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SESSION 1

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The Stockholm Urban Road Tunnels - An Overall Status Report

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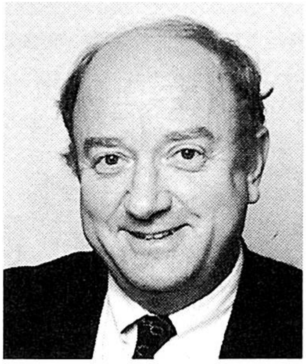

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Summary

The lack of peripheral connections in the Stockholm region has created congestion and environmental problems in the radial road network. With respect to environmental constraints, tunnels present the only possible alternative for creating new accessibility for motor vehicle traffic. This is further enhanced by the favourable geological conditions for rock tunnelling in the region. Two major urban road tunnel systems, Södra and Norra Länken (the Southern and Northern Links), are in different stages of implementation. Construction work for Södra Länken has started. As regards Norra Länken, the further work aims at concluding necessary legal decisions. The time for construction start-up will thereafter depend on political decisions and financing.

1. Tunnels as Solutions to Urban Problems

The layout of Metropolitan Stockholm resembles a star. The nucleus consists of Gamla Stan (the Old Town) situated on the island that made travel possible in a north-south direction across the water between Lake Mälaren and the Saltsjön Sea. The city arose at the cross-roads between the seafaring route and the land route. Until the 1930's when Västerbron (the bridge to the west) was constructed, the passage across Gamla Stan was the only route across the water by land. Essingeleden, with its expansive bridges, was constructed in the 1960's thirty years later.

Fig 1. The central parts of Stockholm

The lack of peripheral connection has created congestion and environmental problems in the radial street and road network. Over the years, many proposals for peripheral traffic routes at various distances away from the city centre have been presented and rejected. In 1992, a political agreement was signed concerning the implementation of a traffic solution which in part included an urban motorway ring road orbiting the heart of Stockholm as well as an outer by-pass route further to the west of the city. The objective of this traffic solution, which also included major investments in public transport, was to create a better environment, better accessibility within the road network and enhanced road traffic safety. This would also stimulate regional growth and development.

The landscape in the Metropolitan Stockholm area, with its deep rift valleys and watercourses, poses special difficulties as far as the design and construction of peripheral routes is concerned. There is also a compelling environmental attraction radiated by the star-shaped formation of the city accentuated by the sea inlets and wedges of green belts that link the core of the city with the surrounding landscape.

As a city, Stockholm has clear age rings. The Old Town from the Middle Ages stands basically intact on its island. The present-day stone city, which is clearly encompassed within the area defined by the former toll stations at the various city entrances, was formed during the intensive period of growth around the turn of this century.

There are two basic reasons why the stone city has not overflown beyond these city limits. The first is the existence of the royal parkgrounds to the north and north-east which prevented urban developmental schemed and which today present an invaluable green belt between the inner city area and the suburbs. The other reason is that the areas immediately to the south and south-east comprised the harbours and industrial land that constituted the city's vital trade and commerce. Now that this industrial use has ceased to exist, these areas present a great potential for new urban growth and development. In similarity to many other European cities, the main theme in Stockholm's new overall city plans is "Build inwards".

Construction major traffic routes across these park areas situated immediately outside the heart of the inner city is simply not possible. This would produce barriers and disruptions that would be totally unacceptable to Stockholmers. The average inhabitant of Stockholm today is environmentally aware and concerned about reducing the disturbance created by city traffic. Instead of being subjected to the impact of additional traffic routes, people want to reduce the effects of those already in existence. Under such circumstances, tunnels present the only possible alternative for creating new accessibility for car traffic. Stockholmers have already had positive experience with urban tunnels through Söderledstunneln (Southern Route Tunnel) and the effect it has on reducing traffic within the city street network and its role in linking the western and eastern parts of Södermalm.

In light of the foregoing, one prerequisite for being able to present a traffic solution including a motorway orbiting Stockholm was that the new parts of the Ring Road would be housed in tunnels. Of the total fourteen kilometres, a little more than twelve were to be in underground tunnels. A particular characteristic of the project is that the access and exit ramps are also situated below ground. It is a matter of a tunnel system that is integrated with the rest of the city's road and street infrastructure. Even if most of the road is housed in underground rock tunnels, certain works must be performed above ground. This applies to tunnel mouths, ventilation towers and the cut-and-cover concrete tunnel stretches that are built from the surface. Certain of these works are permanent while others are temporary during the actual construction period.

Tunnels are not an automatic, indisputable solution for roads in urban environments. This is a fact that the Ring Road Project has experienced in the planning and implementation process that has been going on since 1992 and in which the Swedish National Road Administration has been responsible for the road projects incorporated in the original political agreement.

Public debate has been heated. The review process has taken a long time and the original political agreement broke down in early 1997. At the end of 1997, a new political agreement was reached concerning the financing of Södra Länken. Construction work has already started on some parts.

As regards Norra Länken, the further work aims at concluding necessary legal decisions. The time for construction start-up will thereafter depend on political decisions and financing. Österleden has been excluded and the former road toll system has been cancelled.

2. The Stockholm Project - Different Types of Tunnels

The bedrock in Stockholm is highly suitable for tunnel construction. Major parts of the city infrastructure are today housed in excavated rock tunnels and caverns; e.g., the underground metro system, telecommunication cables, water reservoirs etc. It is therefore quite logical that the new road tunnels in Stockholm be located in rock tunnels, a solution that is both less expensive and which entails less encroachment on the natural environment during the construction period. The majority of both the main tunnels and the ramp tunnels will thus consist of blasted rock tunnels.

Extensive work has been spent on the special technical problems associated with road traffic tunnels in bedrock. Unlike tunnels used for certain other infrastructure purposes, road tunnels are affected by outside climatic conditions. During the winter season, for example, temperatures in the tunnels will fall far below the freezing point. This places requirements on dealing with water seepage to prevent ice formations. Furthermore, the location within the city also demands impermeable tunnels to prevent the ground-water table from sinking which would cause damage to the building foundations in the vicinity. The proximity to buildings and other tunnel systems places additional demands on particular care being take during blasting works.

As this particular conference focuses mainly on constructions in steel and concrete, this paper will offer only a few further comments on rock tunnels as a background for the function and design of concrete and steel constructions in the tunnel system at hand.

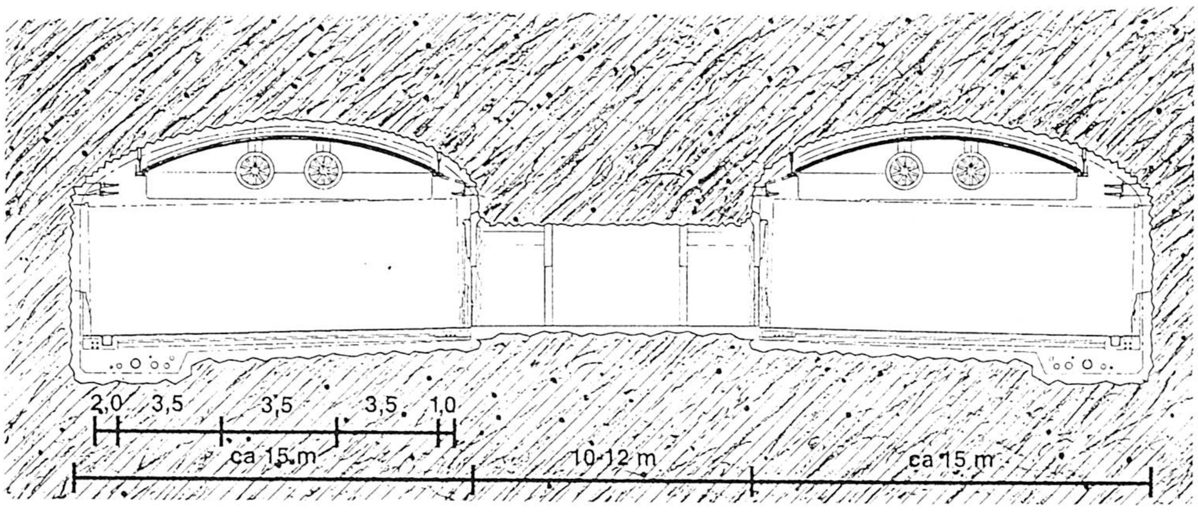

Fig. 2. The main tunnels are housed in two parallel tubes. This drawing illustrates a section where there are three carriageways in each tube as well as an emergency evacuation passage running between the two tubes.

Due to the favourable bedrock conditions in Stockholm, the requirements on dry tunnels demanded by ground water considerations can be met through careful grouting in connection with a drainage system when needed. Lining of the tunnels has therefore not been an issue. The purpose of the installations and other measures implemented in the blasted rock tunnel tubes is to create safe conditions in the tunnels for road-users. The inner ceilings prevent even minimal amounts of water seepage through the rock from dripping on the carriageway or forming overhanging icicles in the winter. The light-coloured ceiling also serves a visual guidance function for motorists as it shows how the tunnel moves horizontally and vertically ahead.

Along the tunnel walls, 1.6 metre high safety barriers will be installed. These function both as collision protection and as reflectors of the light from the ceiling fixtures due to the fact that they consist of material which is highly resistant to dirt-coating and which can easily and regularly be cleaned. The different colours used on these roadside barriers in various sections of the tunnel serve to provide driver orientation as well as information on the speed limit, etc.

The tunnel wall above the safety barriers will remain natural as far as possible. Drains that have been frost-insulated and covered with shotcrete will be installed on those parts where there can be water leakage.

The original Ring Road project included a submerged tunnel under the Saltsjön Sea to the east. As mentioned in the foregoing, this link has been eliminated in the current project layout.

The project in its current form incorporates concrete constructions in certain specific parts. This applies to most tunnel mouths ahead of where there is sufficient rock cover to blast a rock tunnel. There are also certain stretches where tunnels are constructed from above ground as the tunnel depth is shallow. These concrete sections are relatively short parts of the entire system. For the benefit of the road-user, the inner design of the concrete tunnels is therefore similar to that of the rock tunnels. The following presents examples of concrete constructions and the special conditions that apply in these cases.

3. Troughs and Concrete Tunnels

That which is shared in common between different sections with concrete tunnel accesses and mouths is the placement below the ground-water table. Measures must therefore be taken to safeguard these constructions against heave or flooding during construction period. The completed construction must also be sealed from ground-water leakage. Moreover, the proximity to existing buildings places great demands on maintaining the ground-water level to avoid the risk of settlement. Consequently, different techniques, including sheet piling and diaphragm walls, have been examined.

On Södra Länken there are extensive concrete constructions at Åbyvägen and Nynäsvägen for example. At Åbyvägen the concrete trough and concrete tunnel leading into the rock tunnel are being built in clay soils that are highly settlement-prone. An area almost 500 metres long and 50 metres wide will be delimited with steel sheet piling. In order to meet the requirements on maximum water penetration, grouting is needed between the foot of the sheet piling and the bedrock. Curtain grouting is also necessary in other parts of the rock. The sheet piling is braced with lime cement pillars. The excavation is situated extremely close to existing buildings - fourteen-story residential towers. The works on Åbyvägen are expected to be in progress during the four years between 1997 and 2001.

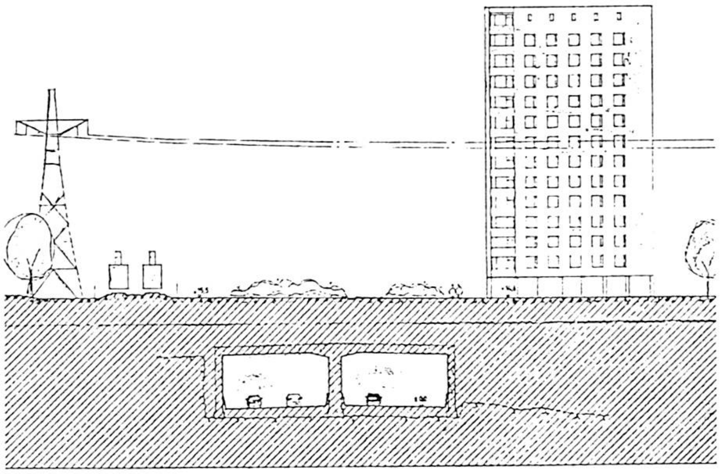

Fig. 3 Picture on Åbyvägen

The works on Nynäsvägen are also very close to existing buildings. In one particular case, the grouted sheet piling will be driven only three metres from a residential building. This area is composed of esker rock materials that are not settlement-prone as the clay at Åbyvägen. That which complicates the works at Nynäsvägen is the extremely narrowly confined construction site where there are over 90000 vehicles driving past per day. This places high demands on the work site organisation and means a prolonged construction period - about five years. In principle, works must be performed on one side at a time. There will be demands placed that the entire area be marked off by steel sheet piling that will subsequently remain in place.

Norra Länken affects a major park area in Stockholm that has been placed under the protection of a new law on a national heritage city park that was passed during the course of the planning and design work. The design of Norra Länken at Norrtull as specified in the city plan and in the enquiry tender documents has been interpreted by the Supreme Administrative Court to stand in conflict with the new law. This court decision was passed during the final negotiations on the contracts for the rock and concrete works. Construction had been planned to start in the beginning of 1997. Norra Länken consists of three city plans: Norrtull, Värtan and Frescati. Norrtull has been repudiated, Värtan has been approved and Frescati has not yet been processed.

The court decision has meant a postponement in the time schedule for Norra Länken. Different ways to reduce the encroachment from above ground have been examined.The present work aims at securing necessary legal permits. The time for construction start-up will thereafter be depending on political decisions on financing.

On Norra Länken, there will be concrete constructions both at Värtan and Norrtull for example. The conditions at Värtan resemble those at Åbyvägen. It is a former sea bed and the ground-water table lies immediately under the surface. There will be a twenty metre deep excavation here. The different sheet piling or diaphragm wall alternatives have been studied to provide the prior conditions necessary for the works.

Norrtull incorporates a longer concrete tunnel as well as an earth tunnel element. The concrete monoliths at Norrtull must be adapted to the adjacent constructions. Part of a new railway bridge will be founded on the tunnel. Provisions will be made between the tunnel tubes for driving foundation piles for future buildings above the tunnel. The main tunnels will run under a park area where old trees of natural and cultural value will be preserved. The excavation works here will not be carried out from the surface. The enquiry documents presented an example of a temporary tunnel support structure comprising drilled-in tubes that expand, after which excavations are done step-by-step in conjunction with the strengthening of the tunnel vault with a sprayed concrete construction. The permanent tunnel structure is then constructed under the protection of this provisional vault structure.

4. Technical Requirements

All the concrete tunnel constructions are procured as design and construct contracts; i.e., the contractor is required to present design proposals as well as assume total responsibility for the constructions. The Swedish National Road Administration performance specifications contained in the enquiry documents are based on general regulations in addition to special requirements and standards that have been drawn up for the project.

