CASE STUDY: EDINBURGH ST JAMES – EMBEDDED PILE RETAINING WALL DESIGN

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ABSTRACT At 1.7 million square foot, Edinburgh St James (ESJ) is one of the largest and most significant regeneration projects currently underway in the United Kingdom (UK). This mixed-use development situated in the heart of Edinburgh, Scotland includes a retail, leisure, hotel and residential offering, with car parking located within a three-level basement reaching into the bedrock up to 22m below ground level. A case study from the Edinburgh St James project is presented, detailing the design of the embedded retaining wall. The case study shows how monitoring data can be used in the context of the Observational Method (OM) to design more efficiently to benefit the project. The OM is a design approach applied in geotechnical construction where site measurements are used to optimise construction methodology and can be done either *ab initio* (from the start) or *ipso tempore* (in the moment). The case study shows the OM method applied *ipso tempore*. Design efficiency could be further enhanced by adopting the OM *ab initio*, which allows more time to develop the necessary decision framework and secure the agreement of all stakeholders. Furthermore, future designs can become justifiably more efficient by using data collected by sensors in back analysis tasks to enhance understanding of structural-geotechnical stiffness and strength. We conclude that through early collaboration between the client, contractor and design teams, construction optimisation can bring about cost reduction, a faster programme and improved sustainability outcomes for the project.

1. Introduction

Edinburgh St James is a 1.7 million sq. ft retail-led, mixed-use development in Edinburgh, Scotland, scheduled to open in 2020. Laing O'Rourke (LOR) became the Principal Contractor in October 2016, following a period of enabling works. The piling package was delivered by Expanded Geotechnical (a Laing O'Rourke company).

LOR worked directly with the client Nuveen from 2014 providing early advice to develop a plan for the project that would be deliverable within the required timeframe and budget. The client's consulting engineer was ARUP, novated to LOR after project award.

This case study details the retaining wall design for the basement, focusing on the performance of drained soil strength parameters for the Glacial Till compared with measured undrained behaviour.

Figure 1 – Architect's impression of the development

2. Site Location

The site is located close to the junction between Princes Street and Leith Street in the city centre of Edinburgh. The site is bounded by St James' Place and Little King Street to the north, Leith Street to the east, James Craig Walk to the south and Elder Street to the west.

The topography of the site is generally sloping down from southwest to northeast. The initial ground levels varied from approximately 70m AOD at James Craig Walk in the south west to 58m AOD on Leith Street in the east/north-east. Level platforms were created within the footprint of the site to enable pile construction.

3. Retaining Wall Overview

The Edinburgh St James development occupies a site footprint of approximately 20,000 sq. m. In order to construct the basement, retaining wall piles were first installed around the full perimeter of the site. The walls were typically comprised of 1200mm diameter secant piles with male piles at two metre spacing, toeing into the bedrock, achieving a maximum retained height of 22m. In the final condition, *in-service*, piles are laterally supported by up to five levels of basement slabs. During construction, temporary support to the walls consisted of up to three levels of ground anchors. An anchored solution was favoured as it provided a largely uncongested workspace within the basement area in which to efficiently excavate approximately 300,000 m^3 of soil and form the basement substructure.

4. Geology

The basic succession of strata encountered on the site is summarised as follows:

- Variable Made Ground
- Glacial Till – Very Stiff CLAY with cobbles and boulders in the matrix with very occasional sand lenses
- Variable rock mass consisting of Gullane Formation and Craigleith Sandstone with intermittent Tholeiitic dyke intrusions from the Edinburgh dyke swarm.

The variable mass included mudstone, sandstone, conglomerate with possible igneous intrusions. Igneous intrusions were not encountered during the investigation but were known to be present on the site based on the local geology. In a similar manner to the topography, the rock level also sloped generally in the direction of the ground down Leith St, but at a steeper angle.

