A Pragmatic and Non-Intrusive Procedure for Assessing the Post-Earthquake Structural Integrity of Piled Foundations

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ABSTRACT: Following the Canterbury Earthquake Sequence several piled buildings were damaged, but not beyond repair. A need arose for the structural integrity of existing, in-service, piled foundations to be evaluated without extracting the piles. Structural engineers needed this evaluation for future load carrying capacity and, conversely, insurers and building owners needed a useful evaluation of the likelihood and extent of damage that occurred to the foundations to determine the scope of the insurance claim.

This paper describes a pragmatic, non-intrusive means of evaluating the likely damage to, and the structural integrity of, existing piled foundations that are subjected to earthquake loading. The approach involves carrying out a pseudostatic lateral pile analysis where account is taken of (1) inertial loads from the superstructure, (2) kinematic loads due to cyclic ground displacements and (3) degraded soil parameters of liquefiable soil. The resulting bending moments and shear forces generated from the lateral pile analysis are then compared to the design moment and shear capacity of the piles.

The method developed, is practical, requires comparatively little computational effort, allows the user to "get a feel" for what may have occurred regarding the likelihood of damage, and provides an indication of how the existing piles are likely to perform under future design events.

1 INTRODUCTION: EVOLUTION OF THE METHOD

The need for high-quality, yet practical, seismic geotechnical engineering solutions for the remediation and rebuild of a large number of buildings following the Canterbury Earthquake Sequence has dramatically changed the nature of the communication between geotechnical engineers, structural engineers and their clients. In typical geotechnical practice, the client is commonly the structural engineer, land developers or some other 'informed' individual. However, in the Canterbury Region of New Zealand, geotechnical engineers have found themselves in an atypical situation where their advice and solutions can have social, political and commercial implications and must be included when evaluating their recommended solution. Additionally, they have to effectively communicate these solutions to property owners, insurers, and other 'non-informed' persons.

During the Canterbury Earthquake Sequence, several piled buildings were damaged, but not beyond repair. A need arose where the structural integrity of existing piled foundations needed to be evaluated without extracting the piles. Structural engineers needed this evaluation for future load carrying capacity and, conversely, insurers and building owners needed a practical evaluation of the likelihood and extent of damage that occurred to the foundations to determine the scope of the insurance claim.

The objective of this study was to develop a simple, practical method of addressing this specific problem: to determine the structural integrity of in-service piled foundations. To evaluate existing piled foundations, the authors first explored the notion of using a physical method to test the piles.

The first method considered was the PIT (Pile Integrity Test). This test is a routine method used to assess the integrity of piles at the time of construction. The PIT involves striking the top of the installed pile with a small hammer. The impact of the hammer generates a compressive stress wave in the pile, and an accelerometer placed on top of the pile monitors the motion associated with this wave. The stress wave propagates down the pile shaft, and is reflected when it encounters either the pile toe or a non-uniformity of the shaft (e.g. a crack or necking). These reflections cause a change in the acceleration signal measured on the pile top, which is picked up and processed by the equipment and interpreted by an experienced engineer[1].

After discussions with the manufacturers of the PIT equipment, it became apparent that it would not be possible to assess the structural integrity of piles under existing structures, especially in situations where access to the pile top is preclude, there are no reliable ‘as-built’ records and the lengths of the piles are not accurately known. Data acquisition and analysis of test records of existing, in-service piles can be particularly challenging as the data is often complex and does not always allow for confident interpretation.

The authors concluded that an alternative method had to be considered that relied upon non-intrusive methods and analysis. A literature review of the methods used to assess the structural integrity of in-service piles was carried out. Given the ‘real-world’ time and cost restraints and considering the frenzied post-earthquake environment, not only would the selected method have to be technically robust, but it would also have to be relatively quick to perform, not depend on expensive lab and field testing, be easy to repeat and be able to use existing commercially available software.