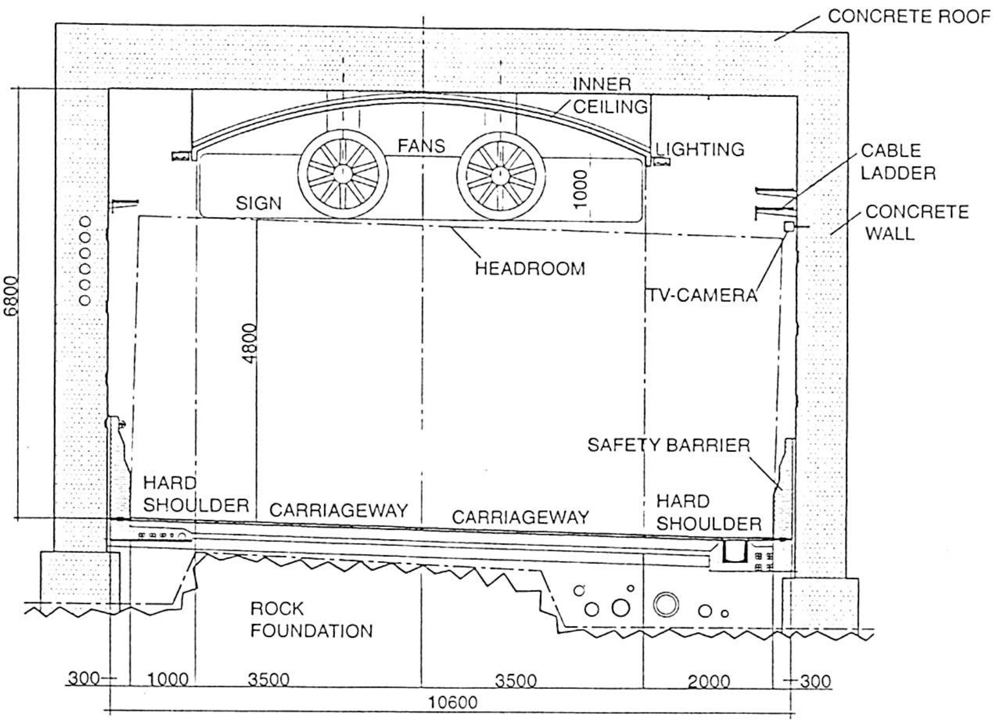

Fig. 4 Concrete Tunnel Section

In addition to requirements related to the ground-water table, there are requirements on the explosion capacity. Concrete tunnels must be able to withstand a detonation of 50 kilograms of explosives. The maximum permissible amount of explosives that can be transported without restrictions is 30 kilograms. Furthermore, the tunnels have been designed to withstand a fire with an intensity equal to 100 MW. A burning car has an intensity of about 3 MW. The tunnels will also be fire-proofed so that the temperature in the concrete surface will never exceed 450 degrees centigrade.

Since most concrete tunnel sections consistute short parts of a rock tunnel system, installations and fittings are adapted to the conditions in the rock tunnels; e.g., fire-proofed cables are placed in trench wells running underneath the tunnel floor. In longer concrete tunnels, electrical cables can be placed in the fire-proofed space between the two parallel tunnel tubes. In many cases where concrete tunnel constructions are the necessary alternative, the vertical height is so limited that there is no room for fans and signs in the normal tunnel tube. To solve the lack of space problem, recesses must be made to serve the purpose at hand.

Comprehensive studies have been conducted in reference to the Stockholm project concerning the subject of road traffic safety and the environment in tunnel systems. The general design concept in reference to these considerations also applies to the concrete tunnel sections. The false inner ceiling and lateral safety barriers are erected in the same way as in the rock tunnels. In confined sections where space is a problem, the inner ceiling is flat rather than curved. The concrete walls above the safety barriers are given a simple geometric pattern as a guidance assistance function for motorists.

5. Through Walls and Tunnel Mouths

As described in the foregoing examples, the construction of most tunnel mouths entails sinking the road into an uncovered concrete trough which leads into the mouth of the tunnel. From here the road continues through a concrete tunnel section until the point where the bedrock is sufficient for blasting a rock tunnel.

The walls in the open trough are sloped to create an impression of space and light. A 700 mm high lateral barrier in granite is erected immediately adjacent to the roadway. To prevent the high trough walls from giving an overbearing impression, they are broken up by landscaped terraces or by the odd touch of non-concrete materials worked into the concrete. The painting and staining of these materials is being considered. Full-scale tests are underway to ensure suitable methods.

Considering the space available, the tunnel mouths cannot normally be designed as large impressive archways; they must therefore be made distinctive through more restrained means. As part of the idea of uniformity, they will be designed with a distinctive frame which is given a surface of polished cement mosaic. Bearing in mind the urban location and the effort to create characteristic forms and transitions between the environment inside and outside the tunnels, there will not be any light screens outside the tunnel mouths. Special additional lighting in the tunnels near the mouths will be used to help the eye adapt to the change in light.

At Värtan, a special steel and glass construction will be built to limit the noise in the immediate neighbourhood.

6. Concrete Constructions inside the Tunnel System

Special types of concrete construction are the bridges and concrete structures built inside the tunnels. One such category is the bridges that must be built to accommodate the intersections between the road tunnels and other parts of the city's underground infrastructure. For example, on

Norra Länken bridge structures are needed where the Stockholm metro system cuts right through the system of main road and ramp tunnels. This is also the case where a telecommunications tunnel crosses Södra Länken necessitating special reinforcement measures.

Underground concrete constructions are also needed for building the substations, water and wastewater plants and the fan control centres.

7. Bridges Outside Tunnels

Bridges will be constructed outside the tunnels in connection with the interchanges included in the project. Two specific bridges deserve mentioning.

A bridge, at Sickla on Södra Länken, will replace an existing two-lane road bridge. The new one will consist of two parts, with three and four traffic lanes respectively. The bridge will be equipped with high glass noise shields to be able to combine it with the ambition of creating a new city suburb in close proximity to the road.

Sickla is the only part of Södra Länken that is not housed in a tunnel and great effort is being exerted to reduce its barrier effect. Ecoducts, which are 40 metre wide green passages for people and animals are being built over the road on each side of the Sickla Canal.

The one at Norrtull on Norra Länken is actually a railway bridge rather than a road bridge. When constructing the concrete tunnels, it will be necessary to demolish an existing bridge and replace it with one that will be designed with steel arches founded on concrete base slabs. A pedestrian and cycle path will be adjoined on the one side of this railway bridge through a system of cantilevers. This new railway bridge forms part of a new entrance into the centre of Stockholm.

8. Ventilation Towers in Steel and Glass

There are five ventilation towers in the Norra and Södra Länken projects. Their function is to discharge and disseminate the air in the tunnels to avoid high concentrations of air in the areas immediately outside the tunnel mouths. There will be a uniform ventilation tower construction based on the results of a design competition.

The towers will be constructed in glass mounted on a stainless steel framework. The structure is characterised by a minimum of materials, and it has been studied, for example, with respect to movements in the framework and how this is transferred to the glass panels. The ventilation towers will be between 25 and 40 metres high and have an interior diameter of five to six metres. In order to maintain good transparency, there will be an installation for automatically cleaning the inside surface.

9. Costs and Time Schedule

The total cost of Södra Länken is calculated to 6.5 GSEK. The time schedule means that most parts of Södra Länken will be opened for traffic in 2003 and the rest in 2004.

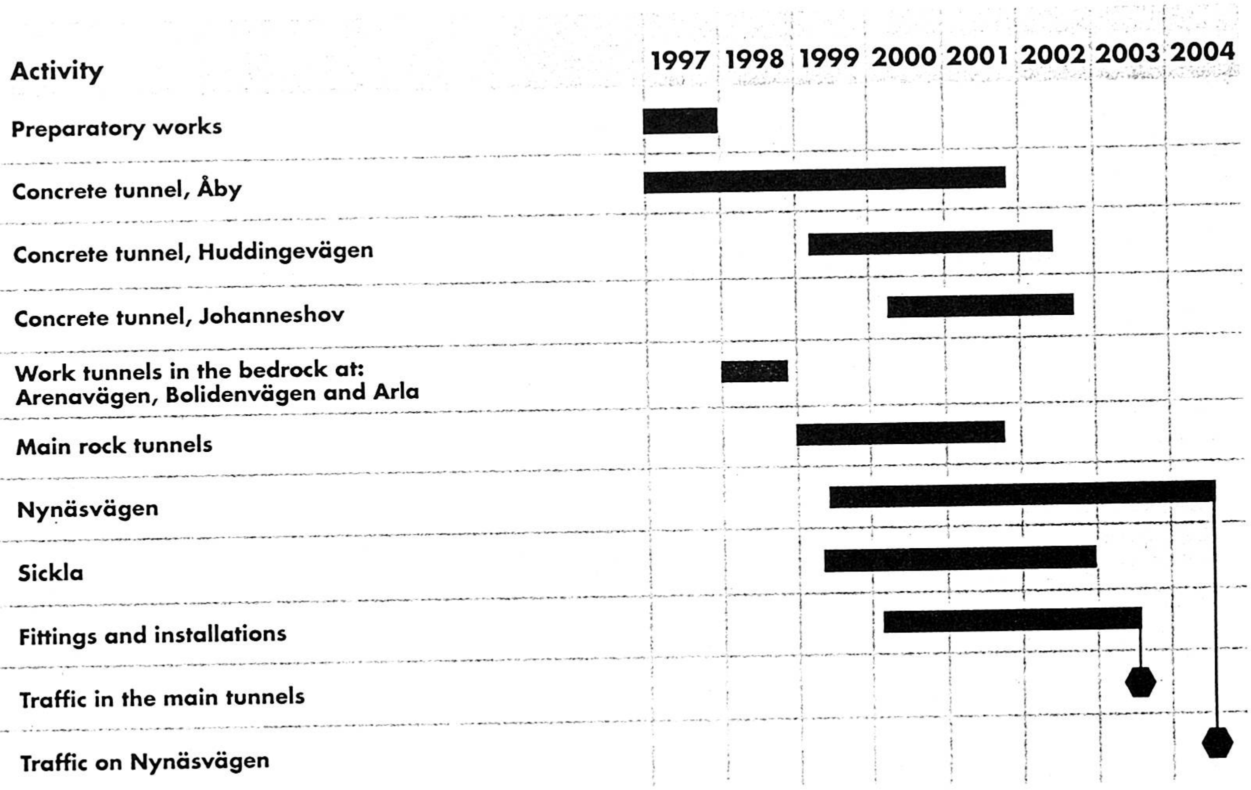

Fig.5 Time Schedule

Central Artery Project Technical Overview

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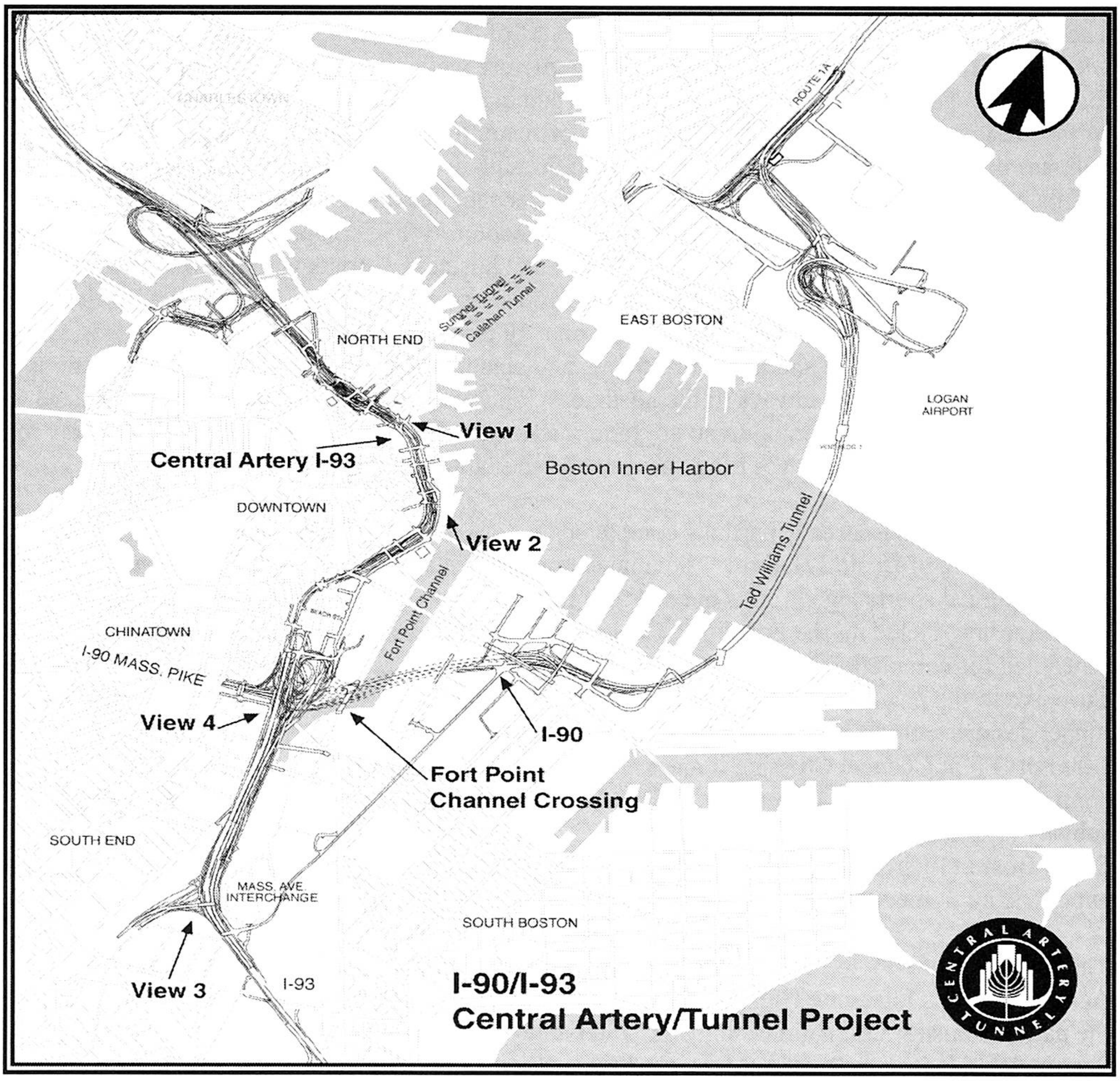
1.0 Project Overview



The Central Artery/Tunnel Project in Boston, Massachusetts, U.S.A. is one of the largest and most complex highway projects ever undertaken in the core of a major American City. The Project will reconstruct and place underground one of the oldest elements of the United States Interstate Highway System and construct the last remaining link of the Interstate System to Boston's Logan International Airport. The Interstate System, originally conceived by President Eisenhower in the 1950's as a National Defense Highway System, is a series of controlled access interstate highways crossing the United States east to west and north to south. The Eisenhower Interstate System, so named in 1996 honoring the 40th anniversary of the first highway opening, is the most complete system of highways in the world.

