Creating underground space at shallow depth beneath our cities using jacked box tunnelling

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Abstract: Underground space beneath our cities is required for a wide range of uses, for example people transport, water storage and distribution, vehicular and pedestrian access-ways and secure storage for valuables. Some of these spaces can be created at depth using conventional bored tunnelling methods with minimal disturbance to overlying infrastructure. Where the space is required at shallow depth it is normally created by excavation from the ground surface, which can be highly disruptive to local infrastructure and detrimental to the human environment. Jacked box tunnelling is a method of construction that enables engineers to create underground space at shallow depth in a manner that avoids disruption of valuable infrastructure and reduces impact on the human environment.

The paper outlines the jacked box tunnelling method and describes examples of its use in practice listing the sensitivities and particular hazards addressed, the solution adopted and the performance achieved.

Consideration is given to the procedure required in selecting, developing and executing a jacked box tunnel scheme for creating underground space, including the importance of a comprehensive site investigation.

Résumé: L'espace souterrain dans nos villes est consacré à toute une série d'applications : par exemple, les transports en commun, le stockage et la distribution de l'eau, des passages pour véhicules et pour piétons, ainsi que des chambres fortes. Certains de ces espaces peuvent être réalisés en profondeur, en faisant usage de méthodes de construction de tunnels à forage traditionnel, conçues pour minimiser l'impact sur les structures qui les recouvrent. Lorsque l'espace doit être réalisé à une profondeur limitée, on l'exécute normalement en excavant de la surface, ce qui risque de perturber considérablement l'infrastructure locale et de nuire à l'environnement de l'homme. La construction de tunnels en caisson (« *Jacked box* ») est une méthode de construction qui permet aux ingénieurs de créer un espace souterrain peu profond de façon à ne pas perturber des infrastructures importantes, et à minimiser l'impact sur l'environnement de homme.

La présente communication décrit la méthode de construction de tunnels en caisson (« *Jacked box* ») et fournit des exemples de son application dans la pratique, illustrant les sensibilités et les risques particuliers sur lesquels on s'est penché, ainsi que les solutions que l'on a adoptées et les résultats obtenus.

On examine également la procédure appliquée pour sélectionner, développer et mettre à exécution un projet de construction de tunnels en caisson (« *Jacked box* ») pour la réalisation d'un espace souterrain, y compris l'importance d'un examen complet du chantier.

Keywords: tunnels, infrastructure, substructures, settlement, geotechnical engineering.

INTRODUCTION

For many years engineers have been creating valuable underground space beneath our cities. Typical examples are the metro systems, road tunnels, water supply and flood water storage tunnels, sewers, cable tunnels and substations, air raid shelters, storage facilities, etc.

Traditionally they have been of circular or arch profile, constructed at depth where the natural arching properties of the ground can be exploited to achieve tunnel stability both during and after construction. At shallow depth the natural arching properties of ground do not develop. Historically, shallow depth tunnels have been constructed using cut and cover techniques, which have often proved highly disruptive requiring road closures and property demolition. They also require large quantities of excavated material to be removed from site and significant quantities of fill material to be subsequently delivered to site. These material movements are generally carried out using fleets of lorries resulting in significant intrusion to the city environment.

Jacked box tunnelling provides planners and designers with a non-intrusive technique for creating underground space at shallow depth beneath existing infrastructure where it is either impractical or inconvenient to undertake construction from the surface (Clarkson & Ropkins (1977), Ropkins (1998)).

To date the technique has been used to create underground space primarily for rail, road and pedestrian accesses together with a major river diversion culvert at Dorney, Berkshire. It could equally well be used to create underground space for car parking and office access, archive and cold storage, machinery rooms, etc.

Recent milestone achievements include (Allenby & Ropkins (2003), Allenby & Ropkins (2004)):

- the first use of the technique under a live motorway in the United Kingdom when a 14m wide, 8.5m high by 45m long vehicular underpass was installed with 1.6m minimum cover to the M1 motorway at junction 15A, Northampton

- the installation of twin road tunnels, each 12.5m wide, 10.5m high by 44m long under Silver Street railway station, London. Limited working space at the station necessitated casting the boxes at ground level as a series of counter-cast interlocking segments, lowering each one in turn into a jacking pit, and incrementally jacking forward, and
- the largest jacked box tunnelling contract undertake in the world to date when three highway boxes were installed under the 13 commuter tracks leading into Boston South Station as part of the Boston Central Artery Project, Boston, USA. The largest box measures 24m wide, 10.8m high by 106.8m long.

This paper has three objectives:

- to outline the principles of the technique
- to describe examples of its use in practice, and
- to describe the procedure to be followed in selecting, developing and executing a jacked box tunnel solution.

