Design of Pipeline Shore Crossings using Trenchless Methods

A.T. Nicholls  
Atteris Pty Ltd

D. R. Campbell  
Atteris Pty Ltd

J. R. Ryan  
Atteris Pty Ltd

E. P. Jas  
Atteris Pty Ltd

ABSTRACT

Pipeline shore crossings are often the most complex and technically challenging element of a subsea pipeline project. Challenges are compounded because shore crossings typically have a large public focus due to the environmental value and social sensitivity of coastal environments.

Increasingly, trenchless methods are being incorporated into shore crossing designs as an alternative to traditional open cut and cover methods. These can be used to help minimise impact on the coastal environment. Two trenchless shore crossing methods being used with an increased frequency are horizontal directional drilling (HDD) and microtunnelling.

Design challenges for a trenchless pipeline shore crossing extend beyond considering pipeline mechanical, stability and cathodic protection design. Engineers must also tackle the challenges associated with the trenchless methods of HDD or microtunnelling at a coastline and ensure they are suitably integrated with the pipeline design. Every pipeline shore crossing is different and no method is universally suitable. Costs and risks involved will change with every site, and every project.

This paper provides an overview of the pipeline shore crossing method selection and design processes. It highlights the issues, benefits and key parameters associated with adopting trenchless designs for pipeline shore crossings.

Keywords: HDD, microtunnelling, pipeline, shore crossing

1. INTRODUCTION

1.1 Background

In the hydrocarbon industry, a shore crossing is required where a pipeline transports natural gas or liquids between onshore and offshore locations. This section of the pipeline is often complex and costly to construct, and is susceptible to failure if inadequately engineered. Pipeline engineers have a number of generalised methodologies available to design pipeline shore crossings. Increasingly, these methods incorporate trenchless techniques where the pipeline traverses the shoreline deep below the natural surface.
Traditionally, pipeline shore crossings have integrated the open cut and cover method into the design. In this method, the pipeline traverses the shoreline within a pre-excavated trench which, after pipeline installation, is backfilled with sand or rock. While proven and reliable, the method can have a high physical impact and is often not compatible with environmentally sensitive coastlines.

In the 1980s, the onshore pipeline construction technique horizontal directional drilling (HDD) was identified as a suitable alternative for use on pipeline shore crossings. By using this trenchless method, engineers could avoid impacting environmentally sensitive sites or large obstructions by drilling underneath them. Today, HDD is the most common trenchless shore crossing method employed for small to medium diameter pipelines.

HDD for shore crossings involves the pre-drilling of a pilot borehole through the ground from a point onshore along the pipeline route, to a suitable location offshore. The borehole is held open with drilling fluid, providing an open conduit for the pipeline to traverse the shoreline. Hole opening or reaming is performed by using the drill rig to push a hole opener forwards along the alignment using the pilot hole as guidance. Forward reaming is the most common method used for shore crossing HDDs. Alternatively; the hole opener can be pulled through the pilot hole from a support barge offshore of the exit point, which is similar to the commonly used back reaming method used for land to land HDDs.

A range of pipeline installation techniques are available, however the most common method is to thrust a pre-fabricated pipeline string into the borehole from an onshore stringing yard as shown in Figure 1.

In the 1990s, shore crossing methods incorporating microtunnelling (a form of pipe jacking), were first adopted by pipeline engineers as a trenchless alternative to HDD. Typically, microtunnels are suited to pipelines where HDD is not feasible due to the large diameter of the pipeline to be installed, or where geotechnical conditions exclude the use of HDD. The tunnel internal diameter for a shore crossing is typically 1.8 to 2.0 metres as a minimum; however diameters may increase with tunnel length.

Microtunnels are formed by thrusting pre-fabricated concrete ring sections (jacking pipes) from an onshore entry shaft along the design profile. Excavation is achieved using a tunnel boring machine (TBM) which is situated at the front of the tunnel. Thrust force is provided at the entry shaft by hydraulic rams which engage the last installed jacking pipe and thrust the tunnel and BM forward along the alignment. At the completion of a cycle, the rams retract allowing space for subsequent jacking pipes to be installed.
After the tunnel has been constructed it is fitted out for pipeline installation. In general, as the tunnel length increases, so too does the complexity of pipeline installation. A simple and commonly used method is to pull the pipeline through the completed tunnel from a pipelay barge moored offshore using a winch located onshore as shown in Figure 2.