The $10.5 billion project, scheduled for full completion in 2004, will replace Boston's aging and inadequate six lane elevated Central Artery, originally conceived in the early 1950's as a urban collector-distributor and later incorporated into the Interstate System as Interstate 93 (I-93), with a modern 8 to 10 lane underground expressway. The Massachusetts Turnpike (I-90) today terminates at the I-93/I-90, South Bay Interchange and will be extended 5.6 kilometers to Logan International Airport through a series of underwater crossings and a new underground full service interchange serving South Boston.

The new I-93 tunnel, which passes through the heart of Boston's business and financial districts, will be constructed below the existing elevated structure while the existing structure is maintained for traffic by a sophisticated and extensive underpinning support system. The highly utilized surface roadway system, which includes many north/south and east/west streets carrying heavy volumes of local vehicular and pedestrian traffic through downtown Boston, will also be maintained throughout most of the area by an independent decking system which will span the entire (up to 61 meters wide) cut and cover tunnel section. When completed, the existing artery will be removed, reconnecting the City's financial and business districts with the waterfront and creating .27 hectares of space, most of which will be allocated for parks. The Project northern limit will extend I-93 across the Charles River on a 10 lane cable stayed bridge which, along with a secondary 4 lane bridge and additional tunnel and viaduct structures, will improve connections with regional and local roadways to the north, east, and west. To the south, a new 8 to 10 lane elevated structure, transitioning to an at grade roadway, will replace the existing I-93 roadway to the southern Project limit at the Massachusetts Avenue Interchange.

The I-90 extension is already partially completed and operational with a 4 lane immersed tube tunnel crossing of Boston Harbor. The tunnel, now known as the Ted Williams Tunnel named after a national sports legend, was opened to traffic on December 15, 1995. The missing 1.6 kilometer link, including the Fort Point Channel Crossing, is currently under construction, scheduled for completion in 2001. This work will provide the connecting roadway from the Mass Turnpike to the new tunnel. This roadway segment is eight lanes wide and utilizes a variety of tunnel designs including cut and cover, concrete immersed tubes, and jacked tunnel sections. The I-90 Fort Point Channel Crossing tunnels east under existing South Station intercity and commuter railroad track, under historic Fort Point Channel while crossing above twin 1915 subway tunnels, and continues through industrial South Boston with ramps surfacing in a new South Boston Interchange. This interchange will serve the needs of an area of Boston that is experiencing tremendous growth and development.

The extension of I-90 to the east will complete one of the last links in the Federal Highway Administration's Interstate Highway System and provide a direct interstate highway link to one of the nation's busiest international airports. Interstate-90 traverses the U.S. coast to coast from Seattle, Washington to Boston, Massachusetts, a distance of 5760 kilometers, and is the system's longest highway. At the airport, the tunnel rises to the surface and into a complex interchange that connects with the airport's at grade and elevated roadway system and also provides connections to and from U.S. Route 1A at the Project's eastern most limit.

The Project includes a complex interchange of the I-90 and I-93 roadways, which will be comprised of multilevel above and below grade structures, constructed in unstable ground and, in part, under water. As with the downtown, the existing heavily traveled I-90/I-93 intersection, with a multitude of interstate and local connecting ramps, along with an extensive commuter rail operation into Boston's South Station, must be maintained for all major traffic movements throughout construction. Because of this, an extraordinary system of temporary ramps, construction staging sequences, and innovative construction techniques has been an integral part of the design.

In total, the Project will build or reconstruct 12 kilometers of urban highway, approximately half in tunnels. Mainline roadways vary from 4 to 10 lanes in width, and are constructed by a variety of different methods including cut and cover with slurrywall support walls, top down, steel and concrete immersed tube tunnels, concrete jacked tunnel sections, and various customized mined sections. The completed system will comprise a total of 267 lane kilometers of mainline and on and off ramp roadways. The total quantity of excavation from the Project is 10 million cubic meters and concrete placements will total 2.9 million cubic meters. The Central Artery/Tunnel Project Map provides the scope of the Project and illustrates how every major district of the city is impacted.

2.0 History

The need for the Project can be traced back to the time not long after completion of the existing six lane elevated collector distributor originally known as the Boston Central Artery and later incorporated into the Interstate System as I-93. When designed and constructed in the 1950's the roadway was envisioned to serve approximately 75,000 vehicles daily. Rapid growth in the New England region throughout the 1960's and early 1970's, however, has led to daily volumes rising to more than 190,000 vehicles per day. Transportation planners soon realized that if improvements and added capacity were not addressed, congestion on the Central Artery would grow beyond the normal three hours in the AM and PM periods to up to 14 hours per day. These delays were projected to cost the region millions of dollars in late deliveries and associated economic impacts as well as costs associated with wasted fuel by idling vehicles. Idling vehicles were also identified as a significant contributor to reduced air quality in the area.

In addition, the elevated I-93 structure has serious deficiencies due to short weaving distances associated with numerous on and off ramps and the outdated roadway design standards used in the original design. By the 1970's it was already recognized that the structure would eventually need in-place reconstruction to extend the life of the aging steel structure, which would have to be performed under live traffic conditions. These repairs would create a traffic nightmare by significantly impacting the already overtaxed facility operating at 2.5 times its design capacity.

Massachusetts Highway Officials in the late 1970's and early 1980's, after considering for a time just the I-90 extension or the I-93 improvements as independent approaches, championed an approach that combined both elements into the current Project. In 1982 a Preliminary Environmental Impact Statement was filed by the State of Massachusetts Department of Public

Works (now called the Massachusetts Highway Department) and the Federal Highway Administration (FHWA). This document underwent an extensive and ultimately successful public review process as administered by the federal and state environmental protection agencies. With a few outstanding issues identified for further evaluation, that were later addressed in a supplemental report issued in 1990, a Record of Decision was issued by the state and federal agencies which allowed the Project to move forward. Upon successfully completion of the environmental process, the Project was found to be eligible for FHWA funding and was included in the Surface Transportation Act of 1987.

3.0 Organization

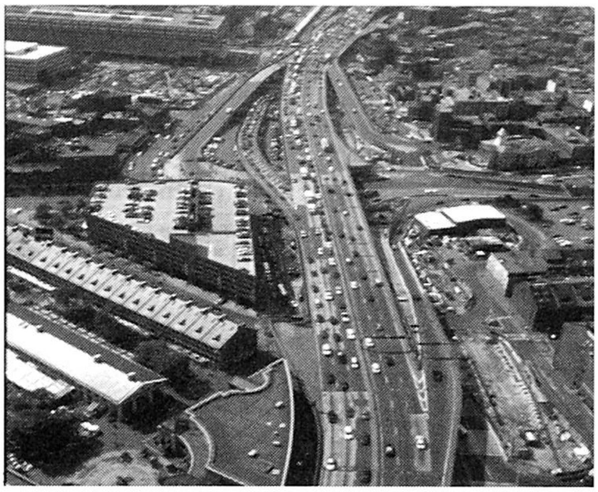
With the funding in place the Massachusetts Highway Department (MHD) selected and placed under contract the Management Consulting Team of Bechtel Corporation and Parsons, Brickerhoff, Quade, and Douglas (B/PB) to perform consulting services for overall project management. MHD and B/PB, in conjunction with the FHWA (which is providing approximately 85% of the funding required for the Project), form the Project's management organization. B/PB's scope of services includes preliminary design of the highway system, management of final design contracts performed by independently selected section designers, and management and overall coordination of the construction as performed under individual construction contracts awarded by a competitive bidding process. In a unique arrangement, B/PB managers take on the role of Authorized Representatives for MHD and manage the efforts of the numerous design and construction contracts directly for MHD. Additional management consulting services related to overall project management include: environmental and permitting support, coordination with outside agencies, right of way acquisition, community relations, procurement, systems operations support, and risk management.

4.0 Technical Challenges

The CA/T Project presents numerous technical challenges. Many of the challenges are directly related to the difficult geological and soil conditions located in many areas of the Project. Others relate to the density of urban infrastructure associated with one of the nation's oldest cities. Existing facilities that must be accommodated or relocated include many kilometers of utilities of all types and sizes; underground transit and at grade commuter rail systems; numerous adjacent historic masonry structures on timber pile foundations, as well as several more recently constructed high-rise buildings; and extensive at grade and elevated roadways.

The following paragraphs touch briefly on some of the major technical issues. More detailed discussions of these technical issues may be found in other papers that have been presented at this colloquium.

4.1 Downtown Cut and Cover Using Slurrywall



View 1 Looking along the I-93 alignment north. Callahan and Sumner Tunnel portals on the right.

View 2 Looking along the I-93 alignment north. View shows new temporary ramp and construction below existing artery.

The 8 to 10 lane tunnel section that traverses the downtown area is being constructed primarily by the cut and cover method utilizing slurrywalls. The slurrywalls serve several purposes: an excavation support and rigid wall system that protects adjacent structures (many of which are only a meter or two away), a water cut off that controls water drawdown impacts to adjacent structures prior to excavation, a foundation element to carry the dead and live loads from the 6 lane elevated artery underpinning system, and the permanent tunnel walls.

The walls are designed as soldier pile and tremie concrete (SPTC) walls with reinforcing consisting of steel soldier piles which are lowered into the slurry and cast into the concrete at a 1.2 to 2.1 meter spacing. The soldier piles are 900mm rolled sections weighing up to 580 kilograms/meter. The soldier piles are needed to provide acceptable wall stiffness both during construction and in the final condition after the tunnel base slab and partially fixed steel roof beams are installed. Approximately one third of the slurrywalls are constructed below the existing elevated artery in a low headroom condition. Low headroom equipment is utilized to dig the slurry trenches and a splice detail is utilized to enable the segments of soldier piles to be lowered incrementally below the elevated structure into the trench.

There are numerous buildings immediately adjacent to the downtown tunnel construction. The walls and lateral support bracing system are designed to keep ground movements and associated impacts to adjacent structures within acceptable criteria. Generally the standard of an angular distortion of less than L/1000 is required. Wall movements are expected to be less than 25mm in most areas. An extensive instrumentation program comprised of more than 25,000 instruments has been incorporated into the design. Instruments of 22 different types are monitored continuously to measure wall movements, groundwater levels, settlements, and impacts to adjacent structures. Programs are in place to compare theoretical to actual values, and stop construction should limiting thresholds be reached.

4.2 Elevated Artery Underpinning

Because virtually all of the existing elevated artery foundations (pile supported footings) are within the footprint of the tunnel excavation, an underpinning support system is required. The system consists primarily of plate girder underpinning beams (up to 2.4 meters deep) that straddle the existing footings and bent structures (comprised of 3 or 4 columns). The girders span between the three tunnel slurry walls (two exterior and one center) and are designed to carry the artery dead and live load.

Load is transferred from the artery to the underpinning girders by two general categories of designs, high pickups and low pickups. The high pickup is comprised of a frame which surrounds the existing column, making contact with the existing structure at the roadway deck beams and bears on the underpinning girders. The low pickup is comprised of two needle beams that rest on and run perpendicular to the underpinning girders immediately adjacent to the existing column. The needle beams support a collar that is directly connected to the existing column.

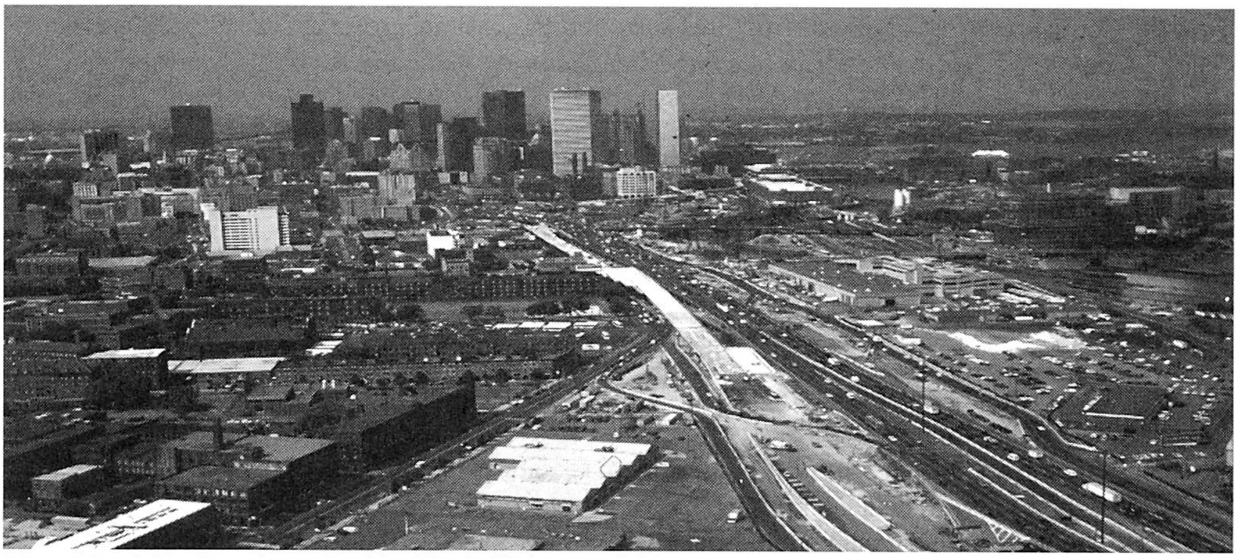
Both systems employ a jacking system that transfers the dead load of the existing structure into the underpinning system prior to cutting and removing the existing supports. The jacking operation is performed in 25% increments. At each jacking increment the jacks are locked off, theoretical deflection measurements compared to actual, and the structure visually inspected. Once all dead load is transferred from a bent to the underpinning structure, traffic will be reduced to ã one lane operation away from the column to be cut (at night) and the column cutting will be performed under a controlled procedure. Completion of the load transfer enables the removal of the existing support system and the follow on excavation and tunnel construction work to progress.

4.3 Underpinning of the Red Line Subway Station

One of the many unique structural challenges of the Project is at Boston's Red Line South Station where the four lane I-93 northbound tunnel box must pass below the Massachusetts Bay Transportation Authority (MBTA) Red Line Subway Station. The work in this area includes the combination of the highway tunnel construction with the MBTA's Transitway Project, a tunnel system designed to run electrified buses between the South Station area and South Boston. The new MBTA tunnel passes above the highway tunnel and through the existing underground station which will be completely rebuilt to accommodate a new bus platform level. Combining the two Projects was cost effective and minimizes the duration of surface disruption.

