# OPTIMISING PRECAST CANTILEVER WALLS FOUNDED IN SYDNEY SANDSTONE

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## ABSTRACT

Linear Infrastructure projects requiring grade separations have historically used a multitude of retaining wall systems, such as gravity, piled and reinforced soil structures (RSS), depending on ground conditions. L-shaped cantilever cast in-situ walls have been used extensively in road projects in the Sydney region. These walls are costly as they use a significant amount of concrete and steel, while achieving an aesthetically pleasing finish is difficult. Such walls may not take full advantage of rock foundations prevalent in the Sydney Basin. This paper presents an updated concept for optimising retaining walls under appropriate conditions, combining precast and cast in-situ elements while increasing the effectiveness of the load transfer mechanism to the ground.

In essence, this system is a retaining solution comprising full-height precast wall facing units secured to a cast-in-situ footing forming a monolithic cantilever concrete wall. The facing units are each precast with a set of counterforts on the rear side to transfer load to the footing. This paper discusses and investigates both the design of this precast solution, focussing on counterforts and footing, and the adequacy of the solution from a geotechnical point of view, as it relates to the prevalence of rock foundations in the Sydney Basin.

## 1 INTRODUCTION

This paper presents an updated concept for optimising retaining walls under appropriate conditions, combining precast and cast in-situ elements while increasing the effectiveness of the load transfer mechanism to the ground given appropriate ground conditions.

This system is a retaining solution comprising full-height precast wall facing units secured to a cast-in-situ footing forming a monolithic cantilever concrete wall. The facing units are each precast with a set of counterforts on the rear side to efficiently transfer load to the footing. Continuity and load transfer between the counterforts and the cast-in-situ footing is achieved by means of construction joints between the elements and reinforcing anchor bars protruding from the counterforts which are incorporated in the in-situ footing pour.

This type of precast retaining wall is an effective solution when a standard wall stem may not be implemented due to space constraints. It is also appropriate when site conditions such as excavation on rock is required, or where backfill unavailability rules out the use of other retaining system such as Mechanically Stabilised Earth (MSE).

TechWall® combines counterfort design advantages with the efficiency of precast concrete in terms of architectural finish possibilities and reduced installation timeframes. Furthermore, it may be considered as an optimisation of retaining walls specified as cast in-situ because:

1. It is based on a standard, well understood design process. The innovative aspects of this system comprise the software used to complete the design and the marriage of precast and cast-in-situ elements. The design method is in line with generally accepted methods used in geotechnical and structural engineering
2. It eliminates significant temporary works on site
3. Temporary props can be removed once the footing is cast and cured
4. Primary structural elements (panel facing and any adjoining elements such as parapets or impact barriers) can be fabricated in a strictly controlled environment off-site
5. Significant time efficiencies are possible with rapid installation of precast elements, reducing the impact of the project works on local communities.
6. Significant efficiencies in concrete volumes in the wall facing can be realised, thus reducing the carbon footprint of the project

Key to the overall efficiency of this solution are two factors:

Firstly, the counterforts act as equivalent cantilever beams structurally connected to the footing to resist lateral earth pressure and minimise the stresses on the facing panels. This allows for relatively thin concrete facing elements.

Secondly, the footing design is key in the optimisation and sustainability of the solution, by allowing for reduced excavation and backfill in comparison with other traditional forms. The system can consider multiple footing arrangements like cast-in-situ concrete walls, including a variety of heel/toe geometries to suit the prevailing conditions on site. Further incidental efficiencies can be realised, such as the case where no footing toe is incorporated. In this scenario, the precast facing elements can also act as formwork when stitching the facing and footing elements together.

The system can incorporate reinforced concrete impact barriers (crash barriers) at top of wall by connecting barrier elements (cast-in-place or precast) to facing panels via the counterfort reinforcement. This provides a solution that can be constructed integral with the retaining walls, but primarily provides efficiency of impact load transfer to the ground. The system is known as its proprietary name “TechWall®”, although it is important to note that the system does not include any proprietary elements. The system is an optimisation of existing counterfort retaining wall design and construction.

