Databases for Data-Centric Geotechnics

Geotechnical Structures

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Chapter 10

The DINGO database of axial pile–load tests for the United Kingdom

Determination of ultimate load

Manar M. Othman, Elia Voyagaki, Jamie J. Crispin, Konstantina Ntassiou, Charlotte Gilder, Flavia De Luca, George Mylonakis, and Paul J. Vardanega

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Chapter 10

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ABSTRACT

Databases containing pile information are widely used to assess the reliability of design and performance prediction methods. The DINGO database of test piles installed in UK soils contains over 500 records collected from both literature and industry sources. This chapter details the collation of the database and details on the distribution of the test piles and previous analyses that have been undertaken. In this work, the DINGO database is used to assess the reliability and usability of eight methods for interpreting the ultimate pile capacity from filed test load–settlement information. The methods include mathematical model approaches, graphical estimations, and settlement limits. Higher ultimate loads were interpreted using the Chin method while lower ultimate loads were calculated using the DeBeer method. Finally, the average factor of safety for the pile tests used in this study was calculated to be 2.63 across all eight methods, with 26.6 and 1.05 being maximum and minimum values, respectively.

10.1 INTRODUCTION

10.1.1 Databases in geotechnical engineering

Databases are used extensively in geotechnical engineering for the development of transformation (regression) models to make *a priori* estimates of design parameters and for exploring interrelationships between parameters. A seminal work that presents such data and models is the *Manual on Estimating Soil Properties for Foundation Design* by Kulhawy and Mayne (1990). The importance of assessing transformation uncertainty using statistical measures such as the standard error (SE) and the coefficient of variation (COV) has been well articulated in the papers by Phoon and Kulhawy (1999a, 1999b). More recent studies investigating design parameter variation include Chen and Kulhawy (1993) who studied the effect of test type on undrained shear strength; Ching and Phoon (2014a, 2014b) who examined variability of soil undrained shear strength parameters; and Beesley and Vardanega (2020) who presented a database (RFG/TXCU-278) used to investigate the effect of shear mode on both undrained shear strength and mobilisation strains.

Due to the expense of full-scale foundation testing, significant research effort has been directed to collecting databases of pile tests. These can be used to establish and assess the accuracy of design and/or prediction methods. The importance of using reliability

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(statistical) methods in conjunction with design methods, focussed on capacity predictions (ultimate states), was articulated by Kulhawy (2010) in the 5th Peter Lumb lecture. The potential of using reliability-focused settlement predictions (e.g., using the mobilisable strength design (MSD) method) was discussed by Vardanega and Bolton (2016). Some examples of different reliability-based design (RBD) approaches are given in the paper by Low and Phoon (2017). All of these approaches require access to significant datasets (for the topic under discussion in this chapter: the availability of pile-load testing) preferably accompanied by detailed ground investigation data from the same site. Some large pile test databases are already available, a number of these were collected in specific countries, including:

- The United States – Paikowsky *et al.* (2004) assessed the performance of Load and Resistance Factor Design (LRFD) methods and Phoon and Tang (2019a) studied the variability in the performance of steel H-piles;
- Ireland – Galbraith *et al.* (2014) assessed the performance of the Chin (1970) method to interpret the ultimate test load; and
- Egypt – AbdelSalam *et al.* (2015) investigated in part the performance of different CPT pile capacity prediction methods.

Some international databases are also available using various sources and locations worldwide, such as (i) the Yang *et al.* (2015) database which includes pile–load tests in sand, (ii) the Chen and Kulhawy (2002) database which includes 53 sites with 100 pile tests (the majority installed in sand) which was used to evaluate the side and tip resistance of bored piles (concluding that beta values reach 6.5 at shallow depths and decrease at depth to reach a value range of 0.24–0.30 at around 20 m), (iii) the Chen *et al.* (2009) database containing 170 load tests across 97 sites in a wide variety of soils, which was used to evaluate the tip capacity of bored piles and concluded that the studied predictions systematically overestimate the tip capacity in drained soils and (iv) the findapile.com (Lemnitzer & Favaretti 2013) database which includes static and dynamic, axial, and lateral load tests.

10.1.2 Pile design in the United Kingdom

Many publications on UK pile design are available in the literature (e.g., Burland 1973; Burland & Cooke 1974; Meyerhof 1976; Parry & Swain 1977; Burland & Twine 1988; Patel 1992; Fleming 1992; Bond & Jardine 1995; Tomlinson & Woodward 2008; Fleming *et al.* 2009). Often discussed in these papers are issues such as the value of the “adhesion” parameter (α), the comparison of total and effective stress methods or the correct friction angle to use in the effective stress calculations (see also Vardanega *et al.* 2012 for further discussion on some of these issues in the context of pile design in London clay).

In the UK, design methods have directly evolved based on observations from collections of pile tests. Skempton’s (1959) paper on the calculation of capacity of bored piles in London clay relied on 34 pile–load tests carried out on 10 different sites in London. These results were used in design practice, before being updated by Patel (1989, 1992) who collected around 50 pile–load tests from more than 15 further sites in London. These were then used to give design recommendations now directly encoded in the LDSA (2017) design guidance for piles in London.

10.1.3 The DINGO database

The DINGO project aimed to build on this past work by producing an open-access database of pile–load test data which could be used for benchmarking new test results and calibration of models for ultimate capacity and pile settlement in various deposits across the United Kingdom (not just in London clay). The DINGO database was first published in 2019 (Vardanega *et al.* 2019; Vardanega *et al.* 2021a). It is an open dataset that comprises over 500 tests conducted on piles in UK soils. The current version of the DINGO database is freely available to download from the University of Bristol Research Repository (Vardanega *et al.* 2024). The focus of the DINGO project was to produce an open-source dataset where the pile–load test data was, where possible, accompanied by site-specific soil parameters.

Database building and curation efforts such as DINGO offer progress towards "data-centric geotechnics" (Phoon *et al.* 2022), which is now possible as geotechnical engineering transitions from a data-poor to a data-centric discipline. The DINGO database has previously been used to investigate pile settlement prediction methods in fine-grained soils (Voyagaki *et al.* 2019, 2022), as well as quantify the settlement reduction due to the application of different design codes (Crispin *et al.* 2022).

10.1.4 Determination of ultimate load

Pile design requires the knowledge of the ultimate load a pile can safely sustain during its service life. A key purpose of routine pile–load testing is to determine the ultimate load a test pile can sustain in order to verify a design prior to installation of the real foundation. However, pile ultimate failure is difficult to define. Most definitions are based on pile "plunging" and so are ultimately settlement criteria, but many pile tests, for cost and practical reasons, often do not reach the load at which this occurs. Therefore, in order to estimate the ultimate load of the pile, several studies have provided methods of capacity estimation using incomplete (for the purposes of observing capacity) load–settlement data. Such methods for the capacity analysis of the pile require testing the pile with various loads and recording the corresponding settlement from such loads. Although these methods are simple, the capacity of the piles is generally estimated with reasonable confidence for pile design. Although more complex models are available for capacity analysis, their complexity and the required geotechnical information deter professionals from using them in routine design.

Chen and Fang (2009) established a database of 133 pile–load tests in 72 sites, where 55 tests were conducted in drained conditions and 78 tests in undrained conditions. Using this database, an evaluation of eight published methods was conducted by Chen and Fang (2009) and these methods were split into three categories: mathematical models (van der Veen 1953; Chin 1970), settlement limits (Terzaghi & Peck 1967; DeBeer 1970; Fuller & Hoy 1970), and graphical constructions (Davisson 1972; O'Rourke & Kulhawy 1985; Hirany & Kulhawy 1988, 1989, 2002) in the aforementioned study. Each of these methods is discussed in detail later in this chapter. The results of the Chen and Fang (2009) study suggested that the methods used present a similar range for both drained and undrained conditions. The Chin (1970) method presented the highest range bound while DeBeer (1970) method presented the lowest bound (Chen & Fang 2009).

Using a database of load tests carried out on 152 driven concrete piles, Marcos *et al.* (2013) also compared the same eight methods used by Chen and Fang (2009). This study divided the tests based on the pile section (square/circular) and the soil conditions (drained/undrained). The outcome of this study showed that the DeBeer (1970) method resulted in the lowest estimated capacity, while the Chin (1970) method produced the highest estimated capacity, indicating both underestimation and overestimation, respectively, which confirmed the results of earlier studies (e.g., FHWA 1993) (Marcos *et al.* 2013). The variability in methods such as those aforementioned for drilled shaft (bored pile) performance is discussed further in FHWA (1993) and Phoon and Tang (2019b).

Similarly, Chen *et al.* (2021) compiled a database containing 34 pile tests from 20 different sites to assess the eight methods described earlier (i.e., the methods used in Chen & Fang 2009 and Marcos *et al.* 2013) with the addition of a ninth method cited as "DIN 4026 1975" in the original paper (the methodology of this method is fully described in Chen *et al.* 2021), hereafter referred to as "DIN 4026."[1] Chen *et al.* (2021) divided the piles in the database as drained and undrained piles based on the ground conditions of the soils and the results of the study showed similar loading trends in drained and undrained conditions, agreeing with the findings of Chen and Fang (2009). Another outcome of this study was that Chin (1970) and Fuller and Hoy (1970) methods consistently produce ultimate load estimations exceeding the maximum load observed in the load–settlement testing (Chen *et al.* 2021).

In a more recent study, Chen *et al.* (2023) utilised the same methods mentioned earlier in the chapter to estimate the ultimate load of a pile (apart from the Davisson (1972) method). In this study, a large database of pile tests was used in the analysis containing 143 drilled shaft compression load tests and the results of the analysis suggested using L1 (Hirany & Kulhawy 1988) and DeBeer (1970) methods in serviceability limit state design due to the underestimation tendency of these methods (Chen *et al.* 2023). The outcomes of the Chen *et al.* (2023) study confirmed the findings of Chen and Fang (2009) and Marcos *et al.* (2013) where the Chin (1970) method was observed to overestimate the ultimate load estimation with values exceeding the other methods and the load–settlement curve.

Laveti *et al.* (2024) utilised 64 rectangular pile–load tests to estimate the ultimate load of the piles using the same methods mentioned earlier in this chapter including "DIN 4026." The estimated ultimate loads were used to calculate the ratio between the predicted and measured ultimate load of each pile and used as model factors for the calibration of the Ultimate Limit State (ULS) design (Laveti *et al.* 2024). Topacio *et al.* (2024) also assessed the methods described previously in estimating the ultimate load of piles constructed in rocks. A database was constructed with 50 compression load tests in 26 different sites where the soils were classified as rocks (Topacio et al. 2024). In this study, the "DIN 4026," "3%D," "4%D," and "5%D" methods used along with the eight methods presented earlier were used to assess the ultimate load estimation of each method when a pile is constructed in rock (Topacio *et al.* 2024). Results of the Topacio *et al.* (2024) paper suggested that the Davisson (1972), DeBeer (1970), 5%D, and L2 (Hirany & Kulhawy 1988) methods were the most suitable methods to estimate the pile ultimate load when constructed in rocks.

In this chapter, similar methodologies to Chen and Fang (2009), Marcos *et al.* (2013), Chen *et al.* (2021), and Chen *et al.* (2023) are followed to assess the performance of the eight methods for determining the ultimate load of piles in the DINGO database. To this end, the assembly and compilation of the DINGO database are summarised, along with a brief review of some analyses previously undertaken using this database; the subset of the DINGO database including tests suitable for this analysis is identified and each of the eight methods is systematically applied to all possible tests in the subset; the resulting ultimate load values are presented and discussed.

10.2 ASSEMBLY AND ANALYSIS OF THE DINGO DATABASE

10.2.1 Assembly of the DINGO database

The DINGO project was funded by the Engineering and Physical Sciences Research Council (EPSRC) (Vardanega 2017; Vardanega et al. 2021a) and was conducted by a research team based at the University of Bristol in collaboration with industrial partners. The full details of the building of the database, the data structure employed, and a list of all sources used to derive the database are available in the summary report (Vardanega *et al*. 2024). A brief outline of the assembly and compilation of the database is included here.

The DINGO database consists of data sourced from both the engineering literature and industry reports and datasets. Published data was sourced from the literature, while industry data was provided by UK-based engineering organisations, including project partners. A large number of sources were identified, including many types of pile tests (e.g., axial, lateral, maintained load, constant rate of penetration), on a variety of pile types (e.g., bored, driven, concrete, steel) embedded in different soils (e.g., clay, sand, chalk) from across the United Kingdom. However, the majority of tests were axial, maintained load (ML) tests, most frequently on bored piles.

The intention was to provide a database useful for many different purposes; therefore, no restriction based on specific type of pile and/or test was imposed. Instead, the data sources were categorised according to the quality of both the pile test and site investigation information. Sources were then prioritised according to these categories, with pile test data that included a full load–displacement curve alongside detailed stratigraphic information with index and strength data digitised first. While some high-quality digital data was available, much of the data was provided in report format, requiring careful digitisation of the graphs from the original sources.

As the various reports and papers were originally prepared with specific purposes in mind, not all of the required information was presented. In particular, locations could be quite general and/or confidential. In these cases, the best effort was made to give an approximate location, particularly when this was relevant to identifying the relevant geological context. Furthermore, the topographic level information available was inconsistent. Ordinance Datum (OD) level data was included in many cases, but in others, only depth data was provided. Where necessary, an indicative site datum was approximated to convert these into level data and allow comparison between pile installation details and local boreholes.

Geological stratigraphic information was sourced in a variety of ways. Where original borehole logs were available, these were included in the database. Otherwise, what geological information available was used to develop a simple ground model for each site. Where possible, a consistent set of geology codes were assigned to each strata, based on British Geological Society definitions, if available. Normally, this only involved modernising outdated terms, but in many cases, the geology was interpreted directly by the research team from the available data. Available geotechnical test data was also directly included in the database, particularly any strength and index testing that might have been provided in the original data source.

A separate record was created for each site within a data source. Every effort was made to ensure a consistent format between each record, although this was not always possible as many test results were published precisely because of their unusual situation or configuration. Each record was stored in a collection of standard tables, organised into an MS Excel Spreadsheet. These were hierarchical, the PROJ table providing general project information was connected to specific LOCA and PILE tables, describing any boreholes or piles, respectively. The former linked a series of tables including site investigation data (e.g., geology, Atterberg limits, Standard Penetration Test (SPT) data, triaxial data), while the latter linked a series of tables describing the piles and pile tests (e.g., test summaries, load–settlement data). The geological data format was heavily inspired by the Association of Geotechnical Specialists (AGS) data format (AGS 2017) that should be familiar to many UK engineers.

Once the database was collated, the tests were categorised according to the date of test, pile type, and geology in order to give a summary of the tests within the database. These are shown in Figure 10.1. As a large database of tests throughout the United Kingdom over a 70-year period, the database can also be used to highlight trends in the pile types and dimensions used in practice, as well as instrumentation, data acquisition, etc. These categories, along with other information on each site, were collected into summary tables that can be used to develop insights into the contents of the database.

10.2.2 Data visualisation

The geotechnical applications of geographic information systems (GIS), providing complex visualisations of geotechnical data, have been useful in geotechnical engineering

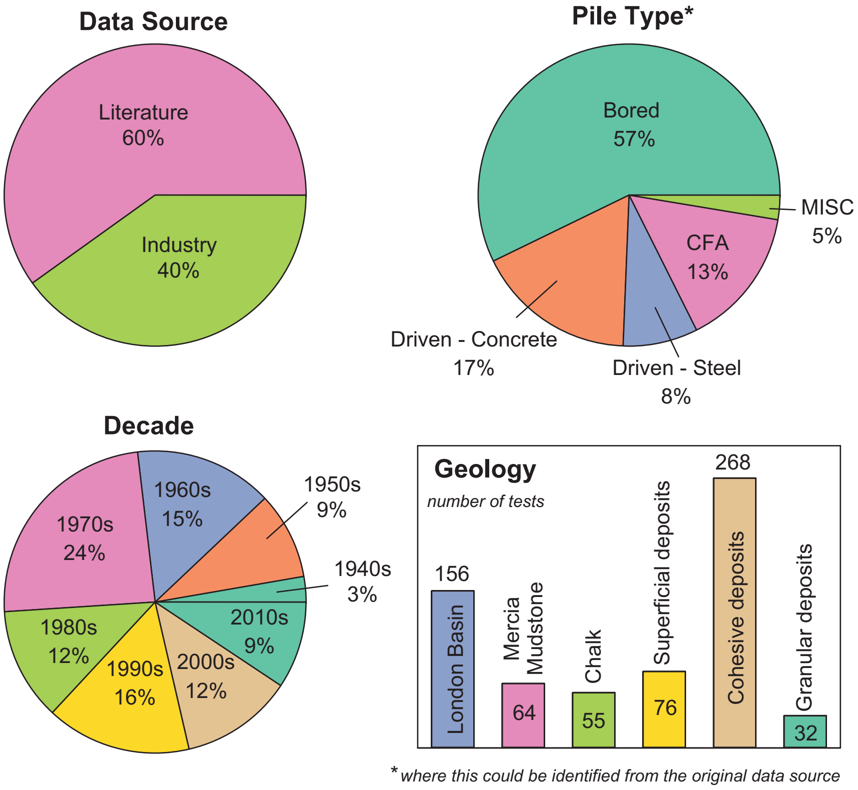

Figure 10.1 Distribution of the DINGO database pile test in the main subcategories. Note that some geology categories are overlapping, i.e., a single pile may be in multiple categories (Source: reproduced from Voyagaki *et al.* 2022, used under the terms of the cc-by 4.0 licence).

(e.g., Player 2006; Wan-Mohamad & Abdul-Ghani 2011; B & Dodagoudar 2018) and GIS platforms have been used to enable the assessment of geotechnical geospatial data distribution (e.g., Kim & Kim 2019) or to construct geotechnical maps (e.g,. Ali & Shakir 2022). The DINGO database has characteristics that allow the visualisation of the geographic distribution of test piles across the United Kingdom.

The procedure for determining or approximating the site locations is described in detail in the database summary report (see: Vardanega et al. 2019; Vardanega et al. 2021b; Vardanega *et al.* 2024). A GIS-based mapping procedure was employed to interrogate the database according to a number of areas of interest, based on characteristics such as the pile type (bored, driven, cast in situ, continuous flight auger); the pile test employed (constant rate of penetration (CRP), maintained load (ML), Osterberg), the geology encountered at the site, etc. In the current study, the analyses and mapping were carried out using ArcGIS Pro software. The data consist of:

i. Summary data from the DINGO database; the sites that populate the database, with all the categorical information (the location, the geology, the type of piles installed, the pile test employed, the year the test was performed, the number of boreholes, the number of piles tested, etc.) were exported as shapefiles, acquiring spatial features.
ii. Open-access spatial data, including 1:250,000 scale geology data derived from the British Geological Survey (BGS) that contains bedrock polygons and is a useful guide to regional geology, as well as administrative borders, the UK cities, and the sea polygons.

