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Jacked tunnels

open-heart surgery on Boston

Boston's Central Artery project moved major roads underground without disrupting nearby railways. By bringing tunnel jacking to the project, British civil engineers facilitated open-heart surgery on the city.

One of the legacies from the development of transport infrastructure, particularly during the latter half of the 20th century, is the elevated urban motorway. With high traffic volumes they now bring noise, pollution and disruption, blighting many of the world's major cities. The Central Artery (C/AT) in Boston, Massachusetts, built in the 1950s, is a prominent example of this problem – but salvation is at hand.

To ease some of the worst urban traffic congestion in the USA, the C/AT project involves putting much of the city's main highway network underground. Known locally as the 'Big Dig', *The Economist* (November 2003: 60) has described it as the single largest civil engineering project in American history. As a landmark in infrastructure redevelopment, it is scheduled for full completion in 2005. With many of the new sections now operational it is already revitalising the city and creating a more sustainable future for its citizens.

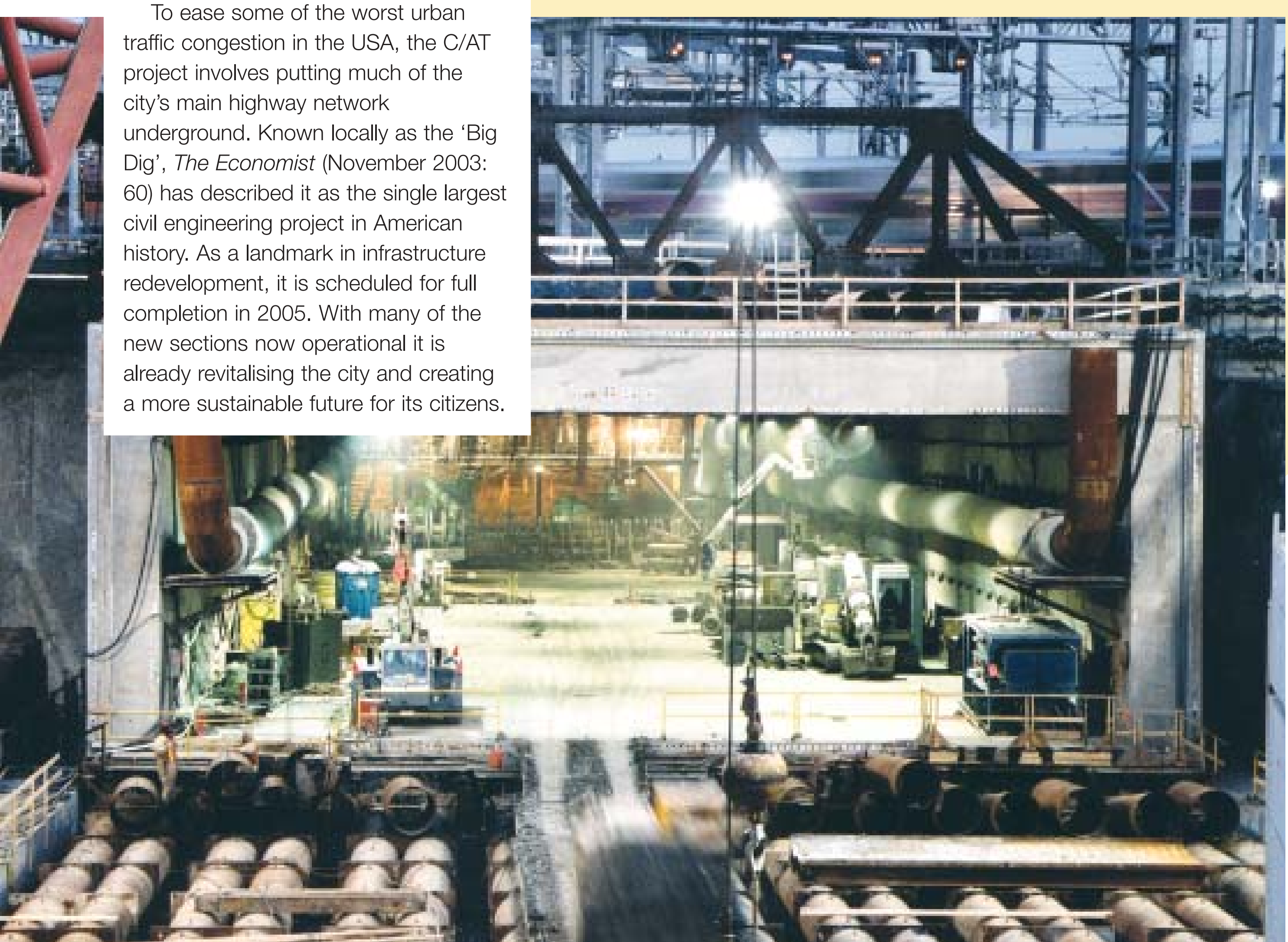

Figure 1 Boston Central Artery: General layout showing I-93 passing north/south through Boston and extension of I-90 eastwards to Logan airport

It was essential to avoid delay to the project and to minimise disruption during construction. A novel approach using a technique known as tunnel jacking brought huge benefits to these issues. The solution led to the largest, most complex project of its kind in the world.

The project involved major innovation, introduced by British engineers, requiring a breakthrough in scale that was well over ten times the size of any jacked tunnels attempted in the USA before. The tunnel jacking, which was recognised as the most challenging component of Boston's C/AT project, has delivered a low maintenance, robust construction while adding substantial environmental advantages and contributed to over US$300 million in construction savings (see reference 1). Taking the scheme from initial concept to reality required over a decade of sustained development and close teamwork.

The project

A key part of the Big Dig was creating the new I-90/I-93 interstate interchange (Figure 1). This required constructing multi-lane highway tunnels under the approach to Boston's South Station involving a complex network of seven interconnecting rail tracks that carries over 40,000 commuters and 400 train movements per day.

