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Load displacement behaviour of piled foundations for assessment and design

J.A. Munro & S.J. Palmer
Tonkin & Taylor Ltd, Wellington.

ABSTRACT

Ultimate limit state (ULS) design of piles in New Zealand is normally based on a factored load and resistance approach. However the effects of pile displacement must also be considered. Piles, and particularly those of large diameter relying on end bearing, can be subject to large displacements in the ULS design case. The displacements could be beyond the tolerance of some structures. It is common practice in New Zealand and internationally to use a resistance factor - strength reduction factor (SRF), in capacity design which is greater than that normally accepted in other ULS design cases. If the use of a higher SRF is to be considered, it is essential that the structural and geotechnical engineers jointly consider the acceptability of this in terms of magnitude and predictability of displacements.

This paper outlines a number of methods available for assessing load/displacement behaviour of piles. Uncertainties inherent in pile load displacement are discussed and guidance is provided regarding how they could be considered. Guidance is provided on selecting SRF for the capacity design case. The conclusions are: the assessment of load/displacement behaviour should include multiple methods, consider uncertainty and apply engineering judgement, dynamic displacements are likely to be less than static displacements, and capacity design should only use a higher SRF when the displacement behaviour at the design loads is understood and the structure can tolerate potentially large displacements.

1 INTRODUCTION

Load resistance factored design (LRFD) is used in New Zealand for the design of piled foundations. Load resistance design of piles is often based on capacity without consideration of displacement. Piled foundations require displacement to mobilise resistance. This must be considered during design and assessment as recommended (Recommendation 12) in the Canterbury Earthquake Royal Commission Final Report (2012). Piled foundations (such as large diameter bored piles) may undergo large displacements in order to mobilise

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the ULS resistance required. The geotechnical engineer must estimate these displacements and communicate the load displacement behaviour to the structural engineer. The uncertainty and potential range of these parameters is also to be communicated. The structural engineer must model this behaviour and assess if the displacement effect on the structure is tolerable, and possibly consider the beneficial effects on the structure's seismic response as a consequence of some foundation flexibility. Methods for estimation and communication of pile behaviour are outlined in the following sections of this paper. The aim is to provide geotechnical and structural engineers with the necessary background understanding and an appropriate methodology to consider the load displacement behaviour of piles in assessment and design. Understanding pile load displacement behaviour is particularly important for the assessment of existing piled foundations, where often it is required to estimate displacements at loads greater than that considered in design.

NZGS/MBIE Guidelines Module 4: Earthquake Resistant Foundation Design (NZGS Module 4, 2016) provides discussion and guidance on load displacement in the design of piled foundations. It recommends a process for ULS and SLS settlement checks under both gravity and seismic load cases. These displacements need to be communicated to the structural engineer to determine if additional analysis is required. Module 4 provides guidance on defining point A in Figure 2 in Section 5; the displacement to mobilise the geotechnical ultimate capacity. For projects where the load displacement behaviour is critical, or the risks/uncertainties associated with predicting pile displacement are significant, then a more detailed assessment is needed. This assessment should consider displacements at design loads in addition to those at the geotechnical ultimate capacity. This paper provides guidance for that more detailed assessment.

Recent projects where the load displacement behaviour of piles has proven to be critical include projects with large diameter end bearing piles supporting a base isolated structure.

2 FOUNDATION/STRUCTURE INTERACTION

2.1 Rigid base assumption

A structure can either be designed/assessed assuming a rigid base or with foundations that require displacement to mobilise resistance. A rigid base assumption is often considered as conservative as more seismic load will be attracted to the superstructure. However, this approach is non-conservative with respect to foundation displacements and associated effects on the structure. A more thorough design/assessment approach is to consider the potential range of load displacement behaviour of the piles. The stiff end of the potential foundation behaviour range is considered in assessing the structure's dynamic response (natural period) and the soft end of the potential range is considered in assessing foundation displacements and associated effects on the structure.

