Forensic Foundation Engineering and Rectification Design

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This paper presents a framework for investigating the possible causes of foundation failure and a summary of the key issues that should be considered when designing rectification measures. A case study is then presented to illustrate the approach and the process undertaken in the design of foundation rectification works.

Keywords: pile foundations; settlement; rectification design

1 INTRODUCTION

As the engineering and construction world becomes more competitive in terms of bidding and securing contracts and more litigious when projects encounter difficulties, forensic foundation engineering is becoming increasingly important when things go wrong in the ground. This paper presents a framework for forensic foundation engineering and provides a case study to illustrate the application of the approach and describes the subsequent rectification design and prediction of the long term performance.

2 FRAMEWORK FOR FORENSIC FOUNDATION ENGINEERING

2.1 Conditions for Failure

Poulos (2009) sets out a relatively simple but systematic approach for investigating the possible causes of foundation failures. This approach can be applied to both foundation failure (ultimate failure conditions) as well as cases involving excessive deformation of the foundation (serviceability failures). The approach involves consideration of the various factors that may have influenced the failure, which include:

- The geotechnical resistance or strength of the foundation
- The structural strength of the foundation
- The magnitude and nature of the applied loads acting on the foundation
- The structural actions developed within the foundation.

Foundation failures can occur either because of failure of the supporting soil (geotechnical failure), or failure of the foundation material (structural failure). For geotechnical failure to occur, the following condition will be satisfied:

$$R_g \leq \sum P \qquad (1)$$

where R_g = ultimate geotechnical foundation resistance, or bearing capacity
$\sum P$ = sum of the loads acting on the foundation

For structural failure to occur, the following condition will be satisfied:

$$R_s \leq \sum S \qquad (2)$$

where R_s = ultimate structural foundation resistance
$\sum S$ = sum of the loads or other structural actions acting on the foundation

Poulos (2009) suggests four broad possibilities of foundation failure that require investigation:

1) The geotechnical resistance R_g may be inadequate to resist the applied loads
2) The structural resistance R_s may be inadequate to resist the applied loads and structural actions

3) The applied loads $\sum P$ may be larger than those considered in design, or contain a component of load not anticipated at design stage
4) The applied loads or structural actions $\sum S$ may be larger than those considered in design, or contain a component not anticipated at design stage

Assessment of each of the above possibilities is discussed below.

2.2 Possibilities of Foundation Failure

2.2.1 Geotechnical Foundation Resistance

The geotechnical capacity of a foundation depends on:

- The geotechnical profile below the foundation
- The strength of the soils within the foundation depth of influence
- The nature of the foundation (e.g. piled or strip footing)
- The direction and nature of the applied loading (e.g. vertical, lateral, moment)

The contribution, if any, of each of these factors to the failure needs to be assessed. For example, with regards to the geotechnical profile, questions that may be asked during a forensic investigation include:

- Have adequate investigations been completed and are the site conditions characterised appropriately?
- Are the interpreted ground conditions consistent with the geological history of the site?
- Have any variations in the subsoil profile across the site been identified and properly accounted for?
- Have the groundwater and hydrogeological conditions been established?
- Has the ground been disturbed or is there uncontrolled fill present due to adjacent work, such as service trenches or lift pit excavations?

2.2.2 Structural Foundation Resistance

Generally foundations comprise primarily of concrete and steel, and failure of the structural elements is often a result of deficiencies in strength or durability issues. The following aspects need to be considered during a forensic investigation:

- Is the structural element adequate to resist the structural actions (e.g. axial compressive and tensile stresses, bending moment, shear, torsion) within the foundation?
- Could the structural element have been damaged during installation or after due to other construction activities (e.g. basement or tunnel excavation)?
- Are there durability issues that may not have been adequately addressed in design (e.g. chemical attack, aggressive environmental conditions, cracking of elements under loading)?

2.2.3 Applied Loads

The loads to be designed for acting on a foundation are normally specified in the relevant loading code and often involve many loading combinations to cover a range of scenarios. Questions that may be raised during forensic investigation include:

- Were the loads acting on the foundation greater than those adopted for the design?
- Are any of the loads dynamic and if so, were they properly considered in the design?
- Have both kinematic and inertial effects resulting from seismic events been considered?
- Have there been externally generated soil movements that have impacted on the foundation (e.g. tunnelling, landslip, consolidation)?