The original design concept involved sequential phases of cut-and-cover construction. This is a traditional technique that was used, for example, to build the first tunnels of the London underground system along Fleet Street. However, this is a very intrusive process that particularly affects surface facilities requiring excavation in trenches directly above the line of the tunnels so that they may be constructed in place and then covered over. For Boston, the very limited surface space at the site would have required five relocations of the railway – an approach that was unacceptable to the railway authorities.

Apart from moving the tracks, each phase would have involved re-establishing the extensive control systems that included sensitive buried fibre optics. It would have also meant building the tunnels in short lengths, working in a series of deep confined trenches between the temporarily relocated rail tracks for each phase. All this would have been very time consuming and a major safety issue.

Tunnel jacking provided a radical alternative (Figure 2). Its underlying concept was dramatically simple: instead of moving the railway, move the structures. The proposal was for the sections of interstate highway tunnels required beneath the railway to be initially constructed beside it and then jacked into position. Success would mean no track relocations, train speed restrictions or interruptions to the service. In practice, this was fully achieved, including an enhanced service for the railway and an excellent safety record.

Figure 2 I-90 Eastbound jacked tunnel

Figure 3 Site looking eastwards towards Logan International airport. The last unit of the I-90 jacked tunnel can be seen in the thrust pit on the lower right

The challenges

The site is located at the intersection of the I-90 and I-93 interstate highways. This is the most complex contract in the entire Central Artery Project and presented severe spatial and operational constraints. The space for construction was limited to an area bound by the interstate highways, the railway system and the Fort Point Channel (Figures 3 and 4). The area available, measuring some 300 by 700 metres, may seem sizeable but it was actually very restricting for the scale of the works involved and the prime need not to affect the operation of the railway.

Tunnel jacking significantly eased limitations as the railway no longer needed phased relocation. The space available was still considerably less than ideal, since there was not enough room to construct all of the tunnel units in the thrust pits before the jacking began. This was solved by the unique use of a combined thrust pit and ground freezing (Figures 4 and 5).