2.2 Pile type and displacement

Different pile types utilise different proportions of shaft and end bearing for mobilising their ULS resistance. Therefore different pile types will have significant variation in load displacement behaviour. For example:

- A continuous flight auger pile (CFA) (say 10m long and 450mm in diameter) relies primarily on shaft resistance to mobilise resistance. Therefore pile displacements to mobilise the assumed capacity can be expected to be small (in the order of 10mm or less).
- A large diameter belled bored pile (say 1.5m diameter shaft and 2.5m diameter bell) will be mobilising a large amount of resistance in end bearing. Therefore the load displacement behaviour is much softer and non-linear. Displacements could be in the order of 200mm to mobilise the assumed capacity. Load displacement behaviour for these large diameter, heavily loaded piles is often critical to the design.

This behaviour is outlined in Section 3.1.

3 LOAD DISPLACEMENT BEHAVIOUR OF PILES – QUALITATIVE

Understanding in a qualitative sense the likely displacement behaviour and failure type of the piled foundation is useful in developing the predicted pile response.

3.1 Mobilising resistance in piled foundations

Piled foundations mobilise resistance from shaft friction and end bearing. Bored piles are usually either designed as predominantly friction piles or end bearing piles. Friction piles rely on shaft friction for their design capacity whereas end bearing piles rely on shaft friction and end bearing. The displacement to mobilise shaft friction is significantly less than that required to mobilise end bearing. This is presented in Figure 1 below.