5. Geotechnical Design Parameters

Glacial Till was the most abundant soil and its behaviour dominated the design of the piled retaining wall. Generally, the Glacial Till presented in all boreholes as a stiff clay and this would often be treated as an undrained material in the temporary condition. However, occasional sand lenses were encountered in the boreholes, indicating that adoption of a simple undrained approach throughout the long excavation phase came with a degree of risk. Sensitive neighbouring structures included the 18th Century General Register House, home to Scotland's national archives. Damage assessments undertaken identified a need to absolutely control wall deflections. Therefore, the decision was taken to conservatively base the wall design on drained soil parameters for the clay, to take into account the lengthy duration of the excavation and basement construction phases. This allowed project risk to be sensibly managed, in the event of a delay in completing this critical stage.

6. Observational Method (OM)

The Observational Method (OM) is a technique used to design more efficiently in the ground and its application to retaining walls is described comprehensively by Gaba et. al., (2017). When applied from the start (*ab initio*), designers either adopt an optimistic approach, based on 'most probable' ground conditions, together with a fully developed contingency involving additional supports, should unfavourable behaviour be observed. Or instead, a cautious approach is adopted, based on characteristic ground and structural behaviour, together with an alternative construction sequence, typically requiring fewer supports, should the wall perform better than expected. OM may also be applied following commencement of construction, in the moment (*ipso tempore*). This is similar to the cautious *ab initio* approach, whereby a decision framework may be developed, based on observations of wall performance, to allow the planned omission of supports when circumstances are favourable.

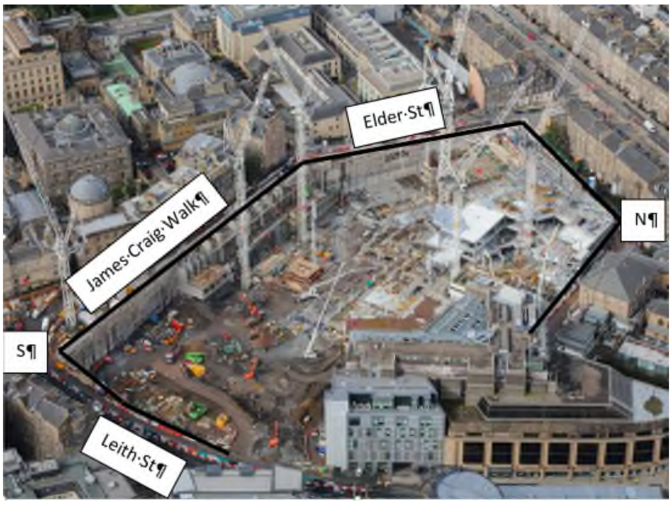
Typically, permanent retaining piles are required to be designed to accommodate the characteristic behaviour, as they cannot be changed after installation, nor can permanent support positions easily be altered. This lends itself well to both the cautious *ab initio* and the similar *ipso tempore* approach. As implementation of OM in staged construction requires two full designs; the default and the alternative sequence, design development takes longer and the consultant's fees are increased. However, on large projects these costs may easily be recovered. Site Investigation costs remain unchanged.

7. Temporary Stability During Construction

The design for the 22m deep basement was both complex and challenging. As mentioned, temporary ground anchors were used extensively to stabilise the piled retaining walls during the excavation until the permanent basement slabs and buttress walls were constructed. An excavation of this magnitude in this location was assessed as both a high risk and high consequence activity, warranting a robust temporary works solution.

The aerial photograph (Figure 2) shows the extent of the excavation. The top of the perimeter retaining wall is outlined in black.

Figure 2 – Basement under construction



WALLAP software was used to determine wall stability for the construction stages through to the final condition and to calculate wall deflections, bending moments and shear forces. Anchor stiffness was included in the model and anchor forces were determined directly at both serviceability and ultimate limit states.

Ground anchors were sequentially installed and then stressed as the excavation progressed and were de-stressed sequentially once the relevant supporting slabs were constructed. A total of 341 anchors were required to support the walls, with individual lengths up to around 30m. Ground anchorages themselves consisted of prestressing steel threadbars, varying in diameter from 36mm to 65mm, grouted into 170mm diameter boreholes in rock. Calculated working loads varied from 330 kN and 1400 kN, with corresponding preloads of between 220 kN and 1150 kN. All anchors were subjected to two cycles of acceptance testing to 150% of their working load, i.e. 2100 kN maximum test load. This represented a change in practice under BS 8081: 2015 – when compared with the previous 1989 standard, acceptance testing of temporary anchorages to 125% of working load was commonplace. Tendon sizing was generally based on limiting the working load to 50% of the tendon ultimate strength, in accordance with the 1989 standard, as it was discovered during design development that the 2015 edition was unduly conservative in this respect. It should be noted that BS 8081: 2015 +A2: 2018 now has substantially revised requirements for tendon sizing, fully addressing this issue and represented a significant cost and carbon saving on the project.

