THE USE OF THE EXPANDER BODY WITH CAST IN SITU PILES IN SEDIMENTARY SANDY SOILS

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ABSTRACT

The Expander Body (EB) technology has been used successfully to increase the pile base capacity of bored piles in loose to medium dense soil. The most important advantage of the EB system is the unique possibility to monitor the pile base expansion process, which provides important information regarding soil strength and soil stiffness. This information, obtained for each installed pile, can be used to detect any deficiencies and to determine the actual shape and pile base area. The expansion pressure can be used to design the pile base capacity.

The Expander Body system has been recently improved by incorporating the possibility of post-grouting of the soil below the expanded pile base. This improvement measure provides additional strength and stiffness to the pile base and reduces pile settlement.

The shaft bearing capacity of bored piles can be increased by using a soil displacement auger, which avoids soil decompression and increases lateral soil stress. This paper describes the principle of the EB system. During the past 20 years a large number of EB piles have been installed in Bolivia and elsewhere, providing a sound database. Results from field loading tests are presented. A comprehensive study of test piles with and without EB base has been carried out which demonstrates the improvement effects that can be achieved by the EB pile system and the combination with the displacement auger pile method. A design concept for the EB pile system with the full displacement auger pile is presented. A high degree of quality control can be achieved by monitoring the entire pile installation process, including the displacement pile and the Expander Body.

1. Introduction

In many regions of South America, soil deposits consist often of predominantly loose to medium dense sands and silts, often with high ground water table. In the Santa Cruz area in central Bolivia, such soils are frequently quaternary sediments, deposited by the river Piray. The city of Santa Cruz is located at the right shore of the river.

The most common deep foundation method during the last 30 years has been cast in situ piles, augered and concreted under support of bentonite slurry. The designs of the piles has been made based on SPT test without good standard quality control of performance. Because of limitations of the quality in the geotechnical data an of installation method and drilling equipment capacity as well as lack of quality control, such piles work basically by shaft friction. Although the construction process and used material are cheap, the final product has variable and limited load carrying capacity. However, the most serious deficiency is that actually achieved pile capacity and pile movement can be erratic and difficult to predict, leading to uncertainties with regard to actual foundation performance.

In order to eliminate uncertainty with respect to pile quality and to increase pile capacity, a new foundation concept was introduce, which combines the auger pile method with an expanded, pressure-grouted base, the Expander Body (EB). The 1 to 2 m long EB consists of a folded steel tube, which can be expanded from 0.12 m to a diameter of approximately 0.6 m. Pressure and volume of grout during inflation of the Expander Body are continuously recorded. Due to the controlled expansion process, horizontal soil stress, soil strength and stiffness of the soil around the EB can be improved significantly. In fact, the EB is a large-scale Pressuremeter, which provides information about stressstrain characteristics of the soil adjacent to the pile toe. This information is used to verify that the anticipated toe bearing capacity has been achieved. During inflation of the EB and with increasing diameter, the EB shortens in length. Therefore, after inflation of the Expander Body, the soil below the EB base can be post-grouted during a second, controlled grouting phase. This process further increases the stiffness of the soil and thus the toe bearing capacity of the pile. In this way, the load carrying capacity of each pile can be tested and verified. The innovative combination of the Expander Body system with the traditional auger pile method has resulted in the increase of service load capacity, cost reductions and safety of the foundations. An additional benefit is the unprecedented level of quality control, which has is important for the designer when offering an economic pile foundation solution. Extensive experience has been accumulated from different parts of the world regarding the practical application of the EB system for different types of piles and as soil anchors, (Bergren et al., 1988, Broms 1985, Broms et al 1985, Massarsch and Wetterling, 1993, Massarsch, 1994, Terceros Herrera, Massarsch and Weterling 1995, Terceros Herrera, 2008).

In loose to medium-dense and silty sands, displacement auger piles are an efficient pile foundation method, which increases in particular the shaft bearing capacity. Combining displacement auger piles with the Expander Body concept has resulted in a pile with high shaft capacity as well as high toe bearing capacity. This solution is particularly suitable for high capacity piles in sandy and silty soils and offers excellent bearing capacity. Particular emphasis in this paper is on the combination of the EB system with the full displacement auger pile system, where during the installation of the pile shaft, the soil is compressed and moved laterally, thereby increasing horizontal soil stress and stiffness.

The paper presents the monitoring of all phases of the pile installation process. Particular emphasis is on the determination of pile capacity based on monitoring parameters during installation of the displacement auger pile and EB inflation. The efficiency of the pile system has been documented by load tests. Several case histories are used to illustrate the application of this novel foundation system.

2. Development of the Expander Body System

The Expander Body (EB) concept was developed by the Swedish engineer Bo Skogberg during the 1980's and its initial application was the "Swellex" rock anchor. Thereafter, the Expander Body soil anchor was developed. It consists of a folded steel tube with a square cross section. By injection of grout the EB can be inflated, thereby creating a water-tight steel balloon of high strength. Gradually, new applications of the EB system were developed, such as for soil anchors, driven, vibrated and bored piles, Broms and Nord (1985). Extensive field tests were carried out to verify the bearing capacity of piles with EB base, on which the Swedish Commission on Pile Research published design and installation recommendations and monitoring procedures (Berggren et al., 1988). The most common application of the EB system, at the beginning, was for underpinning of structures and as soil anchors. Experience from a large number of EB applications has been documented in the geotechnical literature, (Broms, 1985, Massarsch and Wetterling, 1993, Massarsch, 1994, Terceros et al. 1995). The EB pile system is also included in Eurocode CEN 2000 "*Execution of special geotechnical work - Displacement piles*". During the past decade, the design and construction of the EB was further improved in Bolivia. The present EB system consists of a folded steel balloon of cylindrical shape, instead of the initial square cross section. Also, a new post grouting system has been implemented, which makes it possible to inject grout through the center of the inflated body into the soil below. This feature can increase significantly the performance of the EB pile.

Since the start of its introduction to South America, the EB system was used as exclusively in combination with piles. The performance of the EB system has been very successful. In the Santa Cruz region, more than 10,000 EB piles have been installed for a variety of projects, from high-rise buildings and hotels to industries, bridges and silos.

As the EB cross section before expansion is very small, installation of EB piles can be by conventional drilling, driving, jacking or vibration methods or by placement in a preformed hole.

3. How the Expander Body Works

The EB can be manufactured in different sizes. The geometry of different EB types after inflation are shown in Table 1. The EB diameter prior to expansion is approximately 120 mm and increases during the inflation process to between 600 to 800 mm, resulting in an increase of the diameter by about 500 % 660%. This increase in EB diameter is directly related to the injected grout volume. Lateral expansion is one of the main reasons for the high ground improvement effect, which takes place in the soil adjacent to the EB.

Table 1. Geometric parameters of different EB sizes after expansion, Expander Body Incotec (EBI).