Retaining walls are typically classified into four categories, with sub-categories contained therein. The four main categories are gravity, semi-gravity, non-gravity cantilevered, and anchored. The TechWall® system falls under the semi-gravity wall category, since the system relies on structural components to mobilise the dead weight of backfill, which in turn provides lateral load resistance and load transfer to the ground. Back in the mid 1980’s Tierra Armada, the Spanish branch of the Reinforced Earth Company, experienced issues with numerous contractors who could not source select backfill which was chemically and/or physically compliant with accepted MSE technical specifications. This led to the implementation of a research project to develop an alternative retaining system, which would incorporate the software development and precast expertise Tierra Armada possessed. The result of this project was the TechWall® system, and since then over 600,000m$^2$ of TechWall® units have been installed in Spain alone. The TechWall® system, with minor modifications, was also implemented in the United States. The system has also been used in France and most recently in Peru. Refer to **Table 1** below for TechWall® project summary over the past 30+ years.

**Table 1: TechWall® Projects reference summary**

| Country | Total Area (m$^2$) | Max height (m) | Max Area (m$^2$) (individual project) | Timeline |
|---|---|---|---|---|
| Spain | 600,000+ | 17.0 | 4,660 | Mid 1980’s - Present |
| United States | 70,000+ | 11.0 | 800 | Late 1980’s - Present |
| France | 2,000 | 7.0 | 600 | 2014 - Present |
| Peru | 14,000 | 9.0 | 14,000 | 2017 - Present |

## 2 TECHWALL® COMPONENTS & DESIGN PRINCIPLES

The substructure system (called TechWall®) is composed of two precast concrete structural elements: the wall elements (face panel and the counterforts), and the cast in situ footing (Figure 1). The TechWall® units are cast off-site, transported to the construction site, erected and secured in position with temporary props. The TechWall® precast wall unit is connected to the footing through the main flexural reinforcement of the counterfort, which protrudes from the underside of it, in preparation to be cast into the footing. This part of the counterfort reinforcement plays the most important role in providing a full structural interaction between the TechWall® components (precast unit and cast in-situ footing). Then the footing cage is installed, and the cast in-situ concrete footing is poured in the least possible amount of time. Once the concrete footing is set and cured, temporary propping of the precast panel units can be removed. At this point all the elements of the system are structurally joined together and backfilling can commence.

Prior to delivering the TechWall® units to site, the wall component (facing panel + counterfort) is precast in two stages. Firstly, the counterfort is cast and cured, with appropriate provision for starter reinforcement and construction joints. Counterforts are connected to the face panel through extended stirrups into the panel. This reinforcement, combined with a construction joint at the interface, provides the necessary connection such that the wall element can be considered as a single structural element. This enables a fundamental design assumption, whereby facing units are designed and analysed as T-beams; where the face panel is acting as the flange, and the counterfort as the web. Refer to Figure 2 which represents typical details for the features introduced in the TechWall® solution as an efficient alternative to the usual rectangular cross section of a traditional concrete L-shaped wall.