The underpinning method for the highway tunnel box involves the construction of two vertical shafts and then two horizontal grouting access tunnels that are each mined a horizontal distance of 33.5 meters below the station. A grouting procedure is used to improve the soil and facilitate ground water control during the subsequent mining of three stacked tunnel drifts that head out horizontally from each vertical shaft. The three stacked drifts are each individually mined starting at the lowest level ultimately forming the supporting abutment to carry the station loads and to allow the highway tunnel structure to be mined below. After the drifts are mined, reinforced, and filled with concrete, cross beams are mined between access tunnels approximately 1.7 to 2.7 meters below the existing station. Following mining, the cross beams are concreted and post tensioned in a specified sequence, providing the overhead structure that will enable the mining of the highway tunnel below. Throughout the construction of the MBTA's work within the station and on the surface and the MHD's underpinning and tunnel construction below, the station will continue to run a normal schedule of trains to service commuters.

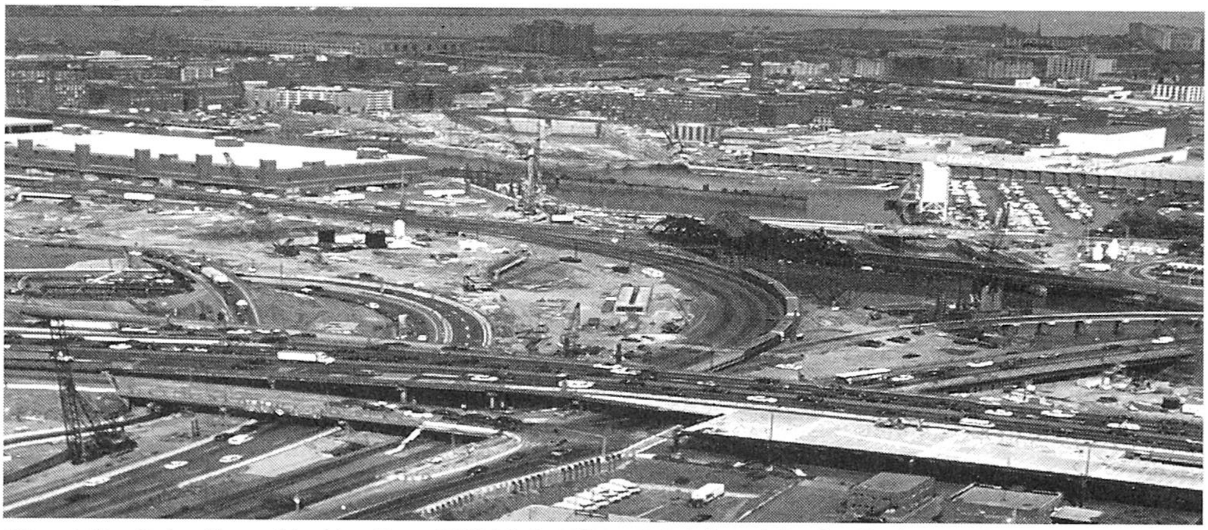
4.4 Fort Point Channel Crossing



View 3 South Bay Interchange Looking North (FPC upper right)

The I-90 Crossing of the historic Fort Point Channel (FPC), site of the Boston Tea Party some 200 years ago, is by most accounts the Project's most technically challenging area. The site of the 137 meter water crossing has been a major transportation corridor to the city for 200 years. The site is littered with old foundations of past piers, wharves, and industrial structures dating back to the 1700's. The advent of steam locomotives turned this port area into one of the nation's largest rail heads at the turn of the 19th century. The old infrastructure has been filled in and rebuilt on and over numerous times, as the waterfront was taken over by filling.

Currently the site is the terminus for the AMTRAK inter-city Northeast Rail Corridor and local MBTA commuter trains at South Station with approximately 200 train moves a day. The station is also serviced by the Massachusetts Bay Transportation Authority (MBTA) Redline Subway system with twin approach tunnels to the station mined under the FPC in 1915. The unreinforced 7.3 meter diameter tunnels run down the center of the FPC 7.9 meters below the existing bottom, cradled in till and enveloped in Boston's infamously weak Boston Blue Clay. The channel is no longer utilized for shipping and all but one of the four moveable bridges crossing the channel ceased operating in the late 1950's.



View 4 Fort Point Channel looking East (USPS left, Gillette Co. right and Casting Basin center)

The current I-90/I-93, South Bay Interchange (located in what was once Boston's South Bay) is immediately west of the channel separated by the five combined rail lines approaching the station from the South and West. Newer structures surround the channel crossing site, including the Gillette Company's North American Shaving Manufacturing Plant and Boston's Metropolitan area US Postal Service (USPS) General Mail Facility, handling 7 million pieces of mail daily. These physical constraints make the crossing very difficult and it required world class design and construction expertise to implement the right plan. The crossing utilizes Deep Soil Mix, Jacked Tunnels and Concrete Box Immersed Tube Tunnels.

4.5 Deep Soil Mix

The Project provides many firsts for North America as well as the world. Due to the extremely weak soils a decision was made to modify the soils in lieu of fighting the soils with massive conventional marine support of excavation structures. This decision resulted in the largest soil modification contract for structural support known to date with over 130,000 cubic meters of Deep Soil Mix (DSM) to be accomplished by triple auger mixers with diameters of 760 to 1520 mm, that will inject and mix cement into the in-situ soil to increase the strength prior to the deep excavation required for the tunnel crossing.

Jet grouting supplements DSM when higher strengths or obstructions prevent the DSM equipment from being utilized. The DSM and the early Support of Excavation contract prepared the western shore adjacent to the South Station train tracks and immediately adjacent to the USPS operations, for the placement of the first of two parallel concrete box immersed tube tunnels (ITT), ranging in size up to 100 meters long by 45.7 meters wide and 9 meters high.

4.6 Jacked Tunnels

Further to the west large pits are to be constructed to fabricate 3 separate highway tunnel elements that are to be jacked under the 5 live rail road tracks. These tunnels range in size up to 110 meters long 24.4 meters wide and 10.67 meters high. They are jacked forward, caterpillar fashion, 450 mm at a time using multiple 180-450 tonne jacks ganged together to develop enough driving force to advance the tunnels through the maze of old sea walls, foundations and piles. The tunnel's are then jacked into the Deep Soil Mix modified soil.

4.7 Concrete Box Immersed Tube Tunnels

The Concrete Box Immersed Tube Tunnels are constructed in a casting basin approximately 305 x 106.7 x 19.8 meters deep. The basin is constructed on the eastern shore of FPC along the tunnels alignment. The basin provides an initial use as the casting basin for the ITTs. The basin is operated like a dry dock, once the ITTs are constructed, they are floated out of the basin. Later the immersed tubes are set on approximately 50 drilled shaft foundation elements 1.83 meters in diameter. The western ends will be sealed against the channel and two more pairs of tube are placed in turn, extending the overall ITTs section 305 meters into the eastern casting basin. Initially used to cast the tubes, the basin will later contain the cut and cover tunnels, extending the tunnel to the South Boston Interchange. Once all the tubes are in place, simultaneous dewatering will allow cut and cover work to continue at each end. The western 45.75 meter cut and cover element is constructed connecting the ITTs to the previously Jacked tunnel elements.

Another first for the Project include the crossing of the Red Line Subway by the ITTs. The distance between the extension of the Red Line crown and bottom of the ITT is only 1.83 meters.

The ITTs are supported on drilled shafts to ensure that no load is ever transferred from the ITT's to the 80 year old Red Line below. In addition, the Ventilation Building for the FPC Crossing tunnels is founded on the first set of ITTs. The building foundation is actually part of the immersed tubes when they are floated into place. This unique feature provided the Project with a significant schedule benefit.

4.8 Traffic Maintenance and Construction Mitigation

One of the major challenges of the Project is to maintain the high volume of interstate and local traffic throughout all phases of the construction. Almost the entire downtown tunnel excavation area will be covered with a high quality concrete plank decking system which will provide a surface suitable for the up to six years of service life required. Extraordinary efforts have been expended by Project designers to develop and review the construction staging and traffic maintenance plans of each of the several downtown mainline construction contracts that are underway simultaneously to assure that the surface roadway system is intact and functional throughout each phase of construction. A regional transportation model is used to calculate traffic volumes through the construction period as various roadway elements are shifted or taken out of service. These volumes are used for more detailed traffic modeling which is used to analyze intersections and set signal timing.

Traffic maintenance is a dynamic process as planned sequences change or different construction methods are proposed by contractors. The Project has made effective use of task forces comprised of city officials from the Boston Transportation Department and project designers, construction managers and communications staff to evaluate traffic issues and develop coordinated and acceptable solutions.

Additional challenges are associated with fulfilling the extensive commitments, as set forth in the Project's environmental documentation, to perform the work while still maintaining the quality of life for the City's vibrant commercial, tourist, and residential interest. Construction mitigation requirements include controlling dust, noise, vibrations, discharges into surrounding water bodies, and disposal of contaminated materials. Some of the key elements of the Project's mitigation program include:

- A computer tracking system and reporting structure to assure that all mitigation commitments are monitored and met.
- A distinctive projectwide construction barrier system that helps route and protect drivers and pedestrians in a uniform and attractive manner.
- A staff of community liaison personnel that work with residents, community representatives, and businesses to resolve concerns about construction.
- A 24-hour monitoring center that maintains video surveillance of traffic and construction, and provides around-the-clock access for the public to register complaints.
- An extensive noise control program, coupled with specific limitations on construction operations.

5.0 Project Firsts

A summary of firsts for the Central Artery/Tunnel Project includes:

1. Most extensive geotechnical investigation and testing program in North America
2. Largest use of slurry wall construction in one location in North America
3. Largest and deepest circular Cofferdam in North America
4. Deepest Immersed Tube Tunnel Interface in North America
5. First use of Soil Mix Construction on East Coast
6. Most extensive use of Soil Mix Construction in North America
7. Most extensive use of Immersed Tube Tunnels in the United States of America
8. First use of Integral Immersed Tube / Ventilation Building design
9. First and largest installation of Jacked Vehicular Tunnels in North America
10. Largest Vehicular Tunnel Ventilation System in the world

ACKNOWLEDGMENTS

The authors wish to express their gratitude to the Massachusetts Highway Department and the Federal Highway Administration, and in particular to Central Artery/Tunnel Project Director, Peter Zuk, Manager of Design and Engineering, Michael Lewis, P.E., and FHWA Division Administrator Peter Markle.

Construction of Trans-Tokyo Bay Highway

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Summary

The Trans-Tokyo Bay Highway (TTB highway), which crosses Tokyo Bay and provides a direct transportation link between the west and east sides of the bay, has long been a sort of "dream-come-true" project in Japan. Linked to the Tokyo Bay Shore Highway, Metropolitan Inter-city Expressway, Tokyo Outer Ring Road, Tateyama Expressway, and others, it will play an important role as an integral part of the regional highway network to help promote spatial redistribution. The TTB Highway is a project of 15.1 km in length designed as a toll highway to cross the bay by tunnel and bridge, and the total cost is more than 1,482.[3] billion yen (US$12.353 billion). The crossing involves a 5-km bridge, a 10-km undersea tunnel, and two manmade islands in the middle of the bay. This report outlines the entire TTB Highway project, including the design and construction method of undersea tunnels.

1. Outline of the Highway Structure

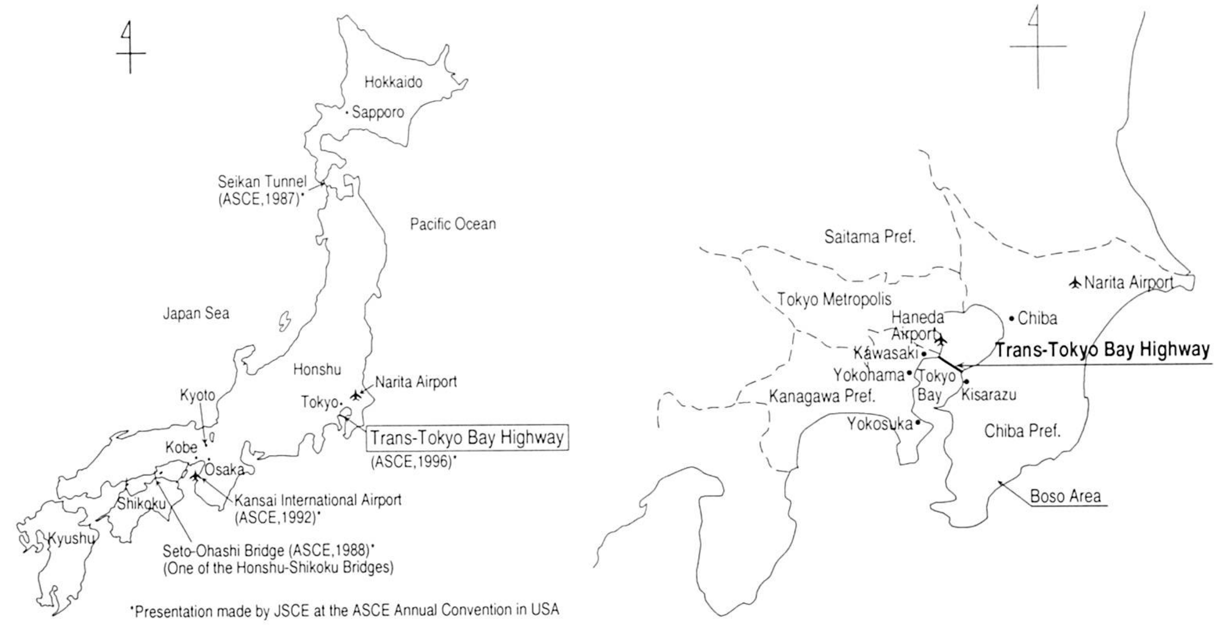
1.1 Highway Structures

The general plan of the highway is illustrated in Fig. 2, and having a highway length of 15.1 km in total, of which the marine section is 14.3 km. At the Kawasaki end, the land section of the highway joins the Tokyo Bay Shore Highway at the Ukishima Interchange. At its Kisarazu end, it is linked to the Tateyama Expressway by the TTB Highway Connector Road (7.1 km). The land sections at the Kawasaki and Kisarazu ends are approximately 0.3 and 0.6 km respectively. An outline of the project under the terms of the project license is given in Table 1 below.

The highway is being constructed as a four-lane facility: two lanes in each direction. For this, two parallel tunnels are being driven in the undersea section. However, in order to accommodate the expected future increase of traffic, the dimensions of major structures such as the man-made islands and the bridge have been determined to make future widening feasible.

1.2 Marine Section

The structural components of the marine section of the highway will consist of a shield-driven undersea tunnel, approximately 10 km in length, for the western two-thirds of the highway where shipping traffic is heavy; and a bridge about 4.4 km in length for the remaining section. Near the middle of the tunnels, a ventilation facility has been provided in the form of the Kawasaki Island, and where the tunnel and bridge meet, the Kisarazu Man-made Island (Kisarazu Island) is being constructed. The Kisarazu Island will serve as a rest area for users of the highway. Both islands have also been used as launching bases for the shield machines driving the tunnel.