Apart from the issues at the surface, the ground beneath the railway added an extra dimension to the overall challenge with a complex array of very difficult conditions. The ground comprised two centuries of land reclamation with uncontrolled fill overlying soft compressible clay strata littered with abandoned artefacts, which became major obstacles during the tunnelling works. These included old seawalls and masonry foundations, reinforced concrete, a buried railroad and forests of timber piles.

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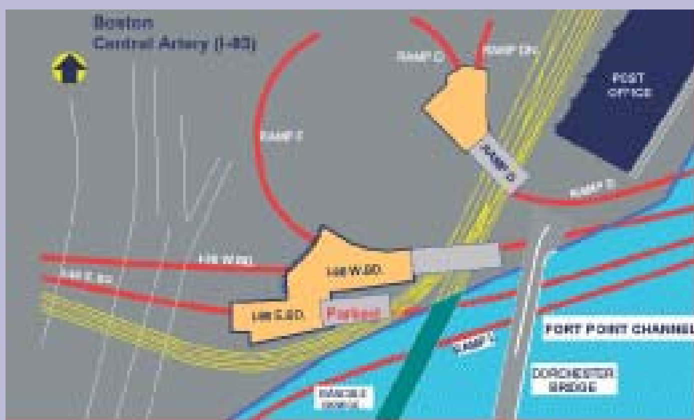

Figure 4 Layout of the three jacked tunnels – stage with Ramp D and I-90 Westbound complete prior to casting remainder of I-90 Eastbound in thrust pit (the first two sections were 'parked' during construction of I-90 Westbound tunnel)

Figure 5 Ground freezing under railway

Tunnel jacking

Jacked tunnels, particularly the longer ones, are typically constructed in several units. These tunnel elements are linked together by intermediate jacking stations and the tunnel is installed through a 'caterpillar' action (Figure 6). This helps to minimise the overall jacking force since it is then only dependent on the maximum required to move the units individually. The units are cast on a thrust base that, apart from being able to withstand the jacking forces, must be constructed to high tolerance since it controls the initial alignment of the tunnel.

A shield supports the face of the excavation at the front of the tunnel. In soft ground, the shield is divided into a series of small compartments across the face and the leading edges of the shield are generally left embedded in the soil to ensure its adequate support. Excavation progressed in each compartment using hand tools or small machines.

All units for a jacked tunnel are usually cast and aligned together on the thrust base prior to jacking. Once started, jacking continues until the whole tunnel has reached its final position. This avoids the risk of ground pressure build-up around a stationary tunnel during an extended interruption in jacking, which could lock the tunnel in place. However, for Boston even the combined thrust pit could not accommodate simultaneously all six units of the I-90 westbound and eastbound tunnels.

The first solution to address this constraint was to utilise the whole combined thrust pit to cast the I-90 eastbound tunnel units, sliding the last unit across from the westbound to the eastbound side to maintain continuity of jacking. The downside would be a substantial delay to the westbound jacked tunnel as it could not commence until its area of the combined thrust pit was cleared of the last eastbound unit. Ground freezing (noted further) brought an extra benefit to this issue, allowing simultaneous construction of both the I-90 jacked tunnels.

Innovation

The proposed alternative required three huge tunnels – totalling over 240 metres in length and weighing 70,000 tonnes – to be jacked under the fully operating railway.

The thrust pits, within which the jacked tunnel units were constructed, are some of the largest ground support structures ever attempted in the USA and used techniques and geometries, which were truly state-of-the-art worldwide. These pits needed to be up to 25 metres deep with minimal lateral support because of the need to move the tunnels through them. They utilised either single high level temporary steel struts or, where strutting was not practicable because of the complex geometry, had walls designed with enough stiffness to cantilever the full height of the pit. This can be seen in Figure 3 where there are no struts above the I-90 eastbound tunnel unit.

