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Application of bi-directional static loading test to deep foundations

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Abstract: Bi-directional static loading test adopting load cells is widely used around the world at present, with increase in diameter and length of deep foundations. In this paper, a new simple conversion method to predict the equivalent pile head load-settlement curve considering elastic shortening of deep foundation was put forward according to the load transfer mechanism. The proposed conversion method was applied to root caisson foundation in a bridge and to large diameter pipe piles in a sea wind power plant. Some new load cells, test procedure, and construction technology were adopted based on the applications to different deep foundations, which could enlarge the application scopes of bi-directional loading test. A new type of bi-directional loading test for pipe pile was conducted, in which the load cell was installed and loaded after the pipe pile with special connector has been set up. Unlike the conventional bi-directional loading test, the load cell can be reused and shows an evident economic benefit.

Key words: deep foundations; bi-directional static loading test; root caisson foundation; large diameter pipe pile

1 Introduction

In China, a number of major construction projects, such as high-rise buildings, river- or sea-crossing expressway bridges, high-speed railways, wind power plants, and harbors, are under construction or to be built in urban and coastal regions. Deep foundations are frequently observed in heavy-load and large-span construction projects. For the large applied loads, the bi-directional static loading test can be adopted (Osterberg, 1984), and it is also called self-balanced test in China (Gong et al., 2002).

The load cell in the bi-directional static loading test is basically hydraulically driven. The high capacity and one-off jack-like device is installed within the foundation unit at the chosen location, where it is typical half way down the “capacity length” of the foundation (Osterberg, 1984, 1989, 2001; England, 2000, 2003). The Osterberg-cell (O-cell) based bi-directional loading test is now widely used around the world (Castelli and Fan, 2002; Castelli and Wilkins, 2004; Russo et al., 2003; Seol and Jeong, 2009; Fellenius and Ann, 2010). The bi-directional loading test results are used to plot an equivalent top-down load-settlement curve (Osterberg, 1998), and multilevel load cell test is now employed frequently (England, 2009). Generally, the pile head settlements in bi-directional static loading tests are calculated by (1) the side shear load-displacement curve, obtained from the upward movement of the top of the load cell, and (2) by the end bearing load-displacement curve, obtained from the downward movement of the bottom of the load cell. The original method proposed by Osterberg (1998) assumes that (1) pile is a rigid body, (2) the movements of the pile head and bottom are the same, and (3) the upward skin friction is equal to the downward skin friction. The equivalent pile head settlement is obtained by adding the side friction to the end bearing load at the same deflection. However, the portion of the elastic shortening of the pile has significant effect on settlement accuracy for long piles (Lee and Park, 2008). The pile head settlement may be underestimated by this method. In order to overcome the limitations of the original method, Fellenius et al. (1999) adopted a numerical method to obtain the load-head settlement curves of rigid and non-rigid equivalent piles. The bearing capacities and the factors of safety decrease when elastic compressions of the piles are considered.

Gong et al. (2002) proposed the precise and

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approximate conversion methods based on the theory of elasticity. Numerous project examples have indicated that the precise method is appropriate for the practical projects (Dai et al., 2005). Lee and Park (2008) proposed a simplified elastic method for constructing a realistic pile load-settlement curve. The shape factor dependent on skin friction distribution is considered for calculating the elastic shortening of the piles. The results obtained from the simplified elastic method are similar to those by static loading test, and the development of approximate method is beneficial to the performance study of pile tests. In pre-holed foundation, the load cell can be embedded at the chosen location with reinforced cage and then concrete is placed through tremie pipe. However, in the driven pipe piles, especially in open-ended piles, the load cell is usually placed at the bottom of the pile, because it is not practicable to place load cell in other locations during installation of the pile. So it is not suitable for pipe piles, in which the end bearing capacity is less than the side friction. Therefore, a new bi-directional loading test should be developed for large-diameter steel pipe pile. Based on this, a relatively simple method is proposed in this paper. The engineering applications of bi-directional static loading test are also introduced to root caisson and pipe pile foundations.