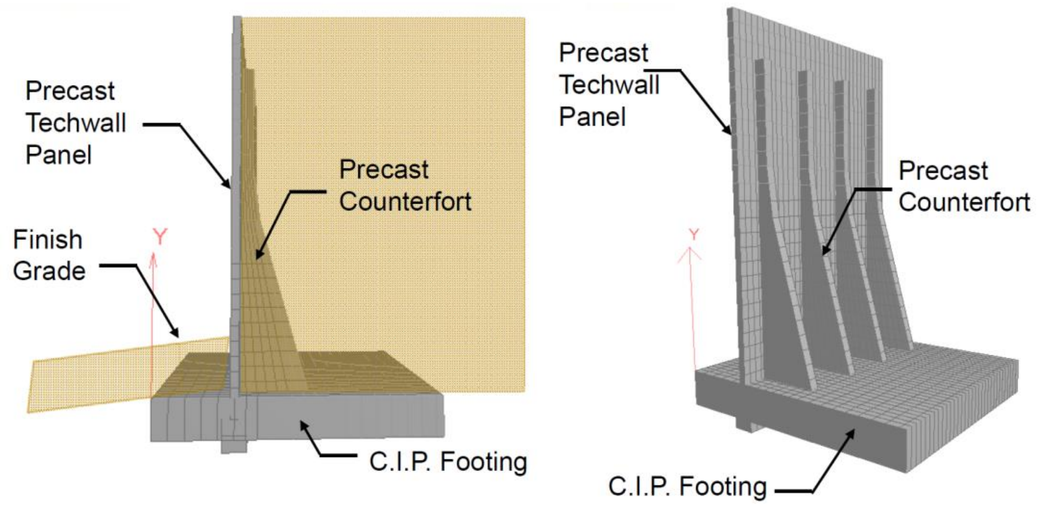


**Figure 1: Typical TechWall® Components**

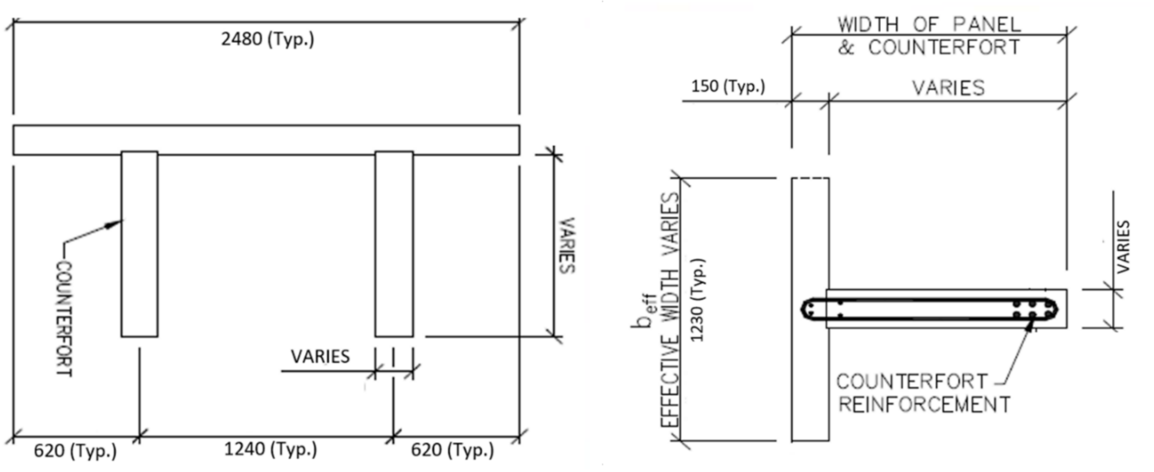


**Figure 2: TechWall® T-Beam configuration**

Strengthening a retaining wall with counterforts changes the structural behaviour of the retaining wall. In conventional cantilever retaining wall systems, the facing panel is the load-resisting component. However, with the introduction of counterforts, these become the main load-resisting component, where the facing panel acts as a continuous one-way slab spanning over the counterforts. This allows the cross section of the wall to be reduced significantly while satisfying the strength and serviceability requirements of the specifications.

Special attention is paid to:

- counterfort and anchorage into the footing: bottom section of the counterfort where the bending moment and shear forces are typically at a maximum.

- face panel and footing design: the midspan between the counterforts for positive moment, and over the counterforts for negative moment. Counterfort position may be considered such that positive moment is minimised, leading to rationalisation in steel reinforcement.

The load calculations are divided into vertical and lateral loads applied on the retaining wall as per the relevant codes, requirements and specific project technical specifications.

## 3 CONCEPTUAL DESIGN ASSUMPTIONS

The TechWall® system facing elements are assumed to deflect as a result of soil pressure action. Therefore, the soil behind the TechWall® facing units will be in the active condition as is allowed to yield sufficiently to cause its internal shearing resistance along a potential failure surface to be completely mobilised and tends to overturn or slide the wall. Thus, the coefficient of active lateral earth pressure, Ka, is used for the calculation.