The GIS tool capabilities allow spatial analyses, data conjunctions, and various types of data representations. Figure 10.2 shows the distribution of test sites in the DINGO database alongside geological information.

Kernel density estimation is a method used in geospatial analyses to identify spatial patterns of data regarding site characteristics and to evaluate the spatial density (e.g. Kim *et al.* 2019). Kernel density estimation is a spatial clustering method, which detects clusters in spatial data distributions (Han *et al.* 2001; Borruso & Schoier 2004) and consists of "… moving three-dimensional function (the kernel) which weights events within its sphere of influence according to their distance from the point at which the intensity is being estimated" (Gatrell *et al.* 1996, p. 259): it calculates a size/attribute for point or line features using a kernel function to fit the produced raster surfaces to each feature (Borruso & Schoier 2004).

Kernel density analysis on the DINGO sites was undertaken to reveal the spatial distribution and intensity of pile test characteristics, such as the test conducted, the year of the test, and the type of the pile. The algorithm that calculates the kernel density by the relative geoprocessing tool (in ArcGIS Pro) results in a heat map symbology; this type of symbology presents the density of the points as a raster, using a colour scheme with a range from a sparse density of points (cool) to a high density of points (hot). In each case, a radius of 10 m was applied.

In Figure 10.3, kernel density heat maps are presented showing the spatial distribution of the ML and CRP tests in the United Kingdom. In total, the density of the ML tests is higher than the CRP; in the south of the United Kingdom, the density is higher than the north for both types of pile tests. Figure 10.4a also shows kernel density heat maps of bored piles, which make up a majority of the database, while Figure 10.4b shows CFA piles which are sparser.

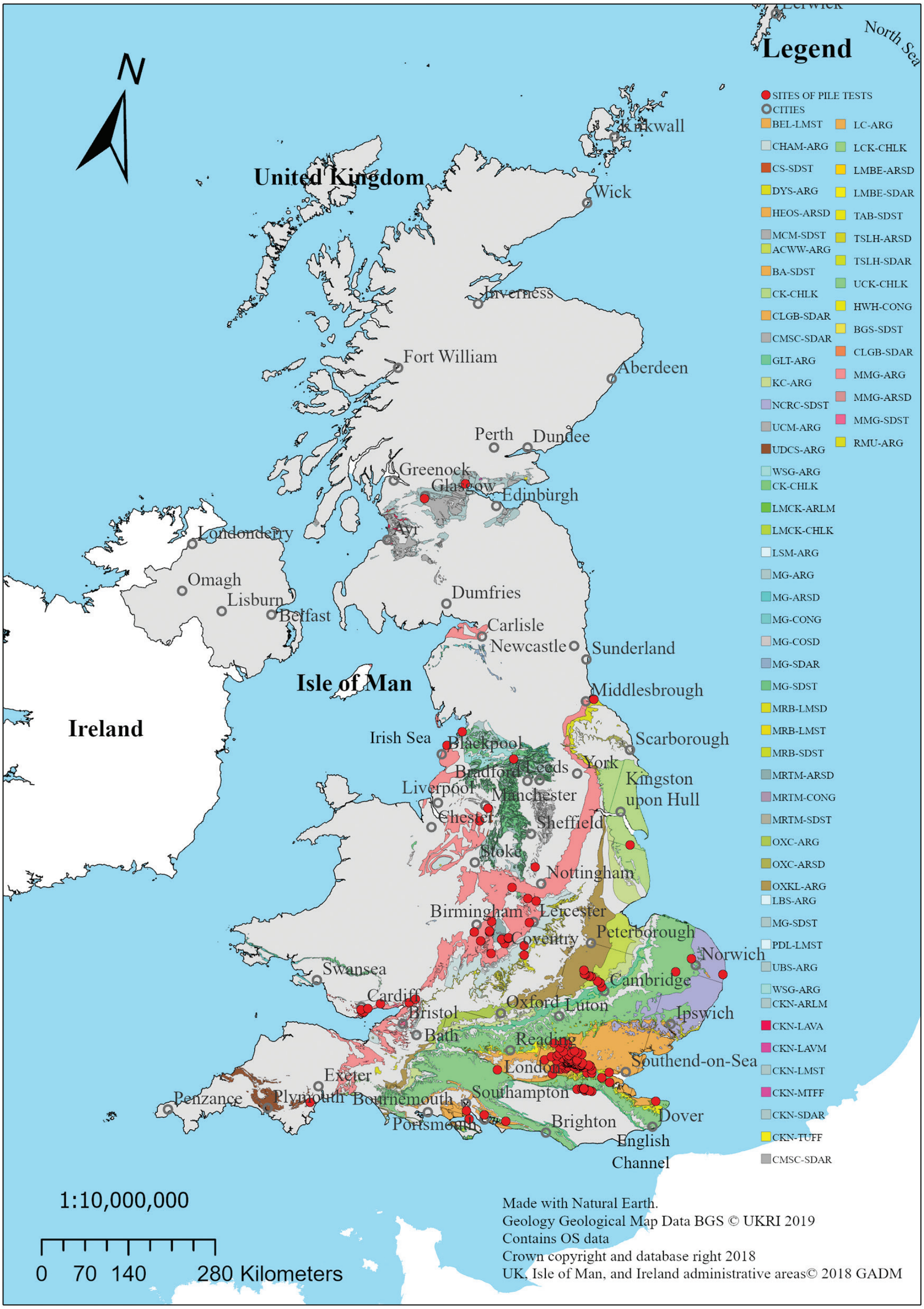

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Figure 10.2 GIS geology map showing the distribution of the DINGO database tests in the UK (Source: adapted from Vardanega et al. 2024, used under the terms of the cc-by 4.0 licence).

Figure 10.5 shows the kernel density heat maps of the piles according to the year the test was performed, split into four periods: 1945–1958, 1958–1970, 1970–1999, and 1999–2018. The 1970–1999 period presents the highest density of piles, while the lowest density appeared in 1958–1970.

10.2.3 Previous analyses using the DINGO database

The DINGO database has been used to investigate the performance of settlement prediction methods for piles in fine-grained soils. Two non-linear calculation methods were investigated: "Model 1" summarised in Figure 10.6 (Vardanega *et al.* 2012, 2018), a power-law non-linear soil model calculation based on mobilisable strength design principles and "Model 2" summarised in Figure 10.7 (Crispin *et al.* 2018), an analytical closed-form elastoplastic Winkler solution (see also Crispin *et al.* 2019 and Crispin 2022 for further details). These were employed to predict pile settlements at various load levels (factors of safety), which were compared with measured results from the DINGO database.

Patel (1989, 1992) presented load–settlement envelopes for piles in London clay based on tests collected in London. As these tests were well reported with suitable ground investigation data, a preliminary study based on these tests was presented in Voyagaki *et al.* (2019) assessing the performance of the prediction methods on this well-studied material. This was followed by a further study of the piles in fine-grained deposits (Voyagaki *et al.* 2022) and 186 pile tests from 57 test sites were found to be suitable for this analysis.

The measured settlements at specific factors of safety (Equations 10.1 and 10.2, defined in Voyagaki *et al.* 2022) were compared with predictions of both models from both Models 1 and 2.

$$F_{total} = P_u / P \tag{10.1}$$

where

$$P_u = P_{u,s} + P_{u,b} = \alpha \bar{c}_u \pi D_s L + N_c c_{ub} \pi D_b^2 / 4 \tag{10.2}$$

P_u is the nominal bearing capacity for compression piles and undrained conditions; $P_{u,s}$ and $P_{u,b}$ are the ultimate total load capacity of the shaft and the base, respectively; $\bar{c}_u$ = mean undrained shear strength over the pile length, c_{ub} = corresponding value at the pile tip, D_s = pile shaft diameter, D_b = pile base diameter, L = pile length, and N_c = bearing capacity factor for undrained conditions in fine-grained soils (Voyagaki *et al.* 2022).

Figures 10.8 and 10.9 are taken from Voyagaki *et al.* (2022). Figure 10.8 shows the predicted versus measured plot comparing the performance of the two models on these piles at F_{total} = 2.5, approximately the working load. Figure 10.9 shows the settlement predictions for four factors of safety values ranging from 1.5 to 5. The plots show that both methods tend to underpredict settlements at high factors of safety and overpredict them at lower factors of safety values. Potentially the "pile capacity" is overpredicted by Equation (10.1), and therefore various methods for computing this quantity will be investigated in more detail in Section 10.3. These results were then further interrogated according to the different categories of pile type, geology, and test age, as well as an interpreted "data quality" category based on the source of the soil strength and stiffness

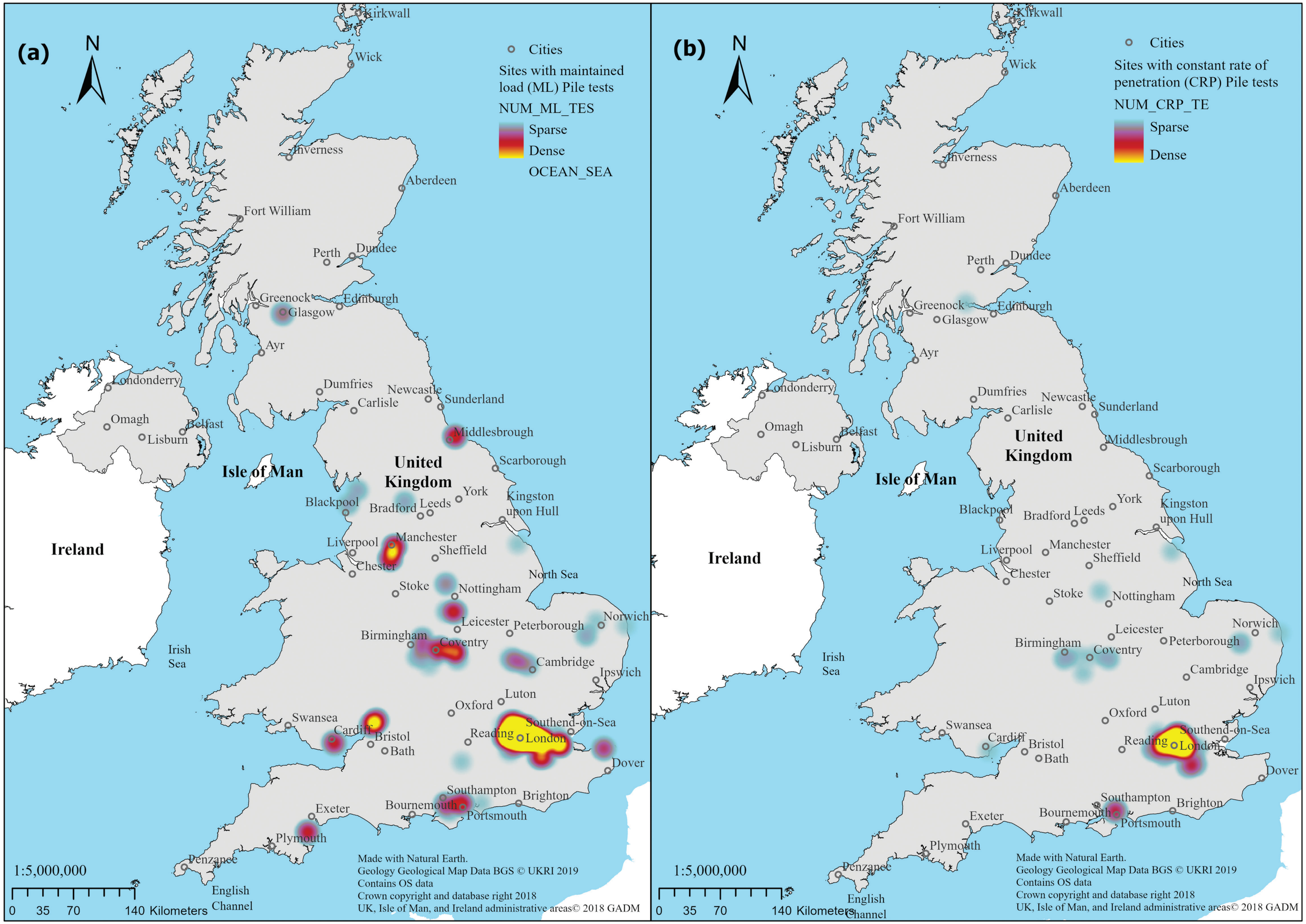

Figure 10.3 Kernel density heat maps of the spatial distribution of (a) maintained load (ML) pile tests and (b) constant rate of penetration (CRP) pile tests.

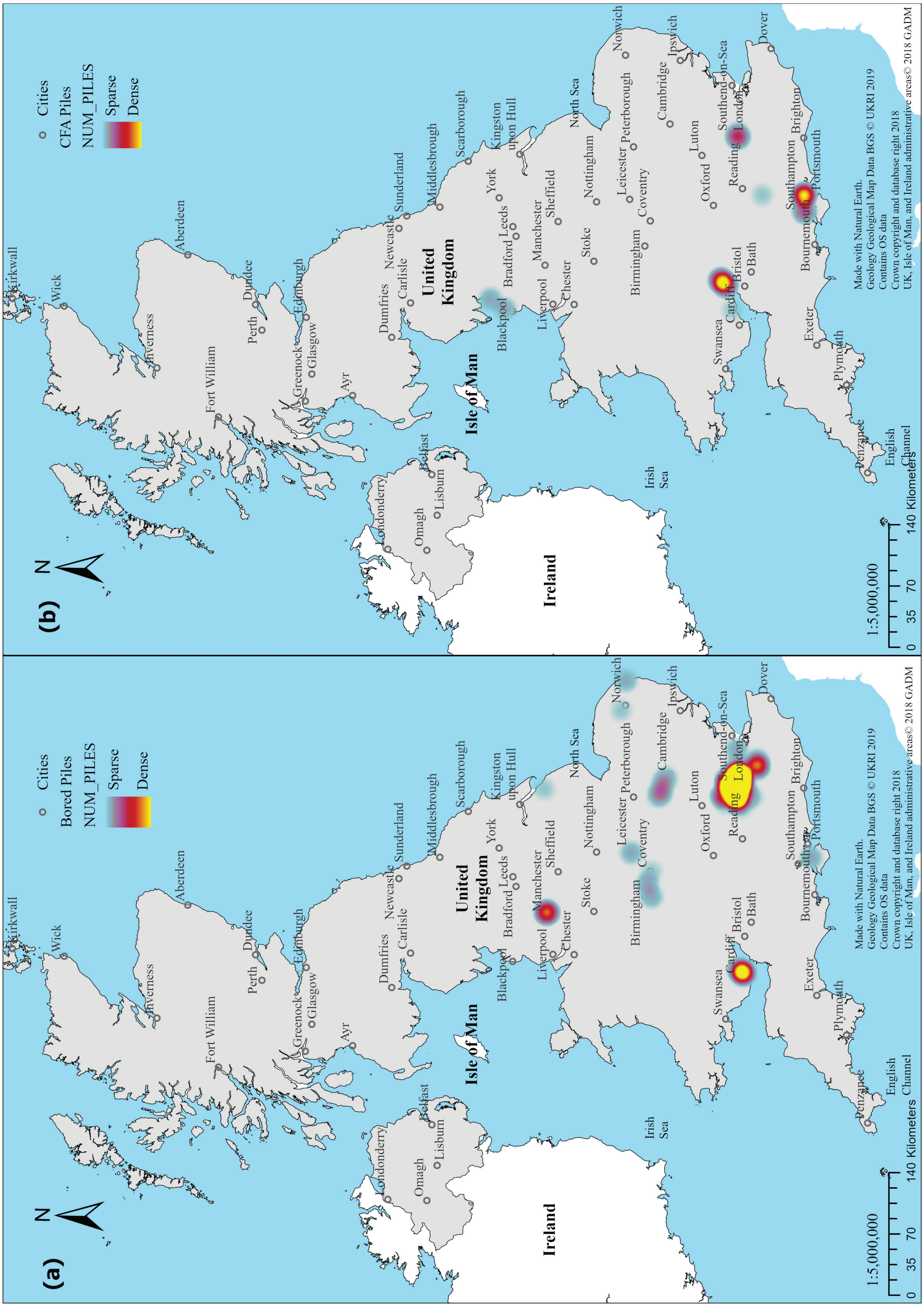

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Figure 10.4 Kernel density heat maps of the spatial distribution of (a) bored piles (b) and continuous flight auger (CFA) piles.