![Diagram of Pipeline Installation through a Microtunnel](image)

**Figure 2 – Example of Pipeline Installation through a Microtunnel**

## 2. TRENCHLESS SHORE CROSSING HISTORY AND EVOLUTION

### 2.1 Horizontal Directional Drilling

The tools and techniques used in the horizontal directional drilling (HDD) process are an outgrowth of the oil well drilling industry (Watson, 1995). In 1971, modified oil well equipment was used to perform the first pipeline river crossing using a drilling method, which became known as horizontal directional drilling (HDD). The installed pipeline was a 500 ft (152 m) 4 inch diameter pipeline beneath the Pajaro River in California, USA (Cherrington, 1995).

The first HDD for a pipeline shore crossing was completed in 1982 for the Tennessee Gas Pipeline Company on Mustang Island off the cost of South Texas. An 8 inch diameter pipeline was installed beneath the sand dunes and past the surf zone, achieving a total subsurface length of 2,639 ft (804 m). HDD had been selected to minimise environmental impact on the sand dunes which extended 900 ft landward of the shoreline (Hale, 1982). It is worth noting that the first HDD performed in Australia was also a pipeline shore crossing; a landfall for one of Esso’s Bass Strait pipelines near Longford in Victoria which was executed by Spie Horizontal Drilling (Horner, 1989).

A major breakthrough for HDD for shore crossings was the development of the forward thrust pipeline installation method. In the method, a thrusting rig is used to clamp and push the pre-fabricated pipeline string into the HDD borehole from an onshore roller track. The key advantage of the method is that minimal offshore support is required during pipeline installation. In 2002, the method was successfully used for the first time to install an 815 m section of 16 inch diameter pipeline as part of the Patricia Baleen Development in Australia (Cherrington, 2003).

To date, the longest pipeline shore crossing using the HDD method was performed for the Kupe Gas Project in 2007. HDD was used to install a 2,300 m, 20 inch diameter casing under steep cliffs across the Taranaki coastline in New Zealand. The casing later provided a conduit for installation of a 12 inch diameter pipeline, which was also installed from onshore and later retrieved by a pipelay barge moored offshore to tie-in and initiate offshore pipelay.
2.2 MicroTunnelling

The term ‘microtunnelling’ was first used to describe the miniaturised combination of available pipe jacking methods with remote control pilot boring machines by Japanese manufactures in the mid to late 1970s. The method was developed in response to demand for construction of small sewer pipes with diameters of 300 to 900 mm, where personnel access is not feasible. The reduced diameters were made possible by a technological advance which saw the control panel being relocated from the front of the tunnel to the entry pit, where the operator could remotely drive the tunnelling equipment (Thompson, 2009).

The concept of remote operation was applied to larger bore tunnels when pressurised shielded tunnel boring machines (TBM) became available in larger sizes in the late 1980s (Thompson, 2009).

In 1994, a microtunnel was constructed for the 42 inch Europipe gas pipeline landfall for Statoil in Germany. The 3.8 m outside diameter tunnel was thrust 2,535 m underneath a dike and mudflats which form part of a national park (Phillip et al., 2010). Despite being one of the first applications for a pipeline shore crossing, it remains the longest single drive microtunnel achieved to date. The tunnel was thrust in a 12 m diameter caisson offshore, where the TBM was recovered. The caisson was also used to support pipeline installation.

3. ADVANTAGES OF TRENCHLESS SHORE CROSSING METHODS

Every pipeline shore crossing is different and no method is universally suitable. The costs and risks involved will change with every site, and every project. A generalised overview of the key advantages and disadvantages of each shore crossing method relative to a conventional open cut and cover is presented in Table 1.