THE TECHNIQUE OF JACKED BOX TUNNELLING

In its simplest form, a monolithic reinforced concrete box is cast on a jacking base, typically inside a sheet piled jacking pit adjacent to a road or railway embankment, see Figure 1a. The jacking pit is carefully positioned to minimise the jacking length whilst at the same time satisfying working clearance requirements to the road or railway.

A purpose designed tunnel shield is cast on to the leading end of the box, and thrust jacks are provided at the rear end reacting against the jacking base.

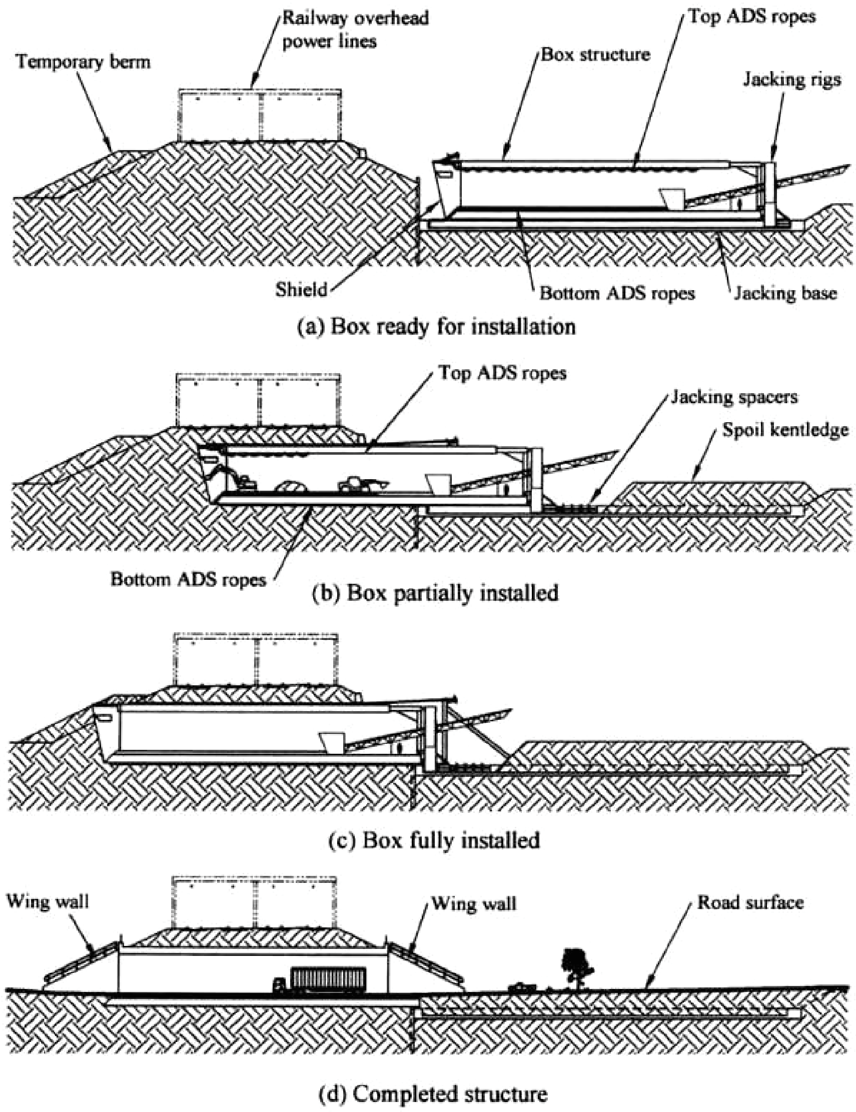

Figure 1. Jacked box tunnel construction phases

The box is jacked to the headwall and using a carefully controlled and phased sequence the headwall loading is progressively transferred to the shield structure as the box advances and the headwall is removed in sections.

Tunnelling then commences by carefully excavating 150mm off the face and jacking the box forward a corresponding amount, see Figure 1b.

Jacking thrust is transmitted into the ground through the shear interaction developed between the jacking base underside/ground interface, and jacking pit wall/ground interface. Placing and compacting tunnel spoil on top of the jacking base can enhance shear interaction at the underside/ground interface.

A temporary earth berm is constructed on the exit side of the embankment to buttress the embankment and prevent distress during the final stages of jacking. When the box has reached its final position, see Figure 1c, the box/ground interface is grouted to minimise settlement, the shield, jacking equipment, etc are dismantled, and the portal structures, internal finishings and roadway are constructed, see Figure 1d.

In both cohesive and granular material face stability is maintained and ground loss controlled using shield tunnelling techniques. Proprietary anti-drag systems (ADS) are installed at the top and bottom of the box to minimise disturbance to the surrounding ground and possible disruption to the infrastructure above. These are discussed in the following section.