Coulomb's approach is considered in calculating lateral the active lateral earth pressure as follows:

Horizontal component: $$k_a = \frac{cos(\phi+\alpha)^2}{cos^2(\alpha).\left(1+\sqrt{\frac{sin(\phi+\delta).sin(\phi-\beta)}{cos(\delta-\alpha).cos(\alpha+\beta)}}\right)^2}$$

Vertical component: $$Z_1 = \frac{k_a}{tan(\alpha+\delta)}$$

$\phi$ = Internal friction angle

$\delta$ = Inclination of the earth pressure

$\beta$ = slope angle at top.

$\alpha$ = slope of counterfort face at rear.

The soil pressure distribution behind the TechWall® differs depending on where the pressure is acting.

Soil pressure on facing panels is assumed to act on a vertical plane right at rear face of facing panels. However, soil pressure on counterforts is assumed to act on a vertical plane at counterfort-footing intersection (as depicted in Figure 3).

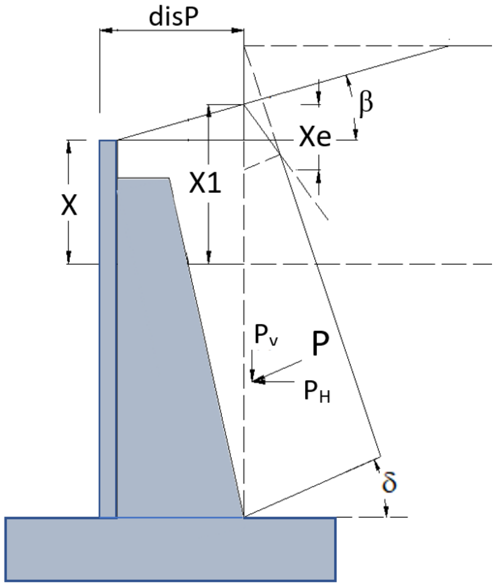


**Figure 3: Soil pressure at rear face of counterfort**

X: Distance from top of wall to soil pressure acting plane

Xe: Top section (height) of the soil pressure distribution.

X1: Backfill height at soil pressure acting plane.

disP: Distance from front face of wall to soil pressure acting plane

In order to capture in the design model, the restrained based of the facing panels, the pressure diagram acting on the facing panel is assumed as follows, in accordance with Huntington 1957 (**Figure 4**)

