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Trenchless Technology Research

Sustainable utility placement via Multi-Utility Tunnels

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ABSTRACT

Due to the adoption of short-term planning cycles and the requirement for lowest initial construction costs, the conventional method for utility installation and maintenance in the UK is via open-cut. When taking a long-term sustainability perspective there is a growing body of evidence which indicates that this method is socially disruptive, environmentally damaging and significantly more expensive, i.e. unsustainable. One long-term solution to this problem could be the adoption of Multi-Utility Tunnels (MUTs); a tunnel that co-locates more than one utility underground facilitating their subsequent repair and renewal while eliminating the need for continuous surface excavation. Unfortunately considerably higher short-term direct costs remain a significant barrier to adoption of MUTs. However, there is a lack of research to show where the economic tipping point between the two methods occurs and how it might be influenced by utility type, pipe number (i.e. density), pipe diameter, number of excavation and reinstatement (E&R) procedures avoided, location (i.e. undeveloped, suburban and urban areas), and the choice of MUT being adopted (i.e. flush-fitting, shallow and deep).

This paper aims to fulfil this research need by investigating the effect of these influences on the economic viability of various types of MUTs. The results indicate that MUTs can provide a more economically sustainable method of utility placement in all three local contexts, with the tipping points occurring where street works are likely more frequent and/or where utility density is high.

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1. Introduction

For the last 200 years open-cut excavation (i.e. trenching) has been the most widely adopted solution for placing utilities below ground in the UK (Rogers and Hunt, 2006). This solution might be considered economically appropriate over a century ago for the installation of potable mains water networks and wastewater networks below ground; there were no alternatives available other than full-scale, man-entry tunnelling, and, with only these pipe networks being located below ground, future disruptions would have been assumed minimal. Allied to this, the ground surface in undeveloped, suburban and urban areas was primarily unpaved and considerably less dense than today. Moreover plentiful labour and construction materials existed while social and environmental costs were less well-defined, and either ignored or simply not considered important enough to offset the health and other social benefits of clean water and sewerage provision.

In 2012 open-cut remains the most widely adopted solution for utility placement by practitioners and yet various alternative solutions exist, such as trenchless technologies and Multi-Utility Tunnels (MUTs) (Canto-Perello and Curiel-Esparza, 2003; Curiel-Esparza and Canto-Perello, 2005; Ludovic et al., 2004).

Moreover open-cut, as an engineering method, has seen little change in its fundamental approach since the early days, the primary improvements being mechanization of the excavation and reinstatement processes, mechanical support of the walls of deep excavations, and significant improvement to pipe material quality. These benefits would have been most helpful were it not for the fact that the local contexts have changed out of all recognition: the overlying surface transport (road, pedestrian or cycle) infrastructures are more sophisticated structurally and susceptible to damage by excavation, there are many more utility types now installed below ground (e.g. stormwater drainage, gas, LV and HV electricity cables, telecommunications cables, street lighting cables), and in the not too distant future, as urban centres grow, significantly more utility types could be prevalent (e.g. non-potable water networks, Pneumatic Waste Collection – PWC, Combined Heat and Power pipelines – CHPs, district heating/cooling, hydrogen; see Hunt et al., 2011). In addition there is growing awareness that future competition for use of underground space (e.g. waste storage, resource extraction, transport and people movement, and living space) is increasing at an accelerated rate (Jefferson et al., 2006; Bobylev, 2009; Parker, 2004; Evans et al., 2009; Sterling et al., 2012). Allied to this ground surfaces are now predominantly paved or built over both in suburban and urban areas (and even in rural areas, where green verges exist, utility services are commonly buried beneath paved roads) leading to significantly greater cost requirements, in terms of: asset location Costello et al.

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(2007); excavation and reinstatement for utility placement; maintenance; repair and renewal; and decommissioning. In addition the Brundtland (1987) report has made engineers significantly more aware that everything they do, including utility placement, needs to take into account current and future costs related to a much broader spectrum than direct economic costs alone (i.e. indirect economic costs, and costs to society and the environment).

As more costs are being recognised for utility placement (e.g. traffic disruption, deleterious environmental effects, health and safety hazards, premature deterioration of paved surfaces, and major risks of damage to adjacent infrastructure, see Tighe et al., 2002) there is a strengthening argument against open-cut being the predominant form of pipe installation and renewal. For example, a significant driver in placing electricity cables within bored tunnels in London, UK was to avoid disturbance claims for repeated excavation and reinstatement procedures. However, if the benefits of reducing environmental and social impacts (through the adoption of MUTs) are to be nationally recognised they need to be fully quantified/qualified and offset against the extra monetary costs associated with building and operating them. Notwithstanding this requirement, they need to be included within utility and road costing schemes. One option would be to include the value of habitat, social amenities, landscape and other 'external' factors directly within 'cost-benefit' equations (POST, 1997). However it has been suggested that alternative 'cost-effectiveness' appraisals may be required; whereby decisions are based upon schemes achieving predetermined objectives (economic, social and environmental) for least marginal cost (POST, 1997). Whatever the route taken, the first requirement must be to define more clearly each sustainability cost for open-cut utility placement (i.e. direct and indirect economic, social and environmental) and within this context to describe all sustainability advantages and disadvantages offered through MUTs (Sections 2 and 3). The next stage would be to quantify/qualify and compare each cost for open-cut utility placement with MUTs (in various situations) in order to build a compelling sustainability argument for or against the adoption of MUTs. In Section 4 we develop a methodology for such a purpose, illustrated through the use of costs which reflect best current real world decisions (i.e. direct economic costs – labour, material and equipment). These direct economic costs are considered using three important stages of open-cut construction (i.e. excavation, pipe placement and renewal) in three locations (undeveloped, suburban and urban areas) and are compared to the direct economic costs of installing three different types of MUT (i.e. flush-fitting, shallow and deep). Future research will look toward adopting this same methodology for the remaining sustainability costs described herein. It is shown that even in the absence of social and environmental costs, which are assumed essential for wider uptake of underground solutions, such as tunnelling (POST, 1997), there is an economic case for deploying certain types of MUT's in certain situations.

2. Sustainability costs for open-cut utility placement

A growing body of research suggests that the total cost for open-cut utility placement should go beyond economic costs alone (e.g. Iseley and Tanwani, 1990; Chapman et al., 2003; Najafi and Kim, 2004; Rogers and Hunt, 2006; Jung and Sinha, 2007; Woodroffe and Ariaratnam, 2008; Ormsby, 2009). For example, Iseley and Tanwani (1990) and Woodroffe and Ariaratnam (2008) suggest that total costs (TC) should be considered as the summation of Direct, Indirect and Social costs whereas Jung and Sinha (2007) expressed TC as the summation of the direct costs (e.g. earthworks, restoration, overheads, material, labour, equipment), Environmental costs (e.g. noise and air pollution), Social costs (e.g. traffic delays and loss of business income) and other factors (e.g. safety, productivity and structural behaviour). Ormsby (2009) assumed TC to be

divided into Direct, Indirect and External costs (i.e. Economic, Social and Environmental), where external economic costs included two factors (i.e. loss of property value due to noise and loss of business income; these being considered as social costs within the other studies. In line with the work of Chapman et al. (2003) and Rogers and Hunt (2006), this study suggests that the total sustainability costs should consist of three distinct pillars of sustainability:

$$C_{\text{SUSTAINABILITY}} = C_{\text{ECONOMIC(DIRECT+INDIRECT)}} + C_{\text{SOCIAL}} + C_{\text{ENVIRONMENTAL}} \quad (1)$$