2 Equivalent conversion method for the bi-directional loading test

In the bi-directional loading test, the testing pile is loaded by the embedded load cell in upward and downward directions. According to the relationship between the settlement *s* and the applied load *Q*, the upward and downward *Q*-*s* curves can be obtained. From the two *Q*-*s* curves and the corresponding *s*-lg*t* (*t* is the loading time) and *s*-lg*Q* curves, the bearing capacities of both upper and lower segments of the testing pile can be determined. The equipments used for field cast-in-situ pile tests are shown in Fig. 1 (Gong et al., 2002).

When the load is applied through the load cell, it works in two directions. The lower segment of the pile balances the applied load through end bearing load and side friction, while the upper segment through side friction. There are two stages to convert the bi-directional load-settlement curve to the equivalent pile head load-settlement curve, i.e. determining the equivalent load and obtaining the settlement of pile head.

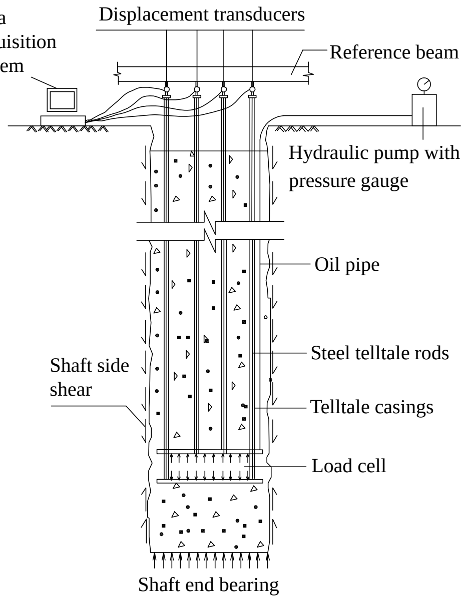


Fig. 1 Sketch of bi-directional static loading test.

The equivalent load at the top of the pile can be determined from the bi-directional loading test results (Gong et al., 2002):

$$Q = \frac{Q_{\mathrm{up}} - G_{\mathrm{p}}}{\lambda} + Q_{\mathrm{down}} \quad (1)$$

where Q_{up} and Q_{down} are the selected or interpolated loads with respect to the selected displacement in upward and downward load- displacement curves, respectively; G_{p} is the deadweight of upper pile segment; λ is the conversion coefficient for upper pile segment from upward friction in the bi-directional loading test to downward friction in top-loaded test, which is dependent on soil properties.

If the selected displacement is larger than the maximum displacement of any other resistance component that does not reach the ultimate values, the extrapolation method is necessary to obtain the load applied. The load-settlement curve for the pile can be fitted by a hyperbolic curve.

The pile head settlement is the sum of the elastic compression (Δs_1) of upper pile segment subjected to the downward load (Q_{down}), the elastic compression (Δs_2) of upper segment subjected to the pile side friction (Q_{s}), and the net settlement of the upper pile. The net settlement of the upper pile is the total movement of the top of the lower pile (s_{down}). Note that unit skin friction (q_{sm}) is assumed to be constant at each segment (upper and lower side shears). Fig. 2 shows the components of the pile head settlement under static loading test.

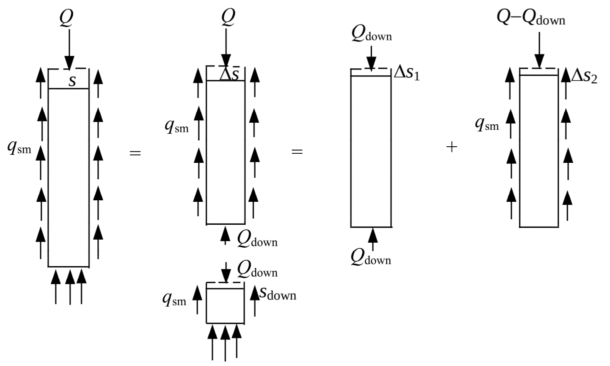


Fig. 2 Sketch of the pile head settlement calculation.