Type	**Length1)**	**Length2)**	**Diameter**	**Toe Area**	**Skin Area**	**Volume**
	m	m	m	m^2	m^2	m^3
EB 610	1.0	0.76	0.6	0.28	1.43	0.21
EB 612	1.2	0.96	0.6	0.28	1.83	0.27
EB 615	1.5	1.26	0.6	0.28	2.38	0.36
EB 815	1.5	1.26	0.6	0.50	3.17	0.63
EB 820	2.0	1.76	0.8	0.50	4.42	0.88

1) Prior to expansion 2) After expansion

1)

The expansion steps of an EB 600 are shown in Figure 1. The grouting process of the liquid-tight EB takes place under controlled conditions without leakage. Thus it is possible to measure the gradual increase in EB volume and the required pressure. All relevant parameters, such as flow rate, pressure and volume of grout are recorded by a computer-controlled data acquisition system, which is an integral part of quality control. The applied grouting pressure reflects the soil resistance during expansion of the EB and is a measure of soil stiffness and soil strength. The grouting record is obtained for each pile and offers in this way a unique method of quality control.

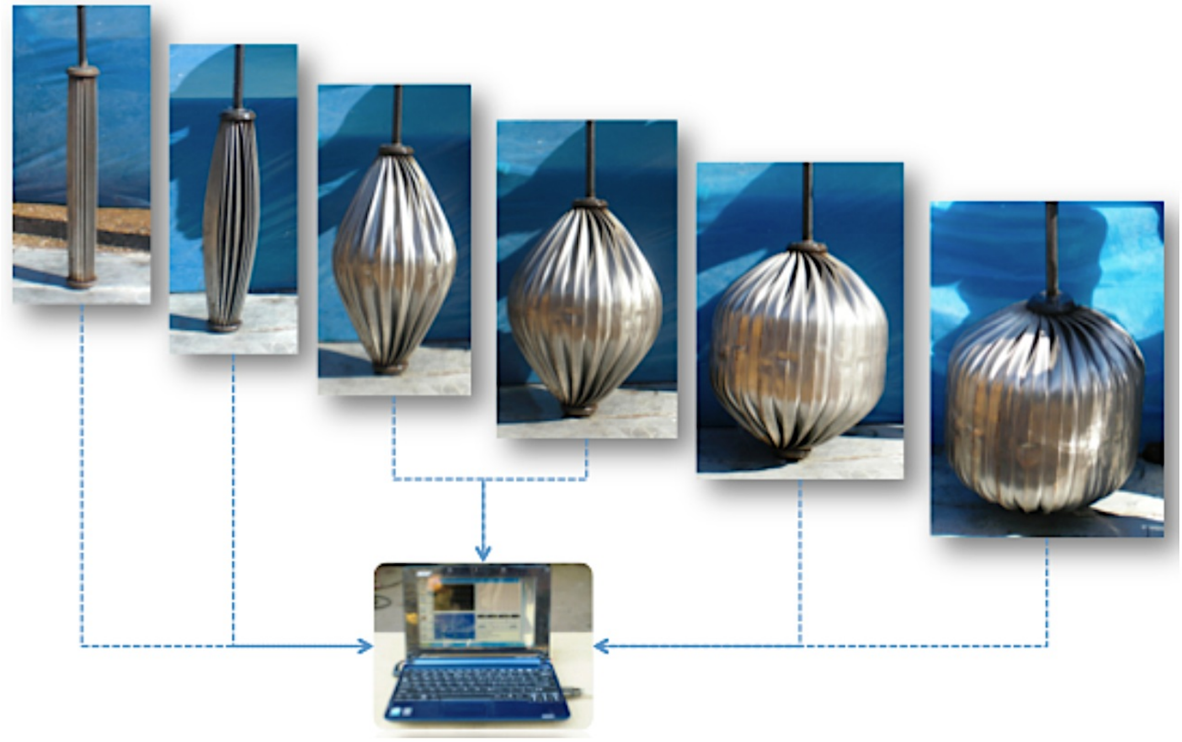


Fig. 1. Expansion steps of the EB Incotec (,) with data acquisition system.

The injection of the EB can be done right after concreting or later, at an appropriate time depending on the hardening progress of the concrete. In one case, EB:s have been injected up to four months after installation of the pile with no difference in bearing capacity of the other piles at the same project. As the concrete layer surrounding the EB is thin, and tension forces are induced during expansion, the initial fracturing of the concrete mantle requires only low pressures. During expansion of the EB, expansion forces the concrete shell surrounding the EB into the soil.

It is possible that leakage of grout occurs before the full EB diameter has been reached. The typical reasons to have leakage before the full volume has been reached are: a) damages to EB during installation (punctures) b) excessively stiff soils that do not allow full expansion. As the injection process is registered it is possible to determine the actual EB volume from the calibration curve, which exists for each EB model. Figure 2 shows a typical calibration curve of volume vs. diameter. In this way, knowing the pressure and the volume is possible to calculate de effective cross section of the EB, and to take into account a reduced EB diameter in the design.

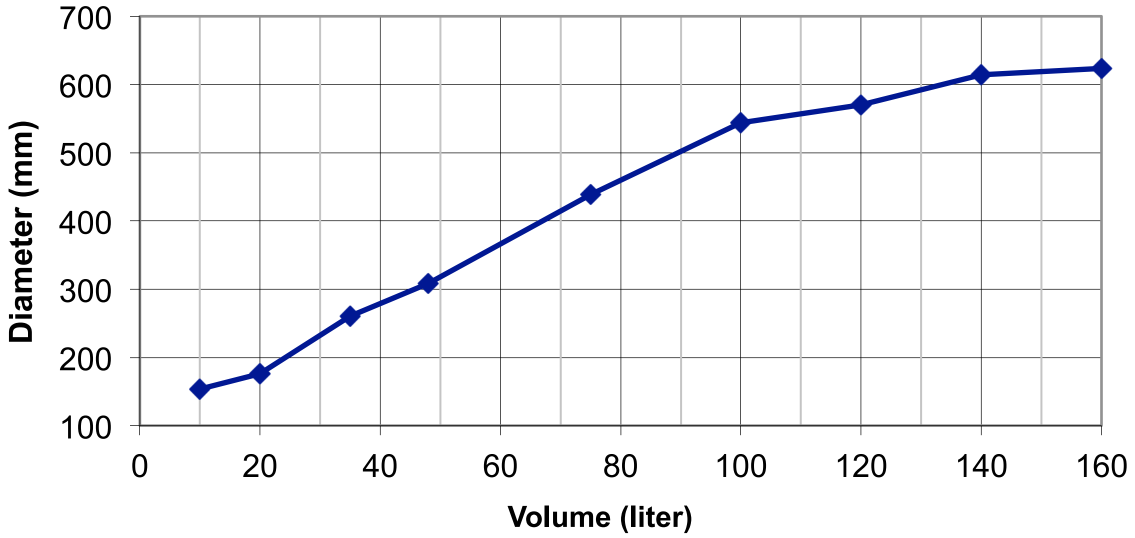


Fig. 2. Calibration curve of volume vs. diameter for EBI 600.

Figure 3 shows the grout pressure vs. grout volume as recorded during expansion of the EB. As the EB functions similar to a Pressuremeter, monitoring of the EB inflation process is in fact an in situ soil test. The initial part of the pressure-volume curve provides information regarding the initial soil conditions prior to EB inflation. The shape of the curve depends on the geotechnical conditions (in situ stress, strength and stiffness) of the soil. Based on a large number of projects, extensive experience has been accumulated, which makes it possible to understand the geotechnical conditions at the pile base.