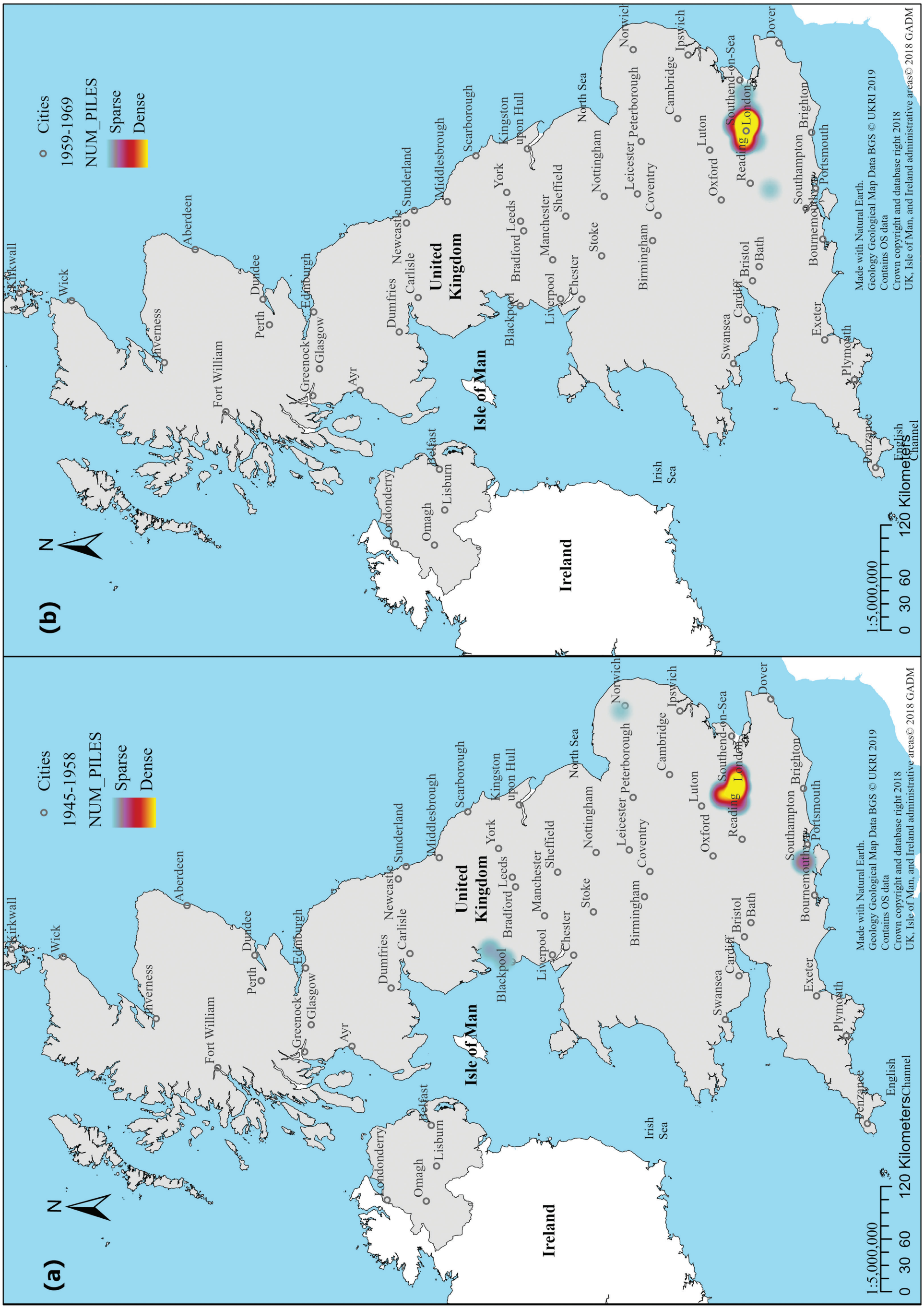

Figure 10.5 Kernel density heat maps of the spatial distribution of the piles in the periods: (a) 1945–1958, (b) 1959–1969, (c) 1970–1999, and (d) 2000–2018.

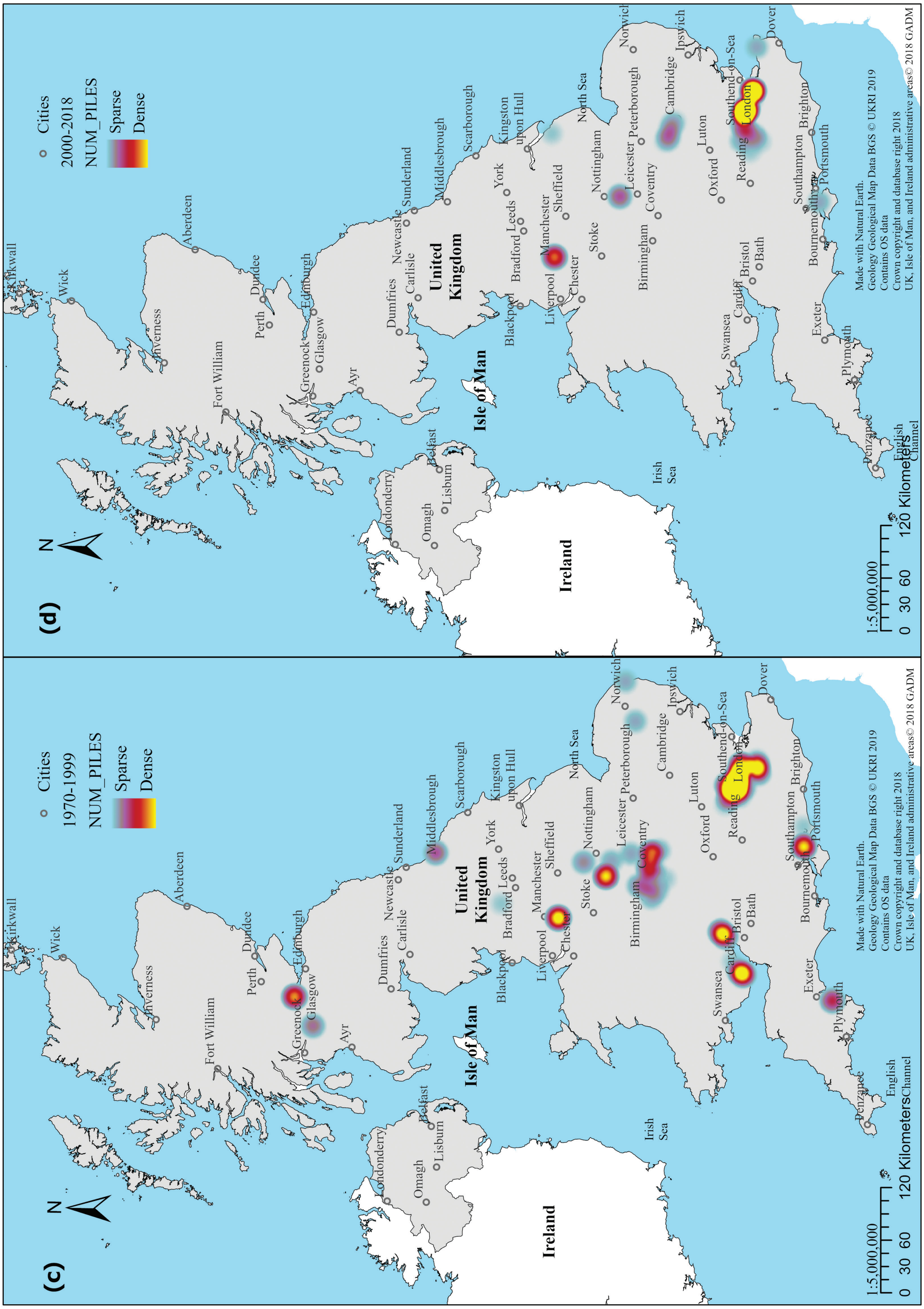

Figure 10.5 (Continued)

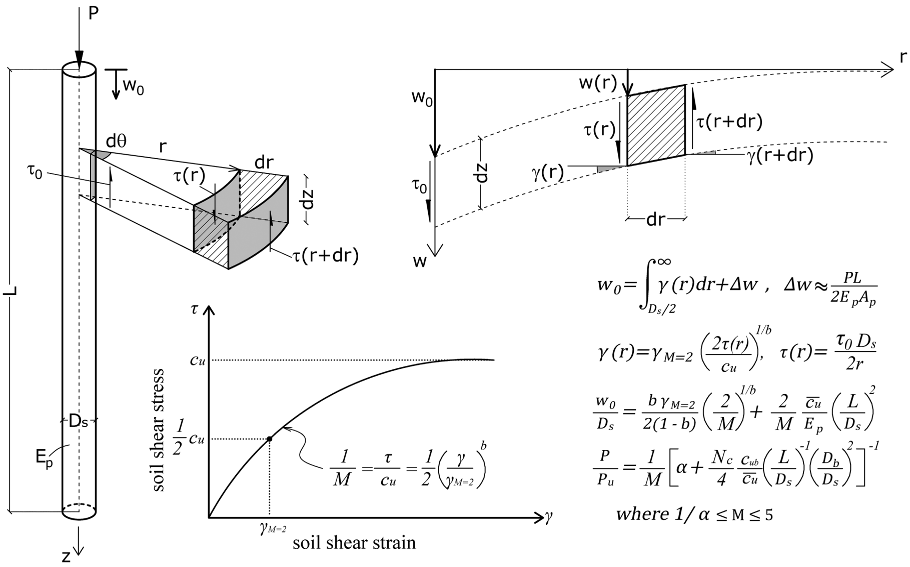

Figure 10.6 Summary of "Model 1": modified load transfer approach for non-linear pile settlement considering shearing of concentric cylinders around the pile, pile compression, and non-linear stress–strain relation (Source: reproduced from Voyagaki *et al.* 2022, used under the terms of the cc-by 4.0 licence).

parameters (Voyagaki *et al.* 2022). Finally, the prediction performance was studied, and the model bias and uncertainty evaluated; the results of this analysis are available in Voyagaki *et al.* (2022).

The DINGO database was also used to quantify the settlement reduction due to the application of different design codes for piles in London clay (Crispin *et al.* 2022). In this work, the pile capacity was calculated using an unfactored method as well as in each of the two design codes studied (Crispin et al. 2022). The settlements at each of these load levels were then compared in order to quantify how much settlement reduction each code provides (Crispin et al. 2022). The results are shown in Figure 10.10, both design codes resulting in over 75% reduction in settlement in most cases (Crispin et al. 2022).

10.3 PILE ULTIMATE LOAD DETERMINATION

10.3.1 Methodologies for determining ultimate load

In this study, a total of eight methods for estimating the pile capacity were compared using pile data from the DINGO database, the methodology follows that of Chen and Fang (2009), Marcos *et al.* (2013), Chen *et al.* (2021), and Chen *et al.* (2023). The methods used in this analysis are (i) Chin (1970) representing a mathematical model approach to estimate the capacity of a pile based on load–settlement data, (ii) the Davisson (1972) method which uses a graphical interpretation of the load–settlement data to estimate the capacity of the pile, (iii) DeBeer (1970) which relies on a settlement limit for estimating the capacity based on the load–settlement data, (iv) Fuller and Hoy (1970) which uses a different settlement limit in estimating the pile capacity, (v) L1–L2 (Hirany & Kulhawy 1988) which present a

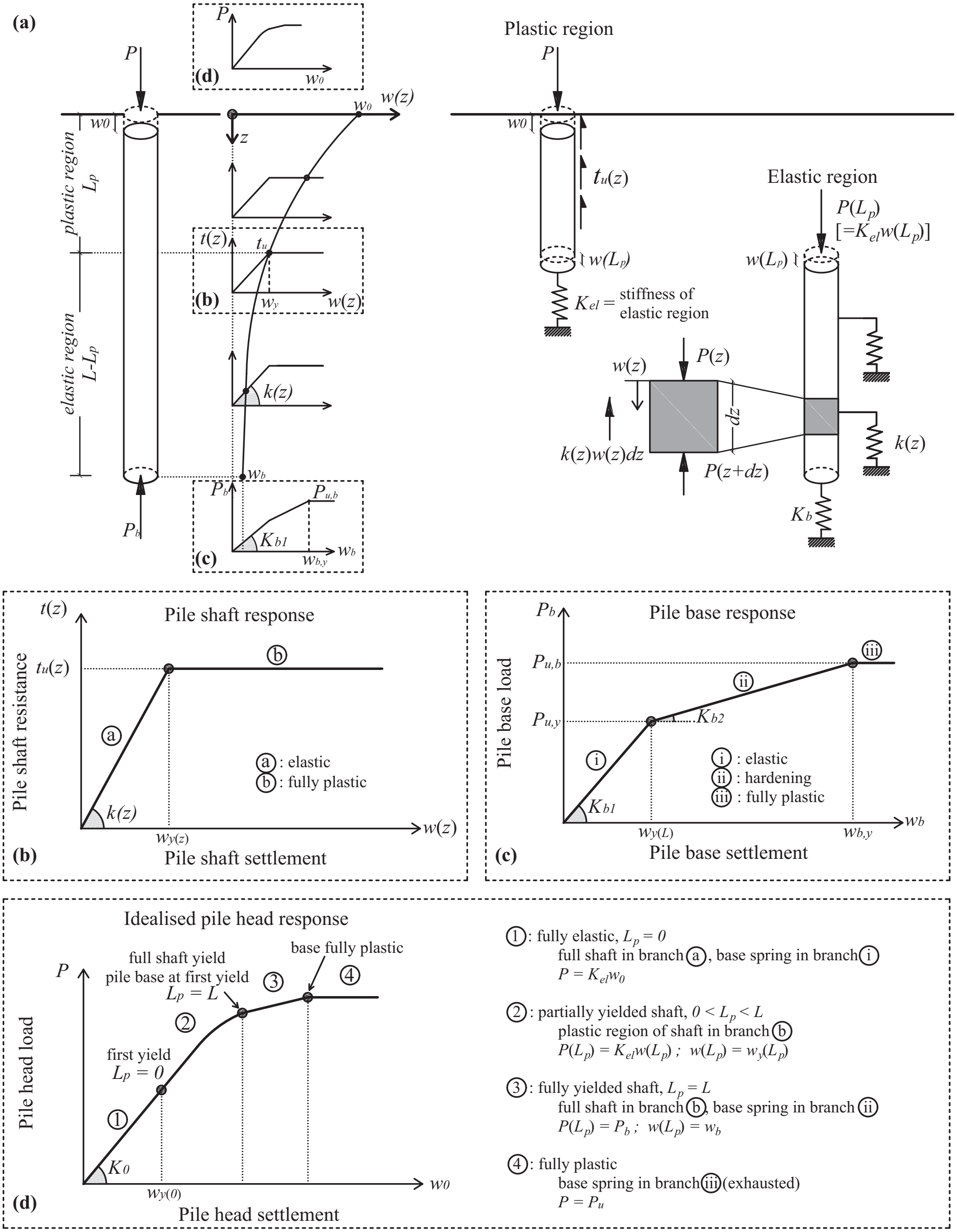

Figure 10.7 Summary of "Model 2": (a) linear elastic-perfectly plastic (LEPP) model, (b) pile shaft response ("$t - z$" curve), (c) pile base response ("$q - z$" curve), (d) idealised pile head response (Voyagaki *et al.* 2022, Crispin 2022) (Source: adapted from Voyagaki *et al.* 2022, reproduced from Crispin 2022, used under the terms of the cc-by 4.0 licence).

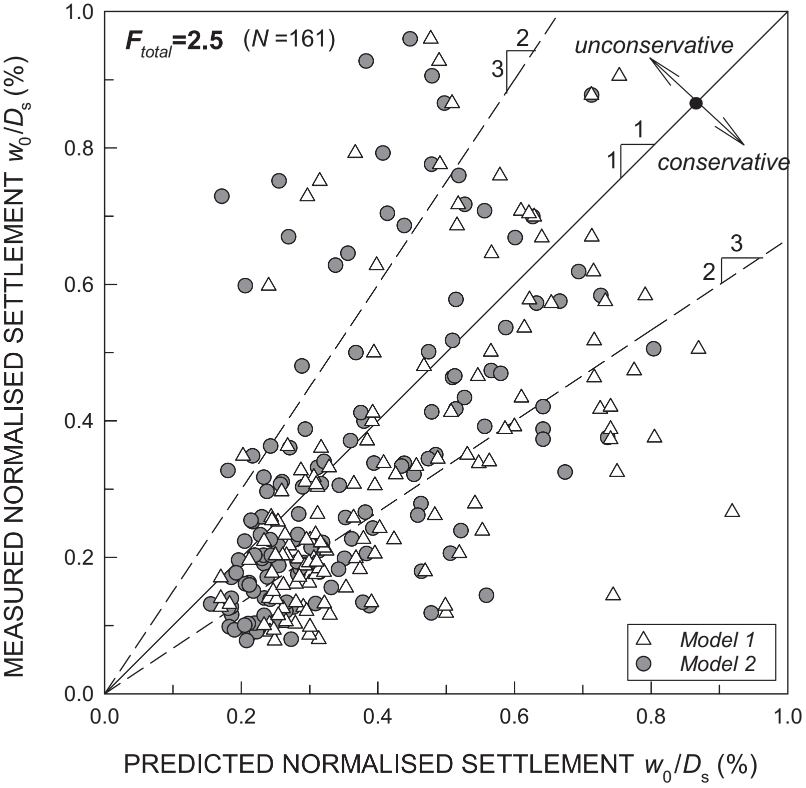

Figure 10.8 Predicted versus measured pile head settlement plot for the DINGO data for piles in fine-grained soil (Source: reproduced from Voyagaki *et al.* 2022, used under the terms of the cc-by 4.0 licence).

direct graphical estimation of the pile capacity based on the load–settlement data and a percent of the pile diameter, (vi) slope tangent (O'Rourke & Kulhawy 1985) presents another graphical estimation of the pile capacity, (vii) Terzaghi and Peck (1967) which uses a fixed settlement limit for the pile capacity estimation, and (viii) van der Veen (1953) which provide a mathematical model for estimating the pile capacity. In the following sub-sections, each of these methods is explained along with information on new automation processes to enable database application, including any assumptions made in the analysis. It should be noted that in this chapter "L1" is considered separately from "L1–L2" and therefore there are two calculations for the Hirany and Kulhawy (1988) approach. This means that while eight methods are used in this work nine calculations of P_u are carried out.