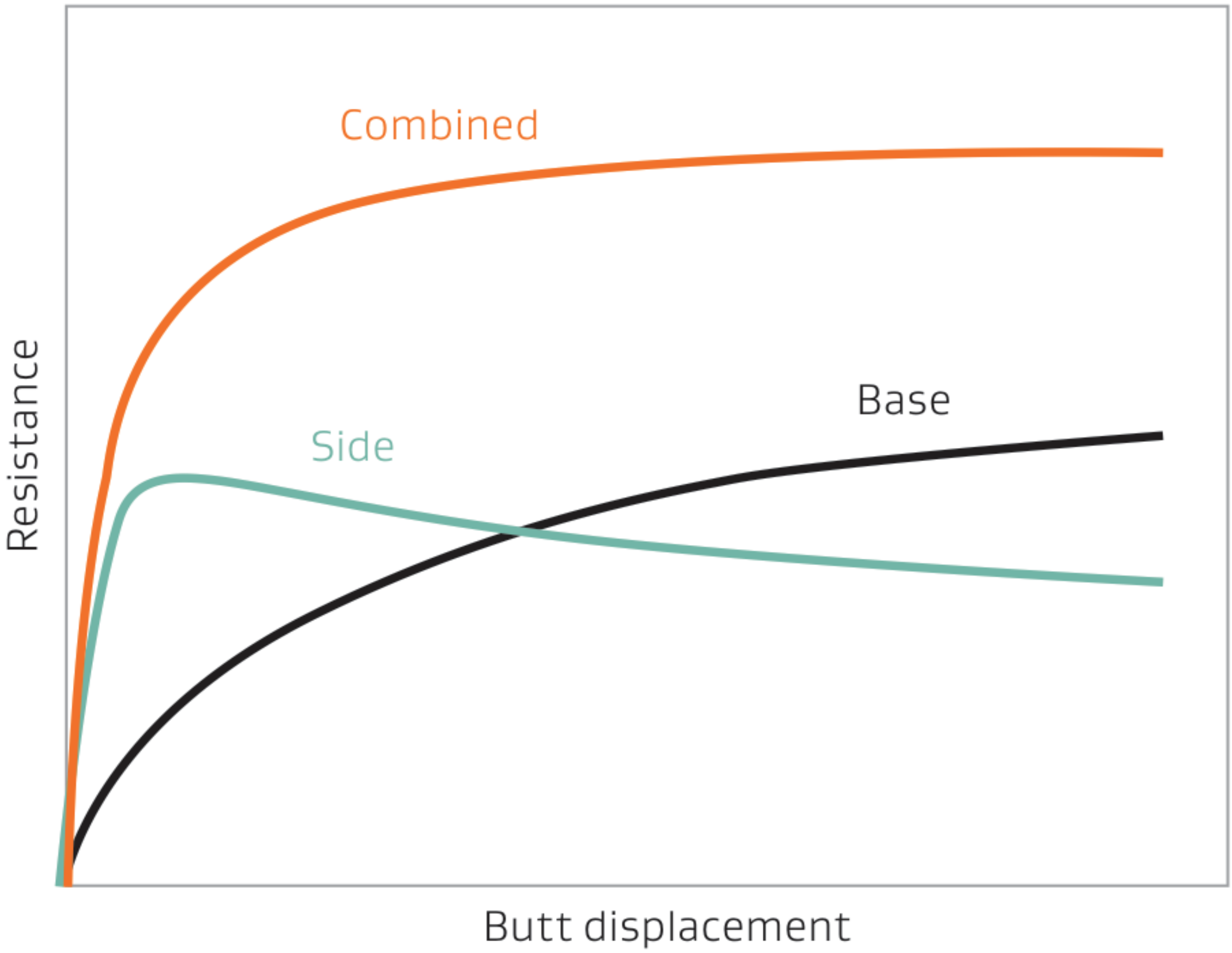

Figure 1: General load-displacement response of a piled foundation. (Reproduced from NZGS/MBIE Module 4, 2016)

Ground conditions and the structure's tolerance to displacement will influence the selection of friction or end bearing piles. A friction pile will generally have a stiffer load displacement response than an end bearing pile.

4 DISPLACEMENT BEHAVIOUR OF PILES - QUANTITATIVE

4.1 Methods of prediction

There are a wide range of methods available to predict load displacement behaviour of piled foundations.

Table 1 below outlines a number of methods available for the estimation of pile load displacement behaviour, with some commentary on usage. A range of methods should be considered when estimating load displacement behaviour. The authors recommend using at least two methods and applying engineering judgement to select parameters for design.

Table 1: Load displacement behaviour prediction.

Prediction type	Method description	Comment
Site and pile specific load tests	Load test pile and measure displacement	Provides site and pile specific and measured response. Load tests in New Zealand are rare due to the perception that costs outweigh benefits and no requirement in design codes. Load tests can offer significant cost benefits, however are generally only considered for large projects where the cost of foundations is relatively high
Pile type specific load tests	Use knowledge of performance of similar piles at nearby sites	Utilise nearby load tests in similar material on similar piles if available
Load transfer methods	Curves (t-z and q-z) relate soil shear strength to pile movement along pile length. Utilises load displacement data from experimental tests defined for different soil/rock types (e.g. Reese & O'Neill, 1989)	Provides a quick estimation based on pile diameter and soil type. Experimental test data may not reliably represent site conditions (i.e. 'sand' or 'clay'). Can account for variability of stress-strain response of multiple soil layers. Use with caution.
Elastic solution methods	Solutions based on elastic properties of soil and pile materials (e.g. Poulos & Davis, 1980)	Requires definition of elastic properties of soil. Can consider group effects, however may not be suitable where the response is non-linear.
Finite element or finite difference modelling	2D or 3D model of pile and founding material	Requires definition of elastic (and inelastic) properties of soil. Complicated and computer intensive compared to other methods. Can assess multiple soil/rock layers, pile group effects, free field ground displacement, installation effects, dynamic loading, and coupled soil - pile - superstructure interaction.

4.2 Uncertainties in load displacement behaviour – sensitivity analysis

Uncertainties due to variability and unknowns in pile behaviour are described in Table 2 below.

Table 2: Uncertainty in pile load displacement behaviour.

Source of uncertainty	Comment
Variation in ground conditions	Ground conditions across a site can vary widely and result in a wide range of potential pile load displacement behaviour. A robust site investigation should aim to explore this uncertainty and help to understand the potential range of pile performance.
Geotechnical design parameters	Soil/rock stiffness parameters are typically not directly measured from common investigation tests (SPT/CPT). Consider additional testing (e.g. pressuremeter) during investigation programme if load displacement is critical to the design or assessment.
Pile construction	Stiffness of end bearing founding material is sensitive to pile construction method and workmanship. Driven piles are generally stiffer than bored piles in end bearing. Bored pile soil relaxation due to excavation and limitations of base clean out influences stiffness. Smear on shaft and hole stability can impact the capacity and stiffness of the shaft friction component. Robust quality control and inspections (by both contractor and engineer) can both mitigate and inform this uncertainty. Pressure grouting can be used to stiffen bored pile base response.
Epistemic uncertainty	Uncertainty due to limitations and assumptions of the load displacement prediction methods. Be aware when applying different methods and use a variety of methods to inform this uncertainty.
Elastic compression of pile (pile stiffness)	Difficulty in accurately defining transfer of skin friction and end bearing to pile. Approximate methods are available (e.g. Fleming, 1992).
Dynamic loading	Available prediction methods are almost entirely based on static pile loading. ULS loads in NZ often include dynamic earthquake loads. Dynamic soil stiffness can be far greater or far less than static soil stiffness. Load rate and number of load cycles will affect stress strain response of soil and should be considered when determining the load displacement behaviour for dynamically loaded piles.
Pile group effects	The majority of methods available to predict load displacement of piles are for single piles. Pile group interaction effects will increase pile displacements, this should be considered in design/assessment.
Negative skin friction (NSF)/dragdown	NSF/dragdown loads arise due to settlement of soil surrounding the pile. This settlement can arise due to consolidation, shrink-swell behaviour or volumetric strain and settlement of soil following liquefaction. These loads will influence the load displacement behaviour of the pile
Strain compatibility between soil layers	Shaft friction is likely to be provided through multiple soil layers. These soil layers will have different stress strain properties, with variations in displacement required to mobilise shaft resistance. These variations are likely to be small, but should be considered in the assessment.

