliance to carry out £1.75 billion of capital investment work during the AMP6 period (2015–2020), with the potential to extend the contract to 2025 [21]. Such partnerships by water companies are designed to put their best people, practices, and techniques in water projects to deliver innovative, sustainable solutions to generate greater value for money and benefits to water companies including a stable return.

2.2 Water Mains Replacement Methods

In many developed countries, the urban water supply infrastructure is in crisis due to various factors, such as increasing urban populations, insufficient attention to maintenance and replacement planning 23. There has been rapid innovation in mains rehabilitation techniques in the water industry within the UK, where existing practices are commonly categorised as "Trench" and "Trenchless" methods. Over the past 30–40 years a suite of "trenchless" technologies has been developed for rehabilitation of water main and wastewater assets that no longer require full ground excavation and replacement 20. The various methods are discussed below.

Open Cut" Trench Methods

Traditionally, pipe rehabilitation is undertaken using an open cut method, as shown in Fig. 2, in which the ground where the old pipe is situated is completely excavated and the old pipe is totally removed and replaced with new pipe. Based on the type of work, this method is also called dig- and—install, dig-and-repair or dig- and- replace [19].

It is often described as more time-consuming and does not always yield the most cost-effective method of pipe installation and renewal [15]. The social costs include cost to public, environmental impacts, damage to pavement existing utilities and

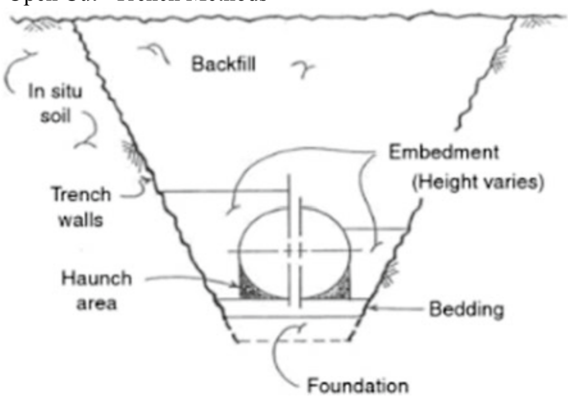


Fig. 2 Open-Cut installation [11]

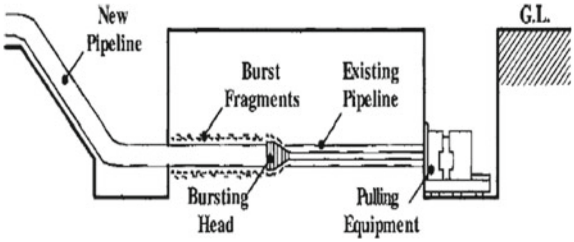


Fig. 3 Configuration for pipe bursting [12]

structures in addition, loss of access to businesses and homes and undesirable noise and sight pollution [8].

Figure 3 shows another method called pipe bursting, a trenchless rehabilitation technique which involves installing a new pipe by pulling or pushing a device as a bursting head through the existing pipe [13]. This method allows the installation of larger diameter pipes, increasing the water pipeline capacity and addressing increased urban water consumption. However, a major limitation of this process includes the need to disconnect and reconnect existing service connections from the surface, so an element of the conventional open-cut method is still required. Additionally, the technique cannot negotiate bends in the existing pipe.

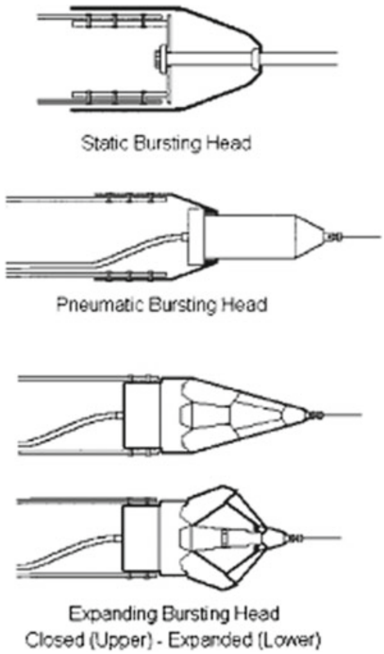
Lueke and Ariaratnam 14 outline the three main systems currently used in the pipe bursting industry as: Static, Pneumatic, and hydraulic. The main difference between each method is the way force is generated and transferred to the original pipe during the bursting operation (See Fig. 4).