Anchor fixed lengths were constructed entirely within the bedrock, resulting in anticipated and actual free lengths within made Ground and Glacial Till which were generally well within excess of the minimum requirement to avoid a global stability failure. Only for the lowest levels of anchors were free lengths required within the bedrock itself, to satisfy global stability. Free lengths were achieved by means of factory fitted HDPE sheathing and the actual extensions measured during stressing corroborated the expected anchor behaviour.

Anchors were installed at angles of between 30° and 45°. Rock head tended to slope in the same sense as the existing ground and in the downhill areas, the steeper angle provided economy on account of the shorter intercept to rock head. This outweighed the increase in load and concomitant increase in bar diameter. Wall stiffness was not significantly altered, as the increase in bar diameter and reduction in free length both offset the change in installation angle. In addition, the shorter overall lengths confined many of the anchors to the adjacent roads, obviating the need for costly separate legal agreements with neighbouring freeholders.

A typical arrangement of anchor heads on the wall is shown in Figure 3. The substantial reinforced concrete capping beam connecting the pile heads afforded a readily available waling beam for the uppermost anchors. It was adapted for the purpose by the addition of reinforcement together with the incorporation of inclined reinforced concrete blisters and ducting through which to commence drilling. The stiff capping beam ensured failure of a single anchor could easily be accommodated by relatively small increases in load in the surrounding tendons. This resilience proved useful when individual tendons had to be removed, aborted or omitted for various reasons as construction progressed.

Anchor heads located lower on the wall were constructed by removing part of the unreinforced female piles and replacing it with a wedge-shaped reinforced concrete block, which engaged the male piles on either side. The block was sized so that its removal was unnecessary, lending efficiency to the de-stressing operations. This was an effective solution, avoiding the need for removal of heavy temporary steel walings under completed slabs where limited space and craneage would hamper the operation.

Figure 3 – View on wall anchors along James Craig Walk

Three vertical trial anchors were constructed and tested to provide parameters for the fixed length design. The first terminated in the Glacial Till, yielding an ultimate bond strength of 289 kPa and the remaining two in mudstone and sandstone, giving corresponding ultimate bond strengths of 1830 kPa and 850 kPa respectively. The lower figure was obtained at shallow depth, 2m below rock head, and this test had to be aborted early. Based on this data, an ultimate shear stress of 1 MPa was adopted for the grout-ground interface in the rock. During acceptance testing, a number of the earliest anchors failed to meet the criteria. This issue was resolved by modifying the drilling technique and marginally increasing fixed lengths for all the subsequent anchors, with only a minimal number of isolated failures occurring thereafter. Sub-standard anchors were either re-drilled or accepted with reduced working loads following local back analysis of the affected walls and applying OM techniques.

8. Wall Performance

On arrival to site, it became clear that the Glacial Till was more competent than accounted for in the wall design. Figure 4 shows a vertically cut column of Glacial Till underneath an existing pad foundation (due for removal). These cuttings remained open and unaffected by their exposure for reasonable periods during the works. The Glacial Till material was evidently behaving as an undrained stiff clay as indicated in the boreholes and the accompanying in-situ and laboratory test data.

