Guide to best practice for the installation of pipe jacks and microtunnels

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Preface

Pipe Jacking was first introduced into the United Kingdom in the early sixties and was used as an alternative tunnelling method to small segmental tunnels and timber headings, for providing short 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 end users.

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 state of the art review (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 desk top 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 co-operation 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**.

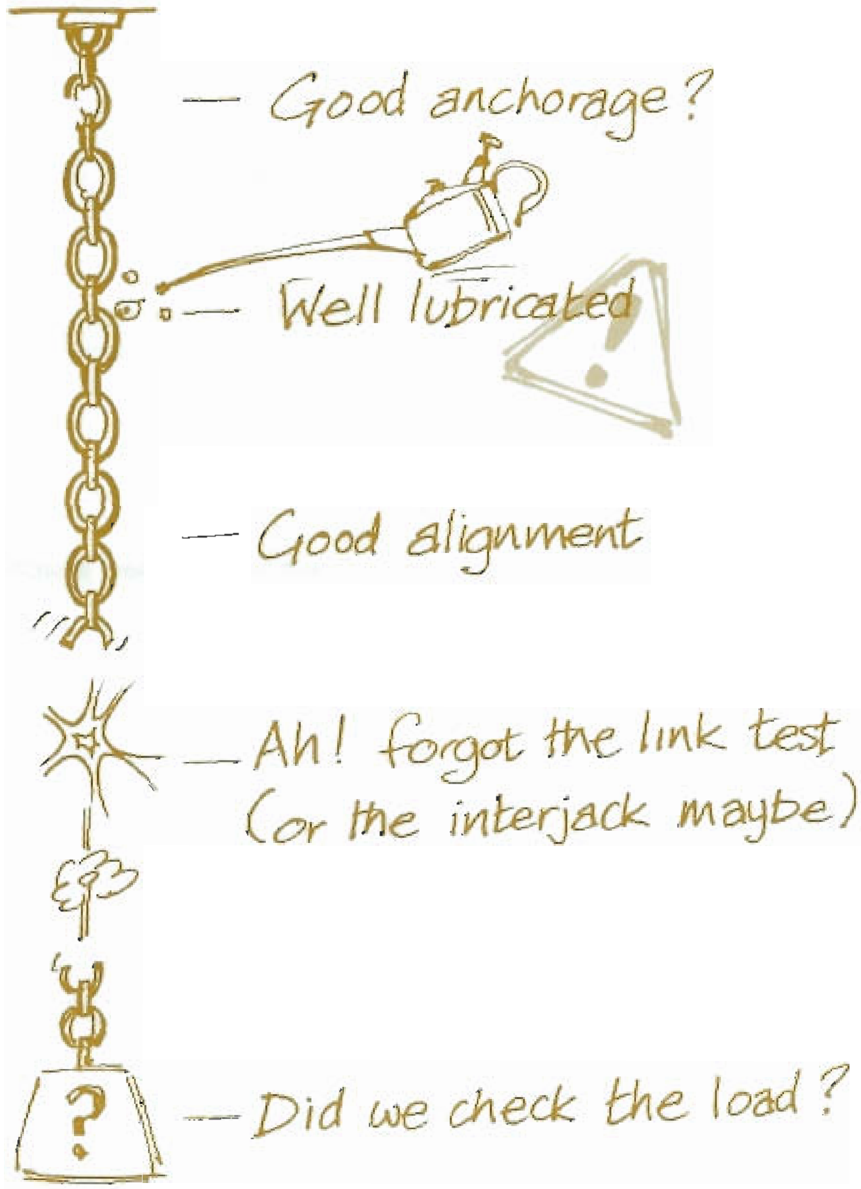
Contents

1.0

Pipe Jacking, generally referred to in the small diameters less than 900 mm as microtunnelling, 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 strung together to achieve success. These include good soil knowledge, jacking shaft design, pipe design, pipe jack shield design, hydraulic considerations, and laser 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 flexible, structural, watertight pipeline tunnelling method available in the market.



2.0

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. Superficial 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 utilised by the UK tunnelling industry, and has generated probably the most experienced pipe jackers in the world.

As prefaced, 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 jack 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

2.1 How to use this guide

Each Section from **3.0** to **7.0** (pages 8 to 41) details the essential information required to produce a good pipe jacking or microtunnelling 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
Select(ion)

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

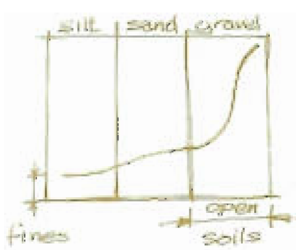
3.1 Soil investigation and interpretation

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	Section **3.2**
the working shaft(s) and thrust wall construction	Section **3.3**
the length and strength of the pipejack	Section **3.4**
any requirement for ground stability control	Section **3.7**

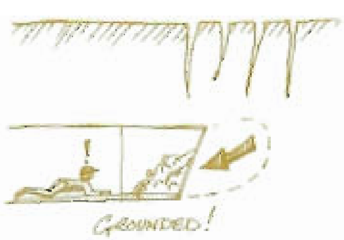
The PJA publication "An Introduction to Pipe Jacking and Microtunnelling Design", Part 3, covers the characteristics of soils likely to be encountered and the minimum information required for a proper interpretation to be undertaken.
Interpretation of soil information is not a precise science and experience, 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 guide toward 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

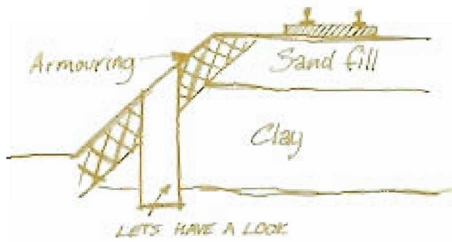
Solution Face support
Tunnel Boring Machine

● Over consolidated clays can create high friction forces as soil stresses are released around the pipe during jacking.

Solution Lubrication
Interjack stations

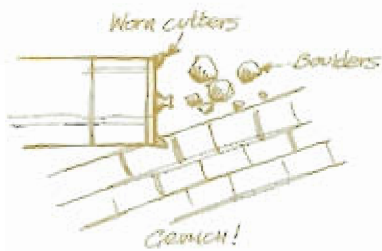
● Mixed soils or material used for filling (embankments etc) should be examined by trial pits to assess the best pipe jacking method.

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

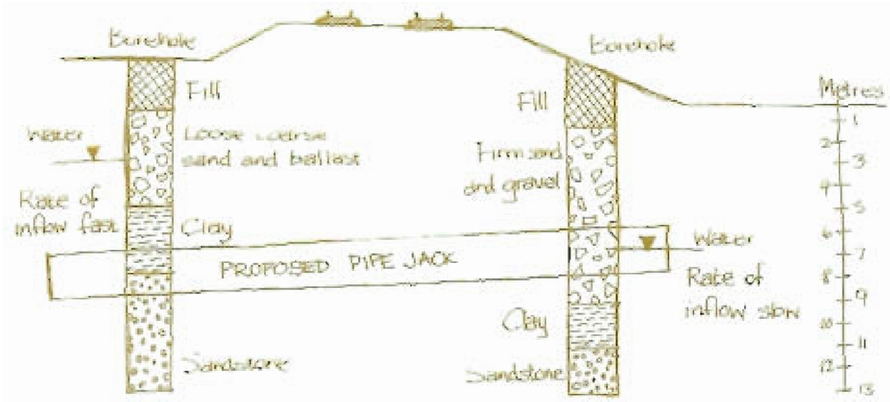
Where the presence of excessive water is expected, evidence of water table(s), artesian head(s), should be noted along with the results of permeability and/or pumping tests.
The presence of, and dealing with water, is probably the most common and contentious contractual element of any tunnelling method 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

3.1 continued

Be guided

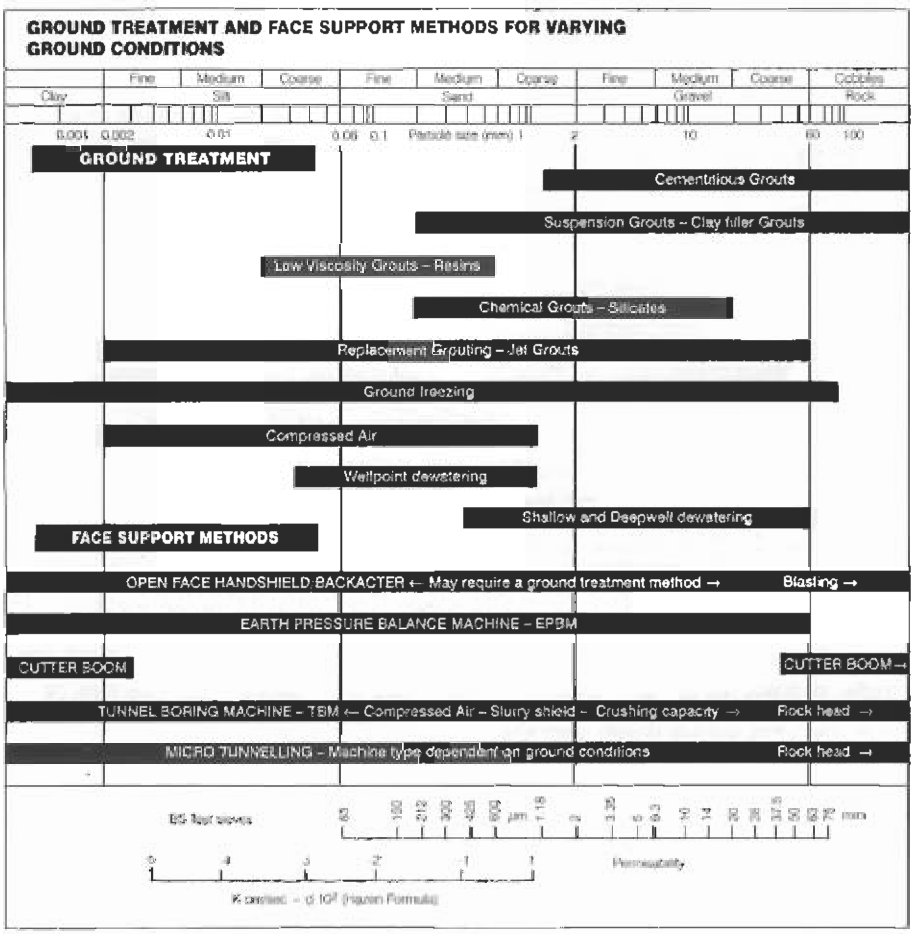
Study Part 3 of "An Introduction to Pipe Jacking and Microtunnelling Design".
The diagram opposite illustrates the minimum information required



Typical ground information required for design and costing

Be guided

Study Part 1 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

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 instabilities 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 1* in the Appendix to this guide.

In cohesive soils the face pressure requires 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.

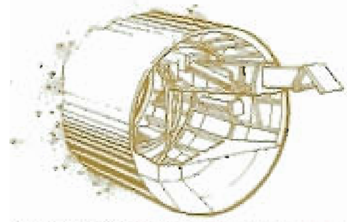
Tunnel stability may be assessed from *Figures* 2 and 3 in the Appendix to this guide.

Excavation for the installation of jacking pipes is undertaken either by hand or machine within a shield, or by a tunnel boring machine.

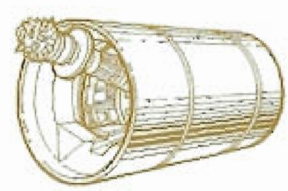
Illustrated are the types of shield currently in use.