10.3.2 Data preparation

For the purposes of this study, only maintained load (ML) load–settlement tests were selected for analysis. The majority of methods used in this study apply to maintained load testing data. Since the methods rely on load–settlement data for the capacity estimation, any pile in the DINGO database with less than three load–settlement points recorded was removed from the analysis (see also the preliminary study from Othman et al. (2023) where a similar process was used to study pile ultimate load prediction utilizing the Chin

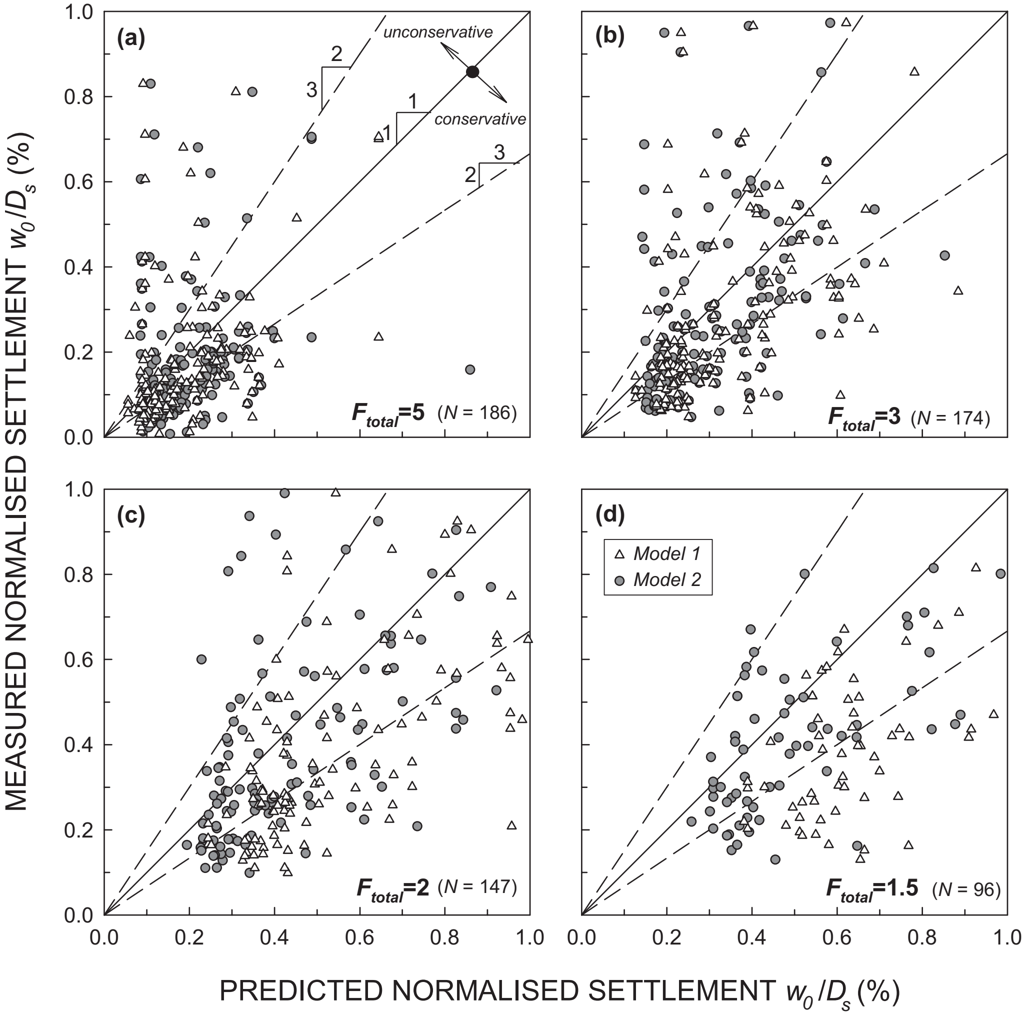

Figure 10.9 Predicted versus measured pile head settlement plot for different values of factors of safety for the DINGO data for piles in fine-grained soil (Source: reproduced from Voyagaki *et al.* 2022, used under the terms of the cc-by 4.0 licence).

method and using version 1.1 of the DINGO database (Vardanega et al. 2021b). The aforementioned methods require graphical interpolation of the load–settlement curve to obtain the ultimate load of the pile, therefore a Python code was used to automate the process. This is described further in the following sections.

The DINGO database contains information for piles constructed in the United Kingdom. Despite the large library of pile information in the database, the methods in this report are correlated to the load–settlement data along with the pile length, diameter, and modulus of elasticity. This requires an automation process to filter the database and remove any unnecessary information for the modelling. To perform this filtration, .xlsx files were extracted from the database, from these files, only “PILE,” “PTST,” and “PSLT” sheets were used. The pile names were compared with the test ID of each load–settlement test

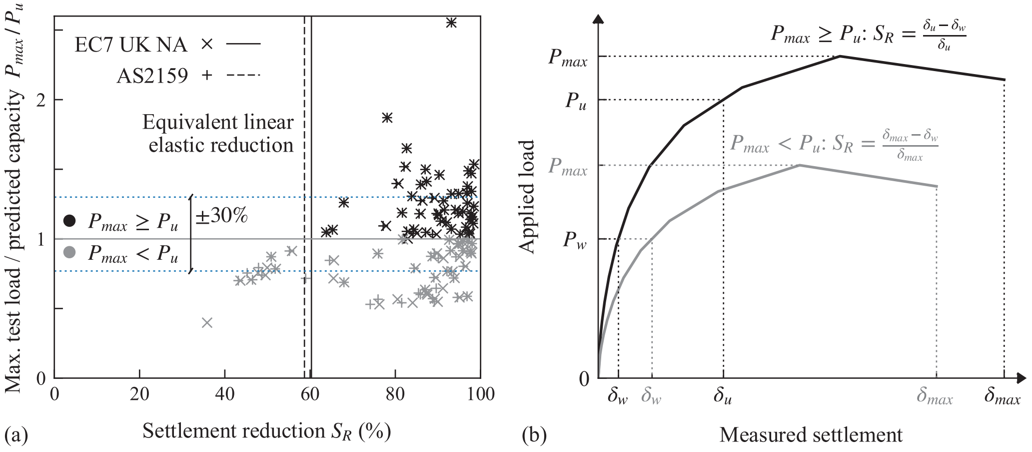

Figure 10.10 (a) Measured settlement reduction due to applied factor set and (b) definition of settlement reduction (Source: reproduced from Crispin 2022, used under the terms of the cc-by 4.0 licence; see also Crispin et al. 2022).

to confirm that each pile extracted from the database has corresponding load–settlement data, the loading type for the pile was ML and that the record contained at least three data points of load–settlement results. After this check, the load–settlement data along with pile diameter, length, and material information are extracted, and the data for each pile were saved in an individual MS Excel file.

After the data extraction process, the load–settlement data in each created file are filtered to remove any empty cells, remove tension-loaded piles, and remove unloading phases in the pile testing. In this process, if the loading remained constant in a part of the test, the highest settlement at this load was kept and the other data points were removed. Following this data filtration, data analysis using the eight methods was performed. A total of 372 tests from the database were suitable for the analysis by at least one of the eight methods.

In this study, a power function was used to represent the load–settlement curve (Figure 10.11). This selection was considered to best represent the data, whilst accommodating the automation procedure, in which a function is required to enable the intersection calculations. Other functions were considered before settling on the power function: the second-degree polynomial function showed an overestimation in the load near the failure region, which can result in overestimation in the ultimate load analysis; on the other hand, the third-degree polynomial function introduces a dip at the end of the curve which does not correlate with the load–settlement behaviour. Although the power function can overestimate the ultimate load in some cases, the observed error in estimation using this function was judged acceptable for the analysis undertaken in this chapter.

10.3.3 Chin method (Chin 1970)

According to this method, the plot of the settlement divided by the applied load (S/L) versus the settlement (S) results in a straight line. The inverse slope is taken as the ultimate load of the pile. The Chin method plots represent the behaviour of piles according to the hyperbolic method which is used in ultimate load estimations and does not rely on soil parameters. Figure 10.12 provides a sample plot of the Chin method using data

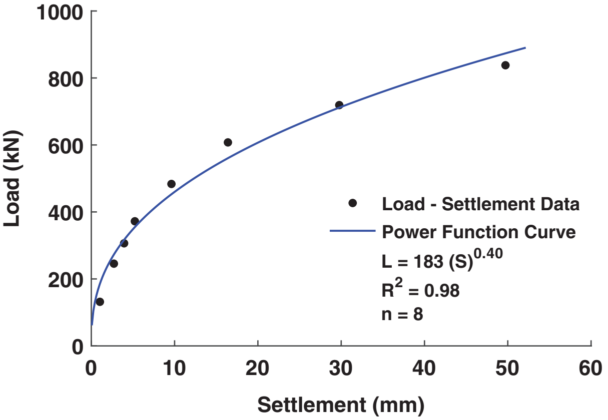

Figure 10.11 Example of using the power function to represent the load–settlement curve.

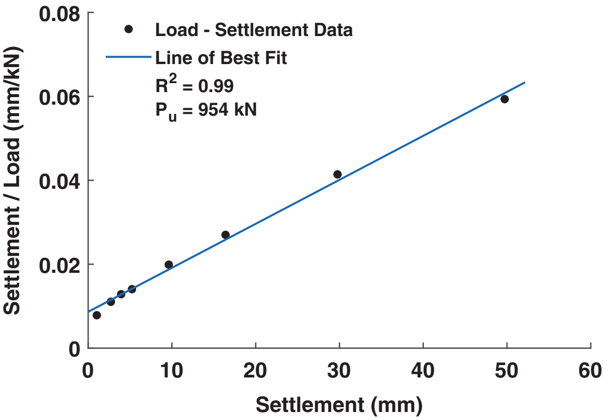

Figure 10.12 Graphical representation of the Chin (1970) method to obtain the pile capacity.

from a pile in the DINGO database. In this method, the load–settlement data are filtered to remove any zero values in the load, to avoid dividing by zero. For the straight line of the method, a best-fit line was utilised to obtain the slope and hence the ultimate load of the pile. The results for the rest of the pile tests in the DINGO database using the Chin method are summarised in Table 10.1. In Table 10.1 (which contains the ultimate load estimations for the eight methods used in the work presented herein), results for 354 tests are presented out of the 372 ML tests in the database that fulfil the requirement of this analysis (have load–settlement data with three or more datapoints with loading as ML and non-tension). The pile tests with no results represent tests with negative slope values, which occur due to sudden changes in the settlement at small increments of increased load. Othman *et al.* (2023) presented an analysis of the ML testing from the DINGO database version 1.1 (Vardanega et al. 2021b) along with data from Galbraith (2011) using the Chin method, concluding that the overprediction of the Chin method is around 19.2% on average when assuming the ultimate load is happening at 10% of the diameter and 24.8% on average when the ultimate load is at the maximum load of the test.

Table 10.1 Calculated ultimate load/proven capacity for the piles in the DINGO database using the eight methods

File name[a]	Pile name	P_u Chin (kN)	P_u Davisson (kN)	P_u DeBeer (kN)	P_u Fuller and Hoy (kN)	P_u L1 (kN)	P_u L2 (kN)	P_u Slope tangent (kN)	P_u Terzaghi and Peck (kN)	P_u van der Veen (kN)	Methods used	Δ Range	Average	Avg./L1
D01_01_1	A46/X/1/N	784	–	–	–	–	–	–	–	670	2	114	727	–
D01_01_2	A46/X/2/N	755	–	340	–	–	–	–	–	860	3	520	652	–
D01_02_1	M1/17/1/N	929	–	336	–	–	–	–	–	770	3	593	678	–
D01_02_2	M1/17/2/N	763	–	326	–	–	–	–	–	760	3	438	616	–
D01_03_1	M1/23A/1/S	898	–	–	–	–	–	–	–	790	2	108	844	–
D01_03_2	M1/23A/2/S	498	–	–	–	–	–	–	–	640	2	142	569	–
D01_04_1	M1/28/1/S	1297	–	–	–	–	–	–	–	1010	2	287	1154	–
D01_04_2	M1/28/1/S-T	711	–	399	–	–	–	–	–	730	3	331	614	–
D01_04_3	M1/28/2/S	914	–	449	–	–	–	–	–	690	3	465	685	–
D01_05_1	A14/X/1/W	760	–	474	–	–	–	–	–	820	3	346	685	–
D01_05_10	M6/0/2/S	676	–	–	–	–	–	–	–	670	2	6	673	–
D01_05_2	A14/X/2/W	737	–	390	–	–	–	–	–	630	3	347	585	–
D01_05_3	M1/19/1/N	685	–	390	–	–	–	–	–	610	3	294	562	–
D01_05_4	M1/19/1/S	872	–	–	–	–	–	–	–	820	2	52	846	–
D01_05_5	M1/19/2/N	736	–	492	–	–	–	–	–	790	3	298	673	–
D01_05_6	M1/19/2/N-T	614	–	403	–	–	–	–	612	600	4	211	557	–
D01_05_7	M1/19/2/N-T	767	–	489	–	–	–	–	–	760	3	278	672	–
D01_05_8	M1/19/2/S	1247	–	–	–	–	–	–	–	1060	2	187	1154	–
D01_05_9	M6/0/1/S	949	–	434	–	–	–	–	–	700	3	515	694	–
D01_06_1	M40/15/1/N	634	–	452	–	–	–	–	–	600	3	181	562	–
D01_07_1	M42/3A/1/E	1007	–	–	–	–	–	–	–	880	2	127	943	–
D01_07_2	M42/3A/2/E	2253	–	328	–	–	–	–	–	950	3	1924	1177	–
D01_08_1	M42/6/1/S	931	–	328	–	–	–	–	–	870	3	603	710	–
D01_09_1	M42/9/2/N	1157	–	346	–	–	–	–	–	790	3	811	764	–
D01_10_1	M6/2/1/N	1171	–	428	–	–	–	–	–	730	3	743	776	–
D01_10_2	M6/2/1/N	956	–	431	–	–	–	–	–	650	3	525	679	–
D01_10_3	M6/2/2/N	888	–	530	–	–	–	–	–	680	3	357	699	–
D01_10_4	M6/2/2/S	943	–	308	–	–	–	–	–	790	3	635	681	–

(Continued)

Table 10.1 (Continued) Calculated ultimate load/proven capacity for the piles in the DINGO database using the eight methods

File name[a]	Pile name	P_u Chin (kN)	P_u Davisson (kN)	P_u DeBeer (kN)	P_u Fuller and Hoy (kN)	P_u L1 (kN)	P_u L2 (kN)	P_u Slope tangent (kN)	P_u Terzaghi and Peck (kN)	P_u van der Veen (kN)	Methods used	Δ Range	Average	Avg./L1
D01_10_5	M6/2/2/S	1740	–	436	–	–	–	–	–	830	3	1304	1002	–
D01_11_1	M69/0/1/S	938	–	373	–	–	–	–	–	710	3	565	674	–
D01_11_2	M69/0/2/S	982	–	190	–	–	–	–	–	810	3	791	661	–
D03_2	TP2	4719	–	–	–	–	–	–	860	3987	3	3859	3189	–
D04_01_1	17	2762	–	812	–	–	–	–	–	965	3	1950	1513	–
D04_01_2	54	3835	–	581	–	1155	–	–	–	2463	4	3254	2008	1.74
D04_02_1	NA4	4091	–	1302	–	1191	–	–	–	2303	4	2900	2222	1.87
D04_03_1	A10/1	2443	–	877	–	995	–	–	–	1675	4	1566	1498	1.50
D04_03_2	P2/1	2320	–	897	–	916	–	–	–	1605	4	1423	1435	1.57
D04_04_1	C41	4672	–	775	–	1404	–	–	–	1416	4	3898	2067	1.47
D04_05_1	B17	3124	–	739	–	1177	–	–	–	2730	4	2384	1942	1.65
D04_06_1	NA4	5749	–	1304	–	1205	–	–	–	3143	4	4545	2850	2.37
D04_06_2	SC1	3769	–	1460	–	1224	–	–	–	2713	4	2545	2291	1.87
D04_07_1	SA4	2787	–	1387	–	–	–	–	–	2453	3	1400	2209	–
D04_08_1	N06	1415	–	357	–	–	–	–	–	1469	3	1112	1080	–
D04_09_1	CSA4	3972	–	1544	–	1339	–	–	–	3153	4	2633	2502	1.87
D05_1	P2	4705	2843	2296	–	1775	3497	2792	3330	5144	8	3369	3298	1.86
D07_01_1	PT01	6416	–	641	–	3326	–	5939	–	5792	5	5775	4423	1.33
D07_02_1	PT02	9923	9484	7990	–	3946	–	6881	9938	8196	7	5992	8051	2.04
D07_03_1	PT03	14153	5909	2579	–	2951	8567	5457	7290	13,875	8	11574	7598	2.57
D07_04_1	PT04	26,528	–	10,271	–	15,386	–	–	–	23,616	4	16,258	18,950	1.23
D07_05_1	PT05	7207	–	543	–	3430	–	5750	–	6289	5	6665	4644	1.35
D07_06_1	PT06	6524	4838	5718	–	3146	–	4719	5749	6132	7	3378	5261	1.67
D07_07_1	PT07	13,326	–	–	–	4991	–	9155	–	10,588	4	8335	9515	1.91
D07_08_1	PT08	8200	7982	7996	–	3154	–	5927	8667	6546	7	5513	6925	2.20
D08_02_1	B1	423	–	–	–	81	–	–	–	201	3	342	235	2.89
D08_02_2	B20	446	–	–	–	141	–	–	–	291	3	305	293	2.07
D08_02_4	B30	235	–	–	–	103	–	–	–	191	3	132	176	1.71

(Continued)

Table 10.1 (Continued) Calculated ultimate load/proven capacity for the piles in the DINGO database using the eight methods

File name[a]	**Pile name**	**P_u Chin (kN)**	**P_u Davisson (kN)**	**P_u DeBeer (kN)**	**P_u Fuller and Hoy (kN)**	**P_u L1 (kN)**	**P_u L2 (kN)**	**P_u Slope tangent (kN)**	**P_u Terzaghi and Peck (kN)**	**P_u van der Veen (kN)**	**Methods used**	**Δ Range**	**Average**	**Avg./L1**
D08_02_6	B35	226	177	–	–	95	–	–	–	191	4	132	172	1.82
D09_1	PTP1	2515	1470	2186	–	607	1779	1270	2208	4014	8	3407	2006	3.30
D09_2	PTP2	1970	636	1358	–	241	975	636	1290	3243	8	3002	1294	5.37
D09_3	PTP2	602	–	–	–	409	–	–	–	576	3	193	529	1.29
D09_4	PTP3	2706	445	1001	–	121	809	600	1184	4046	8	3925	1364	11.25
D09_5	PTP4	1738	1075	1208	–	567	1262	964	1482	2213	8	1646	1314	2.32
D09_6	PTP5	1852	681	817	–	286	959	642	1222	3483	8	3197	1243	4.34
D09_7	PTP5	611	–	399	–	413	–	–	–	703	4	304	532	1.29
D10_1	E14-01	3051	–	–	–	1580	–	–	–	2911	3	1471	2514	1.59
D10_10	W2-02	3304	–	1664	–	1605	–	–	–	2892	4	1699	2366	1.47
D10_11	WR-02-05	3620	–	1146	–	1582	–	–	–	3332	4	2475	2420	1.53
D10_2	E3-02	4312	–	1353	–	1616	–	–	–	3472	4	2959	2688	1.66
D10_3	N18-02	4410	–	1962	–	1848	–	–	–	3632	4	2563	2963	1.60
D10_4	N2-01	3241	–	1454	–	1795	–	–	–	3353	4	1899	2461	1.37
D10_5	N6-01	3750	–	1473	–	1499	–	–	–	3332	4	2276	2513	1.68
D10_6	R5-19	5385	–	–	–	–	–	–	–	5594	2	209	5490	–
D10_7	R5-30	9345	–	4595	–	–	–	–	–	7812	3	4751	7251	–
D10_8	S5-01	3916	–	–	–	1642	–	–	–	3443	3	2274	3001	1.83
D10_9	W13-01	3457	–	1464	–	1907	–	–	–	2841	4	1992	2417	1.27
D11_1	P1	851	460	443	634	290	558	460	645	807	9	562	572	1.97
D13_1	1	707	514	636	574	370	586	526	640	691	9	336	583	1.57
D13_2	2	1684	669	471	–	289	901	618	1118	1444	8	1394	899	3.11
D13_3	3	1323	1002	1101	1261	653	1119	929	1240	1310	9	670	1104	1.69
D15_1	Test pile	–	1289	–	–	476	–	–	–	1400	3	924	1055	2.22
D17_2	CE25	752	463	513	–	241	638	463	–	660	7	510	533	2.21
D17_4	CE26	1177	607	193	–	267	866	572	999	1218	8	1025	737	2.77
D17_6	CW25	2394	643	332	–	191	–	–	–	1944	5	2203	1101	5.75
D18_1	1	1414	–	–	658	34	174	214	336	1240	7	1380	581	17.06
D18_2	2	322	–	253	237	165	246	226	289	318	8	157	257	1.56