2.2.1 Horizontal Directional Drilling (HDD) (Trenchless)

Horizontal Directional Drilling (HDD) which is shown in Fig. 5 is the most rapidly growing method in the range of trenchless technology and techniques available [2]. This technique was originally developed by the oil industry in the United States but is now widely used for installing all pressure pipes under obstacles such as motorway, large rivers and airport runways [6]. The HDD equipment consists of five group components, (1) Drill rigs, (2) Bore drilling, (3) Drilling, fluid system, (4) Tracking system and (5) Accessories. The method involves the pipeline being bored under the crossing to emerge at a target point on the opposite side. Figure 5 opposite illustrates the process of Horizontal Directional Drilling (HDD).

Allouche et al. [1] further identified the advantages of the HDD technique over other trenchless technologies as not requiring vertical shafts as drilling starts from the surface, short installation and setup time, flexibility of borehole elevation alignment and manoeuvrability around the existing underground services and one single drive installation length is longer than any other non-man entry trenchless method.

Fig. 4 Schematic different bursting head [12]



2.3 Environmental and Social Considerations

Allouche et al. [1] noted that trenchless methods are preferred due to the high cost incurred in tackling numerous environmental and social factors. [3] argued that the HDD method gradually evolved to a preferred method due to the high costs associated with the open cut method in crowded urban areas, consideration of social costs such as traffic delays, distraction of business activities and environmental issues such as placement of pipelines across rivers, and other environmentally sensitive areas. Lueke and Ariaratnam [14] further noted that accessibility constraints within urban areas and increased underground congestion has resulted in making the traditional open cut method a more expensive technique and even impossible in some situations. Jung and Sinha [12] highlighted how negative social and environmental impacts influence the effectiveness of pipe laying methods.

McKim [16] argued that disruptive open-cut methods are often not acceptable when working with underground infrastructure systems due to the increase in traffic congestion which causes major inconvenience to the public, and decreased road lane widths which can make road accidents more likely to occur. Myers et al. [18] identified the key considerations for local businesses and residents due to congested construction sites which are likely to result in loss of customers due to traffic disruption or loss of access when the open-cut method is used. This may also result in significant loss of sales for businesses and tax revenue for the local government. Additionally, major inconveniences such as traffic congestion and delays are often imposed

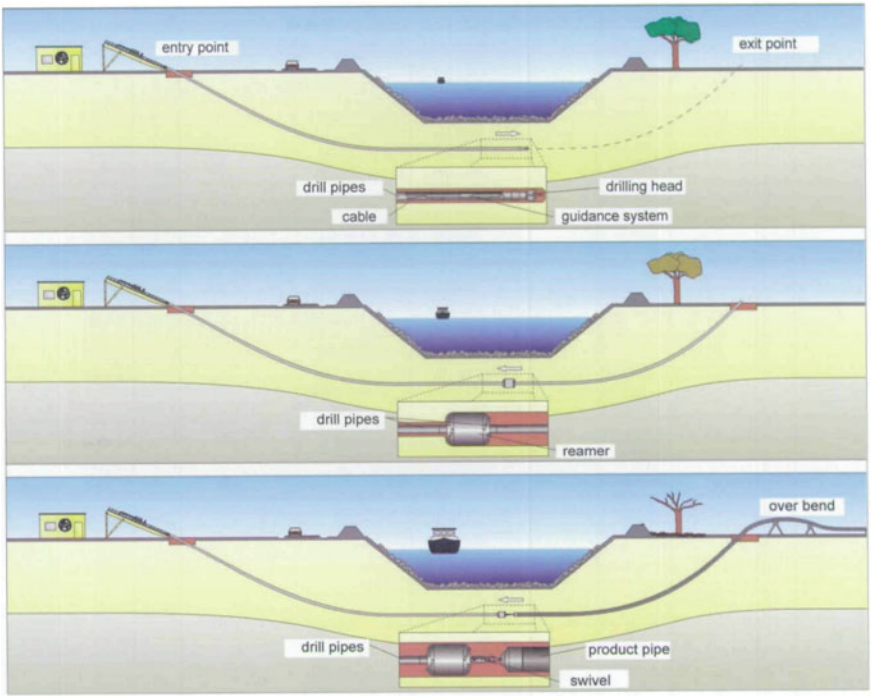


Fig. 5 The stages in horizontal directional drilling [4]

on neighbourhoods which can make commuting strenuous. Jung and Sinha [12] also argued that the open-cut method often requires removal of pavements followed by subsequent restoration, which significantly reduces pavement life. Surface subsidence of the pavement from the cutting and patching process in the open-cut method can reduce pavement life by about 40%. Additionally, Jung and Sinha [12] further argued that the open-cut method frequently causes environmental damage to grass, trees, and other landscaping features and can have negative effects on conservation.