The components of the pile head settlement under static loading test in Fig. 2 can be expressed as

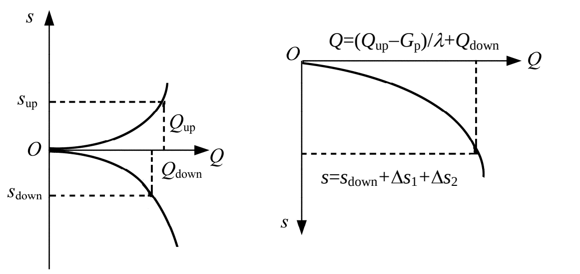
$$\Delta s_1 = \frac{Q_{down} L_{up}}{A_p E_p} \tag{2}$$

$$\Delta s_2 = \frac{Q_s L_{up}}{A_p E_p} = \frac{\lambda (Q - Q_{down}) L_{up}}{A_p E_p} \tag{3}$$

$$s = s_{down} + \Delta s_1 + \Delta s_2 = s_{down} + \frac{[\lambda Q + (1-\lambda) Q_{down}] L_{up}}{A_p E_p} \tag{4}$$

where A_p is the pile cross-sectional area, E_p is the Young's modulus of the pile, and L_{up} is the pile upper length.

The pile head settlement and the equivalent load can be calculated by Eqs. (1)–(4) under different load levels. Fig. 3 shows the equivalent pile head load-settlement curve obtained from the bi-directional loading test results.



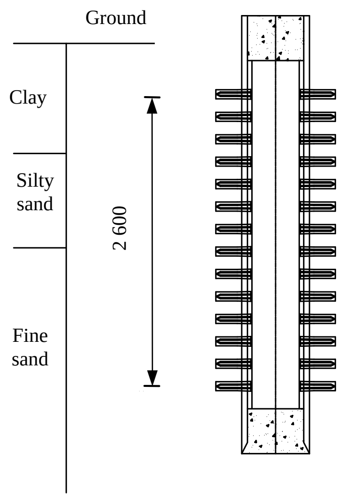
(a) O-cell load-settlement curve. (b) Equivalent load-settlement curve.

Fig. 3 Equivalent pile head load-settlement curve obtained from the bi-directional loading test results.

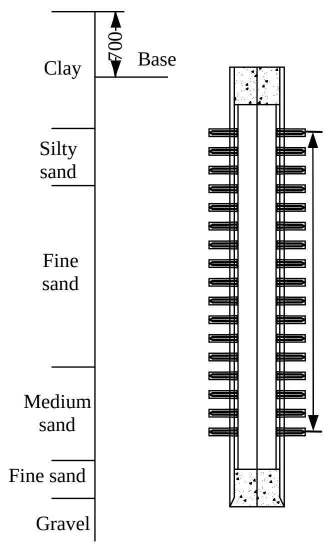
3 Application of bi-directional static loading test to deep foundations

3.1 Caissons with and without roots

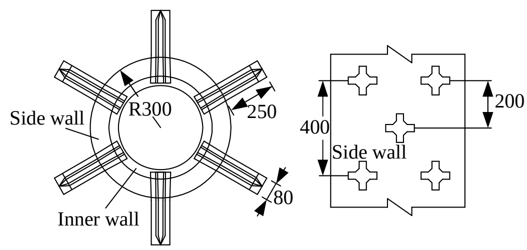
Root caisson foundation is a type of deep foundations used for suspension bridges. With prefabricated roots driven into soils through reserved holes in an installed caisson (Fig. 4), the small-size root caisson can give better load-displacement performances than typical caissons or long piles.



(a) Caisson No. 5.



(b) Caisson F.



(c) Layout of roots.

Fig. 4 Sketch of caisson (unit: cm).