(Continued)

Table 10.1 (Continued) Calculated ultimate load/proven capacity for the piles in the DINGO database using the eight methods

File name[a]	Pile name	P_u Chin (kN)	P_u Davisson (kN)	P_u DeBeer (kN)	P_u Fuller and Hoy (kN)	P_u L1 (kN)	P_u L2 (kN)	P_u Slope tangent (kN)	P_u Terzaghi and Peck (kN)	P_u van der Veen (kN)	Methods used	Δ Range	Average	Avg./L1
D18_3	3	1062	–	441	–	167	568	493	–	851	6	894	597	3.57
D18_4	4	516	–	308	–	170	427	375	–	410	6	346	368	2.16
D18_5	5	1767	–	386	–	107	582	612	–	1265	6	1660	787	7.35
D19_1	1	1330	720	–	–	334	–	809	–	1250	5	996	888	2.66
D19_2	21	957	–	–	–	344	–	–	–	800	3	612	700	2.03
D20_1	21A	2906	–	482	–	692	–	2036	–	2956	5	2475	1814	2.62
D20_2	21B	3608	–	1168	–	564	–	–	–	4004	4	3440	2336	4.14
D21_1	P01	848	–	360	–	283	–	–	–	830	4	565	580	2.05
D23_1	TP1	383	210	247	234	131	263	217	303	360	9	252	261	2.00
D23_2	TP2	706	–	322	–	264	–	–	–	500	4	442	448	1.70
D26_1	21	620	388	248	–	200	–	431	–	760	6	560	441	2.21
D31_1	2	882	454	84	–	233	721	447	742	910	8	826	559	2.40
D31_3	24	939	563	555	–	264	785	557	–	900	7	674	652	2.47
D31_4	46	963	586	614	–	309	775	592	–	830	7	654	667	2.16
D31_5	97	1122	751	413	–	372	995	719	–	1130	7	758	786	2.12
D31_6	120	1313	950	–	–	421	–	902	–	1110	5	892	939	2.23
D31_7	197	1579	617	623	–	239	903	651	1102	1590	8	1351	913	3.82
D31_8	236	1462	–	983	–	651	–	–	–	1580	4	929	1169	1.80
D31_9	257	1436	934	860	–	435	1216	885	–	1270	7	1001	1005	2.31
D32_1	AT121	842	–	145	–	283	–	–	–	1160	4	1015	608	2.15
D33_1	1	488	310	126	–	157	414	310	–	500	7	374	329	2.09
D33_2	2	553	–	362	–	293	–	–	–	485	4	259	423	1.44
D33_3	3	516	–	271	–	221	–	–	–	510	4	295	380	1.72
D34_1	51	3448	484	288	–	124	–	–	–	710	5	3323	1011	8.14
D34_2	335	915	–	423	–	175	–	–	–	1200	4	1025	678	3.88
D35_1	1	1594	1172	964	–	635	–	–	–	1277	5	959	1129	1.78
D35_2	2	1004	–	–	–	646	–	–	–	1800	3	1154	1150	1.78
D36_1	1	859	386	–	550	331	500	470	530	863	8	532	561	1.70
D36_2	3	1103	916	–	–	473	–	876	–	1060	5	630	886	1.87

(Continued)

Table 10.1 (Continued) Calculated ultimate load/proven capacity for the piles in the DINGO database using the eight methods

File name[a]	Pile name	P_u Chin (kN)	P_u Davisson (kN)	P_u DeBeer (kN)	P_u Fuller and Hoy (kN)	P_u L1 (kN)	P_u L2 (kN)	P_u Slope tangent (kN)	P_u Terzaghi and Peck (kN)	P_u van der Veen (kN)	Methods used	Δ Range	Average	Avg./L1
D36_3	35	–	–	–	–	–	–	–	–	610	1	0	610	–
D38_1	P01	–	1242	–	–	510	–	1242	–	2098	4	1589	1273	2.50
D38_2	P02	2649	773	–	–	348	1392	1043	1441	2053	7	2301	1386	3.98
D39_1	1	2792	1205	–	–	638	1907	1522	1959	2220	7	2154	1749	2.74
D40_1	1	1484	–	–	–	468	–	–	–	883	3	1016	945	2.02
D41_1	P1	–	401	543	–	91	555	639	1001	1196	7	1105	632	6.96
D41_2	P2	–	653	1208	–	201	907	707	1315	1410	7	1209	914	4.55
D41_3	P3	6411	728	1387	–	211	993	902	1456	1820	8	6201	1738	8.25
D41_4	P4	–	603	1171	–	122	746	890	1345	1550	7	1428	918	7.53
D41_5	P5	–	218	792	–	25	322	–	901	1800	6	1775	676	26.60
D41_6	P6	3655	341	790	–	79	401	469	775	960	8	3576	934	11.80
D43_1	16	1599	1257	–	–	593	–	–	–	1636	4	1043	1271	2.14
D43_2	60	1532	1094	485	–	568	–	1116	–	1494	6	1047	1048	1.84
D43_3	Trial pile	2327	1024	849	–	510	1606	1043	1652	3043	8	2533	1507	2.95
D44_1	PTP1	824	620	266	789	410	754	620	821	831	9	565	659	1.61
R01_01_1	WBD1	1961	1627	1421	–	839	1713	1381	–	1797	7	1122	1534	1.83
R01_01_2	WBD2	2039	1001	1089	–	381	1194	878	1501	2171	8	1790	1282	3.37
R01_01_3	WCFA	3095	–	–	–	891	–	2272	–	2866	4	2204	2281	2.56
R01_02_1	CBD	3533	–	1258	–	672	–	2095	–	2500	5	2861	2012	2.99
R02_1	PT01	38,022	–	16,470	–	10,682	31,432	20,339	23,324	32,575	7	27,341	24,692	2.31
R03_1	P1	1930	802	620	–	329	892	702	1226	1212	8	1600	964	2.93
R03_2	P2	1750	941	1160	1281	519	1076	926	1293	1393	9	1232	1149	2.21
R03_3	P3	1784	1142	1060	1654	628	1252	1058	1490	1687	9	1157	1306	2.08
R03_4	P4	1814	1047	1124	–	472	1079	865	1404	1505	8	1342	1164	2.47
R03_5	P5	1043	596	691	793	280	610	584	832	900	9	763	703	2.51
R03_6	P6	967	620	–	776	341	630	620	804	906	8	626	708	2.08
R04_1	CP3fs	104	80	76	–	32	75	85	–	77	7	72	76	2.35
R04_3	CP3fs	87	–	–	64	37[b]	56[b]	–	–	147	5	110	78	2.12
R05_1	A	1958	1634	1298	–	1118	–	1581	–	1808	6	840	1566	1.40

(Continued)

Table 10.1 (Continued) Calculated ultimate load/proven capacity for the piles in the DINGO database using the eight methods

File name[a]	Pile name	P_u Chin (kN)	P_u Davisson (kN)	P_u DeBeer (kN)	P_u Fuller and Hoy (kN)	P_u L1 (kN)	P_u L2 (kN)	P_u Slope tangent (kN)	P_u Terzaghi and Peck (kN)	P_u van der Veen (kN)	Methods used	Δ Range	Average	Avg./L1
R06_1	P01	22,597	12,357	8236	–	6844	15,008	11,059	13,081	21,754	8	15,753	13,867	2.03
R07_1	1	–	–	–	–	–	–	–	–	103	1	0	103	–
R07_2	1	42	–	–	–	–	–	–	–	122	2	80	82	–
R07_5	2	–	–	–	–	–	–	–	–	242	1	0	242	–
R08_1	P01	19,013	4706	3622	–	1849	–	–	–	12,160	5	17,164	8270	4.47
R09_1	A	917	–	43	–	–	–	–	–	126	3	875	362	–
R09_2	B	874	–	37	–	88	–	–	–	144	4	837	286	3.25
R09_3	C	209	–	32	–	70	–	–	–	134	4	177	111	1.59
R10_1	C1-9	3008	–	343	–	1430	–	–	–	3562	4	3220	2086	1.46
R10_2	CFA1	3313	1528	598	–	658	2071	1485	–	2658	7	2715	1759	2.67
R10_3	CFA2	2990	2149	267	–	934	–	1940	–	2879	6	2723	1860	1.99
R10_4	TP1-7	4533	–	1170	–	1199	–	2895	–	4929	5	3759	2945	2.46
R11_1	D6 03	3455	–	1500	–	700	–	–	–	4484	4	3784	2534	3.62
R11_10	XU 06	2080	–	–	–	671	–	–	–	1492	3	1409	1414	2.11
R11_6	Tripod	1024	–	607	–	444	–	–	–	1393	4	950	867	1.95
R11_7	XAF 02	4656	–	–	–	1937	–	–	–	4908	3	2972	3834	1.98
R11_8	XO 02	3605	–	–	–	1229	–	–	–	3439	3	2376	2757	2.24
R11_9	XT 14	2381	–	872	–	838	–	–	–	1972	4	1543	1516	1.81
R12_1	P1	5547	3965	1099	–	1663	–	3557	–	4670	6	4448	3417	2.05
R13_02_1	A	1762	596	866	1242	334	833	657	916	1555	9	1428	973	2.91
R14_1	7	788	700	–	–	455	–	–	–	678	4	333	655	1.44
R14_2	8	897	–	–	–	–	–	–	–	379	2	518	638	–
R14_3	9	847	–	–	–	–	–	–	–	410	2	437	629	–
R14_4	10	695	–	–	–	–	–	–	–	391	2	305	543	–
R14_5	11	706	–	–	–	–	–	–	–	390	2	316	548	–
R14_7	13	1567	–	–	–	–	–	–	–	480	2	1087	1023	–
R15_1	P1	–	–	260	–	2396	–	–	–	5968	3	5708	2874	1.20
R15_2	P2	10,198	–	693	–	2596	–	–	–	8948	4	9505	5609	2.16
R16_1	C30	2238	–	–	–	531	–	–	–	1501	3	1707	1424	2.68

(*Continued*)

Table 10.1 (Continued) Calculated ultimate load/proven capacity for the piles in the DINGO database using the eight methods

File name[a]	Pile name	P_u Chin (kN)	P_u Davisson (kN)	P_u DeBeer (kN)	P_u Fuller and Hoy (kN)	P_u L1 (kN)	P_u L2 (kN)	P_u Slope tangent (kN)	P_u Terzaghi and Peck (kN)	P_u van der Veen (kN)	Methods used	Δ Range	Average	Avg./L1
R16_2	C30	3577	1040	1188	–	385	1417	1206	–	1513	7	3192	1475	3.83
R16_3	H17	–	1293	783	–	533	1676	1318	2383	2353	7	1850	1477	2.77
R16_4	H18	2695	1403	1564	–	642	1751	1403	–	2279	7	2053	1677	2.61
R16_5	H19(1)	1447	885	1111	–	455	1110	885	–	1231	7	992	1018	2.24
R16_6	H19(2)	2572	1073	1192	–	468	1377	1103	–	1510	7	2105	1328	2.84
R16_7	H29	1987	–	1896	–	1690[b]	1868	–	1926	1944	6	297	1885	1.12
R16_8	H30	4938	1303	1355	–	428[b]	1820	2247	–	2251	7	4511	2046	4.78
R17_2	B33	1540	892	814	1216	626	1140	881	1152	1294	9	914	1062	1.70
R18_1	PT01	249	123	208	128	85	148	134	170	244	9	164	165	1.95
R18_2	PT02	204	86	183	77	57	106	96	125	201	9	147	126	2.22
R19_1	P01	5237	–	283	–	1054	–	–	–	3745	4	4954	2580	2.45
R20_1	4	894	398	148	–	187	514	423	709	931	8	783	525	2.81
R20_2	5	1108	575	602	–	250	668	554	989	1096	8	859	730	2.92
R20_3	6	1176	523	606	–	178	–	701	–	814	6	997	666	3.74
R20_4	4a	2607	584	524	–	183	827	752	1337	1800	8	2424	1077	5.90
R20_5	5a	1386	370	773	–	129	469	433	784	1153	8	1258	687	5.33
R20_6	5a	1975	562	1216	–	183	688	655	1165	1320	8	1792	971	5.30
R22_1	GP1	538	387	52	–	105	354	330	–	507	7	486	325	3.09
R22_2	GP2	–	–	166	–	51	–	–	–	716	3	666	311	6.15
R22_3	GP3	497	–	201	–	110	–	–	–	389	4	387	299	2.71
R22_4	GP4	687	505	33	–	97	429	403	–	797	7	763	421	4.34
R22_5	GP5	–	–	55	–	47	–	–	–	925	3	878	342	7.27
R22_6	GP6	1186	–	317	–	121	–	–	–	486	4	1066	528	4.37
R22_7	GP7	655	–	201	–	112	446	412	–	620	6	543	408	3.63
R22_8	GP9	–	–	281	–	128	–	–	–	599	3	471	336	2.63
R23_1	TP1	7845	–	632	–	1179	–	3582	–	5931	5	7213	3834	3.25
R23_3	TP2	2653	–	1530	–	1318	–	–	–	2582	4	1335	2021	1.53
R23_5	TP3	2731	–	–	–	837	–	–	–	2913	3	2077	2160	2.58
R23_7	TP4	4352	–	820	–	737	–	2021	–	3275	5	3616	2241	3.04

(Continued)

Table 10.1 (Continued) Calculated ultimate load/proven capacity for the piles in the DINGO database using the eight methods

File name[a]	Pile name	P_u Chin (kN)	P_u Davisson (kN)	P_u DeBeer (kN)	P_u Fuller and Hoy (kN)	P_u L1 (kN)	P_u L2 (kN)	P_u Slope tangent (kN)	P_u Terzaghi and Peck (kN)	P_u van der Veen (kN)	Methods used	Δ Range	Average	Avg./L1
R23_8	TP6	6449	–	665	–	1142	–	3112	–	6122	5	5784	3498	3.06
R24_01_1	P1	17,812	–	7402	–	4872	–	–	–	12,584	4	12,941	10,668	2.19
R24_02_1	Test1	3750	1880	2031	–	1003	2724	1880	2478	3323	8	2747	2384	2.38
R24_02_2	Test2	11,811	3822	4001	–	1145	–	3869	5106	7497	7	10,666	5322	4.65
R24_03_1	2W	23,705	–	7379	–	7607	–	–	–	11,910	4	16,327	12,650	1.66
R24_03_2	3W	24,521	–	5781	–	4756	–	–	–	12,140	4	19,764	11,800	2.48
R24_03_3	4W	7288	–	4408	–	3644	–	–	–	5392	4	3644	5183	1.42
R24_03_4	TEST2	15850	9137	13,720	–	5185	11853	8157	9895	14,105	8	10,665	10,988	2.12
R24_03_5	TEST3	11,195	4697	5386	–	2472	7440	4602	5848	8927	8	8723	6321	2.56
R24_03_6	TEST4	17,027	9556	14,054	–	5509	12,440	8356	10,413	15,050	8	11,518	11,551	2.10
R24_04_1	Test1	60,684	–	–	–	2940	–	–	16,602	36,727	4	57,745	29,238	9.95
R24_04_2	Test2	31,731	–	5958	–	6962	–	17,614	–	28,206	5	25,774	18,094	2.60
R24_04_3	Test3	4163	2571	2520	3924	1819	3247	2523	2974	4061	9	2344	3089	1.70
R24_04_4	Test4	15,238	5734	8738	–	2234	7948	4980	6558	10,762	8	13,005	7774	3.48
R25_1	B1	20,969	13,633	8322	–	6564	18,419	11,696	13,849	19,716	8	14,405	14,146	2.16
R25_2	P1	26,048	18,256	12,979	–	6391	–	14,731	17,172	21,860	7	19,656	16,777	2.62
R25_3	P2	22,326	–	7845	–	7707	–	15,712	–	22,096	5	14,619	15,137	1.96
R26_01_7	90	2682	–	855	–	365	1495	1723	–	2239	6	2318	1560	4.28
R26_01_8	112	3880	1944	1755	–	422[b]	1558	–	–	2158	6	3457	1953	4.63
R26_02_10	1A	2856	1679	1162	–	487[b]	1434	1651	2125	2010	8	2369	1668	3.43
R26_02_9	80	6285	2458	1268	–	359[b]	1535	2216	2602	2362	8	5926	2377	6.62
R27_1	B	4119	–	2220	–	1828	–	–	–	2640	4	2291	2702	1.48
R27_2	C	4862	3949	2784	–	2171	–	3539	–	4169	6	2691	3579	1.65
R28_1	Bridge 130	–	–	524	–	–	–	–	–	1903	2	1379	1214	–
R28_2	F1	2944	–	869	–	994	–	–	–	2731	4	2075	1885	1.90
R28_3	F2	25,250	–	618	–	787	–	–	–	1707	4	24,632	7090	9.01
R28_4	W1	3156	–	797	–	578	–	–	–	2550	4	2578	1770	3.06
R28_5	W2	2409	1300	1339	–	574	1793	1695	–	2120	7	1835	1604	2.80
R28_6	W3	1785	743	964	–	370	1078	1008	1193	1421	8	1415	1070	2.89

(*Continued*)

Table 10.1 (Continued) Calculated ultimate load/proven capacity for the piles in the DINGO database using the eight methods

