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Ground movements associated with pipejacking operations

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ABSTRACT: Pipejacking, including microtunnelling, is an extremely important technique for the installation of services, particularly sewers, without the need to use open trenches. The state-of-the-art of knowledge related to ground movements associated with pipejacking operations is described in this paper. The work reported herein includes field observations, laboratory simulations and theoretical models, particularly empirically based models. This paper highlights a situation where although there have been several detailed studies into pipejacking, more data is required from field operations if understanding is to be increased, predictive techniques are to be verified and confidence in pipejacking, particularly microtunnelling, operations is to be enhanced.

1.0 INTRODUCTION

Trenchless or 'No-Dig' methods for the installation and renewal of underground services are becoming more common and in many situations are now considered as economic alternatives to traditional trenching operations. This increased use, particularly in urban areas, has stemmed from increased awareness of the unacceptable nature of traffic disruptions caused by conventional trenching operations and has also been helped to some extent in the UK by the more stringent controls placed on trenching by the New Roads and Streetworks Act (1991).

There are a number of alternative trenchless methods available depending on the type of service required, its size and whether the service is to be a new installation or if it is to be renewed. This paper concentrates on pipejacking methods, which are essentially used for new service installations. The term pipejacking in this paper will refer to installations of up to approximately 2m in diameter constructed either using an open shield or by remotely controlled machine (microtunnelling). As with other trenchless methods, pipejacking induces disturbances into the surrounding ground during the operation and the resulting ground displacements can potentially cause damage to adjacent services and structures. Pipejacking is similar in some respects to larger diameter transportation tunnels in terms of its influence on the surrounding ground.

On many projects, trenchless methods have often been used in relatively 'safe' regions, i.e. where there is little or no chance of them damaging other services. However, there is a need to extend the scope of trenchless operations in order to maximise their use in the urban environment and where subsurface space is limited due to high concentrations of existing services. An understanding of the extent of influence of these construction operations is therefore vital. There is also a need for a fundamental understanding of how pipejacking operations interact with the surrounding ground if the industry is to continue to advance in the future and improve the efficiency and application of existing methods.

There has been some work conducted into trying to understand, and hence predict, the ground movements caused by pipejacking. This paper examines the state-of-the-art related to current understanding of how pipejacking operations affect the surrounding ground. This paper includes information obtained from case histories, laboratory simulations and theoretical studies.

2.0 THE METHOD OF PIPEJACKING

Pipejacking is a method of trenchless installation involving a tunnelling technique between two shafts, i.e. excavation of material is carried out within a shield, either manually or mechanically, and this excavated material is transported to the surface along the newly installed pipeline. Unlike conventional tunnelling, however, where the tunnel lining is installed as segments erected immediately behind the shield, in pipejacking, the new pipe sections are added at the starting shaft and the pipeline progressed forwards by using jacks to push the whole pipe length from the starting shaft. There are a variety of mechanisms within this procedure that can contribute to stress changes within the soil and therefore lead to ground movements. These mechanisms include:

- Movement of soil into the face during excavation, generating a volume loss. Careful control of the face and slurry pressures exerted by microtunnelling machines should eliminate this problem to some degree, but this control cannot be perfect. In addition, if the machine passes between different soils, or different conditions of the same soil, then face control is more difficult to maintain. The opposite effect of over-pressurisation of the face slurry pressure can also occur, causing movements in the ground away from the face. This is a particular problem when passing through softer soils.
- The action of jacking the pipe train and shield forward applies stresses, hence strains, to the soil ahead of the installation. This problem is minimised by matching the excavation rate and the forward jacking rate as closely as possible.
- Collapse of material onto the installed pipe due to the overcut (the difference in radius between the shield and the installed pipeline). For microtunnelling operations this is small (6-12mm) and the annulus is often filled with slurry. This not only supplies support to the soil, but also reduces the frictional forces at the soil/pipe interface.

3.0 FIELD MONITORING AND LABORATORY MODELLING

There are very few documented observations on ground displacements due to pipejacking operations and particularly microtunnelling operations.

Rogers et al (1989) describe the surface displacements caused by a 1.2m diameter earth pressure balance machine at 5-6m depth below Burnham-on-Sea, UK, in a very soft alluvium soil. The observations showed some anomalies, but suggested a 3-4mm maximum surface settlement through a road pavement.

De Moor and Taylor (1991) describe the monitoring of a 2.1m diameter sewer, constructed at a depth of approximately 10m, through very soft alluvium in Tilbury, UK using an Iseki Crunchingmole. Both surface and subsurface ground displacements were monitored. There was considerable evidence of outward movement away from the excavated face due to difficulties in controlling the slurry pressure in the soft ground. These displacements resulted in immediate heave at the ground surface, which, as the pore water pressures dissipated, turned into a resultant settlement trough after 8 months (maximum heave 25mm, maximum settlement 52mm). This highlights the importance of stress changes in the ground on long term ground movements.