However this study includes also the time element, which is crucial within the overall decision-making and construction process. The development timeline framework, as shown in Fig. 1, builds upon the work of Hunt et al. (2008a,b) and Lombardi et al. (2011) and provides a visual representation for mapping decisions, impacts and costs (i.e. $C_{\text{SUSTAINABILITY}}$) over time (working from the top left to bottom right). The arrows highlighted in bold show the focus of the numerical analysis performed in Section 4. The stages of the utility construction process (1 – Pre-Construction, 2 – Construction, and 3 – Post-Construction) are in line with that reported by Najafi and Kim (2004). Iseley and Tanwani (1990) previously assigned a fourth stage to this process (4 – Decommissioning and Renewal) and this has been included as a broader aspect of Stage 3. Stages 1 and 2 incorporate decisions and $C_{\text{SUSTAINABILITY}}$ over the short-term (i.e. days to years), whereas Stage 3 considers impacts which may last significantly beyond the lifetime of the asset (i.e. 50 or even 100 years). These costs may be comparable or considerably higher than the contract value (Ormsby, 2009). A broader discussion related to each pillar of sustainability shown in Fig. 1 is given in Sections 2.1–2.3.

2.1. Economic costs

Pre-construction costs can be considerable and include *ground investigations* and *survey work* required before the physical construction of the utility takes place. As an integral part of this stage, *asset location* can attract large costs due to limitations associated with soil type, utility type and depth (Sterling, 2000; Thomas et al., 2008). Uncertainty here can increase the risk of unplanned events/construction activities, hence the contractor requires protection (e.g. *insurance*) against expensive *legal claims* (Stein and Drewniok, 1998). Whilst design decisions (e.g. *open-cut versus trenchless versus MUT*) will impact significantly upon life cycle costs including social and environmental (Iseley and Tanwani, 1990) for the project, they are rarely considered in bid preparation for utility projects (Ormsby, 2009). The primary costing here is $C_{\text{ECONOMIC(DIRECT)}}$, traditionally measured in £/m (Podevin, 1998 McKim, 1997) or £/m³ (in order to normalise for the fact that utility operations can be of varying size). Najafi and Kim (2004) suggest that $C_{\text{ECONOMIC(INDIRECT)}}$, examples of which are shown in Fig. 1, is approximately 15% of $C_{\text{ECONOMIC(DIRECT)}}$, whereas actual construction costs (e.g. *materials, labour and equipment*; McKim, 1997), which require double handling of soil and reinstatement of surfaces (Fig. 1), amount to approximately 70% of $C_{\text{ECONOMIC(DIRECT AND INDIRECT)}}$. This is in broad agreement with Jung and Sinha (2007) who reported the following cost breakdown: 21% – earthworks; 30% – pipe laying; 21% – restoration; and 28% – other costs (e.g. *office overheads, traffic control measures and temporary utilities*).

$C_{\text{ECONOMIC(DIRECT AND INDIRECT)}}$ can vary considerably between projects (Ormsby, 2009) due to the influence of specific local factors: speed of construction (Najafi, 2005); utility type (i.e. diameter and material); and depth of excavation (Mohring, 1987; Chapman et al., 2003). With respect to the last of these influences deeper excavations may require *dewatering and shoring* (e.g. sheet piling) as opposed to *sloping work* (Najafi and Kim, 2004) and large-scale

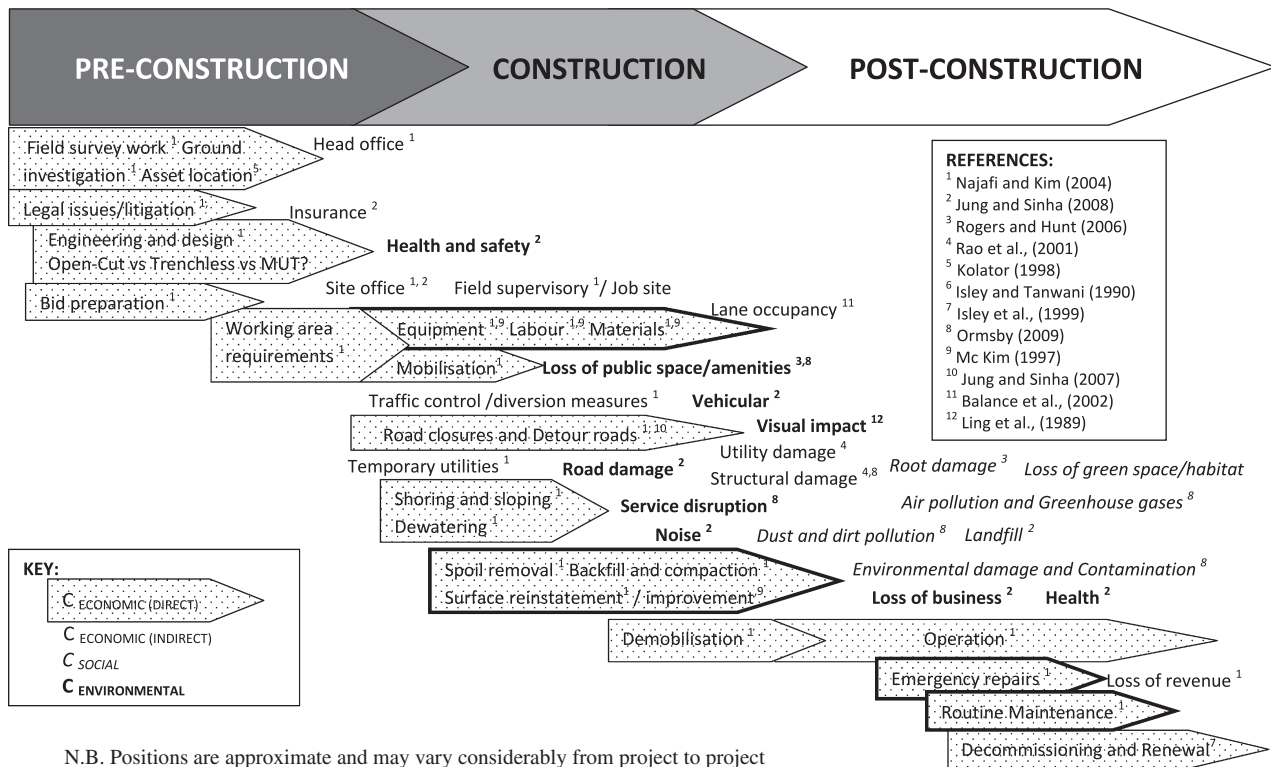


Fig. 1. Utility sustainability costs within a development timeline framework (bold arrows, show focus of this study).

installations may require *road closures and detours* (Jung and Sinha, 2007). In addition congested underground space may require planned *temporary utilities* and/or diversions and careful excavation to avoid *damage to third party utilities* (McKim, 1997; Rogers and Hunt, 2006). These slower speeds of construction (e.g. 8 m/day for open-cut construction as compared to 22 m/day for trenchless; Jung and Sinha, 2007) can be expensive for overheads (Najafi and Kim, 2004), but also for prolonged activities such as *dewatering* and *lane occupancy* (Balance et al., 2002).