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

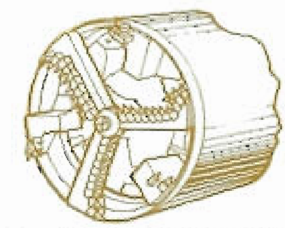
Hand Shield. An open face shield for manual excavation



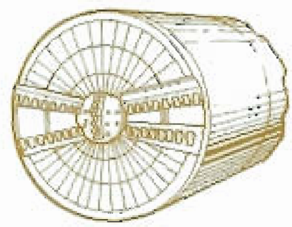
Backacter. An open face shield with a mechanical backacter



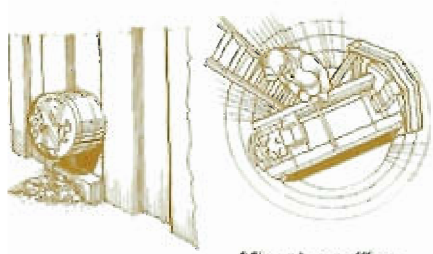
Cutter Boom: An open face shield with a cutter boom or road header



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 control machine

3.2 continued

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

Excavation	type of shield
Pipeline internal diameter	range
Length	range up to?
Face support	inbuilt or additional?
Remarks	other relevant matters

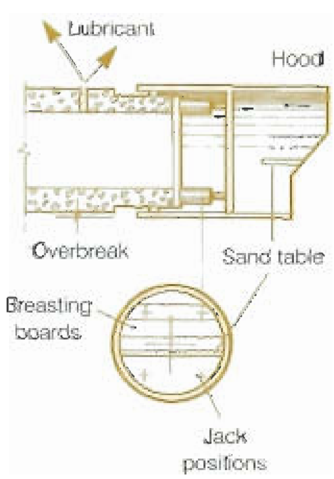
It is **recommended** that this section is studied carefully and used to **select** the best excavation and face support method for the ground conditions applicable to any scheme.

There are many types and manufacturers of pipe jacking shields and TBMs, 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.

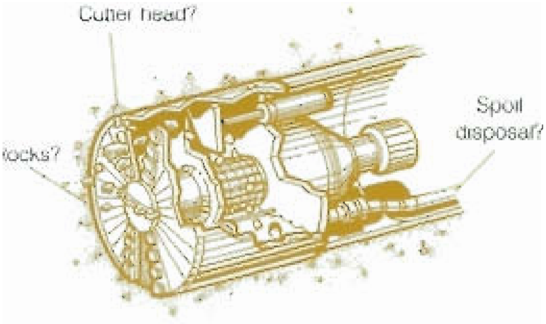


Backacter: Cutter Boom

Backacter or cutter boom shields are essentially open face shields with a mechanical means of excavation. The backacter 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 intrusion
- 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 jacking 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 adaption
- 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

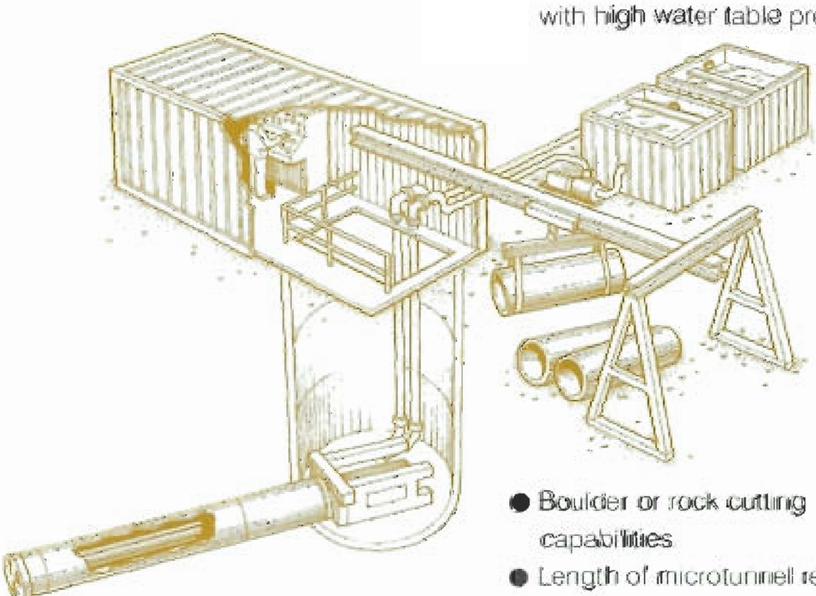
Earth Pressure Balance Machine (EPBM)

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 bulkhead. Pressure is controlled by the rate of passage of excavated material through a balanced screw auger or valves 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!



Typical microtunnelling set up

Microtunnelling

Microtunnels are normally excavated with a TBM auger or slurry type machine adapted for smaller diameters and remotely controlled.

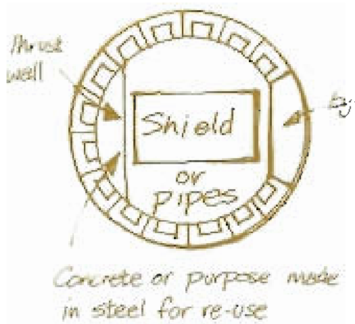
They are equipped with active target systems or close circuit television, for line and level control.

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
- Boulder or rock cutting capabilities
- Length of microtunnel required and whether an interjack facility is practicable

3.3

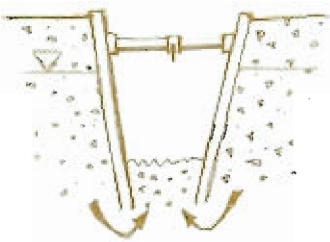
3.3 Working shaft design, thrust walls, and conversion to manholes



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

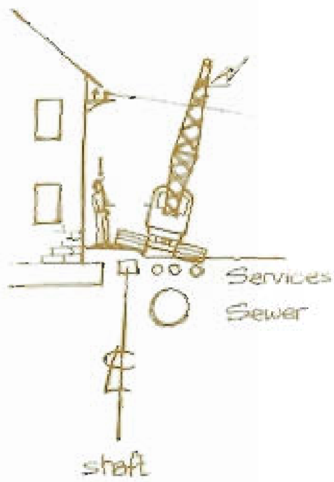
● Its suitability to accommodate the shield and jacking equipment selected. Provision for an adequate thrust wall and pipe jack eye. A facility for removing spoil, and space for lowering and jointing the jacking pipes and/or interjack stations.
If the shaft is reception only, space to remove the shield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

Problems Scheme delay
Cost implications
Lost shield



● Its suitability to support the ground pressure and water intrusion of the subsoils.

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 pipejack 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. Slurry TBMs also require adequate entry and exit seals.
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 freezing of the surrounding soils. In adverse water conditions the shield can be entered and retrieved, using compressed air methods applied to the shafts.

Working shaft construction methods used with pipejacking include.

Segmental linings
Precast or cast insitu caissons
Sheet piling or secant piling
Shallow trench sheeted or timber supported excavation
Battered excavation
Ground anchorages

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

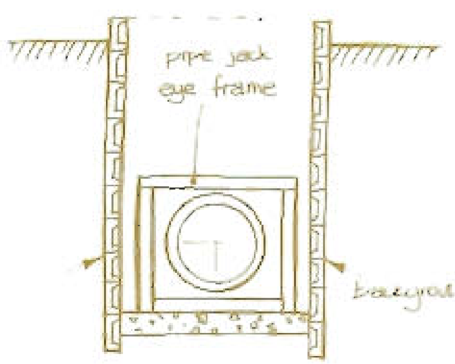
Type	Title of method
Size & Shape	Limitations
Depth	Range up to or unlimited
Ground Treatment	Whether required or additional
Remarks	Other relevant matters

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 imposed 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

Care should be taken to provide good backgrouting 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



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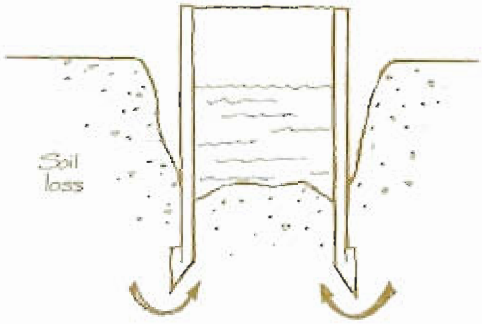
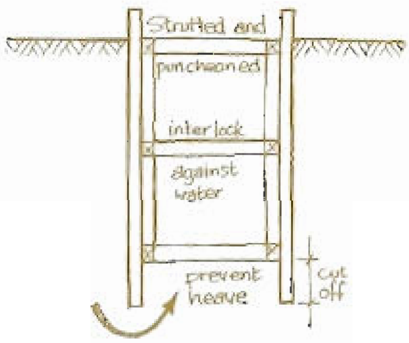


Precast or cast insitu caissons

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 break out and break in.



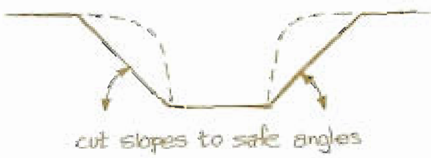
Sheet piling or secant piling

Sheet piling along with segmental linings are probably the most used methods for constructing working shafts.
Sheet piled 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.

Be guided
Study CIRIA
report 97-
Trenching Practice

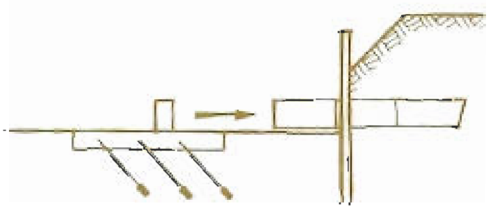
Shallow trench sheeted or timber supported excavation

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.

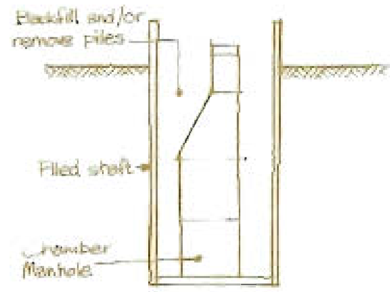
However, failure of a thrust wall can have far reaching consequences, and if the failure is one of internal failure of soil friction or cohesion, it can be very costly to re-establish. Such costs could also include overcoming friction build up to restart the pipe jack (see Section 3.4)

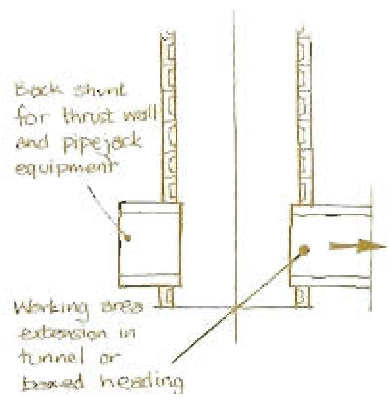
Where a pipejack is to continue from a shaft to which a completed pipeline has been jacked, then consideration must be given to protecting the pipes already installed. Measures should also be taken to ensure that the completed pipeline is not pushed backwards if it is incorporated in a thrust wall.

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 insitu 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

3.4 Drive lengths, jacking and friction loads, intermediate jacking stations, lubrication

Theoretically, there is no limit to the **drive length** of a pipe jack, providing all the elements that make up a pipe jack have no limitations.
In practice a pipe jack will be limited by considerations such as time restrictions, cost evaluations and safety factors.

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

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

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 controlled by spoil disposal limitations.

Taking such factors into account, the practical and economic lengths with current technology are up to 500 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 constraints 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.

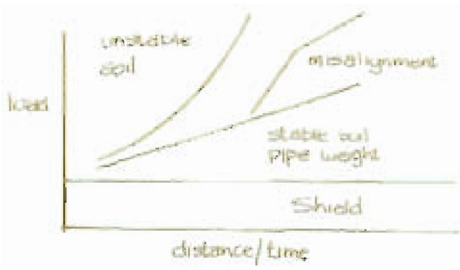
Tight working conditions can be accommodated using special plant, and short pipes, but it should be noted that logistical and access difficulties may lead to inefficient working practices, resulting in cost escalation.

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 arching 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 PJA has given as a guide, frictional forces 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.



3.4 continued

Forces due to **Face load** will be relatively low in cohesive ground and related to the excavation and trimming of the shield.

Hand mining slightly larger than the shield, as against use of shield trimming, can vary a face load from 10 to 100 tonnes.

For a machine drive the average face pressure, including slurry pressure, shield trimming and excavation, can be calculated using the appropriate formulae in the Appendix (Section 8) and Worked Examples Scheme B (Section 9).