File name[a]	Pile name	P_u Chin (kN)	P_u Davisson (kN)	P_u DeBeer (kN)	P_u Fuller and Hoy (kN)	P_u L1 (kN)	P_u L2 (kN)	P_u Slope tangent (kN)	P_u Terzaghi and Peck (kN)	P_u van der Veen (kN)	Methods used	Δ Range	Average	Avg./L1
R28_7	W6	1672	–	680	–	349	–	–	–	1410	4	1323	1028	2.94
R28_8	W7	954	419	403	745	216	544	516	668	888	9	737	595	2.75
R28_9	W8	555	359	–	475	201	458	440	–	508	7	354	428	2.13
R30_1	HC1	2964	–	999	–	–	–	–	1298	3036	4	2036	2074	–
R30_10	SC2	3265	–	1897	–	–	–	–	1663	2826	4	1602	2413	–
R30_11	SC3	2240	–	1167	–	–	–	–	895	2522	4	1627	1706	–
R30_12	SC4	3092	–	1223	–	–	–	–	1312	2645	4	1868	2068	–
R30_13	SC5	3380	–	1602	–	–	–	–	1600	2959	4	1780	2385	–
R30_14	SC6	3481	–	1519	–	–	–	–	1500	2900	4	1981	2350	–
R30_15	Solid pile	13,759	6097	2974	–	2548	9716	5314	7253	13,310	8	11,211	7621	2.99
R30_16	Voided pile	6911	3331	2373	–	1468	–	3585	4439	8305	7	6837	4344	2.96
R30_2	HC2	3088	–	1937	–	–	–	–	1628	2716	4	1460	2342	–
R30_3	HC3	3098	–	1542	–	–	–	–	1473	2758	4	1625	2218	–
R30_4	HC4	1228	–	773	924	–	–	–	820	1166	5	455	982	–
R30_5	HC5	2508	–	1258	–	–	–	–	1443	2263	4	1251	1868	–
R30_6	HC6	3561	–	2046	–	–	–	–	1750	3000	4	1811	2589	–
R30_9	SC1	2031	–	776	–	–	–	–	1043	2075	4	1300	1481	–
R31_1	P1	10,664	7097	5940	–	3543	7151	5262	6797	10,050	8	7121	7063	1.99
R32_1	Hollow pile	9469	7224	6872	–	4738	9472	6625	7822	9050	8	4734	7659	1.62
R32_2	Solid pile	8196	6077	4791	–	4375	7736	5921	6608	7900	8	3821	6451	1.47
R33_01_1	S1	317	191	236	210	125	223	204	267	289	9	191	229	1.83
R33_01_2	S2	323	181	176	210	117	207	181	249	320	9	206	218	1.87
R33_01_3	S2	332	251	254	237	197	273	251	303	327	9	135	269	1.37
R33_01_4	S2	344	206	219	–	145	235	206	273	331	8	198	245	1.68
R33_01_5	S3	349	296	284	285	238	315	295	345	344	9	110	306	1.28
R33_01_6	S4	479	205	400	257	115	248	220	316	438	9	364	298	2.58
R33_01_7	S5	329	177	270	181	125	210	187	239	324	9	205	227	1.82
R33_01_8	S6	479	176	402	258	116	226	225	266	448	9	362	289	2.48
R33_01_9	S7	691	485	591	–	377	522	470	567	687	8	314	549	1.46
R33_02_1	T.A	1421	876	896	–	326	980	857	–	976	7	1095	905	2.77

(Continued)

Table 10.1 (Continued) Calculated ultimate load/proven capacity for the piles in the DINGO database using the eight methods

File name[a]	Pile name	P_u Chin (kN)	P_u Davisson (kN)	P_u DeBeer (kN)	P_u Fuller and Hoy (kN)	P_u L1 (kN)	P_u L2 (kN)	P_u Slope tangent (kN)	P_u Terzaghi and Peck (kN)	P_u van der Veen (kN)	Methods used	Δ Range	Average	Avg./L1
R33_02_10	T4	642	280	583	367	175	334	280	393	608	9	467	407	2.33
R33_02_11	T4	621	482	564	535	320	550	477	631	598	9	311	531	1.66
R33_02_12	T4	–	–	598	–	–	–	–	–	697	2	99	647	–
R33_02_2	T.A	–	–	63	–	–	–	–	–	107	2	44	85	–
R33_02_3	T.A	791	638	683	–	485	667	611	739	781	8	306	674	1.39
R33_02_4	T.B	493	388	379	–	233	–	403	–	418	6	260	386	1.65
R33_02_5	T.B	–	394	208	–	115	–	495	–	464	5	380	335	2.92
R33_02_6	T.B	398	309	315	–	258	328	309	354	394	8	140	333	1.29
R34_1	TP1	11,083	4214	3687	–	2062	6018	3850	5117	9602	8	9021	5704	2.77
R34_2	TP1	9997	4445	6384	–	2200	6072	3718	5207	9600	8	7797	5953	2.71
R34_3	TP2	16,340	12,555	12,904	–	4223	–	7942	11,492	16,750	7	12,527	11,743	2.78
R34_4	TP3	18,903	11,022	–	–	5207	12019	8958	10,589	18,000	7	13,697	12,100	2.32
R34_5	TP4	13,097	5419	–	–	2784	7398	5419	6380	12,230	7	10,313	7532	2.71
R34_6	TP5	11,597	6988	1680	–	3805	8231	6456	7323	11,380	8	9917	7182	1.89
R34_7	TP6	15,065	–	1574	–	4084	–	8070	12,241	15,780	6	14,206	9469	2.32
R35_1	P01	26,560	–	3916	–	8393	18,891	12,992	13,857	27,404	7	23,488	16,002	1.91
R35_2	P02	10,014	4117	–	–	2257	5930	4117	4802	8900	7	7758	5734	2.54
R36_1	PT01	3533	669	103	–	292	1291	669	1031	2998	8	3429	1323	4.53
R37_01_1	TP1	457	–	224	–	236	–	–	–	409	4	234	331	1.41
R37_01_2	TP2	775	–	405	–	467	–	–	–	867	4	462	628	1.35
R37_02_1	TP1	437	–	–	–	–	–	–	–	299	2	138	368	–
R37_03_1	TP1	925	–	333	–	–	–	–	–	669	3	593	642	–
R37_04_1	TP1	1843	–	–	–	747	–	–	–	1956	3	1209	1515	2.03
R37_05_1	TP1	1115	–	584	–	563	–	–	–	837	4	551	775	1.38
R37_05_2	TP2	4548	–	2065	–	–	–	–	–	3319	3	2483	3311	–
R37_06_1	24/710	873	–	–	–	562	–	838	–	820	4	311	773	1.38
R37_06_10	B6	929	–	–	–	–	–	–	–	666	2	263	797	–
R37_06_11	B7	695	633	–	639	504	–	636	–	666	6	191	629	1.25
R37_06_12	B8	1007	888	–	965	663	–	880	–	982	6	344	898	1.35

(Continued)

Table 10.1 (Continued) Calculated ultimate load/proven capacity for the piles in the DINGO database using the eight methods

File name[a]	Pile name	P_u Chin (kN)	P_u Davisson (kN)	P_u DeBeer (kN)	P_u Fuller and Hoy (kN)	P_u L1 (kN)	P_u L2 (kN)	P_u Slope tangent (kN)	P_u Terzaghi and Peck (kN)	P_u van der Veen (kN)	Methods used	Δ Range	Average	Avg./L1
R37_06_13	B9	1334	1186	930	1259	824	–	1152	–	1270	7	509	1137	1.38
R37_06_2	29/2	1055	1038	677	–	670	–	1004	–	971	6	385	902	1.35
R37_06_3	954/25	1090	–	669	–	674	–	–	–	982	4	421	854	1.27
R37_06_4	B10	1327	1216	840	–	797	–	1156	–	1290	6	530	1104	1.39
R37_06_5	B11	1484	–	782	–	924	–	–	–	1355	4	703	1136	1.23
R37_06_6	B11	1365	–	–	–	–	–	–	–	981	2	384	1173	–
R37_06_7	B12	1830	–	744	–	–	–	–	–	1270	3	1086	1281	–
R37_06_8	B4	1114	–	–	–	875	–	–	–	972	3	239	987	1.13
R37_06_9	B5	2377	–	–	–	–	–	–	–	1640	2	737	2008	–
R37_07_1	TP1	2796	–	977	–	–	–	–	–	2024	3	1819	1932	–
R37_07_2	TP2	4067	–	1864	–	2375	–	–	–	3578	4	2203	2971	1.25
R37_08_1	TP1	2199	–	1010	–	1007	–	–	–	1606	4	1192	1455	1.45
R37_08_2	TP2	2454	–	1212	–	1286	–	–	–	1975	4	1242	1732	1.35
R37_09_1	TP1	1007	–	–	–	462	–	–	–	730	3	545	733	1.59
R37_09_2	TP2	685	–	–	–	438	–	–	–	460	3	247	528	1.20
R37_09_3	TP3	768	704	595	703	505	–	685	–	740	7	263	671	1.33
R37_09_4	TP4	3503	–	–	–	–	–	–	–	1050	2	2453	2276	–
R37_09_5	TP5	1892	–	–	–	723	–	–	–	1270	3	1169	1295	1.79
R37_09_6	TP6	1056	–	–	–	–	–	–	–	710	2	346	883	–
R37_10_1	P1	5499	–	–	–	1700	–	–	–	5690	3	3990	4297	2.53
R37_10_2	P2	3489	–	1645	–	1573	–	–	–	4110	4	2537	2704	1.72
R37_10_3	P4	3341	–	1320	–	1158	–	–	–	2660	4	2183	2120	1.83
R37_10_4	P5	6047	–	1578	–	1498	–	–	–	4400	4	4549	3381	2.26
R37_10_5	P6	10,148	–	3087	–	2218	–	–	–	5160	4	7930	5153	2.32
R37_11_1	TP1	1282	1114	–	–	718	–	1024	–	1196	5	564	1067	1.49
R37_11_2	TP2	1541	–	–	–	728	–	–	–	1210	3	813	1160	1.59
R37_12_1	TP1	4814	–	2214	–	–	–	–	–	3888	3	2600	3639	–
R37_12_2	TP2	2534	–	1737	–	–	–	–	–	3083	3	1346	2451	–
R37_13_1	TP1	1367	–	575	–	–	–	–	–	1487	3	912	1143	–

(Continued)

Table 10.1 (Continued) Calculated ultimate load/proven capacity for the piles in the DINGO database using the eight methods

File name[a]	Pile name	P_u Chin (kN)	P_u Davisson (kN)	P_u DeBeer (kN)	P_u Fuller and Hoy (kN)	P_u L1 (kN)	P_u L2 (kN)	P_u Slope tangent (kN)	P_u Terzaghi and Peck (kN)	P_u van der Veen (kN)	Methods used	Δ Range	Average	Avg./L1
R37_13_2	TP2	1614	–	–	–	–	–	–	–	455	2	1159	1035	–
R37_14_1	4138	1930	1775	1437	–	1105	–	1623	–	1794	6	825	1611	1.46
R37_14_2	A	145	–	76	–	–	–	–	–	120	3	69	114	–
R37_14_3	B	232	–	93	–	–	–	–	–	150	3	139	158	–
R37_14_4	C	270	–	104	–	–	–	–	–	190	3	166	188	–
R37_14_5	TP1	3345	–	1103	–	1461	–	–	–	2010	4	2242	1980	1.35
R37_14_6	TP2	2225	–	677	–	868	–	–	–	1220	4	1548	1247	1.44
R37_14_7	TP3	1451	–	412	–	–	–	–	–	770	3	1039	878	–
R37_15_1	TP1	5119	–	1559	–	2259	–	–	–	3965	4	3560	3226	1.43
R37_15_2	TP2	3064	–	–	–	1366	–	–	–	2455	3	1698	2295	1.68
R37_15_3	TP3	1430	–	–	–	–	–	–	–	1407	2	23	1418	–
R38_1	T16	515	574	448	–	273	–	505	–	451	6	300	461	1.69
R38_2	T30	1304	698	111	–	270	–	698	–	786	6	1193	644	2.39
R38_3	T40	308	–	220	–	133	–	–	–	223	4	175	221	1.66
R38_4	T46	369	350	272	–	169	–	334	–	296	6	200	298	1.76
R38_5	T47	356	–	254	–	188	–	345	–	308	5	167	290	1.54
R39_1	FP	2633	–	–	–	983	–	–	–	2648	3	1666	2088	2.12
R40_01_1	1-1	28,582	20,528	–	–	9406	–	17,763	19,432	22,950	6	19,176	19,777	2.10
R40_02_1	2	46,748	–	–	–	5435	–	–	–	27,160	3	41,314	26,448	4.87
R40_03_1	3-1	41,072	–	–	–	15304	–	–	–	28,010	3	25,767	28,129	1.84
R40_04_1	5-1	17,101	10,304	–	–	3263	–	8532	10,491	13,210	6	13,838	10,483	3.21
R40_04_2	5-2	19,398	–	–	–	4795	–	–	–	14,080	3	14,603	12,757	2.66
R40_04_3	5-3	27,179	–	–	–	7366	–	–	–	18,970	3	19,813	17,838	2.42
R41_1	P01	8890	–	647	–	1712	5310	3170	4892	8881	7	8243	4786	2.80
R42_1	TP14	725	484	306	–	210	505	400	686	659	8	515	497	2.37
R42_2	TP75	5273	–	130	–	349	–	–	–	3427	4	5143	2295	6.58
R43_1	P01	23,492	–	13,442	–	7785	16760	11,639	13,559	22,187	7	15,707	15,552	2.00
R45_1	A	3655	1975	–	–	1364	–	2125	2258	4029	6	2665	2568	1.88
R45_10	G	1380	–	1259	–	1074	–	–	–	1279	4	306	1248	1.16
R45_11	H	2483	–	1250	–	1290	–	–	–	1815	4	1233	1709	1.33

(*Continued*)

Table 10.1 (Continued) Calculated ultimate load/proven capacity for the piles in the DINGO database using the eight methods

File name[a]	Pile name	P_u Chin (kN)	P_u Davisson (kN)	P_u DeBeer (kN)	P_u Fuller and Hoy (kN)	P_u L1 (kN)	P_u L2 (kN)	P_u Slope tangent (kN)	P_u Terzaghi and Peck (kN)	P_u van der Veen (kN)	Methods used	Δ Range	Average	Avg./L1
R45_12	H	2343	–	–	–	1456	–	–	–	2059	3	887	1953	1.34
R45_13	K	2609	2090	–	–	1432	–	2079	–	2362	5	1177	2114	1.48
R45_14	K	2232	1819	–	–	1601	2003	1819	1958	2223	7	631	1951	1.22
R45_15	L	1891	–	978	–	1291	–	–	–	1772	4	913	1483	1.15
R45_16	L	1875	1788	1222	–	1361	–	–	–	1838	5	654	1617	1.19
R45_17	M	3918	–	–	–	2340	–	–	–	3180	3	1578	3146	1.34
R45_18	M	4994	–	–	–	3180	–	–	–	3380	3	1814	3851	1.21
R45_19	N	3656	3384	2765	–	2054	–	3262	–	3110	6	1603	3038	1.48
R45_2	A	3855	2375	2678	–	1739	–	2760	2662	7150	7	5411	3317	1.91
R45_20	N	3761	–	3141	–	2564	–	–	–	3489	4	1197	3239	1.26
R45_21	P	5300	–	2542	–	3013	–	–	–	4058	4	2758	3728	1.24
R45_22	P	5311	–	3468	–	3546	–	–	–	4224	4	1842	4137	1.17
R45_23	X	895	–	–	732	–	–	–	768	894	4	163	822	–
R45_3	D	967	–	–	–	490	–	–	–	708	3	477	722	1.47
R45_4	D	768	671	–	702	508	–	705	–	735	6	260	682	1.34
R45_5	E	1677	–	942	–	1226	–	–	–	1395	4	735	1310	1.07
R45_6	E	1716	–	1085	–	1356	–	–	–	1519	4	631	1419	1.05
R45_7	F	1535	1505	–	–	1139	–	1497	–	1602	5	463	1456	1.28
R45_8	F	1695	1680	870	–	1297	–	–	–	1765	5	895	1461	1.13
R45_9	G	1212	–	942	–	908	–	–	–	1116	4	304	1044	1.15
R46_1	PT01	1545	–	618	–	939	–	–	–	1225	4	926	1082	1.15
R46_2	PT02	59	–	21	–	35	–	–	–	81	4	60	49	1.39
R47_1	P01	27,073	–	6185	–	6079	15,580	9715	12,011	28,410	7	22,331	15,007	2.47
R48_1	P01	44,812	–	6562	–	2878	14,160	10,490	11,124	35,780	7	41,934	17,972	6.24

Note: Values in the "P_u L1 (kN)" column are included in the calculations of the values in the following columns "Methods used", "Δ range", "Average", and "Avg./L1".

[a] The file name is taken from Vardanega *et al.* (2024) with the final digit added to indicate different pile tests from the same original file name.

[b] L1 and/or L2 were taken from the extension of the power function curve.

10.3.4 Davisson method (Davisson 1972)

This method assumes the pile as a fixed-base, free-standing column with length (L), cross-sectional area (A), and Young's modulus (E). The elastic deflection of such a column is calculated as (PL)/(EA) where P represents the loading values from load–settlement data. To estimate the ultimate load using this method, the elastic deflection line is shifted in the x-axis direction by a value of $3.8 + D/120$ where D represents the pile diameter at the base measured in mm. The intersection point between the shifted elastic deflection line with the load–settlement curve is defined as the ultimate load of the pile. The analysis of a pile from the DINGO database using this method is shown in Figure 10.13. Ultimate capacities for 150 tests were estimated using this method. The pile tests with no result represent tests with an offset value larger than the settlement (no intersection point) or tests with no information regarding the pile length or the pile diameter. In this study, concrete piles were assumed to have a Young's modulus of 30 GPa (200 GPa for steel piles). Piles with unknown material were assumed to be made from concrete. It is acknowledged that variations in the assumed material E values do influence the calculated ultimate capacities.

10.3.5 DeBeer method (DeBeer 1970)

This method assumes the ultimate load of a pile to be located at the point of slope change in a load–settlement curve plotted on a log-log plot. The ultimate load of the pile is taken as the point of change in gradient on the log-log plot. Since this method requires the load–settlement data to be converted to log values, load–settlement data in each pile were filtered to remove any zero values. To locate the point of slope change on the load–settlement curve, the load–settlement data were split into two groups, each group containing at least three datapoints. For each group, the best-fit line for the data was plotted and the coefficient of determination (R^2) was calculated. This step was repeated to find the split point that corresponds to the highest summation of R^2 for both fits. Using this point, the intersection point between the two best-fitting lines was determined and the load corresponding to this point was assumed to be the ultimate load of the pile. Figure 10.14 shows the two best-fitting lines for the load–settlement data indicating the optimum division of the data (i.e. between the first and second segments) for a specific pile test. From this

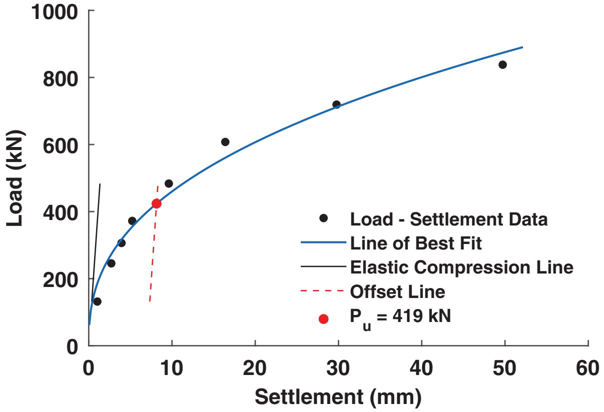

Figure 10.13 Graphical representation of the Davisson (1972) method for estimating the pile capacity.