Post-construction costs include operational costs, emergency repairs, maintenance, decommissioning and renewal. The costs associated with repair and maintenance are not dissimilar to those outlined already in Stages 1 and 2 (i.e. these stages will be repeated to varying degrees through the lifetime of the utilities) and the impact of these costs can be significant. For example, in 2003 in the UK there were estimated to be approximately 1 million street works (DfT, 2003) or 7 million days of utilities' street works (Goodwin, 2005) necessitating more than 4 million excavations within highways and footpaths by utility companies with a direct cost of £1bn (McMahon et al., 2005). Notwithstanding these large costs, it is estimated that pavement service life is reduced by 30% once an open-cut operation has been completed (Tighe et al., 2002). Thus further repairs to the surfacing materials are increasingly more likely. This is attributed to the fact that as trenches are dug, stress-relief softening of the ground occurs, pavements deform progressively and cracks will occur near the edges (Pucker et al., 2006).

2.2. Social costs

For the UK it is estimated that on average C_{SOCIAL} is around 30–80% of $C_{\text{ECONOMIC (DIRECT)}}$, although figures in excess of 400% have been reported (Peters, 1984; McKim, 1997; McMahon et al., 2005). Recent studies in Pennsylvania, USA have estimated traffic impacts on busy roadways to be more than 80 times the contract cost (Jung and Sinha, 2007). It becomes apparent that the

contribution of C_{SOCIAL} to $C_{\text{SUSTAINABILITY}}$ depends upon what has been included, and how costs (typically economic) are measured or factored in. For example, Rahman et al. (2005) include overheads, construction, utility damage, structural damage and reinstatement as social costs, whereas this study, in line with the majority of studies previously mentioned, refer to these as direct and indirect economic costs. That said, when *property damage* occurs at a later date and is not attributable to the contractor this does become a social cost (Kolator, 1998), as is the case when *utility damage* leads to *service disruption* (such as Water and Wastewater Service Interruption – WSI; Ormsby, 2009). Notwithstanding these shortfalls it is estimated that 50% of C_{SOCIAL} is attributed to traffic delays (Matthews and Allouche, 2010), sometimes referred to as traffic disruption costs (Boyce and Bried, 1994). These are monetary *vehicular* costs (Jung and Sinha, 2007; Ormsby, 2009) incurred due to increases in: traffic congestion; frequency of collisions; vehicular travel time; and associated operating costs – VOC's (which are increased significantly due to *road damage*, Rahman et al., 2005).

The remaining costs include: *health and safety* (Jung and Sinha, 2007), for example Accidental Injury and Death – AID (Ormsby, 2009) related to falling into excavations or trench collapses (Isley and Tanwani, 1990), but also mobile plant and vehicles (HSE, 2010a,b). The accident rates for trenching activities are reported to be 112% higher than general construction (Everett and Frank, 1996). There are however wider issues related to *health*, for example Obstruction to passage of Emergency Vehicles – OEV and Psychological and Physical Ailments – PPA (Ormsby, 2009). The latter of these could be related to the impact of *noise*, not least vibration of heavy machinery (Jung and Sinha, 2007) which can cause high blood pressure, sleep disturbance and a drop in productivity (Gilchrist and Allouche, 2005), but perhaps also visual intrusion (Ling et al., 1989). Noise is known also to be connected with reductions in property values of up to 1% per dBA (Allouche and Gilchrist, 2004) whilst *loss of public space and amenities* (Rogers

and Hunt, 2006; Ormsby, 2009) is connected to pedestrian delays when interference with walkways occurs (Matthews and Allouche, 2010). Another inconvenience is loss of parking spaces, which results in pedestrians parking further away and being less productive (Matthews and Allouche, 2010), while in addition there may be revenue lost for those spaces (McKim, 1997; Kolator, 1998). Traffic disruption and lack of access, at best, can cause *loss of business* between 10% and 60% (Lemoine, 2008) and at worst it can cause closure. For example over longer-term projects (i.e. >2 years) Laistner (1997) reported a survival rate of between 40% and 80%.

2.3. Environmental costs

The quantification of $C_{ENVIRONMENTAL}$ for utilities has received less attention than the other two pillars of sustainability and this is not surprising as the costs are not always considered, or their impacts are not recognised, until many years after the works have been carried out. For example Jung and Sinha (2007) recognised that open-cut damages the landscape in terms of *loss of green space* (e.g. removal of trees, grass and other landscape features). However, no mention is made of *loss of habitat* or the impact of *root damage*, where roots are continually damaged during utility operations, subsequently causing the tree to wilt and die (Rogers and Hunt, 2006); there is a flip side (and an economic cost) to this, where tree roots inadvertently damage utilities (Costello et al., 2000). An alternative reason for the poor representation of $C_{ENVIRONMENTAL}$ is because many costs are associated with the other two pillars. For example in older costing models *landfill* is identified as an environmental cost, whereas the introduction of Landfill Tax (£/tonne) has become a direct economic cost. This serves as a good example of how political influences can change behaviour of the cost equation rapidly and significantly (Chapman et al., 2003), and the same argument can now be used for carbon taxes (£/tonne) in the case of *air pollutants* and *greenhouse gas* emissions (also known as APEs; Ormsby, 2009). A methodology (Rehan and Knight, 2007) and associated calculator (Griffin, 2009a) exist for calculating CO₂ costs (£/passenger-km; Zhang et al., 2004) related to variations in *traffic control* plans (Tighe et al., 1999), traffic volumes and uses of construction equipment/machinery. However no consideration is given for other emissions (e.g. chlorofluorocarbons, nitrous oxides, toxic substances, heavy metals, *Dust and Dirt Pollution* (referred to as DPP; Ormsby, 2009) and other greenhouse gases (Gilchrist and Allouche, 2005), although these can be considered to some extent in E-Calc (Griffin, 2009b). Ormsby (2009) recognises that *Environmental Damage and Contamination* – EDC (e.g. fuel, oil, chemicals) provides a significant contribution to overall environmental costs, and one that often extends beyond the boundaries of the construction site due to propagation through soil, water and air. Even dust, which carries health risks through skin irritation/cancers (Ferguson, 1995), has been reported up to 150 m from the construction sites (Watkins, 1980).

3. MUTs: a sustainable alternative to open-cut?

The underlying question allied to the above discussion is: how can a Multi-Utility Tunnel (MUT) help to reduce some of these costs? A Multi-Utility Tunnel (MUT) can be defined as “any system of underground structure containing one or more utility service which permits the placement, renewal, maintenance, repair or revision of the service without the necessity of making excavations; this implies that the structure is traversable by people and, in some cases, traversable by some sort of vehicle as well” (APWA, 1997). As this definition suggests, MUTs can take a variety of forms. Rogers and Hunt (2006) present more than 60 worldwide examples of MUTs which vary in size, shape, depth, material and type of utilities housed. The

accessibility offered within an MUT is either *searchable* – allowing for selective access usually through removable lids – or *visitable* – allowing for man entry along the entire length of the MUT (Cano-Hurtado and Canto-Perello, 1999; Curiel-Esparza et al., 2004). Rogers and Hunt (2006) further categorised MUTs according to depth of placement:

- A. Flush-fitting: 0.0 m cover (Fig. 2a).
- B. Shallow: 0.5–2 m cover (Fig. 2b).
- C. Deep: 2–80 m cover (Fig. 2c).

For direct comparison the current National Joint Utilities Guidelines (NJUG, 2003) for placement of utilities in trenches is shown in Fig. 3. The advantages and disadvantages of the MUT approach will now be discussed in Sections 3.1 and 3.2 respectively.