Forces due to the **Self weight of the pipes** in a stable bore are a function of the weight of the pipes(W) to the local interface friction coefficient (δ). A factor of 25% should be added to cover minor misalignment.

$$F = 1.25W \tan \delta$$

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

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

Even when the excavated tunnel is stable, the ground may close onto 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 pipes will occur, radial stresses will develop, and resistance to jacking start to increase.

In non-stable bores, 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 soil 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 practical skills should be applied to provide good and safe working conditions.

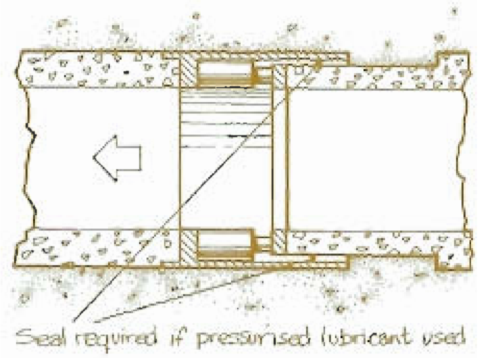
Misalignment must inevitably induce contact stresses between the pipe and the ground. Examples of the effect of misalignment may be obtained from the Oxford research data.

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 to be designed to cater for ground, hydrostatic and thrust load conditions.

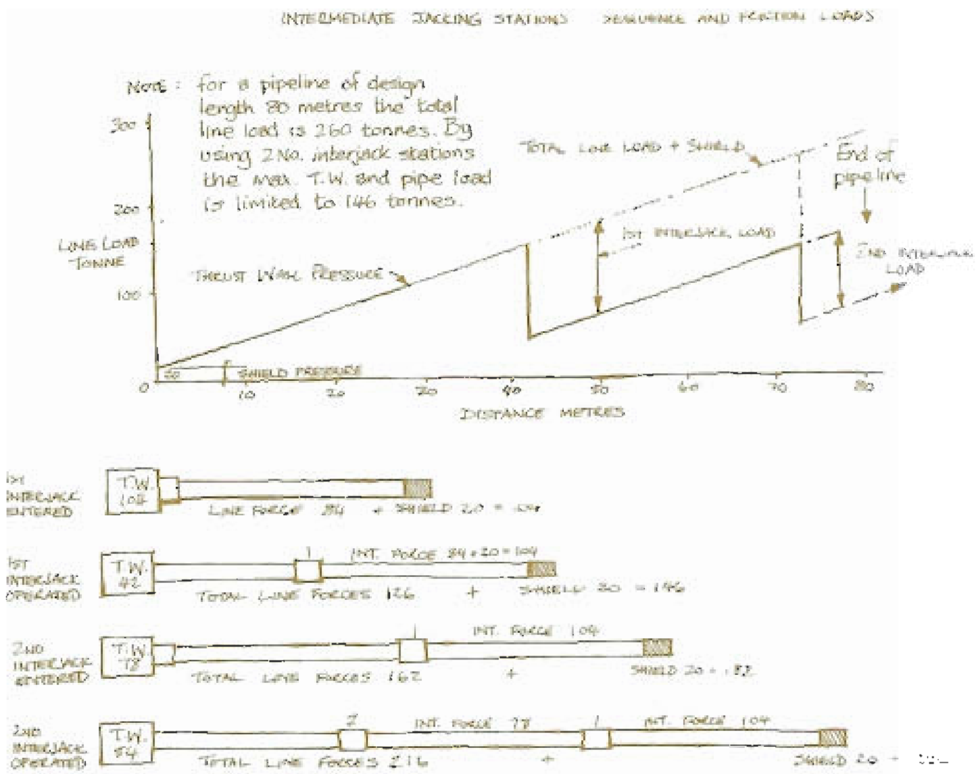


Intermediate Jacking Station (or Interjack)

A trailing interjack pipe, recessed 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 station 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.



21

3.4 continued

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.

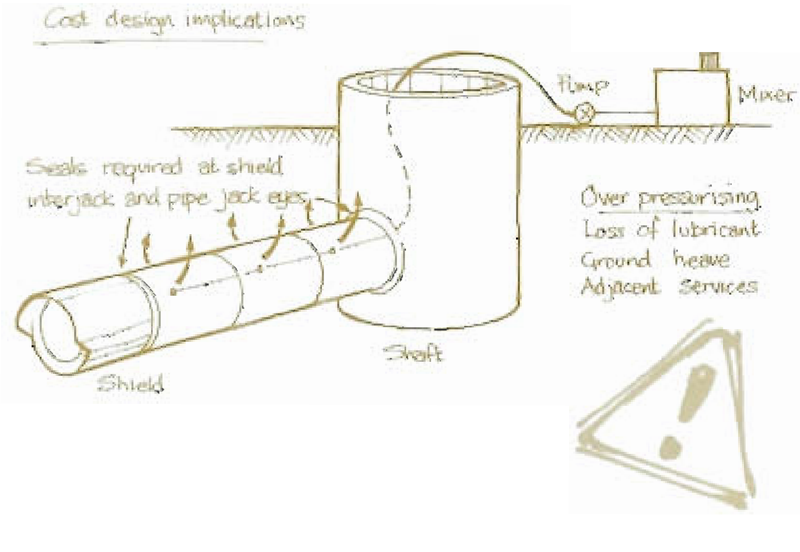
If the lubricant can be designed to fill the entire overbreak then the pipes will theoretically be buoyant.

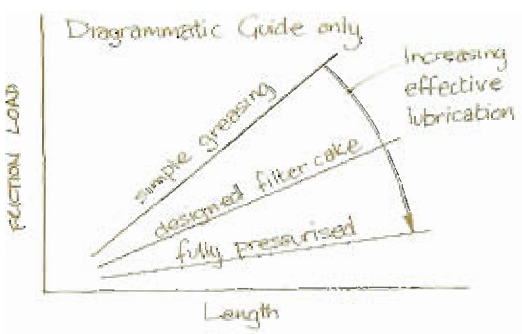
The success therefore of lubrication in varying soils will depend on the lubricant, the sophistication of the lubrication system, and the behaviour of the soil in absorption of the lubricating material.

It has been proved that a fully lubricated drive with an annulus filled with bentonite, results in jacking resistance not 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 clays 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

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 economic and efficient set up in the minimum possible space.

This may be essential in an urban area, where space can be at a premium.

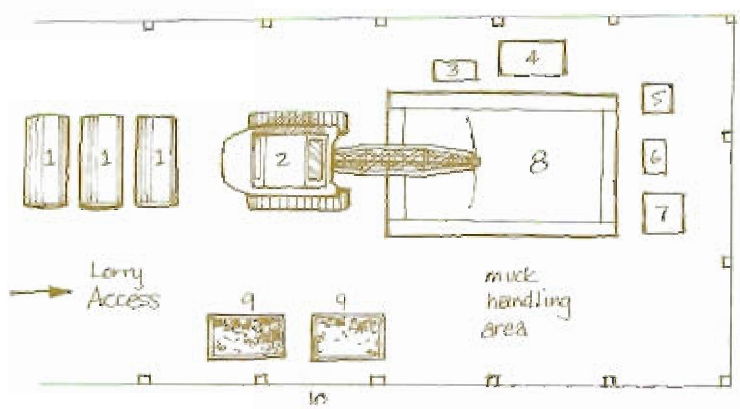
The main support services generally include:

- 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 interjack 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

Microtunnel 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).

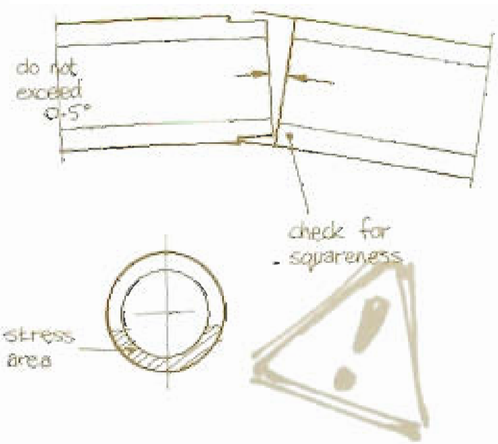
The sketch shows a typical topside set-up:

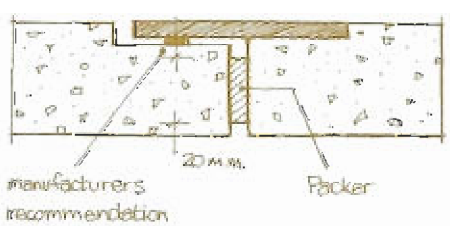
1. Jacking Pipes
2. Crane or gantry
3. Power pack control
4. Compressor
5. Generator – pumping
6. Lubrication equipment
7. Stores – Services
8. Thrust pit
9. Spoil skips or disposal
10. Fencing or hoardings



3.6

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 Microtunnelling 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.

Microtunnelling 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 **barrels** 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 PJA members are generally to a control of 0.05°, 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 unload/reload 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 microtunnelling pipes.

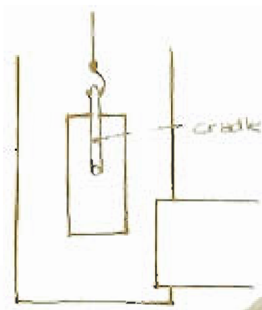
When the jacking force is well distributed over the pipe end area, it is appropriate to use a maximum concrete design stress based on the characteristic strength of the pipe concrete, f_{cu}, divided by a materials factor γ_m of 1.3 and a load factor γ_f of 1.25 when using the design method given in *Figure 7* (Ref. BS8110 Parts I & II).

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 Poissons ratio (i.e.transverse stress) to minimise bursting joint stresses.

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

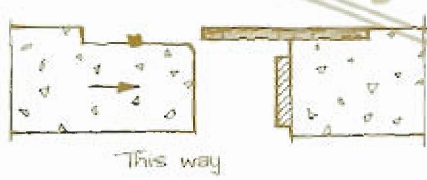
Pipe manufacturers supply a variety of jacking pipes and catalogue pipes with flexible rebated and butt joints, special lead and interjack pipes, microtunnelling pipes, and **reference** to such manufacturers should be made for precise dimensions and strength of their products.
The pipe manufacturer 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.

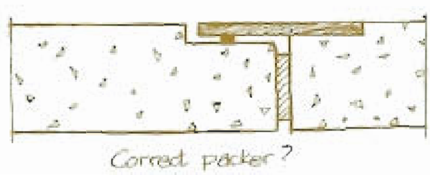
Depending on shaft design, pipes may be lowered horizontally or vertically. If vertical lowering is required then the pipes will require to be handled in a purpose made cradle or lifting device.

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 elastometric sealing ring, and may include secondary sealing. It is essential that all pipes are jointed 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 jointing ring can cause collar failure and may affect the hydraulic performance of the pipeline.



3.6 continued

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.

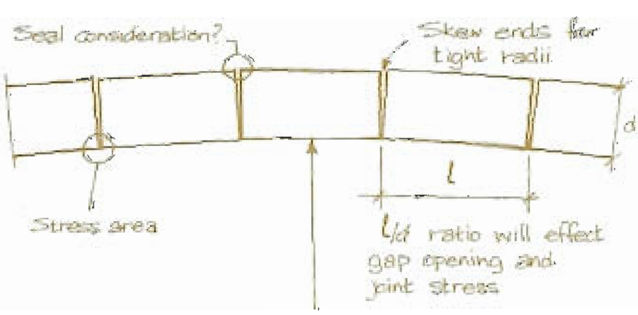
This may be required to avoid an obstruction in the horizontal plane or to reduce the entry and exit depth in the vertical plane.

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

3.7 Ground movement

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

These have been referred to in Section 3 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 tunnelling 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, sub-soil conditions, water intrusions, excavation methods, and not least the skill of the construction team. The cost that the promoter is prepared to pay for the best 'belt 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 effect 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 contentious contractual matter after dealing with water, Section 3.1, and is further discussed in Section 6.1

4.0

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.

