CASE STUDY - UNDERPASS DESIGN FOR 3 URBAN INTERSECTIONS USING TIE-BACK WALLS

P. LEUNG, BE, MEngSc, MIEAust
Design Engineer, Bridge Branch
Roads and Traffic Authority, NSW

L. KEE, BE, MIEAust
Design Engineer, Bridge Branch
Roads and Traffic Authority, NSW

SUMMARY

Three underpass projects in Sydney metropolitan area are described. In each case, tie-back walls and abutments were used instead of conventional retaining walls. This allows excavation adjacent to and below main urban arterial roads without disruption to traffic flow. This paper describes the extensive use of tie-back walls and discusses briefly the design of these tie-back walls.

KEYWORDS

Urban underpass bridge, Grade separation construction, Tie-back wall, Cantilever wall, Rock anchors.

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Peter Leung graduated in Civil Engineering from the University of Newcastle in 1982 and completed a MEngSc degree at the University of Sydney in 1984. Since graduation, he has worked with the Public Works Department of NSW, Connell Wagner and joined the Bridge Branch of the Roads and Traffic Authority, NSW in 1989. He has been involved in the design of various major traffic interchange around the Sydney metropolitan area and the cut and cover section for the Sydney Harbour Tunnel.

Lee Kee graduated from the University of Canterbury, Christchurch, New Zealand in 1969. After graduation, he worked in New Zealand and Singapore on reinforced concrete building design of highrise office development and public housing. Since 1974, he has been involved in the design and construction of bridges with the Roads and Traffic Authority, NSW.
INTRODUCTION

The Roads and Traffic Authority of New South Wales is responsible for the planning, design and supervision of construction for the Gore Hill Freeway in the Sydney metropolitan area. This work involves the construction of 3.1 km of freeway, including two major traffic interchanges at each end of the freeway extending from the Pacific Highway at Lane Cove to the Warringah Expressway. These two sites are shown in Fig 1 and 2. In each case the purpose of the traffic interchange is to separate large volumes of high speed traffic at different grades.

Tie-back walls and abutments were chosen as the least costly of all alternatives to minimize the impact of construction on the already congested traffic. In the past, conventional reinforced concrete cantilever retaining walls were usually used for such projects. However these walls require extensive working space for the base construction and to ensure the associated temporary cut slopes remained stable during construction. With construction in urban areas it is essential to minimize costly land acquisition, interruption to existing properties, traffic and utility services. The use of tie-back wall provide a solution to these requirements.

Similar design and construction techniques were also applied to a third traffic interchange at Top Ryde in Sydney's north west (site plan shown in Fig 3.). The design requirements and site conditions are similar to those at Gore Hill Freeway.

This paper summarizes the main features of each traffic underpass and then outlines the common design procedures adopted for the tie-back walls.

PACIFIC HIGHWAY INTERCHANGE

Project Description

This interchange is located at the western end of the Gore Hill Freeway and serves as a grade separation function at the Pacific Highway/Longueville Road intersection at Lane Cove.

The bridge superstructure comprises a single 24.5 m simply supported span of precast pre-tensioned concrete trough girders with cast in-situ concrete deck. The superstructure is supported on tie-back abutments constructed with 750 mm diameter cast in place reinforced concrete piles spaced at 1.5 m centres founded in shale. The piles have permanent tie-backs stressed into rock and the excavation between piles is laterally supported with 75 mm thick arch shaped shotcrete constructed in stages during excavation. Corrugated sheeting is placed between piles in front of the shotcrete to provide drainage and in-situ concrete infill forms the wall facing to the piles. A typical cross section is shown in Fig 4.

Retaining walls for the ramp area are generally divided into three different types, depending on the height (H) of fill behind the wall and the work space available. See Fig 5 and 7.

Type A Gravity retaining wall  
Type B Pile retaining wall  
Type C Pile retaining wall with tie-backs

Pile retaining walls with tie-backs have similar construction details as the abutment walls described above. The gravity walls are of classical construction and will not be discussed here.
Geotechnical investigation indicated that the proposed cutting have layers of residual soil (up to 10 m) overlying weathered shale. The residual soil is mainly clay of medium plasticity and is generally firm to very stiff. The piles and tie-back bond lengths are designed to be anchored into Class V or better shale.