3.1. Advantages of MUTs

The MUT eradicates the need for repeated excavation and reinstatement (E&R) procedures over its lifetime (60–100 years) and therefore eliminates many of the longer-term costs relating to $C_{SUSTAINABILITY}$ (Cano-Hurtado and Canto-Perello, 1999; Laistner, 1997; Rogers and Hunt, 2006). For example, maintenance works are carried out within the MUT therefore reducing significantly the size of working areas (above ground) and requirements for equipment (e.g. heavy machinery), labour and materials. Mobilisation is quicker and cheaper because roads are not closed and temporary lights and detours are not required; moreover associated impacts on local businesses and residents (e.g. noise, loss of public space and business) are minimised. Damage to roads, footways, 3rd party utilities/structures and tree roots is avoided, while a flush-fitting MUT could also act as a vertical barrier to prevent tree roots damaging utilities within a footway rather than constructing a vertical concrete barrier to do the same job. Costs are further reduced because asset location is no longer an issue and lane occupancy charges are not applicable (Rogers and Hunt, 2006), and improved

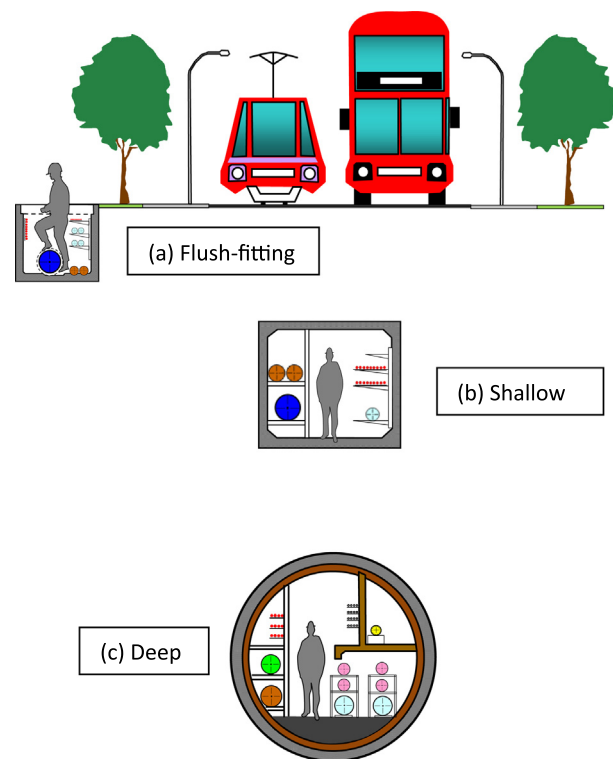


Fig. 2. Different types of MUT construction.

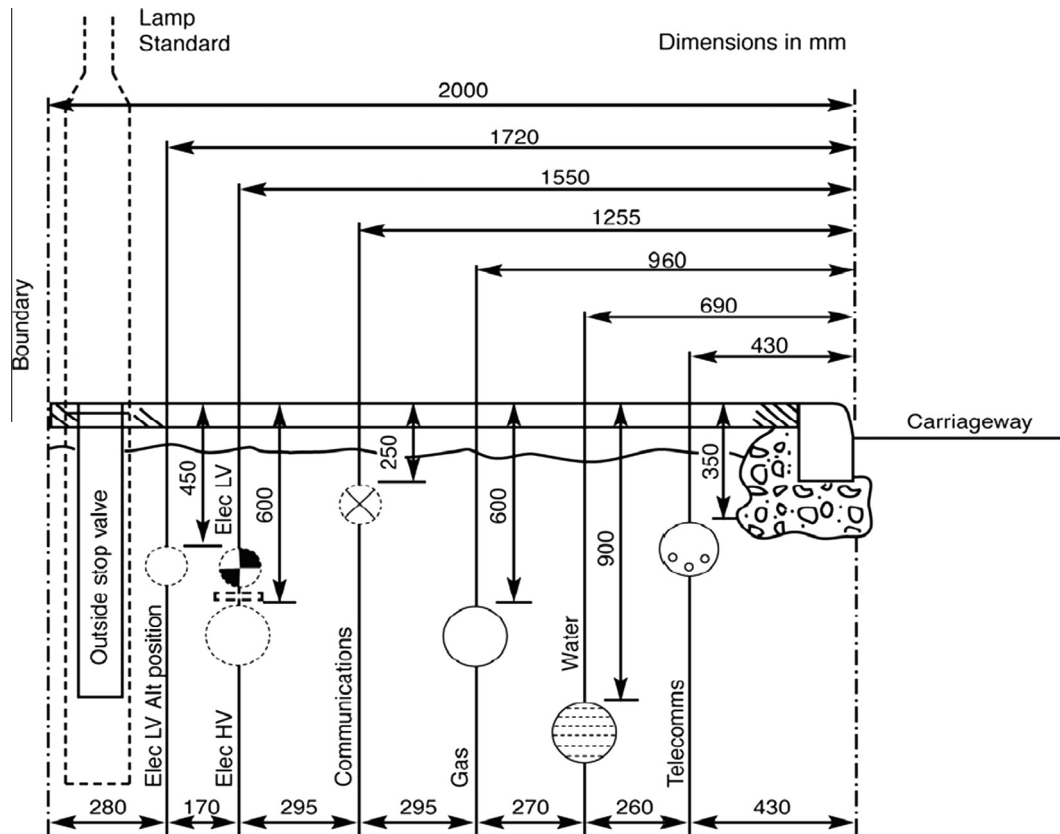


Fig. 3. NJUG guidelines for utility installation in the UK (NJUG, 2003).

accessibility allows for improved inspection and condition assessment. Faults and breakdowns are reduced by approximately 80–95% and asset life is extended by approximately 15–30% (Laistner, 1997), improving the quality of service to the consumer (Cano-Hurtado and Canto-Perello, 1999; Canto-Perello et al., 2009) whilst reducing costs for the utility provider. MUTs facilitate renewal and decommissioning (or perhaps even re-use for a purpose other than which it was intended) and upgrading. This is particularly relevant to the communications industry where technological evolution constantly requires the networks to be changed (ITA, 2010). For example, it is estimated that 80% of the costs associated with rolling out super-fast fibre optic broadband in the UK were related to civil engineering works (BIS, 2010). Allied to this is the introduction of new utilities (e.g. PWC systems, hydrogen, and CHP systems; see Hunt and Rogers, 2005) which are being, or could be, adopted in the not too distant future. MUTs require a smaller combined area than the equivalent utilities installed via open-cut (Cano-Hurtado and Canto-Perello, 1999; Riera and Pasqual, 1992) thereby allowing for more organised planning of underground space for which there are many other uses (Sterling et al., 2012).

3.2. Disadvantages of MUTs

It is clear that a longer-term sustainability perspective is required in order for MUTs to become a viable and widely accepted form of utility placement. This remains a significant barrier to their adoption and thus a significant disadvantage, particularly in the context of short-term planning cycles (Hunt and Rogers, 2005). Allied to this is the fact that there is an expected high initial investment outlay and associated long-term maintenance responsibility, which is highly unlikely to come from any single utility company (Rogers and Hunt, 2006) even though it could rent the space to other utility owners. However these barriers are easily overcome

in university campuses, for example, where this type of investment is encouraged and long-term maintenance requirements of MUTs are well known, hence there are useful examples in the UK (Hunt et al., 2012).

