Guide to best practice for the installation of pipe jacks and microtunnels
The Pipe Jacking Association would like to extend its thanks to the following for their assistance in the compilation and the provision of specialist technical input.

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Members of the Pipe Jacking Association Technical Committee,

and the following water companies who as members of the Oxford Research Project, have made a valuable contribution.
Pipe Jacking was first introduced into the United Kingdom in the early 1960s and was used as an alternative tunnelling method to small segmental tunnels and timber headings for providing road crossings under obstacles such as roads, railways, rivers and canals.

The technique developed and it became practical to use the method for longer tunnel drives, and so pipe jacking found a market in the sewer and surface water sectors. In 1973, six contractors who were using the technique formed the Pipe Jacking Association (PJA) to promote and market the method through a Code of Conduct and Good Practice.

Later the Pipe Jacking Association, in conjunction with the Concrete Pipe Association (CPA), produced a Design and Specification Bulletin on Jacking Concrete Pipes, and this became an adopted document for most uses.

Other publications followed, including a design guide, case histories and newsletters, and the Association embarked on a series of lectures and seminars to educate utility companies and other clients, on the art and benefits of this new tunnelling system.

During these developing years the PJA has attracted new members, including some of the concrete pipe manufacturers and tunnel machine suppliers, and has now established itself as a leading world authority on the technique.

In 1983, the Construction Industry Research and Information Association (CIRIA) were co-opted to promote and support a basic research programme. They embarked on a study of the art and practice (CIRIA Technical Note 112) and from this produced a list of research requirements for detailed study.

These may be summarised as:
- Friction loads in different ground conditions
- Characteristics of pipe joints and joint packing materials
- Effects of cyclic loading on pipes
- Effects of lubricants in reducing friction
- Development of a site investigation test to predict friction forces

Under the initiative of the Pipe Jacking Association, support has been obtained for four stages of research.

The first stage, backed by the Science and Engineering Research Council (SERC), involved a desktop study and laboratory testing of model concrete pipes, carried out at Oxford University.

The second and third stages, have involved full-scale on-site testing and instrumentation, and have been supported by five major water companies: Northumbrian, North West, Severn Trent, Thames and Yorkshire.

A fourth stage is using finite element methods to model pipes and joints in a search for improved designs.

The research projects have been an outstanding example of cooperation between clients and designers, contractors and pipe suppliers, research organisations, and academia.

As a direct outcome of the research programmes this Guide to Best Practice for the Installation of Pipe Jacks and Microtunnels has been compiled to provide a code which includes both past and current knowledge of the Art and Science of Pipejacking.
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Pipe Jacking, generally referred to in the small diameters less than 900 mm as micotunneling, is a technique for installing underground pipelines, ducts and culverts. Powerful hydraulic jacks are used to push specially designed pipes through the ground behind a shield from a thrust pit containing a thrust wall.

To establish the best practice for the installation of good pipe jacks and microtunnels it is essential to understand all the parts that must be sitting together to achieve success. These include good soil knowledge, jacking shaft design, pipe design, pipe jack shield design, hydraulic considerations, and last engineering, but each aspect, whether it may seem very significant or of minor importance, must be considered for every scheme in order that success may be guaranteed.

A successful pipe jack is like a chain which is as strong as the weakest link. It is like the launching of a satellite where all the parts have been properly researched and designed to create a finished project which is well-engineered and, in pipe jacking terms, will provide the best feasible structural, watertight pipeline tunneling method available in the market.
2.0 Objectives of this guide

Pipe Jacking has been with us for over 35 years but is only now coming of age with the skill of pipe and tunnel machinery manufacturers, research and promotion by the Pipe Jacking Association, some innovative scheme designs, and progressive pipe jacking contractors. Separately, glacial deposits in the UK, through which many pipelines require to be positioned, have created the need for a range of sophisticated equipment which has been utilized by the UK tunnelling industry, and has generated probably the most experienced pipe jacks in the world.

As a result, in recent years both desk and field research have been carried out at Oxford University with the involvement of the PJA, CIRIA, SERC (now EPSRC), and five water companies.

Taking all that is known to date, the objectives of this guide are to set out in simple readable and illustrated text the essential elements that are necessary for the design, specification and installation of pipes by the pipe jacking method.

The guide then takes the reader through the problem areas which can adversely affect a pipe jack, provides a check list, and summarises associated matters such as contractual considerations, safety, training, and current regulations and standards, which are all good practice for the pipe jacking method.

It is designed for an audience of promoters, clients, consultants, contractors, estimators, planners, machine manufacturers, material suppliers and any other parties with an interest in the pipe jacking construction process.

Be guided that members of the Pipe Jacking Association are always available to advise on any aspect of the technique, and other publications referred to within this document should be used in conjunction with this guide.

It is the policy of the PJA to continue a planned programme of further research and practical analysis and to update information as it is gained.

2.1 How to use this guide

Each Section from 3.0 to 7.0 (pages 6 to 41) details the essential information required to produce a good pipe jacking or microtunneling scheme design and installation.

The guide is designed to follow a logical sequence and in some sections makes cross reference to other publications and guides.

Headings such as:

- Advise(d)
- Advice
- Be guided
- Beware
- Problems
- Recommend(ed)
- Refer(ence)
- Solution
- Selection

focus key points.

However, all information is important.

Section 8.0 Appendix relates to technical formulae, graphs and calculation data.

Section 9.0 Worked examples provides the reader with a guide to the use of technical data for two sample pipejacks.

Section 10.0 References refers to publications, research data, codes of practice and other appropriate information.

Section 11.0 provides a Glossary of terms used in this guide.
3.1 Soil investigation and interpretation

Before any practical decisions can be made relating to a scheme design for pipe jacking, it is essential that an appropriate soil investigation and interpretative report is available for both the designer and installer. This information is required to evaluate the basic selection of:

- the type of tunnel excavation method
- the working shaft(s) and thrust wall construction
- the length and strength of the pipejack
- any requirement for ground stability control

The PUA publication ‘An Introduction to Pipe Jacking and Microtunneling Design’, Part 3, covers the characteristics of soils likely to be encountered and the minimum information required for a proper interpretation to be undertaken.

Interpretation of soil information is not a precise science and experience, whether it be practical or specialist, should be sought to give the best possible evaluation.

Often forgotten, but of great value, is noting any experience of the ground from previous or current work in the area.

Also special problems such as the presence of flammable gases, de-oxygenated air, or contaminated ground should be investigated, as these may influence or dictate the choice of tunnelling method.

Below are examples of some of the basic problems which may arise and solutions to consider for controlling varying ground:

- The grading of non-cohesive soils will give the compaction or looseness of the soil and the presence of fines, which may cause instability.

  **Solution**
  - Dewatering
  - Stabilisation
  - Face support
  - Tunnel Boring Machine

- Some cohesive soils can become unstable when the presence of water alters their plasticity or creates pressure in fissures.

  **Solution**
  - Face support
  - Tunnel Boring Machine
- Overminimum may create high friction forces as soil stresses are released around the pipe during jacking.

**Solution**
- Lubrication
- Grease

- Mixed soils or material used for filling (embankments etc.) should be examined by trial pits to assess the best pipe jacking method.

**Solution**
- Consult a soil specialist or take advice from the PJA.

- The presence of rock or boulders may disrupt the excavation method. The advice of specialist shield manufacturers should be sought for these conditions.

**Solution**
- Ask a machine manufacturer and take advice from the PJA.

- Some soils which are normally stable may be rendered unstable in the presence of water. The instability is caused by water movement, through or with the soil, due to the differential head created by jacking a pipe below the water table.

**Solution**
- Dewatering
- Stabilisation
- Tunnel boring machine

Where the presence of excessive water is expected, evidence of water table(s), artesian head(s), should be noted along with the results of permeability and/or pumping tests.

The presence of water is probably the most common and contentious contractual element of any tunneling method and pipe jacking is no exception.

Many factors such as location of shafts, interference with surface structures, traffic requirements, and environmental noise regulations, can interfere or limit the best construction method.

It is essential that both the designer and installer work together to find a solution that is both cost effective, technically viable, environmentally friendly and above all safe.

**No soil information = scheme risk**
3.0 Parameters to be considered to produce the best

3.1 continued

Be guided

Study Part 3 of "An Introduction to Pipe-Jacking and Microtunnelling Design" and cross-reference it with Section 3.2 and Section 3.7 of this guide.

Be guided

Study Part 3 of "An Introduction to Pipe-Jacking and Microtunnelling Design" and cross-reference it with Section 3.2 and Section 3.7 of this guide.
3.2 Suitability and selection of pipe jacking excavation methods

The stability of an excavated bore is of considerable importance in pipe jacking. Large ground movements above the pipeline may cause damage to surface structures or services. Ground collapse on to the pipeline will greatly increase the resistance to jacking and may lead to high jacking loads. Face excavation collapse may endanger the pipe jack miners or excavation machinery.

As stated in Section 3.1 of this guide, ground conditions must be carefully assessed to anticipate possible face instability, particularly in cohesionless soils below the water table, soft clays, silts, and mixed soils. Where any possibility of collapse exists, consideration should be given to the use of ground water lowering or removal techniques, grouting or chemical stabilisation of the soil, or the use of earth pressure balance or Slurry support tunnelling machines.

The face stability in cohesive soils may be assessed by reference to Figure 4 in the Appendix to this guide.

In cohesive soils the face pressure required to be controlled to ensure that neither excessive settlement nor heave occur. It is recommended that a factor of safety of 1.5 to 2.0 on soil strength be used in soft clays to limit settlement or heave.

Stability of cohesive soils around a pipeline is a function of the undrained strength of the soil and in cohesionless soils depends on the angle of friction of the soil.

Tunnel stability may be assessed from Figures 2 and 3 in the Appendix to this guide.

Excavation for the installation of jacking pipes is undertaken either by hand or machine within a shield, or by a tunnel boring machine. Illustrated are the types of shield currently in use.

The tunnel boring machine may be adapted into the slurry mode or air pressurised mode for balancing earth or water pressure.

- **Hand Shield**: An open face shield for manual excavation.
- **Backheader**: An over-face shield with a mechanical backwater.
- **Cutter Boom**: An open face shield with a cutter boom or rocket header.
- **Tunnel Boring Machine (TBM)**: A shield with a rotating cutting head.
- **Earth Pressure Balance Machine (EPBM)**: A full face tunnel boring machine with a balanced screw auger to control the face pressure.
- **Microtunnelling**: A fully guided, remote controlled machine.
3.0 Parameters to be considered to produce the best

3.2 continued

The PJA 'An Introduction to Pipe Jacking and Micromanaging Design' illustrates in Part 4. the types of excavation methods available and also tables the selection of pipe jacking shields as related to:

<table>
<thead>
<tr>
<th>Excavation type of ahead</th>
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</thead>
<tbody>
<tr>
<td>Pipeline internal diameter range</td>
</tr>
<tr>
<td>Length range up to</td>
</tr>
<tr>
<td>Face support initial or additional</td>
</tr>
<tr>
<td>Remarks other relevant matters</td>
</tr>
</tbody>
</table>

It is recommended that this section is studied carefully and used to select the best excavation and face support method for the ground conditions applicable to any scheme.

There are many types and manufacturers of pipe jacking shields and TELMs, and each type will have its own design and performance characteristics. After selection of an excavation system the designer/installer should contact the equipment manufacturer to obtain precise information specific to the chosen equipment, to ascertain the suitability of its operational capacity to handle the ground conditions.

Summarised here is a guide to some of the criteria to look for in assessing the suitability of the equipment for good installation.

**Hand Shield**

A hand shield must be equipped with at least four steering jacks spaced around the lead pipe. The shield should be of a diameter slightly greater than the outside pipe diameter to allow it to be steered and provide an annulus for lubrication.

The aspect ratio of diameter to length of a shield can be critical to its steering ability. **Advice** from the shield manufacturers should be sought on this matter.

In firm ground conditions the excavation may proceed with a slight overcut to the shield circumference. Alternatively the shield can be used to trim the under excavated face.

In loose ground conditions, consideration should be given to the provision of a protective hood and/or ground breasting boards or sand tables.

**Backactor: Cutter Boom**

Backactor or cutter boom shields are essentially open face shields with a mechanical means of excavation. The backactor type is suitable in semi-stable to stable soils up to strong cohesion values. The cutter boom is more suitable in higher strength soils, marls and some rock types.