(a) (b)

Fig. 1 Location of Trans-Tokyo Bay Highway

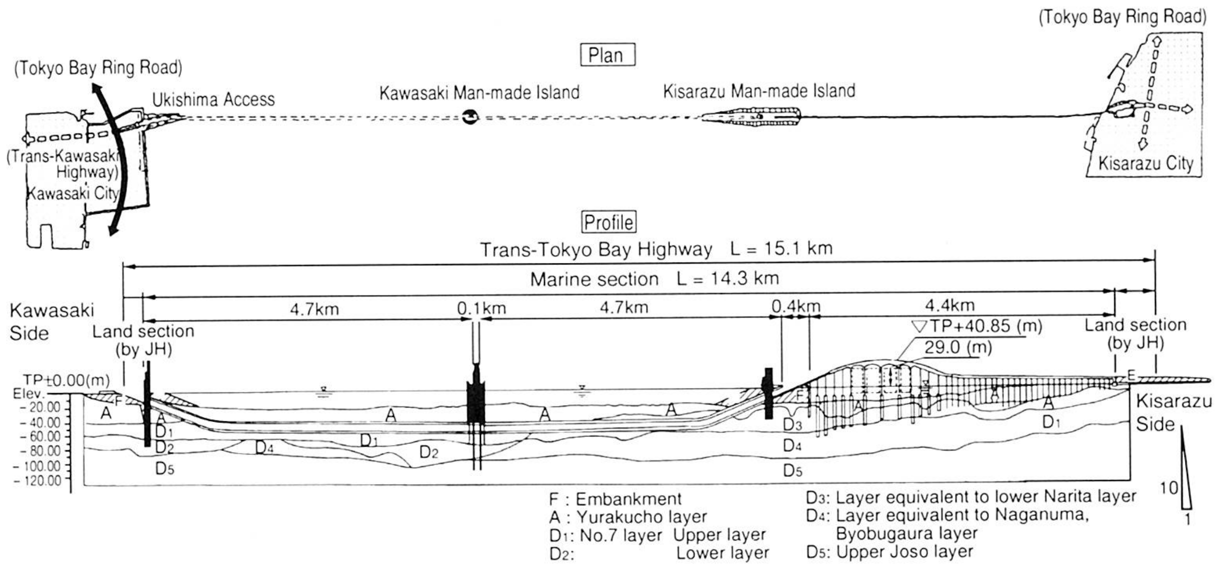


Fig. 2 Project plan and geological profile

Table 1 Outline of the project under the terms of the project license

Name of highway	Trans-Tokyo Bay Highway
Official route designation	National Route 409
Origin and destination	From Ukishima, Kawasaki City To Nakajima, Kisarazu City
Length of highway	15.1 km (Marine section 14.3km)
Number of lanes	Dual 2-lane (6 lanes at final phase)
Design speed	80 kilometers per hour
Design load	TL-20t and TT-43t
Forecast traffic volume	33,000 vehicles per day in the first year of operation (64,000 vehicles per day after 20 years of operation)
Construction period	About 10 years from fiscal 1986 (Completion expected in fiscal 1997)
Total project cost	¥1,482.3 billion (US$12.353 billion)

Exchange rate : US$1 = JPN¥120

1.3 Land Section

The land section on the Kawasaki side serves as an approach section to the tunnel from the interchange, and has structural components of a large U-shaped retaining wall and a box culvert.

1.4 Constructions Schedule

Fig. 3 shows the construction schedule for the highway. Construction began in 1989, and is scheduled for completion by 1997.

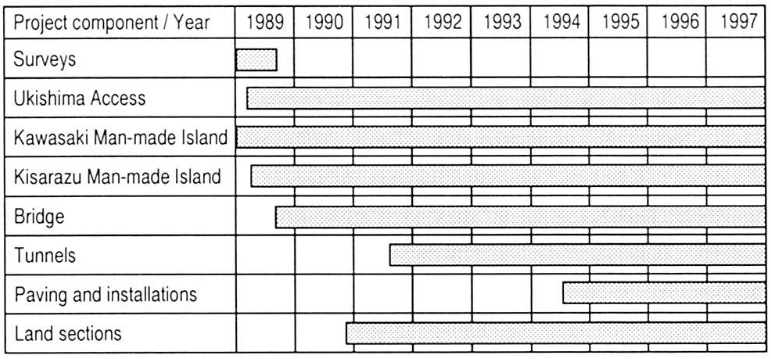


Fig. 3 Construction schedule

2. Design Conditions

2.1 Natural Restrictions and Planning Conditions

The topography of the seabed along the planned highway link is extremely gentle, generally conforming to the shape of a ship's hull, with a maximum depth of approximately 28 m. Geologically, from Ukishima on the Kawasaki side to the center of the Bay, there is a very soft 20-to 30-m-deep layer of alluvial soil, known as the Yurakucho layer; on the Kisarazu side, a relatively dense sand layer has accumulated from the surface. The upper stratum of the Kazura formation, a sandy layer with an N-value greater than 70 at depths below TP-80 to-90 m, is considered to be a suitable bearing stratum for engineering designs.

Along the tunnel route, the geology mainly consists of alluvial and diluvial clay soil layers on the Kawasaki side, with a diluvial sandy layer sandwiched between the two. The Ukishima and Kisarazu ramp sections are on reclaimed land.

2.2 Earthquake Activity

Earthquake activity is common in the Tokyo Bay area. It is believed that 32 major earthquakes occurred in the Bay area in the period from 818 to 1867 A.D.; since 1868, 23 damage-causing

Table 2 Soil Properties and load factors at the tunnel location

Soils	N Blow	q kg / cm	E kg / cm	γ_τ ton / m^3	κ	λ	Water in Soils
Ac1	0	0.44	4.8–9.6	1.3–1.5	0	0.75	Combined
Ac2	0	0.87	5.7–22.9	1.6–1.7	0	0.75	Do.
Dic	12	0.96	35.9–289.0	1.4–1.8	1.5	0.65	Do.
Dis	15-5	–	25.0-204.0	1.6–1.8	0.5–4.0	0.35–0.55	Separated
D3c	20	2.11	–	1.7–1.8	2.0	0.65	Combined
D3s	54	1.57	296.2	1.8–1.9	4.0	0.35	Separated
D3g	78	–	195.5	1.7	5.0	0.35	Do.
Manmade	–	7.5–21.3	–	1.6–1.8	3.5	0.6	Combined

A : Alluvial
C : Clayey soils
N : Number of Blows by SPT
qu : Unconfined Compressive Strength
E : Modulus Elasticity
D : Diluvial
S : Sandy soils
γ_τ : Unit Weight of soils
κ : Modulus of Subgrade Reaction
λ : Earth-pressure Coefficient

earthquakes have occurred. The great Kanto earthquake of 1923 is representative of these major earthquakes. Fig. 4 shows the epicenters of large earthquakes (i.e., those having a magnitude greater than 6.5) that occurred between 1885 and 1979 within 300 km of the TTBH site.

3. Shield Tunnels

3.1 Outline

The tunnel section of the TTB Highway is about 10 km long, or two-thirds of the total length of the 15.1-km highway. It runs from the Ukishima Access on the Kawasaki coast, sloping down through a sloped section into the seabed, then passing through a level section and finally up through a second sloped section, to the Kisarazu Island. Constructed midway along the level section between the Ukishima Access and the Kisarazu Island (at a point about 5 km offshore from the Ukishima Access) is the Kawasaki Island, where ventilation facilities are located. The horizontal alignment of the tunnel is basically straight. The sloped sections have been designed with a 4 percent grade in order to shorten the sections as much as possible. The level seabed section has a 1.0 D-thick overburden (where D is the tunnel outer diameter), so that the combined weight of the overburden and tunnel structure will counteract buoyancy forces.

Fig. 6 shows the basic tunnel cross section.

3.2 Tunnel Design

Since the tunnels would be driven under the severe conditions outlined below, careful and extensive deliberation went into the design and execution work, including meetings of a committee that included advisory experts.

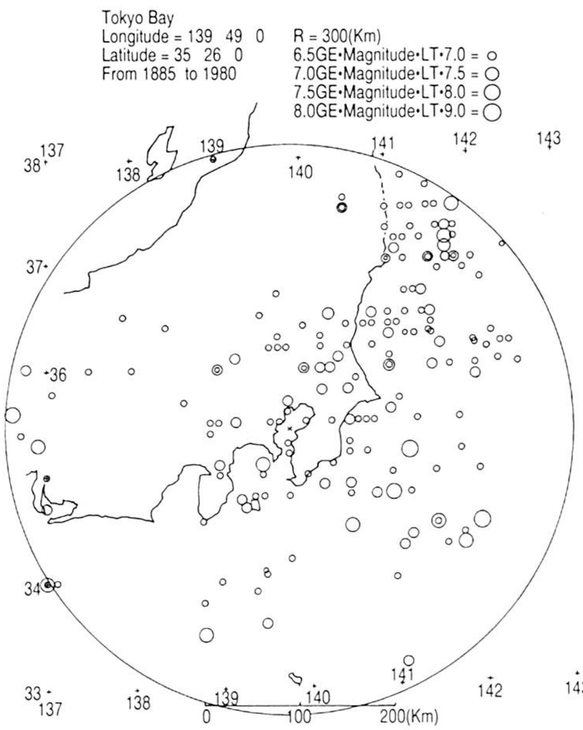


Fig. 4 Earthquakes of magnitude ≥ 6.5 that have occurred within a 300-km radius of the center of Tokyo Bay from 1885 to 1990

Fig. 5 Highway structures of the marine section

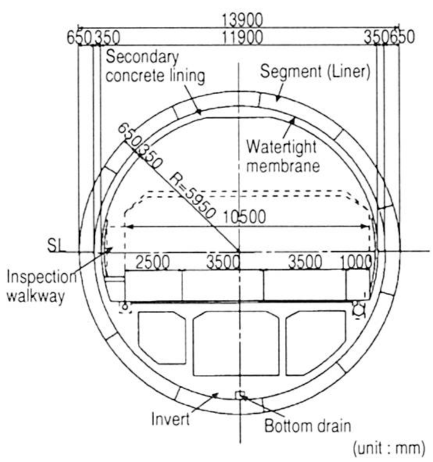


Fig. 6 Tunnel cross section and traffic lanes

1) The roadway configuration would necessitate construction of a shield tunnel having a large cross section (13.9 m in diameter), and requiring long-distance tunneling operations.

2) The tunnels would be driven through soft ground, and in a seismically active area.

3) Since the water depth at the site is high (the maximum head would reach 50 to 60 m), and because there is no impermeable layer, the tunnels would be subject to extremely high water pressure (0.49 to 0.59 MPa).

4) The tunnels would experience the corrosive effects of salts contained in the sea water.

5) The structure being a twin tunnel spaced 0.5 to 1.0 D along the sloping sections and 1.0 D along the level seabed section could cause construction work on one tunnel very easily affecting the other. Shield tunnel cross effects had to be considered in the tunnel design.

6) The tunnels being long, several shield machines would have to advance concurrently from the vertical shafts at the Ukishima Access, Kawasaki Island and Kisarazu Island in order to shorten the construction period. Underground connections would therefore be made below the seabed and under high water pressure.

7) To enhance both safety and work precision, there would be a need to automate various operations such as excavation and assembly of segmental ring liners.

3.3 Standard Specifications for the Shield Machines

Twin parallel tunnels are being driven between the Ukishima Access and the Kawasaki Island, and between the Kawasaki and Kisarazu Islands, making a total of eight work sections. Tunneling involves eight shield machines, each starting from one of the vertical access shafts at the Ukishima Access, Kawasaki Island and Kisarazu Island, to eventually connect below the seabed.

Fig. 7 shows the front view and cross section of the shield machine, and Fig. 8 shows a shield machine assembled at the fabricating plant.

① Basic configuration
a. Bore diameter: 14.14 m
b. Shield machine length: 13.5 m
c. Total weight: 29.4 to 31.4 MN

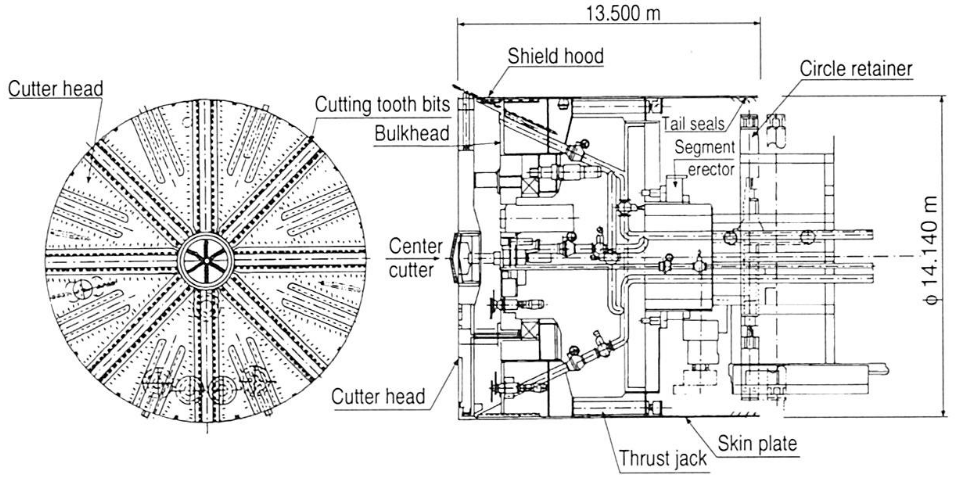


Fig. 7 Slurry shield

② Driving machinery

a. Total thrust: 235 MN (48 jacks with 4.9 MN capacity)

b. Jack stroke: 2,550 mm

Fig. 8 Shield machine

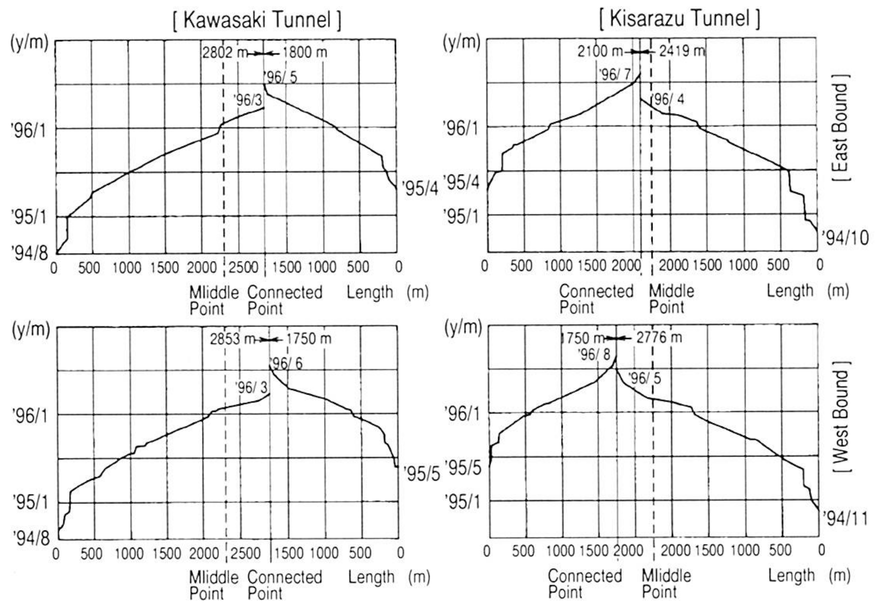


Fig. 9 Tunneling construction process

3.4 Rapid Tunneling

Fig. 9 shows the tunneling progress record of those 8 shields, which bored tunneling length of 1,750 m to 2,853 m. The shields advanced average 150 m or more monthly, which was beyond expected schedule. The best monthly progress is 310.5 m.