2.2.4 Structural Actions

The assessment of the structural actions induced in a foundation is dependent on a number of factors, including the calculation method adopted, the loads and moments assumed to be applied from the superstructure and the strength of the ground supporting the foundation. The following questions may be asked when assessing the validity of the structural actions adopted in the design:

- How were the actions calculated and were any simplifying assumptions made that resulted in non-conservative loads being adopted?
- Was consideration given to additional loads resulting from ground movements?

Once the forensic investigation framework has been developed for the specific project and the questions needing to be addressed have been established, the next step is to formulate one or more credible hypotheses and then test these for consistency with the observed foundation behaviour. This is likely to include 2 or 3 dimensional numerical analysis of the foundation, laboratory or field testing. When testing a hypothesis, consideration must be given to likely variations in the ground characteristics (e.g. strength and stiffness parameters). This is particularly the case if detailed numerical analysis is to be completed as the predicted foundation performance resulting from such analysis is very much dependent on the constitutive models adopted.

3 FOUNDATION RECTIFICATION DESIGN

3.1 Overview

If the foundation under investigation has undergone a serviceability failure, once the cause of the failure is understood it may be possible to design and implement rectification measures such that the rectified foundation meets the design intent without the need for demolition and replacement.

There are at least three key design issues that may need to be addressed when designing rectification works for foundations which are not performing to expectations (Poulos, 2005):

- Correction of uneven settlements, if the foundation has already experienced excessive differential settlement or tilting, or is likely to do so
- Design of remedial works, which may include repair of defective piles, installation of additional piles or extending existing pile caps or footings to increase capacity and stiffness
- Consideration of load sharing between existing and additional foundation elements.

Each of the above is discussed in brief below.

3.2 Correction of Uneven Settlement

Methods to correct uneven settlement are broadly split into two categories, namely hard and soft methods (Poulos, 2005). Hard methods rely on the application of direct force onto the foundation and soft methods rely on processes that induce ground movements. In both cases, either the “high” side of the foundation can be lowered or the “low” side of the foundation be raised and may also be accompanied by foundation strengthening or remediation. Hard methods include:

1) Application of force by stressing of anchors strategically placed within the foundation.
2) Application of additional loading to the high side of the foundation.
3) Cutting of piles on the high side of the foundation in order to transfer load to surrounding piles and induce further settlement of the high side. Once the settlement has occurred, the cut piles may be re-connected to the foundation system.
4) Jacking of the foundations on the low side (compaction grouting or mechanical jacking).
5) Grouting under high pressure causing fracturing of the soil and uplift of the foundation.

Soft methods include:

1) Extraction of soil from beneath or between the foundation elements on the high side, causing the ground to settle and induces settlement of the foundation.

2) Dewatering by lowering the water table on the high side of the foundation to promote settlement. This method has been described as unreliable (Amirsoleymani, 1991) as the effects of groundwater lowering are highly dependent on local hydrogeology, are time-dependent and the effects may extend well beyond the foundation being treated.
3) Compensation grouting via fracturing to control movement of foundations affected by tunnelling or excavation.
4) Removal of soil support by the drilling of a series of vertical or sub-vertical holes just outside the high side of the foundation. The removal of soil reduces the lateral support of the ground and therefore promotes settlement (Poulos *et al* 2003).

3.3 Foundation Rectification Works

Options for foundation rectification works include repair of existing foundations, addition of new piles to stiffen and/or strengthen the existing foundation and extension of existing pile caps or rafts to provide additional bearing capacity and stiffness. Repair methods of existing foundations are often limited due to access constraints, the type and extent of the defects are not well defined and often the repair process itself may cause further issues, such as additional ground movements.

The installation of additional piles to an existing foundation is a well documented method of foundation rectification, particularly for underpinning works. When designing a foundation where additional piles are to be added, factors such as the stiffness and capacity of the existing foundation system and its interaction with the new piles need to be assessed. Another issue to be considered is the impact of any ground movement caused by the pile installation process. Installation of displacement piles will result in both vertical and lateral ground movements that can result in additional vertical and horizontal loads and bending moments in the existing piles. This effect can be exacerbated if the existing piles are restrained from moving laterally or vertically.

Installation of drilled piles can also lead to ground movements, for example those related with release of *in situ* stresses or changes in groundwater level that may occur if appropriate construction controls are not in place. Ground movement associated with release of *in situ* stress can be large if the existing foundation is heavily loaded.