When choosing a machine be guided to:

- The required power of the mechanical excavation device to excavate the soil
- Facilities to contain soft material released from the face and water infiltration
- Steering control facilities
- Independent shield thrust jacks
- A suitable spoil disposal arrangement
Tunnel Boring Machine (TBM)

Tunnel boring machines come in many guises and are probably the most common mechanical face excavation method for pipe-pilling in varying soils. The face excavation is supported by a number of techniques, and a considerable variety of machines are available in the market place for tunnelling through different ground conditions.

Slurry machines use the pressure of the slurry to balance the ground water pressure at the face, and the excavated material is transported from the face in the slurry.

Air pressurised machines balance the ground water pressure by compressed air in the excavation chamber.

In choosing a suitable machine be guided to the following facilities:

- Cutter head, full face support or cutter arms only
- Adjustable cutter face doors
- Slurry or water support chamber
- Compressed air support chamber
- Rock or hard ground cutter adaptation
- Rock or boulder crushing facilities
- Mechanical or slurry disposal method
- Steering control
- Independent shield thrust jacks
- Man-entry and maintenance facilities to the excavation face

Earth Pressure Balance Machine (EPBM)

These shields use the excavated soil to provide a pressure to contain the ground face load. The face is supported by excavated material held under pressure behind a cutter head in front of the forward bulhead. Pressure is controlled by the rate of passage of excavated material through a balanced screw auger or vena as on the screw conveyor.

Because of their specialist nature advice from a shield manufacturer is important if the use of an EPBM is being considered.

Don't guess, check it out!

Microtunnelling

Microtunnels are normally excavated with a TBM auger or slurry type machine adapted for small diameter and remotely controlled. They are equipped with active target systems or closed circuit television, for line and level control. The main be guided points are:

- The type of excavation head required for the soil conditions, bearing in mind that a change of the excavation head below ground, is not normally feasible
- An assessment of the risk of obstructions or onerous ground conditions which could abort a pipe drive, and any contingency arrangements
- Suitability of the method to cope with high water table pressures

- Baulder or rock cutting capabilities
- Length of micropile required and whether an interphase facility is practicable
3.3 Working shaft design, thrust walls, and conversion to manholes

The working shaft requirements for pipe jacking are dependent on the following factors. Be Guided and avoid Problems:

- The suitability to accommodate the shield and jacking equipment selected.
- Provision for an adequate thrust wall and pipe jack eye. A facility for removing spoil, and space for lowering and jacking the jacking pipes and/or manjack stations.
- If the shaft is reception only, space to remove the shield via a pipe jack eye.

Problems:
- Scheme delay
- Cost implications
- Loss of shield

- The suitability to support the ground pressure and water intrusion of the subsols.

Problems:
- Safety of personnel and works
- Difficult working conditions

- The practicability of positioning the working shaft together with the installation plant required in the available site area (including consideration of overhead restrictions).
- The presence of adjacent structures, existing services, traffic considerations, vibration problems, environmental and noise limitations.

Problems:
- Safety of utilities
- Cost implications
- Public safety and relations
- Insurance risk

Working shafts will require the incorporation of pipe-jack eyes which in simple terms are a means of allowing the safe entry and exit of the shield. The eye may be a simple hole through the shaft in stable ground conditions, but will require special design in loose ground to prevent loss of soil around the shield at the shaft entry and exit positions. Shallow TBMAs also require adequate entry and exit shafts.

In high water table conditions, a number of techniques are available including specially designed pressure collars, and/or de-watering, grouting or grout replacement methods, or freeing of the surrounding soils. In adverse water conditions the shield can be sealed and achieved using compressed air methods applied to the shafts.
Working shaft construction methods used with pipejacking include:

**Segmental linings**

- Precast or cast in situ caissons
- Sheet piling or secant piling
- Shallow trench sheeted or timber supported excavation
- Battered excavation
- Ground anchorages

Ref PJA "An Introduction to Pipe Jacking and Microtunneling Design" tables in Part 4, a guide to practice for selection of shafts in dry and wet ground conditions as related to:

<table>
<thead>
<tr>
<th>Type</th>
<th>Title of method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size &amp; Shape</td>
<td>Limitations</td>
</tr>
<tr>
<td>Depth</td>
<td>Range up to or unlimited</td>
</tr>
<tr>
<td>Ground Treatment</td>
<td>Whether required or additional</td>
</tr>
<tr>
<td>Remarks</td>
<td>Other relevant matters</td>
</tr>
</tbody>
</table>

It is **recommended** that this section is studied carefully and used to **select** the best shaft size and construction method for supporting the ground applicable to a scheme, taking into account the other working shaft criteria as necessary.

It is essential that whichever working shaft construction method is selected, it must be properly designed to withstand the stresses which will be imparted by the sub-soil and water pressures, together with the thrust wall loads and local stress concentrations caused by construction of entry and exit eyes for the excavation shield.

Some practical installation matters are **recommended** below.

**Segmental linings**

Core should be taken to provide good background to the linings especially over the area used to construct the thrust wall.

Where linings are to be removed for entry and exit of the excavation shield a frame / pipejack eye must be designed to transfer the stresses from the discontinuous segments.
3.3 continued

Precast or cast in situ caissons
Care must be taken not to lose ground support due to formation heave during the sinking of caissons. The effect of friction lubrication must be considered in relation to the thrust wall design. This choice of construction is likely to be selected for soft, water laden, ground conditions and therefore careful consideration is required for breakout and sneak in.

Sheet piling or secant piling
Sheet piling along with segmental linings are probably the most used methods for constructing working shafts. Sheet piling shafts must be properly designed to incorporate secure walings and struts, positioned so as not to impede the jacking operations. Sheets including corner piles must be interlocked to prevent water ingress, and loss of ground to the detriment and stability of the shaft, thrust wall and pipe jack eye. Piling should have a designed toe in cut off below formation level, dependent on soil conditions.

Shallow trench sheeted or timber supported excavation
Working shafts of this construction are more usual for short or shallow pipejacks. There is likely to be a restriction on the practical thrust wall loads achievable, and such construction is probably only suitable in dry stable ground conditions.
Good safe trenching practice must apply to supporting the excavation.

Battered excavation
Again such construction is applicable to shallow short pipejacks. The batter must be designed against slip conditions, and must comply with the recommended safety regulations.

Ground anchorages
This is a requirement for jacking pipes at ground level or just below, ideal for jacking under a road or rail embankment. The anchorage could take the form of propped cantilever piles or a ground anchor arrangement, and will be purpose designed for each scheme.
Thrust walls have for many years been designed empirically by taking a conservative ground passive resistance stress, and determining the area of the thrust wall against a calculated maximum jacking load. In many cases these empirical designs are adequate and experienced pipe jacking contractors have designs that have been proved effective in practice.

It is not normally necessary to reinforce a concrete wall except sometimes for punching shear reinforcement. Bending moment loads should be avoided by having an adequate back spreader between the thrust wall and the thrust jacks to distribute the load.

In many cases, for example with segmentally lined shafts, a purpose made steel thrust wall can be designed to spread the load over the segments, and be re-usable for many drive lengths (see sketch page 14).

It is advised that standard structural design practice is used for each specific scheme as the design parameters of depth, soil strata, and thrust load, will be unique to each project.

It should be recognised that a thrust wall is a temporary structure which is likely to be aborted after use. Therefore it is acceptable to use lower factors of safety in design calculations than would be acceptable for permanent works.

However, failure of a thrust wall can have far reaching consequences, and if the failure is one of internal failure of soil friction or cohesion, it can be very costly to re-establish. Such costs could also include overcoming friction build up to restart the pipe jack (see Section 3.4).

Where a pipejack is to continue from a shaft to which a completed pipeline has been jacketed, then consideration must be given to providing the pipes already installed. Measures should also be taken to ensure that the completed pipeline is not pushed backwards if it is incorporated in a thrust wall.

Manhole requirements will vary with each scheme design, but practical and cost considerations should be taken into account when assessing the requirement(s) of the working shaft(s) and how this might be converted to a manhole(s).

Segmentally lined shafts are ideal for conversion, but in some cases may be too large as manholes. In such cases consideration may be given to using a smaller shaft and enlarging the bottom to create a working area for the pipe jacking rig. Such designs may be cost effective on deep pipe jacking schemes. Precast and cast in situ caissons lend themselves to an all-embracing design for working shaft and final manhole or pumping chamber.

Sheet piled shafts are ideal for incorporation of a chamber type manhole which can be backfilled and the piles removed, or not as necessary, after due consideration of ground pressures and/or costs. Other working shafts are easily converted, but in all cases it is advised that early discussion is held with the promoter or designer to ensure that both the scheme design and the installation requirements are being met for both good practice and cost evaluation.
### 3.4 Drive lengths, jacking and friction loads, intermediate jacking stations, lubrication

The following tabulates the elements which make up a pipe jack and detail the limitations:

<table>
<thead>
<tr>
<th>Element</th>
<th>Limitation to drive length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working Shaft</td>
<td>No limitation other than thrust wall load which can be limited by use of interjack stations</td>
</tr>
<tr>
<td>Jacking Shield</td>
<td>Physical limitation of time for removal of spoil, and build up of friction load</td>
</tr>
<tr>
<td>Hand shield</td>
<td></td>
</tr>
<tr>
<td>Machine shield</td>
<td>Cost limitations to the distance of spoil removal from the face to the shaft. Auxiliary</td>
</tr>
<tr>
<td></td>
<td>pumping required for slurry machines. Limited by the need to refurbish the face cutters</td>
</tr>
<tr>
<td></td>
<td>in abrasive soils</td>
</tr>
<tr>
<td>Jacking Pipes</td>
<td>No practical limitation: providing interjack stations are designed to limit the jacking load</td>
</tr>
<tr>
<td>Interjack stations</td>
<td>Time/cost limitation after several interjacks have been employed, due to the speed of the</td>
</tr>
<tr>
<td></td>
<td>shield against the time required to operate the interjacks</td>
</tr>
<tr>
<td>Spill removal</td>
<td>An important limitation on practical drive lengths. Both mechanical and pumping disposal will</td>
</tr>
<tr>
<td></td>
<td>limit the practical and economic production</td>
</tr>
<tr>
<td>Lubrication</td>
<td>Some practical injection limitations for long drive lengths</td>
</tr>
<tr>
<td>Friction loads</td>
<td>Dependent on the jacking behaviour (or stand up characteristics) of the soil. Slow build up</td>
</tr>
<tr>
<td></td>
<td>with time will determine the ultimate drive length</td>
</tr>
<tr>
<td>Tolerance checking</td>
<td>Sophisticated control systems will be required for long drives</td>
</tr>
</tbody>
</table>

It may be seen from the above table there are some practical limitations to long drive pipe jacking, and these may be summarised as time restrictions affecting friction limits, and cost restrictions due to practical production being governed by spoil disposal limitations.
Taking such factors into account, the practical and economic lengths with current technology are up to 900 metres for pipes in the 1200mm to 2500mm diameter range, although in some cases longer lengths could be considered.

Large diameter pipe jacks have been driven up to 1500 metres, and over.

It is considered that in the market place of sewer and water conduits, where long pipe jacking finds its major use, that most schemes will require to be designed with working shafts at 500 metres or less.

Microtunnelling is restricted by the jacking load limit of the pipes, the practicability of introducing interjack stations, and the constraint of guidance systems in the smaller diameters.

Drives of 150 metres are common place and greater lengths are achievable.

Where practicable it is recommended that to achieve good drive lengths and good pipe jacking, the maximum space facilities are granted for the working shafts, and the shafts are designed of sufficient size to easily accommodate the main elements of a pipe jack i.e. the shield, the jacking rig and pipes, thrust wall and pipe jack eyes, spoil removal plant, guidance systems and all other ancillary equipment.

Tight working conditions can be accommodated using special plant, and short pipes, but it should be noted that logistical and access difficulties may lead to inefficient working practices, resulting in cost escalation.

The Jacking load required to install a pipe jack is derived from the following:

- Face load to advance the shield
- Self weight of the jacking pipes in stable ground
- Friction around the jacking pipes due to ground closure or unstable soils
- Misalignment or time delays during jacking

The shield load is normally a constant whilst the self weight of the pipes is a linear load distance increase. The ground soil friction may vary both linearly or exponentially, depending on the anchoring behaviour of the soil, the accuracy of the pipejack, and the time and/or delay. Misalignment and time delays are discussed elsewhere.

