Not so B.E.S.T. Class A predictions of pile behaviour

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ABSTRACT. Class A predictions of axial response to loading of four single piles are presented. The Author's approach to develop his predictions is described, and an attempt is made to explain the success or otherwise of the prediction.

1. INTRODUCTION

In conjunction with the 3rd Bolivian International Conference on Deep Foundations, held in Santa Cruz in 2017, a pile prediction event was organized. This followed a comprehensive site investigation carried out at the "*Bolivian Experimental Site for Testing*" (B.E.S.T.). The prediction event included axial static tests of No. 4 single piles: one pile (Pile A3) was bored with slurry, one (Pile B2) was constructed with a continuous flight auger (CFA), and two (Piles C2 and E1) were constructed by full displacement equipment (FDP). In addition, Pile E1 was supplied with an expanded base (EB) at the pile toe, while the others were straight-shaft piles. Piles A3, B2, and C2 were tested in head-down tests while Pile E1 was tested by means of a bidirectional cell.

A few months before the loading tests, geotechnical engineers throughout the world were invited to submit Class A predictions of the load-movement curves to be measured in the tests and to assess the pile capacity from these curves. The submission also included the profile of axial load along the piles at the so-assessed capacities. In this paper, the geotechnical assumptions and analysis method adopted by the Author to develop his predictions are described, and the comparison between predicted and measured response is discussed.

2. ANALYSIS METHOD

The load-movement response and axial load distribution of the piles have been analyzed using the commercial software Repute (Basile 2015, Bond and Basile 2017). Repute computes the response of single piles and pile groups under general loading conditions (i.e. vertical, horizontal, and moment) by means of a complete 3D boundary element (BEM) formulation (i.e. the reciprocal influence of all the pile elements within the group is considered). Soil nonlinearity is modelled by employing a hyperbolic continuum-based relationship which makes use of the initial value of soil Young's modulus (E_s).

In all the Class A predictions below, the initial value of E_s has been derived from correlation with the shear wave velocity (V_s) measurements from SDMT. It is noted that the derivation of initial E_s from shear wave velocity measurements is generally expected to provide upper bound values of the soil modulus derived from a pile loading test. However, the above choice has been made on the basis that, for the purpose of a pile prediction event, use of a 'best estimate' value of E_s can be justifiable (rather than a more conservative, i.e. lower, 'design' value of E_s). In addition, it has been assumed that the initial values of E_s are unaffected by construction effects. This is based on the consideration that construction effects mainly influence pile capacity, while the initial pile stiffness depends primarily on the initial values of E_s (e.g. Mandolini 2001).

All pile-heads are assumed at ground level, and the pile Young's modulus is taken as 30GPa.

3. PILE A3

Pile A3 is a bored pile with a length of 9.5m and a diameter of 620mm. In making his predictions using Repute, the Author derived the required parameters as follows (as summarized in Table 1):

a) The soil stratigraphy is mainly derived from CPTU-A3 results according to the charts proposed by Robertson and Cabal (2014). The CPT values of q_t, f_s, and R_f assigned to each soil layer are taken as equal to the average values calculated from the raw data provided.

b) The pile ultimate shaft (f_s) and base (f_b) resistance at each layer is determined using a direct correlation with CPTU-A3 results, i.e. the LCPC Method of Bustamante and Gianeselli (1982), as recommended by Robertson and Cabal (2014). Specifically, the f_s value is correlated to q_c (cone tip resistance) via a friction coefficient (α), while the f_b value is correlated to q_c via a bearing capacity factor (k_c).

c) The initial value of soil Young's modulus (E_s) required by Repute is derived from correlation with the shear wave velocity (V_s) measurements from SDMT-A3.