The outward movements due to over-pressurisation of the face have been modelled in the laboratory in sand by the current author. The simulation was carried out by jacking a 220mm diameter closed shield, followed by a 200mm diameter steel pipe, into a tank of sand. An example of the typical movements observed in the longitudinal plane for a 10mm forward jacking distance into a dense Leighton Buzzard sand is shown in Figure 1. As expected, the movements indicate a large forward and upward movement in the sand creating a heave profile at the surface. Further details of this work can be obtained in Rogers and Chapman (1994).

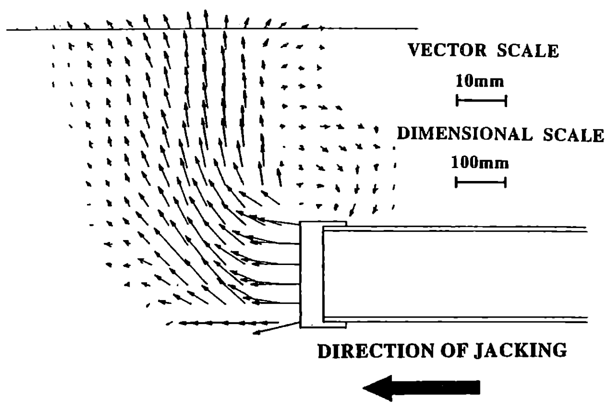


Fig. 1: Typical soil displacements observed due to a closed shield being jacked 10mm into a dense Leighton Buzzard sand.
(after Rogers and Chapman, 1994)

A research project at Oxford University, UK has involved monitoring four pipejacking projects so far. The results from three of these projects are summarised in Milligan and Marshall (1995). These projects involved a range of soil types (sand and clay), pipe diameters (1.2 - 2.17m), depths of installation (5.6 - 8.5m) and excavation methods (hand dug and slurry machines). Extensive instrumentation was employed to monitor both surface and subsurface movements and the results obtained considerably extend the database of information on ground movements due to pipejacking operations. Maximum surface settlements ranged from 6-9mm.

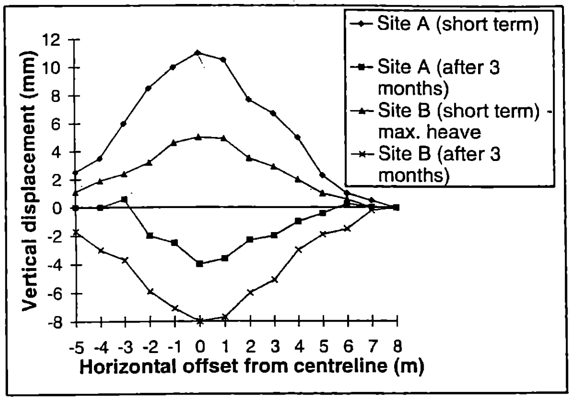
The only published information from monitoring controlled field trials using microtunnelling operations was carried out at the US Army Corps of Engineers' Waterways Experiment Station as part of the Construction Productivity Advancement Research (CPAR) programme (Bennett and Taylor, 1993 and Bennett et al, 1994). Although only limited data on ground movements has been published so far, the extensive nature of this trial (103.6m long, running through a variety of made ground conditions from clays to sands) should have offered an extremely good opportunity to understand more about the ground behaviour associated with microtunnelling operations. Ground monitoring instruments were installed along the length of the trial and included inclinometers, settlement plates and piezometers. The trial was able to compared an auger microtunnelling machine to slurry microtunnelling machines. All these machines were approximately 600mm in diameter.

For the slurry microtunnelling machines, the initial findings show only small displacements (<6mm) throughout the drive (measured at 600mm above the crown of the operation). The auger machine performance was more variable and produced ground heaves of 12 to 38mm and in a region of flooded sand produced up to 200mm settlement. This illustrates that the careful control and operation of these machines is a very important factor on the likely ground deformations caused during use.

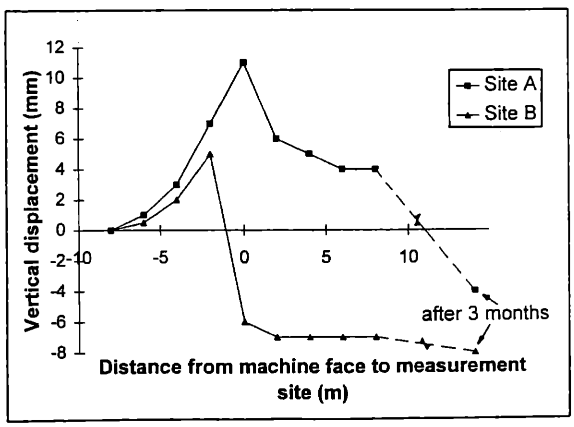
This is the first trial (where details have been published) to investigate the behaviour of microtunnelling machines through different ground conditions all on one drive. However, each trial was still only one scenario produced using one machine and using one operating team. It does not answer the question of what are the expected limits (confidence limits) of ground displacements that can realistically be placed on microtunnelling operations for different site conditions, i.e. there is still a need for detailed information on ground movements from many microtunnelling operations.