For many years the PUH has given as a guide, frictional losses in the range of 0.5 to 2.5 tonnes per square metre of the external circumferential area of the pipes, depending on soil conditions.
Forces due to the self weight of the pipes in a stable bore are a function of the weight of the pipe (W) to the interface friction coefficient (δ). A factor of 25% should be added to cover minor misalignment:

\[ F = 1.25 \cdot W \cdot \tan \delta \]

In soft clay a more appropriate model is that of Haslam (1986) as in Figure 4 of the Appendix to this guide.

When the ground crosses onto a pipeline, the resistance will increase considerably compared to that of a stable bore.

Even when the excavation tunnel is stable, the ground may cave into the pipe due to "elastic" unloading of the ground around the tunnel. The reductions in vertical and horizontal diameter of the opening may be estimated from the elastic analysis as given in Figure 5 of the Appendix to this guide. If these reductions exceed the initial overbreak, contact between soil and pipe will occur, axial stresses will develop, and resistance to jacking will start to increase.

In non-stable zones, the ground soil friction created is a function of the internal friction of the soil and its interaction with the pipe.

A model for loading in cohesionless soils may be found in Figure 6 of the Appendix to this guide. From the Oxford research, measured friction forces during pipe jacking tended to be slightly below past empirical experience, and compared well with theoretical analysis.

However, readers should beware that pipeline construction does not always occur in homogeneous soil conditions. Also soils do not always behave as predicted. Both theoretical and empirical data should be applied to provide ground and safe working conditions.

Misalignment must inevitably induce contact stresses between the pipe and the ground. Examples of the effect of misalignment may be obtained from the Oxford research data.

It is well known that time delays will create restart jacking loads higher than those needed to maintain steady motion. Research data has confirmed that such increases can occur during short stoppages and may increase by 25% within an hour, and up to 75% in twenty four hours.
The intermediate jacking station is used to limit the pressures applied to the pipes and the thrust wall by making use of the friction forces created by the following pipes.

The interjack is entered at any position determined by the overall frictional resistance and operating load available from the thrust wall.

The interjack itself consists of a steel cylinder which matches the outside diameter of the jacking pipe and is fitted, either as a tolerance fit to the leading interjack pipe, or in some cases comes factory fitted from the pipe manufacturer. It must be designed to cater for ground, hydrostatic and thrust load conditions.

A trailing interjack pipe, accessed to slide into the interjack shield, is positioned behind hydraulic jacks. These are used to activate the station to move the forward train of pipes independently of the trailing pipes, using the friction resistance of the trailing pipes to reduce the load on the main thrust wall.

A number of interjack stations may be employed for long jacking distances, and it is usual to design the jacking capacity of the interjack stations to have reserve in the event of jacking loads increasing for any reason.

The example below shows the sequence of installation and operation of interjack stations, together with the effect on the jacking loads required by the thrust wall.
Lubrication can only work effectively if a layer is maintained between the exterior of the pipe and the adjacent excavated soil surface.

In a crude form this can be provided by a simple greasing of each pipe before it enters the ground.

Once the ground has collapsed onto the pipe the effect of lubrication will be greatly reduced. The lubricant must therefore provide sufficient pressure to prevent this happening.

If a slurry is used it must be designed to form a filter 'cake' in the surrounding soil without excessive bleeding of material, and be pressurised to the necessary level to overcome ground water pressures and stabilise the tunnel.

If the lubricant can be designed to fill the entire overbreak then the pipes will theoretically be buoyant.

The success therefore of lubrication in varying soils will depend on the lubricant, the sophistication of the lubrication system, and the behaviour of the soil in absorption of the lubricating material.

It has been proved that a fully lubricated drive with an annulus filled with bentonite results in driving resistance no much in excess of that created by the shear strength of the bentonite slurry.

Bentonite slurries are recommended in silty, sandy and gravelly soils, but may create swelling in clay due to the absorption of water, leading to increased contact stresses between pipe and ground.

Non-aqueous lubricants should be considered for cohesive soils.
3.5 Surface establishment

The surface establishment (or "topside" in jargon) is a support service of equipment required to feed the main pipe jacking operation.

The arrangement of these services is important from an ergonomic point of view, to provide an ergonomic and efficient set up in the minimum possible space. This may be essential in an urban area, where space can be at a premium.

The main support services generally include:

- Craneage or gantry for handling the shield, pipes and ancillary equipment
- Storage facilities for pipes and other materials
- Muck handling facilities, skips, slurry disposal, separation or settlement plant
- Lubrication mixing and injection plant
- A control station for the main and inew jack power units, remote control units
- Services: electrical, communications, water supply
- Pumping plant and disposal outlet
- General stores, workshop
- Hoardings: fencing, lighting, security and safety arrangements
- A survey station

Micromet tunnel topsides have been rationalised to provide a fully equipped and mobile container type control module, which sits alongside or over the working shaft, and provides all the service functions, including gantry lifting facilities, within a small confined area (see Page 13).

The sketch shows a typical topside set-up:

![Diagram of topside setup]
3.6 Pipe jacking pipes

Pipe jacking pipes and typical flexible joints are described and illustrated in Part 5 of An Introduction to Pipe Jacking and Microtunneling Design.

The majority of pipes jacked are concrete manufactured to BS 5911: Part 120: 1989. They should be obtained from a certified manufacturer and quality assured to BS EN ISO 9002. All pipes should be certificated.

Microtunneling pipes smaller than DN 900 are outside the current scope of B.S. 5911: Part 120: 1989 and should conform to the Pipe Jacking Association and Concrete Pipe Association "Concrete Pipes for Jacking Smaller Diameters (Microtunnel) and Unreinforced Pipes".

The stresses affecting a jacking pipe are barrel and joint stresses.

Research has shown that longitudinal tensile stresses are not critical and pipe barrel stress may be safely designed using simple compression theory. Only nominal longitudinal reinforcement is required. Hoop reinforcement is required to resist bending due to ground pressures, and also to protect the pipe ends which are subject to complex three-dimensional stress conditions.

Joint stress is a function of the maximum allowable concrete stress, the stiffness of the packing material, and the maximum allowable deflection angle between the pipes (see Figure 7).

Deflection angles may be as a result of deviation in line and level tolerance or due to lack of squareness of the pipes. Although BS 5911 allows a maximum angle of 0.15° for lack of squareness (i.e. 0.3° for opposing errors between two pipes), pipes manufactured by PUA members are generally to a control of 0.06°, and therefore this error may, in practice, be discounted where this accuracy is maintained.

Research shows that even with a small joint deflection the stresses in the joint are highly localised to a short part of the pipe circumference, the exact area depending on the load transmitted and the stress-strain behaviour of the packing material.

In controlled pipe jacks angles may range between 0.0° to 0.3° with a maximum value of 0.5°. It is not recommended to exceed these values under high load conditions.

Beware the allowable end jacking load decreases rapidly as joint deflection increases (see Figure 8).

Packers to the pipe joint must be resilient enough to take the unloading jacking stress and thick enough to take the compression of the maximum joint stress. They should cover the maximum exposed concrete joint area but be kept 20mm back from the edge of the concrete to reduce the risk of local spalling. This dimension may require to be varied for microtunneling pipes.
When the jacking force is well distributed over the pipe end area, it is appropriate to use a maximum concrete design stress based on the characteristic strength of the pipe concrete, $f_{ck}$ divided by a materials factor $T$, of 1.3 and a stress factor $T$ of 1.25 when using the design method given in Figure 5 (Ref: BS8410 Parts 1 & 4).

Further pipe jacking end load calculation methods are awaiting publication under the CEN codes.

Figure 8 of the Appendix shows the relationship between permissible pipe end loadings at various angular misalignments for typical pipe jacks with packers of good stiffness and recovery, but low Poisson's ratio (i.e. transverse stress) to minimise bursting joint stresses.

Further analysis of other packers may be found in the Oxford research data (Ripley 1989).

Pipe manufacturers supply a variety of jacking pipes and catalogue pipes with flexible reated and butt joints, special lead and interjack pipes, microtunneling pipes, and reference to such manufacturers should be made for precise dimensions and strength of their products.

The pipe manufacturer will recommend packers to be used with their pipes. These should either be factory fitted, or site fitted to the manufacturers instructions.

Pipes should be unloaded, stored or stacked and lifted in accordance with the Concrete Pipe Association recommendations, and in compliance with the appropriate health and safety regulations.

Depending on shaft design, pipes may be lowered horizontally or vertically. If vertical lowering is required then the pipes will require to be handled in a purpose made crane or lifting device.

If lubrication is required it is recommended that the pipes be provided with grouting holes and non-return valves.

Each manufacturer will have a joint sealing system which may be a sliding type seal or an elastomeric seal ring. and may include secondary sealing. It is essential that all pipes are painted in accordance with the manufacturers instructions. Jointing of pipes in the working shaft must be carried out with care and in clean conditions.

A badly positioned jacking pipe can cause collar failure and may affect the hydraulic performance of the pipeline.
Other materials such as steel, GRP, fibrous cement and vitrified clay are used in pipe jacking. Each material will have special characteristics and it is recommended that both manufacturer and installer work closely on projects designed for such pipes.

It is quite possible to jack pipes to a controlled curvature, either in an horizontal, or vertical plane, or both.

This may be required to avoid an obstruction in the horizontal plane or to reduce the entry and exit depth in the vertical plane.

If a curve is required it is advised that the scheme design is discussed with both the pipe jacking shield designer and the pipe manufacturer, to ensure that the load transfer through the joints can be taken, and that the shield can be steered to the curve required.

The following factors require to be considered when designing a curved pipe jack drive:

- **Radius of curvature**
- The ability and design of the shield, or TBM, and interjack stations to negotiate the curve
- **Pipe length and diameter**
- **Joint configuration and packing**
- **Transfer stresses through the joint**
- **Joint seal design**
- **Working tolerances and alignment control**

There is a clear relationship between these factors; eg a tight radius will require short pipes or maybe skew ended pipes, whereas a large radius may only require a modified packing and sealing arrangement to standard pipes.
3.7 Ground movement

During pipe jacking ground movement may occur due to the instability of the face of the tunnel, or from the elastic unloading of ground caused by excavation (see Figure 5).

These have been referred to in Section 3.6 of this guide and may be categorised as short term settlement and heave. Providing good practice is followed, the effect of such movements should not be adverse.

Long term settlements will occur due to closing of the overbreak, and may be assessed using methods developed for other forms of tunnelling (see Figure 11).

Pipe jacking has the advantage that the overbreak is minimal and may be pressurised in certain soil conditions.

The Oxford research discusses ground movement findings and may be used in reference with other field observations where settlement is a major concern.

Continuing research is being undertaken on this subject and the PJA will be publishing their findings in due course.

For the designer/installer a number of be guided points are worth consideration and are listed below.

**Problem**
- Shallow construction and cover to services

**Solution**
Consider physical support to services and/or localised grouting.

**Problem**
- Effect on parallel services

**Solution**
Monitor their position and design with sufficient clearance to avoid interference from ground movement or drag. Consider grout support with stabilised face shield control.

**Problem**
- Railway and/or Road embankments

**Solution**
Minimise embankment movement by using a slip plane method and/or interjacks. Protect shield drag exit with a strong reception retaining wall.

It must be recognised that any tunneling method will create some ground movement, which may be significant or otherwise, dependent on the location of the tunnel related to third party structures, depth, subsurface conditions, water intakes, excavation methods, and not least the skill of the construction team. The cost that the promoter is prepared to pay for the best ‘best and braces’ scheme must also be taken into consideration.

The important lesson to address is not that ‘there shall not be any ground movement’, but what will it be, will it seriously affect third party property, is it safe, have we a monitoring system, what movement can we accept, and what are the long term ramifications?.

This point is laboured as the second concern contractual actual matter after dealing with water, Section 3.6.1 and is further discussed in Section 6.1.
The Oxford research addresses the importance of pipeline alignment and the relationship of angular deflection between pipes against the requirement for line and level of a scheme design.

The simple fact that a "rifle barrel" pipework avoids problems as against a "wiggle" pipework has been known and experienced by both promoters and installers over many years.

