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Development and Implementation of a High-Pressure, Double-Acting, Bi-Directional Loading Cell for Drilled Shafts

Reference

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ABSTRACT

Drilled shaft foundation elements provide a cost-effective foundation alternative for the support of building and bridge superstructure loads. Bi-directional pile loading tests (BDPLTs) to evaluate the capacity of drilled shafts have become popular owing to their capacity to save time and effort as compared to the use of top-down loading tests. However, the use of BDPLTs requires that production shafts be post-grouted following testing in order to assure appropriate in-service performance. Commonly used single-acting loading cells and/or loading cell construction details can pose the potential for the development of voids following post-grouting due to their monotonic jacking action and large footprint. This paper described the development and use of high pressure bi-directional loading cells intended to minimize the possibility of post-test construction defects. First, a comparison was made between the single-acting and double-acting loading cells. Second, the results of laboratory calibrations on the pressurized loading cells were performed, as were component testing of the pumps, hoses, and hydraulic fluid synchronization lines. Then, the use of the new high pressure double-acting loading cells in production testing of instrumented shafts was described, and the efficacy of the new loading cells was illustrated. The new loading cells provided the profession with a load cell alternative for conducting BDLTs and should serve to help reduce the risk of post-test grouting defects in drilled shaft foundations.

Keywords

field testing, deep foundations, site infrastructure and construction, cementing/grouting

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Introduction

Recent trends in building construction across the world indicate that tall structures, including those 100 stories or higher, are proliferating to meet the demands of booming urban populations within areas of high land costs (Tse et al. 2012). Tall structures include residential and commercial high-rises, offices, hotels, and mixed-use buildings, all of which comprise the needs of densely populated urban areas. Correspondingly, the use of large-diameter driven piles and drilled shafts has increased in order to provide foundation support for such heavy structures. Owing to the demand for such buildings, loads required to be transferred from the superstructures to their foundations are increasing in magnitude so that design loads ranging from 10 to 60 MN are common (Schmertmann et al. 1998; Osterberg 1998), and test loads of up to 320 MN are now a reality (Hayes 2012).

The conventional static quick pile loading test (ASTM D1143/D1143M-07(2013)) is commonly used in conjunction with conventional top-down testing to check the load bearing capacity of constructed deep foundations. This method, while reliable and widely accepted, suffers from certain limitations when testing the capacity of large-diameter deep foundations because of the significant reaction system required to displace the tested element sufficiently (Choi and Nam 2012). Additionally, the likelihood of detecting "soft toe" conditions or other construction-related defects using top-down methods can be significantly reduced if the test loads remain well below the ultimate shaft resistance of a drilled foundation. To help meet the challenge associated with developing sufficient resistance, the bi-directional pile loading test (BDPLT) was developed as a feasible alternative test method to the top-down static loading test. The BDPLT achieves test loads by reacting against all or a majority of the shaft resistance of the constructed element; hence pushing the element in opposing directions simultaneously. The Osterberg cell test (O-cell test), a type of BDPLT, is the most widely used in the world and uses hydraulic pressure to displace single-acting hydraulic cells to generate the required test load (Osterberg 1986).

However, some single-acting load cells can experience deficiencies by virtue of its operation, construction detailing, and by the end-user in the field. For instance, after a loading test, a void is generated inside the cell. If the foundation element will perform as a production shaft, the space must be filled by structural grout to avoid a reduction in the strength of the drilled shaft. Grouting is possible in single-acting loading cell systems, but the integrity of the grouted voids cannot be verified. Depending on the location of the loading cell, voids may serve to significantly reduce the load carrying capacity of the drilled shaft (O'Neill et al. 2002; Petek et al. 2002; Iskander et al. 2003; Nam and Choi 2007), and the effect of the voids could be encountered during construction of the supported structure, or during a strength or extreme limit state when performance is most critical. Furthermore, because low-pressure cells are constructed using larger diameters to achieve their target loads, the cells require a large foot print, exacerbating the potential for voids due to improper grouting between and within the cells to result in poor shaft performance. To address potential shortcomings, Lee et al. (2007) developed the first double-acting BDPLT cell; however, this initial effort used typical hydraulic pressures and suffered from the same cell pressurization sequence as that of single-acting cells (described in greater detail below).