TABLE 1. Geotechnical parameters adopted in Repute analysis for Pile A3

Layer	Depth (m)	E_s (MPa)	m_{Es} (MPa/m)	ν_s	f_s (kPa)	f_b (MPa)
Sand mixtures	0.0-2.0	152	0	0.2	35	-
Clay	2.0-6.3	160	0	0.5	35	-
Sand	6.3-9.5	286	-32	0.2	80	-
Values at pile base	9.5	181	84	0.2	-	3.45

Note: E_s=initial Young's modulus (at top of layer), m_{Es}=rate of increase of initial Young's modulus, ν_s=Poisson's ratio, f_s=ultimate shaft resistance, f_b=ultimate base resistance

The predicted pile-head load-settlement curve is reported in Figure 1a, together with the measured response. Figure 1b shows the predicted profile of axial load for a pile-head load equal to the assessed value of capacity, i.e. 1795 kN. This value has been derived from the predicted load-settlement curve as the pile-head load that generates a pile-head settlement equal to 10% of the pile diameter (as suggested by Poulos 2016).

A considerable lack of agreement between predicted and measured load-settlement response is observed. The unavailability (at the time of writing this paper) of the detailed load distribution measured in the field precludes an optimal investigation of this discrepancy. However, based on visual inspection of the curves' shape (predicted and measured), it appears that the prediction has largely overestimated the pile shaft capacity (f_s). This is confirmed by a post-prediction Repute back-analysis which indicates that, by using only a fraction (i.e. 25%) of the initially assumed f_s, the predicted load-settlement curve becomes very similar to the measured one. Some possible explanations for this significant discrepancy in shaft capacity may be 1) the limited reliability of CPT correlations for soils with significant microstructure (possibly due to cementation), as discussed by Robertson (2016), and/or 2) an unexpectedly large reduction of actual shaft capacity due to construction effects (i.e. drilling causing extra loosening of the sand and/or softening of the clay).

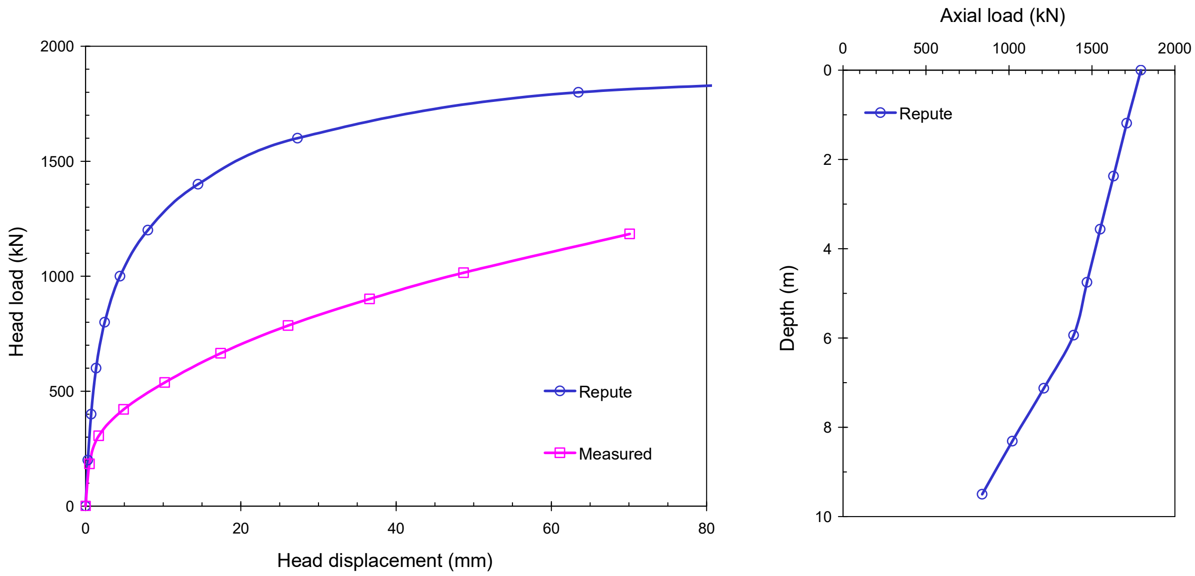

Figure 1. Pile A3: (a) Load-settlement response: (2) Axial load profile

4. PILE B2

Pile B2 is a continuous flight auger (CFA) pile, with a length of 9.5m and a diameter of 450mm. The following parameters have been assumed in the predictions using Repute, as summarized in Table 2:

a) The soil stratigraphy is mainly derived from CPTU-B2 results according to the charts proposed by Robertson and Cabal (2014). The CPT values of q_t, f_s, and R_f assigned to each soil layer are taken as equal to the average values calculated from the raw data provided.

b) The pile ultimate shaft (f_s) and base (f_b) resistance at each layer is determined using a direct correlation with CPTU-B2 results, i.e. the LCPC Method of Bustamante and Gianeselli (1982).

c) The initial value of soil Young's modulus (E_s) is derived from correlation with the shear wave velocity (V_s) measurements from SDMT-A3.