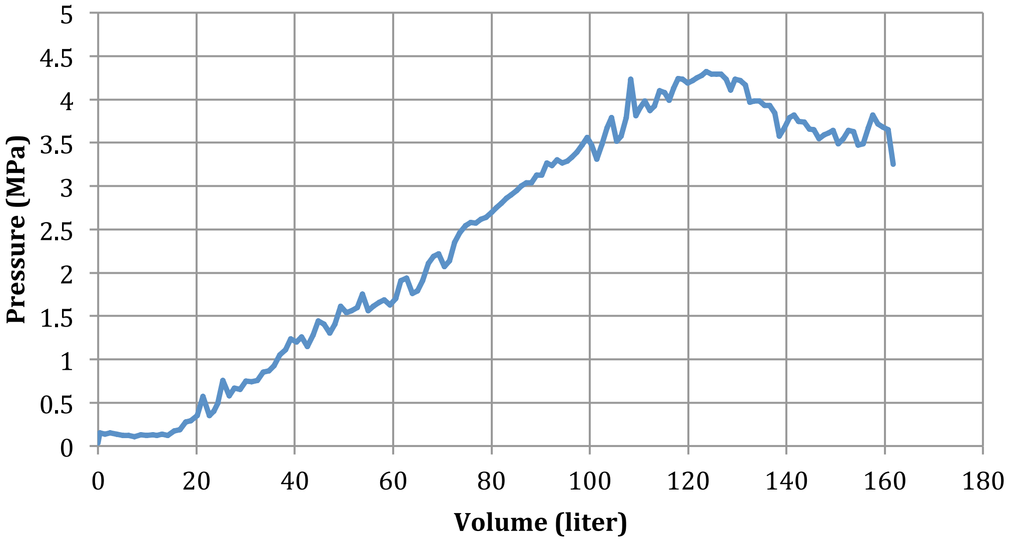


Fig. 3 – Typical grouting curve in medium dense sandy soil with maximum grout pressure over 4 MPa.

In loose granular soil, the shape of the grouting curve looks differently. Figure 4 shows initially a slow increase in grout pressure, indicating a low soil resistance. After injection of a volume of approximately 130 liter, the soil surrounding the EB has been compacted and starts to build up passive earth pressure.

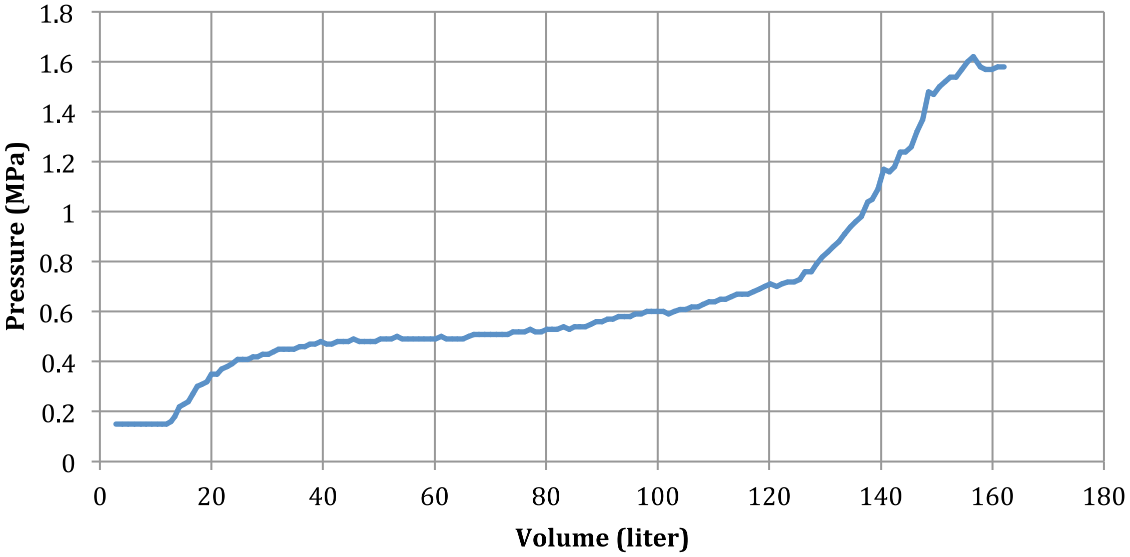


Fig. 4. Typical grouting curve in loose sandy soil. Note that the maximum pressure is significantly lower than in a medium dense sand, cf. Fig. 3.

Comparison of Figure 3 and 4 clearly shows the different behavior of EB inflation in loose and medium dense soil, which is reflected by the shape of the pressure curve and the maximum grout pressure.

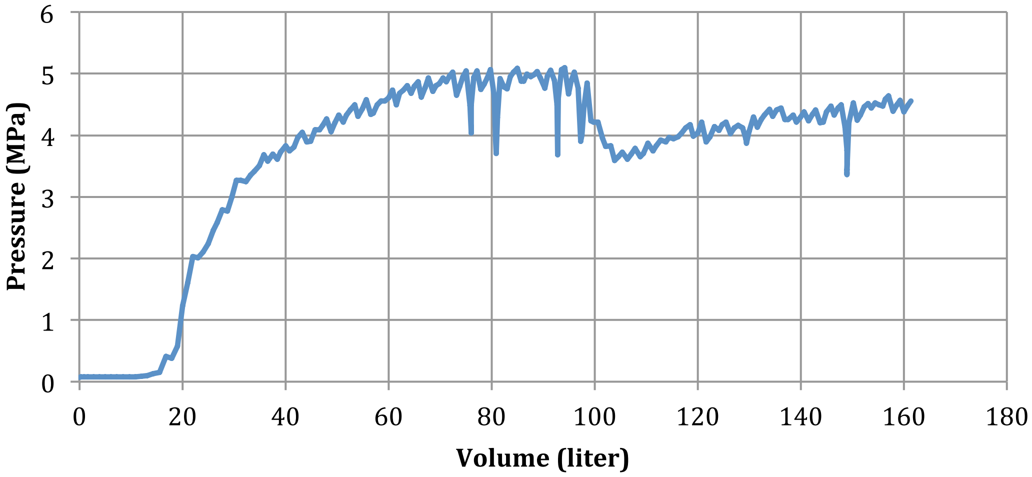
An important advantage of the EB monitoring system is that the actual condition of each EB pile base can be monitored and evaluated. Any leakage of the EB due to damage during installation or inflation can be noted from the grout pressure – volume curve. The maximum pressure during EB inflation does not necessarily correspond to the final expansion pressure. This is illustrated by two cases shown in

Fig. 5. Figure 5a) shows a grouting curve where - after having reached the peak – the grout pressure drops slightly and then stabilizes at a slightly lower value. This is an indication that some grout leakage has occurred but that this effect does not affect pile base capacity. Figure 5b shows a sudden drop in grout pressure, indicating leakage of grout pressure. During continued inflation, the pressure recovers only slightly. This type of grout pressure curve is generally considered unreliable and suggests a reduced pile toe capacity.