| Summary of Key Advantages / Disadvantages of Trenchless Shore Crossing Methods |
|---------------------------------|---------------------------------|
| Horizontal Direction Drilling | Microtunnelling |
| Summary of Key Advantages |
| • Reduced environmental impact and avoidance of culturally significant sites | • Reduced environmental impact and avoidance of culturally significant sites |
| • Most suited to difficult topography or to negotiate obstructions | • Suited to difficult topography |
| • Reduced offshore civil works in shallow water and the intertidal zone and minimal offshore support. | • Less sensitive to geotechnical conditions than HDD |
| • Proven track record | • Compatible with standard pipeline installation techniques |
| Summary of Key Disadvantages |
| • Highly sensitive to geotechnical conditions. | • Typically more costly than HDD |
| • Potential for pipeline installation and tail-end stability issues. | • TBM recovery and pipeline transition typically requires complex offshore civil works. |
| • Technical limits on HDD length and diameter. | • Pipeline installation can be complex and costly. |
4. SELECTION OF SHORE CROSSING METHOD

4.1 Landfall Site Selection

A robust site selection process is crucial to successfully design a pipeline shore crossing and will typically consider method selection simultaneously.

Pipeline shore crossing designs incorporating trenchless methods have unique design requirements, which differ significantly to conventional open cut and cover methods. For a particular project, the optimal shore crossing landfall site may be different if an open cut and cover method is selected, compared to a HDD or again to a microtunnel.

Pipeline engineers should always remain open minded and re-consider landfall site selection if the proposed design method changes. In general, landfall site selection should consider the following key elements at a minimum:

- Operational requirements including minimising the distance between the proposed offshore platform or wellhead and the onshore processing facility.
- Site constraints, including heritage, environment and social or community constraints and land access.
- Site conditions, including onshore topography, nearshore bathymetry, geotechnical, weather, metocean and geomorphology.

Once potential landfall sites have been shortlisted, further engineering design can be undertaken to examine the feasibility of potential pipeline shore crossing methods. This is expanded on in Section 5.

4.2 Pipeline Shore Crossing Method Selection

For a given project, there may be numerous viable permutations of each shore crossing method. This will lead to the development of a number of options that the pipeline engineer will consider and develop early in the project development cycle. Options will extend beyond those normally considered for a typical land to land HDD or microtunnel design.

For example, it may be desirable to use microtunnelling to avoid disturbing coastal sand dunes and cliffs. The pipeline engineer may propose tunnelling underneath the sand dunes to meet an open trench on the beach which will house the pipeline through the narrow surf zone. As an alternative, the engineer may also propose that the tunnel is extended so that the tunnel meets the open trench beyond the surf zone.

The option that is selected by the project will depend on a number of site specific factors. Continuing the example, the pipeline engineer may establish the presence of a strong, thick limestone cap rock layer offshore which is not present on the beach and will make underwater TBM recovery following completion of the tunnel construction difficult. This alone may push the pipeline engineer to opt for a shorter tunnel; however, they may also establish that dredging a trench in the surf zone will be very costly due to onerous sea state or geotechnical conditions.
The solution to this problem may be to allow for rock fragmentation, at the tunnel exit point and select a longer tunnel option.

The example simplifies an often intricate problem to illustrate the types of constraints that are considered when developing a pipeline shore crossing design method. In reality, the option that is selected will depend on the site specific constraints and the site conditions which have been discussed previously. Constructability of the option is also considered in detail, including fresh water requirements, laydown areas, footprint for pipeline stringing yards, offshore equipment operability, pipelay barge access and seabed dredgability.

A process for evaluating the shore crossing methods and their respective permutations is required to select the most suitable option for the chosen landfall site. A suitable process involves considering project costs, risks and project scheduling requirements. The option that will prevail is the one that is best suited to the chosen landfall site from a cost and risk perspective, while meeting the project schedule requirements. This process is usually performed at a pre-FEED project level. Engineers should be cautious when executing this process with very limited site data, as the results will be inconclusive.

Returning again to the example, the shore crossing selection process may establish that an HDD option is in fact more cost effective than a microtunnelling option. It may also establish that the option is of equivalent risk while complying with the project schedule requirements. The reality of such a conclusion will always vary between different landfall sites and pipeline projects.

When selecting a pipeline shore crossing method, the advantages of using a microtunnel or an HDD must be considered in conjunction with a number of other design and constructability elements which will affect costs, risks and the schedule. Typically, these include at a minimum:

- Mechanical design of the pipeline.
- Corrosion protection design, which includes coating selection, field joint coating selection and cathodic protection design.
- Temporary and operational pipeline stabilisation design.
- Pipeline transition design (from the subsurface to the seabed or trench).
- Pipeline installation method and tie-in to the onshore and offshore sections of the pipeline.