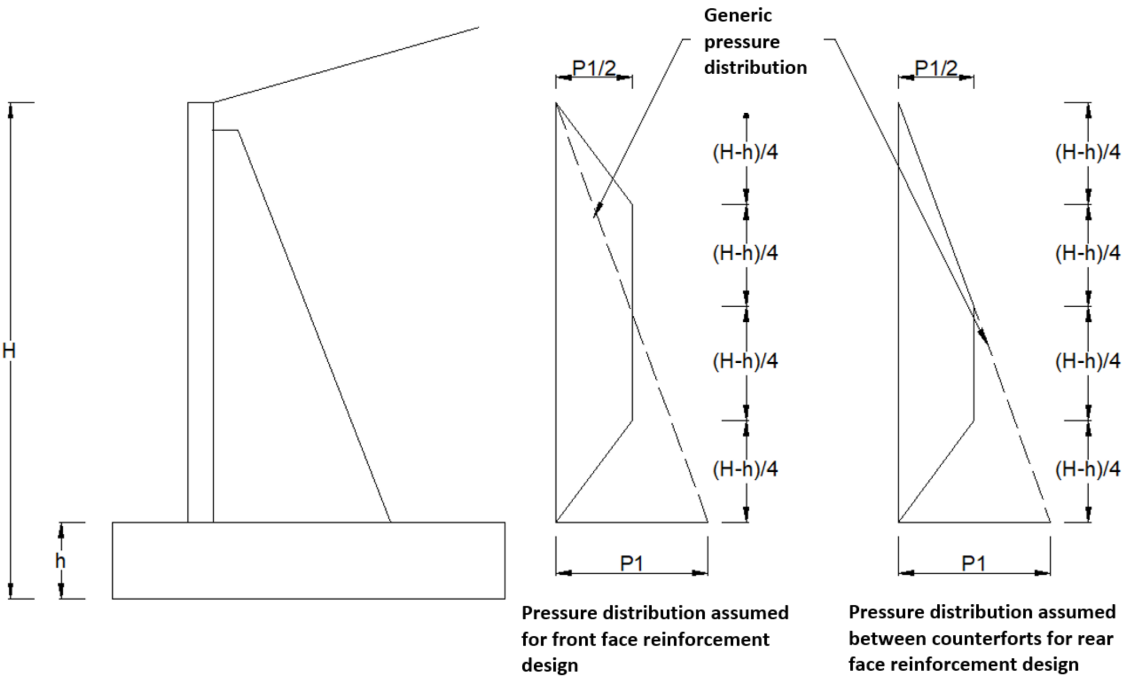


**Figure 4: Soil pressure at rear face of facing panel**

# 4 TYPICAL DESIGN PROCEDURE

The design procedure of the system is similar to that of a cast-in-place concrete counterfort retaining wall for the typical components. However, it is different for individual elements of the TechWall® system such as facing panels, counterforts and footing.

The typical design procedure is as follows:

1. **GEOMETRY:** Nominate panel width and counterfort spacing/dimensions, along with other relevant constraints (such as geometry. Two main geometric parameters contribute to the structural behaviour of TechWall® system: the counterfort spacing and the length of the counterfort at the base (Figure 5) (counterfort-footing interface). Counterfort spacing and sizing determines the load applied to each counterfort and hence the counterfort thickness and volume of steel reinforcement required

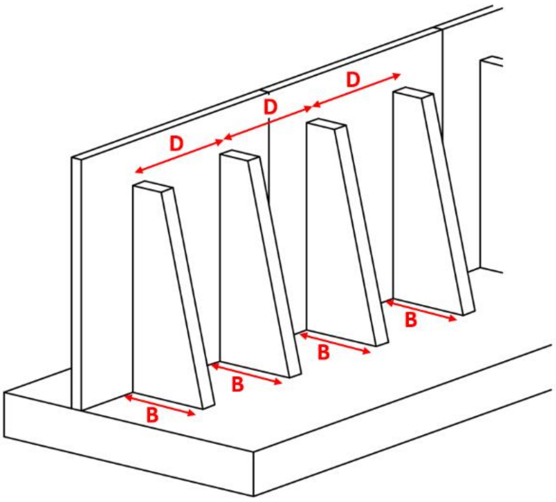


**Figure 5: Counterfort wall - geometrical arrangement (dimension at base and spacing)**

2. Calculate all of the applicable ultimate loads in compliance with the nominated specifications.
3. **EXTERNAL STABILITY:** Perform the necessary external stability checks to ensure that the system meets the required safety factors. The system is checked against overturning, sliding, and bearing failure modes. This stage determines the footing dimensions and arrangement.
4. **INTERNAL STABILITY:** Determine the ultimate loads acting on each TechWall® element (i.e. loads on facing and counterforts). Counterforts are assumed to be in fully connected to the footing.
    a. Design for the required ultimate moment and shear capacity required, providing steel reinforcement that meets the specifications requirements for all the TechWall® elements (wall elements and footing).
    b. Check for crack control and serviceability failure modes

In calculating the required steel reinforcement when carrying out the internal stability design, the considered forces and stresses can include but not limited to:

- Precast elements (panel + counterfort):
    - Bending Moment and shear force in the counterfort (T-Beam web)
    - Shear force at panel-counterfort interface as a result of counterfort bending.
    - Bending Moment and shear force in the panel (T-Beam flange)
    - Shear force at counterfort-footing interface
- Cast in place element (footing):
    - Bending Moment and shear force due to:
        - External forces (Dead and Live loads)
        - Axial force at counterfort-footing connection

## 5 OPTIMISATION

The number and spacing of counterforts affect the structural design of the facing panel and footing. When the counterfort spacing is reduced, the bending moments in the face panel are reduced and a thinner concrete face panel may be used. The choice of the counterfort spacing is based on conventional beam theory. Therefore, counterfort spacing is adjusted in order to balance positive and negative moments. (Figure 6) The resulting distribution of bending and shear stresses allows reduction of the face-panel thickness compared to a typical L-Shaped retaining wall.