Control of Ground Disturbance

When a box section is jacked through the ground at shallow depth it does not benefit from soil arching effects associated with traditional pipe jacking and tunnelling. Instead the box carries the full overburden and superimposed loads on its flat roof and transmits them into the ground below.

Ground relaxation occurs into the face accompanied by ground closure along the sidewalls resulting in the formation of a shallow settlement trough along the box alignment, whose magnitude and extent are dependent upon the physical and time dependent properties of the ground and the effectiveness of face support.

Because the box/ground interface cannot be grouted until box installation has been completed there is a potential for increased time dependent settlement. This may be further increased by drag or shear effects causing remoulding of the ground with a subsequent loss in ground volume.

The principal measures used to control and minimise ground disturbance are as follows.

Control of Face Loss

Face excavation causes a three-dimensional stress redistribution in, ahead of, and around the advancing face accompanied by ground relaxation. The ground relaxation element is controlled by buttressing the face using shield tunnelling techniques. Each shield is purpose designed to suit the ground conditions predicted from the site specific ground investigation and the chosen method of face excavation.

Figure 2 illustrates a composite reinforced concrete and steel shield for a 17m wide by 6.2m high rail tunnel box installed at Lewisham Station, London. This shield was designed for a mixed face comprising loose silt and sand in the top half and soft clay in the bottom half. The steel shield has a sloping face and hood section designed to be thrust into the loose silt and sand to provide face and roof support and protection to the miners, while the lower concrete shield with its relatively thick walls is designed to support the soft clay. Each top compartment was hand mined and 360° backacter excavators positioned on the box floor excavated the remaining face area.

Figure 2. The composite reinforced concrete and steel shield, Lewisham Station, London

In contrast the 23m wide by 9.5m high flood relief culvert installed at Dorney, Berkshire through artificially frozen sands and gravels had a reinforced concrete shield divided into four full height compartments. Figure 3 illustrates two compartments being excavated with roadheader equipment.

Shield design calculations must take into account face loads, overburden and superimposed loads, lateral loads and jacking loads including localised loads from face rams, gun struts, etc.

Control of Ground Drag

Referring to Figures 1b and 1c, it will be seen that as the box is jacked forward there will be a tendency to drag the ground. In the case of a wide box with low cover the ground on top of the box could be dragged forward, causing major disturbance and possible disruption to the overlying infrastructure. Similarly, the underside of the box will tend to drag and shear the ground, resulting in remoulding accompanied by a loss in volume causing the box to dive.

These effects can be minimised by using proprietary top and bottom "anti-drag systems" (ADS) as illustrated in Figure 4 to effectively separate the external surface of the box floor and roof from the adjacent ground during tunnelling. They comprise arrays of closely spaced greased wire ropes anchored to the jacking base with their free ends passed through guide holes in the shield and stored with their free ends inside the box. As the box advances the ropes are progressively drawn out through the guide holes in the shield and form a stationary layer between the moving box and the adjacent ground. The drag forces are absorbed by the ADS and transferred back into the jacking base. In this manner the ground is isolated from the drag forces and remains largely undisturbed.

Ground drag on the sides of the box is normally reduced by lubricating with bentonite slurry.

Figure 3. Excavation of frozen sands and gravels, Dorney, Berkshire

Constructional Tolerances

To minimise ground drag, jacking loads and settlement it is essential that all external box surfaces are straight, smooth, free from steps and defects, and that opposite faces are parallel and free from twist and distortion. These requirements are achieved by rigorous control of setting out, the use of high quality shuttering materials, checking finished surfaces and rectification of defects.

It is standard practice to accurately define the three-dimensional shape of the box and shield and make adjustments to the trimming beads attached to the shield cutting edges to allow free passage of the box through the ground.

Clearly oversize trimming beads increase overcut around the box sides, and/or roof, with the potential for increased settlement.