This paper describes the background and development of a new high pressure, double-acting bi-directional loading cell, designed to address the potential shortcomings of low pressure single- and double-acting loading cells, and its use in two full-scale axial loading tests of constructed drilled shafts. First, a brief review of BDPLT systems is provided. Then, the development of the high pressure double-acting bi-directional loading cell is described, including the factors affecting grouting quality, loading capability, and the hydraulic flow system. The results of laboratory tests required to assess the cell capacity, consistency of hydraulic pressure, and integration of the hydraulic system are described. To illustrate the successful application of the high-pressure double-acting loading cell, two full-scale loading tests of large-diameter drilled shafts constructed on a building site in Korea are presented, including load-displacement curves and the load-transfer observed using instrumentation distributed along the shafts. This paper intends to introduce the feasibility of the high pressure double-acting loading cell system for performing loading tests and reducing the possibility of post-construction defects in production foundation elements.

Background on Bi-Directional Loading Tests

SINGLE-ACTING LOADING CELLS

Bi-directional pile loading tests were introduced by Osterberg (1986) and applied to the first commercial project in 1987; following the application of bi-directional tests to many post-Northridge bridge foundation elements constructed in California circa 1995, the BDPLT became largely accepted in the public transportation infrastructure sector (Hayes 2012). The Osterberg cell, or O-cell, is the single-acting hydraulic "jacking element" that forces one portion of a drilled shaft to react against the other. Single-acting cells presently range in diameter from 230 to 860 mm in diameter, delivering uniaxial forces of approximately 1.8 to 27 MN, respectively, when used in single-cell arrangements (Brown et al. 2010). Assuming adequate soil resistance is available for reaction, the total load provided by single-acting cells are limited by the supply of hydraulic pressure; typical tests are carried out with a maximum pressure of 70 MPa (10,000 psi) or less (e.g., LoadTest 2005). Nonetheless, BDPLTs can greatly exceed 53 MN by using multiple single-acting cells at a given elevation and multiple elevations to mobilize various portions of the shaft and toe resistance; Hayes (2012) reports test loads as large as 321 MN for multi-stage testing of drilled shafts.

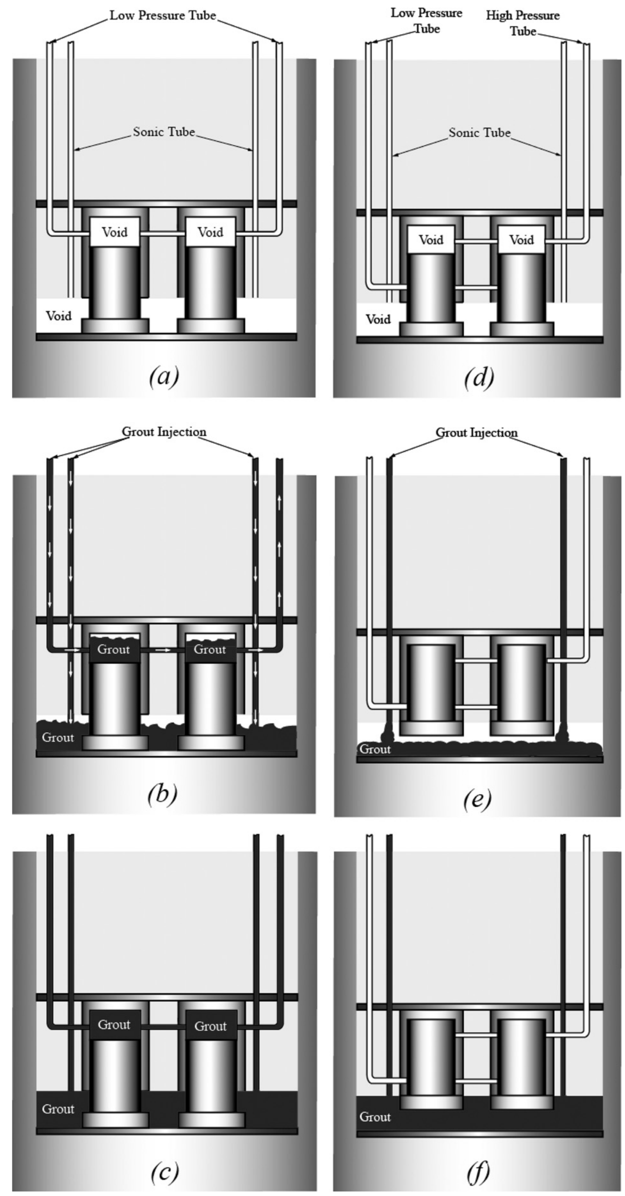
For efficiency, loading tests are often conducted on production drilled shafts. However, the expansion of the single-acting cell(s) necessarily creates: (1) a void between the top and bottom loading plates that must be filled, and (2) a void within the cell itself following removal of the hydraulic fluid (**Fig. 1**). In order to strengthen the shaft section at the location of the single-acting cell(s), grout is pumped into the void spaces via cross-hole sonic logging tubes placed for the purposes of verifying shaft integrity prior to load testing or other dedicated conduits. Upon completion of a loading test, the top and base plates remain in their expanded state because of the inability of the loading cells to be retracted. Therefore, the possibility of voids or poorly distributed grout exists owing to the difficulty of grouting around and within the expanded loading cells, which can occupy a significant footprint of the shaft cross-section.