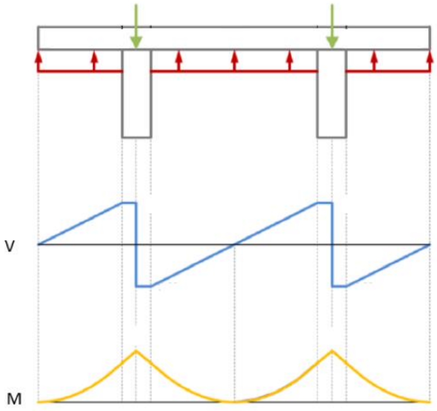


**Figure 6: Typical bending moment and shear distribution along TechWall® facing panel**

Finding the most efficient footing dimensions is key in order to optimise the TechWall® design. Multiple factors such as materials cost, excavation volume required, and labour associated are analysed. As a result of the combination of all these variables, hundreds of different combinations need to be computed. This intensive and time-consuming task is carried out by the in-house design software developed for this purpose. The overall efficiency of the TechWall® system relies on this footing optimisation process.

## 6 COMPARISON BETWEEN TECHWALL® AND L-SHAPED WALL

The TechWall® system has been optimised to provide geometric efficiency that can be reflected in the form of a reduction in the weight, sizes, and concrete volume of some of the wall components compared with traditional cast-in-situ L-shaped walls. Owing to the software used in design, the geometric efficiency does not rely on burdening designers with iterative and time-consuming work. Anecdotally, the system is considered to provide up to 40% cost reductions when materials, installation and temporary works efficiencies are realised. However, regarding materials only (being concrete and steel), we have analysed a single retaining wall contained in a recent (2018) “For Construction” issue of drawings on an RMS road upgrade in the Sydney metropolitan area. The conforming design comprises a combination of L-shaped and cast-in-situ counterfort walls. The counterfort supports are detailed on approximately 55% of the total wall length. The counterforts are 350 mm wide at 5 m centres. Analysis shows a significant reduction in the concrete and steel volumes required is achievable if a TechWall® solution is implemented. This analysis is presented in Table 2. It is worth pointing out that the facing area has increased in the TechWall® solution proposed, owing to minor variations in geometry proposed to optimise precast panel production. A marginal increase in footing concrete is also evident, due to the variation in load transfer mechanism to the ground. However, generally in a similar approach to the panel-counterfort interaction (based on conventional beam theory) the TechWall® footing reinforcement can be optimised as a result of the reduced longitudinal Mx bending moment along the footing in opposition to the conventional L-shape footing arrangement (Figure 7).

Significant savings are realised in all other elements individually, and in aggregate, as presented in the table.

**Table 2: Comparison of fully cast-in-situ vs TechWall® Solutions**

| **Retaining Wall** | **Wall Area ($m^2$)** | **Footing** | | **Facing & Counterforts** | | **Total** | |
|---|---|---|---|---|---|---|---|
| | | **Concrete ($m^3$)** | **Steel (T)** | **Concrete ($m^3$)** | **Steel (T)** | **Concrete ($m^3$)** | **Steel (T)** |
| CIP | 1043 | 554 | 111 | 616 | 117 | 1170 | 228 |
| TechWall® | 1304 | 634 | 69 | 315 | 42 | 949 | 111 |
| % Difference (Techwall®/CIP) | 125% | 114% | 62% | 51% | 36% | 81% | 49% |