Extending an existing pile cap to increase its capacity and stiffness is a method that can be considered, though the supporting soils would need to be of reasonable strength and stiffness for this option to be effective. The remediated foundation could then be considered as a piled raft type foundation where the load is carried by both the piles and the pile cap (Randolph, 1994; Poulos 2002).

The following case study shows the application of the forensic foundation engineering framework discussed above and provides an overview of the foundation rectification design adopted.

4 FOUNDATION RECTIFICATION CASE STUDY – PRECAST DRIVEN PILE FOUNDATION

4.1 Background

The original proposed foundation system for a multi-level residential development in Melbourne's Docklands comprised individual pile caps supported by groups of precast concrete piles ranging in size from 270mm to 450mm square and driven to rock. During the installation of the foundation for the two towers (20 levels and 31 levels) and the surrounding 6 level podium, it was discovered that a significant number of the driven piles had not reached their target design depth, which was to top of rock.

The ground conditions at the site comprise alluvial deposits overlying siltstone bedrock at some 37m depth. The alluvial deposits comprise soft to firm Coode Island Silt (CIS) (15m – 20m thick), underlain by firm to very stiff Fisherman's Bend Silt (FBS) (6m – 12m thick) which overlies an approximately 5m thick layer of medium dense to very dense sand and gravel (Moray Street Gravel (MSG)). This gravel layer is underlain by stiff to very stiff Newport Silty Clay (NSC) approximately 5m thick, and weathered siltstone of the Melbourne Formation (MF).

Review of the piling records indicated that a significant number of the precast concrete piles had not penetrated through the MSG and onto the MF as was the design intent of the foundation. Concerns were raised that the long term total and differential settlement of the as-installed foundation may exceed the design criteria values. Therefore the author's firm was commissioned by the piling contractor to undertake a review of the as-installed pile foundation and the subsequent foundation rectification design. Whilst the foundation had not failed as the problem had been identified early before the building loads had been applied, the approach adopted in the review of the as-constructed foundation generally followed the forensic framework given above.

4.2 Nature of Foundation Serviceability Failure

The individual piles within the foundation had been driven to the target set and it was assessed that the foundation had adequate geotechnical and structural capacity. However, the majority of the piles had not reached rock and therefore consolidation settlement and creep of the underlying the NSC could result in excessive total and differential settlement beneath the pile groups, and this was the major concern. It was considered necessary to undertake further ground investigation and laboratory testing to better establish the consolidation and creep characteristics of the NSC. Results from the additional consolidation (oedometer) and quick undrained triaxial testing was used to establish consolidation and creep behaviour which could then be included in estimates of long term settlement.

Another important consideration in the foundation performance was the variation in ground conditions across the site and the impact of ongoing consolidation settlement of the upper CIS layer. In addition, interpretation of the additional laboratory test data indicated that the NSC in the western section of the site was more compressible than that found in the eastern section. Geological sections and contour plots of the thickness of the various strata were generated to assist in the development of geotechnical models for the western and eastern sections of the site which reflected the variations in subsurface conditions. The design parameters adopted for the various units are presented in Table 1.

Table 1: Adopted Design Parameters

Unit	Skin friction f_s (kPa)	Modulus E (MPa)	End bearing f_b (MPa)
CIS	20	2	-
FBS	75	22.5	-
MSG	150	150	10
NSC	75	30	-
MF	500	1000	30

4.3 Assessment of the As-constructed Foundation Performance

Using these geotechnical models, an assessment of the likely short and long term settlements of the as-constructed pile foundations was carried out using Coffey's in-house program PIGS for the calculation of the settlement of pile groups under axial loading. PIGS is based on the simplified elastic method after Randolph & Wroth (1978), but allows for non-linear pile response via an assumed hyperbolic load-settlement behaviour for each pile. Different pile lengths and sizes can be accommodated in the PIGS analysis and different soil profiles can be specified for individual piles. The interaction effects of the individual piles on the pile group settlement are modelled and the program allows the application of external soil movements of varying magnitudes on individual piles or groups of piles.

The findings of this assessment indicated that the predicted settlement of as-installed piles in the western section of the site could not be accommodated by the proposed structure and therefore rectification works were required.

4.4 Design of Rectification Works

A remedial solution was proposed for the western section which comprised the installation of a number of steel H piles within the existing precast concrete pile groups. A test pile (310 UC 158 steel H pile) was installed to rock to confirm the driveability of this type of pile in areas where densification of the underlying MSG had occurred due to the installation of the concrete piles. Dynamic load testing was carried out on the H pile to allow calibration of the geotechnical model and adopted design parameters. Class A predictions of the load settlement behaviour of the test pile were completed, including consideration of down drag due to long term consolidation of the CIS layer.