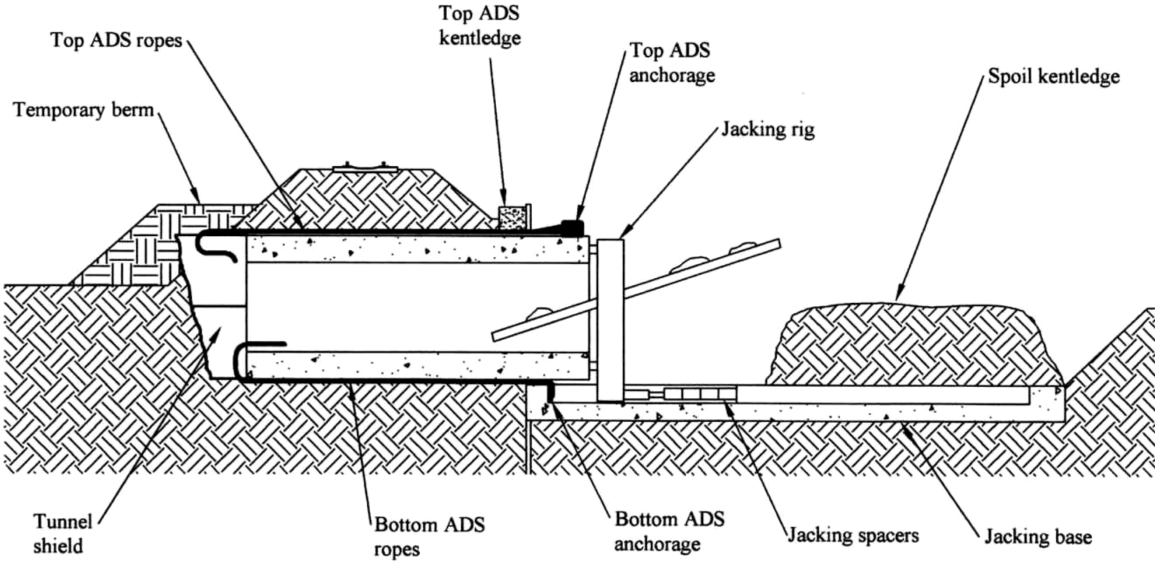

Figure 4. Top and bottom anti-drag system [ADS]

Lubrication

Friction and drag effects are minimised by adequately greasing the ADS ropes with a good quality grease during their installation, and regularly greasing them during the actual jacking process through arrays of grease injection holes and spreader channels cast into the extrados surfaces of the box.

Sidewall drag effects can be minimised by injecting bentonite slurry through the shield's sidewalls immediately behind the trimming beads. Additional lubrication can also be injected through the box side walls.

EXAMPLES OF JACKED BOX TUNNEL INSTALLATIONS

Didcot, Berkshire

Project

To construct a pedestrian/cyclist tunnel 5.9m wide, 3.6m high through a 5m high railway embankment carrying a four track main line railway. Ground conditions comprise 0.6m of track ballast and track formation overlying a loosely compacted siltstone fill founded on natural ground of soft to firm clay. The ground water table is situated just below the proposed tunnel invert level.

Sensitivities

- railway closure not permitted
- during tunnelling temporarily reduced line speeds of 40mph and 20mph to be maintained on Inter City main line and local tracks respectively
- ducted trackside signalling and communication cables to remain undisturbed
- movement joints not permitted in the tunnel as these could present long term maintenance problems, and
- residential properties close by.

Particular hazards

- insufficient ground information
- uncontrolled ground loss in the tunnel face
- excessive drag induced ground movement
- excessive ground movements associated with construction of tunnel portal works
- damage to, or failure of, the ducted trackside signalling and communication cables, and
- unauthorised intrusion of plant and personnel on the operational railway.

The solution

To jack a monolithic box 5.9m wide, 3.6m high by 30m long through the railway embankment 1.7m below the railway sleepers, see Figure 5. Additional site investigation comprised a radar survey of the railway embankment and in-situ strength tests of ground exposed in trial pits excavated each side of the railway tracks.

The box was constructed on a jacking base inside a sheet piled jacking pit with the headwall located in the embankment side slope. A sheet piled reception pit was constructed in the other side slope. Careful positioning and design of the headwall and reception pit strutting and supports facilitated an efficient and timely passage of the tunnelling shield both into and out of the embankment.

Figure 5. Subway box half way into embankment

A purpose designed steel cellular shield, with three compartments on two levels, was rigidly attached to the leading end of the box. The shield was designed to be thrust into the face to ensure face stability whilst permitting safe working access for miners to carry out the excavation. Didcot was the first application of the proprietary wire rope ADS. This comprised 13mm diameter wire ropes placed at 26mm centres across the full width of the box roof.

A single 1200 tonne working capacity jacking rig was used to develop the required jacking thrust which was dissipated into the soft to firm clay ground via adhesion on the underside of the jacking base, and shear/adhesion on the jacking pit side walls.

Performance achieved

Once the jacking pit headwall had been entered the tunnelling operation took 5 days to complete without distress to the railway or interference to its operations. Ground movements were so well controlled that it was found necessary to fettle the tracks only twice in order to maintain the rails within operational tolerances for the reduced line speeds. The maximum recorded aggregate ground settlement was 75mm and maximum recorded aggregate horizontal displacement of the ground in the direction of jacking was 25mm. The monolithic box resulted in a simple tunnelling operation and a tunnel alignment within 25mm of line and 55mm of level.

Silver Street Railway Station, London

Project

To construct a 44m long section of vehicular underpass beneath the platforms and railway tracks of Silver Street railway station in Edmonton, north London comprising two boxes placed side by side each 12.5m wide and 10.5m high. Ground conditions comprise made ground overlying water bearing gravel, which in turn overlies London Clay beneath which there is a layer of water bearing sand. The ground water table is situated just above the top of the proposed underpass.