The method must also be able to be adaptable to the soil conditions in Christchurch. The soils in Christchurch consists of geologically-young, deep alluvial soils. These ground conditions are complex, highly variable over short distances and generally provides numerous challenges for geotechnical engineers. The city of Christchurch is low lying and as a result the groundwater table is generally high all year round. These ground conditions provide the perfect conditions for liquefiable soils. It is therefore not surprising that one of the main geo-hazards in the region is the severe ground deformations associated with liquefiable soils.

In their 2005 publication, Liyanapathirana and Poulos state that liquefaction of saturated soils subjected to earthquake loading is one of the major factors affecting the behaviour of pile foundations and subsequent building failure in seismically active areas. They discuss a number of methods for the seismic analysis of piles based on the one-dimensional Winkler model. However, these methods cannot predict pile behaviour in liquefiable soil and are therefore inappropriate for instances where deep liquefiable deposits will govern the pile response during seismic events. Since then other Winkler-type models have been developed but these methods require complex dynamic finite element analyses be carried out to determine the pile response in liquefiable soils. These methods are technically challenging and time consuming and are difficult to apply in routine practice. It would be difficult to employ these methods under time and delivery constraints for a large volume of projects.

More recently, pseudostatic methods have been developed to evaluate the response of single piles under earthquake loading. Although simplified methods to carry out pseudostatic analyses on piles have been proposed (e.g. Tabesh and Poulos 2001, Liyanapathirana and Poulos 2005, Castelli and Maugeri 2009) they still require relatively advanced analyses, such as seismic free-field analysis to obtain time histories and soil displacements.

The authors have found that the pseudostatic lateral analysis presented by Cubrinovski, Ishihara and Poulos (2009), provides the user with a simple, practical and user-friendly means of calculating the bending moments and shear forces generated in a pile subject to earthquake loading. The crux of the method presented in our paper to assess the post-earthquake structural integrity of piles foundation is based on this method. This paper also discusses how the results of the developed analysis method were interpreted and their practical significance.

2 THE PROCEDURE

A flow chart has been developed to describe the procedure used for assessing the structural integrity of in-service piled foundations, Figure 1.

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[1] http://www.grlengineers.com/services/pit/