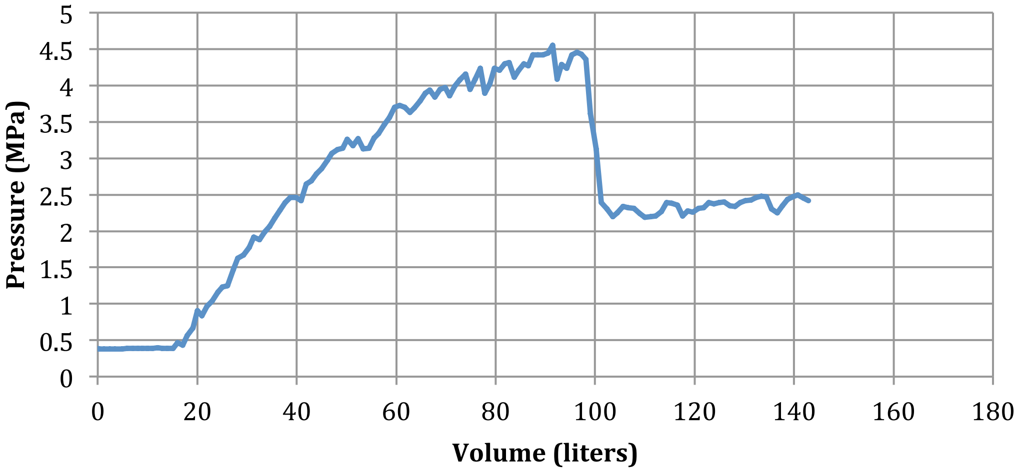
In cases the full EB volume is not achieved, it is possible to estimate the actual toe diameter from a calibration graphic showing grout volume vs. diameter, cf. Fig. 2. In the case of the Fig. 5a, the volume used for calculation of pile toe capacity was 99 liters at a pressure of 48.5 bar (4.85 MPa). In the case shown in Fig. 5b, the volume used for calculation of pile capacity was 77 liter at a pressure of 40.5 bar (4.05 MPa).

In many cases the maximum grout pressure is achieved before the full EB volume has been reached. In such a case, the EB diameter is smaller than the maximum value given in Table 1. In such a case, it is still possible to estimate the actual pile base diameter, which is used for calculating the toe capacity.

The possibility to monitor the inflation process is an important part of the EB pile system. No other known pile system can provide information regarding the in-situ strength and stiffness properties at the pile toe. Any deviations from the design assumptions can be taken into account by adjusting the actually achieved pile base capacity.



a) Temporary leakage and gradual recovery of grout pressure – assumed EB volume: 97 l



b) Permanent leakage and unreliable recovery of grout pressure – assumed EB volume: 96 l

Fig. 5. Two examples of anomalies of grout pressure during EB expansion, indicating reduced pile toe capacity.

4. Post-grouting Below Pile Base – EBI Pile System

During the inflation, the EB diameter increases but at the same time, its length is reduced. The risk of soil decompression below the pile toe due to the shortening of the EB is in most cases not significant as lateral displacement pushes the soil downward and compensates for the shortening of the EB. However, it is desirable to increase the stiffness and strength of the soil below the pile base in order to reduce pile settlement. An important new development is the possibility to grout the soil below the pile base after EB expansion. Thereby, the strength and stiffness of the soil below the EB can be further increased. By measuring the grouting pressure, valuable information is obtained regarding the improvement effect below the pile base. The EB pile with post-grouting is known as the EB Incotec (EBI) system. The Expander Body is especially suitable for foundations in deep soil deposits, consisting of loose to medium dense sands and silts, which occur in the Santa Cruz region. The most common method for installation of EBI piles in Santa Cruz is bored piles where the auger borehole is temporarily supported by bentonite slurry. Conventional bored or auger piles can be installed rapidly but are frequently used even in soil conditions, which are not suitable. One of the most serious problems is soil decompression, which occurs when the speed of auger penetration is slower than the critical speed, v_{crit} below which the auger starts to transport soil up to the ground surface, (Massarsch et al. 1988). The critical penetration speed depends on the equipment parameters, which are identified in Figure 5.

$$v_{crit} = n\,l\left(1 - \frac{d^2}{D^2}\right) \tag{1}$$

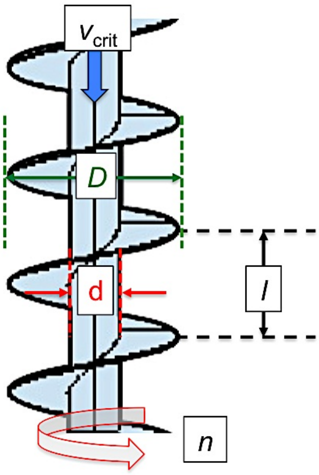


Fig. 5. CFA pile equipment parameters, which define the critical penetration speed according to Eq. (1).

Based on Eq. (1) it is possible to determine the minimum auger penetration speed required to avoid soil decompression and movement of the soil up to the ground surface, Figure 6. The risk of soil decompression can be avoided by assuring that the thrust and torque of the auger equipment is sufficient to exceed the critical penetration speed.

As the shaft capacity of conventional bored and CFA piles is usually low, the EB system provides a reliable pile toe resistance. In spite of the more sophisticated manufacturing and installation process compared to traditional methods, EB and EBI piles are competitive due to the significantly higher load bearing capacity. Also, the client can be assured of the consistent and verifiable quality of each pile.

The EB system has several important, beneficial effects on pile bearing capacity:

- The pile has an enlarged pile base with known shape and cross section, which can be verified by field monitoring.
- The inflation of the EB is similar to a Pressuremeter test, where monitoring of the expansion process provides information regarding soil stiffness and strength.
- The soil strength and stiffness of granular soils increases adjacent to the expanded pile base due to compaction and increase in lateral stress.
  In soft, cohesive soils, the shear strength increases as a result of consolidation.

Thanks to the information from the EB inflation process it is possible to develop design concepts, which can be based on the measured expansion pressure.