The authors recommend that these uncertainties are discussed and considered during the design and assessment process and accounted for accordingly. When estimating pile load displacement behaviour it is important to quantify these uncertainties as a way of providing a lower and upper estimate of what the behaviour could be. This is often crudely reported as halving and doubling the estimated pile stiffness value estimated. A more robust approach is to attempt to quantify what the uncertainty could be based on the information available (e.g. a soil stiffness of plus or minus 20 MPa) and carry out a sensitivity analysis. From this exercise, appropriate values can be determined for reporting.

4.3 Strength reduction factors and overstrength design

Module 4 recommends selection of a strength reduction factor using AS2159:2009 (Standards Australia, 2009). Module 4, however, provides no specific guidance on selection of geotechnical strength reduction factor (SRF) for overstrength design. Palmer (2013) explores the debate for higher than conventional geotechnical SRFs for overstrength design.

Higher geotechnical SRFs are currently being used in NZ engineering practice for overstrength design. This can shift pile response into a less predictable and less elastic zone. This must be considered in the prediction of pile load displacement behaviour and in the range reported to the structural engineer. This is discussed further in Section 5.

Design should only use a higher SRF when the displacement behaviour at the design loads is understood and the structure can tolerate potentially large displacements. Structural engineers must have confidence that the hierarchy of failure mechanisms in the superstructure will not be compromised by lower foundation stiffness. This decision requires effective communication of the anticipated range of potential pile load displacement behaviour between the structural and geotechnical engineers.

5 COMMUNICATING LOAD DISPLACEMENT BEHAVIOUR

Pile load displacement behaviour is often provided to structural engineers as a single spring value (i.e. ks = 500kN/mm) with a recommendation to half and double this value. The authors recommend providing a load displacement plot to represent the modelled behaviour of the pile and potential range. A load displacement plot is a useful tool for communicating the elastic and non-linear portions of load displacement and how this relates to the ultimate geotechnical capacity and selected strength reduction factor.

An example plot is shown below as Figure 2. In this case the softer range of potential behaviour has been increased for the overstrength SRF to account for the uncertainties at loads/displacements nearer to the ultimate capacity.

The authors recommend providing a plot and table with corresponding values to be used in the design or assessment.