Traffic control

To minimize disruption to existing traffic and to provide sufficient working space for construction, this interchange is constructed in 4 stages.

Stage 1 - Construction of utility bridge and temporary diversion road.
Utility bridge which form the pedestrian walkway for the final bridge is constructed at the eastern end of the interchanges providing space for all utility relocations. Temporary diversion road is constructed around the site for traffic diversion. Both of these activities are completed without disruption to the traffic.

Stage 2 - Construct bulk of bridgeworks and on-load ramp walls.
Traffic is re-directed on to the temporary diversion road around the site, enabling construction of the bridge to begin. At the same time pile retaining walls for on-load ramps on the southern side are started.

Stage 3 - Construct southern side and part of northern side retaining walls.
Direct traffic over bridge, in areas north of bridge site and next to on-load ramp to provide work space for construction of walls on the southern side and part of northern side.

Stage 4 - Completion of structure.
At this stage two traffic lanes are diverted under the bridge and sufficient work space made available for completing northern walls.

WILLOUGHBY ROAD INTERCHANGE

Project description

This interchange is located at the eastern end of the Gore Hill Freeway and serves as a grade separation function for Willoughby Road and the Warringah Expressway.

With the main bridge span at 23.0 m and with an overall width of 64 m, the superstructure design and the construction details for the abutment wall/tie-back retaining wall are similar to the Pacific Highway Interchange. The 750 mm diameter cast in place reinforced concrete piles for these wall are spaced at 2.0 m centres and are founded in sandstone. A typical cross section is shown in Fig.4.

Retaining walls for the ramp area comprise similar Type A and C walls described above for the Pacific Highway Interchange plus Type E wall, which is a cantilever retaining wall (see Fig.7).

The ground conditions in this site are mainly sandstone varying from Class V to II overlaid with residual soil varying in depth of up to 4 m.

Traffic Control

Traffic control for this site was not as complicated as that for the Pacific Highway, requiring only two stages of construction.
Stage 1 - Construct southern half of bridge and ramp retaining walls. Northbound traffic is diverted around the site through Donnelly Road and Willoughby Road providing enough work space to complete southern half of the project.

Stage 2 - Complete northern half of bridge and ramp retaining walls. On completion of the southern half of bridge, traffic is transferred over the bridge enabling construction of the northern half of project to commence.

TOP RYDE INTERCHANGE

Project Description

The construction of the underpass bridge at Victoria Road over re-aligned Devlin Street, Ryde, is to be carried out in three stages.

The overall length of the bridge is 23m. The overall width of the deck varies from 73.4m at the abutments to 66.1 at mid span. A longitudinal deck joint divides the deck into two independent sections. The superstructure comprises precast pre-tensioned trough girders composite with insitu deck slab and integral with cast-in-place post-tensioned voided slabs.

Overhanging slabs supporting by cantilever beams at each corner of the abutments form part of the 'Texas Turn' located at the edge of the deck.

Some underpass retaining wall panels are located in filled area where part of Victoria Road is founded. Shale, ranging from sound to highly weathered, is present at varying depth. The large variation in the elevation of the sound rock strata allows the change from tie-back to cantilever retaining walls.

The pile toes are generally founded 3.5m below the design surface level of the underpass with 111 socket into Class II shale. At locations where only Class III shale is present, the length of the pile socket is lengthened.

Traffic control

In order to maintain existing traffic flow on Victoria Road during the early stage of construction, the two outer sections of the wide deck are located clear of the existing footpaths. Westbound traffic from Sydney to Parramatta will then be transferred to part of the completed Stage 1 deck. Subsequently, traffic will be temporarily diverted in stages as each stage construction is completed.

The stage construction allows the transfer of traffic without closure or reduction of traffic lanes. However, the deck construction sequence necessitates excavation to be carried out very close to the existing roadway at some stage of the construction.