TABLE 2. Geotechnical parameters adopted in Repute analysis for Pile B2

Layer	Depth (m)	E_s (MPa)	m_{Es} (MPa/m)	ν_s	f_s (kPa)	f_b (MPa)
Sand mixtures	0.0-2.0	149	0	0.2	35	-
Sand mixtures	2.0-6.3	120	0	0.2	33	-
Sand	6.3-9.5	272	-31	0.2	57	-
Values at pile base	9.5	166	77	0.2	-	1.97

Note: E_s=initial Young's modulus (at top of layer), m_{Es}=rate of increase of initial Young's modulus, ν_s=Poisson's ratio, f_s=ultimate shaft resistance, f_b=ultimate base resistance

The predicted pile-head load-settlement curve is reported in Figure 2a, together with the measured response. Figure 2b shows the predicted profile of axial load for a pile-head load equal to the assessed value of capacity of 835 kN (i.e. the load generating a pile-head settlement equal to 10% of the pile diameter).

A good agreement between the predicted and measured initial pile stiffness is observed, thus confirming the suitability of employing the initial soil modulus (E_s) in Repute analyses. However, the actual pile capacity (herein intended as the load corresponding to the horizontal asymptote of the load-settlement curve) is underestimated by about 40%, thereby indicating that the empirical correlations with CPT results adopted by the Author were unable to fully capture the more complex mechanisms of behaviour (this may partially be due to the limited reliability of CPT correlations as discussed earlier). The larger actual resistance may also partially be attributed to pressure-grouting, a circumstance which was not known to the predictors when submitting the prediction.

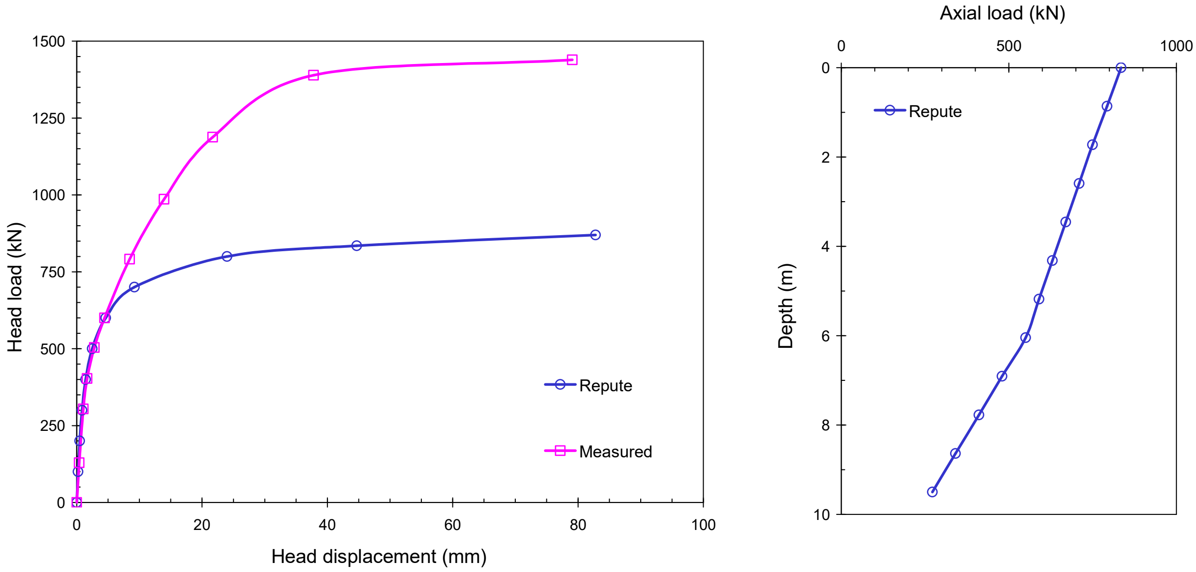

Figure 2. Pile B2: (a) Load-settlement response: (2) Axial load profile

5. PILE C2

Pile C2 is a full-displacement pile (FDP), with a length of 9.5m and a diameter of 450mm. The following parameters have been adopted in Repute calculations, as summarized in Table 3:

a) The soil stratigraphy is mainly derived from CPTU-C1 results according to the charts proposed by Robertson and Cabal (2014). The CPT values of q_t, f_s, and R_f assigned to each soil layer are taken as equal to the average values calculated from the raw data provided.

b) The pile ultimate shaft (f_s) and base (f_b) resistance at each layer is determined using a direct correlation with CPTU-C1 results, specifically the method proposed by Bustamante and Gianeselli (1998) for screw piles.

c) The initial value of soil Young's modulus (E_s) is derived from correlation with the shear wave velocity (V_s) measurements from SDMT-F1.

TABLE 3. Geotechnical parameters adopted in Repute analysis for Pile C2

Layer	Depth (m)	E_s (MPa)	m_{Es} (MPa/m)	ν_s	f_s (kPa)	f_b (MPa)
Sand mixtures	0.0-6.3	130	0	0.2	13	-
Sand	6.3-9.5	305	-39	0.2	91	-
Values at pile base	9.5	175	81	0.2	-	4.11

Note: E_s=initial Young's modulus (at top of layer), m_{Es}=rate of increase of initial Young's modulus, ν_s=Poisson's ratio, f_s=ultimate shaft resistance, f_b=ultimate base resistance

The predicted and measured pile-head load-settlement curves are shown in Figure 3a, while Figure 3b reports the predicted axial load profile for a pile-head load equal to the assessed value of capacity of 1039 kN (i.e. the load generating a pile-head settlement equal to 10% of the pile diameter).