A more recent field monitoring exercise was carried out by the current author during a microtunnelling operation to install a new 600mm O.D. sewer, at an average depth of 5m, using an Herrenknect AVN600 slurry machine. Due to contractual and access problems, the monitoring was restricted to surface monitoring at two locations along the drive. Monitoring points were located on both an unsurfaced area, i.e. an area of garden, above the drive (site A) and also on a section, further along the drive, covered by a road pavement (site B). At each monitoring site, the measurement points were placed in a line transverse to the line of the drive and monitored using precise levelling. The measurement points had to be skewed about the drive centreline due to access problems.

The site consisted of a soft to medium firm clay with water bearing sand lenses occurring randomly within the clay. The water table was at approximately 1m below the ground surface. The ground surface was monitored as the machine approached the monitoring sites and as it passed. Measurements were also recorded at both sites for 3 months after the operation was complete (contractual problems prevented any longer periods of monitoring). Although this longer term monitoring was not long enough for full dissipation of the excess porewater pressures to occur in the clay, the results give an indication of the likely long-term ground movements.



(a) Transverse displacements showing maximum and minimum values for sites A and B.



(b) Centreline displacements for sites A and B.

Fig. 2: Surface displacements observed during a 600mm diameter slurry microtunnelling operation in soft to medium firm clay at 5m depth.

The displacements observed are shown in Figure 2(a) and (b). At site A, there was noticeable heave movements created at the surface as the machine approached, i.e. indicating a substantial over-pressurisation of the slurry at the face of the machine. This was probably the result of an over cautious operator. When the surface heaves were reported to the operator, the slurry pressures were reduced, resulting in a rapid reduction of the heave movements as the machine moved away from the monitoring site. In the longer-term, a resultant settlement at the surface was measured (4mm max.) due to dissipation of excess porewater pressures and possible collapse into the overcut.

At site B, measured above a road pavement, there was a small amount of heave initially. This was smaller than observed at site A due to the lowering of the slurry pressure subsequent to passing site A and also the influence of the road pavement. However, just as the heave profile was developing, there was a dramatic settlement of the ground surface. This was caused by a slurry 'blowout', as slurry found a way to the ground surface. The slurry pressure had to be subsequently reduced, allowing some movement of the ground into the face. This resulted in an immediate 6mm settlement at the ground surface which in the longer term increased to 8mm.

All these observations show that movements can occur around pipejacking operations and may cause problems for subsurface services. It is also important to understand both the short-term and longer-term displacements caused by the stress changes occurring during pipejacking operations, particularly in clay soils due to consolidation or swelling effects. If the trenchless pipelaying industry is to carry out pipejacking operations at shallower depths, and within the more congested region of the urban subsurface, then every aspect of the ground behaviour needs to be fully understood.

4.0 THEORETICAL PREDICTION OF GROUND DISPLACEMENTS

O'Rourke (1985) was one of the first authors to attempt to predict the behaviour of ground around trenchless techniques. In this work, the techniques are divided into convergent and expansive installation methods. The ground displacements observed from convergent techniques were based on large scale soft ground tunnelling operations. This assumes that the operations of pipejacking and conventional tunnelling are similar, which is true in some respects. However, there are peculiarities to pipejacking which need to be considered in any rigorous analysis, such as the advancement of the whole tunnel lining rather than constructing the lining from segments behind the shield. Subsequent stress changes in the soil due to the jacking operation, particularly if the drive is not straight, could cause additional displacements in the ground.

There is some published evidence to show that the ground settlements resulting from pipejacking operations exhibit an error function distribution at the surface (Milligan and Marshall, 1995). However, some of the observations from monitoring pipejacking operations described in this paper have initially exhibited heave movements at the surface.

O'Reilly and New (1982) describe a method of predicting both surface and subsurface ground movements around conventional tunnelling operations based on the assumption that the surface settlement profile can be represented by an error function curve, using empirical evaluations for the width parameter of the trough and an assumption of constant volume. New and Bowers (1994) discusses improvements to the original model.

Theoretically, the model described by O'Reilly and New (1982) can also be used for pipejacking methods. However, as mentioned previously, it is difficult to be confident in this method due to the limited data on ground movements from pipejacking operations, the scale differences compared to the tunnels used to develop the model (particularly the trough width parameter, i) and the greater influence of the ground surface on the movements (the possibility of heave).