NEW HIGH PRESSURE DOUBLE-ACTING LOADING CELL

The high-pressure and double-acting BDPLT has been developed to overcome some of the possible limitations of the low-pressure, single-acting bi-directional pile load tests, which include: (1) the possibility of poor grout integrity or distribution, (2) use of high pressures and therefore larger loads for a given cell diameter, and (3) the sequence of pressurization of the loading cells, which may affect the concentricity of the applied load. Each of these aspects is described in more detail below.

Following the BDPLT, the voids within single-acting cells are grouted to reduce the potential for poor structural performance. Grout is pumped into each cell until grout exits a return line, which should indicate that grouting of the void has been successfully accomplished (**Fig. 1(a)–1(c)**). However, this procedure could result in the existence of post-grouting voids, which can be difficult to detect and remediate. Should voids in fact exist and the shaft is placed into service, the structural integrity of the shaft may prove insufficient if it experiences a strength limit event, for which loads may be transferred to deeper portions of the drilled shaft element. Whenever possible, coring of the post-grouted zone should be performed so that the integrity of samples (e.g., continuity, stiffness, and strength) can be evaluated and compared to the design structural concrete specifications; coring into the loading cell itself for verification of void grouting is largely infeasible. However, the use of a double-acting BDPLT cell, as shown in **Fig. 1(d)–1(f)**, can be used to mitigate the likelihood of poor grout integrity. A double-acting

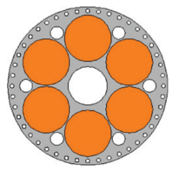
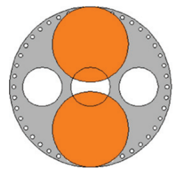
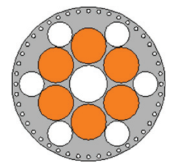
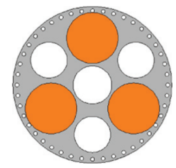
FIG. 1 Post-test grouting procedures for single-(a)–(c) and double-acting (d)–(f) bi-directional loading tests: (a) voids in single-acting cells following loading, (b) grouting of voids between loading plates and cells, and (c) grouting complete, (d) voids in double-acting cell following loading, (e) retraction of loading cells followed by grouting, and (f) grouting complete.



cell is a cylinder in which pressurized fluid can alternatively act to expand or retract the loading cell, and this allows for the formation of a uniform void space between the loading cells and the base plate that is easier to grout.