In an ideal pipework no deviations would exist, but in practice irregularities in ground conditions or cutting control will cause the shield to stray from the ideal course, and this in turn will create additional friction forces and higher loads transferred through the pipe joints. Angular deflection between pipes and deviation from line and level.

It is important to realise the relationship between a tolerance for line and level, and a tolerance for angular deflection between pipe joints.

In practice it is quite possible to stay within a line and level tolerance yet go outside the angular deflection tolerance and vice versa.

The following sketches illustrate this point:

![Pipeline out of line and level tolerance but within angular deflection tolerance](image)

![Pipeline out of angular deflection tolerance but within line and level tolerance](image)

The purpose of this guide is to continue to educate all users of the pipework system to good practice, and to use the research knowledge to maintain and improve the skills that have been promoted by the PJA.

Understanding the relationship between alignment deviation and joint deflection is fundamental to good pipework, and research continues to develop sophisticated control systems to measure both the above criteria.

The Oxford publication, "Pipe jacking - Research Results and Recommendations", refers in some detail to a three-dimensional control system and a graphical method, which allows decisions about steering corrections to be made to minimise subsequent joint angles.
Tolerances of ±75mm for line and ±50mm for level have been generally accepted by the industry as being both practical for the user’s final design, and also providing sufficient latitude for the installer to cope with the steering demands of varying ground conditions.

With the increasing sophistication of pipe jacking equipment and control systems, there is an increasing demand for tighter tolerances for some activities (e.g. flat gradient sewer schemes).

Also it should be recognised that tighter tolerances are required for microtunneling, especially in the smaller diameter range, taking into account the diameter/pipe length/deflection angles.

If tighter tolerances are required, it must be understood that these may not be possible in all planes, and therefore the promoter/designer must decide which tolerance (i.e. vertical or horizontal) is of most importance to the scheme.

For a sewer design, it may be that level is more important than line, and the tolerances could be revised to say ±150mm for line and ±25mm for level.

For a sleeve pipe to take a steel gas main, it is probable that both line and level are of equal importance in order for the sleeve to accept the rigid carrier pipe. In such a case it may be sensible to design the sleeve pipe to provide an internal diameter greater than a normal fit to allow for tolerance variations in both plane.

Whatever tolerances are specified it must be emphasised that the ultimate criterion is the joint detection which must not exceed the value used in calculating the pipe design load.

The following graph provides some be guided advice on this point.
4.0 Good installation practice

4.1 Steering control

Good steering control requires the following:

- An accurate survey between the thrust and reception shafts.
- An accurate set up, break out and shield entry.
- An accurate and steerable shield.
- A control system to monitor line and level.
- A system to measure and control joint deflection between pipes.

Normal surveying equipment is quite adequate to provide an accurate survey between the thrust and reception shafts. It is advised that the initial survey be carried out twice using independent survey stations, and preferably different surveyors. Also of great importance is the transfer of the survey to the bottom of the shafts, and a discipline for checking survey stations on a regular basis throughout the pipe jack.

It cannot be emphasised enough how important it is for an accurate set up, break out and shield entry. A shield that has been sent off in the wrong direction will require that every pipe behind it will have to follow the wrong path created by the shield, with the consequent joint deflection problems and increased friction loads. Shield entry should be slow with frequent checks and the shield steering positioned at neutral until the whole shield is buried. Using the body of the shield for steering rather than the face steering jack.

Beware of unstable ground conditions and avoid loss of soil entry. This may cause differential pressures on the shield.

For good practice follow these guided points:

- Make sure the jacking frame will not deflect under the weight of the pipe/shield.
- Secure the jacking frame to the correct line and level on a firm base that will also take shock loads.
- Make an allowance on the jacking frame to account for the overbreak of the shield to the lead jacking pipe, so that the pipe lies central to the shield.
- Check that the thrust wall, backspreader and jacks are all at right angles or aligned, depending on the jacking rig, to the line and level gradient of the designed bore.
- Set up the shield and jack it up to the shaft face or pipe jack eye, and check that it is correctly aligned before excavation commences.
- If using a laser, make sure that it is rigidly mounted and fixed independently of the thrust wall. Lasers should be of the self-leveling type.

Above all keep checking and re-checking.
Pipe jack shields must be **accurate** (i.e., cylindrical to a line tolerance) and should incorporate a **steering arrangement**.

In a hand shield this can be simple jacks for adjusting the shield in relation to the lead pipe, but a TBM will require a **steerable head** which articulates relative to the body of the shield.

If a shield is not manufactured to tolerance or has been damaged during use, it may create its own steering characteristics which will cause it to "crab" or roll out of control.

The shield must be provided with a target as near to the face as practicable on to which normal instrument surveying or laser beams can be set to provide a control for the tunnel miner or machine operator.

Constant monitoring and small steering corrections are essential to maintain good alignment control.

**A control system to monitor line and level** can be as simple or as sophisticated as the diameter or length of the bore determines.

Normal surveying instruments have been used for years and laser technology is now common in all fields of civil engineering and tunnelling. More sophisticated methods such as gyro compasses and computerised automatic control systems are available.

Whichever system is employed the important message is that it must be fully understood by all the operating personnel.

Checks must be regular and recorded, and the system must be checked back to the main survey on a regular basis.

If misalignment does occur for any reason, it is important to keep steering corrections small in order to avoid large angular deflections of the pipe joints.

If small corrections mean that the pipeline will travel outside the scheme design tolerance, then it is better to exceed the line tolerance rather than the level tolerance.

Depending on the size of the misalignment, a philosophy of striking a new line and level target is always better than trying to go back to the original.

**A system to measure and control joint deflection between pipes** is required to ensure the angular deflection limits in Section 3.6 are not exceeded.
4.2 Loading control

The thrust loads necessary to install a pipe jack are created by the length and diameter of the bore and the forces generated in the ground conditions.

The loads that can be applied depend on the strength of the jacking pipes and the ability to construct a jacking anchorage and/or provide interjack stations.

The thrust load is normally generated by powerful hydraulic jacks, and must be transferred to the pipes and thrust anchorage by using strong distributor plates.

In the thrust anchorage this can take the form of a back spreading steel plate to distribute the load evenly onto the surrounding shaft or ground.

To transfer the load onto the pipes it is advisable to provide a strong thrust ring and to use sufficient jacks around the ring to provide even pressures.

It is recommended that the jack arrangement is designed to provide a resultant thrust load which is concentric to the pipe to avoid overturning moments.

The power of hydraulics is not always appreciated. Kinetic energy is a function of load and speed and damage may be caused depending on the ability of the receiver to absorb energy.

Pipe jacks require large energy to install, but jacking pipes are low speed energy absorbers. Hydraulic jacks should therefore be designed to give high loads and low speeds to avoid kinetic damage and provide good jacking control.

The jacking system must be supplied with a device to measure the jacking loads being applied, and for safety include a control valve to limit the system to the maximum allowable design load.

It is recommended to provide a factor of safety to both the ultimate forces calculated to install the pipe jack and the design thrust load of the pipes at their minimum deflection.

Interjack stations will incorporate a number of jacks distributing their loads through steel plates around the pipe circumference.

It is sensible to correlate the speed of the interjack stations and the main jacking station in order to achieve the minimum time to move the whole pipeline forward.

Interjack stations should be considered as insurance policies and installed at regular distances commensurate to the overall design forces anticipated, and should include a good factor of safety.

It is not unknown for the scheme design forces to increase substantially due to changed ground conditions or behaviour of the ground.
4.3 Record control

A pipe jack is only completed when the shield enters the reception shaft and is disconnected from the jacking pipes and the interjacks closed.

In this respect and until this moment the pipeline may be considered to be in a temporary work state and requires constant monitoring.

Monitoring without recording is a halfway house and it is recommended that the following minimum records are kept.

The table below indicates the information that can be obtained both for the pipe jack in construction or completed, which can be invaluable to future pipe jacks to be constructed.

<table>
<thead>
<tr>
<th>Record</th>
<th>Information obtainable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main survey checks</td>
<td>Movement of shafts, surface to tunnel survey check</td>
</tr>
<tr>
<td>Line and level</td>
<td>Sinking, scouring, alignment</td>
</tr>
<tr>
<td></td>
<td>Settlement considerations</td>
</tr>
<tr>
<td>Shield position</td>
<td>Crabbing, rolling, sensitivity</td>
</tr>
<tr>
<td>Pipe rolling</td>
<td>Differential soil pressures</td>
</tr>
<tr>
<td>Joint deflection</td>
<td>Stress limitations, alignment</td>
</tr>
<tr>
<td>Main jacking load</td>
<td>Thrust wall limitations</td>
</tr>
<tr>
<td></td>
<td>Soil friction characteristics</td>
</tr>
<tr>
<td></td>
<td>Start up and time delay loads</td>
</tr>
<tr>
<td></td>
<td>Pipe stress limitations</td>
</tr>
<tr>
<td>Interjack load</td>
<td>Friction loads, time related loads</td>
</tr>
<tr>
<td>Shield load</td>
<td>Face load, obstructions, slurry and/or earth balance requirements</td>
</tr>
<tr>
<td>Total load</td>
<td>Equipment losses and efficiency</td>
</tr>
<tr>
<td></td>
<td>Overall ground and friction loads</td>
</tr>
<tr>
<td>Surface checks</td>
<td>Short term ground loss or heave</td>
</tr>
<tr>
<td></td>
<td>Long term settlement</td>
</tr>
</tbody>
</table>

A recommended pipe jacking record sheet is shown in the Appendix, Figure 12.
5.0 What can go wrong?

Sections 3 and 4 of this guide have covered matters relating to good practice for scheme design and installation of pipe jacks. They have been written to encourage users to go good practice. Practical and commercial evaluation of the results that make up a successful pipe jack contract.

However well advised, humans make mistakes or errors, rarely deliberately but more likely from pressure of time, misunderstanding, forgetfulness. Poor disciplines and checking. How often does one check the oil level or tyre pressure when running into the car to attend a deadline meeting?

Good pipe jacking is a discipline to keep out of trouble, rather than get out of trouble. Providing the user understands what can go wrong, then the pipe jack should be successful.

This section will identify a check list of poor disciplines and the resultant likely failures if these disciplines are ignored or given low priority.

No list can ever be exhaustive and all parties to a pipe jack scheme should be prepared to add their own disciplines peculiar to their scheme.

<table>
<thead>
<tr>
<th>Poor Discipline</th>
<th>Likely Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inadequate soil investigation</td>
<td>Stalled or aborted pipe jack</td>
</tr>
<tr>
<td>Wrong selection of pipe jack shield</td>
<td>Poor production, lack of face control, surface disruption</td>
</tr>
<tr>
<td>Poorly designed or sized working shaft</td>
<td>Uneconomic working conditions water and soil intrusion</td>
</tr>
<tr>
<td>Under designed thrust wall</td>
<td>Shaft damage, contract delay design length failure</td>
</tr>
<tr>
<td>Non assessment of friction loads</td>
<td>Stalled pipejack, over stress on thrust wall and jacking pipes</td>
</tr>
<tr>
<td>No allowance for interjack stations or lubrication</td>
<td>No margin for change in soil friction characteristics or hold up/delay load requirements</td>
</tr>
<tr>
<td>Unplanned requirements for surface establishment</td>
<td>Uneconomic working conditions, double handling of materials, interference with public rights</td>
</tr>
<tr>
<td>Insufficient research into pipe design, joint sealing, packings</td>
<td>Pipe failure due to jacking overload, ground pressure, damaged pipejacks, non-watertight pipe</td>
</tr>
<tr>
<td>Poor set up and shield entry</td>
<td>Built in problem throughout the pipe jack, with higher friction loads and joint stresses</td>
</tr>
<tr>
<td>Inadequate surveying control</td>
<td>Scheme tolerance exceeded, joint deflection risk</td>
</tr>
<tr>
<td>No jacking load control or record control</td>
<td>&quot;Gamble&quot; pipejacking, anything could go wrong</td>
</tr>
</tbody>
</table>

Many of the poor disciplines listed above create unacceptable safety risks.
6.0 Other matters

6.1 Contractual considerations

Whilst the mechanics of pipe jacking is controlled by the law of science, the construction is more than likely to be controlled by the law of contract.