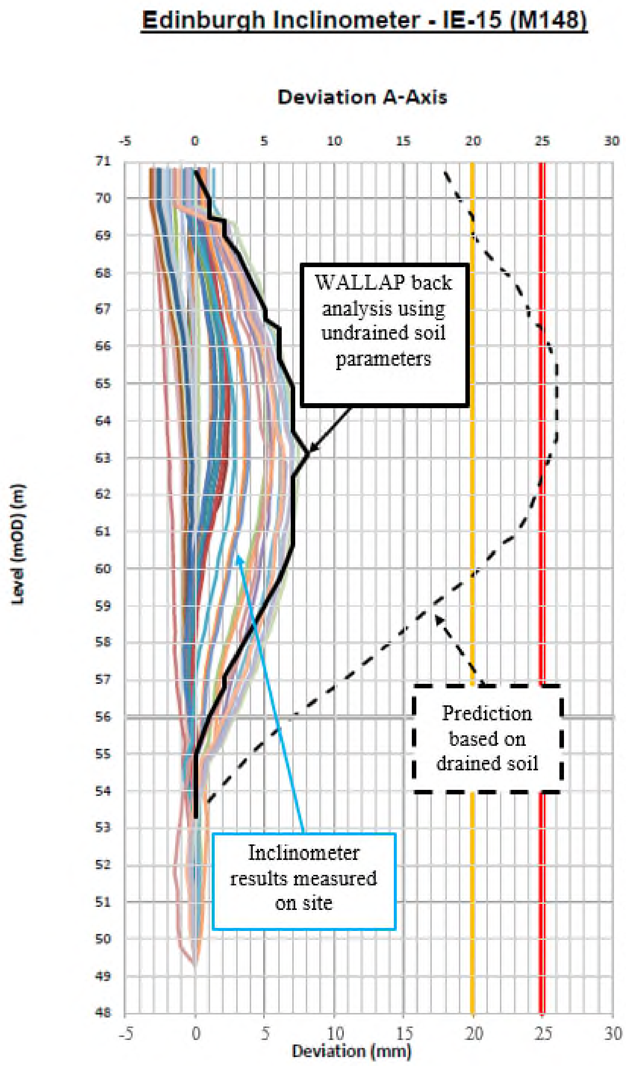
Figure 4 – Photograph showing undrained behaviour of the Glacial Till

A thorough instrumentation and monitoring plan was put in place on the project, specified by the Engineer. Wall deformations were measured using inclinometers positioned along the retaining wall at intervals of 20 to 30 metres, some of which were taken to a depth of 4m below the male pile toe. Wall and ground studs, tiltmeters and optical targets provided additional data provding a comprehensive picture of ground movement due to the excavation.

Instrumentation and monitoring was carried out by Select Instrumentation and Monitoring (a Laing O'Rourke company). Monitoring data was routinely inspected and interpreted as part of the instrumentation and monitoring plan. Figure 5 shows inclinometer data from the wall pile experiencing the largest deflection during excavation. The black dashed line represents the wall movement prediction from a WALLAP (Borin, D. 2019) analysis using drained soil parameters. The coloured lines represent the weekly inclinometer readings and are indicative of the measured wall movement. The thick black line is the output from a revised WALLAP model using undrained (rather than drained) soil parameters. The overall performance of the anchored wall was very good, with deflections remaining well within the defined limits for the duration of the project.

Use of drained parameters in the initial design caused the soil to apply a higher theoretical pressure on the back of the wall, with lower passive resistance in front, resulting in much higher predicted wall movements. For the back analysis, use of undrained parameters in a revised WALLAP model produced a more realistic deflection profile which closely matched the observed behaviour, validating the model. This back analysis justified the use of undrained parameters for temporary works design on the project, allowing the Observational Method to be applied *ipso tempore* on subsequent areas of the site. This enabled the project team to improve constructability, solve problems as they arose and speed up the build wherever possible. The client benefited from a faster, safer, more environmentally sustainable project and the contractor benefited from a more buildable project.