McKim [16] discusses how pollution in the form of air, noise and water can be caused through trench excavating. Firstly, air pollution in the form of fine soil particles may become airborne in the form of dust due to wind blowing over the soil stockpiles created during the process with the open-cut method. Secondly, rain or water encountered during construction using open-cut methods can cause soil erosion and run off of contaminated solids into streams, rivers, and sewers. Thirdly, mains replacement techniques require the use of heavy equipment that produces high levels of noise causing a great deal of disturbance, especially to established communities and residents. Allouche et al. (2001) highlighted the importance of geotechnical investigation and the need for awareness of the soil type. Geotechnical investigations are used to define the existing soil types and conditions to enable the contractor to make the best arrangements and to choose the most suitable equipment for maximum productivity. The quality and quantity of the available geological information during design and bidding phases is very important in estimating production rates, shaft design and maximum drive length for any construction method. Hegab [10] reiterated the importance of knowledge of the soil type as contaminated soil is often encountered during pipeline construction. This is particularly the case within open-cut methods as it requires removing large volumes of soil. The disposal of this material, which requires specialized equipment and labour can be costly. Hegab [10] noted further that unexpected soil conditions may cause a loss of connection with the drilling head and can delay the whole pipe installation process. HDD drilling bits are used according to soil type and pipe length. Ariaratnam and Allouche [3] argued that prior to job initiation, work field should be visited for a visual inspection to address important issues that affect quality and speed of work (i.e., sufficient room for entrance and exit pits; equipment; support vehicles; and fusion machines). In addition, it is noted that weather conditions have a major effect on any form of trenchless technique. Temperature, humidity, rainfall, and snow might cause an obvious delay in work due to their direct effect on machine, soil and worker productivity.

3 Research Method

A case study approach was selected as the authors wanted to conduct an in-depth analysis to understand the social, economic, and environmental considerations of replacement of water mains. After the privatisation of regional water authorities in England, maintenance became the responsibility of private companies, rather than the state which led to the first Asset Management Period (AMP) [22]. The sixth asset management period which is known as AMP6 commenced from year 2015. AMP6 water main replacement project in Reading was selected as the single case study due to its typical nature. Mixed method of both quantitative and qualitative research techniques was used within the case study. Quantitative data was collected through questionnaire survey in order to capture the main replacement methods and key considerations associated with environmental and social factors. Qualitative data was derived through interviews with six (6) key decision-making personnel in the case study project. The interviews provided greater insight on tendering and operational issues and the findings are summarised below.

4 Findings and Discussion

4.1 Main Replacement Methods and Key Considerations

80 web-based questionnaires were distributed via e-mail to those related to the selected case study project. 27 respondents completed the questionnaire, making

the response rate as 33.75%. From the completed questionnaires, the respondents range from Quantity surveyors (25.9%), Directors (18.55%) and Site Supervisors (22.2%) and others involved with the delivery of mains replacement projects within the UK Construction Industry. Horizontal Directional drilling is overwhelmingly the most preferred method favoured by 70.4% of the participants. Sliplining is the second preferred method with 18.5%, followed by the open cut method (11.1%). The trenchless method of pipe bursting was not selected. Most common factors leading to a change in technique is utility obstructions (34.2%) and ground conditions (27.6%). Others included value engineering (9.2%), space restriction (17.1%) and inadequate designing (11.8%). When deciding on the most appropriate method, labour force and quality of equipment was not considered a major factor. However, cost and level of disruption were selected by 21.4% and 23.2% respectively, suggesting that these are the two major influences when deciding on the most appropriate method. Of the 11 subcontractors who participated, 8 selected '*cost'* as key factor and 3 out of the 4 client/ local authority selected '*customer satisfaction*' as a key factor, clearly indicating that subcontractors are more driven by cost whilst clients/local authorities are more concerned with customer satisfaction. On external factors impacting projects, road restrictions (29.6%) and permit issues are the most cited, though utility services (25.9%) is also noted as a prominent factor. However, environmental impacts on wildlife, environmental regulations and pollution were not highlighted as having any impact by participants. The notion that it is harder to achieve productivity in London in comparison to the regions in the UK was widely acknowledge with 92.6% of participants agreeing to that. On other environmental or social factors which impacted productivity, the additional comments made by participants are shown in Table 1.