As well as the huge leap in scale, the tunnel jacking scheme included many other innovations. Prominent among these was the global ground freezing beneath the railway and the development of a special anti-drag system. The ground freezing – the largest ever undertaken beneath an operating railway – converted the potentially unstable strata into a stable mass (Figures 6 and 8). It provided a safer and easier process for removing normally onerous obstructions, such as

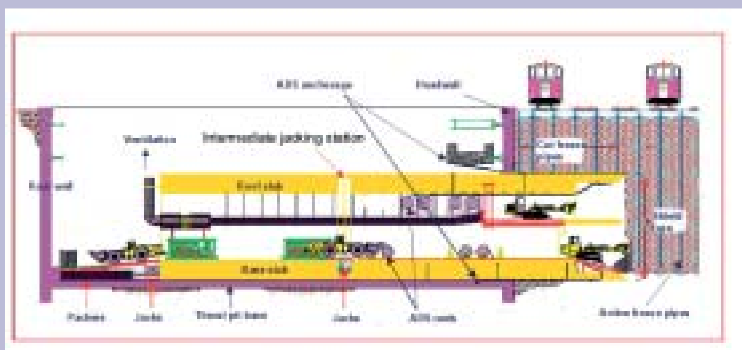

Figure 6 Jacked tunnel – long section showing overall system

Figure 7 Antidrag system (ADS): upper level of tunnel shield (indicated) showing anti-drag ropes just behind roof exit slots

timber piles, because they were now frozen and locked into position.

The frozen ground greatly simplified the entry of the tunnels through the headwalls of the thrust pits. This is a critical phase in the overall process as a large hole has to be cut through the headwall of the thrust pit so that the shield at the front of the leading unit of each tunnel can pass through and support the ground. This ground also supports the infrastructure above (in this case the railway), so entry is undertaken progressively, usually with a horizontally inclined headwall. The stability of the frozen ground avoided this complication. Instead, the headwalls were efficiently aligned at right angles to the direction of jacking and the complete hole cut in one stage.

The permeable deposits above the clay would have also created the hazard of seepage from contaminated groundwater. Ground freezing effectively eliminated this, along with the need for constant handwork at the tunnel face, thus creating a much safer and agreeable working environment. However, despite all of these attractive benefits, ground freezing was not initially accepted. There were concerns regarding the scale and, understandably, the potential for large ground heave from such an extensive application. Although ground freezing was the designer's preferred option, it was rejected during the design phase in favour of more conventional methods of ground stabilisation such as soil reinforcement and grouting. It was re-introduced as part of a 'value engineering change' proposal early in the construction contract.

Ground freezing also created the opportunity to temporarily 'park' the first two units of the I-90 eastbound jacked tunnel beneath the railway. This innovation was the final part of the solution to overcome the site's space constraints (Figure 4). The stability created by ground freezing and the precautionary provision of local heating elements around and within the tunnel walls eliminated the risk of the ground locking on to the tunnel during a long interval in jacking so that the partially installed tunnel units could be left in position. It was therefore no longer necessary to cast the eastbound units at one time, avoiding the clash with the westbound tunnel. Concurrent construction of the westbound and eastbound jacked tunnels could then take place in the combined thrust pit.

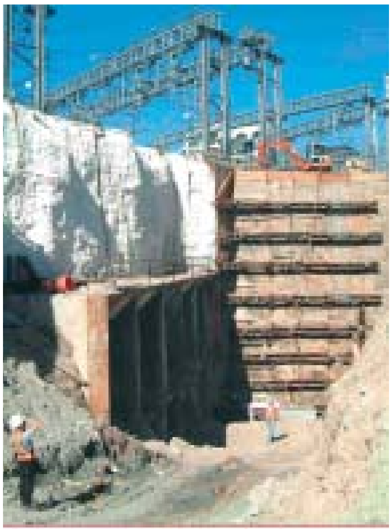

Figure 8 I-90 Westbound tunnel breakthrough on east side of railway. Jacked tunnel shield shown emerging below world's largest man-made iceberg

The ground stability meant that much larger compartments could be used for the shield without requiring the front of it to be buried to support the soil. In turn this allowed the use of large machines for excavation, substantially reducing the need for handworking at the face. This made it considerably easier and safer to deal with the many obstructions.

A bespoke anti-drag system (ADS) utilised nearly a thousand steel ropes on the roof of each tunnel (Figures 6 and 7). The key role of the ADS is to decouple the tunnels from the ground and infrastructure above. This prevents the ground from moving with the tunnel as it is jacked forward.