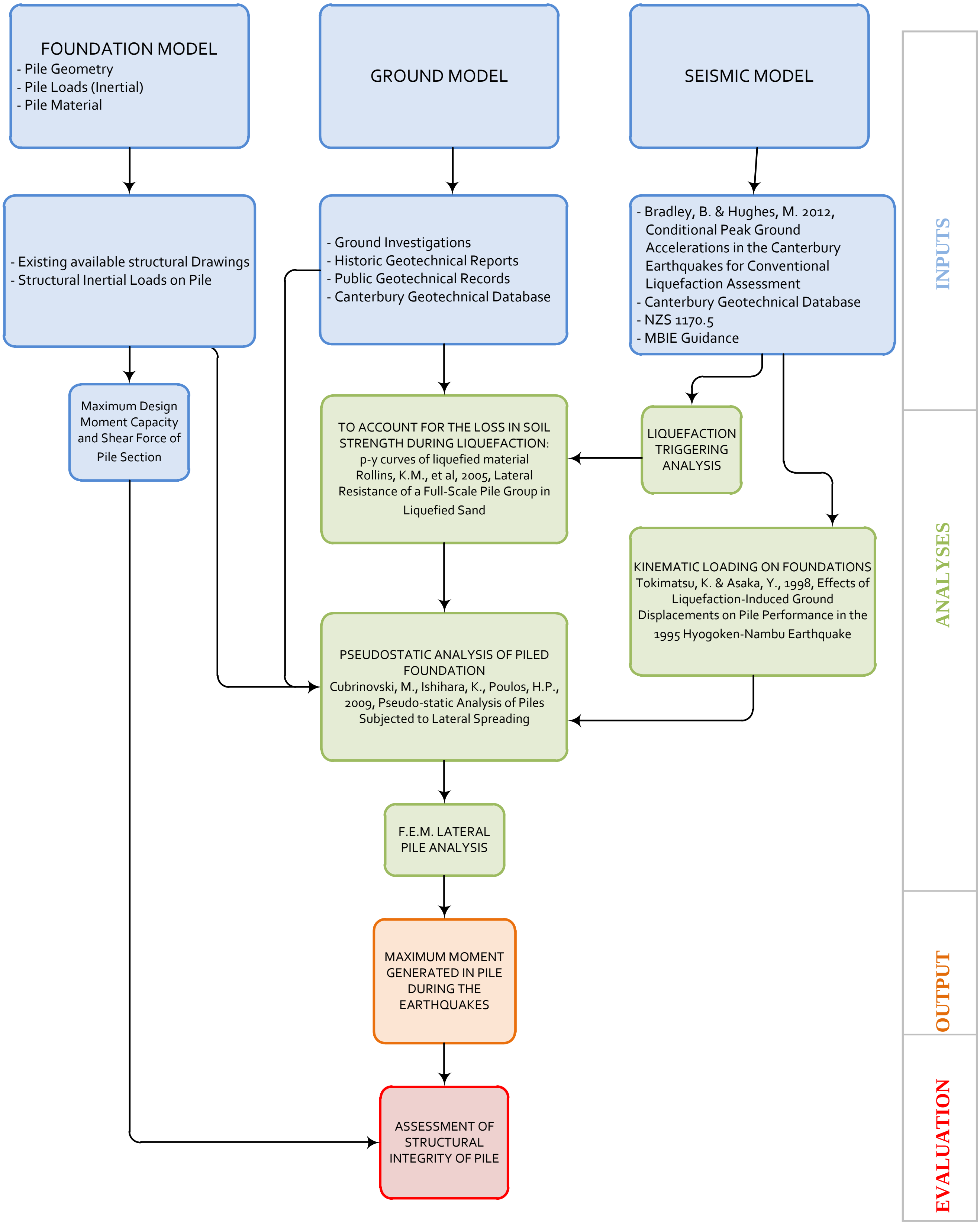

Figure 1. Flowchart showing a summary of the structural assessment of in-service piled foundations

2.1 Inputs

The inputs of the procedure are the foundation model of the existing piled foundation, the ground model under the existing structure, and the seismic demand that the structure has been or will be subjected to.

Modelling existing in-service foundations can be a real challenge, depending on the quality and availability of as-built drawings and the age of the building. The user should be aware that they are essentially modelling an idealized version of the foundations that were actually installed. Examination of construction quality control documents can provide an appreciation of the as-built condition of the existing foundations, which can differ significantly from the design drawings. This, of course, is one of the limitations of modelling an existing foundation.

The ground model can be determined from conventional geotechnical investigation methods.

Bradley and Hughes (2012) developed a methodology for prediction of experienced conditional peak ground acceleration (PGA) values which provides distributions with both median and standard deviations for the major events of the Canterbury Earthquake Sequence. These values are represented through contours and are available on the Canterbury Geotechnical Database. These contours were used to estimate the ground demand experienced at a particular site in the Canterbury region for individual events. The demand from each event, in the form of the cyclic stress ratio profile was then compared to the ground demand from various proportions of design events (e.g. 50% ULS, 75% ULS, 100% ULS). This is useful because it allows the user to evaluate the actual damage that occurred to the site using the design event as an index. Additionally, it is easier to estimate inertial loads for some proportion of a design event than it is for an actual event where time-history data is not available.

A liquefaction analysis was carried out using the standard proprietary software. From analysis the soil layers which are susceptible to liquefaction triggering are deduced and the ground model for the analysis is developed.

2.2 **Using the Simplified Pseudostatic Analysis**

The method of pseudostatic lateral pile analysis is a lateral pile analysis where account is taken of (1) inertial loads from the superstructure, (2) kinematic loads due to cyclic ground displacements and (3) degraded soil parameters of liquefiable soil layers.

The pseudostatic method, as presented by Cubrinovski, Ishihara and Poulos (2009) is based on the model presented in Figure 2. The model is based on a three-layer soil system where the pile is represented by a continuous beam. The upper layer is a non-liquefiable ‘crust’ layer. Its contribution to the ground response is accounted for in the form of a lateral earth pressure.