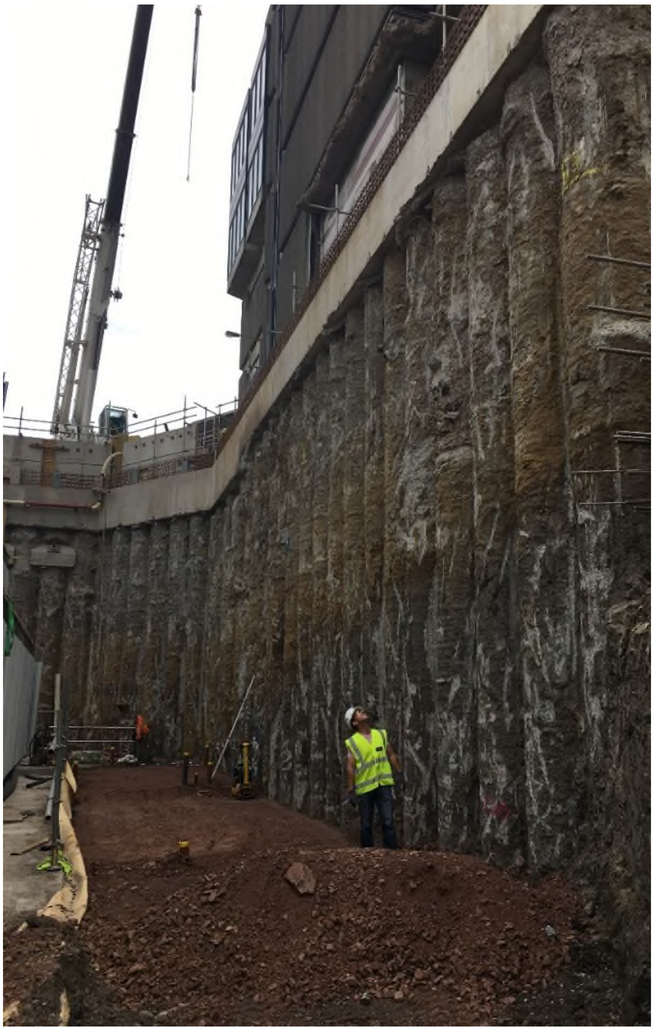
Figure 5 – Retaining wall inclinometer results shown combined with initial and back analysed deflection predictions.



One notable area of the site where application of OM *ipse tempore* proved invaluable was a section of retaining wall adjacent to the existing contiguous piled wall of a neighbouring basement. Anchoring through the gaps between existing male piles below the basement was likely to be a practical impossibility, and the retained height was such that struts within the excavation would seriously hamper planned work on a nearby structural core. The undrained analysis showed that an unpropped solution was viable, and an ambitious 12m high free-standing cantilever was adopted (Figure 6). Coincidently, this wall was situated in the area of the site where a sand lens was found in the boreholes and whose presence had greatly contributed to the widespread adoption of drained parameters in the first place.

Application of OM to the basement design enabled much flexibility in the sequencing of the removal of the anchors. This proved beneficial in responding to changing circumstances during the construction of the basement itself, e.g. permitting removal of occasional anchors found to clash with formwork or permanent structural elements.

Figure 6 - 12m high free-standing cantilever wall



9. Conclusion

This case study shows the benefit of a collaborative project approach between the client, contractor and consulting engineer. On this project, early contractor involvement during a Pre-Construction Services Agreement (PCSA) period allowed the design to be steered, enhancing constructability as a result. Each party was incentivised to optimise the design within their area of expertise, enabling risk, design responsibility and associated advantages to be shared appropriately. This approach allows contractors to generate savings for clients by taking on more design responsibility and effectively managing project risk from an early stage.

Efficiency gains were realised on the project through the use of the OM, applied *ipso tempore*, to optimise construction sequencing. Proposals to implement OM on the project were not always successful due to the limited timeframe to secure third-party approvals. This would seem to be the main drawback to the *ipse tempore* approach – there is often much less time to secure the agreement and participation of all stakeholders than if the method is declared *ab initio* and approved from the outset. It is a logical conclusion that there would be even greater project benefits if used *ab initio*. OM facilitates cost reduction, a faster programme and improved sustainability outcomes for the project.

Back analysis was shown to be a powerful method for justification of improved soil parameters. However, back analysis of monitoring data is seldom carried out, yet it plays a crucial part in improving the skill and experience of design engineers and should be done on all geotechnical construction projects in a collaborative way to drive improvement throughout the industry. The instrumentation and monitoring report should include the basis for starting the analytical work to check design assumptions, to reduce uncertainty, to increase understanding and to learn lessons to apply on future projects.

10. Acknowledgements

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