Experience to date would seem to suggest that the model is reasonable, although tending to overestimate the resulting movements (Milligan and Marshall, 1995). The current author has applied this model, with some success, to the surface displacement data for the most recent microtunnelling project to be monitored, which was mentioned earlier in this paper. The error function curve does seem to fit the heave profiles quite well and also fits the short-term settlement trough for site B. However, the longer-term settlement trough for site A does not accurately fit the error function profile.

De Moor and Taylor (1991) applied the error function curve to the heave profile observed at the surface during their field monitoring and there seemed to be good agreement between the observed and the predicted profiles. However, they also tried to apply the error function curve to the long-term settlement profiles and this proved less satisfactory. The lack of agreement of the error function curve with long-term settlement profiles has been recognised for some time.

Attewell et al (1986) show that the long-term settlement trough, although deeper, is also much broader and the error function curve is not such a good fit. Attewell et al (1986) proposed a method of predicting the long-term settlements above tunnels by summing two error function curves together to form the final settlement profile.

The current author has been involved with the development of a very simple, yet highly effective, method of approximately predicting the short-term soil displacements caused by both expansive and convergent trenchless methods. This method is based on a modified fluid flow analysis originally suggested by Sagaseta (1987), which has been modified to account for compressibility within the soil. Preliminary indications are that this model, although extremely simple, can produce good indications of the likely magnitudes of movements under a variety of conditions. This model was first suggested as a method of predicting ground displacements caused by pipejacking operations by O'Reilly and Rogers (1990) in an incompressible form. It has also been successfully used to predict movements associated with other trenchless operations.

There have been many attempts to model tunnelling operations by using finite element methods (Rowe et al, 1983, Clough and Leca, 1989 and Rowe and Lee, 1992). However, the complexity of these programs and the sensitivity to the input parameters, is still a major problem for routine design, although rapid progress is being made. Pipejacking is potentially similar to large scale tunnelling, although allowances need to be made for the differences in scale, the advancement of the tunnel lining, and the closeness of the operation to the surface (potentially more influence from unsaturated soil conditions).

There are only a few published work on finite element analyses specifically being applied to trenchless operations and most apply to methods other than pipejacking. Probably the most important aspect when trying to model the soil behaviour around trenchless operations is the fact that due to the shallow nature of these operations, the soil is unlikely to be fully saturated. This creates problems with producing a realistic constitutive model for the soil. This adds to the inaccuracies of the theoretical models for trenchless operations and why simpler more empirical based predictive techniques are still favoured at the present time.

5.0 CONCLUSIONS AND RECOMMENDATIONS

There have been several published investigations on the effect of pipejacking operations on the surrounding ground. The most important work has been reviewed in this paper, although more details can be obtained from Chapman (1993).

Although the industry says that negligible ground movements occur as a result of pipejacking operations, there seems to be evidence that observable movements can occur. As a consequence, much more monitoring is required if a comprehensive understanding of the effects these operations have on the surrounding ground is to be gained.

With the information currently available it is possible to make reasonable predictions on the likely ground movements caused by pipejacking operations. However, the methods used are still relatively crude and although developing all the time, the information on which they are based (i.e. field measurements) is still lacking in some respects.

With many of the observations, particularly relating to microtunnelling operations, there is a high degree of interaction between the observed ground displacements and the level of operator skill. This makes absolute predictions of ground displacements very difficult. It is therefore important to gain an understanding of the likely range of potential movements that are possible under given conditions.

There is a need to conduct more extensively instrumented controlled field trials. These trials should not only investigate the microtunnelling operation under the best operational conditions with careful machine control, but also under poor operational conditions and poor control of the machine, eg. in difficult ground or due to a more inexperienced operator. This would enable extreme effects on the ground to be monitored, such as over-pressurisation of the slurry, under-pressurisation of the slurry and also mismatching of the jacking and excavation rates. This would give some idea of the best and worst results in a variety of ground conditions, which would aid overall understanding and go some way to enable limits of likely ground behaviour to be placed on microtunnelling operations.

Many of the problems associated with pipejacking operations occur due to insufficient effort being spent on trying to determine, and understand the likely effects of, the geotechnical conditions prior to work commencing on site.

It is important that consideration is not only given to the immediate ground movements, but also to longer-term effects (i.e. the fully drained situation created by the change in stress conditions within the soil after the operation has been completed, as opposed to the immediate, undrained condition). In addition, it should also be remembered that although ground movements may not be obvious at the surface, there is every possibility that movements are occurring at depth and these could potentially affect adjacent buried services.

It is fundamental to the advancement and improvement of trenchless operations that there is a good understanding at a fundamental level of the effects of these techniques on the surrounding soil. Greater understanding will also help to improve client confidence in these operations and ensure that these methods are specified wherever possible.

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