Compared with a typical caisson foundation, the small-size root caisson has its benefits, including avoiding differential settlement of pile foundations and saving engineering costs. The detailed root caisson construction process is introduced as follows. First, the caisson is installed to a designed depth as a typical caisson, except that a polyethylene plate matching the size of the root is positioned at the location of root installation beforehand. During the caisson installation, the plate must resist lateral earth pressure and prevent water seeping into the caisson. When driving a root, the plate must be easily smashed into small pieces with nothing left at the root tip; otherwise, the driving process would be much difficult due to an enlarged root tip. Second, after the caisson is installed, all prefabricated roots must be driven into the soils by a hydraulic jack from the inside of caisson, starting from the bottom of the caisson to the top. After root penetration, the root end is welded to the caisson and the inner ring concrete is cast to form a whole caisson. Using a combination of conventional large caisson and long piles, the root caisson partly changes the load transfer mechanism along the caisson and shows a good global stiffness.

To investigate the vertical bearing capacity of the root caisson foundation, four groups of field bi-directional static loading tests have been conducted in two root caisson foundations (caisson No. 5 with 6 m in diameter, 39 m in height and 14 layers of roots; caisson F with 6 m in diameter, 47 m in height and 17 layers of roots) in Maanshan Yangtze River Bridge. The parameters of caissons are listed in Table 1. The load cell is shown in Fig. 5. The distance between the adjacent layers is 200 cm, and six piles are installed in each layer.

Using the proposed equivalent conversion method, the equivalent conversion curves of the caissons No. 5 and F with and without roots are shown in Fig. 6. The results show that the root caisson foundations have a larger vertical bearing capacity than common caisson foundations with improvement amplitude of 52% for caisson No. 5 and 44% for caisson F, respectively. The root caisson foundation can be an applicable choice for the anchor foundation of suspension bridge.

3.2 Large diameter steel pipe pile

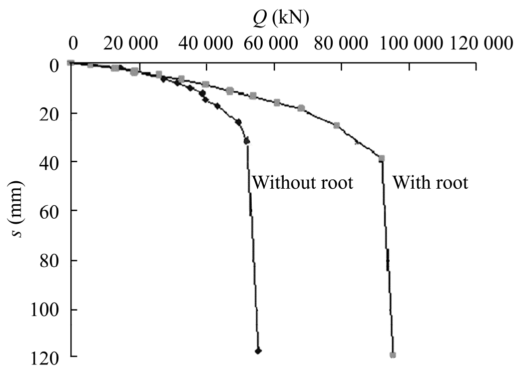
The sea wind power plant near the East Sea Bridge is the first sea wind power plant in China with installed capacity of 102 MW at present. It includes 34 offshore wind power sets with capacity of 3 MW each. Each foundation is composed of a concrete pile cap on 8 inclined steel pipe piles of 1.7 m in diameter. The steel pipe piles are made of Q345C steel. The upper pipe wall thickness for steel pipe pile is 30 mm, and the lower wall thickness is 25 mm. The upper part of the steel pipe pile, 30 m below the pile head, is filled with concrete C30. The parameters of pipe piles PZ1 and PZ2 are shown in Table 2. The site-specific soils are listed in Table 3.

The bi-directional static loading test is used in preholed foundation. However, in the driven or jacked pipe piles, the load cell cannot be welded on pipe pile at the designed location, especially in open-ended pipe pile. Therefore, a new bi-directional static loading test device is developed for large diameter pipe piles, as shown in Fig. 7. The testing procedure is the same as that of the conventional bi-directional loading test. The installation procedures of instruments including load cell are listed as follows:

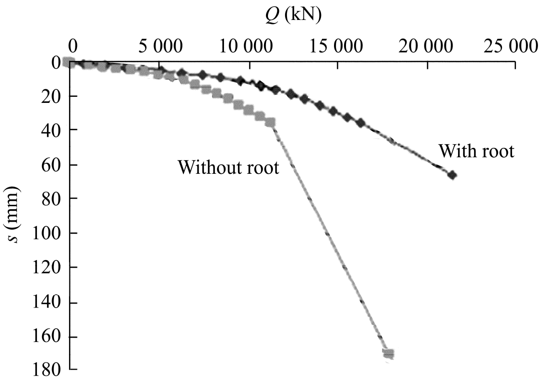
Table 1 Parameters of caissons.