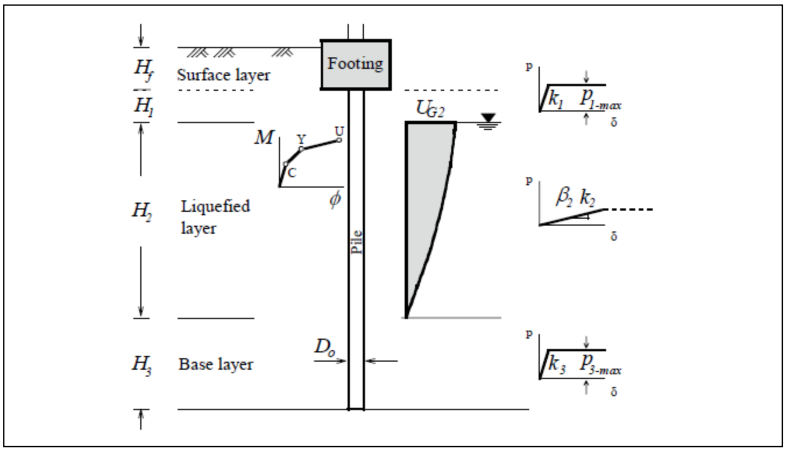

Figure 2. Characterization of non-linear behaviour and input parameters of the pseudo-static model

The interaction between the soil and the pile in the liquefied layer is represented by an equivalent spring (b_2k_2). The subgrade reaction is represented by k_2. b_2 is a scaling factor representing the degradation of stiffness due to liquefaction and nonlinear behaviour.

To estimate b_2 a relationship between stiffness degradation and ground displacement was provided in the paper by Cubrinovski, Ishihara and Poulos (2009) . However, the uncertainty in the range of values provided for b_2 was the greatest for ground displacements less than 10 cm. This made it difficult to incorporate stiffness degradation into the analyses. Given that the authors were interested in developing a method for cases where lateral spread had not occurred, and pile deflections were not large, other methods for accounting for the stiffness degradation were explored.

Rollins et al. (2005) developed an empirically derived equation which describes the load-displacement relationship for fully liquefied sand. Subsequently, *p-y* curves were developed using this equation and has since been integrated into the commercially available software LPILE. Users are cautioned that the use of the equation be limited to deflections of less than 150mm. This would be appropriate in instances where liquefaction had occurred but there was no lateral spread. Rollins et al (2005) state that these *p-y* curves provide reasonable estimates of the measured response of full-scale piles in liquefied sand. Another benefit of using LPILE was that it allows the user to analyse a more detailed soil system.

The kinematic loads due to cyclic ground displacements were derived using a method presented by Tokimatsu and Asaka (1998). In their paper, a chart is presented giving the maximum cyclic shear strain developed during an earthquake as a function of SPT *N-value* and the Cyclic Stress Ratio (Figure 3). When the strain is multiplied by the thickness of the liquefied layer, the result is the cyclic ground displacement.

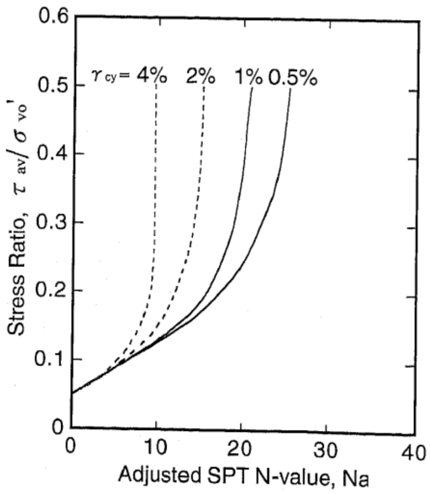

Figure 3. Maximum cyclic shear strain during earthquakes (Tokimatsu and Asaka, 1998)

The pseudo-static analysis process is carried out parametrically, proportionately varying the ground demand and the inertial loads.

2.3 Evaluating the Output

The resulting bending moment and shear force profiles are examined and an evaluation of the structural integrity of the piles can be made. Evaluation of the practical significance of the profiles requires structural engineering experience.