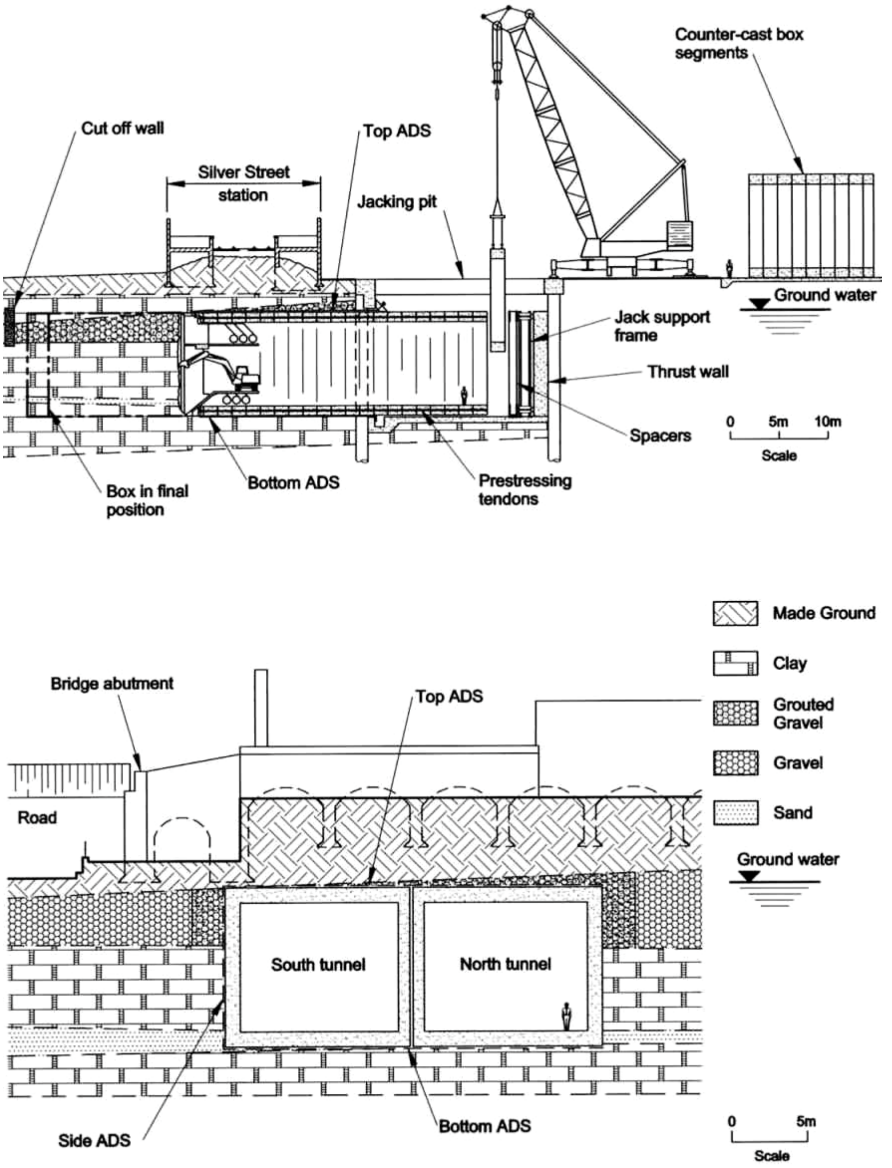

Figure 6. Vehicular tunnels, Silver Street Station, London

Sensitivities

- railway tracks and station to remain fully operational at all times
- integrity of station structures to be maintained and maximum cumulative settlement limited to 75mm
- signalling, communication and power cables mounted on the station structures to be safeguarded
- adjacent abutment supporting railway bridge over busy main road to remain undisturbed, and
- restricted working space, access and noise limits due to close proximity of main road / residential properties.

Particular hazards

- very difficult ground and groundwater conditions
- uncontrolled ground loss in the tunnel face
- excessive drag induced ground movement
- excessive ground movements associated with construction of jacking pit
- damage to station structures and adjacent bridge, and
- damage to, or failure of the signalling, communication and power cables.

The solution

Because of the limited working space it was not possible to construct a large jacking pit capable of containing the tunnel boxes required. Instead a relatively small jacking pit was used and the boxes were constructed at ground level as a series of 1.5m long counter-cast interlocking segments, see Figure 6. These were individually lifted into the jacking pit, see Figures 7 and 8, mated and stressed together using longitudinal tendons. Each tunnel comprised 30 segments each weighing 160 tonnes.