One of the design issues that had to be addressed was the modelling of the interaction effects within composite pile groups comprising H piles driven to rock and concrete piles founding in the MSG, as well as the interaction between the pile groups. To this end, each of the pile groups was modelled as an "equivalent pier" in the PIGS analysis and the pile group stiffness was determined as follows:

No H Piles – each pile group converted into an equivalent pile having the following properties:

For up to 3 piles: Equivalent shaft diameter (D_s) = Group Perimeter/ π (3)
Equivalent base diameter (D_B) = √ (Net Concrete Area x 4 / π) (4)
Equivalent modulus E_{eq} = (Net Concrete Area/Gross Shaft Area) x E_c (5)

For >3 piles: D_s = Group Perimeter/ π (6)
D_B = Calculated to give equivalent base area of the block (so NSC is "seen") (7)
E_{eq} = (Net Concrete Area/Gross Shaft Area) x E_c (8)

With H Piles – to convert the pile group with different pile lengths to an equivalent single pile, the following approach was used:

Step 1 - A separate analysis using PIGS was firstly completed with individual, varying length piles modelled. For the H piles, a zone of influence below the toe of the piles of 5 times the pile diameter was modelled. For the concrete piles, in order for the pile group behaviour to be influenced by the underlying NSC, the following zones of influence were used:

Table 2: Adopted Zones of Influence

Number of H Piles in Group	Zone Of Influence (m)
1	$3D_B$ / d_B
2	$2D_B$ / d_B
3	$1D_B$ / d_B but not less than 5
4	$0.5D_B$ / d_B but not less than 5

where: d_B = diameter of an individual pile
D_B = equivalent diameter of the pile group without H piles

Step 2 - An equivalent diameter pile (having D_s' and D_B') to rock is then chosen to act as a single pile, such that (d_s < D_s' < D_s) and (d_B < D_B ' < D_B) and produces similar load/settlement characteristics as the pile group. The equivalent pile modulus for this equivalent single pile is calculated as follows:

$$E_{eq} = (A_{st} \times E_{st})/\{p \times (\pi D_B'^2)/4\} \quad (9)$$

where: A_{st} = area of each H pile
E_{st} = elastic modulus of steel
p = percentage of load on the pile group taken by one H pile (as calculated by Step 1)

A PIGS analysis was then completed using these equivalent pile parameters to assess the overall performance of the remediated foundation. In order to provide the structural designers with an enhanced level of confidence, an assessment of the reliability of the predicted settlements was carried out using the method proposed by Duncan (2000). Assessment of the likely upper and lower bound values of four variables (skin friction, end bearing, Young's modulus and unit thickness) was made and a suite of PIGS analyses completed in order to calculate the standard deviation of maximum settlement. This assessment suggested a coefficient of variation of settlement of about 28%. The author is of the view that a settlement prediction can be considered successful if it is within 30% of the actual measured value given the many variables that influence foundation settlement.

4.5 Measured Foundation Performance

Settlement of selected columns was recorded during the construction of the towers (up to Level 20) and was compared to the estimated settlements from the PIGS analysis, an extract of which is presented in Table 3. It can be seen from these results that in general, the measured and predicted settlements were in good agreement.

Table 3: Settlement Monitoring Results

Column No.	No. of Piles	Recorded Settlement (mm)	Predicted Settlement (mm)
98	3 x 400 square	25	23
99	3 x 400 square	20	19
109	5 x 350 square	17	13
146	5 x 400 square	23	24
Raft 6 & 7	15 x 400 square	20	19

5 CONCLUSION

With the construction industry becoming more competitive and, at the same time, more litigious, the requirement for forensic engineering when things go wrong is becoming increasingly common. The behaviour of any foundation is complex as there are many elements interacting, including Mother Nature. Accurate prediction of this behaviour can be difficult even when the foundation is designed and constructed using well established and reliable methods. Prediction of behaviour is further complicated when the foundation is found to be inadequate, as this indicates that actions or conditions not identified or considered in the design are prevalent. One needs to understand the reasons for the foundation failure in order to develop appropriate rectification measures. Adopting a framework for forensic investigation allows the foundation designer to systematically assess the possible causes of foundation failure and develop suitable rectification works.

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