Typical single-acting loading cells use fluids pressurized to a maximum of 70 MPa; this particular element of a loading cell is of consequence since the fluid pressure directly controls the capacity of the loading cell. In practice, the new high pressure double-acting cell us typically pressurized to 100 MPa,

TABLE 1 Comparison of cell arrangements required to conduct loading tests on a drilled shaft with 2000 mm diameter and with design working load and capacity of 30 and 60 MN, respectively.

	Single-Acting Loading Cells		High Pressure, Double-Acting Loading Cells	
Cell Capacity (MN)	10	30	10	20
Cell Diameter (mm)	540	870	425	600
Working Pressure (MPa)	70		150	
Number of cells	6	2	6	3
Plan View of Cell Arrangement				
Concrete Area (m^2)	1.31	1.50	1.84	1.84
Grout Footprint (%)	48.9	55.8	68.3	68.4

but can achieve pressures of up to 150 MPa as discussed below and in the discussion of the instrumented loading tests. **Table 1** compares the arrangements and capacities of single- and double-acting loading cells for a hypothetical 2000 mm diameter drilled shaft constructed for design loads of 30 MN (*n.b.*, cells have been selected to achieve a test load of 60 MN). Because the same loading requirements can be achieved using the high pressure double-acting cells, the void space around the cells that must be post-grouted is larger and better connected, leading to improved likelihood for achieving the structural integrity required. For example, the structural grout consists of two-thirds of the total shaft footprint when using high pressure double-acting cells as compared to approximately half of the shaft footprint when using commonly available single-acting loading cells. Furthermore, the use of fewer cells (owing to the higher pressures) can reduce the costs of performing a BDPLT.

Another consideration for conducting BDPLTs is the distribution and sequence for pressurizing the loading cells when multiple cells are used. **Fig. 2(a)** shows a typical single-acting system where individual cells are pressurized separately. As a result, the cells do not expand simultaneously, and consequently, differential displacement can develop during the test and remain in place after the test is complete. This can result in problems when the test shaft serves as a production element. To overcome the potential for this problem, a synchronized flow line system, in which the flow lines for the requisite number of cells are connected, was adopted in the development and production of the high pressure and double-acting cells as shown in **Fig. 2(b)**. A pressure gauge mounted to the supply hose allows measurement of the actual pressure being applied to the loading cells. This system provides a significant advantage over an individual pressurizing system, as the cells displace simultaneously such that no eccentricity can develop.

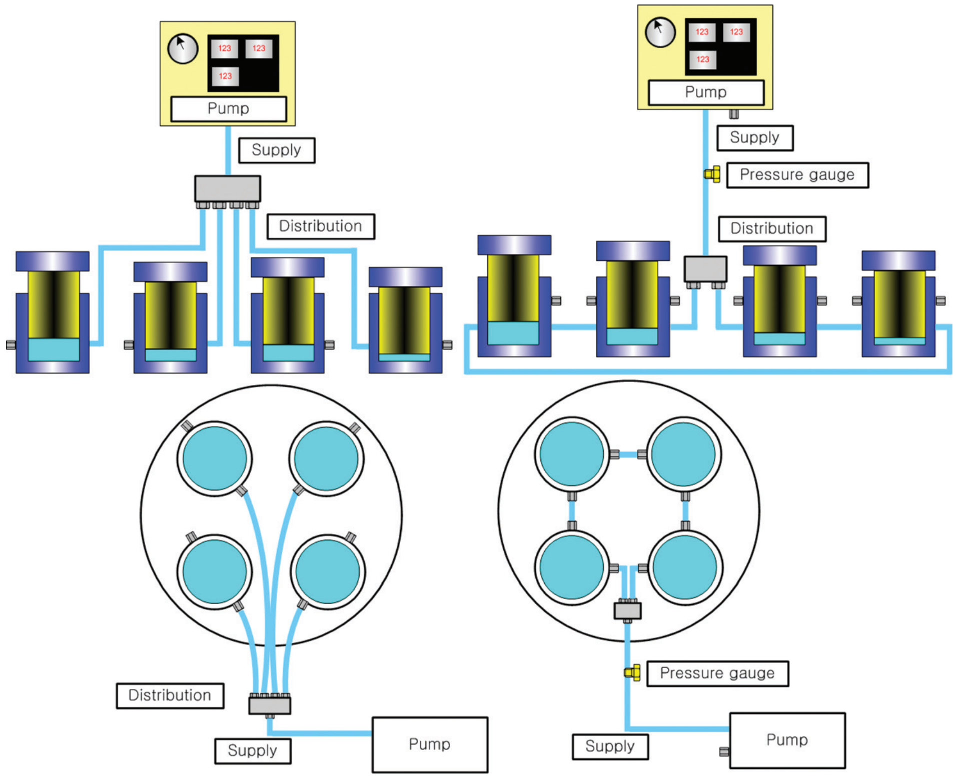
Calibration of the Double-Acting Loading Cell