SUMMARY FOR THESE THREE TRAFFIC INTERCHANGE

The tie-back wall method of construction eliminates the necessity for temporary shoring such as sheet piling at the junction of the remaining roadway and the new deck. Tie-back wall construction also allows early use of the bridge deck which permits excavation and construction activity underneath the bridge to start at an early stage. A typical construction stage and the excavation sequence are shown in Fig.8.
The main features for these three interchanges are summarized in Table 1 with tender prices included. The tie-back wall heights for these three interchanges varies from 3.5 to 9 m, with an average of 6.5 m. With tie-back levels spacing at 2.5 m along each pile. Construction costs are approximately $1,800 per m² of wall surface. This rate is competitive to the conventional cantilever retaining wall system with the same height i.e. counterfort retaining wall where large scale excavation and temporary support are required.

It should also be noted that at each construction stage, traffic lanes are permitted next to or very close to the final wall locations with the tie-back wall arrangement. This would not be possible if the cantilever retaining wall option was adopted.

**DESIGN OF TIE-BACK WALLS AND BRIDGE ABUTMENTS**

**Design parameters and procedure**

The major design parameters considered are as follows:

- earth pressure coefficient behind wall,
- pile spacing and diameter,
- tie-back design load and spacing,
- ground conditions behind the retaining wall and around tie-back bond length,
- tie-back inclination angle,
- construction staging/sequence.

The design parameters for the tie-back wall listed above are inter-related. The first step is to establish the maximum design working load for the tie-back, with an assumed bond length, for the proposed site. After obtaining the earth pressure diagram behind the wall (Mackey and Kiric 1967), the pile size, spacings, number of tie-backs and its inclination angle can be determined.

At each stage of excavation, the bearing pressure at the founding level of the piles and the structural capacity of the piles and tie-backs are checked to ensure no overstressing occurs.

**Computer model for simulation of tie-back wall**

A 2-D "microSTRAN" model was set-up for the analysis of the tie-back wall. Nodes for structural members are created at key positions uniformly spaced. Lateral earth pressure from ground surface to excavation line was applied to these structural members. Soil below the excavation line was modelled as springs with their respective subgrade modulus $K_{s1}$ (Bowles 1977).

$$K_{s1} = \frac{1.3}{B} \cdot \frac{E_s B^4}{12 \sqrt{E_p I_p}} \cdot \frac{E_s}{1 - u^2}$$

The tie-backs loads vary at different stages of excavation. To facilitate convenient output results, the tie-backs are modeled as springs with equivalent stiffness $K_{s2}$. The prestress load on these tie-backs is input as a displacement within the tie-back.
\[ K_{s2} = \frac{E_t A_t}{L} \]

\[ A_t \]  
Tie-back X-sectional area (mm²)

\[ B \]  
Width of pile (mm)

\[ E_p \]  
Modulus of elasticity of pile (MPa)

\[ E_s \]  
Modulus of elasticity of soil (MPa)

\[ E_t \]  
Modulus of elasticity of tie-back (MPa)

\[ I_p \]  
Moment of inertia of pile (mm⁴)

\[ K_1 \]  
Partially mobilised active pressure

\[ K_{s1} \]  
Modulus of subgrade reaction (N/mm)

\[ K_{s2} \]  
Equivalent spring stiffness for tie-back

\[ L \]  
Tie-back free length (mm)

\[ u \]  
Soil poisson's ratio

The "microSTRAN" model was chosen for analysis due to its simplicity in considering a number of design cases. The results of the analysis provided information on:-

- the displacement of wall,
- the effect of different construction stages on the tie-back wall,
- the effect of varying tie-back prestress load,
- the effect of varying pile stiffness.

**Design criteria for tie-back wall**

In designing the tie-back wall, the design earth pressure behind the wall was assumed to be neither active nor at-rest pressure, but somewhere in-between. This is termed partially mobilized active pressure \( K_1 \).

Choice of \( K_1 \) was based on past experience on similar projects and the required settlement control in the adjacent area at each site. For the Pacific Highway and Willoughby sites a value of \( K_1 = 0.6 \) was used, while in the Top Ryde site a value of \( K_1 = 0.9 \) was adopted due to the over consolidated soil properties. Soil properties were obtained from the field sampling and testing of site soils. By assuming a triangular pressure distribution, the spacing of the tie-backs was adjusted so that approximately the same load was transmitted into each tie-back. In addition, a surcharge load of 1.2 m of fill was included in the design.