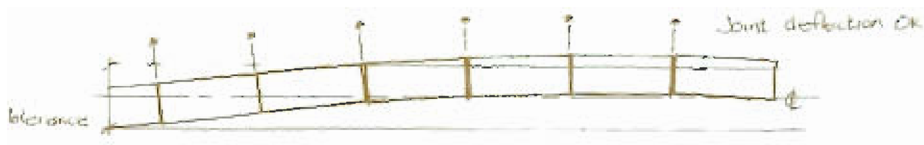
The simple fact that a "rifle barrel" pipejack avoids problems as against a "wriggle" pipejack has been known and experienced by both promoters and installers over many years.

In an ideal pipejack 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 transfered 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

Pipeline out of angular deflection tolerance but within line and level tolerance

The purpose of this guide is to continue to educate all users of the pipe jacking 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 pipejacking, 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 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 users 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 microtunnelling, especially in the smaller diameter range, taking into account the diameter/pipe length/joint deflection angles.

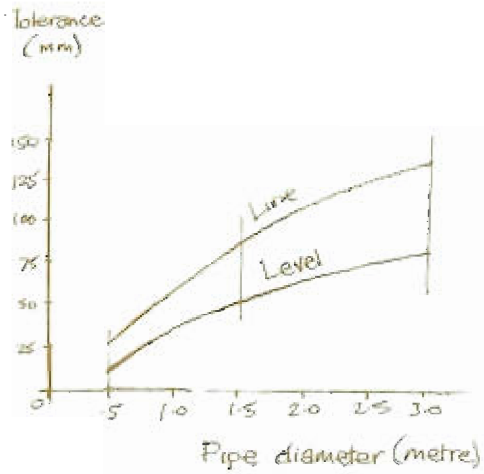
If tighter tolerances are required, it must be understood that these may not be possible in all planes, and therefore the promoter/designer must decide which tolerance (i.e. vertical or horizontal) is of most importance to the scheme.

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 any plane.

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

The following graph provides some **be guided advice** on this point



4.1

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

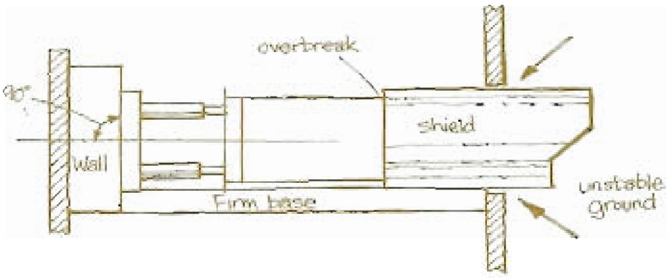
Normal surveying equipment is quite adequate to provide an **accurate survey between the thrust and reception shafts**.
It is **advised** that the initial survey be carried out twice using independent survey stations, and preferably different surveyors.
Also of great importance is the transfer of the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

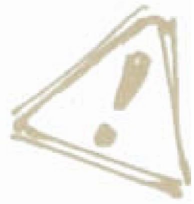
It cannot be emphasised enough, how important it is for an **accurate set up, break out and shield entry**.
A shield that has been sent off in the wrong direction will require that every pipe behind it will have to follow the wrong path created by the shield, with the consequential joint deflection problems 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 jacks.
Beware of unstable ground conditions and avoid loss of soil on entry. This may cause differential pressures on the shield.

For good practice follow these **be guided** points.

- Make sure the jacking frame will not deflect under the weight of the pipes/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 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 pipejack 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 levelling type.

Above all keep checking and re-checking





Pipe jack shields must be **accurate** (i.e. cylindrical to a fine 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.

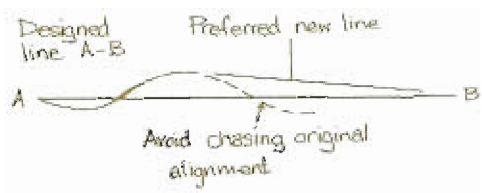
A control system to monitor line and level can be as simple or as sophisticated as the diameter or length of the bore determines.

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

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 maximum 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

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 pipejack in construction or completed, which can be invaluable to future pipe jacks to be constructed.

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

A **recommended** pipe jacking record sheet is shown in the Appendix, *Figure 12*.

5.0 What can go wrong?

5.0

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 good practical and commercial evaluation of the parts 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 hurrying 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.

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

Many of the poor disciplines listed above create unacceptable safety risks

6.1

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.

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

Coping 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 fees for the legal profession.

The responsiblity 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 availabilty 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.

6.1 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 neccessary experience, skills, finance and management to carry out the work.

6.2

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 microtunnelling.

6.3

6.3 Training

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 catagories of staff and operatives attend regular 'tool box' talks on appropriate subjects.

7.0

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 unforseen 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
- ☐ Self 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
- ☐ Spoil 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 recommendations
- ☐ 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:

- ☐ Enviromental 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
- ☐ Liason with other services/authorities
- ☐ Good signing of the site
- ☐ Tipping and off site lorry movements
- ☐ Completion and clearance of the site

8.0

Principal symbols

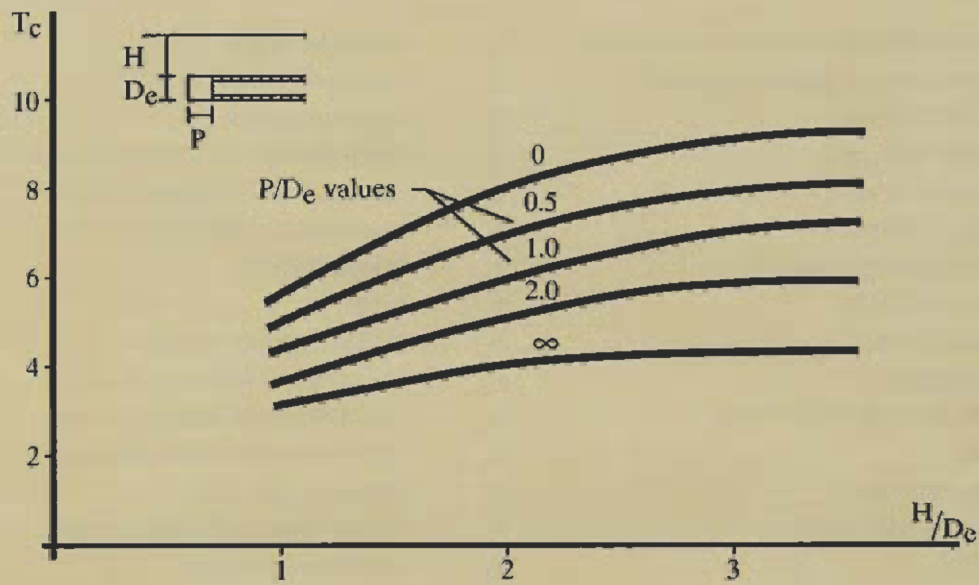
a	Thickness of packing after initial compression
b	Contact width between pipe and ground
D_e	Diameter of excavation
D_p	Outside diameter of pipe
d	Internal diameter of pipe
E_j	Joint elasticity coefficient
E_D	Reloading stiffness of packing
E_p	Elastic modulus of pipe
E_s	Elastic modulus of soil
F	Frictional resistance
f_{cu}	Compressive strength of concrete
H	Ground cover
i	Trough width parameter
k	Lateral pressure coefficient
L	Length of pipe
P	Unsupported length of excavation
P_u	Contact force per unit length
p	Internal support pressure (bentonite pressure)
R	External radius of pipe
r	Internal radius of pipe
S	Surface settlement
s_u	Undrained shear strength
S_{max}	Maximum surface settlement
T_c	Stability ratio (cohesive soils)
T_s	Stability number (cohesionless soils)
T_γ	Stability number (cohesionless soils)
t	Pipe wall thickness
t_j	Packing width
u_o	Water pressure at tunnel axis
V	Transverse distance from centre line
V_s	Settlement volume
W	Unit weight of pipe
z	Contact width at pipe joint
$\mathscr{z}$	Depth of tunnel axis
αs_u	Adhesion between pipe and clay
β	Deflection angle at pipe joint
γ	Unit weight of soil
γ_b	Buoyant weight of soil
γ_l	Load factor
γ_m	Materials factor
γ_s	Saturated weight of soil
δ	Angle of friction
δ_h	Reduction in horizontal diameter
δ_p	Symmetrical increase in radius
δ_v	Reduction in vertical diameter
ν	Poisson's ratio
θ	Angle
σ_c	Circumferential stress
σ_{ca}	Circumferential stress at axis
σ_{cc}	Circumferential stress at crown
σ_h	Total horizontal stress at crown
σ_j	Stress at pipe joint
σ_r	Radial stress at tunnel surface
σ_s	Surcharge pressure
σ_T	Pressure to maintain face stability (cohesive soils)
σ_v	Total vertical stress
σ_{max}	Maximum circumferential stress
σ'_h	Effective horizontal stress
σ'_v	Effective vertical stress
σ_θ	Stress at tunnel surface
τ	Shear stress
ϕ	Friction angle of soil

Note: The above symbols and nomenclature are consistent and specific to this document

In cohesive soils, the pressure σ_T required to maintain stability of the tunnel face is given by

$$\sigma_T > \gamma(H + D_e/2) - T_c s_u$$

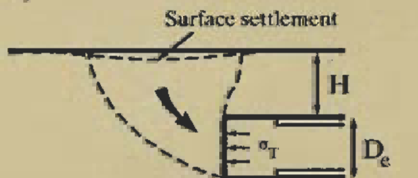
Where γ = unit weight of soil, s_u = undrained strength of soil
and T_c = stability ratio - see plot below (Atkinson and Mair 1981).
In pipe jacked tunnels the unsupported length P is usually small or zero, and $P/D_e = 0$.
e.g. for $\gamma = 20\ kN/m^3$, $H = 4m$, $D_e = 2m$, the plot gives $T_c = 8$
hence $\sigma_T = 100 - 8s_u$ kPa
and for $s_u > 12.5$ kPa, no support is needed.



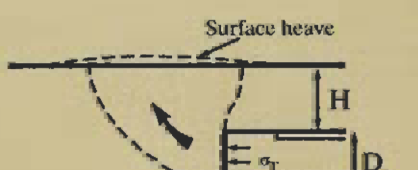
To prevent blow-out due to excessive face pressure,

$$\sigma_T < \gamma\,(H + D_e/2) + T_c s_u$$

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 $\gamma = 20\ kN/m^3$, $D_e = 2.0m$, $s_u = 10kPa$, then $\gamma D_e/s_u = 4$.
For $H/D_e = 2.0$, and dividing s_u by a factor of safety of 2, $\sigma_T = 20\,(4+2/2) \pm 8 \times 5 = 100 \pm 40$
hence σ_T must lie between 60 and 140 kPa.