Copying with the law of science is not onerous, providing logical decisions are made when changes are demanded.

Copying with the interpretation of the law of contract can be more contentious, but confrontation can be limited if the parties involved are aware of, and set out to avoid, the pitfalls.

Contract documents should be drawn up by the promoter/client in order that pipe jacking contractors can make sound engineering and economical offers to carry out the work.

However, too often vested interests, such as transfer of risk, inadequate site investigation, unclear engineering requirements, onerous clauses, amendments to standard conditions (contrary to those accepted and agreed by industry bodies), lead to misunderstanding, confrontation, dispute, claims, and litigation.

None of this is conducive to the proper and timely construction of the work, and will invariably lead to loss of goodwill between the parties to the contract, increased costs, and more tests for the legal profession.

The responsibility for drawing up contract documents lies with the client and such advisors that are instructed.

This guide is not intended to be other than a practical look at the factors that contribute to good pipe jacking, but as linked in the introduction, no pipe jack will be successful if part of the chain is a potential contractual weakness.

Listed alongside and overleaf are some of the key points which need consideration when drawing up a contract. These will go a long way to avoid contractual misunderstanding.

Conditions of Contract

Where possible use standard forms of contract. Many hours of effort and thought have gone into production of these forms, with representation from most of the industry. If changes are necessary due to a specific requirement, then make it clear to all parties.

Time for completion

So often little or no thought is given to a realistic period for completion of the pipe jacking element of the works. The client will have concerns with regard to finance programmes, planning requirements, design periods, legislation, and numerous other factors.

The pipe jacking contractor will have concerns to current workload, utilisation and availability of equipment.

The pipe manufacturer will need to check the stock load and any special design requirements. If the pipejack is part of a main contract, time planning is of great importance to achieve completion, or part completion, in order to avoid disputes and/or delays which could lead to arguments including liquidated damages.

When ready to go out to tender, thought must be given to a sensible time to obtain a considered bid (taking the above points into consideration), time for a proper evaluation of the tender offer(s), and award of contract.
6.0 Other matters

6.1 continued

Specification
Specifications are required to define the standard of workmanship and materials required for the contract. They should be clear and take account of standards and codes appropriate to current practice. If the client is uncertain of the market and technical skills available, then specification in the form of a performance contract is a useful tool. In such a contract the client can specify the performance required for the finished project. This type of contract is especially suitable to pipejacking and microtunnelling because of its specialist nature. However, it requires that the installer has sufficient experience and skills to offer a proper engineering solution, and that the client’s engineer or designer has sufficient knowledge to evaluate the solution on offer.

Bill of Quantities
Although the Civil Engineering Standard Method of Measurement (CESMM) is used consistently in the UK, it is in fact not particularly appropriate to pipejacking and microtunnelling. The PJA are currently studying a preferred method of measurement, and this is planned for publication in due course.

Bills of quantities (B.O.Q.) are primarily required to provide a contractor with a basis for pricing the works which can be compared with other bids. Their secondary role is to provide a basis for evaluating the works for payment, both for the work specified, and any variations. To be of value, the B.O.Q. must be accurate in quantities and activities, and be linked to the specification, drawings and soil investigation report, so that there can be minimal argument between the parties to the contract as to what is required. Sketches with a few unit rates will only lead to misunderstanding.

Prequalification
To ensure good installation it is recommended that suitable contractors are required to demonstrate that they have the necessary experience, skills, finance and management to carry out the work.
6.2 Health and safety

The Pipe Jacking Association regards health and safety matters as being of prime importance.

All employers in the construction industry have legal, personal and economic reasons for reducing risks of injury to personnel, damage to expensive equipment, and wastage of materials.

Safety matters are referred to in various sections of this guide, and attention must be given to the overall safety of the pipejacking operations.

Many of the features of effective health and safety management are indistinguishable from sound management and construction practices recommended within this document.

It is the policy of the PJA to promote and encourage health and safety and welfare practice. Clients, designers and contractors have a duty to bring their business expertise to bear on health and safety, as they do on other aspects of their organisations.

Health and Safety legislation is in four stages:

- Acts
- Regulations
- Approved Codes of Practice
- Guidance Notes

Regulations tend to state the scope of compliance, leaving more prescriptive aspects to approved Codes of Practice and Guidance Notes.

Referenced in Section 10. are documents which are applicable but not exhaustive to good practice.

It is recommended that these documents are used as a sound starting base for safe pipejacking and microtunneling.
The object of training personnel is to achieve the optimum performance in terms of quality, efficiency and safety.

Careful planning is required to:

- Analyse each part of the work cycle to determine its criticality to the complete cycle of operations.
- Determine the most efficient and cost-effective method of undertaking the work by referring to:
  - Company and personal experience
  - Equipment manufacturers' experience
  - Suppliers' experience
  - Local knowledge

Any deficiencies in knowledge or experience will quickly become apparent, and can be rectified by appropriate training.

There can be no substitute for the hard-won experience of both equipment and material suppliers. Their experience must be sought and full use made of their in-house training schemes, simulators, site operators, training and handling manuals.

Today the cost of training is insignificant when compared with the cost of equipment, its operation and maintenance. An untrained operator can incur unnecessary costs for the sake of a small investment in relevant training.

Site personnel fit into one of three groups:

- Permanent contractor's staff
- Experienced travelling operatives
- Inexperienced locally recruited operatives

Each requires a different type and depth of training.
Permanent contractor's staff
Should be broadly trained in their company requirements with specific training covering the following:
- Geotechnical work and the interpretation of field and laboratory results
- Survey including the correlation of surface and underground surveys
- Underground working methods, specialist materials, plant and equipment
- Understanding the influence of underground work on surface installations, buildings and the like
- The requirements of current Health and Safety Legislation applicable to the work being undertaken

Experienced travelling operatives
Usually have a good command of the practical aspects of a variety of tunnelling techniques. Their suitability for the work to be undertaken must be assessed, and any deficiencies made good by an appropriate training course. Such courses could include:
- External machine manufacturers, or material suppliers courses
- In-house courses, specifically tailored and directed at chosen parts of the work content

Equipment operators require to be carefully chosen and specifically trained and rewarded, on a quality and cost effective basis.

A number of colleges, run full time courses dealing with both theoretical and practical aspects of tunnelling, and National Vocational Qualifications (NVQ's) are to be introduced for tunnelling operatives. It is recommended that such courses and certification procedures should be investigated and used if appropriate.

Inexperienced locally recruited operatives
Traditionally this source has provided some of the manpower in the industry. The operative arrives on site for the first time, often innocent of the dangers, the work content, or what will be expected to be done.

Training needs are immediate and must include:
- Basic site safety
- Use of protective equipment
- Full training for the duties required to be undertaken
- How these duties fit into the cycle of work and any personal responsibilities

The newly recruited operative must be fully supervised, and ideally not left alone until adequate training has been proved and demonstrated.

It is recommended that all categories of staff and operatives attend regular 'tool box' talks on appropriate subjects.
7.0 Check list for pipe jacking and microtunnelling

Soil investigation
- Availability: If not why not? Commission as necessary
- Is it sufficient?
- Experience from previous or current work

Shield or tunnelling machine
- Excavation method, Production capability
- Pipeline dimensions
- Face support and/or pressure control
- Access for maintenance: Breakdown recovery
- Adaptability to unforeseen or changed ground conditions

Working shaft
- Location and dimension
- Construction method
- Suitability to accommodate the shield and other equipment
- Control of ground pressures and water intrusion
- Thrust wall requirements
- Pipe jack eye facility
- Conversion to manhole or permanent structure

Drive lengths
- Shield face loads
- Soil weight of jacking pipes
- Ground friction loads
- Misalignment allowance
- Time delay allowance
- Interjack requirement: closure provision
- Lubrication arrangement

Surface establishment
- Offices and accommodation
- Equipment layout
- Pipe storage and handling
- Craneage or gantry
- Soil handling: storage spillage
- Separation or slurry control
- Fencing and hoardings
- Traffic control
- Safety and security

Pipe jacking pipes
- Pipe type and joint design
- Stress requirement: ground load/jacking load
- Joint deflection requirement: load limitation
- Joint packing accommodations
- Joint sealing arrangement
- Special pipes: lead pipe/interjack pipes
- Requirement for curved pipe jacks
- Lubrication facility
- Transport, handling and storage considerations

Ground movement
- Location and protection of services
- Monitoring system
- Backgrouting as required
Steering control
- Surface survey: double check procedure
- Transfer survey to pipe tunnel level
- Jacking frame and thrust wall alignment
- Shield entry procedure
- Pipe tunnel survey policy: laser: target
- Monitoring method: frequency, information required
- Deviation control and monitoring
- Remote control and camera checking for microtunnelling
- Recording procedure

Loading control
- Estimated jacking loads
- Transfer thrust ring and backspreader
- Power pack and jacking arrangement
- Jacking load measurement procedure and factor of safety
- Interjack load measurement and control

Record control
- Main survey
- Line and level
- Shield position
- Pipe rolling
- Joint deflection
- Main jacking load
- Interjack load
- Shield load
- Total load
- Surface checks

Other matters
- Contractual considerations
- Health and safety
- Training
- Regulations

The preceding check list, whilst not exhaustive, is a be guided list which covers the essential requirements for the best practice for installation of pipejacks and microtunnels.

There are many other factors that need consideration to complete an installation which are not appropriate to detailed discussion within this guide.

However, in order to be comprehensive the following list is added for the consideration of the reader:
- Environmental and noise control
- Public awareness and advantages
- Public health and safety
- Third party safety
- Working conditions and safety
- Employment conditions: site facilities
- Working hours: emergency policy
- Liaison with other services/authorities
- Good signing of the site
- Tipping and off site lorry movements
- Completion and clearance of the site
| Figure 1 | Face stability in cohesive soils |
| Figure 2 | Tunnel stability in cohesive soils |
| Figure 3 | Tunnel stability in cohesionless soils |
| Figure 4 | Model for ground loading in cohesive soil after Hastom (1986) |
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| Figure 12 | Recommended pipe jacking record sheet |
| Figure 13 | Soil parameters |
### Principal symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>Thickness of packing after initial compression</td>
</tr>
<tr>
<td>$b$</td>
<td>Contact width between pipe and ground</td>
</tr>
<tr>
<td>$D_A$</td>
<td>Diameter of excavation</td>
</tr>
<tr>
<td>$D_p$</td>
<td>Outside diameter of pipe</td>
</tr>
<tr>
<td>$d$</td>
<td>Internal diameter of pipe</td>
</tr>
<tr>
<td>$E_J$</td>
<td>Joint elasticity coefficient</td>
</tr>
<tr>
<td>$E_p$</td>
<td>Elastic modulus of pipe</td>
</tr>
<tr>
<td>$E_s$</td>
<td>Elastic modulus of soil</td>
</tr>
<tr>
<td>$F$</td>
<td>Frictional resistance</td>
</tr>
<tr>
<td>$f_{cm}$</td>
<td>Compressive strength of concrete</td>
</tr>
<tr>
<td>$H$</td>
<td>Ground cover</td>
</tr>
<tr>
<td>$i$</td>
<td>Trough width parameter</td>
</tr>
<tr>
<td>$k$</td>
<td>Lateral pressure coefficient</td>
</tr>
<tr>
<td>$L$</td>
<td>Length of pipe</td>
</tr>
<tr>
<td>$P$</td>
<td>Unsupported length of excavation</td>
</tr>
<tr>
<td>$P_u$</td>
<td>Contact force per unit length</td>
</tr>
<tr>
<td>$p$</td>
<td>Internal support pressure (bentonite pressure)</td>
</tr>
<tr>
<td>$R$</td>
<td>External radius of pipe</td>
</tr>
<tr>
<td>$r$</td>
<td>Internal radius of pipe</td>
</tr>
<tr>
<td>$S$</td>
<td>Surface settlement</td>
</tr>
<tr>
<td>$s_u$</td>
<td>Undrained shear strength</td>
</tr>
<tr>
<td>$S_{max}$</td>
<td>Maximum surface settlement</td>
</tr>
<tr>
<td>$T_c$</td>
<td>Stability ratio (cohesive soils)</td>
</tr>
<tr>
<td>$T_{cl}$</td>
<td>Stability number (cohesionless soils)</td>
</tr>
<tr>
<td>$t$</td>
<td>Pipe wall thickness</td>
</tr>
<tr>
<td>$t_p$</td>
<td>Packing width</td>
</tr>
<tr>
<td>$V$</td>
<td>Water pressure at tunnel axis</td>
</tr>
<tr>
<td>$V_c$</td>
<td>Transverse distance from centre line</td>
</tr>
<tr>
<td>$V_s$</td>
<td>Settlement volume</td>
</tr>
<tr>
<td>$W$</td>
<td>Unit weight of pipe</td>
</tr>
<tr>
<td>$z$</td>
<td>Contact width at pipe joint</td>
</tr>
<tr>
<td>$z_p$</td>
<td>Depth of tunnel axis</td>
</tr>
<tr>
<td>$z_A$</td>
<td>Adhesion between pipe and clay</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Deflection angle at pipe joint</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Unit weight of soil</td>
</tr>
<tr>
<td>$\gamma_b$</td>
<td>Buoyant weight of soil</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Load factor</td>
</tr>
</tbody>
</table>

**Note:** All the above symbols and nomenclature are consistent and specific to this document.
In cohesive soils, the pressure \( \sigma_y \) required to maintain stability of the tunnel face is given by

\[
\sigma_y > \gamma (H + D_y/2) + T_c S_u
\]

Where \( \gamma \) = unit weight of soil, \( S_u \) = undrained strength of soil and \( T_c \) = stability ratio - see plot below (Atkinson and Mair 1981).