Prior to tunnelling the water bearing gravel was stabilised by constructing a jet grout cut-off curtain around the perimeter of the proposed tunnels and then fully grouted using the tube-a-manchette system. Horizontal pressure relief drains were installed to relieve artesian water pressure in the sand layer.

Figure 7. Tunnel segments at ground level in constricted site

Two purpose designed reinforced concrete cellular shields were constructed in the jacking pit and subsequently mated with the tunnel segments. Vertical thrust walls were incorporated at the rear of the jacking pit to receive thrust from the jacks arranged in groups at each corner of the box. Jacking thrust from each group was adjustable to provide the vertical and horizontal steerage necessary in the early stages of tunnelling when the length of box being jacked was short.

Figure 8. Lifting tunnel segment into jacking pit with railway station and bridge in background

The north tunnel was installed first followed by the south tunnel. The south tunnel was jacked sideways off the north tunnel during its installation in order to maintain adequate support to the ground underlying the adjacent bridge abutment. Proprietary wire rope ADS were used at the top and bottom of both tunnels and on the side of the south tunnel adjacent to the bridge abutment. On completion of each tunnel the face was boarded, the top ADS ropes were pulled out for re-use elsewhere and the longitudinal tendons fully stressed.

Performance achieved

Once the difficult operation of shield entry through the jacking pit headwall had been achieved each tunnel took approximately 4 weeks to install with a maximum jacking thrust of 5,500 tonnes. In spite of the need for careful steerage in the early stages of tunnelling, both boxes were installed to a positional accuracy within 25mm on both line and level.

As the railway tracks carried a temporary speed restriction of 20mph during tunnelling it was only necessary to fettle the tracks on the completion of each tunnel.

The maximum aggregate settlement of the ground and overlying structures arising from the installation of both tunnels was within the 75mm maximum specified. As the settlement curve was extremely shallow the very small gradients induced were easily accommodated by the brickwork structures. It was only necessary to re-lay the platform copings and surfacing in the settlement zone.

M1 Motorway, Junction 15A, Northamptonshire

Project

To enhance the capacity of junction 15A by constructing a vehicular underpass 14m wide, 8.5m high by 45m long alongside the existing A43 underpass. Existing roundabouts at both ends of the A43 underpass were required to be remodelled to handle traffic flows from the new underpass and to provide dedicated accesses to future industrial developments.

Existing road levels, gradients and underpass dimensions dictated a minimum clearance of 1.6m between the vehicular underpass roof and the motorway running surface.

Ground conditions through the motorway embankment comprise 0.8m of road construction overlying 3.5m of compacted pulverised fuel ash, which in turn overlies 1.7m of engineered clay fill founded on boulder clay. The ground water table is approximately 1.5m beneath the underpass structure.

Sensitivities

- motorway used by 112,000 drivers each day
- major motorway intersection
- adjacent to an existing underpass
- close proximity to the Grand Union Canal, streams, industrial estate and motorway service areas located on both sides of the motorway
- stringent settlement criteria based on trigger levels, which if exceeded, could lead to the cessation of construction works, closure of those sections of the motorway affected and resurfacing, and
- scaled lane rental costs for the closure of one or more lanes, commencing at £1,000 per hour, per direction, per lane increasing to £20,000 per hour (£240,000 per day), per direction, for the closure of one carriageway.

Particular hazards

- insufficient ground information, in particular the degree of cementing of the pulverised fuel ash
- uncontrolled ground loss in the tunnel face
- uncontrolled heave of ground ahead of advancing shield
- excessive drag induced ground movement
- excessive ground movements associated with construction of tunnel portal works
- damage to existing A43 underpass structure, and
- damage to motorway drainage system with possible water ingress into the advancing tunnel face.

The solution

To jack a monolithic box 14m wide, 8.5m high by 45m long under the motorway from a steel sheet piled jacking pit, with integral jacking base. Figure 9 shows the box partially installed. Special provision was made at the jacking pit headwall to facilitate an efficient and timely entry into the embankment. The reception works comprised steel sheet piled wing walls with a clay bund to buttress the embankment during shield breakthrough.

Immediately following contract award a number of slit trenches were machine excavated in the embankment side slopes to investigate the short-and long-term strength and stability of the pulverised fuel ash and engineered clay fill, and to observe the integrity of the interfaces. One trench remained open for six months without showing signs of instability.

An open-face cellular reinforced concrete shield divided into three working levels, each with seven compartments, was designed to support the face, see Figure 10.

Key aspects of the shield design were:

- the top-level compartments were designed for hand excavation and the lower and middle level compartments for machine excavation, with an option of hand excavating inside the middle level compartments should the need arise
- the top and middle level decks were conveniently positioned at the pulverised fuel ash/engineered clay and engineered clay/boulder clay interfaces respectively, and
- each of the top and middle level compartments were equipped with face rams designed to support face timbering and automatically pressure-relieve as the box advanced.