(a) Potential instability of tunnel face arising from insufficient face pressure



(b) Potential blow-out arising from excessive face pressure

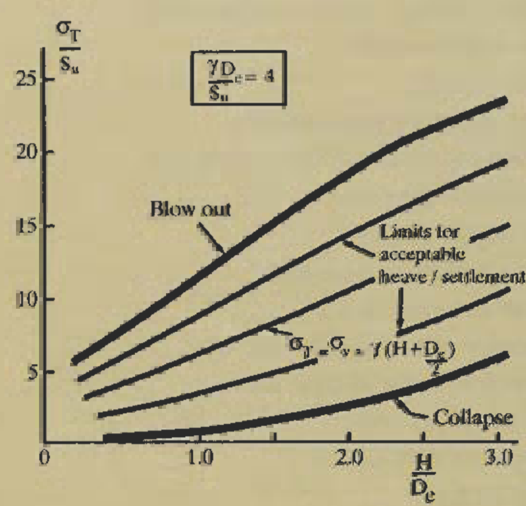


Figure 1 Face stability in cohesive soils

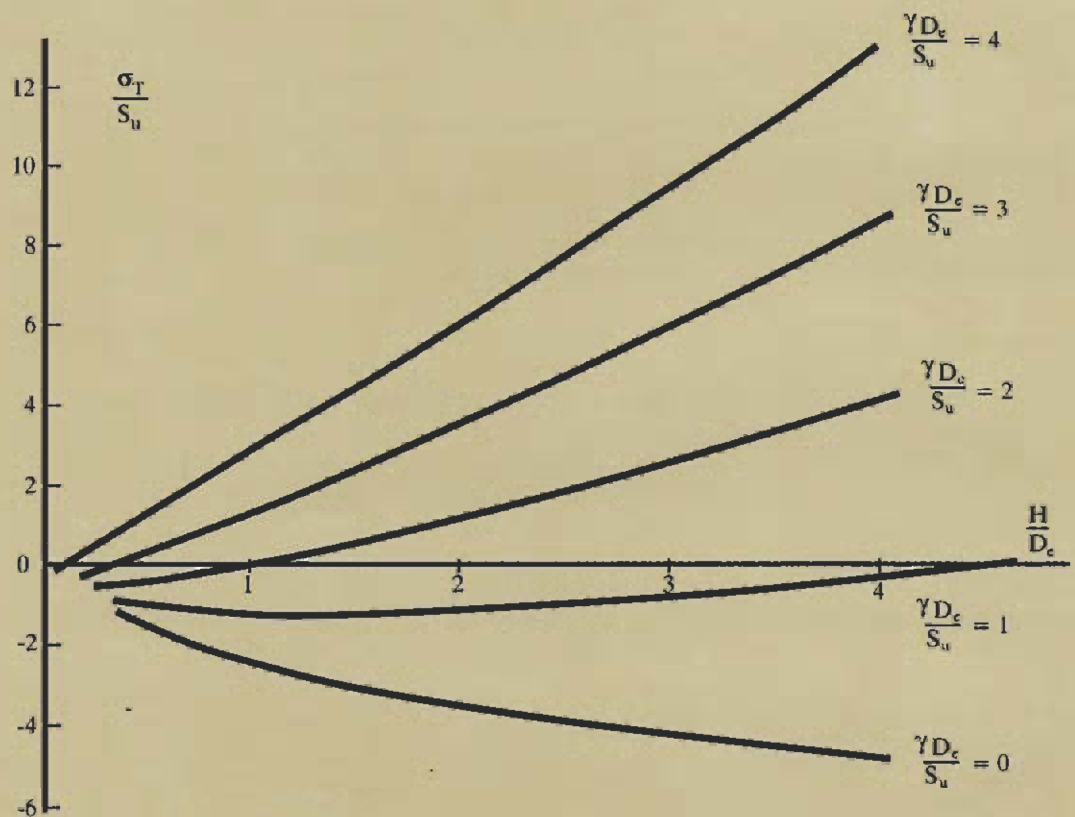
For the tunnel behind the shield, the conditions correspond to the case in Figure 1 of $P/D_e \rightarrow \infty$. The equation for calculating the support pressure required to prevent collapse is as before

$$\sigma_T = \gamma(H + D_e/2) - T_c s_u$$

Which may be re-arranged to give

$$\frac{\sigma_T}{S_u} = \frac{\gamma D_e}{S_u}(H/D_e + 1/2) - T_c$$

This gives rise to plots shown below. Again, values of σ_T less than zero indicate that the tunnel is stable without any support pressure. Note that for microtunnels $\gamma D_e/s_u << 1{\cdot}0$ in most cases, and the tunnel bore will normally be stable.



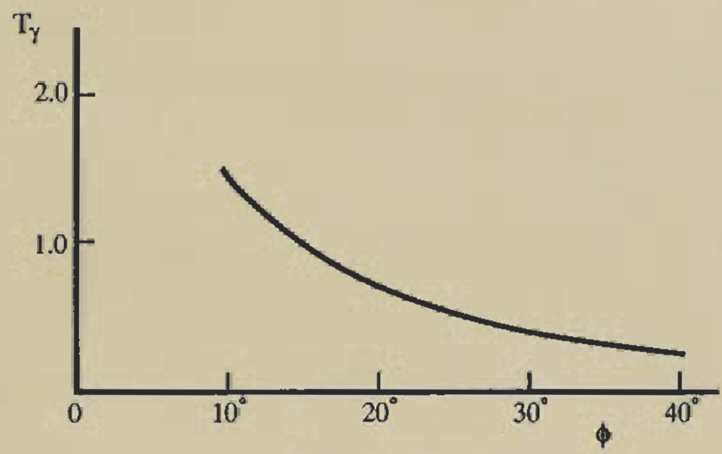
For example, for $H/D_e = 2$, and $\gamma D_e/s_u = 4$, from Figure 1: $T_c = 4$ then $\sigma_T/s_u = 4 \times 2{\cdot}5 - 4 = 6$. or directly from plot above, i.e for $s_u = 10$ kPa, $\sigma_T = 60$ kPa.

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

$$\sigma_T = \gamma D_e T_\gamma$$

where T_γ is the stability number given by the plot below; it is a function only of ϕ, the friction angle for the soil.

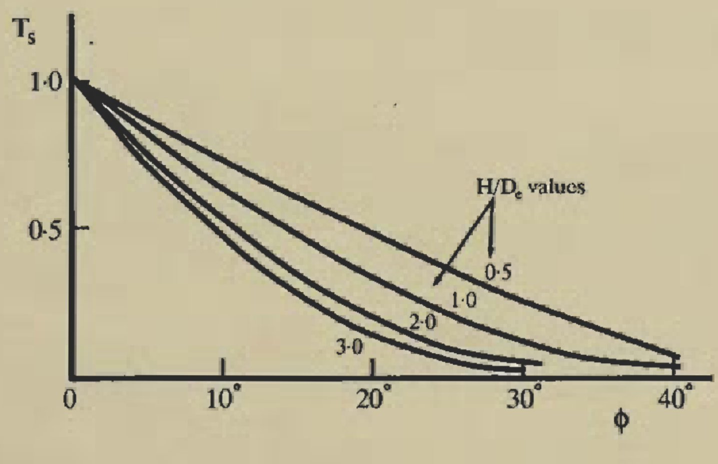


For example, if $\gamma = 18$ kN/m³, $D_e = 1.6$m, and $\phi = 35°$
from then the plot $T_\gamma = 0{\cdot}3$ and $\sigma_T = 18 \times 1{\cdot}6 \times 0{\cdot}3 = 8{\cdot}6$ kPa

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

$$\sigma_T = \sigma_s T_s$$

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 σ_T 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)

$$F = \alpha s_u b$$

Where $\alpha\, s_u$ is the "adhesion" between the pipe and clay.
b is the contact width between pipe and ground.

$$b = 1{\cdot}6\,(P_u k_d C_e)^{\frac{1}{2}}$$

where

P_u = contact force per unit length

$k_d = \dfrac{D_e D_p}{(D_e - D_p)}$

D_e = internal diameter of the cavity

D_p = external diameter of the pipe

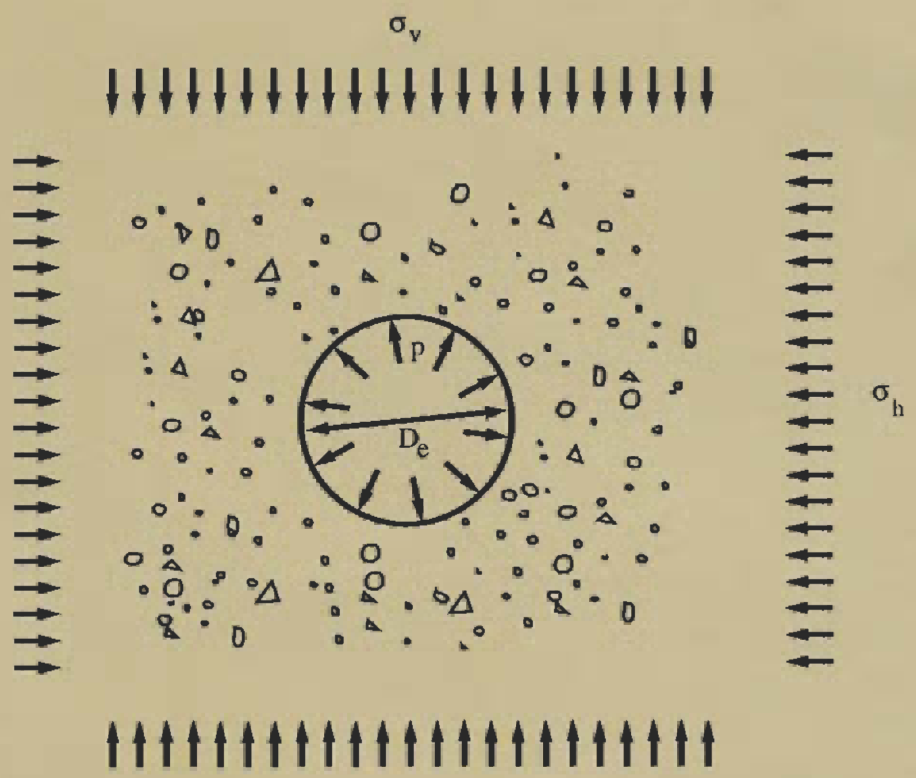
$C_e = (1-\nu_s^2)/E_s + (1-\nu_p^2)/E_p$

E_s = elastic modulus of the soil

E_p = elastic modulus of the concrete pipe

ν_s, ν_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 σ_v and σ_h, the reduction in vertical diameter of the tunnel bore due to elastic stress relief is given by

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

and similarly the reduction in the horizontal diameter is given by

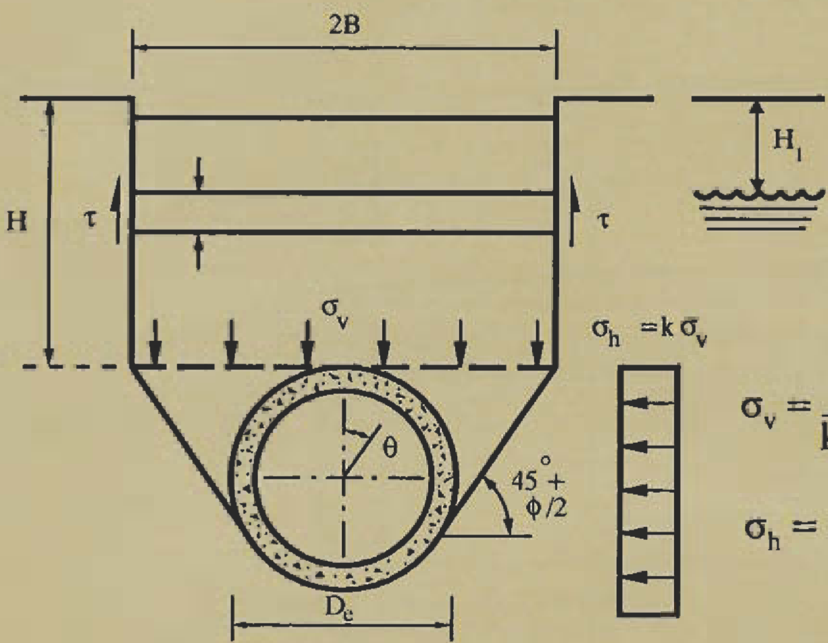
$$\delta_h = \frac{(1-\nu^2)}{E_s} D_e (3\sigma_h + \sigma_v)$$

where E_s and ν 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

$$\delta_p = \frac{(1+\nu)}{2E_s} p D_e$$

Figure 5 Calculation of ground closure



$$\sigma_v = \frac{\gamma B}{k\tan\phi}\left(1-e^{-k\tan\phi H/B}\right)$$

$$\sigma_h = k(\sigma_v + 0{\cdot}5\gamma D_e)$$

The radial stress around the pipe is

$$\sigma_p = \frac{(\sigma_v+\sigma_h)}{2} + \frac{(\sigma_v-\sigma_h)}{2}\cos 2\theta$$

and the total frictional resistance is

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

where ϕ is the angle of internal friction of the soil, and δ is the angle of friction between the pipe and the soil.