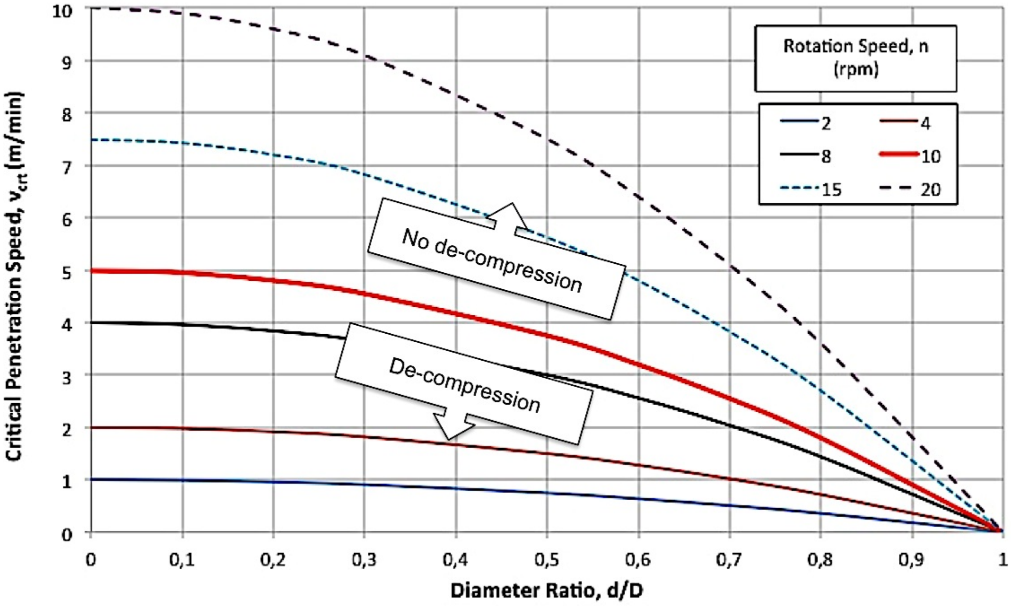


Fig. 6. Determination of critical auger penetration speed, v_{crit} as function of auger rotation, n and auger diameter ratio d/D, cf. Fig. 5. A typical value of the auger pitch $l = 0.5$ m has been assumed.

5. EBI with Full Displacement Auger Pile (FDP)

An important improvement of the auger pile method was the introduction of a specially designed displacement auger, the full displacement auger pile (FDP) cf. Figure 7. Figure 7a shows the specially designed drilling tool, which during penetration displaces the soil laterally. Due to the high torque and crowd (down-ward force), the lateral soil stress along the pile shaft is increased significantly. The typical shaft diameter of the FDP, used in Bolivia, varies between 360 mm or 440 mm. Another important advantage of the FDP method, compared to conventional bored and auger piles is, that the installation process can be monitored and documented in great detail, cf. Fig. 7b. Different parameters can be recorded during pile installation, such as crowd, torque, probe penetration and extraction speed, grout volume and grout pressure. These parameters provide valuable information to the machine operator who can adjust the installation and pile construction process to the prevailing soil conditions. Also, interpretation of the measured parameters provides valuable information regarding the soil conditions along the pile shaft during installation. In many ways, the FDP system is an ideal complement to the EBI pile system. The pile installation concept of the FDP method is similar to that of the EB, as it increases lateral soil stress, thereby enhancing soil stiffness and strength along the pile shaft. Combination of the EBI with the FDP results in an efficient foundation solution especially in loose and medium dense soils. The FDP provides high pile shaft resistance and the enlarged toe of the EBI significantly increases pile toe resistance.

Lateral soil compression achieved by the FDP is also beneficial for the performance of the EBI at the pile toe. This effect is reflected by the grout pressure vs. volume curve registered during EBI inflation shown in Figure 8. The initial slope of the pressure-volume curve is much steeper, indicating high soil resistance. Recent load tests on instrumented piles show that the addition of the EBI greatly enhances the stiffness response of the pile toe.

a) Displacement auger pile tool (FDP) *b) Monitoring of auger FDP installation*

Fig. 7. Example of displacement auger pile (FDP) tool and electronic monitoring of pile installation process.

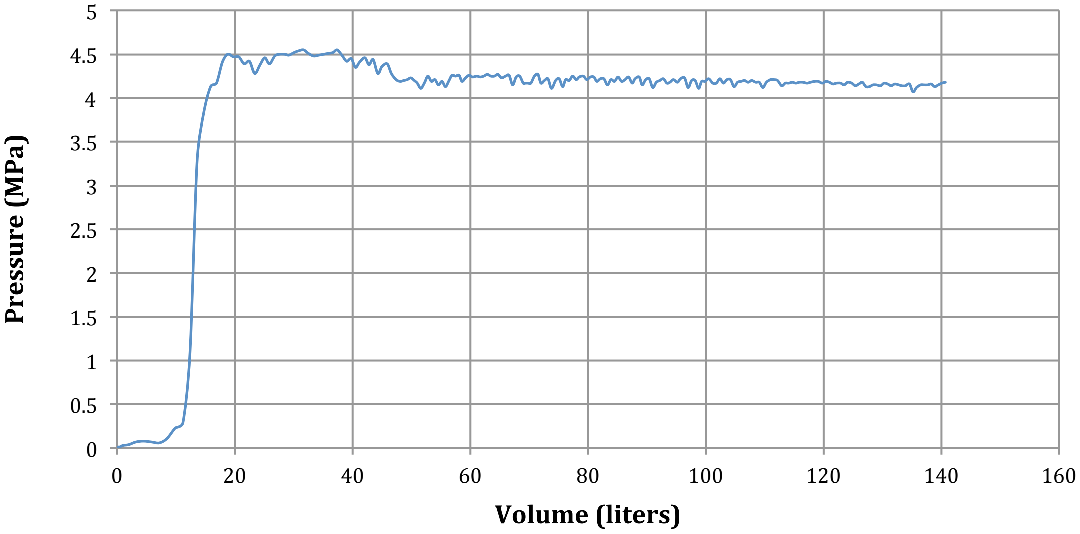
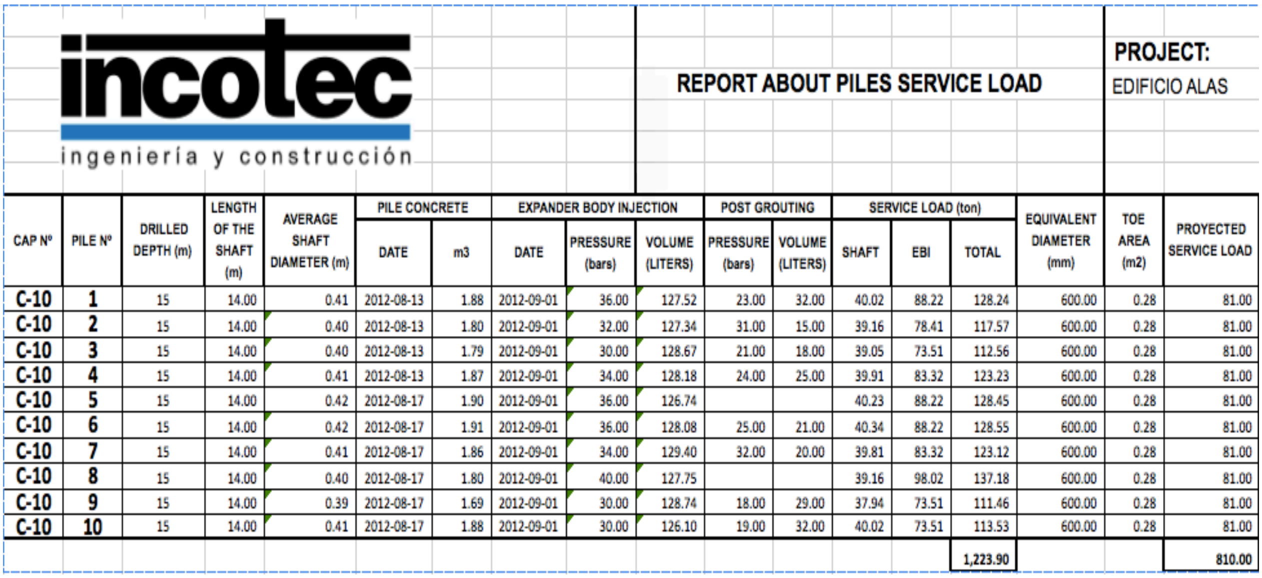


Fig. 8. Grout pressure vs. volume curve showing the high initial stiffness of an EBI installed at the toe of an FDP, cf. Fig. 3 and 4.