In pipe jacked tunnels the unsupported length \( p \) is usually small or zero, and \( P/D_e = 0 \),

e.g. for \( \gamma = 20 \text{kN/m}^3, H = 4 \text{m}, D_y = 2 \text{m}, \) the plot gives \( T_c = 8 \)

hence \( \sigma_y > 100 - 8 \times 4 \text{ kPa} \)

and for \( S_u > 12.5 \text{ kPa}, \) no support is needed.

To prevent blow-out due to excessive face pressure,

\[
\sigma_y < \gamma (H + D_y/2) + T_c S_u
\]

In both cases, a factor of safety of 1.5 to 2.0 on \( S_u \) is needed to limit heave and settlement in soft clays, for example see below (Mair 1987).

In this case, say \( \gamma = 20 \text{kN/m}^3, D_y = 2.0 \text{m}, S_u = 10\text{kPa}, \) then \( D_y/S_u = 4 \).

For \( H/D_y = 2.0, \) and dividing \( S_u \) by a factor of safety of 2, \( \sigma_y = 20 \times 4/2/2 = 8 \times 5 = 100 \pm 40 \)

hence \( \sigma_y \) must lie between 60 and 140 kPa.

---

**Figure 1** Face stability in cohesive soils
For the tunnel behind the shield, the conditions correspond to the case in Figure 1 of P/D_2 \rightarrow \infty. The equation for calculating the support pressure required to prevent collapse is as before

\[ \sigma_z = \gamma (H + D_z/2) - T_z S_u \]

Which may be rearranged to

\[ \sigma_z = \frac{\gamma D_z}{S_u} (H/D_z + 1/2) - T_z \]

This gives rise to plots shown below. Again, values of \( \sigma_z \) less than zero indicate that the tunnel is stable without any support pressure. Note that for microtunnels \( \gamma D_z / S_u \) << 1 in most cases, and the tunnel bore will normally be stable.

For example, for \( H/D_z = 2 \) and \( \gamma D_z / S_u = 4 \), from Figure 1: \( T_z = 4 \) then \( \sigma_z = 4 \times 2.5 \times 4 = 8 \), or directly from plot above, i.e. for \( S_u = 10 \) kPa, \( \sigma_z = 60 \) kPa.

*Figure 2* Tunnel stability in cohesive soils
For tunnels in cohesionless soil without a surcharge on the surface, the required support pressure is independent of the cover depth and is given by

$$\sigma_r = \gamma D_s T_r$$

where $T_r$ is the stability number given by the plot below; it is a function only of $\phi$, the friction angle for the soil.

For example, if $\gamma = 18 \text{ kN/m}^3$, $D_s = 1.6 \text{ m}$, and $\phi = 35^\circ$ from then the plot $T_r = 0.3$ and $\sigma_r = 18 \times 1.6 \times 0.3 = 8.6 \text{ kPa}$

Alternatively, if the tunnel is at shallow depth and a large surcharge $\sigma_s$ acts on the surface, the weight of soil may be neglected and then

$$\sigma_r = \sigma_s T_s$$

with the stability number $T_s$ as given in the plot below.

Note that both solutions apply to dry soil. Water pressure, if present, must be added to $\sigma_r$ and the buoyant weight of soil used in the first equation.

Figure 3 Tunnel stability in cohesionless soils
Cohesive with a stable bore
Haslem (1986)

\[ F = \alpha s_b b \]

Where \( \alpha s_b \) is the "adhesion" between the pipe and clay, 
b is the contact width between pipe and ground.

\[ b = 1.6 \left( P_u k_u C_e \right)^{1/3} \]

where

\( P_u \) = contact force per unit length
\( k_u = D_e D_p \)
\( D_e - D_p \)
\( D_e \) = internal diameter of the cavity
\( D_p \) = external diameter of the pipe
\( C_e = (1-v_e^2)E_e + (1-v_p^2)E_p \)
\( E_e \) = elastic modulus of the soil
\( E_p \) = elastic modulus of the concrete pipe
\( v_e, v_p \) = Poisson's ratios

---

**Figure 4** Model for ground loading in cohesive soil after Haslem (1986)
For initial vertical and horizontal stresses in the ground $\sigma_v$ and $\sigma_h$, the reduction in vertical diameter of the tunnel bore due to elastic stress relief is given by

$$\delta_v = \frac{(1-v^2)D_e (3\sigma_v + \sigma_h)}{E_s}$$

and similarly the reduction in the horizontal diameter is given by

$$\delta_h = \frac{(1-v^2)D_e (3\sigma_h + \sigma_v)}{E_s}$$

where $E_s$ and $v$ are the Young's modulus and Poisson's ratio for the soil.

If internal support pressure $p$ is applied, the symmetrical increase in radius is given by

$$\Delta = \frac{(1+v)pD_e}{2E_s}$$

Figure 5 Calculation of ground closure
The radial stress around the pipe is

\[ \sigma_v = \frac{\gamma B}{k \tan \phi} (1 - e^{-3.36 \phi H_1}) \]

\[ \sigma_h = k(\sigma_v + 0.5 \gamma D_e) \]

and the total frictional resistance is

\[ F = \frac{\pi D_e}{2} (\sigma_v + \sigma_h) \tan \delta \]

where \( \phi \) is the angle of internal friction of the soil, and \( \delta \) is the angle of friction between the pipe and the soil.

When a water table is present at depth \( H_1 \), the expression for \( \sigma_v \) becomes

\[ \sigma_v' = \sigma_v e^{-\frac{B H_1}{45 \tan \phi}} + \frac{\gamma B}{k \tan \phi} (1 - e^{-3.36 \phi H_1}) \]

where

\[ \sigma_v' = \sigma_v = \frac{\gamma B}{k \tan \phi} (1 - e^{-3.36 \phi H_1}) \]

and

\[ \sigma_h' = k(\sigma_v' + 0.5 \gamma D) \]

Note that
\( \gamma \) is bulk unit weight (above water table), and \( \gamma \) is submerged unit weight (below water table), and

\[ B = \frac{D_e \tan(45^\circ - \phi/2)}{2} + \frac{D_e}{2 \sin(45^\circ + \phi/2)} \]

\[ \gamma = \frac{D_e}{2} \tan(45^\circ - \phi/2) + \frac{D_e}{2 \sin(45^\circ + \phi/2)} \]
Formula Correction – Guide to best practice for the installation of pipejacks and microtunnels

The formula on page 50, figure 7, re permissible jacking loads has an error and one of the negative signs is misplaced. The correct formula appears below.

Permissible Jacking load

\[
\sigma_j = \frac{1}{(R-h)^3} \left[ \frac{2}{3} \left( (R^2-h^2)^{\frac{3}{2}} - (r^2-h^2)^{\frac{3}{2}} \right) \right] - \frac{h}{180} \left( R^2 \cos^{-1}\left( \frac{h}{R} \right) - \frac{\pi}{180} R^2 \cos^{-1}\left( \frac{h}{r} \right) \right) \\
+ \frac{1}{180} h^2 \left( R^2 \cos^{-1}\left( \frac{h}{R} \right) - \frac{\pi}{180} R^2 \cos^{-1}\left( \frac{h}{r} \right) \right)
\]

for \( -r \geq h \geq r \)

The second formula, for \( h > r \), is correct.
From the Australian Concrete Pipe Association linear stress approach

\[ z = \frac{180}{\pi} \frac{a}{\Delta n} \max \sigma_i \beta \]

where \( E_j = \frac{E_j}{E_j + t E_j L} \) at \( E_j \) and \( E_j L \) at \( E_j + t E_j L \)

Permissible jacking load

\[ \frac{\sigma_t}{(R-h)} \left\{ \frac{2}{3} \left[ (R^2 - h^2)^{1/2} - (r^2 - h^2)^{1/2} \right] \cdot h \left[ \frac{\pi}{180} R^3 \cos \frac{h}{R/180} \right] - r \cos \frac{h}{R/180} \right\} \]

\[ + h^2 \left[ (R^2 - h^2)^{1/2} - (r^2 - h^2)^{1/2} \right] \]

When \( h > r \) permissible jacking load

\[ \frac{\sigma_t}{(R-h)} \left\{ \frac{2}{3} \left[ (R^2 - h^2)^{1/2} \right] \cdot h \left[ \frac{\pi}{180} R^2 \cos \frac{h}{R/180} \right] + h^2 (R^2 - h^2)^{1/2} \right\} \]

Figure 7: Jacking forces from linear joint stress model.
Figure 8: Permissible pipe end loadings at various angular misalignments.
Figure 9 Uniaxial compression tests on joint packer material (Milligan & Norris 1992)
For a tunnel with initial vertical and horizontal stresses in the ground

\[ p_r = \sigma_v = \gamma H \]
\[ p_a = \sigma_h = K p_r \]

the radial stress \( \sigma_r \) at the tunnel surface is zero and the maximum value \( \sigma_{max} \) of the circumferential stress \( \sigma_c \) may be obtained from the figure below for the appropriate value of \( K \). Note that the largest values occur for \( K > 1 \), i.e. in beds of heavily overconsolidated clay.

![Graph showing circumferential stress](image)

Note: \( K = \frac{\sigma_c}{\sigma_r} \)

If there is an internal pressure in the tunnel (e.g. due to bentonite lubricant) of \( \sigma_r = p \), then this causes stresses at the tunnel surface of

\[ \sigma_0 = -p, \quad \sigma_r = +p \]

For local yielding to occur,

\[ \sigma_0 - \sigma_r = 2s_u \]

\[ \therefore (\sigma_c - p) - p = \sigma_c - 2p = 2s_u \]

**Figure 10** Conditions for local yielding at the tunnel surface
From O'Reilly and New (1982)

Surface settlement $S$ at given point

$$S_{max} e^{-y^2/2i^2} = \frac{v_i}{\sqrt{2\pi}} e^{-y^2/2i^2}$$

where $v_i$ = volume loss/unit length

**Figure 11** Calculation of long-term settlements
It is recommended that for each drive a line and level record is produced together with a jacking load and progress graph.

For machine drives other information will be relevant, dependant on the shield excavation method e.g.

- Slurry pressures, viscosity, discharge, flow rate
- Shield roll, pitching, steering adjustment
- Thrust rate, cutting torque, soil discharge

These can be adapted to suit specific scheme designs.

Figure 12 Recommended pipe jacking record sheet
Soil parameters

Wherever possible, soil parameters for design should be obtained from suitable in situ or laboratory tests.

For preliminary calculations, friction angles for cohesionless soils may be obtained from SPT tests using the table below:

<table>
<thead>
<tr>
<th>Number of Blows</th>
<th>State of Compaction</th>
<th>Equivalent value of $\phi$ (approx.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-4</td>
<td>very loose</td>
<td>30°</td>
</tr>
<tr>
<td>4-10</td>
<td>loose</td>
<td>30°</td>
</tr>
<tr>
<td>10-30</td>
<td>medium</td>
<td>30-35°</td>
</tr>
<tr>
<td>30-50</td>
<td>dense</td>
<td>35-40°</td>
</tr>
<tr>
<td>50 and over</td>
<td>very dense</td>
<td>40-45°</td>
</tr>
</tbody>
</table>

Interface friction angles between cohesionless soil and concrete pipes are usually found to lie within the range $0.7\phi < \delta < 0.9\phi$.