3 CASE STUDY

The following case study is a simplified example of the procedure. When we have run an analysis for a project we have conducted sensitivity checks and run a series of load cases. The entire process can be carried out parametrically, proportionately varying the ground demand and the inertial loads; however, in this case, the process will be demonstrated once. The resulting bending moment and shear force profiles are examined and an evaluation of the structural integrity of the piles can be made.

3.1 **Case Study - Inputs**

<u>FOUNDATION MODEL</u>

275mm Square Reinforced Concrete Pile

Pile Length: 20m

Concrete Compressive Strength: 82.5 MPa *(Note: This is the estimated long-term in-ground strength from a real site)*

Max. Coarse Aggregate Size: 19mm

Rebar Yield Strength: 460 MPa

Elastic Modulus: 200,000 MPa

Bar Size: US Std. #8

No. of Bars: 12

Concrete Cover to Edge of Bar: 76.2mm

Pile Loads (Inertial): Axial Load = 500kN and Shear Force = 20kN, 40 kN and 60 kN

<u>SEISMIC MODEL</u>

Seismic Demand: Design ULS IL2 Event, M: 7.5 and PGA: 0.35g

<u>GROUND MODEL</u>

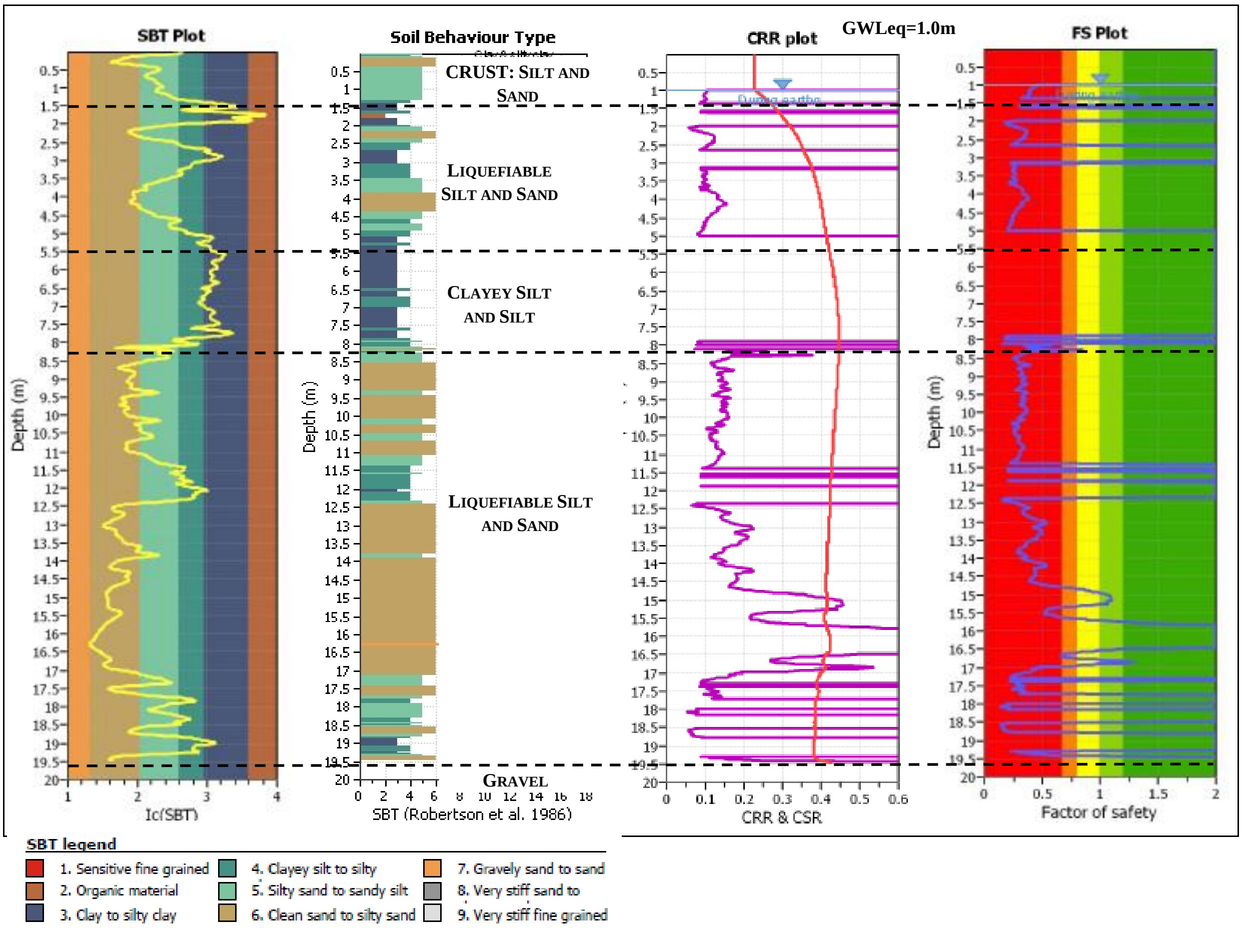

Figure 4. Ground model identifying liquefiable soil layers

3.2 Case Study - Analyses

The ground displacement profile was carried out using the method presented by Tokimatsu and Asaka (1998). This ground displacement profile and the inertial pile loads were entered into LPILE. The following charts show how the soil profile was modelled and the soil parameters that were assigned to each layer.