The construction method is reportedly not well known, although a knowledge base certainly exists and is growing as worldwide examples increase (Hunt and Rogers, 2005). It is more likely that a 200 year legacy of placing utilities below ground by open-cut is hard to change (Rogers and Hunt, 2006) and many valid reasons have been put forward to support this disadvantage. For example, costs associated with the Pre-Construction and Construction stages would likely be increased considerably, not least in areas where logistically complex retrofitting of such a solution would be required (Curiel-Esparza et al., 2004; Hunt and Rogers, 2005). Indeed in some urban areas the congestion below ground is so extreme that only deep MUTs are likely to be contemplated if continuity of service provision is to be provided while the new system is commissioned. In addition there is the added problem of compatibility and safety issues, both now and in the future (Cano-Hurtado and Canto-Perello, 1999; Hunt and Rogers, 2005). For example, concerns are quoted for housing gas and electricity together (although these are straightforwardly overcome by compartmentalising utilities), and for housing stormwater, wastewater or combined systems that require large diameter pipes and gravity flow (Canto-Perello and Curiel-Esparza, 2001; Legrand et al., 2004; Canto-Perello et al., 2009). In addition, concerns are raised in relation to the above co-location arguments over the added complications of confined spaces, fire risk, poor lighting and ventilation (Rogers and Hunt, 2006; Chasco et al., 2011), and the fact that if one utility fails dramatically the other utility services are potentially put at risk of damage. Nevertheless no single element poses an engineering risk, and there are examples of where each concern has been satisfactorily addressed.

4. Methodological approach

It is clear that a methodology is required to allow for direct comparison of $C_{\text{SUSTAINABILITY}}$ when considering open-cut utility placement and MUTs. However this must come with an appreciation that, in the real world, decisions are still taken on basis of financial or monetary models, i.e. a comparison between C_{ECONOMIC} for both open-cut and MUT utility placement. In this chapter a methodological approach is presented for conducting a rigorous analysis using $C_{\text{ECONOMIC(DIRECT)}}$. Future research will look toward adopting the same methodological approach for the broader $C_{\text{SUSTAINABILITY}}$ set. Even with discounting C_{SOCIAL} and $C_{\text{ENVIRONMENTAL}}$, it is shown that a valid case for deploying certain types of MUT in certain situations can be made. Therefore it is expected that the role of $C_{\text{SUSTAINABILITY}}$, once fully developed, will evidently favour MUTs. This paper puts in place a methodology that moves us progressively towards such an end-state.

4.1. $C_{\text{ECONOMIC(DIRECT)}}$

Decision-making for the adoption of MUTs will be predicated on short-term costs and long-term savings: A financial appraisal will compare revenues with expenses (i.e. initial investment against maintenance and operation costs) for open-cut utility placement and MUTs and calculate the financial return ratios (e.g. IRR) for each; In contrast an economic appraisal will identify and compare economic and social benefits accruing to the economy as a whole. In this section we concentrate on the former as a precursor to the later being undertaken in future research.

Whilst many authors have argued that the long-term advantages, not least cost savings, related to the adoption of MUTs far outweigh the short-term disadvantages (Laistner, 1997; Rogers and Hunt, 2006; Canto-Perello et al., 2009), there is a lack of evidence to show where the tipping points occur between open-cut construction and MUT constructions when short-term and long-term costs are considered; a tipping point being defined as the point at which costs balance for each method. Moreover there is a lack of evidence to show how these tipping points are influenced by choice of MUT (i.e. flush-fitting, shallow, deep), location (i.e. undeveloped, suburban, urban), pipe number (i.e. density) and pipe diameter. This section investigates these further through the use of short-term direct costs (Section 3.1) and long-term direct costs (Section 3.2).

4.1.1. Short-term direct costs (one utility)

In the majority of cases the direct short-term economic costs (i.e. equipment, labour and materials) used during excavation, pipe placement and reinstatement are broadly similar and take into account the following (CSMG, 2010):

1. Depth of installation.
2. Ground conditions.
3. Material excavated.
4. Size of conduit/pipe/cable.
5. Surface type.

However many of the other short-term direct costs can be significantly different across projects and are influenced greatly by factors outside of the construction itself (CSMG, 2010; Henderson, 2011). These include:

6. Contract size (discounts for larger contracts).
7. Contractor used.
8. Way leave costs.
9. Construction permits (lane closures, parking bay suspensions, etc.).

10. Restrictions on time of works (therefore higher labour rates for night work).

11. Traffic management.

Therefore in order for the findings of this research to be broadly generic, consideration will be given only to the breakdown of direct short-term costs for excavation, pipe placement and surface reinstatement (Tables 1a–1c respectively). Fig. 1 shows the focus of the study in relation to the broader sustainability costing model. All UK-based costs have been estimated using SPON's Civil Engineering and Highway Works Price Book (Langdon, 2009). Throughout these are compared to reported cost data for utility installations via open-cut (UK-specific data) and via MUTs (European-specific data); nevertheless the trends are evident and can be interpreted for any country worldwide via the use of local context knowledge of costing.

4.1.1.1. Open-cut. The various cost data related to three locations (undeveloped, suburban and urban) are shown in Fig. 4. For data generated during this study several utility sizes (100, 150, 200 and 300 mm diameter) are adopted in order to represent those likely to be placed at shallow depth via open-cut installation within a footway (Fig. 3). In addition placement at a depth of 900 mm represents the maximum likely to occur (the UK does not have concerns over frost penetration). In undeveloped areas it is assumed that excavation occurs in soft material, which is subsequently used as backfill. In urban areas it is assumed that a 500 mm depth of bitumen macadam (including a bound base course and contaminated sub-base) is removed and sent to landfill (within 15 km), the remaining 500 mm of soft material is excavated and reinstated as backfill. The surface is reinstated using a hardcore sub-base (200 mm), overlain by a dense bitumen macadam base course (150 mm), binder course (100 mm) and surface course (150 mm). Preparation of all surfaces is assumed. In both cases excess soft material (i.e. a volume equivalent to that of the pipes) is assumed to be sent to landfill (within 15 km). The data from CSMG (2010) relate to telecommunications, gas and HV and LV electricity cables located in footways (Fig. 3), and 100 mm water pipes located at 900 mm depth in carriageways/footways. The data are collected from three UK network operators, one non-UK network operator, four construction contractors and a water contractor. The costs from an experienced engineer (Henderson, 2011) are from a water utility company and refer to various water pipe diameters (100, 150, 200, 300 mm) located at 900 mm depth. Fig. 4 shows that the cost of utility installation increases steadily with pipe size and the cost ratio for undeveloped, suburban and urban areas, using average values this is approximately 1.0: 1.8: 2.3.

4.1.1.2. MUTs. The various cost data related to three different types of MUT installation (i.e. flush-fitting, shallow and deep) are shown in Fig. 5. It is assumed that a flush-fitting MUT (1.0 m × 1.0 m culvert with lid) has 0.0 m cover and a shallow MUT (1.0 m × 1.0 m) has 2.0 m cover. Excavation for both is assumed to require 45° slopes for stability and working space. The volume of soft material and tarmacadam taken to landfill is substantially greater than open-cut due to the size of excavation required and the size of the MUT conduit being installed. The deep tunnels are assumed to be 3.0 m in diameter (200 mm liner thickness) and are constructed at 40.0 m below ground surface level. The costs for shaft construction (every 500.0 m) and removal of excavated materials is considerable (£1575/m) and the cost of tunnelling in rock is almost twice that of a soft material. Laistner (1997) reported that the cost of a fully equipped MUT would be approximately 5–20% more than the equivalent open-cut installation. However, in line with the expectations of Hunt and Rogers (2005) and

Table 1a

Excavation costs for utility construction (adapted from SPONS 2010, see Langdon, 2009).