Caisson No.	Outer diameter (m)	Length (m)	Caisson head level (m)	Location of load cell above caisson bottom (m)	Date of caisson construction	Date of root construction
5	6	39	8.6	5.5	Dec. 24, 2005–May 5, 2006	May 5–Oct. 10, 2007
F	6	47	2.0	4.0	Feb. 14–Sept. 3, 2008	Oct. 13–Dec. 10, 2008

Fig. 5 Load cell for caisson testing.



(a) Caisson No. 5.



(b) Caisson F.

Fig. 6 The equivalent conversion curves of caissons.

Table 2 Parameters of pipe piles PZ1 and PZ2.

Diameter (mm)	Pile length (m)	Pile head level (m)	Base level (m)	Seabed level (m)	Inclined ratio	Estimated load (MN)
1 700	82.1	7.1	–75	–11	6:1	16

Table 3 Parameters of the site-specific soils.

Soil layer	Soil type	Top level of soil layer (m)	Estimated friction resistance (kPa)	Estimated tip resistance (kPa)
1	Silt	–11	0	—
3	Silty clay	–11.4	10	—
4-1	Silty clay	–15	15	—
4-3	Silty clay	–24.1	25	—
5-3	Clay	–28.2	40	—
7-1-2	Silty sand	–38.8	80	—
7-2-1	Fine silty sand	–48.2	100	6 000
7-2-2	Fine silty sand	–66	110	7 000

(1) The construction staff cuts the steel pipe pile at the chosen position into two parts with a slope of 45°.

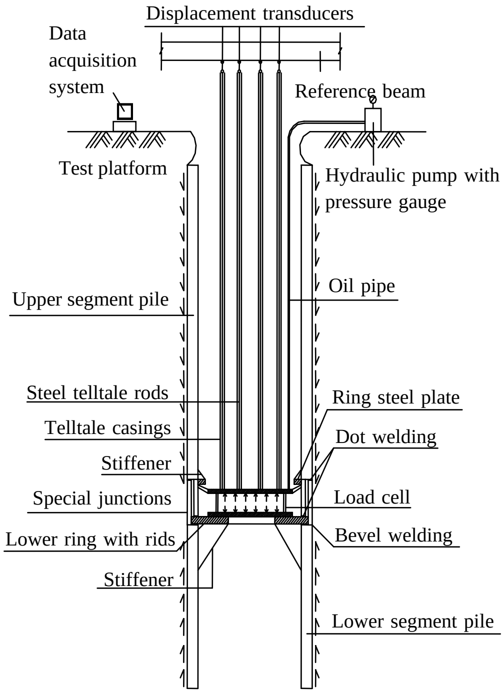
(2) The special junctions of the load cell are welded to the ends of the two parts. The diameter of the junction is the same as the outer diameter of steel pipe pile.

(3) The strain gauges are welded outside the steel pipe pile under the protection of the angular steel.

(4) During the transportation of the special junction, it should be kept horizontal, and heavy pressuring and crashing should be avoided to prevent the distortion of pipe pile.

(5) The soil inside the steel pipe pile over the junction should be cleared away, ensuring that no fillings above the bottom of special junction are left.

(6) The pile head should be covered to prevent other sundries from falling inside after clearing up the soil.



(a) Testing sketch.

(b) Special junction.

(c) Load cell with retractable claws.

Fig. 7 Testing sketch and load cell of steel pipe pile.

(7) The load cell and related displacement instruments are mounted on the special junction. The special junction should be installed smoothly and slowly to avoid rotating. After the test, the load cell can be reused through suspending the retractable claws by crane.

The bi-directional loading test was conducted during August 7–16, 2008. The equivalent conversion curves are shown in Fig. 8 using the proposed equivalent conversion method. Table 4 shows the bearing capacity of piles.