6. Application of EB Piles in Bolivia

A large number of mainly bored piles with EB base have been installed in Bolivia. At each project, the grouting process was documented and detailed information of inflation parameters was compiled. An example of the compiled information for each EB pile is shown in Table 2.

Table 2. Typical compilation of grouting process during EB inflation.



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REPORT ABOUT PILES SERVICE LOAD

PROJECT:
EDIFICIO ALAS

CAP Nº	PILE Nº	DRILLED DEPTH (m)	LENGTH OF THE SHAFT (m)	AVERAGE SHAFT DIAMETER (m)	PILE CONCRETE		EXPANDER BODY INJECTION			POST GROUTING		SERVICE LOAD (ton)			EQUIVALENT DIAMETER (mm)	TOE AREA (m2)	PROYECTED SERVICE LOAD
					DATE	m3	DATE	PRESSURE (bars)	VOLUME (LITERS)	PRESSURE (bars)	VOLUME (LITERS)	SHAFT	EBI	TOTAL			
C-10	1	15	14.00	0.41	2012-08-13	1.88	2012-09-01	36.00	127.52	23.00	32.00	40.02	88.22	128.24	600.00	0.28	81.00
C-10	2	15	14.00	0.40	2012-08-13	1.80	2012-09-01	32.00	127.34	31.00	15.00	39.16	78.41	117.57	600.00	0.28	81.00
C-10	3	15	14.00	0.40	2012-08-13	1.79	2012-09-01	30.00	128.67	21.00	18.00	39.05	73.51	112.56	600.00	0.28	81.00
C-10	4	15	14.00	0.41	2012-08-13	1.87	2012-09-01	34.00	128.18	24.00	25.00	39.91	83.32	123.23	600.00	0.28	81.00
C-10	5	15	14.00	0.42	2012-08-17	1.90	2012-09-01	36.00	126.74			40.23	88.22	128.45	600.00	0.28	81.00
C-10	6	15	14.00	0.42	2012-08-17	1.91	2012-09-01	36.00	128.08	25.00	21.00	40.34	88.22	128.55	600.00	0.28	81.00
C-10	7	15	14.00	0.41	2012-08-17	1.86	2012-09-01	34.00	129.40	32.00	20.00	39.81	83.32	123.12	600.00	0.28	81.00
C-10	8	15	14.00	0.40	2012-08-17	1.80	2012-09-01	40.00	127.75			39.16	98.02	137.18	600.00	0.28	81.00
C-10	9	15	14.00	0.39	2012-08-17	1.69	2012-09-01	30.00	128.74	18.00	29.00	37.94	73.51	111.46	600.00	0.28	81.00
C-10	10	15	14.00	0.41	2012-08-17	1.88	2012-09-01	30.00	126.10	19.00	32.00	40.02	73.51	113.53	600.00	0.28	81.00
														1,223.90			810.00

Table 3 presents a summary of information from more than 1,000 EB installations from 20 projects implemented during 2012. In those projects, the SPT N-values at the level of the Expander Bodies varied between 19 and 34.

Table 3. Results of EB expansion monitoring during grouting, with soil strength indication by SPT N-values.

Project	Average Injection Pressure	Average Volume	Maximum Pressure	Minimum Pressure	Standard Deviation	Nº of Registra-tions	SPT N-value at EB Level
		liter	MPa	MPa			
Dresco	37.30	124.76	4.90	1.00	7.23	59	35
Silos Sofia	19.73	159.78	2.80	0.40	4.04	45	21
Tres Carabelas	45.37	120.47	5.30	3.10	5.30	19	25
Santa Elena	40.63	124.53	6.00	1.00	10.67	87	28
Florencia	38.13	117.56	4.90	1.70	5.94	32	33
Itaguazú	44.43	137.03	5.40	1.50	7.76	37	32
Uagram	38.09	150.91	6.00	2.70	9.64	11	35
Parqueo Alas	36.30	124.82	6.20	2.00	7.63	95	28
Itati	49.51	137.11	6.20	2.00	7.62	92	28
Ferrotodo	45.33	128.22	5.90	2.50	11.90	9	25
Platino	48.91	108.76	6.60	2.00	11.86	55	34

Domani	36.68	135.77	7.00	1.40	8.87	133	32
Clinica Nuclear	17.6	117.65	2.89	0.64	6.2	38	19
Torres Duo	33.0	132.96	5.85	1.02	10.0	167	30
Zurita (1)	24.8	124.82	4.54	1.20	9.7	38	23
Equipetrol Norte	52.2	125.17	3.80	0.97	14.65	6	36
Alianza	29.91	130.00	4.90	2.10	6.58	47	27
Artemisa	31.48	117.77	4.33	2.16	4.45	94	24
Torre Salto	34.26	124.45	5.80	2.20	8.25	73	26
Equipetrol Norte 4	33.31	121.73	4.50	2.30	5.79	34	32

The use of loading test as design tool has increased locally in the recent times. Until the beginning of 2012, all tests performed were static loading test. Those test were according with ASTM D 1143, short test.

Figure 11 shows the superimposition of several static loading tests performed on bored piles with EB.

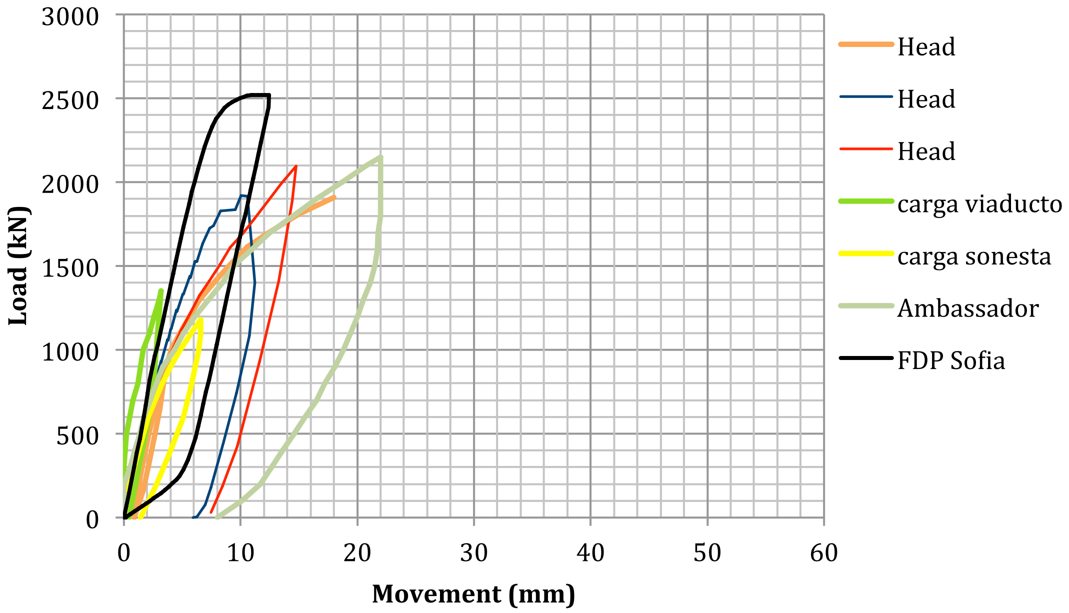


Fig. 11. Results of static loading tests of bored, cast in situ piles with EB in Bolivia.