The design elements are often co-dependent, and changing one will in turn change how the rest are designed. An example of co-dependency is pipeline stabilisation design and pipeline installation methodology. A standard method for installing pipelines through microtunnels is by using the shore pull method, where the pipeline is fabricated on a pipelay barge offshore and pulled through the tunnel using a linear winch located onshore.

The pipeline offshore of the tunnel must be kept stable at all times, which means it cannot be displaced due hydrodynamic loading from waves and currents. At a site with onerous metocean conditions, a pipeline engineer may incorporate a robust concrete weight coating into the primary stabilisation design to achieve stability.
Weight coating will increase the submerged weight, which will result in higher pull loads required to install the pipeline. In many circumstances this will increase the installation complexity. Often, this equates to an increase in cost and risk. The pipeline engineer may instead elect to apply an alternative stabilisation technique where excessive weight coating is not required, such as using concrete mattresses. Alternatively, reducing the length of the tunnel may reduce the pull loads, and the pipeline installation process.

This simplified case illustrates just one co-dependent consideration that must be dealt with when designing a pipeline shore crossing. There is no universally applicable method, and the assessment should always be performed on a case by case basis.

Figure 3 – Pipeline installation for HDD with Thrust Machine (left) and Tunnel with two Linear Winches (right)

5. KEY DESIGN CONSIDERATIONS FOR A TRENCHLESS SHORE CROSSING

Once a landfall site and the shore crossing concept design have been selected the following key parameters should be evaluated:

- Geological and geotechnical conditions
- Pipeline route alignment and longitudinal profile design
- Pipeline mechanical design
- External corrosion protection system for the pipeline
- Pipeline on-seabed hydrodynamic stability

Throughout the design process the constructability, social, health and safety, and environmental constraints and impacts are required to be considered through risk assessments, HAZIDs and constructability reviews.

This section discusses the key parameters for a trenchless pipeline shore crossing. Many of these parameters are also important for conventional open cut and cover shore crossings. However, these parameters are only discussed in terms of trenchless installation techniques.
5.1 **Geological and Geotechnical Conditions.**

Early in the landfall site selection and conceptual design phase, detailed geotechnical information is not usually not available. At this stage, it important undertake a geological desktop study and an initial site visit in order to develop a inferred geological engineering model of the proposed shore crossing area. The assessment should be able to identify any areas of concern for the design engineer.

Geophysical and geotechnical surveys are usually adequate for providing detailed information. A suite of geophysical investigations, CPTs and geotechnical boreholes both onshore and offshore should be carefully planned and executed. An analysis of the seismic refraction data will assist in locating the CPTs and boreholes in the most appropriate locations for the pipeline shore crossing design.

It is important for the pipeline engineer to ensure that boreholes are not drilled directly onto the alignment because this may cause problems during tunnelling or HDD operations. An offset of 10-50 m is typically required depending on the site conditions.

The concept of drilling exploration HDD ‘pilot holes’, although it may be perceived to provide a greater level of confidence, is not a substitute for a thorough geotechnical drilling campaign and may provide misleading data. This technique of ground investigation is usually also more expensive compared to a conventional geotechnical campaign.

As the project progresses and further information becomes available the inferred geological engineering model should be updated. An example of an inferred geological engineering model overlayed on an HDD Longitudinal Pipeline is presented in Figure 4.

![Figure 4: A Typical Example of a HDD Longitudinal Profile with Geotechnical Data Overlay](image)

5.2 **Geotechnical Consideration for the Subsea Exit Point**

A major focus in the design of a trenchless shore crossing is the subsea exit point, where the pipeline transitions from the tunnel or borehole out on the seabed or trench. Where the pipelines transitions directly to the seabed (without seabed preparation), a hard seabed at the exit point should be avoided. A hard, uneven seabed can cause excessive pipeline spanning, which can
induce high stresses in the pipeline and can also make it susceptible to fatigue. Stabilisation of the pipeline at the exit point is discussed in Section 5.3.

For an HDD, an ideal exit point would comprise with a competent rock underlying a 2 – 3m thick veneer of sand. This allows the HDD to confidently punch-out of the seabed, but also provides a softer layer for the pipeline to transition on the seabed, avoiding a point of high stress. A very soft seabed should also be avoided given that this may cause tunnelling or drilling difficulties.