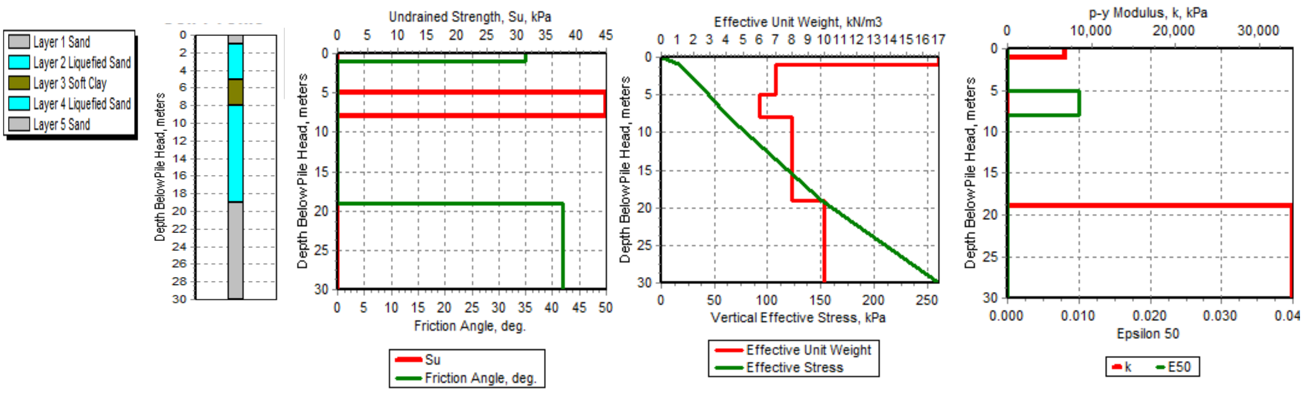

Figure 5. Idealised soil profile and soil parameters used in case study

3.3 Case Study – Output and Evaluation of Output

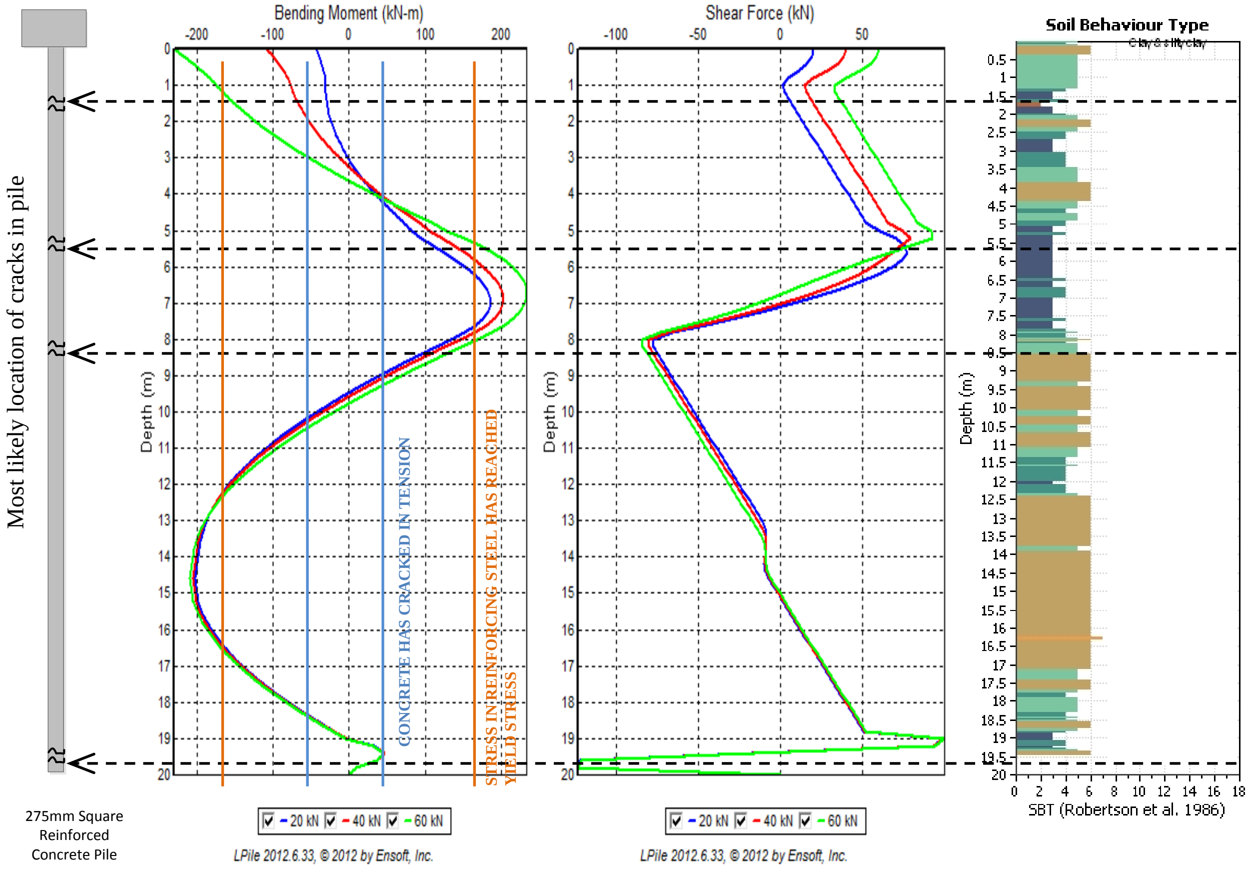

Figure 6. Pseudostatic lateral pile analysis results: bending moment and shear force diagrams

The results of the analysis are presented in Figure 6. During physical inspection of piles damaged during the 1995 Kobe earthquake it was found that most of the piles suffered the most damage at the pile top and in the zone of the interface between the liquefied layer and the underlying non-liquefied layer. (Cubrinovski, Ishihara and Poulos, 2009). The results of the analyses in this case study show that the maximum shear forces are developed at these interfaces. We infer that it is most likely that damage may occur at these locations.

A more refined analysis can be carried out by splitting the soil profile into more layers but the complexity of the soil model needs to be consistent with the quality and quantity of the given input data and also consistent with the inherent limitations the analysis method presents. This case study is presented for illustrative purposes only. An actual project will require a more in depth examination of the output.

4 CONCLUSION

The authors considered that this simplified method should be published and made readily available to practicing engineers, to assist in closing the gap between theory and practice. This paper is a demonstration of how a complex theoretical procedure can be adapted for use in everyday practice. The authors recognize the limitations of this method. This method is meant to be a 'first-cut' determination in forming an opinion as to the likely damage to the pile. Additional work clearly needs to be done to refine and define the applicability of the method.

Physical examinations of in-service piles subjected to earthquakes in liquefiable soils need to be done to verify the accuracy of the predictions of this method. Although similar methods have been verified in other parts of the world, such as Japan, and have had favourable correlations with predicting damage, no such work has been carried out to date in Christchurch to the authors' knowledge.

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