4. Afterword

Twenty years after the preliminary feasibility study, the project finally started with a newly organized system taking advantage of vital capacity of the private firms, and it has now achieved over 90 % of completion. It is expected that the highway will be open by the end of 1997. In the project implementation, adequate considerations have been given to the natural and living environment, and navigational safety in the area, and the construction safety. The authors wish to express their indebtedness and thanks to each and every personnel of various organizations involved in the project.

Optimizing the construction method of a surface tunnel south of Vienna

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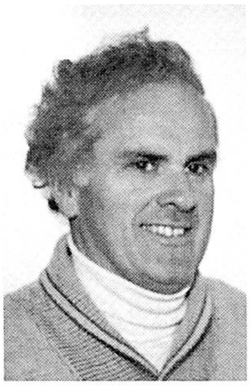

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Summary

Within the framework of planning a by-pass road in the south of Vienna a pass under will be required in order to traverse a built-up area. Since any re-settlement of the population concerned would be difficult to implement for political reasons, several economically, technologically and ecologically favourable variants were investigated in the context of an EU-wide planning competition and submitted to a comparative evaluation. The project refers to an approx. 2 km long route that would have to be executed near the surface and only in the immediate vicinity of buildings would mining constructions be necessary.
Three technologically different solutions were proposed both for the section to be realized in open construction and that requiring mining construction work.

1 Problem

A high-grade road link is needed on the south side of Vienna between the A 2 South motorway and the A 4 East motorway. The role of the road link is firstly to keep local traffic from the densely populated area of South Vienna out of the towns and villages, and secondly to link up the southern and eastern sectors of the city without putting a burden on the urban road network.

The traffic prognosis for this highway says that there will be between 30,000 and 60,000 vehicles per day in the year 2010, different in the various sections of the highway. The project involves a total of 14 kilometres of road. Five tunnels with a total length of about 4 km have to be built up as well as 5 surface tunnels, each with a length of 40 to 70 metres and about 20 bridges are included in this project.

As part of this planned road link, the Schwechattal has to be crossed in the vicinity of Rannersdorf. Surface solutions such as bridging the Schwechattal or a combined tunnel and bridge solution were discarded for town planning or environmental reasons.

In the General Project dating from 1994, the open tunnel method was therefore further pursued. This requires as shallow a depth below level as possible, while the mining construction tunnel requires as deep a position as possible because - according to the state of knowledge at the time - the intention was to cross the river bed in less permeable subsoil. In both cases, on completion of the motorway the Schwechttal is crossed by a tunnel approximately 2 km long. The open construction method involves relocating 22 houses, however.

In its wider setting, the planning area for the tunnel lies at the edge of the Vienna Basin, a typical trough created at the time of the Alpine rock formation. The basin linings are Neocene tea-green marls and sand in more or less parallel strata. During the 4 major ice ages, rubble with predominantly well-rounded components, loams and loess accumulated.

In the course of the preparatory work for the project, extensive subsoil investigations and hydrogeological investigations were carried out. These produced the following picture:

Under a thin layer of top soil or loess lies a thick layer of alluvial sediment, mainly sandy gravel. Below this is tertiary coarse clay and gravelly fine to medium sand. The upper edge of the sand stratum is encountered between 13 m and 22 m below the surface of land. Below the sand, at a depth of 20 - 29 m, come layers of clay and silt, in turn lying on top of layers of sand with clay or silt lentils embedded. Like the unhomogeneous geological structure of the planning area, the hydrogeological situation is also very unhomogeneous. The groundwater flows northwards through the quaternary gravel and tertiary sand strata more or less vertically to the proposed line of the tunnel. The groundwater table has a slight eastwards fall. The groundwater is very intensively used locally, including by one of the biggest breweries in the Vienna area.

Representatives of the local authorities and the State of Lower Austria vigorously championed the mining construction tunnel by the shield tunnelling method to keep disturbance to the local population to a minimum, particularly during the construction stage.

The estimated price difference at the time between an open construction tunnel and the mining construction tunnel was about ATS 370 million. The higher cost was felt to be quite disproportionate to the benefit that could be obtained with the mining construction method. The Federal Ministry of Economic Affairs therefore gave preference to the General Project with an open tunnel construction method.

In view of the controversy between the population affected and the construction sponsor over the method of tunnel construction, Österreichische Autobahnen- und Schnellstraßen Aktiengesellschaft decided to throw open a Europe-wide competition for ideas for alternative construction methods in order to tap the know-how of European specialists and thus find a cost-effective and environmentally compatible solution.

2 Competition

On the basis of the survey findings from the General Project, a Europe-wide search for potential tenderers was launched. Twenty-two candidates came forward with ideas for qualification in the first stage.

After a preliminary selection from the solutions submitted, 8 planning firms were invited to a hearing before a panel set up by Österreichische Autobahnen- und Schnellstraßen Aktiengesellschaft. The ideas were examined in detail by both the panel and representatives of Österreichische Autobahnen- und Schnellstraßen Aktiengesellschaft and 3 solutions were finally pronounced suitable for further development.

Accordingly, the engineering firms of

- Bösch & Gebauer - Munich — Study A
- Stella & Stengel - Vienna — Study B
- Strobl & Intergeo - Vienna/Salzburg — Study C

were then asked to produce technical tunnel construction studies.

The terms of reference for the panel, formed of 2 university professors (Professor Jodl and Professor Semprich), a foundation engineering specialist (Sochatzy) and Mr Hörhan, were to evaluate the project from a technical point of view, identify imponderables, assess risks and work out technical advantages.

The planning firms were required to produce cost estimates to a preset comparable price level. These were examined in detail by the panel. Extras were allowed in cost estimating for geological method and cost risks associated with the projects.

3. Technical Solutions Proposed in the Studies

3.1 Study A

Study A comprises a combination of a single-shell open construction method with a mining construction tunnel building method at a shallow depth.

Open construction methods are used in the non-built up areas, which are mainly devoted to agriculture. The open construction tunnels can be backfilled and covered on completion to restore the site to its original state.

The way the open construction is done depends in particular on whether the routes pass above or through the groundwater. Accordingly, three different ways of making the excavations watertight were proposed. The open areas above the groundwater can be conventionally constructed with sloping cuttings. The slopes would penetrate the loess and gravel strata and were calculated at a 35° angle. Geotextile, sheeting or tried-and-tested shotcrete are proposed as temporary waterproofing of the slopes. The method suggested for open construction in the groundwater uses sheet piling to form a temporary water barrier. Because the rubble is expected to be densely packed, it is proposed to open up the ground by boring ahead of the sheet piling. The sheet piling will be put in place by the vibratory flushing method. Due to the relatively permeable sand layers in the integration area, tricky lengths of up to 25 m of sheet piling will be involved.

There is a relatively short section where open slope excavation is not possible. The excavations will therefore have to be secured by means of triple-anchored sheet piling in this area.

The actual tunnel structure will be constructed in the open area as a rectangular section with a centre partition and two lanes in either direction. At the point of transition to closed construction, 2 individual tubes will be constructed.

One advantage of using vibrated sheet piling as a barrier that was acknowledged during the evaluation is that it can be removed again once the construction work has been completed to minimise interference with the groundwater. Another point that has to be taken into account, however, is that sheet piling is not very flexible with respect to the changing depth. Relatively thick layers of sand are to be expected underneath the gravel stack.

The proposed method of tunnel construction in the built-up area is the New Austrian Tunnelling Method (NATM), which would be used to drive two individual tunnels protected by a watertight casing. As a rule, a subterraneous curtain with a 40 cm bulkhead width is used. In the section where the working area is too small, it is proposed to use the jet grouting method for the bulkheads. The two tubes of the tunnel will be driven in a protective vault from injection anchors. Inside the watertight casing, the groundwater table will be temporarily lowered to below the subsequent tunnel floor by means of vertical wells.

The panel judged Study A to be a feasible project with a manageable geotechnical risk. The proposed standard construction methods for both the open and the closed sections together with the recoverable bulkhead were regarded as advantages. A further point in its favour is the partial over and under flowing of the shallow tunnel structure in its final state. The single-shell construction in the fully overflowed area may lead to maintenance problems in the long term.

3.2 Study B

Study B comprises a combination of a twin-shell underground construction under top cover with mining construction tunnelling at a shallow depth.

As in the case of Study A, open construction is proposed in the non-built up area. In the section below the groundwater, the excavation would be sloped. In the parts where the tunnel cross-section penetrates the groundwater, it is protected by a narrow wall or curtain casing. The narrow walls are sunk from a preliminary level just above the groundwater table and tail into the groundwater bank. They are set back into the slope of the excavation so that when the excavations are carried out, the slopes will form the supports for the narrow walls. In the area of the subterraneous curtain casing, the tunnel is constructed under top cover with underground excavation. Inside the casing, the excavation is protected by an interior water barrier.

In the built-up area, both tunnels are constructed by the NATM using compressed air to control the rush of water. This requires preliminary sealing using cement bentonite via injection shafts from the surface. In addition to this shield, injection over the area of the cross-section is also proposed to stabilise the local face. The intention is to reduce pressure losses and permit roof driving. The maximum pressure head of 1 bar will be required while driving.

This Study was also acknowledged in principle by the panel as a feasible project with a manageable geotechnical risk. The tried and tested top cover construction method and the short duration of surface work, with less disturbance of surface structures and the population, was regarded as an advantage of this Study. Driving with compressed air is difficult and involves technical risks. On the other hand, the permanent levelling out of the groundwater using only drains is considered a drawback for the project as a whole from the point of view of maintenance.

3.3 Study C

In contrast to the other two studies, Study C involves a continuous single-shell construction at optimum shallow depth using guided caissons. This requires the construction area to be cleared along the whole length of the route, and hence resettlement of people living along the route.

The open tunnels are constructed separately with a distance between centres of 15.8 m. This leaves a body of earth 5.0 m wide between the tunnel wall exteriors. Construction involves sinking 15 m long prefabricated wall sections with a knife-shaped foot in pairs. During the sinking process the walls are held apart by 2 steel braces at the long ends and held in place and guided by a driver.

Temporary damming beams close the front of the excavations to prevent soil entering. Bentonite suspension can be introduced between the soil and the walls or between the soil and the damming beams to reduce the frictional forces during the driving process.

Following driving, the underwater concrete floor will be put in place. The walls of a section of tunnel will thus be fixed in position. After that, the assembly and sinking of the next pair of wall sections can start. A primary tubular seal will be fitted in the collapsed state in a recess on the front of the walls and cross-cutting between adjacent wall elements and cross-cutting. This is sealed by synthetic resin for chafing protection until the seal is inflated. Point sliding bearings are used to transmit the soil pressure from the caisson to be lowered to the adjacent sunk caisson.

The tunnel is roofed by 30 cm thick, 1 m wide prefabricated concrete panels. These serve as shuttering for the impermeable in-situ concrete roof.

Once the tunnel roof has been put in place and surcharged, full heave protection is guaranteed, and the tunnel can therefore be pumped completely free of groundwater.

To guard against any leaks in the primary seal, an additional compression seal is provided during the sinking process. Swallow-tail sealing sheets are to be fitted between the wall elements and the watertight floor. The joints between the individual wall plates and the sealing sheet are designed as pressure joints and sealed with swelling strips.

Injection tubes run parallel to all the sealing strips, allowing any leaky joints to be repaired if necessary. The project was evaluated by the panel as very innovative with a higher yet manageable technical risk. The construction risk is also high insofar as there are no comparable examples of implementation. In cost terms, at any rate, this is clearly the most favourable project, especially since in contrast to the other studies it involves a solution using wholly open construction.

4 Summing-up

The study has shown that it is entirely possible from a technical and economic point of view to construct a surface tunnel using mining construction methods. Combined solutions using open construction in open countryside and closed construction in built-up areas are also attractive from an economic point of view.

The cheapest method to emerge from the study is wholly open construction using caissons, with a total construction cost of approximately ATS 1.20 billion. This contrasts with combined methods costing around ATS 1.55 billion and the wholly mining construction tunnel at about 1.95 billions. The difference of ATS 370 million between open construction and mining construction mentioned at the beginning has increased to around ATS 770 million due to the technically highly innovative solution using caissons. From a technical point of view, the outcome can be judged very satisfactory, though local people could not be convinced of the appropriateness of an economic solution, even with the now even greater difference between the construction methods. On the basis of the study results, the price difference between combined solutions and open construction is still so great that the decision to use an environmentally compatible construction method has not yet been taken.

Having regard to the diverse range of solutions carefully and painstakingly worked out by the firms concerned, the competition should nevertheless be considered a success.

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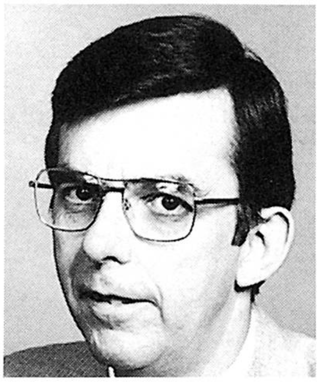
A50 Blythe Bridge to Longton - Meir Tunnel

Bob McKittrick
Director
Scott Wilson
Chesterfield, UK



Bob McKittrick, born 1944, graduated with a BSc in Civil Engineering from Glasgow University. He joined Scott Wilson in 1967 and worked for 7 years in Hong Kong project managing developments in Tuen Mun New Town. His main expertise is bridgeworks.

Summary

Meir Tunnel, 284 metres long between portals, forms part of the upgrading of the A50, through a heavily trafficked urban area of Stoke-on-Trent in England, to dual carriageway. Construction was preceded by the diversion of a large number of utilities, followed by temporary traffic diversions. The walls of the twin cell were formed by contiguous bored piles; ground was then excavated to a depth of 2 metres to enable the roof slab to be constructed. Excavation was then carried out beneath the roof, the base was cast, carriageway laid, linings, lighting and controls installed. The tunnel is self-ventilating. Varying levels of lighting are provided; radio re-broadcast facility is provided for emergency services; three crossover openings are provided in the central wall.