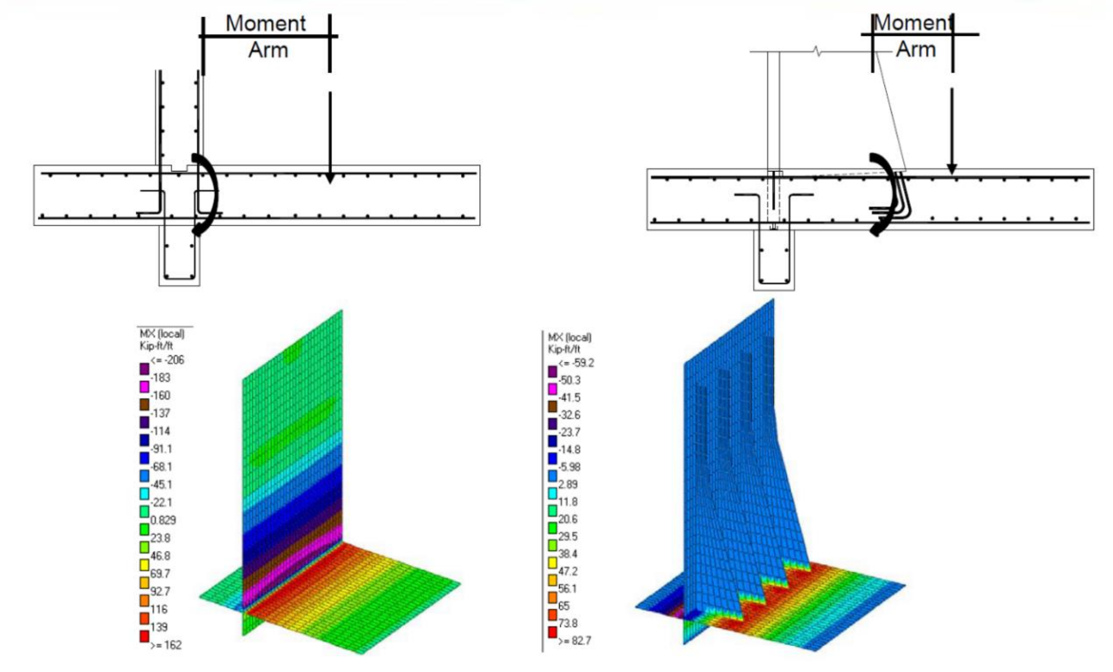


**Figure 7: Footing optimisation (Mx distribution). Comparison between L-Shaped Wall & TechWall®**

## 7 TECHWALL® FOUNDATION

The TechWall® system is not suited for all retaining wall applications. In particular, where low strength, soft ground conditions prevail, alternative retaining methods should be considered. High strength soils or preferably rock foundation is preferred for the TechWall® system. The geology of the Sydney basin consists primarily of gently-formed Triassic sandstones and shales (Branagan 1985). The geotechnical parameters of these founding materials are further described by Pells, Mostyn and Walker (1998). While Pells et al provides guidance on strength and deformation characteristics, it should be understood that the TechWall® system relies on a strength input only, namely bearing capacity. This paper limits its discussion to a trivial assessment of bearing capacity of Sydney rock foundations only. The reader is referred to this and other literature for further discussion on Sydney Rock classifications.

In particular, where TechWall® can be founded on Class V Shale as a minimum, the ultimate bearing capacity of 3000 kPa may be used, and 700 kPa for serviceability assessment. The Table presented below (Table 3) is an abridged version of Table 5 of Pells et al,1998.

**Table 3: Bearing capacities of Sydney rock foundations**

| Class | Ultimate End Bearing[1] (MPa) | Serviceability end bearing pressure[2] (MPa) |
|---|---|---|
| V Sandstone | > 3 | 1.0 |
| V Shale | >3 | 0.7 |

Notes: [1]Ultimate values occur at large settlements (> 5% of minimum footing dimensions).
[2]End bearing pressure to cause settlement of < 1% of minimum footing dimension.

A brief comparative study has been carried out for the purpose of this paper. Different wall heights and foundation bearing capacities have been combined to show the adequacy of the TechWall® solution as retaining solution for firm foundation materials. The base case for material and cost comparison is the 750 kPa assumed bearing capacity case. Refer to Table 4, and Table 5 for results.