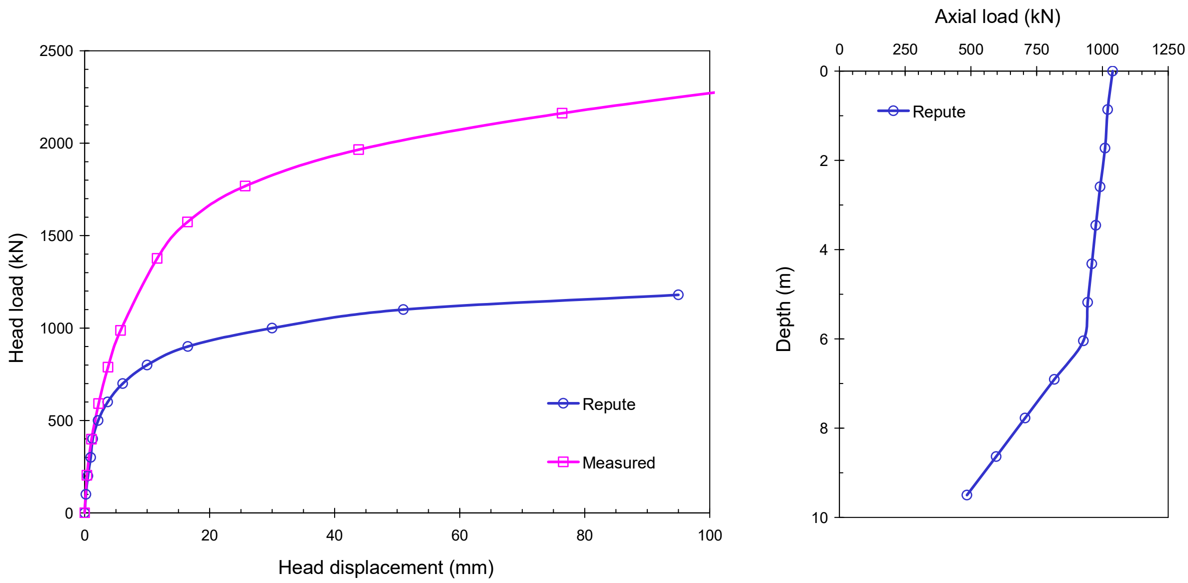

Figure 3. Pile C2: (a) Load-settlement response: (2) Axial load profile

A fair agreement between the predicted and measured initial pile stiffness is observed, thereby confirming the suitability of employing the initial soil modulus (E_s) in calculations. However, the actual pile capacity (herein intended as the load corresponding to the horizontal asymptote of the load-settlement curve) is underestimated by about 45%. Such a significant discrepancy was also observed in the predictions submitted by most participants and confirms the general difficulty in estimating pile capacity, an issue which becomes even more prominent in the case of screw piles. Indeed, the installation of screw piles induces complex changes to the soil state (holding a major influence on pile capacity) which are highly dependant on the specific installation procedure and drilling tool employed. Nevertheless, presently available design methods are too general and further research is needed in order to develop design procedures which are more specific to the many different installation methods existing in industry (e.g. Atlas, De Waal, Fundex, Olivier, Omega, APGD, SVV, Franki VB, Bauer FDP piles, etc). There is also a need for design methods to be more discriminating, going beyond just textbook soils (i.e. sand and clay).

Indeed, currently available design methods (e.g. the method by Bustamante and Gianeselli 1998, the "Belgian" method described by Huybrechts et al. 2016, the method by NeSmith 2002) are mainly related to the specific installation method and to the site conditions for which they were developed. As a consequence, these methods imply a certain degree of conservativism to account for more general installation methods and soil conditions. For example, the method by Bustamante and Gianeselli (1998) adopted by the Author for his prediction of pile capacity (i.e. f_s and f_b) was mainly derived on the basis of 24 loading tests carried out in the 1980s on the pioneer Atlas piles which are short-displacement auger systems. However, the FDP pile at the B.E.S.T. site is a modern long-displacement auger system and is therefore expected to change the soil state differently, thereby leading to different pile capacities as compared to Atlas piles.

A confirmation of the inherent conservativism of the method by Bustamante and Gianeselli (1998) can be derived from Table 4 which compares the pile shaft and base capacities computed by the Author using three different methods: 1) the LCPC Method by Bustamante and Gianeselli (1982) for bored piles, 2) the method by Bustamante and Gianeselli (1998) for screw piles, and 3) the Belgian method for screw piles. It is observed that the shaft capacity predicted by Method 1) (which is intended for standard bored piles) is actually greater than that computed using Method 2) which was specifically developed for screw piles. This appears to be an inconsistency given that FDP screw piles are expected to develop a greater shaft capacity than bored piles. As an indication, on the basis of several loading tests in soil conditions similar to the B.E.S.T. site, Terceros and Fellenius (2014) report that the FDP pile develops at least twice the shaft capacity of a standard bored pile. This feature confirms another important aspect of pile design, i.e. the issue of experience from prior similar work at a site and, in particular, past records of a contractor for the specific construction method.

TABLE 4. Comparison of capacities for Pile C2

Method	Shaft capacity (kN)	Base capacity (kN)	Total capacity (kN)
(1) LCPC method by Bustamante and Gianeselli 1982 (bored piles)	581	418	999
(2) Bustamante and Gianeselli 1998 (screw piles)	527	653	1180
(3) Belgian method (screw piles)	585	733	1318

6. PILE E1

Pile E1 is a full-displacement pile (FDP) equipped with an Expander Body (EB), having a length of 9.5m and a shaft diameter of 300mm. The base diameter is also assumed to be equal to 300mm (after inflation of the EB). The following parameters have been assumed in Repute calculations, as summarized in Table 5:

a) The soil stratigraphy is mainly derived from CPTU-E1 results according to the charts proposed by Robertson and Cabal (2014). The CPT values of q_t, f_s, and R_f assigned to each soil layer are taken as equal to the average values calculated from the raw data provided.

b) The pile ultimate resistance is determined using a direct correlation with CPTU-E1 results, specifically the ultimate shaft (f_s) resistance from the method by Bustamante and Gianeselli (1998) for screw piles, and the ultimate base (f_b) resistance from the method proposed by Massarsch and Wetterling (1993) for EB piles.

c) The initial value of E_s is derived from correlation with V_s measurements from SDMT-G1.