In the case of a microtunnel, the exit point can be several metres below the natural seabed surface so that a minimum depth of cover is retained above the concrete segments. The cover provides resistance to tunnel buoyancy effects and reduces the risk of differential settlement and joint displacement. Consequently, an exit pit is required at the microtunnel exit point to ensure that the pipelines transition smoothly from the tunnel to the seabed (or open trench). The exit pit can potentially extend over 200 m.

5.3 Route Alignment and Longitudinal Profile Design

The route alignment for a pipeline shore crossing should be selected by considering suitable locations for onshore entry points, offshore exit points and the longitudinal profile between the two. Where practical, the length of the HDD or tunnel should be minimised to reduce construction risks; however, there may be advantages for increasing the subsurface length such as avoiding a subsea feature or reducing dredging requirements. The location of the onshore entry point and offshore exit point are selected by considering site constraints and conditions.

The onshore area surrounding the entry point should be sufficiently large to contain the construction site, laydown areas and necessary stringing yards. Offshore, the exit point should be selected to ensure that sufficient water depth is available for floating construction equipment to perform pipeline installation, pipeline tail-end retrieval, dredging and TBM recovery for a microtunnel. If shallow water extends for several kilometres beyond the shoreline, significant dredging may be required so that construction equipment can reach the tunnel or HDD exit points. Alternatively very shallow pipeline construction barges could be deployed or alternative pipeline installation methods could be considered.

As an example, a typical shallow water pipelay barge needs 4 – 5 m minimum water depth for operation. If this water depth is only achieved several kilometres beyond the shoreline, the route alignment should be avoided if possible. In some circumstances, the route alignment may be constrained for environmental or social reasons. In this case, significant dredging would be required to provide an access channel for the pipelay barge to reach a target mooring location closer to the shoreline or alternative pipelines installation techniques could be applied.

The longitudinal profile design of the HDD should consider the minimum allowable bending radius of the pipeline. Tight vertical bending radii increase the installation and operational stresses on the pipeline and increase the risks during pipeline installation. The substrata must be sufficiently competent to resist the load from the pipeline bending.

When considering the microtunnel radius of curvature, angular deflection between consecutive jacking pipes needs to be considered. Angular deflections cause the thrust load to be transferred between the jacks unevenly, which can lead to significant de-ratings in the loads that can be
transferred. Excessive angular deflections are induced by tight profile radii of curvature, differential settlement or misalignment.

Typically, the minimum radius of curvature for pipeline installation and operation is smaller than that required for microtunnel construction; however, this should be checked on a case by case basis. Bending of pipelines can also lead to stresses in the pipeline wall, potentially leading to a pipeline buckling.

The entry and exit angles should be as steep as practical to maintain a minimum depth of cover above either the microtunnel or HDD for the maximum possible length; however, the actual angles are typically limited by constructability constraints. The angle at which a tunnel exit pit is dredged must match the exit angle of the tunnel to provide a smooth transition between the tunnel exit and the natural seabed (or trench) for pipeline installation. Consequently, the length and dredging volume of the exit pit is dependent on the exit angle of the tunnel.

5.4 Pipeline Stability Design

A pipeline must be stable on the seabed. If it is too light, it will slide sideways under the action of currents and waves (hydrodynamic loading). If it is too heavy, it will be difficult and expensive to construct (Palmer, King 2008).

The shore crossing must be designed to ensure that the pipeline is stable under installation and operational conditions. The difference between the two scenarios is the magnitude of hydrodynamic loading that the pipeline must be designed for. There are two methods to achieve pipeline stability, which are the following:

- Primary stabilisation
- Secondary stabilisation

Typically, primary stabilisation involves adding a layer of concrete weight coating over the pipelines external corrosion coating. The thickness of the weight coating can be modified from a minimum of 40 mm to a practical limit of approximately 150 – 250 mm (constrained by a number of constructability considerations related to the pipelay barge). A thick weight coating will ensure that the pipeline is stable, but may complicate pipeline installation significantly. Where practical thickness limitations are exceeded, secondary stabilisation measures are introduced to the design.