High-strain dynamic test of pile PZ1 was conducted on July 7, 2008 by PDA piling analyzer with D-220 diesel hammer. The test results of pile PZ1 are shown in Table 5. It is very close to the results obtained by the bi-directional loading test.

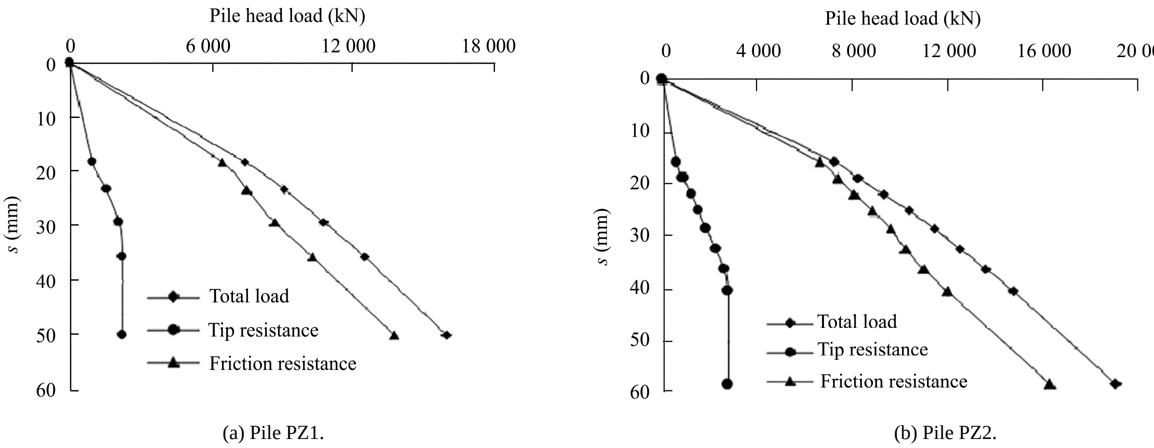


Fig. 8 The equivalent conversion curves of pipe piles PZ1 and PZ2.

Table 4 Bearing capacity of pipe piles PZ1 and PZ2.

Pile No.	Friction resistance		Tip resistance		Total load (kN)	Displacement (mm)
	Value (kN)	Ratio (%)	Value (kN)	Ratio (%)		
PZ1	13 733	86.16	2 207	13.84	15 939	49.76
PZ2	16 335	85.57	2 755	14.43	19 090	58.32

Table 5 Dynamic test results of pipe pile PZ1.

Pile length (m)	Number of hammer blows	Final penetration (mm/N)	Maximum blow force (kN)	Measured stress (MPa)	Blow energy (kJ)	Pile integrity (%)	Total bearing capacity (kN)
82.1	3 013	4.0	19 500	123.8	219	100	20 200

4 Conclusions

The bi-directional static loading test is widely used in the world. The development of the bi-directional loading test for the high bearing capacity of piles gives engineers a new and powerful tool to evaluate the bearing characteristics of piles. The bi-directional loading test results could be analyzed in the same way as the conventional test results using equivalent conversion curve. The following conclusions can be drawn:

(1) A new conversion method is put forward, which can consider the influences of conversion coefficient and elastic shortening on the bearing capacities and settlements. The equivalent pile head load-settlement curve can be calculated from bi-directional loading test, although the differences in load transfer mechanism from conventional loading test are observed.

(2) To determine the bearing capacities of the root caisson foundation, the bi-directional loading test is performed. Special combined load cells are designed in the test which enlarges the application scopes of bi-directional loading test.

(3) A new technology of bi-directional static loading test has been developed for large diameter steel pipe piles compared with conventionally driven piles test. In the test, the special junctions and load cells with retractable claws are designed. The new bi-directional loading test could be widely used in offshore platform with large diameter pipe piles.

Although the bi-directional static loading test is becoming a common practice in deep foundations with large bearing capacity, there are some differences in load transfer between bi-directional loading test and conventional top-down loading test, for which further study to construct a reasonable equivalent top-down load-settlement curve is needed.