TABLE 5. Geotechnical parameters adopted in Repute analysis for Pile E1

Layer	Depth (m)	E_s (MPa)	m_{Es} (MPa/m)	ν_s	f_s (kPa)	f_b (MPa)
Sand mixtures	0.0-2.0	154	0	0.2	70	-
Silt mixtures	2.0-6.3	181	0	0.5	43	-
Sand	6.3-9.5	303	-39	0.2	92	-
Values at pile base	9.5	180	81	0.2	-	3.58

Note: E_s=initial Young's modulus (at top of layer), m_{Es}=rate of increase of initial Young's modulus, ν_s=Poisson's ratio, f_s=ultimate shaft resistance, f_b=ultimate base resistance

The predicted and measured load-movement curves are shown in Figure 4. As for Repute predictions, the (base) downward response of the bidirectional (BD) cell is simulated using the standard soil profile reported in Table 5. In order to compute the (shaft) upward load-movement response, the Repute analysis is performed using a 'mirror' soil profile (in order to account for the fact that the shaft upward response measured by the BD test engages the deeper located stiffer soils first and the more shallow weaker soils last), and assuming a negligible base diameter (in order to ignore the base contribution). In addition, the equivalent head-down load-movement response predicted by Repute is also reported in Figure 4.

Unfortunately, during the test, the telltale measuring the downward movement of the bidirectional cell failed and therefore only the (shaft) upward movement was measured and can be compared with Repute predictions. The comparison shows a general overestimate of movements while a good agreement between predicted and measured shaft capacity is achieved.

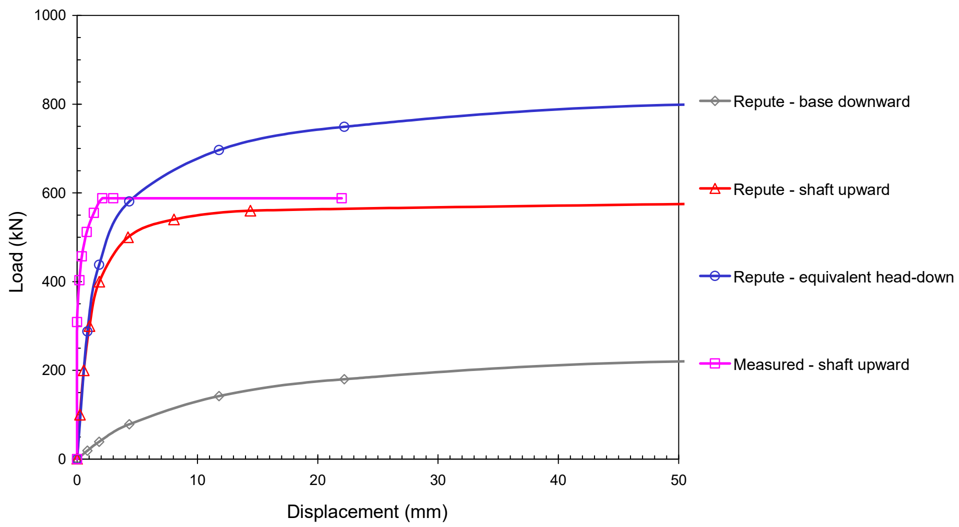

Figure 4. Load-movement response of Pile E1

7. CONCLUSIONS

The paper presents a comparison between Class A predictions and full-scale axial loading tests on four single piles constructed using different methods (i.e. bored, CFA, FDP, and FDP with Expander Body). The geotechnical assumptions and analysis method adopted by the Author to develop his predictions are described.

It is found that, with the exception of Pile A3, all predictions are on the conservative side (from a design viewpoint). In particular, the predicted pile-head settlements generally show a reasonable agreement with the measured response within the usual serviceability range (say below 10mm); this agreement also attests the suitability of adopting the initial soil modulus (E_s) in Repute calculations. However, some significant discrepancies in predicted and measured pile capacities are observed, thus confirming a critical (but often neglected) aspect of pile design, i.e. predicting pile capacity is usually more difficult and less reliable than predicting deformations.

8. REFERENCES

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