**Table 4: TechWall® Footing Optimisation H =6.0m. Standard backfill conditions ($\phi$=36º, $\gamma$=20kN/m$^3$, C=0kPa)**

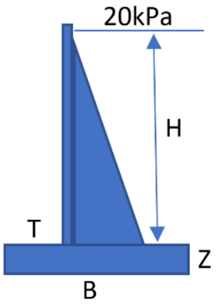
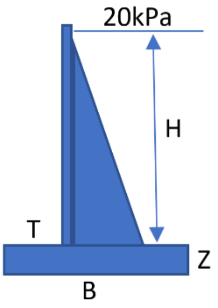
| Bearing Capacity (kPa) | Wall Height 'H' (m) | Optimised Cost effective solution. Dimensions (m) | | | Bearing Pressure (Meyerhof) | | Materials | | Estimated Cost. Materials Labor Excavation (%) |  |
|---|---|---|---|---|---|---|---|---|---|---|
| | | T | B | Z | Min | Max | Conc Kg/m$^3$ (%) | Steel m$^3$/ml (%) | | |
| 100 | 6.0 | 2.1 | 4.6 | 0.6 | 86 | 117 | 350 | 47 | 215 | |
| 250 | 6.0 | 0.6 | 3.0 | 0.6 | 22 | 243 | 227 | 45 | 135 | |
| 500 | 6.0 | 0.5 | 2.6 | 0.3 | 0 | 370 | 100 | 103 | 103 | |
| 750 | 6.0 | 0.4 | 2.6 | 0.3 | 0 | 390 | 100 | 100 | 100 | |

**Table 5: TechWall® Footing Optimisation H =8.0m. Standard backfill conditions ($\phi$=36º, $\gamma$=20kN/m$^3$, C=0kPa)**

| Bearing Capacity (kPa) | Wall Height 'H' (m) | Optimised Cost effective solution. Dimensions (m) | | | Bearing Pressure (Meyerhof) | | Materials | | Estimated Cost. Materials Labor Excavation (%) |  |
|---|---|---|---|---|---|---|---|---|---|---|
| | | T | B | Z | Min | Max | Conc Kg/m$^3$ (%) | Steel m$^3$/ml (%) | | |
| 100 | 8.0 | Not suitable for TechWall® application | | | | | | | | |
| 250 | 8.0 | 1.0 | 4.5 | 0.8 | 72 | 246 | 170 | 82 | 155 | |
| 500 | 8.0 | 0.5 | 3.5 | 0.6 | 0 | 409 | 100 | 110 | 105 | |
| 750 | 8.0 | 0.4 | 3.5 | 0.6 | 0 | 430 | 100 | 100 | 100 | |

# 8 CONCLUSIONS

This paper presents the design principles for a partially prefabricated concrete counterfort retaining wall system TechWall®, as well as the suitability of the system from a geotechnical point of view as it relates to the prevalence of competent rock foundations in the Sydney Basin. In addition, a comparison between the proposed system and traditional cast-in-situ concrete L-shaped/counterfort retaining wall system was established demonstrating materially significant savings in concrete and steel reinforcement.

The following conclusions can be drawn:

- A partially prefabricated counterfort retaining wall system is an efficient solution for construction in congested areas on appropriate foundations.
- It provides advantages in terms of:
    - Environmental: carbon footprint reduction
    - Time: speed of construction
    - Quality: controlled fabrication process
    - Safety: reduction in temporary works
    - Community: Community impact reduction
    - Cost: reduction in materials and site works

The system is based on classic retaining wall design theory, and in the author's opinion does not contain any innovation in terms of design method. It is best suited to competent rock foundation and provides efficiencies in two primary ways. Firstly, the design software is a powerful iterative program which can automatically determine the most optimised arrangement depending on input constraints. Secondly, the precast elements provide significant advantages over cast-in-place systems in terms of quality, safety and speed of installation.

# 9 ACKNOWLEDGMENTS

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