The ADS is the most extensive ever used and also provides improved alignment control with additional sets of steel ropes beneath the tunnels. Drums in the roof and floor of the jacked tunnels held the ADS ropes, which unwound as the tunnels moved forward. Trains safely moved uninterrupted overhead as the tunnel sections were installed below the tracks at a rate of between one and two metres per day.

Teamwork

The comprehensive success of the tunnel jacking has been underpinned by close teamwork and mentoring, not only between the designers and constructors but also with the local and federal authorities, including those representing the railway and their consultants (see reference 1).

The designers, working closely with the Massachusetts Turnpike Authority and its management consultant, took tunnel jacking to a stage where it could be presented to the Federal Highways Administration – the principal funding authority for the entire project. This process of advocacy and concept development took 18 months.

With final approval secured, the designers developed the extensive level of detail required for the construction tender. After appointment of the contractors, the designers maintained this close collaboration with the contractors' team to continue the process of value-engineering and generating further savings.

The integrated approach brought additional confidence to the railway authorities and their consultants. A liaison committee was formed where all parties were represented and met weekly to review progress and manage any potential risk by closely monitoring the effect of the construction on the railway.

There were large ground movements – causing accumulative track displacements up to 300 mm both vertically and horizontally. The major component of these movements arose from the heave from ground freezing. However, like the rest of the tunnelling process, it took place in phases each spread over many months. This was the key factor in addressing the issue of ground movements. Establishing a sequential basis provides enough time to track trends and to apply corrections progressively. Risks can then be managed safely. Although large accumulative movements affected the railway, they were generated over a timescale that allowed the ballasted tracks to be maintained within an acceptable tolerance. This benefit also applied to settlements during the thawing cycle.

The total heave movement, although greater than originally predicted, also proved acceptable. The railway authorities adopted a very mature attitude to these issues and were fully satisfied with the system adopted.

Benefits to the community

It is tempting to describe the Central Artery project as open-heart surgery for a city. It is certainly vital to keep the patient alive during the operation (see reference 2).

The project placed an additional burden on transport during construction, increasing the need for commuters to leave their cars at home and use public services. The tunnel jacking not only ensured continuous safe operation of the railway but also created an important extra benefit by allowing overhead electrification to proceed with tunnel construction, thus advancing a safer and more efficient railway service for commuters (Figures 3 and 8).

Compared to traditional cut-and-cover methods, tunnel jacking also considerably reduced excavation as the substantial volume of ground directly below the railway remained in place. This brought further environmental benefits by minimising transportation of heavily contaminated materials through a very congested city.

Recognition and success

The size, complexity and innovation of tunnel jacking has excited engineers, academia and the public worldwide. It has also heightened awareness of advances in construction and increased appreciation of how civil engineers maintain and improve the infrastructure so fundamental to our quality of life.

Winning many awards for engineering excellence and innovation, both in the UK and USA, the scheme's national and international prestige has led to strong client recognition of tunnel jacking and it is fitting for the client to have the last word. Anthony Caserta from the US Department of Transportation commented:

> The tunnel jacking operation … was by far the most complex and challenging design contract of the entire $15 billion Central Artery/Tunnel Project. It required the most innovative and 'out-of-the-box' thinking, in addition to specialized engineering teamwork, to provide a satisfactory and safe solution … without any risk or danger to the daily railroad commuter … It was a bold and challenging endeavor that has proven to be an engineering marvel. The quality and excellence of engineering is quite obvious as the project was delivered on schedule and budget with no major claims. ■

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Photo credits: www.bigdig.com: Figures 3 and 5

References

1 Powderham A. J., Howe C., Caserta A., Allenby D. and Ropkins J. (May 2004). Boston's massive jacked tunnels set new benchmark. In *Proceedings ICE, Civil Engineering,* vol. 157, issue 2, pp 70–78. London: Thomas Telford.

2 Wheeler, P. (May 1997). Boston's heart bypass. In *Ground Engineering*, vol. 30, no. 4, pp. 30–31. London: Emap.

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