Secondary stabilisation can be achieved by numerous methods and some commonly used examples include pre-trenching the seabed, rock dumping, rock bolts or concrete mattresses. These methods can be costly to implement, so pipeline engineers typically optimise designs to ensure the stabilisation measures being used are functional without being excessive. A typical side dump vessel is presented in Figure 5.
Trenchless shore crossings designs pose a range of stability issues which are closely linked to pipeline installation. For example, in many cases, it is considered impractical to use concrete weight coating on a pipeline that will be installed using the HDD thrust method. When the pipeline is installed and the pipeline tailend (the section of pipeline string just outside the HDD exit point) rests on the seabed, it may be susceptible to stability problems because of the low submerged weight. Any lateral movement of the pipeline will risk a buckle at the HDD exit point, which is impractical to repair.

5.5 Corrosion Protection System

Corrosion protection systems for subsea pipelines incorporate an external coating, for primary protection and a cathodic protection system for secondary protection. The intertidal zone presents a major technical challenge for corrosion protection design of pipeline shore crossings.

Intertidal zones create a highly corrosive environment because of the cyclic wetting and drying of the pipeline with each tide. Exposure to air provides a supply of oxygen which aids the corrosion process. Consequently, it is critical that the corrosion protection system functions adequately across the intertidal zone. This can be complicated because of the increased electrical resistivity of the ground when it dries at low tide. This can result in insufficient protective potential at the onshore end of the intertidal zone, allowing external corrosion to transpire on sections of the pipeline where coating damage has been sustained.

Key issues specific to trenchless pipeline shore crossings include the following:

- The abrasive nature of pipeline installation has a high risk of corrosion coating and field joint coating damage.
- External coatings are impractical to inspect or repair under water after installation.
- Bracelet anodes are typically are not used on HDD sections of pipelines.
- Incorrectly applied coatings or field joints can disband from the pipe material. Incorrect coating selection can also lead to cathodic disbondment.
- The interface between the cathodic protection systems for the onshore and subsea
The selection of appropriate coating system in combination with the Cathodic protection is essential to ensure the long-term integrity of the pipeline through this high risk area.

6. CONCLUSION

Pipeline shore crossings are often the most complex and technically challenging element of a subsea pipeline project. As such, it is important that an early focus in a project is given to the design of the pipeline shore crossing and site data collection surveys.

A key advantage for selecting trenchless technology for pipeline shore crossing is that it avoids impacting environmentally sensitive sites or large obstructions by drilling or tunnelling underneath them. In addition, there can also be project cost and schedule benefits when selecting these methods.

In addition to the standard pipeline design challenges, attention should be focussed on the following aspects for a successful trenchless pipeline shore crossing:

- Geophysical and geotechnical surveys should be performed to support site and method selection. Typically, this will commence with a geophysical survey on a select range of preferred sites. The data should be used to create an inferred geological model, which will be used to plan subsequent geotechnical campaigns, and provide input into the site selection process.

- The shore crossing design concept should be selected in conjunction with the pipeline landfall site selection and should be chosen on the basis of cost, risk and schedule. This is typically performed at a pre-FEED project stage on the basis of preliminary site data.

- The design of the subsea exit point, where the pipeline transitions from the tunnel or borehole out on the seabed or trench should be a major focus of the design. Pipeline engineers should ensure the pipeline makes a smooth transition from the borehole or tunnel onto the seabed or trench. This avoids configurations which may cause the pipeline to overstress, freespans to form and potentially fatigue issues.

- Corrosion protection design should consider the additional complexities inherent to a trenchless shore crossing. The selection of a pipeline coating and cathodic protection system must be compatible with the trenchless method being employed.

- Constructability of the trenchless shore crossing including pipeline stabilisation, pipeline installation, dredging and TBM recovery should also be considered.

- A detailed risk assessment process should complement the design.
7. REFERENCES

Cherrington, M., 1995, *How the HDD Industry Began*

Cherrington Group, 2003., Video Publication *Patricia Baleen Pipeline Shore Crossing*

Hale, D., 1982, Pipeline & Gas Journal *First Drilled Beach Crossing Protects Mustang Island Dunes*


Jas, E., Campbell, D., Van Boesschoten, S., 2007, Coast and Ports *A State of the Art Shore Crossing – Otway Gas Project*


Thompson, J., 2009, Trenchless International *Microtunnelling and How We Got There*