For design of pipe jacks a figure near the upper end of this range should be used to ensure that friction forces are not under-estimated.

Stiff fissured clays (e.g. London Clay, Oxford Clay, Keuper Marl, boulder clays) are also best assessed using SPTs. The ratio of undrained strengths in kPa to SPT blow count is typically about 4.5, rising to 6 for low-plasticity clays. The ratio of drained elastic modulus $E'$ to blow count is about 600, increasing to about 1500 for low-plasticity clays.

Figure 13 Soil parameters
9.0 Worked examples

9.0 Scheme A

9.1 Overall scheme requirement
A hand shield driven pipe jack of internal diameter 1.5 metres, 150 metres in length at a depth of 12.0 metres to invert, in ground conditions of 7.0 metres of wet ballast overlying London Clay using steel-banded bun jointed concrete pipes.

9.2 Specific data to the scheme

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal diameter of pipe</td>
<td>d</td>
</tr>
<tr>
<td>External diameter of pipe</td>
<td>D_e</td>
</tr>
<tr>
<td>Wall thickness of pipe</td>
<td>t</td>
</tr>
<tr>
<td>Depth to invert of pipe</td>
<td>D_i</td>
</tr>
<tr>
<td>Depth to axis of pipe</td>
<td>D_a</td>
</tr>
<tr>
<td>Length of drive</td>
<td>L</td>
</tr>
<tr>
<td>Water table - below ground level</td>
<td>w</td>
</tr>
</tbody>
</table>

9.3 Calculate
- Tunnel face stability
- Tunnel bore stability
- Elastic ground closure
- Local yield of ground
- Ground movement
- Pipe friction and pipe joint loading

9.4 Workings
(References are to Figure Nos in the Appendix to this guide, unless otherwise stated)
9.0 Worked examples

Ground conditions

In ballast, overlaying London clay water table 15m below Q.L.

Assume London clay has N-value of ~30, undrained strength Sw = 135 kPa.

From literature, undrained stiffness of London clay for small strains
~ 750Sw, giving Es = 100 x 10^6 kPa.

<table>
<thead>
<tr>
<th>Depth to invert of pipe</th>
<th>12.0m</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 of pipe</td>
<td>1.47m</td>
</tr>
<tr>
<td>6 of pipe</td>
<td>1.25m</td>
</tr>
</tbody>
</table>

Unit weight of ballast = \( y_c = 19 \text{ kN/m}^3 \)

Saturated unit weight of London Clay = \( y_s = 21 \text{ kN/m}^3 \)

Total vertical stress at tunnel axis \( \sigma_v = \frac{19 + 4.25 \times 2}{1} = 222 \text{ kPa} \)

Water pressures approximately hydrostatic in top of London Clay.

Water pressure at axis of tunnel \( U_0 = (0.35 - 15) \times 10 = 97.5 \text{ kPa} \)

Effective vertical stress at tunnel axis \( \sigma_v' = \sigma_v - U_0 = 124.5 \text{ kPa} \)

At this depth in London clay, typically \( K_o = 16 \)

Effective horizontal stress at tunnel axis \( \sigma_h' = 1.6 \times \sigma_v' = 1.6 \times 124.5 \text{ kPa} \)

Total horizontal stress at tunnel axis \( \sigma_h = \sigma_v' + \sigma_h' = 297.5 \text{ kPa} \)

Pipes

<table>
<thead>
<tr>
<th>External diameter</th>
<th>Dp</th>
<th>1800mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal diameter</td>
<td>di</td>
<td>1470mm</td>
</tr>
<tr>
<td>Wall thickness t</td>
<td>16.5mm</td>
<td></td>
</tr>
<tr>
<td>Weight of pipe W</td>
<td>= ( \pi Dp (Dp^2 - di^2) / 24 = 20.3 \text{ kN/m} )</td>
<td></td>
</tr>
</tbody>
</table>
Tunnel face stability - Ref. Figure 1

\[ G_s = G_t - T_c \] for stability

Cover depth, \( H = 12.0 - 1.47 + 0.155 = 10.42 \) m

\( b = 5.75 \), \( P = 0 \) for smooth close to tunnel face

From plot, \( T_c = 9 \), \( \therefore G_t - T_c = 222 - 9 \times 135 < 0 \)

\( \therefore \) Tunnel face very stable, F.o.S > 5

Tunnel box stability - Figure 2

\[ \frac{H}{b} = 5.75, \ P = \infty, \ \therefore T_c = 4.2 \]

\[ \frac{G_t}{b} = 222 - 4.2 \times 135 < 0 \]

\( \therefore \) Tunnel box very stable, F.o.S > 2.5
9.0 Worked examples

Elastic ground closure - Figure 5

\[ \delta_v = \frac{(1 - \nu^2) \delta_p (3\delta_v + \delta_h)}{E_s} \]
\[ \delta_h = \frac{(1 - \nu^2) \delta_p (3\delta_h + \delta_v)}{E_s} \]

For undrained conditions immediately after excavation

\[ \delta_v = 222 \text{ kPa}, \ \delta_h = 293 \text{ kPa}, \ \ E_s = 100 \times 10^3 \text{ kPa}, \ \nu = 0.5 \]
\[ D_p = 1.8 \text{ m} \]

This gives \[ \delta_v = 13.0 \text{ mm} \]
\[ \delta_h = 15.7 \text{ mm} \]

In longer term deformation will increase due to drainage

For full drainage \[ E' = G' = K' = E_s \text{ where typically } \nu' = 0.2 \]
\[ \frac{2(1 + \nu')}{2(1 + \nu)} \]

(Since \( G \), the shear modulus, is the same in both drained and undrained conditions.)

Hence \[ E' = 0.2E_s \times \delta_v' = 16.3 \text{ mm}, \ \delta_h' = 18.8 \text{ mm} \]

These figures suggest that to prevent elastic deformations causing ground closure on to the pipe, an initial overbreak of 25mm in diameter might be needed (see later).
Check local stresses around tunnel opening

\[ \gamma = 222 \text{ kPa}, \quad \sigma_2 = 298 \text{ kPa} \]

\[ K = \frac{\sigma_2}{\gamma} = 1.34 \]

...at crown of tunnel

Local circumferential stress \( \frac{\sigma_2}{\gamma} = -1 + 3K = 3.0 \quad : \sigma_2 = 666 \text{ kPa} \)

at axis of tunnel, \( \frac{\sigma_2}{\gamma} = 3K = 1.66 \quad : \sigma_2 = 368 \text{ kPa} \)

Local yielding will occur if \( (\gamma - \sigma_2) > 2 \sigma_0 \)

For unpressurized tunnel \( \gamma = 0 \), and \( \sigma_2, \sigma_0 \) both \( > 2 \sigma_0 = 270 \text{ kPa} \)

Thus local yielding will occur unless tunnel is pressurized with suitable lubricant sum to a pressure of \( 666 - 270 = 400 \text{ kPa} \)

If local yielding is avoided, prediction of contact stresses between pile and ground is not possible without sophisticated finite element analysis. However, they may be reduced by increasing the initial overbreak, and unless surface or subsurface settlements are a major problem (see later), the overbreak could be increased to say 400 mm in diameter.
Ground movement – Figure 11

If overbreak of 30mm on diameter used (see previous), then ground loss for complete closure of ground onto pipe, giving maximum settlements.

\[ V_S = \frac{V}{2\pi i} \] \( \theta = 90^\circ \)

Because face stability is very high, assume ground loss there negligible.

From plot, \( i = 0.435 \times 11 \)

\[ \frac{V}{2\pi i} = 0.435 \]

For \( S = \) depth to tunnel axis = 11.25 m

then \( S_{max} = \frac{V_S}{2\pi i} = 7.7 \text{mm} \)

If overbreak increased to 50mm on diameter,

\[ V_S = \frac{V}{2\pi i} (\theta = 180^\circ \rightarrow 180') = 0.443 \]

\[ S_{max} = 9.6 \text{mm} \]

In either case, width of settlement trough = 6c = 36 m

Such a wide, shallow settlement trough is unlikely to cause any problems unless there are sensitive structures or services above the pipeline.
Pipe friction and Pipe joint loading - Figures 7, 8 & 9

For estimation of pipe friction, see results from Honor Oak (Fig. 9.8.5.3 of the Oxford Report). At similar depth in London Clay overall friction force averaged 5L kN/m. To allow for increases in resistance due to lapages, increase by 50%, giving maximum of 8L kN/m.

Assume packer of chipboard or MDF, 130mm thick, 15mm thick, located 15mm from inside surface of pipe.

Allow for maximum joint misalignment angle of 0.5°, requiring good control of tunnel curvature.

Assuming normal design criteria, then from information given by pipe manufacturer for Fig. 8.8 maximum pipe jacking load at angular deflection of 0.5° = 440T (4300 kN).

Then length of pipe between interjacks = 4300 / 53 = 81 m

For first length, include face load of ~300 kN (see Table 5.1 of Oxford Report)

Then length of pipe = 4300 / 49 m

Revision should be made for 3 interjacks, the first after 18 pipes (45m), the others after pipes 38 (95m) and 58 (145m). Monitoring of jacking records and use of lubrication may allow these intervals to be increased in practice.
Summary of Scheme A

**Tunnel face stability**
- Very stable
- Factor of safety 5.0

**Tunnel bore stability**
- Very stable
- Factor of safety 2.5

**Elastic ground closure**
To prevent elastic deformation causing closure onto the pipe, use an initial overbreak of 25mm on diameter.

**Local yield of ground**
Lack of yielding will occur unless the tunnel is pressurised to 400 kPa with a suitable lubricant slurry.
- This may be reduced if the overbreak is increased to 40mm, subject to settlement considerations.

**Ground movement**
Even with overbreak up to 50mm the settlement trough will be wide and shallow, and is unlikely to cause problems unless there are sensitive structures or services above.

**Pipe friction and Pipe joint loading**
Using a chipboard packer 100mm wide, and allowing a maximum angular joint deflection of 0.5°, the maximum pipe load is 440 tonnes.

From the estimate of pipe friction, provision should be made for 3 interlocks at 45m, 95m and 145m.

These may be reduced, provided monitoring indicates lower friction figures.

Using a factor of safety of 1.5, it is suggested that the thrust will be designed to accommodate 660 tonnes.
Scheme B

9.5 Overall scheme requirement
A slurry TBM shield driven pipe jack of internal diameter 1.8 metres,
300 metres in length at a depth of 7.0 metres to invert, in ground
conditions of wet ballast using steel-banded butt-joined pipes.

9.6 Specific data to the scheme

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Internal diameter of pipe</td>
<td>1600 mm</td>
</tr>
<tr>
<td>External diameter of pipe</td>
<td>2120 mm</td>
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<tr>
<td>Wall thickness of pipe</td>
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<tr>
<td>Depth to invert of pipe</td>
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<tr>
<td>Depth to axis of pipe</td>
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<tr>
<td>Length of drive</td>
<td>300m</td>
</tr>
<tr>
<td>Water table - below ground level</td>
<td>2.00m</td>
</tr>
</tbody>
</table>

9.7 Calculate
- Tunnel face pressure
- Tunnel face load
- Tunnel bore stability
- Ground closure
- Ground settlement
- Pipe friction
- Pipe joint loading

9.8 Workings
(References are to Figure Nos in the Appendix to this guide, unless otherwise stated.)
Ground conditions

Assume gravelly sand, SRF N-values = 25
Drained stiffness $E_d = 4000$ (kPa)

$= 100 \times 10^3$ kPa

Assume water table at depth 2.0 m below ground level
Saturation weight of soil $Y_s = 19.5$ kN/m$^3$
Buoyant weight of soil $Y_b = 9.5$ kN/m$^3$
Water pressure at axis of tunnel $p = 41 \times 10 = 41$ kPa
Total vertical stress at axis of tunnel $\sigma_y = 61 \times 19.5 = 119$ kPa
Effective vertical stress at axis of tunnel $\sigma'_y = 119 - 41 = 78$ kPa

Take friction angle of soil $= 33^\circ$ then $k_0 = 1 - \sin \phi = 0.455$

Effective horizontal stress at axis $\sigma'_h = 0.455 \times 78 = 35.5$ kPa
Total horizontal stress at axis $\sigma_h = 35.5 + 41 = 76.5$ kPa
Tunnel face pressure

To keep movements at the face to a minimum, surmount pressure should be equal to total horizontal stress or slightly greater, say 80-100kPa.