Table 1 Additional comments on environmental and social factors

Environmental and social factors that impacted productivity
• Technology—Regarding ground conditions, as laid surveys, utility drawings and CAT (cable avoidance tool) and Genny (signal generator) equipment are improving all the time with technology, making it easier to pre-determine ground conditions.'
• Coordination—The coordination between Highways Agency, client, sub-contractor and customer are misaligned. Permit restrictions and limited working length will impact on productivity, cost per metre, which will result in slowing the process, delays and low productivity on site, ultimately causing more customer dissatisfaction and complaints
• Awareness of the project—The sooner the local authority is informed about proposed work, the more likely disruptions will be reduced
• Location—is a key factor which is influenced by density of housing/urbanisation, parked cars, restricted roads, built up areas and busy road due to large volume of vehicles
• Other factors—such as surrounding environment, existing network construction and conditions

Table 2 Profile of the respondents

Participant reference	Sector (job title)	Years of experience in construction industry	Years of experience with water sector
A	Client (Customer Relation Department)	18	8
B	Highways Agency	7	3
C	Main contractor (Construction Manager)	35	35
D	Sub-contractor (Project Delivery Manager)	33	30
E	Client (Contracts Manager)	25	18
F	Sub-contractor (Site Supervisor)	12	10

4.2 The Case Study Project

The project is AMP6 Water Mains Replacement Project in Reading. The contract commenced in June 2017 and finished in April 2018. The project involved the replacement of a total of 12,449 m (m) Cast Iron main to Plastic Polystyrene new mains as well as renewing services. The original design drawings had 11,186 m (89.85%) of the 12,449 m scheduled being replaced using a trenchless (no excavation) technique and the balance 1,263 m using the open cut (OC) method. The contract value was £2,002,435.90 million and it was implemented using an Early Contractor Involvement (ECI) approach. The profile of the interview respondents within the case study are given in Table 2.

4.2.1 Main Factors Influencing Selection Process

Trenchless methods such as directional drilling and slip lining are preferred in general to trench method due to several factors such as they are quick, cheap, efficient, and productive. For example, one of the participants mentioned that "…. *slip lining is cheaper, productive and most importantly it enables customers not to be out of water for more than the 4 h window*" (Participant C). Participant F also stated that "*As we work on price our main objective is to get as much new main in the ground as quick as possible, so speed and productivity is the main factor for me*".

According to the interviews, sliplining can be efficient but the main factor preventing it from being used is the fact the water mains that needed to be two ways fed for customer supply should not be affected. Further due to urbanisation and the demand for water increasing all the time most of the 90 mm existing main had to be replaced by 125 mm and 180 mm so slipping lining was not appropriate as "*Sliplining requires a smaller main to go in larger one*" (Participant C). The element of open cut is guaranteed, for roads with poor ground conditions, restricting accessibility, for launch pits, pipe connection, bends, services, valves, hydrants, and wash outs.

In addition, risk was considered as one of the main factors influencing the selection of appropriate water replacement methods. Participant D supports this by stating as "*we don't like to take risks especially with drilling as we are liable to any utility or cable strikes, which can cost anything from three thousand to five thousand pounds to repair as well as delay the programme*".

4.2.2 Environment, Social and Economic Factors

Environmental and social issues are a major concern in water mains replacement project and are key factors to be considered as early as possible. Participants expressed strong views on environmental issues, for example, Participant A noted "*Environment is a very sensitive factor, especially wildlife issues when working in the provinces. I've experienced problems with nesting, Japanese's knotweed which causes much panic and suspends works, asbestos, TPO on trees (which means they cannot be knocked down). Bushes are not allowed to rip down anymore so works need to be adapted around it"*. Contamination within excavations is a major issue now with the directional drilling method, as sometimes the ground conditions are too difficult to drill, so to avoid switching to an expensive method like Open Cut, adding a fluid called bentonite into the drilling rig makes it easier to drill. However, the environmental issue occurs when the bentonite remain that can contaminate the water is left in the excavations. In order to avoid tankers are required to suck the slurry out of the excavation. Whether this counts as a compensation event as such has been a debate as subcontractors argue they are having to incur an additional cost they would not have allowed for in their original price. Noise pollution is also a major environmental concern. The project has taken adequate measures to minimise the impact of noise pollution as acoustic barriers are commonly used. To confirm, Participant B stated, "*the noise from machine has led to strict guidelines that no machine can be turned before 8am and after 6 pm. Night works in residential areas are very minimal too.*"

Accessibility is a general issue rather than one related to a replacement method itself. Participant D commented as *"within this job we had numerous issues in obtaining road closure approval and digging permits on time. This is a continuous problem I've seen working for the Main Contractor"*. When there is a space restriction such as working on tight roads and the trenchless machines are unable to access, an Open Cut method is usually the preferred method as it allows for hand digging in such space restricted areas.