When a water table is present at depth H_1, the expression for σ_v becomes

$$\sigma'_v = \sigma'_{v_1} e^{-k\tan\phi(H-H_1)/B} + \frac{\gamma B}{k\tan\phi}\left(1-e^{-k\tan\phi(H-H_1)/B}\right)$$

where

$$\sigma'_{v_1} = \sigma_{v_1} = \frac{\gamma B}{k\tan\phi}\left(1-e^{-k\tan\phi(H_1/B)}\right)$$

and

$$\sigma'_h = k(\sigma'_v + 0{\cdot}5\gamma D)$$

Note that
γ is bulk unit weight (above water table), and
γ' is submerged unit weight (below water table), and

$$B = \frac{D_e}{2}\tan(45°-\phi'/2) + \frac{D_e}{2\sin(45°+\phi'/2)}$$

Figure 6 Model for ground loading in cohesionless soil after Terzaghi (1943)

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.

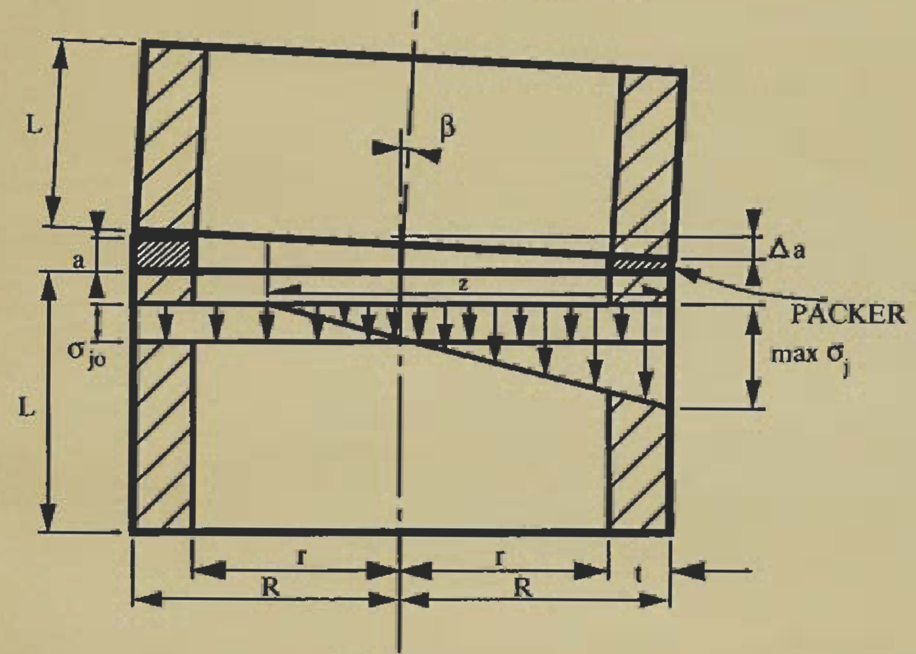
Permissible Jacking load

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

for $-r \geq h \geq r$

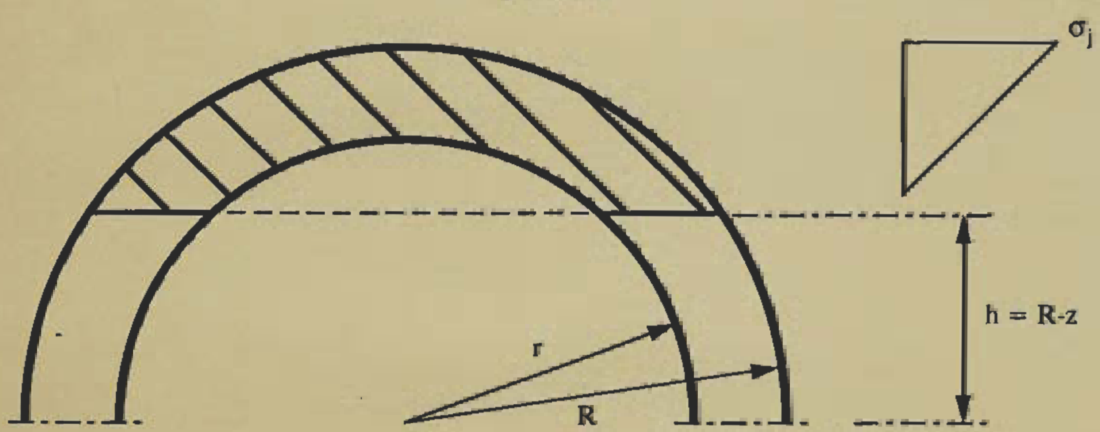
The second formula, for $h > r$, is correct.

From the Australian Concrete Pipe Association linear stress approach



$$z = \frac{180}{\pi}\,\frac{a}{E_j}\,\frac{\max \sigma_j}{\beta}$$

Where $$E_j = \frac{a t E_D E_p}{a t E_p + t_j E_D L}$$



Permissible jacking load

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

When $h > r$ permissible jacking load

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

Figure 7 Jacking forces from linear joint stress model

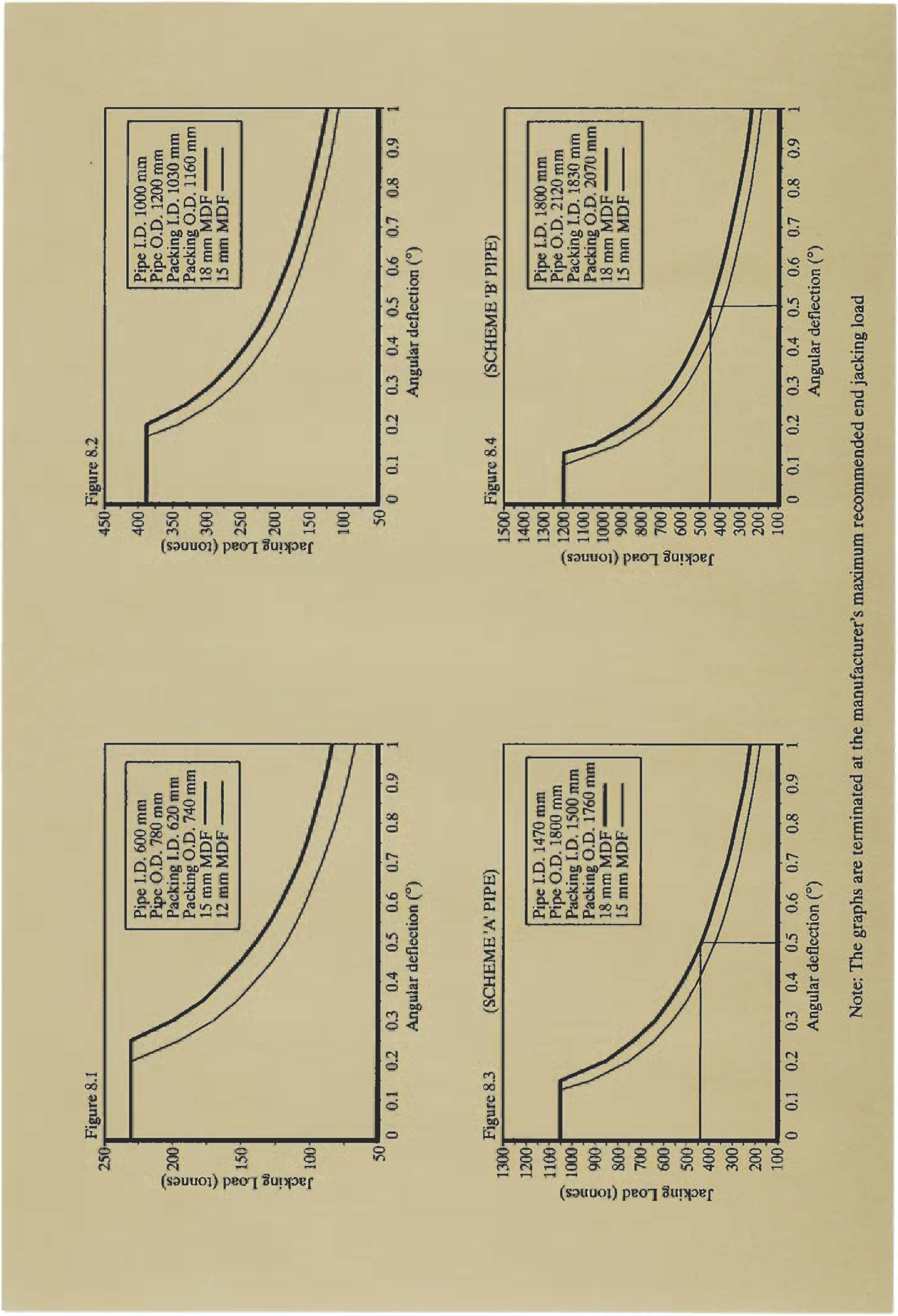


Figure 8 Permissible pipe end loadings at various angular misalignments

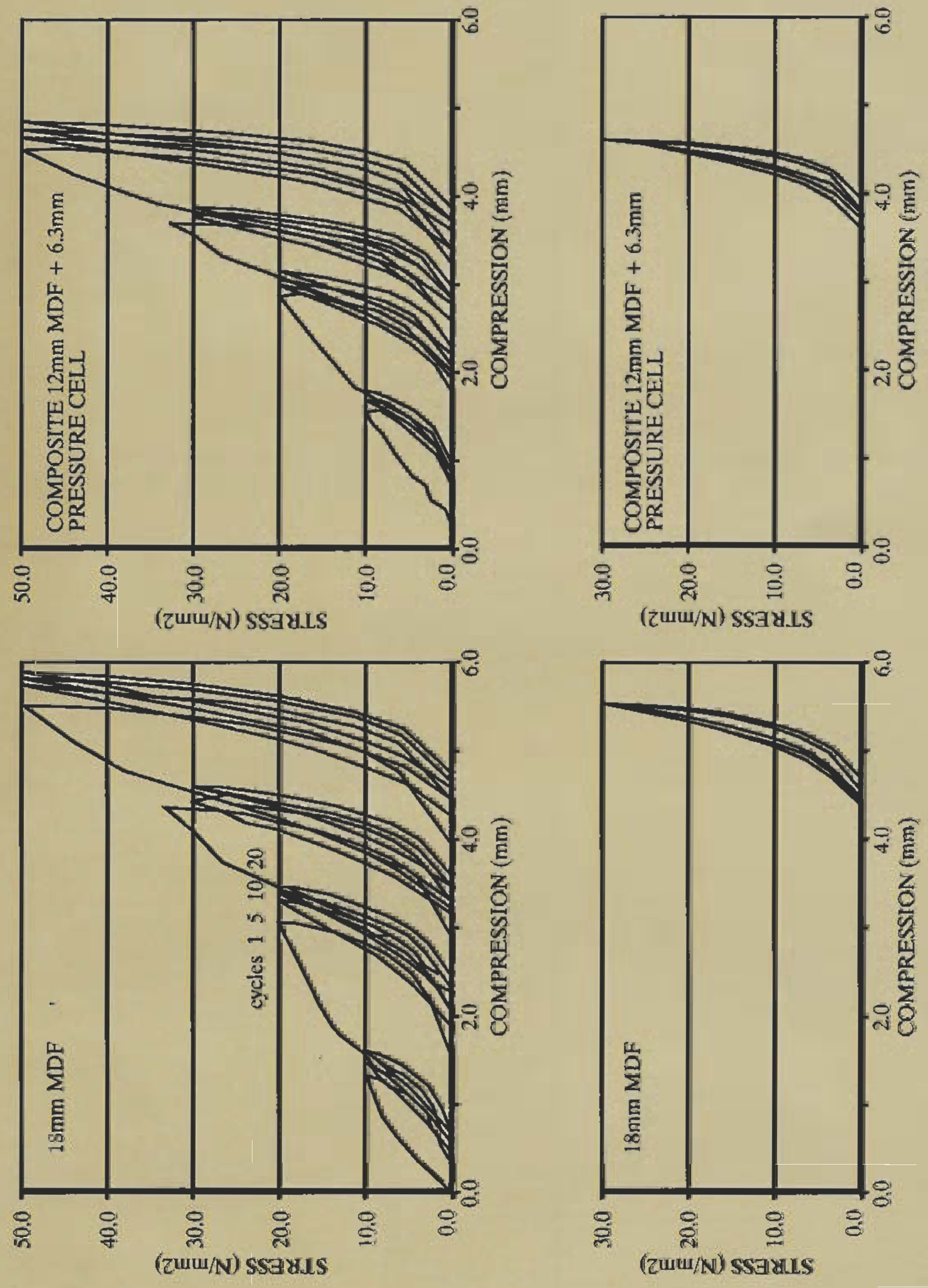


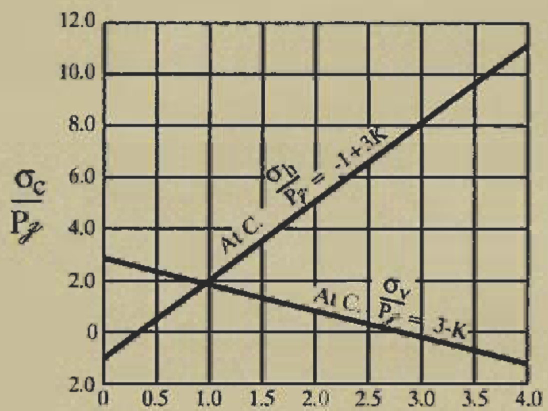
Figure 9 Uniaxial compression tests on joint packer material (Milligan & Norris 1992)