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References

Castelli R J, Fan K. O-cell test results for drilled shafts in marl and limestone. In: O’Neill M W, Townsend F C ed. Deep Foundations 2002: An International Perspective on Theory, Design, Construction, and Performance. Florida, USA: American Society of Civil Engineers, 2002: 807–823.

Castelli R J, Wilkins E. Osterberg load cell test results on base grouted bored piles in Bangladesh. In: Tunner J P, Mayne P W ed. GeoSupport 2004: Drilled Shafts, Micropiling, Deep Mixing, Remedial Methods, and Specialty Foundation Systems. Florida, USA: American Society of Civil Engineers, 2004: 587–602.

Dai G L, Gong W M, Ji L, You Q Z. Static loading test of a self-balanced approach to a pile in the Yangtze River. In: Anson M, Ko J M, Lam ESS ed. Advances in Building Technology. Oxford, UK: Elsevier, 2002: 695–701.

Dai Guoliang, Gong Weiming, Cheng Ye, Xue Guoya. Application of self-balanced testing and post grouting to large diameter and super-long piles. Chinese Journal of Geotechnical Engineering, 2005, 27 (6): 690–694 (in Chinese).

England M. Method of analysis and prediction of pile recovery from an applied load. In: Mets M ed. Proceedings of the 9th Baltic Geotechnical Conference. Parnu, Estonia: Estonian Geotechnical Society, 2000: 239–245.

England M. Bi-directional static loading testing—state of the art. In: van Impe W F ed. Deep Foundation on Bored and Auger Piles. Ghent, Belgium: Millpress Science Publishers, 2003: 309–313.

England M. Review of methods of analysis of test results from bi-directional static loading tests. In: van Impe W F ed. Deep Foundation on Bored and Auger Piles. London, UK: Taylor and Francis Group, 2009: 235–239.

Fellenius B H, Altaee A, Kulesza R, Hayes J. O-cell testing and FE analysis of 28-m-deep barrette in Manila, Philippines. Journal of Geotechnical and Geoenvironmental Engineering, 1999, 125 (7): 566–575.

Fellenius B H, Ann S T. Combination of O-cell test and conventional head-down test. In: Proceedings of the Art of Foundation Engineering Practice Congress (GSP 198). Virginia, USA: American Society of Civil Engineers, 2010: 240–259.

Gong Weiming, Dai Guoliang, Jiang Yongsheng, Xue Guoya. Theory and practice of self-balanced loading test for pile bearing capacity. Journal of Building Structures, 2002, 23 (1): 82–88 (in Chinese).

Lee J S, Park Y H. Equivalent pile load-head settlement curve using a bi-directional pile load test. Computers and Geotechnics, 2008, 35 (2): 124–133.

Seol H, Jeong S. Load-settlement behavior of rock-socketed drilled shafts using Osterberg-cell tests. Computers and Geotechnics, 2009, 36 (7): 1 134–1 141.

Osterberg J O. A new simplified method for load testing drilled piles. Foundation Drilling, 1984, 23 (6): 9–11.

Osterberg J O. New device for loading testing driven piles and drilled shaft separates friction and end bearing. In: Proceedings of International Conference on Piling and Deep foundations. London, UK: A.A. Balkema, 1989: 421–427.

Osterberg J O. The Osterberg load test method for bored and driven piles: the first ten years. In: Proceedings of the 7th International Conference and Exhibition on Piling and Deep Foundations. Vienna, Austria: Westgrade Group Limited, 1998: 1–11.

Osterberg J O, Hayes U A. The Osterberg load cell as a research tool. In: Proceedings of the 15th International Conference on Soil Mechanics and Geotechnical Engineering. IL, USA: A.A. Balkema, 2001: 977–979.

Russo G, Recinto B, Viggiani C, de-Sanctis L. A contribution to the analysis of Osterberg’s cell load test. In: Proceedings of the 4th Geotechnical Seminar on Deep Foundation on Bored and Auger Piles. Ghent, Belgium: Millpress Science Publishers, 2003: 331–338.