Construction phase	Material	D – diameter (m), Z – depth (m)	Labour (£/m ³)	Plant (£/m ³)	Total (£/m ³)
Excavation ^a	Tarmacadam	Z = 0.0–0.25	9.2	13.6	22.8
		Z = 0.25–0.5	10.4	15.4	25.8
	Soft material ^b	Z = 0.0–0.25	1.01	1.38	2.38
		Z = 0.25–0.5	1.01	1.40	2.40
		Z = 0.5–1.0	1.34	1.79	3.13
		Z = 1.0–2.0	2.01	2.72	4.73
Tunnel shaft excavation	Soft material	Z = 2.0–5.0	3.36	4.51	7.86
		D = 3.0	–	–	107.5
		D = 3.0	–	–	185.0
Tunnel excavation	Soft material	D = 3.0	–	–	125.0
	Rock	D = 3.0	–	–	300.0
Soil disposal ^c	Excavated earth	–	–	–	19.72
	Rock/tarmacadam	–	–	–	20.44

^a Including removal/breakage of carriageway and other works.^b Material other than topsoil, rock or artificial hard material.^c Includes landfill at a rate of 3.75/m³ disposed 15 km off site.**Table 1b**

Placement costs for utility construction (adapted from SPONS 2010, see Langdon, 2009).

Construction phase	Material	D – diameter, d = dimensions (m)	Labour (£/m)	Plant (£/m)	Material (£/m)	Total (£/m)
Pipe placement (cost of pipe installation)	Carbon steel pipes to BS EN 10126; welded joints; (placed in trenches) ^a	D = 0.1	10.5	8.2	25.6	44.2
		D = 0.15	11.9	9.3	39.4	60.6
		D = 0.2	12.6	9.9	41.7	64.1
		D = 0.3	14.0	11.0	60.1	85.0
	Carbon steel pipes to BS EN 10126; welded joints; (placed in MUT)	D = 0.1	3.18	0.49	25.58	29.24
		D = 0.15	3.18	0.49	39.40	43.06
(additional cost of MUT)	MUT culvert (with lid) ^b	D = 0.2	4.08	2.27	41.67	48.03
		D = 0.3	4.99	0.77	60.09	65.85
		d = 1.0 × 1.0	–	–	–	500.0
		d = 2.0 × 2.0	–	–	–	850.0
	Pre-cast shaft lining	d = 3.0 × 2.0	–	–	–	1050.0
		D = 3.0	–	–	–	439.82
	Pre-cast tunnel lining	D = 3.0	–	–	–	501.40
		D = 3.0	–	–	–	501.40

^a Applicable only to pipes laid in excavation (supported) and backfilled up to 1.5 m depth.^b Cost information on pre-cast concrete sections has been provided by Hanson – Heidelberg Cement Group.

Cano-Hurtado and Canto-Perello (1999) this study shows the costs to be considerably more. For example when considering the costs for excavation, pipe placement (one 200 mm carbon steel pipe) and reinstatement the following increases were found: flush-fitting (+800%), shallow (+1700%), and deep (+2300%). Whilst case history data does report significantly higher costs (Fig. 5), this is not surprising due to the fact that more than one utility is installed; moreover costs related to items 6–11 listed in Section 4.1.1 are included.

4.1.2. Long-term direct costs (>one utility)

In this section the long-term costs savings are considered when adopting MUTs in each of the three locations. These long-term savings are created through elimination of excavation and reinstatement (E&R) procedures required for emergency repairs and/or routine maintenance (Fig. 1). E&R costs adopted for open-cut construction in each location, with and without pipe placement, are shown in Fig. 5. Unfortunately, within the confinement of this paper it is not possible to include analysis of the complete range of utility types in Fig. 4 hence the focus will once again be on carbon steel pipes.

4.1.2.1. Undeveloped. Fig. 6 shows the costs for constructing three types of MUT in undeveloped areas. It can be seen that the costs

increase as the number of (200 mm) carbon steel pipes installed increases when compared to the cost for placing these same pipes using open-cut installation. It can be seen that the economic gap between flush-fitting MUTs and open-cut decreases as more pipes are placed, however open-cut remains 20% less expensive than the cheapest MUT when 15 pipes are placed. If it is now assumed that 1 (E&R)/m occurs for each pipe placed over the lifetime of the MUT (Fig. 6), a tipping point (A) occurs for flush-fitting MUTs at 14 pipes placed. In other words this means that for the costs to break even 14 E&Rs, i.e. 14 pipes × 1(E&R), per metre of MUT would need to be saved over the design life for the MUT (assumed 60 years). This equates to 1 (E&R) per metre of MUT every 4.3 years (i.e. 60/14) or 0.23 (E&Rs)/m/year. If the number of E&Rs is increased to, say, 3, 6, 9 or 12 a range of other tipping points can be found (Fig. 6). For example a tipping point (B) occurs for flush-fitting MUTs when three utility pipes are placed and nine (E&Rs) are required. This means that three utilities would need to be placed and 27, i.e. 3 × 9, (E&Rs)/m would need to have been saved for the tipping point to occur. This equates to 1 (E&R) per m every 2.3 years (i.e. 60/27) or 0.43 (E&Rs)/m/year. For deep MUTs in soft ground (assuming a 100 year design life) the tipping point (C) occurs when 14 utilities are placed with 1 (E&R)/m every 0.6 years (i.e. 100/12 × 14) or 1.67 (E&Rs)/m/year.

Table 1c
Reinstatement costs for utility construction (adapted from SPONS 2010, see Langdon, 2009).

Construction phase	Material	T –thickness (m)	Labour (£/m ³)	Plant (£/m ³)	Material (£/m ³)	Total (£/m ³)
Reinstatement (including all surface works)	Fill using selected excavated materials	–	1.62	3.41	–	5.03
	Hardcore ‘sub-base’; spread and graded	T = 0.2	4.34	5.35	18.04	27.72
	Dense bitumen macadam ‘base’ course	T = 0.15	19.45	24.15	49.90	93.50
	Dense bitumen macadam ‘binder’ course	T = 0.1	15.55	19.35	28.05	62.95
	Dense bitumen macadam ‘surface’ course	T = 0.5	11.65	14.50	19.95	46.10
	Preparation of filled surface (£/m ²)		0.54	1.19	–	2.45

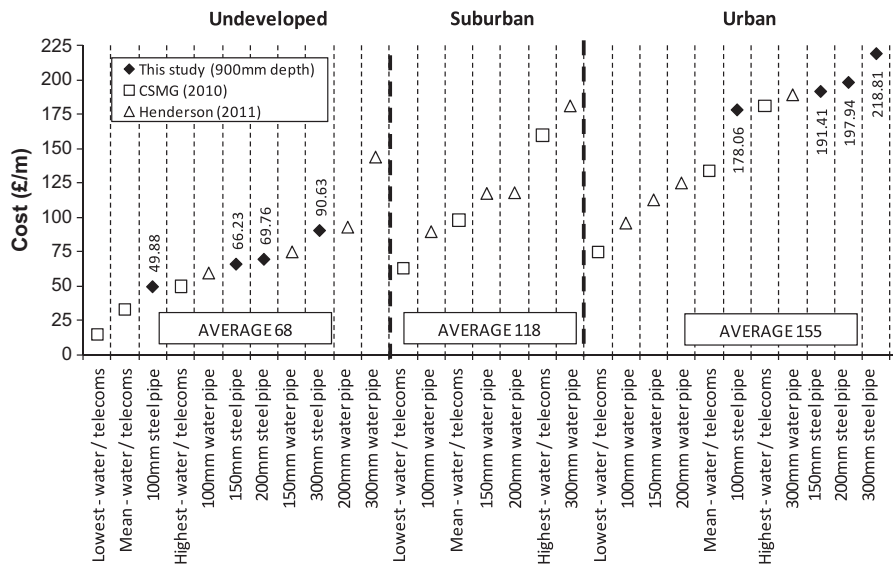


Fig. 4. Urbanisation and the short-term cost of open-cut utility installation.