For a tunnel with initial vertical and horizontal stresses in the ground

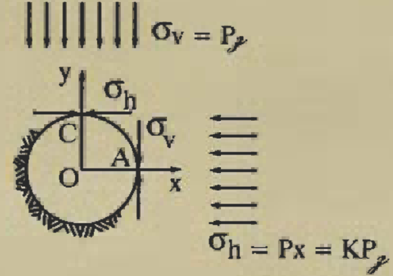
$$P_y = \sigma_v = \gamma H$$

$$P_x = \sigma_h = KP_y$$

the radial stress σ_r at the tunnel surface is zero and the maximum value σ_{max} of the circumferential stress σ_θ 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.



Circumferential principal stress at surface of circular tunnel as function of K (Terzaghi and Richart, 1952).



Note: $K = \dfrac{\sigma_h}{\sigma_v}$

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

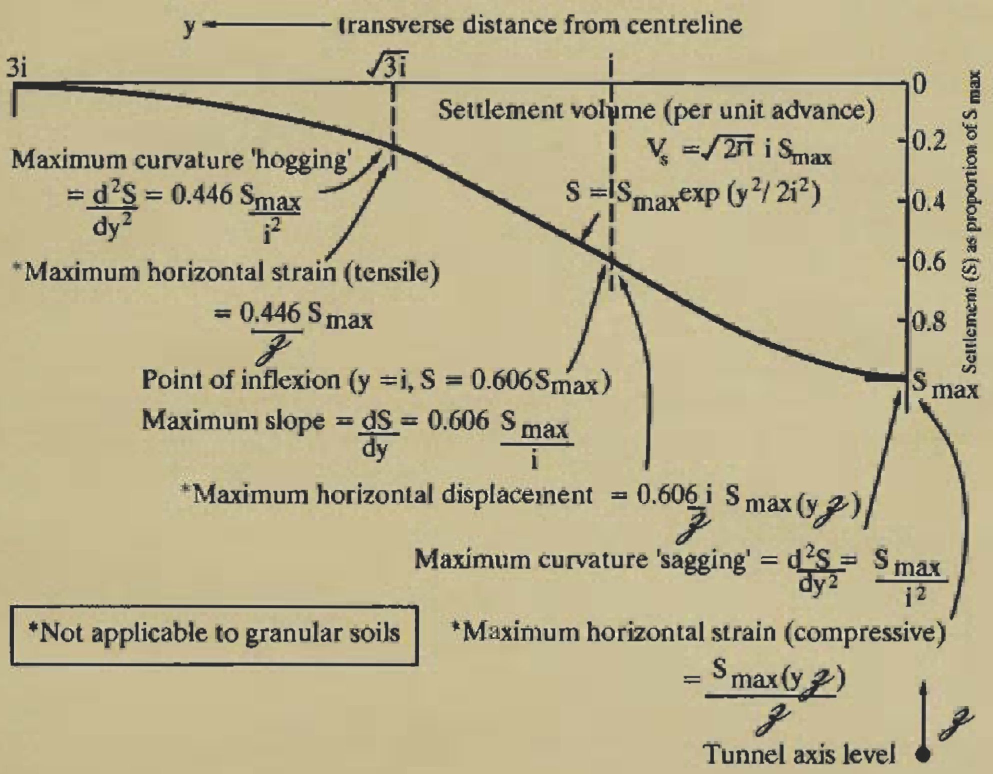
$$\sigma_\theta = -p, \quad \sigma_r = +p$$

For local yielding to occur,

$$\sigma_\theta - \sigma_r = 2s_u$$

$$\therefore (\sigma_c - p) - p = \sigma_c - 2p = 2s_u$$

Figure 10 Conditions for local yielding at the tunnel surface



From O'Reilly and New (1982)

Surface settlement S at given point

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

where V_s = volume loss/unit length

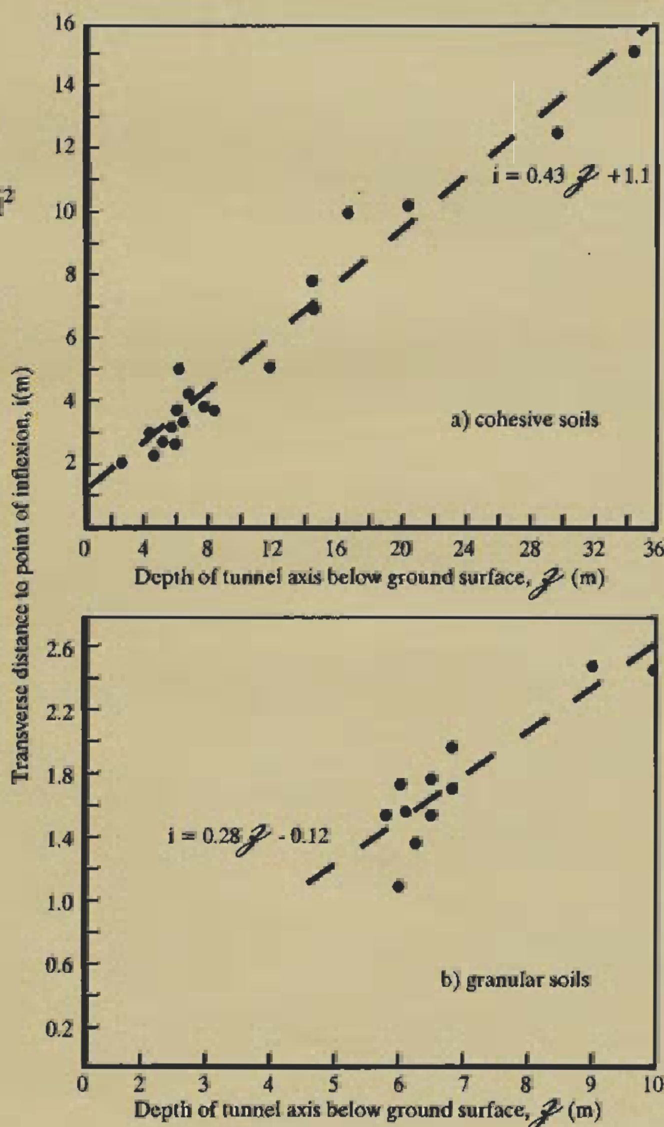


Figure 11 Calculation of long-term settlements

Contract No. Date:

Drive No.: Diameter: Total Length:

Pipe No.	Distance	Front Shield	Back Shield	Jacking Load	
		Line Level	Line Level	Main	Interjack

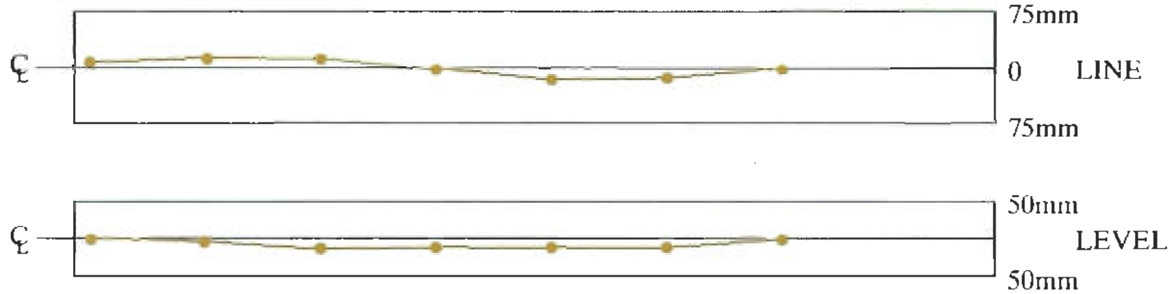
Lubrication:

Soil Conditions:

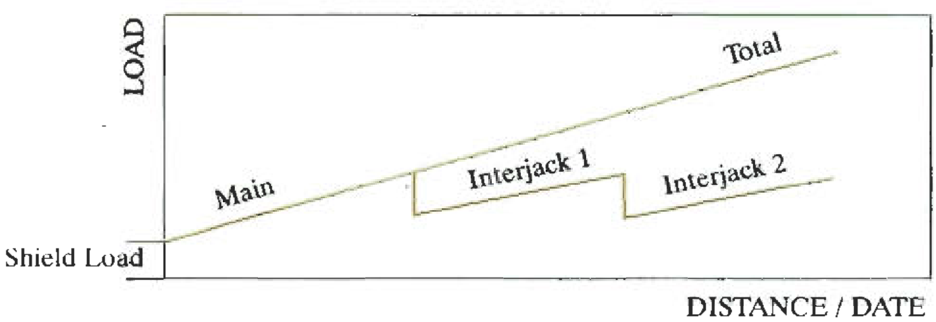
Water Intrusion:

Remarks:

It is **recommended** that for each drive a line and level record is produced together with a jacking load and progress graph.



Line and Level record



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:

Number of Blows	State of Compaction	Equivalent value of ϕ (approx.)
0-4	very loose	30°
4-10	loose	30°
10-30	medium	30-35°
30-50	dense	35-40°
50 and over	very dense	40-45°

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 SPT's. 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

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 butt-jointed concrete pipes.

9.2 Specific data to the scheme

Internal diameter of pipe	d	1470 mm
External diameter of pipe	D_p	1800 mm
Wall thickness of pipe	t	165 mm
Depth to invert of pipe		12.00 m
Depth to axis of pipe	z	11.25 m
Length of drive		150 m
Water table - below ground level		1.50 m

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)

Ground Conditions

7m ballast, overlying London clay water table 1.5m below G.L

Assume London Clay has N-value of ~30, undrained strength $S_u = 135\,kPa$
From literature, undrained stiffness of London clay for small strains
$\sim 750 S_u$, giving $E_s = 100 \times 10^3\,kPa$

Depth to invert of pipe = 12.0m
ID of pipe = 1.47m (1500mm nominal ID)
∴ Depth to axis of pipe = 11.25m

Take saturated unit weight of ballast = $\gamma_1 = 19\ kN/m^3$
saturated unit weight of London Clay = $\gamma_2 = 21\ kN/m^3$
Total vertical stress at tunnel axis σ_v = $7 \times 19 + 4.25 \times 21 = 222\,kPa$

Water pressures approximately hydrostatic in top of London Clay.