It is anticipated that the tie-back load will decrease slightly from its design value as the excavation is carried out. This is due to the piles deflecting slightly into the excavation face producing a trapezoidal or parabolic shape earth pressure diagram. For these three underpass projects triangular shape pressure diagrams were used, assuming that the piles are rigid. (Clough 1972)

All the tie-backs in these three sites are designed on the basis of 'failure' criteria (Pinelo...
and Fernandes 1980). The maximum design working loads for the tie-backs are fixed according to the ultimate limit load, with an appropriate factor of safety established by a semi-empirical approach, verified by in-situ testing of anchors.

Six test anchors were installed in an area close to the Pacific Highway site to provide information on the ultimate anchor bond capacity and long-term creep behaviour.

Tie-back walls for all the underpass studies were designed under the criteria of maximum displacement of wall less than 0.005 times the wall height (Liu and Dugan 1974).

**REQUIREMENTS AND PERFORMANCE TEST ON ANCHORS**

The supply, installation and stressing of tie-backs is in accordance with the technical specification issued by the Roads and Traffic Authority, New South Wales. Long-term corrosion protection for these tie-backs is provided over the full length by encasing each anchor in PVC sheathing in conjunction with internal and external grouting. Corrugated type sheathing was applied to the bond length and smooth sheathing to the free length.

After the hole for the tie-back is drilled and cleaned, the tie-back is inserted and water tested, then the hole fully grouted. Once the grout has achieved its specified strength, performance tests are made on each tie-back. The tie-backs are loaded in accordance with their prescribed cyclic load increments.

In order to ensure that the free stressing length is effective, it is specified that the total elastic movement must be at least 90% of the theoretical elastic elongation of the tendon but not greater than the elongation of the free-stressing length plus half the bond length in each case (RTA Technical Specifications (Bridgeworks) 1991).

**MONITORING**

**Monitoring during construction**

After all tie-backs have passed the performance test, selected tie-backs are monitored by performing lift-off tests at 7 days, 14 days and 1 month intervals. Variation of residual load within these tie-backs is required to be within 10% of that measured immediately after lock-off. If the 10% limit is exceeded, then the tie-back working load is downgraded and additional tie-backs installed to recover the lost load capacity or by increasing the working load of adjacent tie-backs (RTA Technical Specifications (Bridgeworks) 1991). Survey marks are installed at selected piles to monitor wall deflections at different stages of construction.

**Long term monitoring**

Inclinometers are installed at selected piles for long term deflection measurement. At the time of writing this paper, permanent load cells are being considered to be installed at selected anchor heads to provide extra information about the behaviour of these tie-backs.
CONCLUSION

The tie-back support system for permanent retaining walls as adopted for the construction of these three urban underpass projects, permits construction with minimum interruption to existing traffic conditions. This method also provides substantial saving in construction time and is competitive compared to the conventional cantilever retaining wall system.

REFERENCE

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**TABLE I**

**COMPARISON OF THE THREE TRAFFIC INTERCHANGES**

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Fig 1 - Site plan for Pacific Highway Interchange
Fig 2 - Site plan for Willoughby Road Interchange
Fig. 3 - Site plan for Top Ryde Interchange
Fig. 4 - Typical X-section for pile retaining wall with or without tie-backs

Fig. 5 - Gravity retaining wall

Fig. 6 - Cantilever retaining wall
EXISTING SURFACE LEVEL
BACKFILL AFTER INSTALLATION
OF 1st TIE-BACK

INITIAL BACKFILL LEVEL
BEFORE INSTALLATION
OF 1st TIE-BACK

CRUSHED ROCK BACKFILL
COMPACT IN 150mm THICK
MAXIMUM LAYERS

EXISTING SURFACE LEVEL

BACKFILL AFTER INSTALLATION
OF 1st TIE-BACK

INITIAL BACKFILL LEVEL
BEFORE INSTALLATION
OF 1st TIE-BACK

CRUSHED ROCK BACKFILL
COMPACT IN 150mm THICK
MAXIMUM LAYERS

Fig. 7 - Pile retaining wall with tie-backs

STAGE 1
STAGE 2

Original surface

Direction of excavation

Fig. 8 - Stage construction of bridge next to existing traffic

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