Further, having a good relationship with efficient communication with the local authorities and communities was highlighted as an important social factor. To minimise any social issues, it is essential to liaise with residents, schools, and local businesses to ensure that they are kept aware about the planned work. Participant A from the Customer Relation Department emphasised this point by stating *"Before a construction programme is agreed we must meet with the designers and operation* *team in order identify any "red flags" which will impact the locals. I then meet with the local council to discover whether it will be signed off .... this needs to be conducted 6 months sometimes 12 months before the proposed start date"*. To minimise the impact of the project on the locals, project programmes that can cause most disruptions are usually scheduled around school holidays or outside school hours. When the water supply needs to be turned off residents and businesses are given 48 and 72 h' notices respectively. The lack of notice commonly delays the works as the Client usually refuses to turn off water with no notices. At public buildings such as schools and hospitals, water supply is never turned off.

The actions taken to mitigating the cost of the environmental and social disruptions were also discussed during the case study interviews. As per the project delivery manager (Participant D), cable strikes can cost anything from three to five thousand pounds (£3000–£5000) to repair every time they are hit. This is more likely to occur when there are a lot of utility services present. The cost of full road closure varies from two to four thousand pounds (£2000–£4000) a week which is a cost for the Main contractor. It can cost up £1250 to gain early road access as such it is key to plan early and adequately to ensure road permits are in order.

Road restrictions/permits, and utility services have a major impact on productivity too. This is echoed by the participants by emphasising the significance of delays in obtaining road permits, the need to conduct trial holes to ascertain the ground conditions and the utility services frequency of the working areas. With the amount of time being spent on conducting trial holes to establish ground conditions, the question posed on the significance of pre-investigation to improve productivity. Pre-investigation is absolutely necessary as it enables the contractor to make the best arrangements and to choose the most suitable equipment for maximum productivity. Participant D stated that "*trial holes are supposed to be done every 25 m when drilling but this is commonly not done to save time and money, but this is a main catalyst for reduction in productivity'*. It has been suggested that the traditional culture of having a short-term view in time and money saving is a reason why thorough pre-investigation is not being conducted which is ironically leading to further loss in time and costs. The delay that occurred in the project due to not obtaining notices and having to conduct trial holes amounted to £31,931.21 which is about 8% of the overall cost of compensation events.

Looking at the processes currently in place to deal with change in technique, submitting Technical Queries (TQ's) has been seen to have received mixed views. The case study highlighted that Participant C (Construction Manager/Main-contractor) requested for a change in technique within 24 h. However, Participant D (Project Delivery Manager—Sub-contractor) argued this is hardly ever achieved within 24 h and that the site supervision should have more delegated powers due to the productivity caused by waiting for protocols to be completed. Changing methods amounted to costs of £131,232.37 which represents about 34% of overall compensation events.

5 Conclusions

Trenchless techniques are methods which are preferred due to lower cost, speed and productivity. Directional drilling was not only selected due to its cost, speed and productivity qualities but it is the most customer driven method as keeping customers with a constant supply of water has been the most determining factor. It has also been established that the drive to be more customer focus is coming at a cost, as additional work is now required to keep customers in constant supply by the installation of under pressure tees and riders during connections from old to new mains. Environmental and social issues are a major concern in water mains replacement project. Several actions such as work time restrictions, use of acoustic barriers, adequate notices on the possible disruptions, choosing appropriate methods according to the site conditions etc. were taken to minimise the social and environmental impact of water main replacement projects. Good relationship and efficient communication with local authorities and communities are key factors as their early involvement in the discussions relating to design and accessibility issues can speed up the process and eliminate additional costs associated with delays and extra work. Despite, the higher initial costs, pre-investigation are strongly recommended as it enables the contractor to make the best arrangements and to choose the most suitable equipment for maximum productivity and will reduce the costs on the long run.

6 Data Availability Statement

Please note, that no data, models, or code were generated or used during this study.

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