∴ Water pressure at axis of tunnel $u_0 = (11.25 - 1.5)10 = 97.5\,kPa$
∴ Effective vertical stress at tunnel axis $\sigma_v' = \sigma_v - u_0 = 124.5\,kPa$

At this depth in London clay, typically $K_0 = 1.6$
∴ Effective horizontal stress at tunnel axis $\sigma_h' = 1.6\sigma_v' = 1.6 \times 124.5$
$= 200\,kPa$
∴ Total horizontal stress at tunnel axis $\sigma_h = \sigma_h' + u_0 = 297.5\,kPa$

Pipes

External diameter = D_p = 1800mm
Internal diameter = d = 1470
Wall thickness t = 165mm
Weight of pipe $W = \pi/4\,(D_p^2 - d^2)\,24 = 20.3\,kN/m$

<u>Tunnel face stability – Ref: Figure 1</u>

$\sigma_T = \sigma_v - T_c S_u$ for stability
Cover depth $H = 12.0 - 1.47 - 0.165 = 10.4m$
$\therefore \frac{H}{D_p} = 5.75$, $\frac{P}{D_e} = 0$ for shield close to tunnel face

From plot $T_c = 9$, $\therefore \sigma_v - T_c S_u = 222 - 9 \times 135 << 0$
$\therefore$ Tunnel face very stable, F.of S >5

<u>Tunnel bore stability - Figure 2</u>

$\frac{H}{D_p} = 5.75$, $\frac{P}{D_e} \approx \infty$, $\therefore T_c \approx 4.2$

$\sigma_T = 222 - 4.2 \times 135 << 0$
$\therefore$ tunnel bore very stable, F.of S. >2.5

<u>Elastic ground closure - Figure 5</u>

$$\delta_v = \frac{(1-\nu^2)\, D_p\, (3\sigma_v + \sigma_h)}{E_s}$$

$$\delta_h = \frac{(1-\nu^2)\, D_p\, (3\sigma_h + \sigma_v)}{E_s}$$

For undrained conditions immediately after excavation

$\sigma_v = 222\ kPa$, $\sigma_h = 298\ kPa$, $E_s = 100 \times 10^3\ kPa$, $\nu = 0.5$
$D_p = 1.8m$

gives $\delta_v = 13.0mm$
$\delta_h = 15.1mm$

In longer terms deformation will increase due to drainage

For full drainage $\frac{E'}{2(1+\nu')} = G' = G_u = \frac{E_s}{2(1+\nu)}$ where typically $\nu' \approx 0.2$

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

hence $E' = 0.8E_s$, $\delta_v' = 16.3mm$, $\delta_h' = 18.8mm$

These figures suggest that to prevent elastic deformations causing ground closure on to the pipe, an initial overbreak of 25mm on diameter might be added (see later).

Local yield of ground – Figure 10

Check local stresses around tunnel opening

$\sigma_v = 222$ kPa, $\sigma_h = 298$ kPa $\quad \therefore K = \frac{\sigma_h}{\sigma_v} = 1{\cdot}34$

$\therefore$ at crown of tunnel

local circumferential stress $\frac{\sigma_{cc}}{\sigma_v} = -1+3K = 3{\cdot}0 \quad \therefore \sigma_{cc} = 666$ kPa

at axis of tunnel, $\frac{\sigma_{ca}}{\sigma_v} = 3-K = 1{\cdot}66 \quad \therefore \sigma_{ca} = 368$ kPa

Local yielding will occur if $(\sigma_c - \sigma_T) > 2S_u$

For unpressurised tunnel $\sigma_T = 0$, and σ_{cc}, σ_{ca} both $> 2S_u = 270$ kPa

Thus local yielding will occur unless tunnel is pressurised with suitable lubricant slurry to a pressure of $666 - 270 \approx 400$ kPa

If local yielding is allowed, prediction of contact stresses between pipe 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 40mm on diameter.

Ground movement - Figure 11

If overbreak of 40mm on diameter used (see previous), then ground loss for complete closure of ground onto pipe, giving maximum settlements.

$V_s = \frac{\pi}{4}(1{\cdot}84^2 - 1{\cdot}80^2)' = 0.1144$ m³/m (4·5%)

Because face stability is very high, assume ground loss there negligible
From plot, $i = 0{\cdot}433 \, z + 1{\cdot}1$
$= 5{\cdot}94$m for z = depth to tunnel axis = 11·25m

Then $S_{max} = \frac{V_s}{\sqrt{2\pi}.i} = 7{\cdot}7$mm

If overbreak increased to 50mm on diameter,

$V_s = \pi/4(1{\cdot}85^2 - 1{\cdot}80^2) = 0{\cdot}143$

$S_{max} = 9{\cdot}6$mm

In either case width of settlement trough ≈ 6i = 36m
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 4.9 & 5.3 of the Oxford Report): at similar depth in London Clay overall friction force averaged 54 kN/m. To allow for increases in resistance due to stoppages, increase by 50%, giving maximum of 81 kN/m

Assume packer of chipboard or MDF, 130mm wide, 18mm thick, located 15mm from inside surface of pipe.
Allow for maximum joint misalignment angle of 0.5°, requiring good control of tunnel curvatures.
Assuming normal design criteria, then from information given by pipe manufacturer see Fig. 8.3
maximum pipe jacking load at angular deflection of 0.5° = 440T (4300 kN)

Then length of pipe between interjacks $= \frac{4300}{81} = 53\,m$

For first length, include face load of ~300 kN (see table 5.1 of Oxford Report)
then length of pipe $= \frac{4000}{81} = 49\,m$

∴ Provision 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 might 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

Local 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 130mm 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 interjacks 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 wall be designed to accommodate 650 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-jointed pipes.

9.6 Specific data to the scheme

Internal diameter of pipe	d	1800 mm
External diameter of pipe	D_p	2120 mm
Wall thickness of pipe	t	160mm
Depth to invert of pipe		7.00m
Depth to axis of pipe	[illegible]	6.10m
Length of drive		300m
Water table - below ground level		2.00m

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, SPT N-Values ≈ 25
Drained stiffness $E_s' \approx 4000K$ (Stroud)
$= 100 \times 10^3$ kPa

Assume water table at depth 2.0m below ground level
Saturated weight of soil $\gamma_s = 19.5$ kN/m³
Buoyant weight of soil $\gamma_b = 9.5$ kN/m³
Water pressure at axis of tunnel $= 4.1 \times 10 = 41$ kPa
Total vertical stress at axis of tunnel $\sigma_v = 6.1 \times 19.5 = 119$ kPa
Effective vertical stress at axis of tunnel $\sigma_v' = 119 - 41 = 78$ kPa

Take friction angle of soil = 33°, then $k_o = 1 - \sin\phi = 0.455$
$\therefore$ 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, slurry pressure should be equal to total horizontal stress or slightly greater, say 80-100kPa.
For 100kPa, total face pressure load $= 100\,\frac{\pi}{4}\cdot 2.12^2 = 350\,kN\,(36T)$

Tunnel face load - Figure 6

In addition to load due to face pressure calculated above (36T) there will be ground resistance on the cutting edges of the shield and friction on the outside of the shield and the first few pipes until pipeline lubrication is fully effective. Assume this length extends over 4m for the shield, plus 5m for the first two pipes. To calculate resistance over this length use ground loading model of Fig.6

Here $2B = D_e \tan(45° - \phi'/2) + D_e / \sin(45° + \phi'/2)$ where $(45° + \phi'/2) = 61.5°$,

$\therefore B = 1.78m$ $\qquad (45° - \phi'/2) = 28.5°$

$H = 6.1 - \frac{2.12}{2} = 5m$

From depth 0 to 2.0m $\gamma_1 = \gamma_s = 19.5\ kN/m^3$

$$\therefore \sigma_v = \frac{\gamma B}{K \tan\phi'}\left(1 - e^{-K\tan\phi \cdot H/B}\right)$$

$$K = \frac{(1 - \sin\phi')}{(1 + \sin\phi')} = 0.295 \qquad \therefore \frac{K\tan\phi}{B} = 0.1076$$

$$\therefore \text{At depth 2m } H = 2.0,\ \sigma_{v1} = \sigma'_{v1} = \frac{19.5}{0.1076}\left(1 - e^{-0.1076 \times 2.0}\right)$$

$$= 35.1\ kN/m^2$$

Below $z = 2.0m$, $\gamma' = 9.5 kN/m^3$

then $\frac{K \tan\phi (H - H_1)}{B} = 0.323$

and $\sigma_v' = \sigma_{v_1}' e^{-0.323} + \frac{\gamma'}{0.1076}(1 - e^{-0.323})$

$= 25.4 + 24.4$

$= 49.8$ kPa

then $\sigma_h' = K(\sigma_v' + 0.5\gamma' D) = 17.7 kPa$

and frictional resistance $F = \frac{\pi D}{2}(\sigma_v' + \sigma_h')\tan\delta$

taking $\delta = 0.87\phi = 28.7°$

$F = 119.5 kN/m$

$\therefore$ For length of 9m, frictional resistance = 1076 kN

Add 200kN estimated for cutting edge resistance, then total front-end load

= 1076 + 350 + 200 = 1626 kN

Tunnel bore stability - Figure 3

For $\phi' = 33^\circ$, $T_\gamma = 0.3$

$\therefore \sigma_T = \gamma_b D_p T_\gamma +$ water pressure

$= (9.5 \times 2.12 \times 0.3) + 41$

$= 47kPa$, say $50kPa$ slurry pressure

Ground closure - Figure 5

$\sigma_v' = 78kPa$, $\sigma_h' = 35.5kPa$, take $\nu \approx 0.2$

then $\delta_v = (1-\nu^2)\dfrac{2.12}{100}(3 \times 78 + 35.5) \quad = 5.5mm$

$\delta_h = (1-\nu^2)\dfrac{2.12}{100}(78 + 3 \times 35.5) \quad = 3.8mm$

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

$$\delta_p = \frac{(1+\nu)p\,D_p}{E_s} = 0.2mm \text{ (negligible)}$$

$\therefore$ Provided adequate slurry 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,

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

From p107, $i = 0.28z - 0.12$, and $z = 6.1$

$\therefore i = 1.59m$,

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

And maximum settlement

$$S_{max} = \frac{V_s}{\sqrt{2\pi}\,i} = 16.8mm$$

<u>Pipe friction</u>

For fully lubricated pipe,
buoyancy uplift force $= \frac{\pi Dp^2}{4} 10 = 35.3$ kN/m

but pipe weight $\pi (Dp^2 - De^2) 24 = 23.6$ kN/m
$\therefore$ nett force on tunnel wall (crown) $= 11.7$ kN/m

$\therefore$ friction force $= 11.7 \tan \delta$
where $\delta = 0.87 \phi' = 28°$

$\therefore$ friction force $= 6.2$ kN/m

Add friction from lubricant/soil in annulus, at say 0.5 kN/m^2
$0.5 \times \pi Dp = 3.3$ kN/m

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

Total friction $= (6.2 + 3.3) \times 1.2$
$= 11.4$ kN/m

Pipe joint loading - Figure 8

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

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

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

$\therefore$ Distance to first interjack = $\frac{4400 - 1626}{11.4}$ = 243 m (Plus 5m for two leading pipes)

Frictional load on remaining pipe length = 11.4 x (300-248)
= 593 kN

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

If placed after 100m, interjack load
= 1626 + (100-5) 11.4 = 2709 kN (276T)

and final load on main jacks
= 200 x 11.4 = 2280kN (232T)

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 9.5metres

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 450 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

10.0 References

Pipe Jacking Association Publications

An Introduction to Pipe Jacking & Microtunnelling Design

Concrete Pipes for Jacking Smaller Diameters (Microtunnel) and Unreinforced Pipes
(Reference BS5911: Part 120)

Pipe Jacking - Research Results and Recommendations
George Milligan & Paul Norris. Oxford University Department of Engineering Science

Principal Legislation and Standards

Construction (Design and Management) Regulations 1994

Health and Safety at Work etc. Act 1974

Management of Health & Safety at Work Regulations 1992

BS5911: 1989 Part 120 Specification for reinforced jacking pipes with flexible joints

BS6164: 1990 Code of Practice for safety in tunnelling in the construction industry

BS8005: Part III: 1989 Sewerage - Guide to planning and construction of sewers in tunnel

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11.0

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.

Backacter
A mechanical device for excavation within an open shield.

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

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

Closed shield
A shield with a closed 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 shaft 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 face 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 intermediate jacking 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 shield 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 jacked 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 interjack pipe

The recessed pipe immediately behind the interjack station which slides 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.

Notes

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