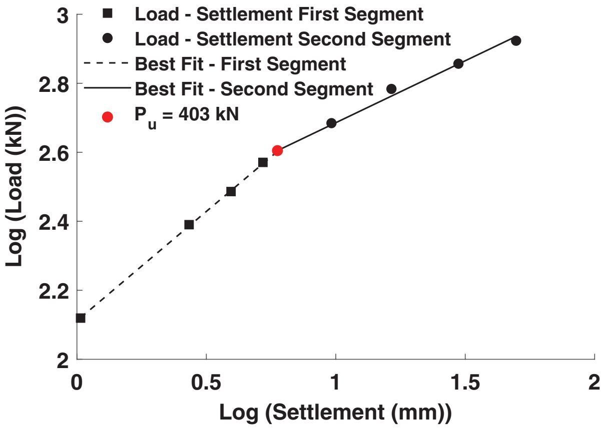

Figure 10.14 Graphical representation of the DeBeer (1970) method for estimating the pile capacity.

figure, the ultimate load was calculated at around 403 kN. The results for the analysis of the DINGO database using the DeBeer method are summarised in Table 10.1. Since this method requires at least three points in each data group, pile tests with less than six data points have no result for the ultimate load in Table 10.1. The total number of pile tests from the DINGO database with ultimate load values calculated using the DeBeer method is 281. Baligh and Abdelrahman (2005) proposed some modifications to the method which could be explored in future work using the DINGO database.

10.3.6 Fuller and Hoy method (Fuller & Hoy 1970)

This method calculates the ultimate load of a pile by finding the minimum load at which the slope of the load–settlement curve reaches 0.14 mm/kN. This method assumes the failure criteria of a pile is represented by a slope of 0.14 mm/kN or higher as the ultimate load of the pile. The tangent value at each point of the fitted curve is calculated until a slope of 0.14 mm/kN is located. Figure 10.15 shows an estimation of a pile's ultimate load using this method. The ultimate load results for the DINGO database pile tests using this method are summarised in Table 10.1. The total number of tests with valid estimates of the ultimate load using this method was 36.

10.3.7 L1–L2 method (Hirany & Kulhawy 1988)

This method was developed by Hirany and Kulhawy (1988) and estimates the ultimate load as corresponding to 4% of the pile diameter. In this method, the load–settlement curve is divided into the elastic zone, the transition zone, and the failure zone. These zones are separated by L1 and L2 values that are calculated by 0.4% of the diameter for L1 (elastic limit) and 4% of the diameter for L2 (failure threshold) (Chen & Kulhawy 2002). L2 estimates the failure threshold of piles subjected to compression load constructed in both drained and undrained soils (Chen *et al.* 2009).

This method defines the ultimate load of a pile as the corresponding load for a settlement of 4% of the pile diameter. Figure 10.16 shows the estimated elastic limit and ultimate load of a pile from the DINGO database. For this method, the number of pile tests

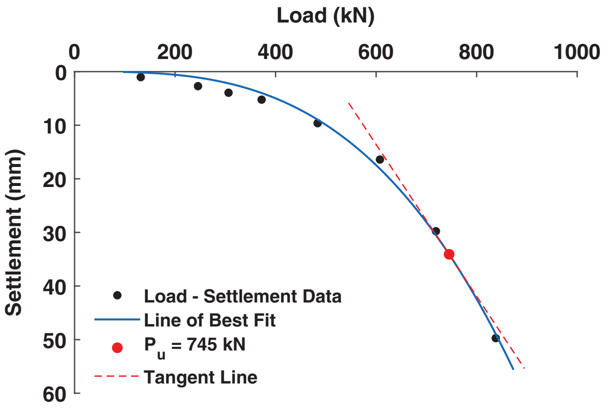

Figure 10.15 Graphical representation of the Fuller and Hoy (1970) method for estimating the pile capacity.

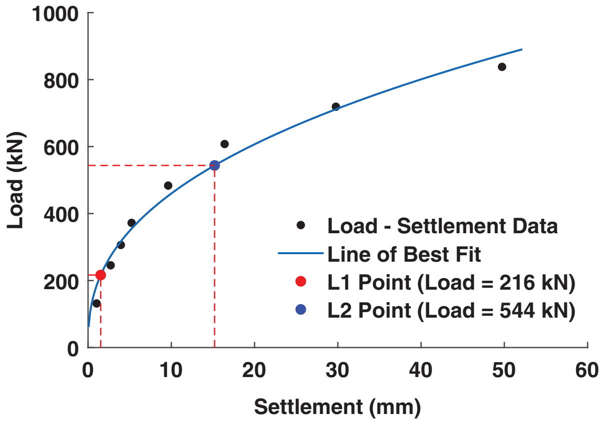

Figure 10.16 Graphical representation of the Hirany and Kulhawy (1988) method for estimating the pile capacity.

with a calculated elastic limit was 290 tests, while the tests with a calculated ultimate load was 116 (see Table 10.1).

10.3.8 Slope tangent method (O'Rourke & Kulhawy 1985)

In this method, the initial slope of the load–settlement curve is shifted by $3.8 + D/120$ where D is the pile diameter at the base. The intersection between the offset and the load–settlement curve is taken as the ultimate load of the pile (see Figure 10.17). The results for the rest of the DINGO database pile tests are shown in Table 10.1. The number of pile tests with ultimate load values computed using this method was 166 (see Table 10.1).

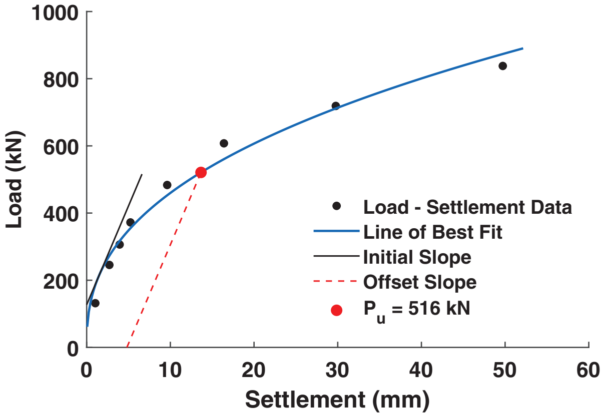

Figure 10.17 Graphical representation of the slope tangent (1985) method for estimating the pile capacity.

10.3.9 Terzaghi and Peck method (Terzaghi & Peck 1967)

This method assumes that the ultimate load of a pile occurs at a settlement of 25.4 mm (i.e., one inch) (see Terzaghi & Peck 1967, Art. 56 "Pile Foundations," p. 537). Often this settlement level was not recorded as tests were only maintained to working load or those commissioning the tests required validation of this load. This settlement value is an empirical estimation of the ultimate load of a pile presumably based on past observations. Figure 10.18 shows the ultimate load of a pile using this method while Table 10.1 summarises the results for all DINGO database pile tests. The total number of pile tests with ultimate load calculated by this method was 118 (see Table 10.1).

10.3.10 van der Veen Method (van der Veen 1953)

This method assumes the ultimate load of a pile as the value that yields a straight line when plotting $Log(1-P/P_u)$ against the settlement. In this method, the value of P_u is assumed initially for the plot, the value is then changed until the plot produces a straight

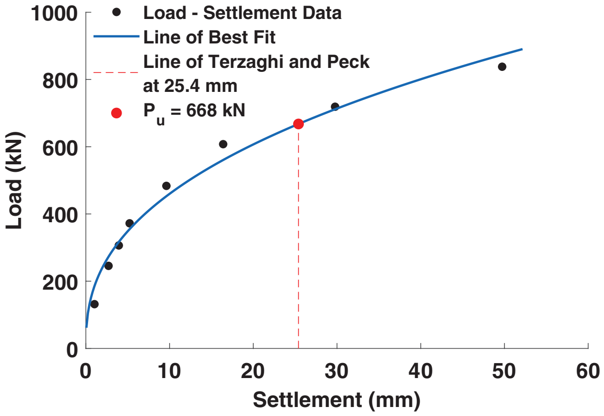

Figure 10.18 Graphical representation of the Terzaghi and Peck (1967) method for estimating the pile capacity.

line. This method is similar to Chin method (see Section 10.3.3) in the assumption of the asymptote aspect of the load–settlement curve. In this method, the value of P_u is initially assumed to be the maximum load value from the load–settlement data. Then a straight line is fitted for the plotted data. The value of R^2 is then calculated. The value of P_u is then changed until the highest value of R^2 is obtained. The value of P_u corresponding with the highest R^2 is the ultimate load of the pile. Figure 10.19 shows the ultimate load of a pile from the DINGO database using this method. Table 10.1 summarises the ultimate load calculation for all the pile tests in the DINGO database.

10.3.11 Discussion of estimated ultimate capacities

This study presents the ultimate load analysis of piles from the DINGO database using eight methods that rely on load–settlement data taken during pile testing. Based on the results shown in Table 10.1, the following observations are made. For the Fuller and Hoy (1970) method only 36 out of 372 possible pile tests could be analysed with this method, while the van der Veen (1953) method yielded 372 out of 372 possible ultimate load estimations using this method. The van der Veen (1953) method relies only on load–settlement data with no limitations defined. As expected, methods with no boundary limitation and not requiring additional data like pile length or diameter such as Chin (354 out of 372) and DeBeer (281 out of 372) tend to have higher conversion rates compared to methods with boundary conditions such as Terzaghi and Peck (118 out of 372) and L1–L2 (116 out of 372) or methods that rely on other factors in the analysis such as the Davisson (150 out of 372) and slope tangent (166 out of 372) methods.

When comparing the ultimate load estimation between each method, the Chin method was found to give the highest ultimate load estimation, which usually exceeds the maximum recorded load in the load–settlement curve (therefore adjustments to this approach may be needed for this dataset). The DeBeer method was found to give the lowest estimation of the ultimate load. These observations confirm the findings of Chen and Fang (2009), Marcos *et al.* (2013), AbdelSalam *et al.* (2015), Chen *et al.* (2021), and Chen *et al.* (2023). In general, the Chin and van der Veen methods produce the highest ultimate load estimation. The average range difference between the maximum estimated and minimum estimated for each pile test was computed as 3225 kN in ultimate load estimation, this high range difference suggests high variability between the reviewed methods. To fully

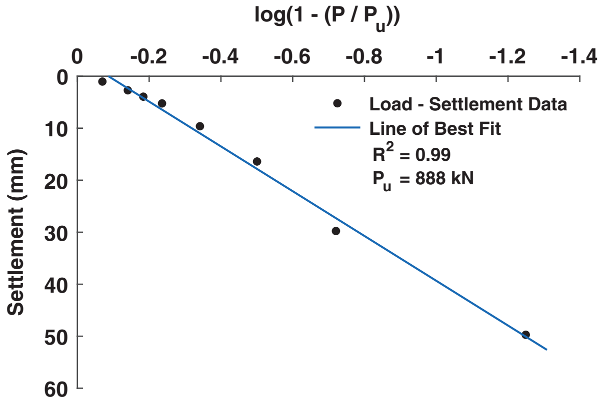

Figure 10.19 Graphical representation of the van der Veen (1953) method for estimating the pile capacity.

understand the degree of variability between the different methods, the average ultimate load for all the pile tests reviewed in this study was calculated to be 2715 kN, which is less than the average range difference for the eight methods. This high variability suggests removing the Chin and DeBeer methods from the analysis as per the suggestion of Marcos *et al.* (2013) and Chen *et al.* (2023).

Finally, when calculating the "factor of safety" of the pile tests used in this study (i.e., dividing the average ultimate load for each pile test calculated using all the methods by the elastic limit L1), the average factor of safety for all the pile tests was found to be 2.63 with a maximum recorded factor of safety of 26.6 and a minimum of 1.05. Factor of safety values estimated in the present study agrees with the finding of Chen and Fang (2009) where the Chin (1970) method factor of safety was estimated to be 3.0, a factor of safety of 2.2 was estimated for L1–L2 and Terzaghi and Peck (1967) methods, and a value of 2.0 was estimated for the remaining methods.

10.4 SUMMARY

This chapter has presented a summary of the development of the DINGO database for piled foundations. The need for geo-databases to characterise geotechnical variability has been reviewed and the uses of the DINGO database for data visualisation and settlement prediction have been summarised. New analysis following the general methodology of Chen and Fang (2009), Marcos *et al.* (2013), Chen *et al.* (2021), and Chen *et al.* (2023) saw eight methods used for calculation of pile capacity to the test data contained in the DINGO database where the use of at least one of these methods was possible. A total of 372 tests from the database of over 500 piles were suitable for analysis by at least one of the methods. The results indicate that selection of the method has a considerable impact on the calculated capacity supporting the results of earlier studies. Engineers making use of the methods reviewed in this chapter should examine a range of approaches especially when using pile–load test data to extrapolate a pile capacity.

However, it is worth asking whether 'pile capacity' is a helpful term when examining pile–load test data. Performance-based design approaches that make use of clear criteria for structural damage due to foundation movements (e.g., Skempton & MacDonald 1956; Polshin & Tokar 1957; Boscardin & Cording 1989) (see also the reviews of Poulos *et al.* 2001 and Vardanega & Bolton 2016) are arguably more useful for foundation engineers. This idea is not new, e.g., Gorbunov-Possadov and Davydov (1973, p.48) stated: "The guiding principle in designing bases of foundations in the USSR is design based on limiting deformations of the structure." Fellenius (1999) points out that many traditional bearing capacity formulae do not represent foundation behaviour, noting that "…geotechnical design should place the greater emphasis on determining the settlement of the foundations" (Fellenius 1999, p. 16). Open-source pile–load test databases such as DINGO allow the variability of foundation settlements to be better analysed within reliability frameworks.

DATA AVAILABILITY STATEMENT

The DINGO database can be freely downloaded from the data.bris repository via the following weblink: https://doi.org/10.5523/bris.1jraem68g7ara21p2oi6hv4z22 (Vardanega *et al.* 2024).

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NOTE

1. See Chen et al. (2021) for full bibliographic details for "DIN 4026."

REFERENCES

AbdelSalam, S.S., Baligh, F.A. & El-Naggar, H.M. (2015). A database to ensure reliability of bored pile design in Egypt. *Proceedings of the Institution of Civil Engineers – Geotechnical Engineering*, **168**(2): 131–143. https://doi.org/10.1680/geng.14.00051

Ali, H.M. & Shakir, R.R. (2022). Geotechnical map of Thi Qar governorate using geographical information systems (GIS). *Materials Today: Proceedings*, **60**(3): 1286–1296. https://doi.org/10.1016/j.matpr.2021.09.138

Association of Geotechnical and Geoenvironmental Specialists (AGS). (2017). *Electronic Transfer of Geotechnical and Geoenvironmental Data*, Edition 4.0.4. Bromley, Kent.

B., D.P. & Dodagoudar, G.R. (2018). An integrated geotechnical database and GIS for 3D subsurface modelling: Application to Chennai City, India. *Applied Geomatics*, **10**(1): 47–64. https://doi.org/10.1007/s12518-018-0202-x

Baligh, F.A. & Abdelrahman, G.E. (2005). Modification of Davisson's method. In: *Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering*, Millpress Science Publishers/IOS Press, pp. 2079–2082. https://doi.org/10.3233/978-1-61499-656-9-2079

Beesley, M.B. & Vardanega, P.J. (2020). Parameter variability of undrained shear strength and strain using a database of reconstituted soil tests. *Canadian Geotechnical Journal*, **57**(8): 1247–1255. https://doi.org/10.1139/cgj-2019-0424

Bond, A.J. & Jardine, R.J. (1995). Shaft capacity of displacement piles in a high OCR clay. *Géotechnique*, **45**(1): 3–23. https://doi.org/10.1680/geot.1995.45.1.3

Borruso, G. & Schoier, G. (2004). Density analysis on large geographical databases. Search for an index of centrality of services at urban scale. In: *Computational Science and Its Applications – ICCSA 2004. ICCSA 2004* (Laganá, A. *et al.* (eds.)). Lecture Notes in Computer Science, vol 3044. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-24709-8_106

Boscardin, M.D. & Cording, E.J. (1989). Building response to excavation-induced settlement. *Journal of Geotechnical Engineering (ASCE)*, **115**(1): 1–21. https://doi.org/10.1061/(ASCE)0733-9410(1989)115:1(1)

Burland, J.B. (1973). Shaft friction of piles in clay – a simple fundamental approach. *Ground Engineering*, **6**(3): 30, 32, 37, 41, 42. Available from: < https://cdn.ca.emap.com/wp-content/uploads/sites/13/1973/05/1973-05_Pages_30_32_37_41-42.pdf > [25/03/2024].

Burland, J.B. & Cooke, R.W. (1974). The design of bored piles in stiff clays. *Ground Engineering*, **7**(4): 28–30, 33–35.

Burland, J.B. & Twine, D. (1988). The shaft friction of bored piles in terms of effective strength. In: *Deep Foundations on Bored and Auger Piles* (Van Impe (ed.)). Balkema, Rotterdam pp. 411–420.

Chen, Y.J. & Kulhawy, F.H. (1993). Undrained strength interrelationships among CIUC, UU, and UC tests. *Journal of Geotechnical Engineering (ASCE)*, **119**(11): 1732–1750. https://doi.org/10.1061/(ASCE)0733-9410(1993)119:11(1732)

Chen, Y.J. & Fang, Y.C. (2009). Critical evaluation of compression interpretation criteria for drilled shafts. *Journal of Geotechnical and Geoenvironmental Engineering (ASCE)*, **135**(8): 1056–1069. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000027

Chen, Y.J. & Kulhawy, F.H. (2002). Evaluation of drained axial capacity for drilled shafts. In *Deep Foundations 2002: An International Perspective on Theory, Design, Construction, and Performance (GSP 116)* (O'Neill, M.W. & Townsend, F.C. (eds.)), American Society of Civil Engineers, Reston, VA, pp. 1200–1214. https://doi.org/10.1061/40601(256)86

Chen, Y.J., Fang, Y.C. & Chu, T.H. (2009). Evaluation of compression tip capacity for drilled shafts. In: *Contemporary Topics in Deep Foundations (GSP 185)* (Iskander, M., Laefer, D.F. & Hussein, M.H. (eds.)), American Society of Civil Engineers, Reston, VA, pp. 63–70. https://doi.org/10.1061/41021(335)8

Chen, Y.J., Lin, W.Y., Topacio, A. & Phoon, K.K. (2021). Evaluation of interpretation criteria for drilled shafts with tip post-grouting. *Soils and Foundations*, **61**(5): 1354–1369. https://doi.org/10.1016/j.sandf.2021.08.001

Chen, Y.J., Phoon, K.K., Topacio, A. & Laveti, S. (2023). Uncertainty analysis for drilled shaft axial behavior using CYCU/DrilledShaft/143. *Soils and Foundations*, **63**(4): 101337. https://doi.org/10.1016/j.sandf.2023.101337

Chin, F.K. (1970). Estimation of the ultimate load of piles from tests not carried to failure. In: *Proceedings 2nd Southeast Asian Conference on Soil Engineering*, Singapore, pp. 81–92.