Since February 2013, Dynamic Tests with PDA equipment are available in the Bolivian market. This development will further increase the database of load test results from bored EB piles. Figure 12 shows the results from a dynamic loading test on a drilled pile (Ambassador Project Piles), constructed under bentonite with Expander Body.

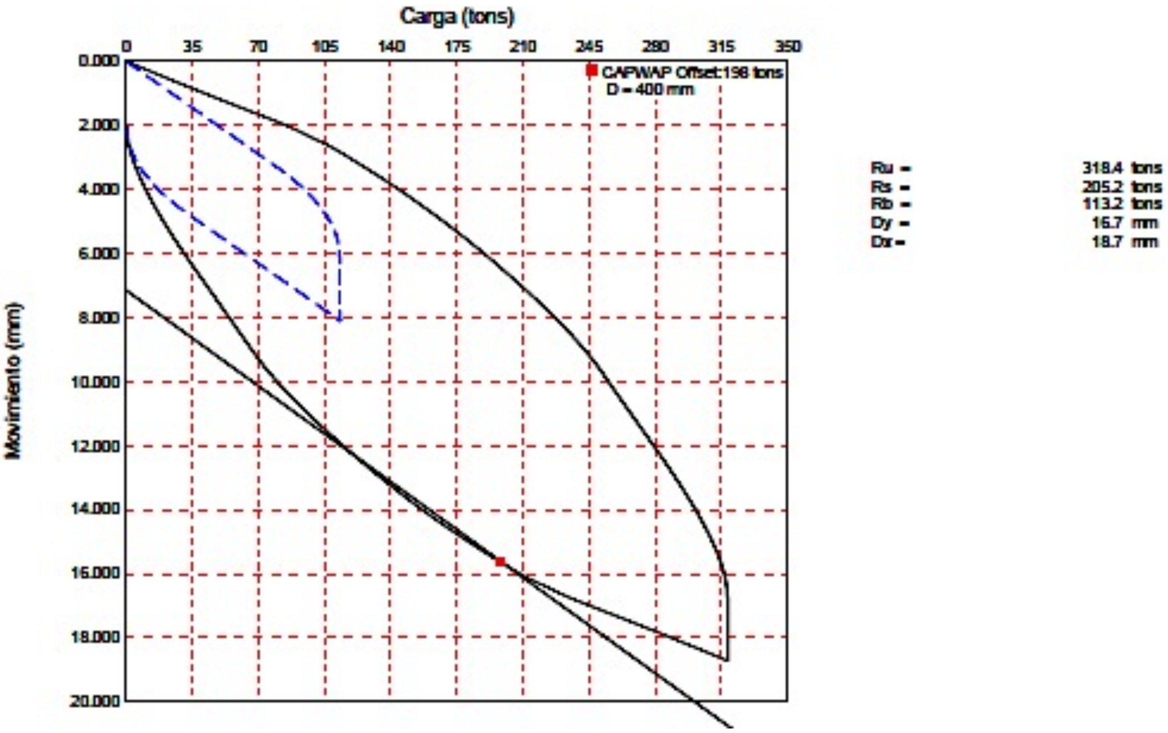


Fig. 12. Results of dynamic load test, drilled under bentonite, shaft diameter: 400 mm, length:18 m. with EBI 600.

7. Pile Testing Program - UAGRM

An extensive pile testing program was carried out at the site of the University of Santa Cruz, UAGRM. The results of a series of static and dynamic pile loading tests, carried out on four different types of bored piles with and without EBI, are described in a paper by Fellenius and Terceros (2014) submitted to this conference. In this paper, only a limited part of the extensive information is summarized. Four different pile types were investigated:

TP1: a nominal 400 mm diameter pile, 17.5 m long, bored under bentonite ("standard pile").
TP2: a nominal 360 mm diameter pile, 11.6 m long, installed as a FDP.
TP3: a nominal 360 mm diameter pile, 9.6 m long, installed as a FDP with a 600 mm diameter EB placed at the pile toe.
TP4: a nominal 450 mm diameter pile, 17.5 m long, bored under bentonite with a 600 mm diameter EB, placed at the pile toe and with an Osterberg cell above the EB.

The results of static loading tests, presented by Fellenius and Terceros (2014) are summarized in Figure 9. Due to limitations in the capacity of the pile loading system and limits of the structural pile capacity, full toe resistance could only be mobilized for TP4 (FDP with EB). One of the piles (TP4), which was equipped with an Osterberg cell just above the EB, could be loaded to failure. A comparison of TP1 (conventional bored pile) and TP4 (conventional bored pile with EB) shows the large increase in toe resistance, which corresponds to almost 1,500 kN. Full displacement piles TP2 and TP3 were significantly shorter than TP1 but achieved approximately the same load capacity, albeit the toe resistance could not be fully mobilized during the load test.