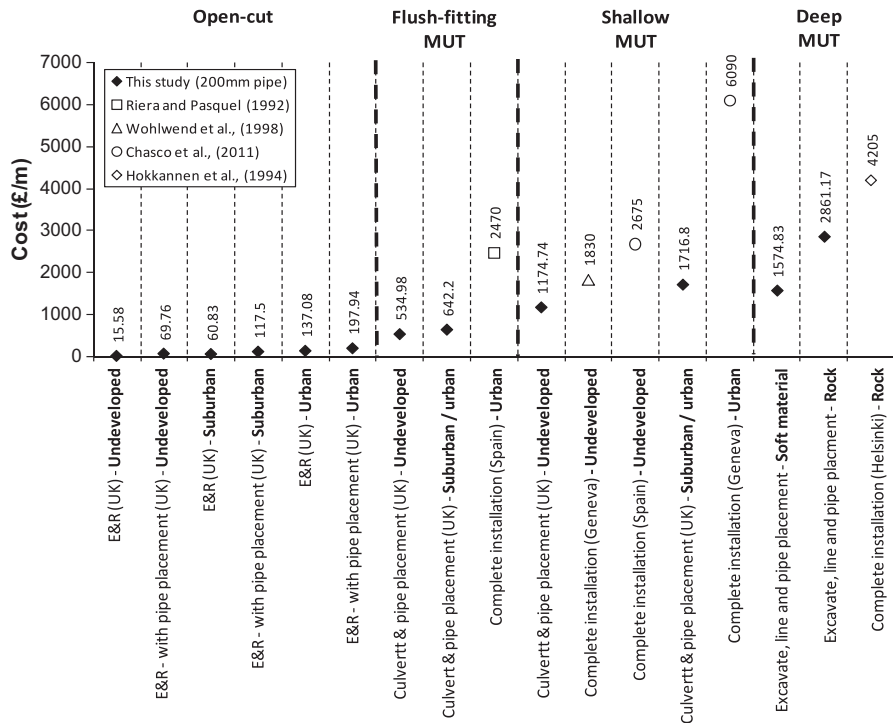


Fig. 5. Urbanisation and the short-term cost of MUT installation. (See above-mentioned references for further information.)

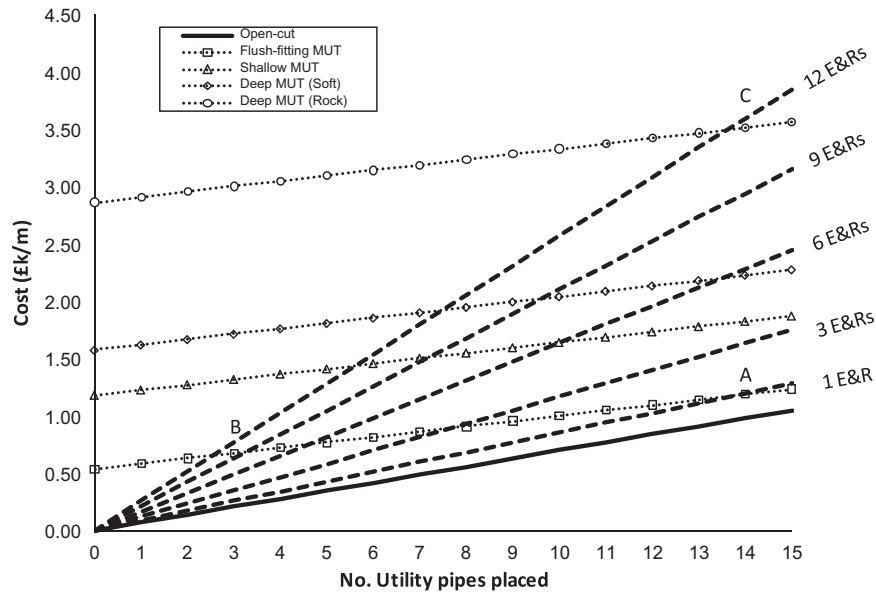


Fig. 6. MUT costs versus open-cut costs with and without yearly E&Rs (200 mm pipe, undeveloped).

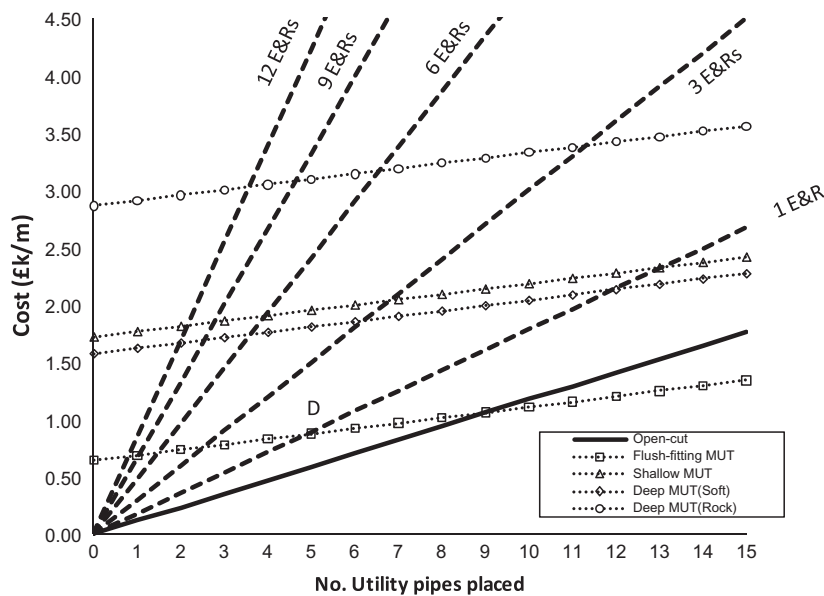


Fig. 7. MUT costs versus open-cut costs with and without yearly E&Rs (200 mm pipe, suburban).

4.1.2.2. Suburban and urban. The same analysis was conducted using the costs for suburban and urban areas (Figs. 7 and 8). Once again it can be seen that the economic gap between flush-fitting MUTs and open-cut decreases as more pipes are placed, however this time a tipping point (D) occurs on the line 1 (E&R) in suburban areas when five utilities are placed (Fig. 7), likewise a tipping point (E) occurs in urban areas when two utilities are placed (Fig. 8). In contrast to undeveloped areas the cost of placing 15 utilities by open-cut is significantly more expensive than flush-fitting MUTs in both suburban (+132%) and urban areas (+220%). Thus the solution could be assumed cost effective. Numerous other tipping points can be seen in Figs. 7 and 8. For example, tipping points for a flush-fitting MUT in urban areas, assuming a 60 years design life and three utility pipes placed, is 1 (E&R) per m every 40 years (i.e. $60/3 \times 0.5$), whereas in suburban areas it is 1 (E&R) per m every 6.67 years (i.e. $60/3 \times 3$). The same is true for deep MUTs although

the value is somewhat lower (i.e. the frequency of E&R's to achieve a break-even status is less).