Ching, J. & Phoon, K.-K. (2014a). Transformations and correlations among some clay parameters – The global database. *Canadian Geotechnical Journal*, **51**(6): 663–685. https://doi.org/10.1139/cgj-2013-0262

Ching, J. & Phoon, K.-K. (2014b). Correlations among some clay parameters — The multivariate distribution. *Canadian Geotechnical Journal*, **51**(6): 686–704. https://doi.org/10.1139/cgj-2013-0353

Crispin, J.J. (2022). *Static and Dynamic Analysis of Piles in Inhomogeneous Soil*. Ph.D. thesis, University of Bristol, Bristol UK.

Crispin, J.J., Leahy, C.P. & Mylonakis, G. (2018). Winkler model for axially-loaded piles in inhomogeneous soil. *Géotechnique Letters*, **8**(4): 290–297. https://doi.org/10.1680/jgele.18.00062

Crispin, J.J., Vardanega, P.J. & Mylonakis, G. (2019). Prediction of pile settlement using simplified models. In: *Proceedings XVII European Conference on Soil Mechanics and Geotechnical Engineering – Reykjavík, Iceland, 1–6 of September 2019: Geotechnical Engineering, foundation of the future* (Sigursteinsson, H., Erlingsson, S. & Bessason, B. (eds.)), The Icelandic Geotechnical Society (IGS), Reykjavík, Iceland, 8pp. https://doi.org/10.32075/17ECSMGE-2019-0388

Crispin, J.J., Voyagaki, E. & Vardanega, P.J. (2022). Quantifying settlement reduction from two design codes for piles in London clay. In: *Proceedings of Twentieth International Conference on Soil Mechanics and Geotechnical Engineering (ICSMGE 2022), A Geotechnical Discovery Down Under, Sydney*, New South Wales, Australia, 1–5 May 2022 (Rahman, M.M. & Jaksa, M. (eds.)). Australian Geomechanics Society, Sydney, vol. 2, pp. 3217–3222. < https://www.issmge.org/uploads/publications/1/120/ICSMGE_2022-551.pdf > [17/04/2024]

Davisson, M.T. (1972). High-capacity piles. *Proceedings, Lecture Series on Innovations in Foundation Construction*, American Society of Civil Engineers, Illinois Section, Chicago, IL, pp. 81–112.

DeBeer, E.E. (1970). Experimental determination of the shape factors and the bearing capacity factors of sand. *Géotechnique*, **20**(4): 387–411. https://doi.org/10.1680/geot.1970.20.4.387

Fellenius, B.H. (1999). Bearing capacity of footings and piles – A delusion? – DFI Annual Meeting, October 14–16, 1999, Dearborn, Michigan – Summary. 17 pp. Available from: < https://www.fellenius.net/papers/219%20Delusion%20of%20Bearing%20Capacity.pdf > [17/04/2024].

FHWA (Federal Highway Administration). (1993). Axial load-displacement behavior of drilled shaft foundations in piedmont residuum. FHWA Reference No. 41-30-2175, Georgia Tech Research Corporation. Available from: < https://geosystems.ce.gatech.edu/Faculty/Mayne/papers/Axial%20Drilled%20Shafts%20in%20the%20Piedmont.pdf > [25/03/2024].

Fleming, W.G.K. (1992). A new method for single pile settlement prediction and analysis. *Géotechnique*, **42**(3): 411–425. https://doi.org/10.1680/geot.1992.42.3.411

Fleming, W.G.K., Weltman, A.J., Randolph, M.F. & Elson, W.K. (2009). *Piling Engineering*, 3rd Ed. Wiley, New York, NY.

Fuller, F.M. & Hoy, H.E. (1970). Pile load tests including quick-load test method, conventional methods, and interpretations. Highway Research Record, No. 333, pp. 74–86. Available from: < https://onlinepubs.trb.org/Onlinepubs/hrr/1970/333/333-008.pdf > [03/11/2024].

Galbraith, A.P. (2011). *Design & Performance of Deep Foundations in Ireland*. Ph.D. thesis, Trinity College Dublin, The University of Dublin, Dublin, Ireland.

Galbraith, A.P., Farrell, E.R. & Byrne, J.J. (2014). Uncertainty in pile resistance from static load tests database. *Proceedings of the Institution of Civil Engineers – Geotechnical Engineering*, **167**(5): 431–446. https://doi.org/10.1680/geng.12.00132

Gatrell, A.C., Bailey, T.C., Diggle, P.J. & Rowlingson, B.S. (1996). Spatial point pattern analysis and its application in geographical epidemiology. *Transactions of the Institute of British Geographers*, **21**(1): 256–274. https://doi.org/10.2307/622936

Gorbunov-Possadov, M.I. & Davydov, S.S. (1973). General report: 'Interaction of Soil Bases and Structures (Prediction of settlement, design of massive foundations based on the limiting state, design of flexible foundation beams and slabs). In: *Proceedings of the 8th International Conference on Soil Mechanics and Foundation Engineering*, August 1973, Moscow, vol. 3, pp. 47–92. Available from: < https://www.issmge.org/uploads/publications/1/37/1973_06_0002.pdf > [25/03/2024].

Han, J., Kamber, M. & Tung, A.K.H. (2001). Spatial clustering methods in data mining: A survey. 29 pp. Available from: < https://www.comp.nus.edu.sg/~atung/publication/gkdbk01.pdf > [25/03/2024].

Hirany, A. & Kulhawy, F.H. (1988). Conduct and interpretation of load tests on drilled shaft foundations: volume 1, detailed guidelines, *Report No. EPRI-EL-5915-Vol. 1*. Electric Power Research Institute, Palo Alto.

Hirany, A. & Kulhawy, F.H. (1989). Interpretation of load tests on drilled shafts Part 1: Axial compression. In: *Foundation Engineering: Current Principles and Practices (GSP 22)* (Kulhawy, F.H. (ed.)), American Society of Civil Engineers, New York, NY, pp. 1132–1149.

Hirany, A. & Kulhawy, F.H. (2002). On the interpretation of drilled foundation load test results. In: *Deep Foundations 2002: An International Perspective on Theory, Design, Construction, and Performance (GSP 116)* (O'Neill, M.W. & Townsend, F.C. (eds.)), American Society of Civil Engineers, Reston, VA, pp. 1018–1028. https://doi.org/10.1061/40601(256)71

Kim, H.S. & Kim, H.K. (2019). Optimizing site-specific geostatistics to improve geotechnical spatial information in Seoul, South Korea. *Arabian Journal of Geosciences*, **12**(4): [104]. https://doi.org/10.1007/s12517-018-4171-5

Kim, H.S., Sun, C.G. & Cho, H.I. (2019). Site-specific zonation of seismic site effects by optimization of the expert GIS-based geotechnical information system for western coastal urban areas in South Korea. *International Journal of Disaster Risk Science*, **10**(1): 117–133. https://doi.org/10.1007/s13753-018-0208-3

Kulhawy, F.H. (2010). Uncertainty, reliability, and foundation engineering: The 5th Peter Lumb Lecture. *HKIE Transactions*, **17**(3): 19–24. https://doi.org/10.1080/1023697X.2010.10668200

Kulhawy, F.H. & Mayne, P.W. (1990). Manual on estimating soil properties for foundation design. *Rep. No. EL-6800*, Electric Power Research Institute, Palo Alto, CA.

Laveti, S., Chen, Y.J., Phoon, K.K. & Topacio, A. (2024). Evaluation of model factors for barrette piles based on CYCU/Barrette/64. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering*, **10**(1): [04023056]. https://doi.org/10.1061/AJRUA6.RUENG-1147

Lemnitzer, A. & Favaretti, C. (2013). Find a Pile.com. http://www.findapile.com/ [25/03/2024].

London District Surveyors Association (LDSA). (2017). *Foundations no. 1: Guidance Notes for the Design of Straight Shafted Bored Piles in London Clay.* London District Surveyor's Association Publications, London UK.

Low, B.K. & Phoon, K.-K. (2017). Insights from reliability-based design in geotechnical engineering. In: *Geo-Risk 2017: Reliability-Based Design and Code Developments (GSP283)* (Huang, J., Fenton, G.A. & Zhang, L. & Griffiths, D.V. (eds.)). American Society of Civil Engineers, Reston, VA, pp. 459–470.

Marcos, M.C.M., Chen, Y.J. & Kulhawy, F.H. (2013). Evaluation of compression load test interpretation criteria for driven precast concrete pile capacity. *KSCE Journal of Civil Engineering*, **17**(5): 1008–1022. https://doi.org/10.1007/s12205-013-0262-8

Meyerhof, G.G. (1976). Bearing capacity and settlement of pile foundations (11th Terzaghi Lecture). *Journal of the Geotechnical Engineering Division (ASCE)*, **102**(3): 195–228. https://doi.org/10.1061/AJGEB6.0000243

O'Rourke, T.D. & Kulhawy, F.H. (1985). Observations on load tests on drilled shafts. In: *Drilled Piers and Caissons II* (Baker Jr., C.N. (ed.)), American Society of Civil Engineers, New York, NY, pp. 113–128.

Othman, M.M., Voyagaki, E., De Luca, F., Mylonakis, G., Vardanega, P.J. & Crispin, J.J. (2023). Preliminary study of ultimate load prediction using the DINGO database. In: *Smart Geotechnics for Smart Societies: Proceedings of the 17th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering (17ARC)*, Astana, Kazakhstan, 14–18 August 2023 (Zhussupbekov, A., Sarsembayeva, A. & Kaliakin, V.N. (eds.)), CRC Press/Balkema, Abingdon, Oxon, pp. 1487–1492. https://doi.org/10.1201/9781003299127-220

Paikowsky, S.G., Brigisson, B., McVay, M., Nguyen, T., Kuo, C., Baecher, G., Ayyub, B. *et al.* (2004). Load and Resistance Factor Design (LRFD) for Deep Foundations. *NCHRP Report 507*, National Cooperative Highway Research Program, Transportation Research Board, Washington, DC.

Parry, R.H.G. & Swain, C.W. (1977). A study of skin friction on piles in stiff clay. *Ground Engineering*, **10**(8): 33–37. Available from: < https://cdn.ca.emap.com/wp-content/uploads/sites/13/1977/11/1977-11_Pages_33-37.pdf > [25/03/2024].

Patel, D.C. (1989). *A Case Study of the Shaft Friction of Bored Piles in London Clay in Terms of Total and Effective Stresses.* M.Sc. thesis, Imperial College London, London, UK.

Patel, D. (1992). Interpretation of results of pile tests in London Clay. In: *Piling: European practice and worldwide trends.* Thomas Telford, London UK, pp. 100–110.

Phoon, K.-K. & Kulhawy, F.W. (1999a). Characterisation of geotechnical variability. *Canadian Geotechnical Journal*, **36**(4): 612–624. https://doi.org/10.1139/t99-038

Phoon, K.-K. & Kulhawy, F.W. (1999b). Evaluation of geotechnical property variability. *Canadian Geotechnical Journal*, **36**(4): 625–639. https://doi.org/10.1139/t99-039

Phoon, K.-K. & Tang, C. (2019a). Effect of extrapolation on interpreted capacity and model statistics of steel H-Piles. *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards*, **13**(4): 291–302. https://doi.org/10.1080/17499518.2019.1652920

Phoon, K.-K. & Tang, C. (2019b). Characterisation of geotechnical model uncertainty. *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards*, **13**(2): 101–130. https://doi.org/10.1080/17499518.2019.1585545

Phoon, K.-K., Ching, J. & Cao, Z. (2022). Unpacking data-centric geotechnics. *Underground Space*, **7**(6): 967–989. https://doi.org/10.1016/j.undsp.2022.04.001

Player, R.S.V. (2006). Geographic information system (GIS) use in geotechnical engineering. In: *GeoCongress 2006: Geotechnical Engineering in the Information Technology Age*. (DeGroot, D.J., DeJong, J.T., Frost, D. & Baise, L.G. (eds.)), American Society of Civil Engineers, Reston, VA, 6pp. https://doi.org/10.1061/40803(187)123

Polshin, D.E. & Tokar, R.A. (1957). Maximum, allowable nonuniform settlement of structures. In: *Proceedings 4th International Conference on Soil Mechanics and Foundation Engineering*, vol. 1, Butterworths Scientific Publishing, London, pp. 402–405. Available from: < https://www.issmge.org/uploads/publications/1/41/1957_01_0085.pdf > [25/03/2024].

Poulos, H.G., Carter, J.P. & Small, J.C. (2001). Foundations and retaining structures—Research and practice. In: *Proceedings 15th International Conference on Soil Mechanics and Geotechnical Engineering*, vol. 4, A.A. Balkema, Lisse, Netherlands, pp. 2527–2606. Available from: < https://www.issmge.org/uploads/publications/1/30/2001_04_0007.pdf > [25/03/2024].

Skempton, A.W. (1959). Cast-in-situ bored piles in London clay. *Géotechnique*, **9**(4): 153–173. https://doi.org/10.1680/geot.1959.9.4.153

Skempton, A.W. & MacDonald, D.H. (1956). The allowable settlement of buildings. *Proceedings of the Institution of Civil Engineers*, **5**(6): 727–768. https://doi.org/10.1680/ipeds.1956.12202

Terzaghi, K. & Peck, R.B. (1967). *Soil Mechanics in Engineering Practice*, 2nd Ed. Wiley, New York.

Tomlinson, M. & Woodward, J. (2008). *Pile Design and Construction Practice*, 5th Ed. Taylor & Francis, Abingdon, Oxon.

Topacio, A., Chen, Y.J., Phoon, K.K. & Tang, C. (2024). Evaluation of compression interpretation criteria for drilled shafts socketed into rocks. *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering*, **177**(1): 17–33. https://doi.org/10.1680/jgeen.21.00120

van der Veen, C. (1953). The bearing capacity of a pile. In: *Proceedings 3rd International Conference on Soil Mechanics and Foundation Engineering (Switzerland)*, vol. 2, pp. 84–90. Available from: < https://www.issmge.org/uploads/publications/1/42/1953_02_0017.pdf > [25/03/2024].

Vardanega, P.J. (2017). Databases to INterrogate Geotechnical Observations (DINGO). Grant reference EP/P020933/1, Engineering and Physical Sciences Research Council, Swindon, UK.

Vardanega, P.J. & Bolton, M.D. (2016). Design of geostructural systems. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering (ASCE)*, **2**(1): [04015017]. https://doi.org/10.1061/AJRUA6.0000849

Vardanega, P.J., Williamson, M. & Bolton, M.D. (2012). Bored pile design in stiff clay II: mechanisms and uncertainty. *Proceedings of the Institution of Civil Engineers – Geotechnical Engineering*, **165**(4): 233–246. https://doi.org/10.1680/geng.11.00063

Vardanega, P.J., Crispin, J., Gilder, C., Voyagaki, E., Shepheard, C.J. & Holcombe, E.A. (2018). Geodatabases to improve geotechnical design and modelling. *ce/papers*, **2**(2–3): 401–406. https://doi.org/10.1002/cepa.704

Vardanega, P.J., Crispin, J.J., Gilder, C.E.L., Voyagaki, E. & Ntassiou, K. (2021a). DINGO: A pile load test database. In: *Piling 2020: Proceedings of the Piling 2020 Conference* (Higgins, K.G., Ainsworth, Y., Toll, D.G. & Osman, A.S. (eds.)). ICE Publishing, London, pp. 229–234.

Vardanega, P.J., Voyagaki, E., Crispin, J., Gilder, C. & Ntassiou, K. (2019). The DINGO database, v1.0. University of Bristol, Bristol, UK, https://doi.org/10.5523/bris.3r14qbdhv648b2p83gjqby2fl8

Vardanega, P.J., Voyagaki, E., Crispin, J.J., Gilder, C.E.L. & Ntassiou, K. (2021b). The DINGO Database, v1.1. University of Bristol, Bristol, UK, https://doi.org/10.5523/bris.89r3npvewel2ea8ttb67ku4d

Vardanega, P.J., Othman, M.M., Voyagaki, E., Crispin, J., Gilder, C. & Ntassiou, K. (2024). The DINGO database, v1.2. University of Bristol, Bristol, UK, https://doi.org/10.5523/bris.1jraem68g7ara21p2oi6hv4z22

Voyagaki, E., Crispin, J., Gilder, C., Nowak, P., O'Riordan, N., Patel, D. & Vardanega, P.J. (2019). Analytical approaches to predict pile settlement in London clay. In: *Sustainability Issues for the Deep Foundations: Proceedings of the 2nd GeoMEast International Congress and Exhibition on Sustainable Civil Infrastructures, Egypt 2018 – The Official International Congress of the Soil-Structure Interaction Group in Egypt (SSIGE)* (El-Naggar, H., Abdel-Rahma, K., Fellenius, B. & Shehata, H. (eds.)). Sustainable Civil Infrastructures. Springer, Cham, pp. 162–180. https://doi.org/10.1007/978-3-030-01902-0_14

Voyagaki, E., Crispin, J., Gilder, C.E.L., Ntassiou, K., O'Riordan, N., Nowak, P., Sadek, T., Patel, D., Mylonakis, G. & Vardanega, P.J. (2022). The DINGO database of axial pile load tests for the UK: settlement prediction in fine-grained soils. *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards*, **16**(4): 640–661. https://doi.org/10.1080/17499518.2021.1971249

Wan-Mohamad, W.N.S. & Abdul-Ghani, A.N. (2011). The use of geographic information system (GIS) for geotechnical data processing and presentation. *Procedia Engineering*, **20**: 397–406. https://doi.org/10.1016/j.proeng.2011.11.182

Yang, Z., Jardine, R., Guo, W. & Chow, F. (2015). A new and openly accessible database of tests on piles driven in sands. *Géotechnique Letters*, **5**(1): 12–20. https://doi.org/10.1680/geolett.14.00075