1 History

In the mid 1980s a scheme was developed by Scott Wilson, as consultants to the (then) Department of Transport, to improve the environment of the centre of Meir (Figure 1) by constructing the proposed A50 dual carriageway below existing ground level and carrying the A520 on a low level bridge over a new pedestrian area. This plan was presented in June 1986 to the public who rejected it on the grounds that they wished the Meir crossroads area to remain unchanged. The scheme was then amended considerably and a Public Inquiry was held in November 1990. The proposals were rejected in part and the scheme was further changed and re-presented to the public in 1992 followed by a second Public Inquiry in the summer of 1993. The final scheme which evolved resulted in a lengthened tunnel and an at-grade roundabout above it so as to minimise changes to Meir.

The main objectives of the project were to:

- improve safety for pedestrians, cyclists and drivers
- reduce traffic noise and air pollution
- improve the appearance and amenity of the centre of Meir
- minimise the traffic impact on Meir and retain its existing character and potential for development.

2 Description of the Works

The contract comprises:

- 2 km of dual two-lane carriageway with a 2.5 m wide central reserve
- a tunnel some 284 metres long
- a roundabout and slip roads above the tunnel
- four footbridges (including a cable-stayed one using carbon fibre cables)
- numerous retaining walls.

Figure 1: Meir Crossroads prior to construction

3 The Tunnel

3.1 Ground Conditions

The general geology of the route consists of Middle Coal Measures overlain successively by pebble beds, Keuper Sandstone and Keuper Marl. The tunnel is located within the pebble bed strata. The pebble bed strata consist of interbedded red weakly-cemented sandstones and weakly-cemented to un-cemented quartzitic conglomerates. The pebble bed strata are underlain at depths of about 35 m (west end) to 70 m (east end) by Middle Coal Measures deposits at the tunnel site. In the vicinity of the tunnel construction, groundwater is about 14 m below existing ground. There are many coal seams beneath the site but there are no recorded workings and no plans to mine beneath the site in the future.

3.2 Concept Design

Both 'bottom up' and 'top down' methods of construction were considered.

For 'bottom up', thought was given to forming temporary excavation sides by grouting, soil nailing, sheet piles and king piles/lagging walls. A sequence of construction was developed. For 'top down', consideration, for the side walls, was given to diaphragm walls, secant piled walls and contiguous bored pile walls. Again a sequence of construction was prepared.

The following comparisons resulted:

'Top Down' Construction	'Bottom Up' Construction
• Excavation support walls form integral part of Permanent Works	Excavation support walls independent of permanent works.
• Depth of walls depends on ground conditions and will have to be specified by the Engineer	Excavation support is the responsibility of the Contractor.
• No ground anchors or temporary works impinge on adjacent buildings.	Temporary ground anchors located beneath some adjacent buildings.
• Excavation width is the minimum required and is not enlarged in tunnel approaches.	Excavation width is larger and is further widened in tunnel approaches to construct heel of retaining wall.
• Sequence of excavation is dependent on permanent works requirements.	Sequence of excavation is not dependent on permanent works requirements.
• Monitoring of excavation is required to ascertain deflection of the wall and settlement and displacement behind the wall.	Monitoring of excavation is required as for 'top down' construction plus monitoring of ground anchors.

Although 'bottom up' construction appeared to offer a cost saving it imposed significantly more disturbance and 'cut and cover - top down' using contiguous bored piles was specified in the contract.

3.3 Detailed Design

The tunnel comprises two cells, each being 9.5 m wide between secondary cladding, and contains a 7.3 m carriageway together with 0.2 m edge strips, a 1.0 m outer verge and a 0.8 m inner verge. 900 mm diameter contiguous piles form the side and central walls which are clad using vitreous enamelled steel panels. The East tunnel portal is to have a decorative brickwork feature as it effectively will be a 'gateway' to the City of Stoke-on-Trent.

During the detailed design a trial bore was constructed to confirm the feasibility of constructing bored piles and measure the resulting noise and vibration levels both of which were less than those generated by passing traffic. The piles forming the tunnel walls were generally to penetrate six metres below the tunnel invert giving them an overall length below existing ground level of at least 13.5 metres.

The design was based on the concept of constructing the south cell first and diverting traffic through it whilst the north cell was built. Consideration was given to using the road pavement as a prop for the piled walls but this was rejected as imposing an unnecessary constraint on the contractor.

The original public utilities were located in the existing roadway or footways. To allow construction of the new road and tunnel they had to be diverted and have been repositioned in the new cycleway, footways or service roads. The costs involved, which were paid separately by the Client, were estimated to be about £5 million.

3.4 Tunnel Statistics

Length of tunnel	:	284 m
Volume of structural concrete	:	8700 m^3
Tonnage of reinforcement	:	3700 tonnes
Number of contiguous piles	:	810
Total length of piles	:	7500 m
Volume of earth excavated	:	50,000 m^3
Predicted peak hour traffic flows in the year 2012	:	Westbound 2600 vph Eastbound 3300 vph
Permitted traffic speed	:	64 kph (40 mph)
Costs	:	£4 million between portals + £2 million for lighting & communications

3.5 The Tunnel Equipment

The tunnel is provided with sophisticated monitoring and environmental equipment. Although its length of 284 metres does not require forced ventilation (the piston effect of passage of vehicles through the tunnel will achieve this) many other features are provided.

All control and monitoring systems emanate from the tunnel control building located on the western approach to the tunnel. The tunnel control building is protected by fire detectors linked to an automatic gas extinguishant system and by an anti-intruder security system.

Two separate 11kV substations are provided in the tunnel control building, each being supplied independently from primary sources by the MEB. Each of the two supplies, A and B, will be capable of independently maintaining all tunnel and control building services with automatic changeover in the event of a failure of either one. In the event of a complete failure of the mains electricity system, an uninterruptible power supply (UPS) will come into operation, again with two alternative systems, to supply power to essential services for a minimum of two hours to allow time for evacuation of the tunnel, diversion of traffic and restoration of mains electricity supplies.

The tunnel lighting provides varying lighting levels controlled by photometers on each approach to the tunnel, in accordance with ambient lighting levels. The lights at each end of the tunnel are arranged in four lines along each cell, with a variety of luminaires in each line. The arrangement at each tunnel threshold is different from that in the central section which has two lines of luminaires. Six stages of illumination are provided to allow for all levels of ambient lighting in the transition between day and night, with automatic switching between the stages controlled by the photometers and monitored in the tunnel control building. In the event of a failure of the mains supply a reduced level of overhead lighting and an additional set of emergency lights at low level will be fed from the UPS supply.

Four full-colour pan tilt and zoom closed circuit television cameras, with a zoom ratio of 10:1, are located in the tunnel. Additional ones cover the approach roads. All are linked via the tunnel control building to the Stoke City Monitoring Centre. In the event of an emergency or an incident, control of the monitoring and recording operation can be assumed at either the tunnel control building or at the police control centre in Hanley Police Station.

Eighteen Motorway Standard emergency telephones are provided in the area of the tunnel - seven in each cell with four more on the tunnel approaches. Each is linked to the tunnel control building and to police headquarters. A radio re-broadcast system is installed to allow the use of radios by the emergency services within the tunnel.

When it is necessary to close the tunnel for an emergency, road traffic accident or for general maintenance work, variable message signs are provided on the approaches to the tunnel to divert traffic onto the slip roads and across the roundabout in the centre of Meir. A total of fourteen traffic queue loops are installed in the road surface within the tunnel to detect standing traffic. Visibility sensors are situated on the tunnel walls to warn of low visibility caused by exhaust fumes etc.. A series of signs warn drivers of stationary vehicles to switch off their engines to avoid a build-up of exhaust fumes.

Sensors are installed in the drainage system within the tunnel to detect any significant build-up of oil, diesel etc. and a valve is provided to prevent the discharge of these liquids into the public sewers. Fire extinguishers are located in separate cabinets throughout the tunnel adjacent to the emergency telephones and near the emergency crossover doors. Fire hydrants are provided for the use of the fire and rescue services at each end of each cell of the tunnel.

3.6 Roadworks

A 150 mm thick layer of cement bound sub-base material is placed on compacted ground through the tunnel area and the approach ramps. This is overlain by a 250 mm thick layer of continuously reinforced concrete roadbase.

Two layers of bituminous material are laid on top of the concrete roadbase. The lower layer is 60 mm thick rolled asphalt, which forms an impermeable barrier to protect the concrete roadbase from the effects of water and salt. The final surface comprises 50 mm of porous asphalt, which has been selected for its environmental and safety benefits. This type of surfacing not only lowers noise from the road, but reduces the effects of spray in wet weather.

Actual construction details for the road through the tunnel are:

Bituminous Surfacing (porous asphalt)	50 mm
Bituminous Basecourse	60 mm
Concrete Roadbase	250 mm
Cement Bound Sub-Base	150 mm

4 Tunnel Construction

The contract, at a tender cost of £21.3 million, was awarded to Amey Construction Ltd, under the ICE 5th Edition Conditions of Contract, and construction commenced in April 1995 for a planned completion in spring 1998. Construction of the tunnel itself started in July 1996 once the area had been cleared of all service cables and pipes. Three rows of contiguous bored piles were bored and concreted to form the central division and two outside walls. In December 1996 the first of the tunnel roof slabs was cast in a 20 metre section, and this was followed on a regular basis by other sections of roof. (Figure 2) Soil was excavated from both halves of the tunnel by a combination of a tracked excavator and a rubber tyred shovel. Special precautions were taken to ventilate the air inside the tunnel and to keep it free from obnoxious exhaust fumes. Some of the excavated material was used on another local road scheme in Stoke, while the rest was disposed of at local tips.

Figure 2: Road diversion during tunnel construction

Two sections of the tunnel which could not be constructed at the same time were those under Broadway and Weston Road where these crossed the construction area. Following the casting of adjacent roof slabs, both roads were diverted across the new tunnel roof in January 1997, allowing access to the remaining two sections of tunnel construction which were completed in mid March 1997. Excavation was completed in mid April 1997.

The piles exposed within the tunnel were then cleaned and the casting of concrete plinths etc. was commenced. (Figure 3) At the same time the road slab was cast and this was followed by installation of the tunnel linings, lighting and control systems.

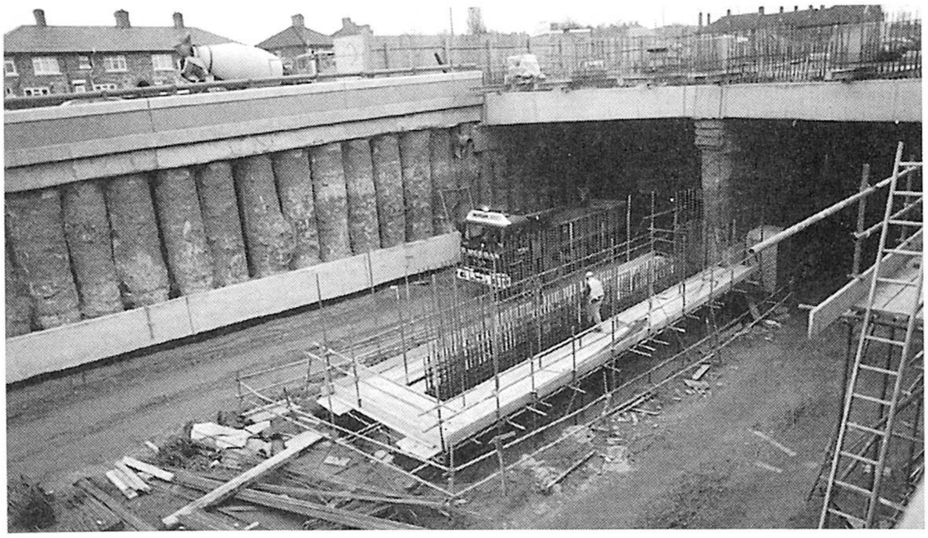


Figure 3: Tunnel construction

The tunnel is due to open by the end of 1997, some four months ahead of programme.

Planning of Tunnel Structures for Mass Rapid Transport System, Dehli

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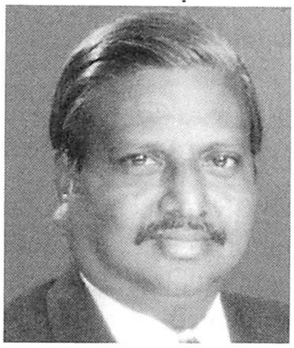

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Summary

Delhi, the national capital of India with a population of about 11 million is, perhaps, the only city of its size in the world, which depends almost entirely on buses as its sole mode of mass transport.The proposed Integrated Multi-Modal Mass Rapid Transport System for Delhi envisages construction of a network, having a combination of underground, elevated and surface sections totaling 198.5 km. The Modified First Phase, expected to cost around US$ 1.39 billion, shall have a 11 km Underground Metro Corridor passing through diverse types of soil and rock and hence calls for various types of construction methods; 7.53 km is proposed to be constructed by "Cut and Cover", 1.97km by "Bored Tunneling", and 1.53 km by "Rock Tunneling". The paper describes the project and details the philosophy of planning and designing the proposed "Tunnel" structures. It also analyses the economic considerations and reports the proposed financing plan.

1. Introduction

In Dehli, the bus services are inadequate and because heavily over-crowded. This has led to proliferation of personalized vehicles (around 2.7 million), and nearly 70% of these vehicles are two-wheelers. The result is extreme congestion on the roads, slow speed, increasing accident rate, fuel wastage and environmental pollution. With a view to reduce the problems of Delhi commuters, Government of India (GOI) and Government of National Capital Territory of Delhi (GNCTD) have launched the Integrated Multi- Modal Mass Rapid Transport System (MRTS) for Delhi at an estimated cost of Rs 48.60 billion (1.39 billion US$) at April 1996 price level, which includes a discounted Interest during construction of US$ 38.9 million. Like that of Singapore Mass Transit Project, which had a gestation of some 14 years, Delhi MRTS project also had a gestation of more than 20 years from 1974, when the first planning started. This was mainly due to the initial high priority of the developing country on public housing, schools, drainage, water supply and many other basic requirements than projects of this nature requiring heavy investments. Delhi Mass Rapid Transport System project will be implemented through Delhi Metro Rail Corporation Ltd., a para-statal joint venture company, set up on 50:50 partnership basis by GOI and GNCTD. The Delhi MRTS is essentially a "social" sector project, whose benefits will pervade wide sections of the economy. The economic IRR of the project has been worked out as 21.4%, and the financial IRR is less than 3%. The full system (**Figure 1**) will have a network of 198.5 km. The Modified First Phase (**Figure 2**) shall cover a network of 55.3 km consisting of 11 km underground **Metro Corridor** (**Figure 3**) and 44.3 km of elevated/surface **Rail Corridors** (**Figure 4**). The Modified First Phase is estimated to carry 3.18 million passengers per day in the year 2005, when all the sections (55.3 km) of the Modified First Phase is planned to be commissioned. The passenger-km carried per day would be of the order of 23 million and the mean trip length would be 7.12 km [1].