In order to verify the reliability of the high pressure and double-acting loading cell, calibration tests were conducted to assess the cell capacity, consistency of pressure, and synchronization of the hydraulic fluid flow line system connecting high-pressure cells. To determine the accuracy of the load capacity of the high-pressure cells, two capacities of the double-acting loading cells were evaluated, including 14 of the 295 mm inside diameter, 10 MN and two of the 415 mm inside diameter, 20 MN cells. Tests were performed using the compression test device shown in **Fig. 3**, whereby the expansion of the bi-directional cell forces the lower plate of the device on a separate calibrated load cell. The 10 MN cells were typically jacked to a target displacement of about 30 mm prior to placement in the compression device; thereafter, the cell was further pressurized to 146 MPa, corresponding to its rated capacity, and the linearity of the pressure-load relationship evaluated. The 20 MN cells were jacked to target displacements of 25, 50, and 75 mm prior to placement and evaluation in the compression device. In order to evaluate repeatability, each cell was assessed twice within the compression device. **Figs. 4(a)** and **4(c)** show the resulting correlation between the measured load and the average fluid pressure required to achieve the targeted load for the 10 and 20 MN load cells, respectively. The load-pressure calibrations show satisfactory linearity, with coefficients of determination, R^2, equal to 0.9999 each. **Fig. 4(b)** shows the % difference in fluid pressure at a given target load for each of the 14–10 MN load cells. Although several cells showed pressure differences of about 3 % at low loads, a considerable majority of cells produce repeatable pressures within 1 % over the range in capacity of the load cell, indicating satisfactory repeatability.

Owing to the longer drilled shaft elements being required to support increasingly heavy structural loads, hydraulic hoses

FIG. 2

Pressurizing systems for bi-directional loading tests: (a) individually-operated single-acting loading cells, and (b) simultaneously-operated double-acting loading cells.



have necessarily increased in length. Higher pressures and longer hoses generate potential implications of energy losses when pressurizing to achieve a new loading increment; therefore, an investigation of the sensitivity of fluid pressure to hose length and supply pressure was required to establish an appropriate calibration procedure if deemed necessary. The test program for the pressure hose calibration checks consisted of checking 50 m hoses along intervals of 10, 20,…,50 m in length and with pump supply pressures ranging from 20, 40,…,100 MPa. Four pressure gages were installed in series at intervals of 10 m at the hose connections in order to observe the potential loss in pressure (energy). **Fig. 5(a)** shows the variation of pressure as a function of hose length and pump supply pressure; as indicated, no significant variation in pressure was noted along the length of the 50 m hoses. Additionally, the exterior diameter of the hose was measured to check for deformations caused by the application of pressure during the testing. The maximum increase of the exterior diameter of the hose was approximately 0.5 mm; this amount was considered negligible.

In order to show the stability in the pressure for the hydraulic supply lines, fittings, and pumps used to conduct a high-pressure double-acting BDPLT, high-pressure cells were connected to the synchronized oil flow line system. A pump supply pressure of 116 MPa was applied and maintained for 24 h, and the variation in pressure with time and location along the supply line is shown in **Fig. 5(b)** relative to the supply pressure. For the supply pressure, the **Fig. 5(b)** presents the variation in pressure with respect to the initially supplied pressure, whereas the % difference in instantaneous pressure is reported for the pressure at intermediate supply locations. At each location, the pressure remained relatively stable with respect to the supply pressure and with no significant fluctuations measured over the during the 24 h testing time.