Figure 9. Partially installed underpass box

Top and bottom anti-drag systems were used comprising 13mm diameter ropes. The top ropes were spaced at 26mm centres across the box roof and the bottom ropes were laid touching in two distinct rope tracks, each 3.5m wide. Friction loading developed in the top anti-drag system was transmitted into the rear of the jacking base using a compensation jacking system. During box installation two direct-reading reflex geodometers, mounted on towers, one each side of the motorway, continuously monitored settlement points on a 5m square grid established across both carriageways covering the predicted settlement zone. Results were presented in three-dimensional and graphical format on a real time basis.

Prior to tunnelling a 25mm maximum thickness settlement "hump" was laid on both carriageways of the motorway to mirror the surface settlement profile allowed by the settlement criteria.

Figure 10. Cellular shield with steel plated cutting edges exposed at end of tunnelling

Performance achieved

Box installation through the jacking pit headwall, under the motorway and into the reception pit took 4 weeks, working 24 hours per day, 7 days per week. Maximum progress was 2.7m in 24 hours and the maximum jacking thrust used was 4,200 tonnes.

During box installation, face excavation and box advance were carefully controlled in response to the settlement monitoring results. This, together with the use of top and bottom anti-drag systems, resulted in a maximum recorded settlement of just 26mm. As a result additional surfacing was not required. Figure 11 shows the underpass in use.

Figure 11. Underpass in use

Snow Hill Station, Birmingham

Preparations are being made to construct and jack a monolithic subway box 5.10m wide, 3.85m high by 12.065m long under the main lines and associated platform structures at Snow Hill Station. The subway will provide a secondary station access, improve passenger facilities, provide a link to a proposed coach station and ultimately the new Metro Station in an inner-city area undergoing redevelopment.

Station structure configuration and space constraints have dictated a unique solution to box installation, necessitating the box to be constructed and fitted out on a casting base constructed in an adjacent car park. The box will then be pulled on a 20m long slide path through a brick arch structure leading to a purpose designed jacking base, and entered into the ground through a 0.8m thick brick headwall in a controlled sequence.

Ground conditions under the tracks and platforms comprise fill material consisting principally of medium dense fine to medium sand with many angular fine to medium gravel sized weakly cemented sandstone lithorelics. Ground water is some distance below the proposed box invert level.

The steel cellular shield, used on the Didcot pedestrian/cyclist tunnel, has been resized for the Snow Hill box and will be used in conjunction with top and bottom wire rope ADSs. Because of the sensitive nature of the station structure, built circa 1852, the jacking base will be isolated from the adjacent structures and a series of ground anchors will transmit the jacking force into the underlying ground.

Box installation will be undertaken on a round the clock basis. Rail tracks and platform copings will be monitored using a combination of electro-levels and precise levelling, and fettling will be undertaken according to a schedule of predetermined trigger levels.

SELECTING, DEVELOPING AND EXECUTING A JACKED BOX TUNNEL SOLUTION

The jacked box tunnelling technique described above is a specialised field of work based on a proprietary system for controlling ground drag. It competes with other forms of construction which may be more familiar to engineers in general but which result in greater disruption of overlying infrastructure. Selecting, developing and executing a jacked box tunnel solution requires a client to engage the services of a jacked box tunnel engineer and a jacked box tunnel contractor.

Selection

The selection of a jacked box tunnel solution is likely to be the result of a comparative study of alternative solutions carried out by a client, or by a consulting engineer acting on his behalf. To facilitate the study, the client, or his consultant, will engage the services of an experienced jacked box tunnel engineer for advice on feasibility and budget cost for a potential jacked box tunnel solution.

Ideally the jacked box tunnel engineer should visit the site with the client to fully understand and appreciate the client's requirements. The jacked box tunnel engineer will then examine and assess all ground, archive, infrastructure and topographical information available and, based on his highly specialised knowledge of geology, soil mechanics, structures, tunnelling, etc, make a judgement as to whether a jacked box tunnel is feasible and the manner in which it should be undertaken.

His assessment will typically consider:

- the box application, its dimensions and ground cover
- the strength and stability characteristics of the ground
- the ground water regime
- site access routes and the most suitable position for the jacking base
- topography and infrastructure, including condition surveys
- whether the strength and stability of the ground need to be improved by adopting a geotechnical process such as dewatering, grouting or freezing, and how will this affect overlying infrastructure
- whether face support will be required and suitable methods for excavating the face
- whether anti-drag measures will be required and how these forces are to be dissipated
- anticipated jacking loads and how they are to be transmitted through the jacking base, and
- the magnitude of any ground movements and their influences on overlying infrastructure.