2. Planning Objectives and Basic Parameters

The planning of Delhi Mass Rapid Transport System had 4 main planning objectives: (a) should meet the demand for the year 2001 and beyond, (b) should reduce the journey time, (c) should provide relief to the road system, and (d) should involve least investment. Naturally the system had to be a proven one instead of being experimented for the first time. This lead to a few other secondary objectives/ decisions: (a) should be such that the overall capital and operating costs are minimized, (b) should not only be efficient but the foreign exchange requirement should be minimum, (c) should be possible to easily manufacture the coaches in India; if imported, technology transfer should be feasible, (d) should exploit the airspace development (property development) over the stations and depots, (e)multi modal transport integration should be given importance to attract the commuters, (f) alignment shall be such that the requirement of urban land and disturbance to existing properties are minimized, (g) should link the existing Railway system, and adopt Indian Railway Standards as far as possible.

As per the Government policy of Unigauge, the "Broad Gauge"and a corresponding tunnel size of 5.4m has been adopted for Delhi MRTS. Several techno-economic studies were undertaken to optimize coach design, the guiding criteria being passenger comfort, reduced journey time and energy efficiency. Whereas the coaches proposed for Rail Corridors is 25kv Electric Multiple Unit (EMU) coaches, for the Metro Corridor three-phase AC induction motor drive with Variable Voltage Variable Frequency (VVVF) control and light weight coaches (3.2m wide) have been planned. Initially, coaches for Metro Corridor will require to be imported along with transfer of technology. Subsequently, the coaches will be manufactured indigenously. Considering the economy in the requirement of power during operation and the low initial investment, 1500 v dc with fixed overhead conductors have been proposed for Metro corridor. On economic considerations, only air cooling has been proposed in the underground Metro stations. Coaches also are not planned to be air conditioned. The requirement of the property development and multi-modal integration aspects have greatly influenced the planning and design of stations and the tunnel structures in the stations. Property development has been planned over the stations and depots and about 198 hectares of area is planned to be built.

3. Planning and Designing of Tunnels

The 11 km underground Metro Corridor between the proposed Vishwa Vidyalaya station and Central Secretariat station passes under some of the busiest areas of the city. The alignment passes through diverse types of soil and rock and hence calls for various types of construction methods. The work also involves working under the water table which is generally at 7 m below the ground level. The alignment has been kept shallow and the platform level is, generally, about 13 m below ground level. Rock comprisisng of quartzite and interbeded micaceous material is encountered between Delhi Main and New Delhi Stations, for a length of about 1.6 km. Near Chawri Bazar station, the rock is at about 10 m depth from ground level. The rock is jointed with low RQD (Rock Quality Designation) with uniaxial compressive strength of 750 kg/sqcm to 1250 kg/sqcm. The balance portion of the alignment has non plastic to low plastic silty sand (alluvial) facilitating long lengths of bored tunneling. Plasticity Index of of soil varies from 2 to 8 and field permeability varies from 10^{-3} to 10^{-5} cm/sec. The section beyond ISBT upto Vishwa Vidyalaya has mixed type soil conditions of silty-sandy soil alternating with rocky ridge and, hence "Cut and Cover" construction method has been proposed, in this section. Thus, 7.53 km of the underground Metro Corridor is proposed to be constructed by "Cut and Cover" method, 1.97 km by "Bored Tunneling" method in soil with Tunnel Boring Machines (TBM) and 1.53 km by "Rock Tunneling" method. Presense of silty sand and high water table has necessitated adoption of diaphragm wall for retaining the soil in "Cut and Cover" section.

Cross sections of "Cut and Cover" box section and circular tunnel are shown in **Figure 5** and **Figure 6**. The tunnels are circular in shape considering the methodology of the execution of the tunnels and usage of tunnel boring machines. Whereas the diameter of tunnel adopted in Hong Kong, Calcutta and Singpore metros is 5.2m, Delhi shall have a tunnel diameter of 5.4m. In-situ lining in concrete in "Rock Tunneling" section and precast concrete lining segments in the "Bored Tunneling" are proposed. However, in the "Cut and Cover" section twin boxes are preferred considering easy method of construction. In most of the projects in India the desirable option is only concrete. Obviously, for the tunnels for the MRTS, the natural choice was concrete.It is proposed to construct the tunnels through design and construct contracts so that contractor can adopt their construction method and equipment. It is estimated that the construction of Metro Corriodor (11km) shall involve 3 million cum of earthwork, 0.68 million cum of concreting and also shall require 0.12 million tonne of steel.

Measures for controlling subsidence and settlement during tunneling have been proposed, which include provision of adequate soil cover over the tunnel, adoption of appropriate tunneling technology, use of segmental lining, use of tunneling shield, efficient and immediate grouting and soil stabilization over the tunnel and proper dewatering techniques. During construction, ground movement will be monitored regularly.

4. Stations

Stations in Underground Metro Corridor have been located on considerations of accessibility, integration with other modes, availability of space for parking, ease of passenger dispersal, etc. The Modified First Phase envisages construction of 10 underground stations; 9 stations by "Cut & Cover" method, in order to minimize the cost of construction and one station (Chawri Bazar), being located in a thickly populated area shall be constructed by "Rock Tunneling". The facilities provided in the stations shall be comparable to that provided in any other Metro in the World.

5. Estimated Costs and Financing Plan

The total estimated cost of the Modified First Phase at April 1996 price level works out to Rupees 48.6 billion (1.39 billion US$). The Civil Engineering construction cost of the tunnels of 5.4 m finished diameter by "Bored Tunneling" works out to approximately as US$ 22 million per route km at April 96 price level. The cost of construction of tunnel in rock works out to approximately US$ 19 million per route km. Cost of construction by "Cut and Cover" tunnels works out to approximately US$ 29 million per route km. Whereas the total capital costs including that of rolling stock, land etc., incurred/ estimated (updated to April 1996 price level) for the Metros in the World works out to 61-201 million US$ per route km [3], the estimated cost of the proposed MRTS for Delhi is 60.9 million US$ (based on the exange rate of Rs. 35 per 1 US$). It could be seen that the system planned for Delhi is economical, in addition to being easier to construct by national contractors. The project shall be financed by the Overseas Economic Cooperation Fund (OECF) loan of Japan to the extent of 56% of the estimated capital cost; 30% of the capital cost shall be contributed equally by GOI and GNCTD and 8% shall be subordinate debt towards the cost of land. It is estimated that property development may generate the balance requirement of about 6% of capital cost, during construction stage.

6. Conclusions

Efforts are on to optimize the size of structural members and to improve the aesthetics further. Utility of space in underground tunnels and stations has also been planned to be optimized by adopting economic layout techniques. The Project will throw up a number of challenges to the Design Engineers and Construction Engineers, in view of a wide variety of constraints that are required to be taken care of during construction.

7. Acknowledgement

The author wishes to acknowledge the support and enthusiasm received from Mr. B.I. Singal, Managing Director, RITES and Mr. A.K. Chakravarty, Group General Manager, UT Division, RITES during the preparation of this paper. Special thanks are due to Mr. Rakesh Kapur, Deputy General Manager, RITES, for his active help in preparing this paper. The author also wishes to acknowledge the support received from the Civil Engineering Departmet, University of Malaya, during the finalisation of the paper.

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Fig. 1 Full System of Delhi MRTS

Fig. 2 Modified First Phase of Delhi MRTS

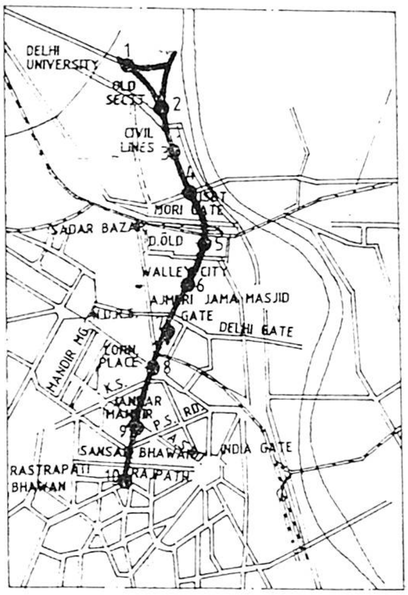

Fig. 3 Key Plan of Metro Corridor

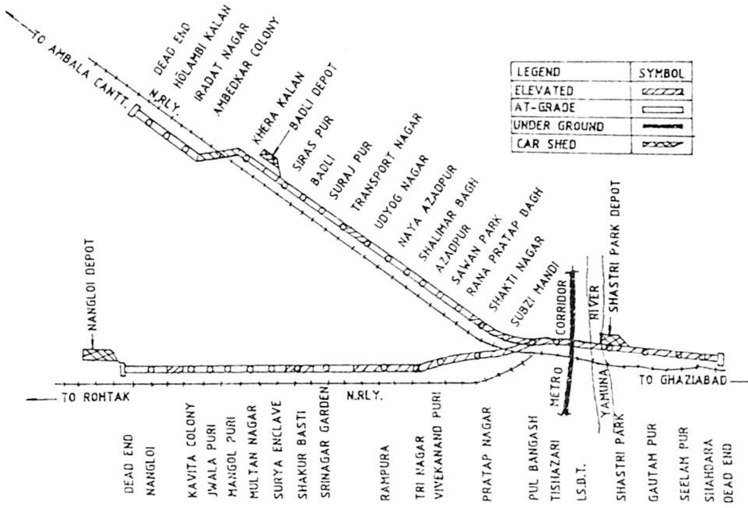

Fig. 4 Key Plan of Rail Corridor

STATIONS OF METRO CORRIDOR

1. VISHWA VIDYALAYA
2. OLD SECRETARIAT
3. CIVIL LINES
4. ISBT
5. DELHI MAIN
6. CHAWRI BAZAR
7. NEW DELHI
8. CONNAUGHT PLACE
9. PATEL CHOWK
10. CEN. SECRETARIAT

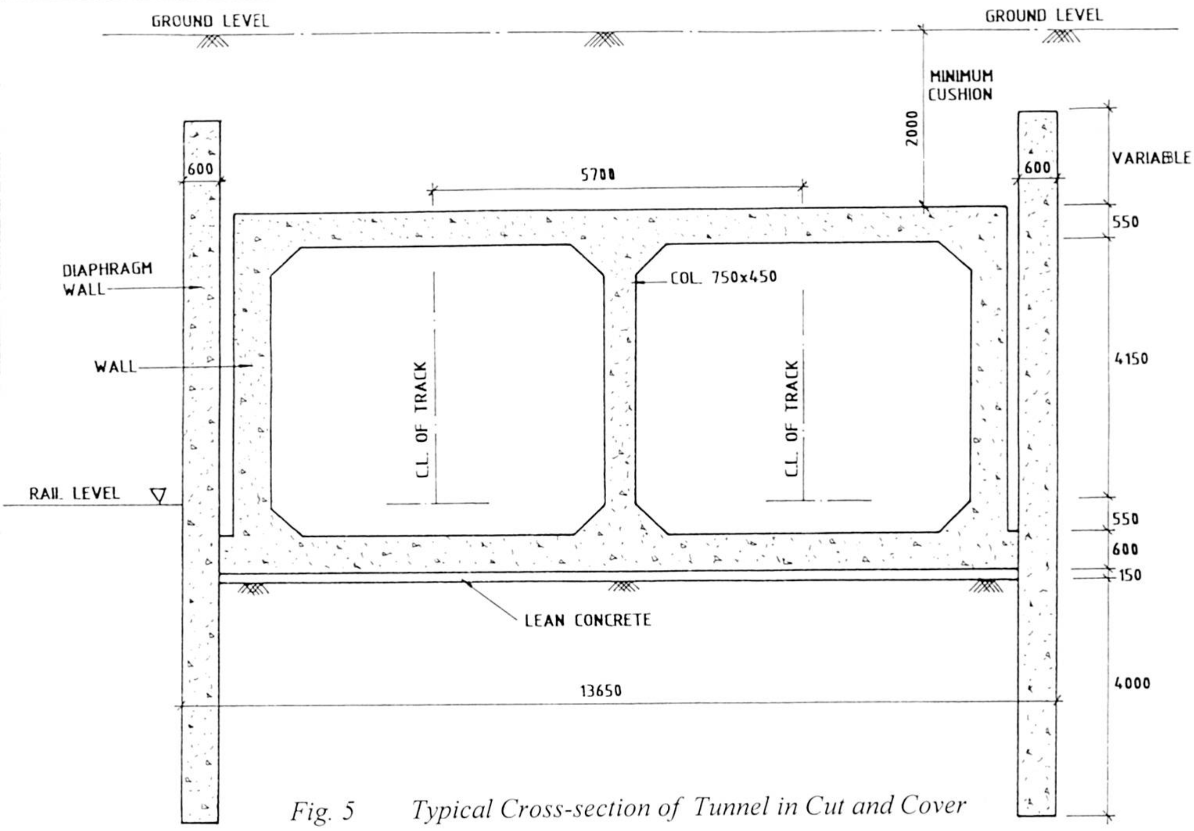

Fig. 5 Typical Cross-section of Tunnel in Cut and Cover

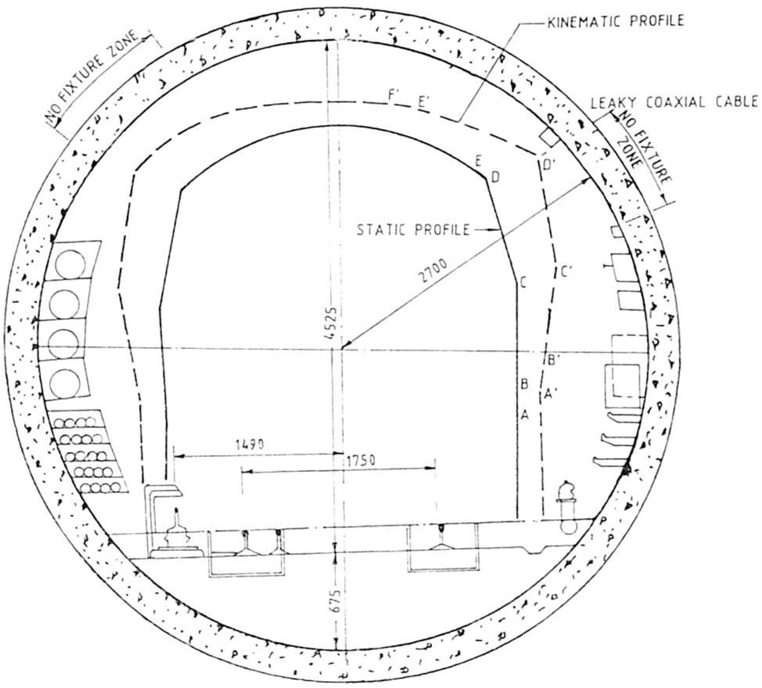

Fig. 6 Typical Cross-section of Tunnel in Rock Tunneling