Each tipping point in Figs. 6–9 is essentially the result of a cost-benefit analysis. The advantage is that multiple criteria have been assessed and economic competitiveness has been highlighted in different locations for completely different reasons. This is an essential requirement for decision makers when deciding to undertake an investment in MUTs rather than open-cut. It can be seen from Figs. 6–9 that some of the E&R lines do not exactly cross data points and therefore calculation is required to find their exact values. Fig. 9 shows exact values for 100 tipping points (i.e. the equivalent of 100 cost benefit analyses) for a flush-fitting MUT in all three areas, and shows the number of E&Rs required for cost effectiveness to occur when considering different pipe numbers (i.e. density) and pipe diameters. It can be seen tipping points are lowest in urban areas followed by suburban and undeveloped areas.

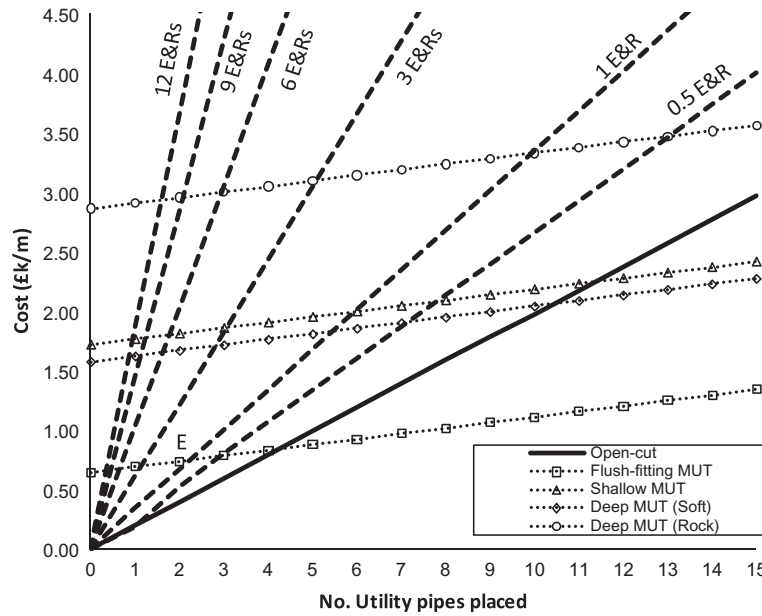


Fig. 8. MUT costs versus open-cut costs with and without yearly E&Rs (200 mm pipe, urban).

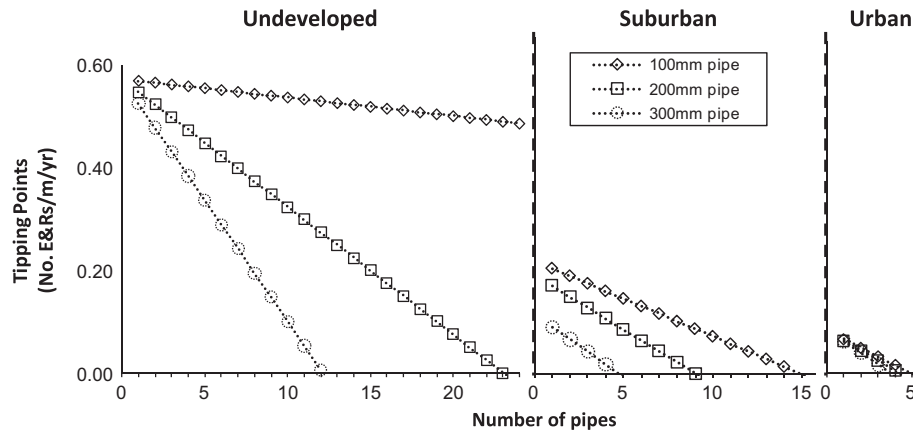


Fig. 9. Influence of pipe number (density) and diameter on tipping points for flush-fitting MUT's.

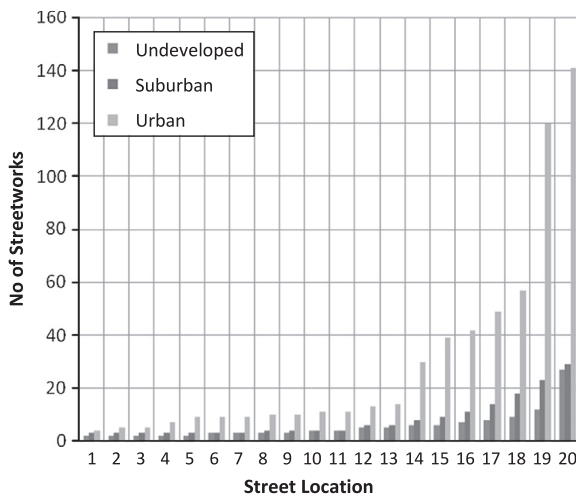


Fig. 10. Utility operations in 20 locations over a 5 year period (Bluett, 2011).

Moreover, pipe diameter influences greatly tipping points in undeveloped areas, less so for suburban areas and little/no influence occurs in urban areas. In addition it can be seen that tipping points are reduced as pipe numbers (i.e. density) increase, in other words the economic competitiveness of MUTs is better in areas of higher utility density, thereby providing an evidence base for the expectations of many authors including Laistner (1997), Hunt and Rogers (2006) and Canto-Perello et al. (2009). Economic competitiveness remains plausible for areas of low utility density, provided that frequency of E&Rs is sufficiently high. The question is whether this is a realistic expectation; Section 4.1.2.3 examines this further using the UK's experience as the example.

4.1.2.3. Frequency of utility operations. In order for the findings of this research to have practical future applications it is necessary to understand better how location might affect the frequency of E&R operations. Fig. 10 shows data collected by Nottinghamshire County Council (Bluett, 2011) over a 5 year period in 20 rural streets (village of East Bridgford), 20 suburban streets (Gamston, Nottingham) and 20 urban streets (Mansfield). When plotted together in order of increasing streetworks, it can be seen that there

is a general trend toward the number of utility operations (hence E&Rs) increasing when going from undeveloped to urban areas. However it shows also that streets in undeveloped areas can have just as many utility operations performed as suburban and urban areas. For example Street location 20 has more utility operations performed in undeveloped areas than Streets 1–13 have in urban areas. In other words, frequency of E&Rs in low utility density areas may be sufficiently high for economic competitiveness to occur. Whilst the study is far from exhaustive, it is believed from anecdotal evidence to be typical of the frequency of street works occurring elsewhere in the UK. Future work could look towards collecting, collating and comparing such data for the UK, or for any country in which utility streetworks pose a problem.

5. Conclusion

Results of this research suggest that an MUT, during its lifetime, can provide a more economically sustainable method of utility placement as long as it is used in the right location and houses the right number of utilities, i.e. is used in a situation that otherwise would require numerous E&R procedures if placed using open-cut. A detailed and comprehensive review has been provided to establish the context in which the above analysis must take place, and this indicates many features of streetworks that might be given greater or lesser emphasis in any cost model. It might, for example, be swayed by local political or societal influences: if air pollution is a long-term sensitive issue for a city, then its weighting in any cost model would necessarily increase. A better understanding of the tipping points for the economics of MUTs in three locations (undeveloped, suburban and urban) has been gained and the evidence base thus provided will contribute significantly towards building a robust economic costing model. Such modelling is required as part of a much larger sustainability costing model if the case for MUTs is to be made, but the results reported herein provide the starting point for a step-change in thinking for utility service infrastructure provision in cities where 'more of the same' is becoming untenable and traffic congestion due to repeated streetworks is becoming politically, as well as socially and environmentally, unacceptable.

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