If a jacked box tunnel solution is considered feasible and the budget cost is of interest the client will request development of the solution supported by detailed geotechnical input.

Development

The jacked box tunnel engineer requires geotechnical input in order to predict the behaviour of the ground and to design both the tunnelling system and the permanent works. This normally requires the specification of a detailed site investigation, its execution and subsequent interpretation to provide the following information:

- soil types and their elevations
- in-situ densities
- permeabilities
- short-term (undrained) strength parameters for design of the tunnelling system
- long term (drained) strength parameters for design of the permanent works
- the elevation(s) of any ground water table(s), and
- the nature and extent of any buried obstructions.

With regard to the tunnelling system the main aspects of design in which geotechnical input is required are as follows:

- tunnel shield and method of face excavation
- estimate of jacking thrust required to advance the shield and box through the ground
- top ADS and bottom ADS
- provision of reaction to the jacking thrust from a stable mass of adjacent ground, and
- soil movements induced by tunnelling.

The above information enables the jacked box tunnel engineer to prepare conceptual drawings, outline method statements and a schedule of quantities. These are then reviewed jointly with the jacked box tunnel contractor who is then able to prepare an accurate budget for the works.

If the scheme proposals and budget meet with the client's approval, the next stage is for the client to enter into a contract with the jacked box tunnelling contractor for the detailed design and construction of the works.

Execution

The jacked box tunnel contractor, with assistance from the jacked box tunnel engineer, will prepare detailed designs, construction drawings, specifications, method statements and programmes for the works. He will obtain all necessary approvals to these documents and proceed to construct the works on site accordingly.

SUMMARY

The authors have presented a highly effective and well proven technique for creating underground space beneath existing infrastructure. Experience has shown that the technique results in significantly reduced quantities of materials being removed from and brought to the site as compared with surface down construction, thus reducing environmental intrusion.

The full range of projects constructed using this technique is given in Table 1. Most of the projects are located in cities and all have avoided disruption and minimised environmental intrusion. Many of these projects have been undertaken in very difficult ground conditions necessitating sophisticated geotechnical ground stabilisation measures, including grouting, ground water lowering and artificial ground freezing.

Certain clients, in particular railway authorities and more recently highway authorities, have appreciated the significant cost benefits of reduced disruption to surface infrastructure and services.

The Silver Street station project proved that large boxes can be installed under buildings as well as under railway tracks and highway pavements. The authors envisage open space being created under existing buildings for car parking, access and storage. Where a building is particularly sensitive to movement, compensation jacking could be employed in the building foundations to maintain the building location precisely.

As the technique becomes more widely understood and appreciated, the authors anticipate that it will become a routine solution to the creation of shallow depth underground space in cities for a wide variety of purposes, particularly where valuable surface infrastructure cannot be disturbed and environmental intrusion is required to be minimised.

Table 1. Jacked box tunnel projects

Projects	Size	Cover	Date	Ground Conditions	Ground Treatment
Pedestrian and cyclist subway Didcot, Oxfordshire, UK	30m long 5.9m wide 3.6m high	1.7m	1989	Silt-stone fill overlying soft clay	None
Highway tunnels West Thurrock, Essex, UK	30m long 16.5m wide 9.5m high	8.0m	1991	Chalk with swallow holes loosely filled with sand	None
Highway underbridge Silver Street Station, London, UK	Twin tunnels each 44m long 12.5m wide 10.5m high	7.0m	1995	Water-bearing gravels above over-consolidated clay containing sand layer with water under artesian pressure	Grouting of water bearing gravels. Dewatering of sand layer
Rail tunnel Lewisham Railway Station, London, UK	48.0m long 17.0m wide 6.2m high	1.7m	1998	Loose silt and sand overlying soft clay	None
3 No subways Lewisham Railway Station, London, UK	Up to 32.0m long 4.4m wide 3.65m high	2.0m	1998	Loose silt and sand overlying soft clay	None
Flood relief culvert Dorney, Berkshire, UK	50.0m long 23.0m wide 9.5m high	6.0m	1999	Clayey granular fill overlying water bearing sands and gravels, overlying weathered chalk.	Artificial ground freezing
3 No highway tunnels Boston, Massachusetts, USA	Up to 106.8m long 24.0m wide 10.8m high	6.0m	2001	Weak water bearing strata with numerous man-made structures, tidally influenced water table	Artificial ground freezing
Highway underbridge M1 Junction 15A, Northamptonshire, UK	45.0m long 14.0m wide 8.5m high	1.6m	2002	Pulverised fuel ash and clay fill overlying stiff clay with rock inclusions	None

Acknowledgements: The authors wish to acknowledge the assistance and encouragement offered by both Edmund Nuttall Limited and John Ropkins Limited in the preparation of this paper.

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