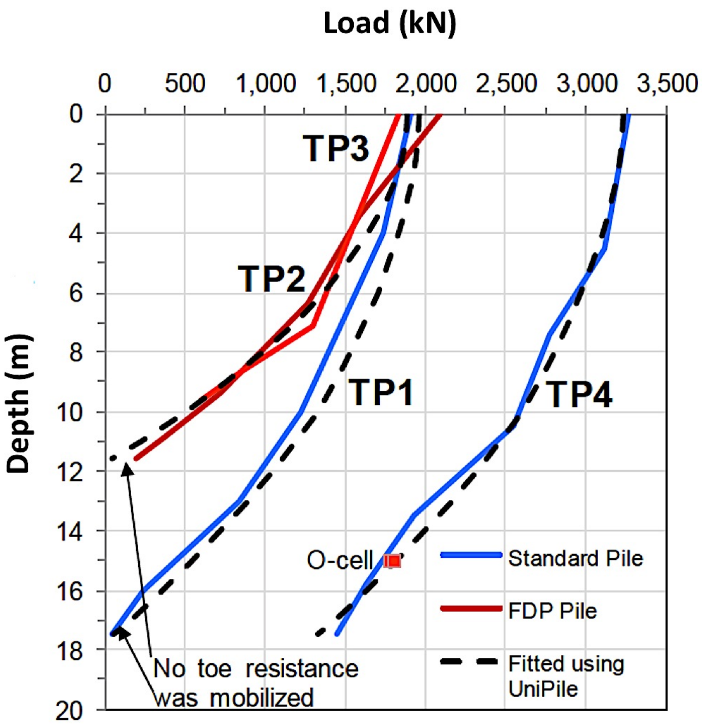
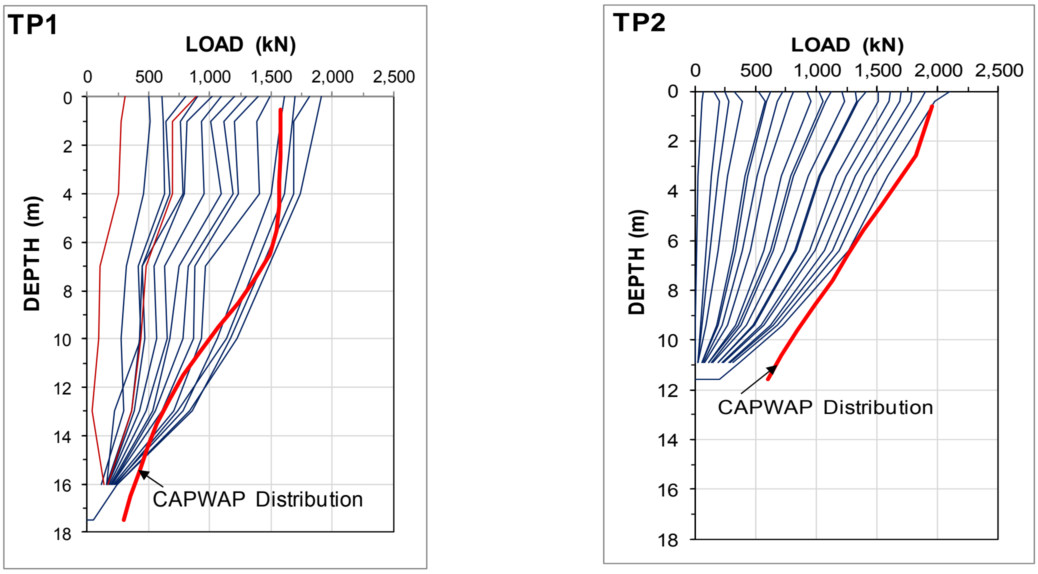


Fig. 9 Compilations of the load distribution at maximum load, from Fellenius and Terceros (2014). Note the difference in pile length and that the pile diameter of TP2 and TP3 was 360 mm and that of TP1 and TP4 400 and 450 mm, respectively.

From the shape of the load distribution of piles TP2 and TP3 it can be seen that the shaft resistance is significantly higher for these two piles, installed by the FDP method.

Dynamic pile loading tests were also carried out and the results were analyzed with CAPWAP® software. Figure 10 shows the calculated distribution of shaft resistance for the four tests piles. The shaft resistance and its distribution is clearly higher in the case of FDP piles (TP2 and TP3). The highest pile capacity was achieved by TP4, the longest pile, which was provided with an EB.

The test results show that in granular soil, a high degree of soil compaction can be achieved by the FDP, resulting in improved shaft assistance. An analysis by Fellenius and Terceros, using the computer software Unipile, showed that the lateral soil stress acting along the pile shaft was about 2 to 3 times higher than that for conventional bored piles.



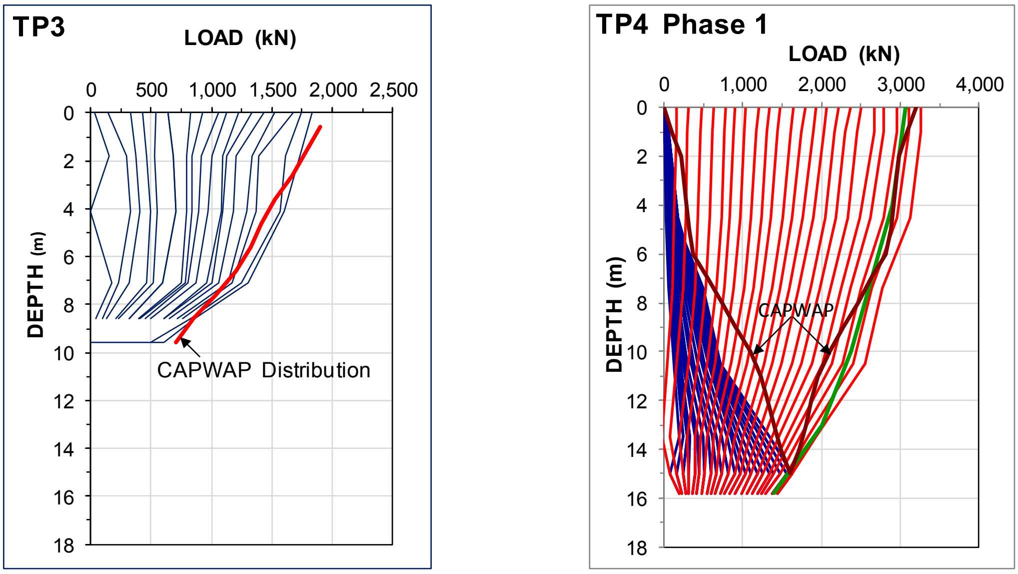


Fig. 10. The CAPWAP-determined static load distributions compared to the distributions evaluated in the static loading tests (Fellenius and Terceros, 2014)

8. Design Methods

Different design methods can be used for the EB pile system. The method used in Sweden is based on results of the cone penetration test (CPT) and has been described by Massarsch and Wetterling (1993). The design method presented below is based on Pressuremeter theory and consists, in its simplified form, of the following expression:

$$Q_T = Q_B + Q_S \qquad (2)$$

where Q_B is the pile base resistance of the Expander Body

$$Q_B = k \ \sigma_l \qquad (3)$$

and Q_S is the shaft resistance

$$Q_S = A \, \sigma_l \tan \Phi_l \qquad (4)$$

with

k : Pressuremeter coeficient, typically 1.95

σ_l: Limit pressure from grout-volume curve

A: Side area of the Expander Body

$\O_l$: Steel-soil friction angle, with a typical values of 10º.

Equations (2) though (4) are used for design purpose in medium dense to dense soils with $N_{SPT} > 18$. Based on extensive experience from EBI projects, an average value of $\sigma_l = 2$ MPa is used.

Determination of the pile shaft resistance of FDP piles, the method proposed by NeSmith (2002) can be used. Good correlation has been obtained between results from loading test and predicted values of shaft friction.

In both cases, EB and FDP, the recent incorporation of SCPTu in the local market, will improve the quality of the data used for the design.

9. Summary and Conclusions

Extensive experience from different parts of the world, and in particular from many applications in Bolivia demonstrate that the Expander Body provides an efficient, enlarged pile of cast in situ piles. A high degree of quality control can be achieved, as the expansion process of each EB pile base can be recorded and documented. An important new development has been the introduction of post-grouting below the expanded pile base, called the EBI pile. Post-grouting further increases soil strength and stiffness and reduces pile settlement.

When installed at the base of bored piles, the EB system increases the pile toe resistance in a wide range of soils, from very loose, silty sands to medium dense sands and stiff clays. In spite of the more sophisticated installation process, the increased pile capacity makes the EBI pile a cost-efficient deep foundation solution, compared with low-cost, less reliable pile types.

EB installation by the full displacement methods (EB + FDP) further increases pile shaft capacity. Recent field tests, reported in this paper, demonstrate that pile capacity can be increased at least four times compared to conventional, bored piles.

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