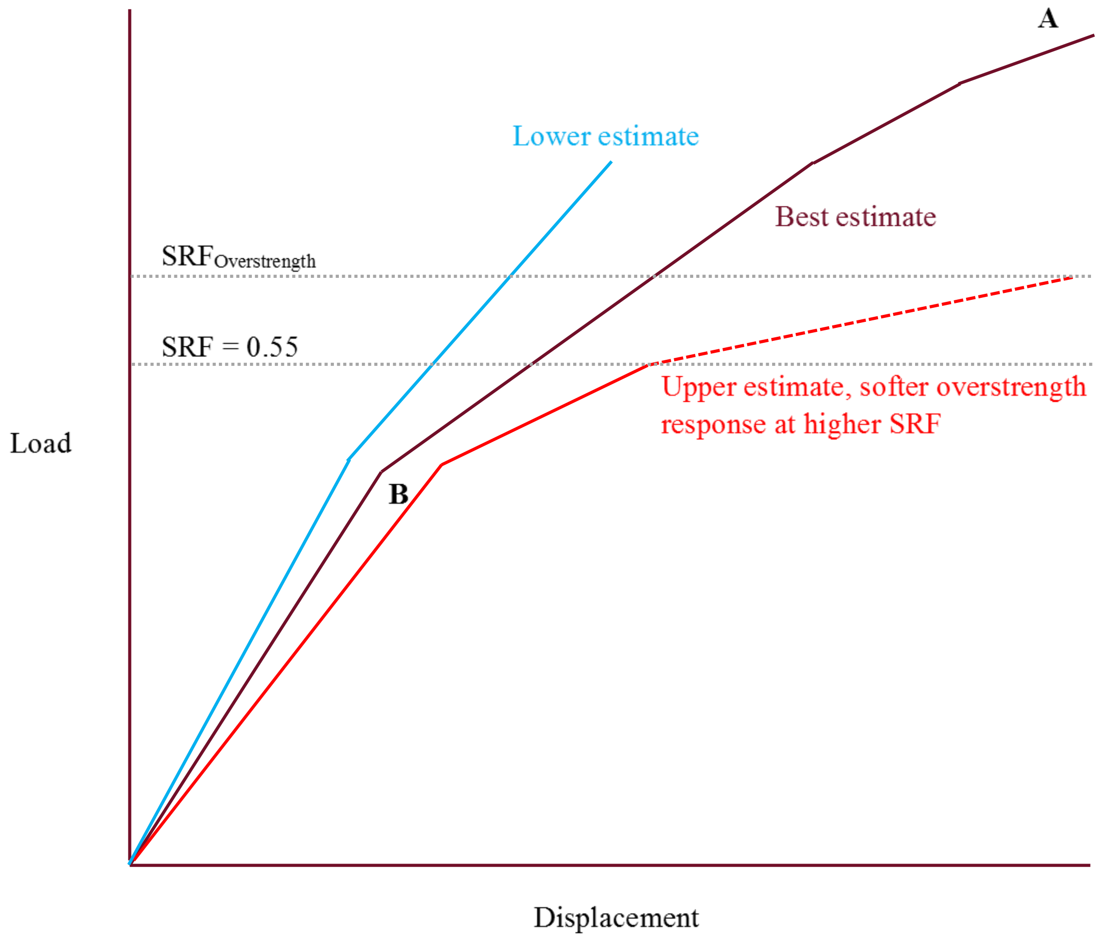

Figure 2: Example load displacement plot with lower, best and upper estimate behaviour indicated. Note that upper estimate stiffness has a softer response to account for the greater uncertainties present at the higher SRF. Point A describes the displacement to mobilise the geotechnical ultimate capacity (as outlined in Module 4). The change in stiffness at point B is due to the pile mobilising the full shaft resistance

6 CONCLUSIONS

This paper has presented a background on pile load displacement definition and provided some guidance for communication from geotechnical to structural engineers. Key conclusions/recommendations are as follows:

- Structural design or assessment assuming a rigid foundation base is generally conservative for loading but generally non-conservative for displacements. Foundations require displacement to mobilise resistance and as such the foundation system should be modelled considering its load displacement behaviour. The sensitivity of results compared with a rigid base should be considered.
- The first step in analysis/assessment is understanding the qualitative load displacement behaviour of piled foundations – how shaft/end bearing capacity is mobilised.
- Module 4 provides a means of checking displacements at the geotechnical ultimate capacity. If these displacements are critical (or their prediction involves significant uncertainties) then further more detailed assessment should be carried out as recommended in this paper
- Prediction of pile load displacement has uncertainties. Consider uncertainties and carry out a sensitivity analysis on parameters. Quantify potential behaviour range with a lower and upper estimate. Consider at least two prediction methods and apply engineering judgement when defining load displacement behaviour for reporting and communication.

- The foundation system should be modelled considering the full range of estimated load displacement behaviour.
- Higher strength reduction factor for overstrength should only be considered if the structure can tolerate the associated increased displacement and uncertainty. This potentially softer response and increased uncertainty must be communicated by the geotechnical engineer and assessed by the structural engineer.
- Load displacement diagrams with tabulated values are effective tools for communication between the structural and geotechnical engineers.

7 REFERENCES

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