For 100kPa, total face pressure load \( \sigma_{e^2} \) = \( \frac{(100 \times 212^2)}{4} = 350 \text{ kN/m}^2 \).

Tunnel face load - Figure 6

In addition to load due to face pressure calculated above (35) there will be ground resistance on the cutting edges of the shield and friction on the surface of the shield and the first few pipes until pipeline installation is fully effective. Assume this length extends over 2m for the shield plus 5m for the first two pipes. To calculate resistance over this length use ground loading model of Fig. 6.

Thus \( 2B \) = \( 0.78 \times (45^\circ - 9^\circ) + 0.16 \times (45^\circ - 9^\circ) \) where \((45^\circ - 9^\circ)\)

\( B = \frac{1.78 \times 6}{2} = 5 \text{ m} \)

\( H = 6 - 2 \times 2 = 2 \text{ m} \), \( (45^\circ - 9^\circ) = 28^\circ \)

From depth 0 to 25m \( y_s = y = 0 \text{ kN/m}^3 \)

\( g_1 = \frac{g}{B} \times (1 - e^{-\lambda y_s}) \times H/B \)

\( g = \frac{(1 - \sin 9^\circ)}{(1 + \sin 9^\circ)} = 0.295 \times \frac{K \times \tan \phi}{B} = 0.1076 \)

\( g_1 = \frac{19.5 \times (1 - e^{-0.1076 \times 2.2})}{0.1076} \)

\( = 35.1 \text{ kN/m}^2 \).
Below $\beta = 2.0\Omega$, \newline then $K = \tan \phi (1 - \cos \gamma) = 0.323 \frac{Y'}{B}$

and $O' = O_0 e^{-0.323} + \frac{Y'}{0.323} (1 - e^{-0.323})$

$= 25.4 + 24.4$

$= 49.8 \text{ kPa}$

then $O_1 = K (\beta + 0.5 Y' \delta) = 17.7 \text{ kPa}$

and frictional resistance $F = \frac{P Q (O_1 + \beta)}{2} \tan \delta$

taking $\delta = 0.874 = 28.7^\circ$

$F = 119.5 \text{ kN/m}$

.$\text{For length of 9m, frictional resistance } = 1076 \text{ kN}$

hold $200 \text{ kN}$ estimated for cutting edge resistance, then total from-end load

$= 1076 + 250 + 200 = 1526 \text{ kN}$
Tunnel bore stability - Figure 3

For $\theta = 330^\circ$, $\tau_0 = 0.3$

.: $\tau_0 = \mu \mu_0$, water pressure

$= (9.5 \times 2.1/2 \times 0.3) + 4.1$

$= 7.9kPa$, say 50kPa, summary pressure

Ground closure - Figure 5

$\delta_T = 78kPa$, $\delta_T = 35.5kPa$, take $\mu = 0.2$

then $\delta = (1 - \mu^2) \frac{2.12}{100} (3 \times 78 + 35.5) = 5.5mm$

$\delta_T = (1 - \mu^2) \frac{2.12}{100} (18 + 3 \times 35.5) = 3.8mm$

Less outward movement due to summary pressure less water pressure of ~10kPa is

$\delta_p = (1 + \mu) \mu_0 = 0.2mm$ (negligible)

$E_s$

.: Provided adequate summary pressure is provided, an overbreak on diameter of 20mm will be adequate to maintain an annulus of lubricant around the pipe.

Ground settlement - Figure 11

Provided adequate face pressure is provided, settlement of tunnel face should be negligible (possibility of some heave if face overpressurised). For full closure of overbreak in the long term,

$V_s = \frac{\pi}{4} (2.14^2 - 2.12^2) = 0.0669 m^3/m$ (1.9%)

from plot, $i = 0.28, j = 0.12$, and $j = 0.1$

.: $i = 1.59m$

then total width of settlement trough $= 6i = 9.5m$

and maximum settlement

$S_{max} = \frac{V_S}{E_s} = 16.8mm$
Pipe friction

For fully lubricated pipe, buoyant uplift force = \( \frac{\pi D^3 \rho_2}{4} \) \( = 35.3 \text{ kN/m} \)

but pipe weight, \( \frac{\pi (D^2 - d^2)}{2} \cdot g \cdot \rho_1 \) = 23.6 \text{ kN/m} \)

\( \therefore \) net force on tunnel wall (knew) = 11.7 \text{ kN/m} \)

\( \therefore \) friction force = 11.7 \text{ kN/m} \)

\( \text{when } \theta = 0.374 \Rightarrow 28^\circ \)

\( \therefore \) friction force = 6.2 \text{ kN/m} \)

Add friction from lubricant/bed in annulus, at say 0.5 \text{ W/m}^2

\( 0.5 \pi D \rho \) = 3.3 \text{ kN/m} \)

Increase total by about 20\% to allow for effects of misalignment

Total friction = \((6.2 + 3.3) \times 1.2\)

\( = 11.4 \text{ kN/m} \)
Pipe joint loading - Figure 8

Allow for pachet of 18mm thick chipboard or M.D.F. of width 120mm.

Assuming normal design criteria, given from information given by pipe manufacturer see Fig. 8.4.

Maximum pipe jacking load angular deflection 0.5° = 450T (4,400kN)

Distance to first interjack = \( \frac{4400 - 1626}{11.4} \) m

\( \text{Proxional load on remaining pipe length} = 11.4 \times (300 - 248) = 593 \text{kN} \)

Since only one interjack will be needed, better to position it nearer to front to reduce repeated jacking on pipes close to the interjack.

If placed after 100m, interjack load

\( = 1618 + (100 - 5) \times 11.4 = 2709 \text{kN} \)

and final load on main jacks

\( = 200 \times 11.4 = 2280 \text{kN} \)

This provides a useful margin of error in case of less-than-perfect lubrication, or larger maximum misalignment angle.
Summary of Scheme B

Tunnel face pressure
Slurry pressure to equal face pressure = 36 tonnes

Tunnel face load
Friction on the shield (4 metres) and the first few pipes (5 metres) where pipeline lubrication is not fully effective = 110 tonnes
Cutting edge resistance of the shield = 20 tonnes
Total front end load is 110 + 36 + 20 = 166 tonnes

Tunnel bore stability
Use 50kPa slurry pressure (0.5 bar)

Ground closure
With adequate slurry pressure maintained an overbreak of 20mm is sufficient.

Ground settlement
Provided adequate face pressure is maintained settlement should be negligible
Long term settlement is calculated at 16.8mm with a trough width of 0.5 metres

Pipe friction
Total friction from the lubricant/soil annulus, allowing 20% increase for any misalignment, is calculated at 1.16 tonnes/m

Pipe joint loading
Using a chipboard packer 120mm wide, and allowing a maximum angular joint deflection of 0.5°, the maximum pipe load is 189 tonnes.

From the estimation of pipe friction only one interjack is required. It is suggested that this is placed after 100m which will result in an interjack load of 276 tonnes and a final main jack load of 232 tonnes.

Using a factor of safety of 1.5, it is suggested that the thrust wall be designed to accommodate 675 tonnes.
10.0 References

Pipe Jacking Association Publications

An Introduction to Pipe Jacking & Microtunneling Design
Concrete Pipes for Jacking Trimmed Cylinders (Microtunnel) and Unreinforced Pipes (Microtunnel), Part 1 and 2
Pipe Jacking - Research Results and Recommendations
George McNab & Brian News, Oxford University Department of Engineering Science

Principal Legislation and Standards

Construction (Design and Management) Regulations 1994
Health and Safety at Work Act 1974
Management of Health & Safety at Work Regulations 1992
ES502: 1989 Part 120 Specification for reinforced jackpping pipes with flexible joints
BS5666: 1982 Code of Practice for safety in tunnelling in the construction Industry
ES3902: Part II: 1984 Sewage - Guide to planning and construction of sewers in tunnel
Code of Practice for Design and Construction

Other References

Angular deflection
The angle between two consecutive pipes.

Annular space
The void created by the difference in diameters between the shield and jacking pipes.

Articulated head
A shield of two sections where the front section can be deflected to steer the shield or cutting head.

Backanter
A mechanical device for excavation within an open shield.

Bentonite
A natural clay with pseudotopic properties which can be used as a lubricant.

Butt-end
The term used for square end jacking pipes.

Closed shield
A shield with a capped pressure chamber or cutting head which does not allow direct access to the face.

Cutter boom
A mechanical device for excavation within an open shield.

Cutting head
The arrangement at the leading end of the shield which cuts the soil face.

Deviation
The variation from line and level to that specified.

Earth pressure balance
The creation of pressure to counter the movement of soil into the shield.

Earth Pressure Balance Machine (EPBM)
A full face tunnel boring machine with a balanced screw auger to control the face pressure.

Eye (Pipe jack eye)
A sealing device placed in the slush walls of the thrust and reception pits to allow the shield and pipes to enter and exit without soil, water and slurry flowing into the shafts.
Face
The undisturbed soil immediately ahead of the shield.

Guide rails
Steel or timber rails set firmly in the thrust pit to give directional control of the pipes to be jacked and for accurate location of the pipe joints.

Hand shield
An open facing shield for manual excavation.

Hydraulic jacks
High pressure hydraulically operated jacks providing the power to move the pipeline.

Interjack pipes
Two specially designed pipes used with the interjack station.

Intermediate Jacking station
A fabricated steel shield incorporating hydraulic jacks designed to operate between the interjack pipes to provide additional thrust load as necessary.

Jacking frame
A fabricated frame for launching the shield and pipes from the thrust pit.

Jacking pipe
A pipe designed specifically for jacking which has a flexible joint.

Jacking shield
A fabricated steel cylinder within which the excavation is carried out either by hand or machine. Incorporated within the shield are facilities to allow the shields to be adjusted to control line and level.

Joint
The flexible sealing and jointing arrangement between two pipes.

Leading Interjack Pipe
The pipe immediately ahead of, or attached to, the interjack shield.

Lead pipe
The leading pipe manufactured to fit the rear of the jacking shield and over which the trailing end of the shield is fitted.
Lubrication
Injection of a fluid such as bentonite to reduce pipe skin friction whilst jacking.

Microtunnel
A remote control method of installing pipes using a fully guided microtunnelling machine.

Open shield
A shield which allows direct access to the soil face.

Overcut
The difference between the outside dimensions cut by the shield or face excavation and the external diameter of the pipe.

Packing
Material placed between pipe joints to distribute the jacking load.

Power pack
An hydraulic pump unit feeding fluids to activate the hydraulic jacks.

Pressure plate (Backspreader)
A steel pressure plate or plates located between the rear end of the jacks and the thrust wall to backspread concentrated loading.

Rebated joint
A term used to describe a joint which is formed within the thickness of the pipe wall.

Reception pit
A shaft at the end of the jackup section of pipeline from which the jacking shield is recovered.

Skin friction
The resisting force created between the pipes and soil when the pipes are jacked forward.

Slurry
A term used for clay-water muds which can be pumped.

Slurry tunnel boring machine
A shield which incorporates a counter-balance slurry chamber.

Steel banded joint
A term used to describe a joint formed with a steel band to locate and join each pipe. Usually used with butt-ended pipes.
Thrust pit
A working shaft at the beginning of the jacked section of pipeline, in which the specialist equipment is installed, and from which the jacking operations are carried out.

Thrust ring
A steel ring that is placed against the cross sectional area of the pipe to ensure that the jacking forces are spread around the circumference of the pipe.

Thrust wall
A wall at the rear of the thrust pit designed to spread the reaction loads to the ground behind the thrust pit.

Trailing interjacket pipe
The recessed pipe immediately behind the interjacket station which enters into the rear of the shield.

Tunnel boring machine (TBM)
A shield with a rotating cutting head.

Working shafts
A general term applied to the more specific description of thrust or reception pits.