FIG. 3 Schematic of the compression test device and setup used to evaluate repeatability of load cell measurements.

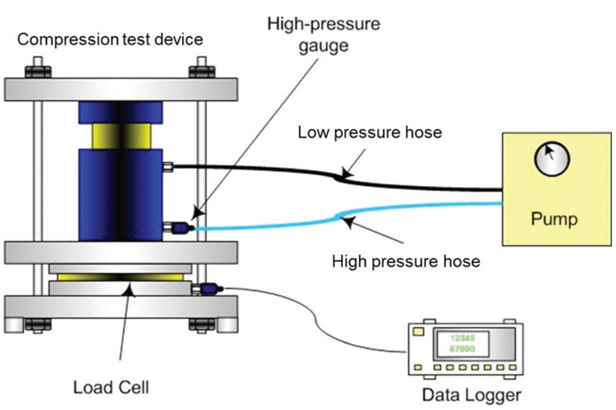
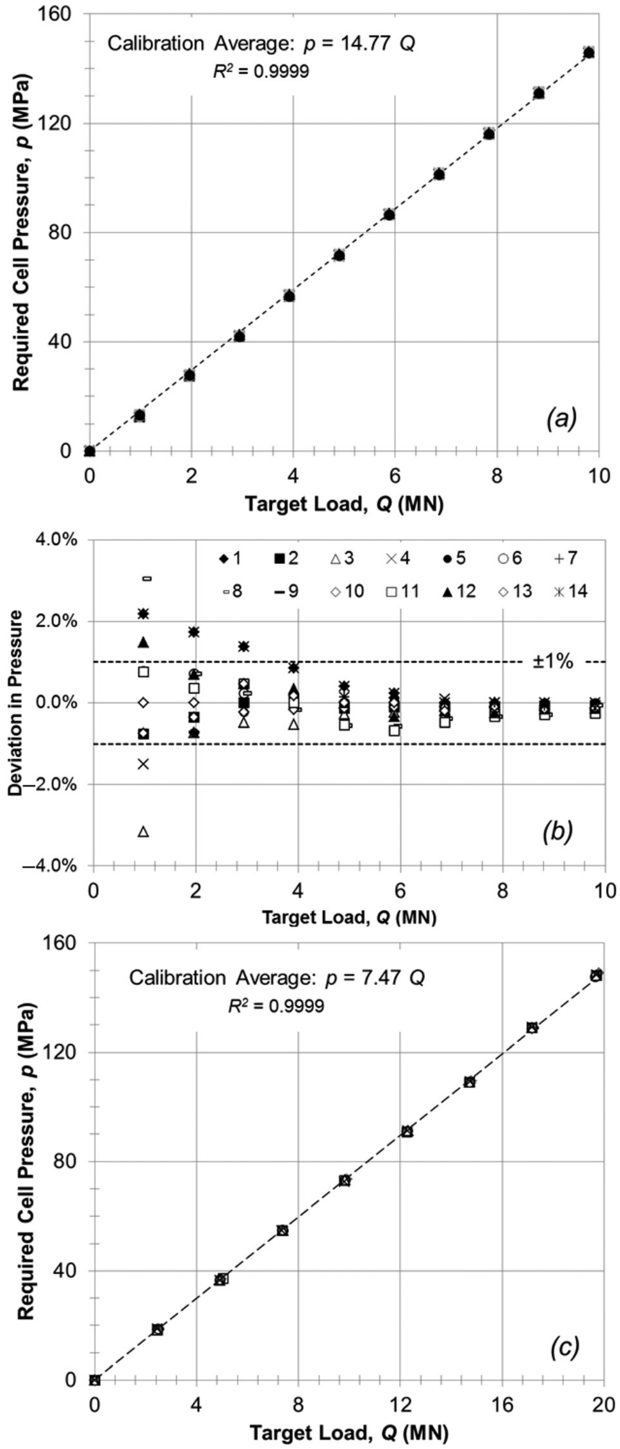
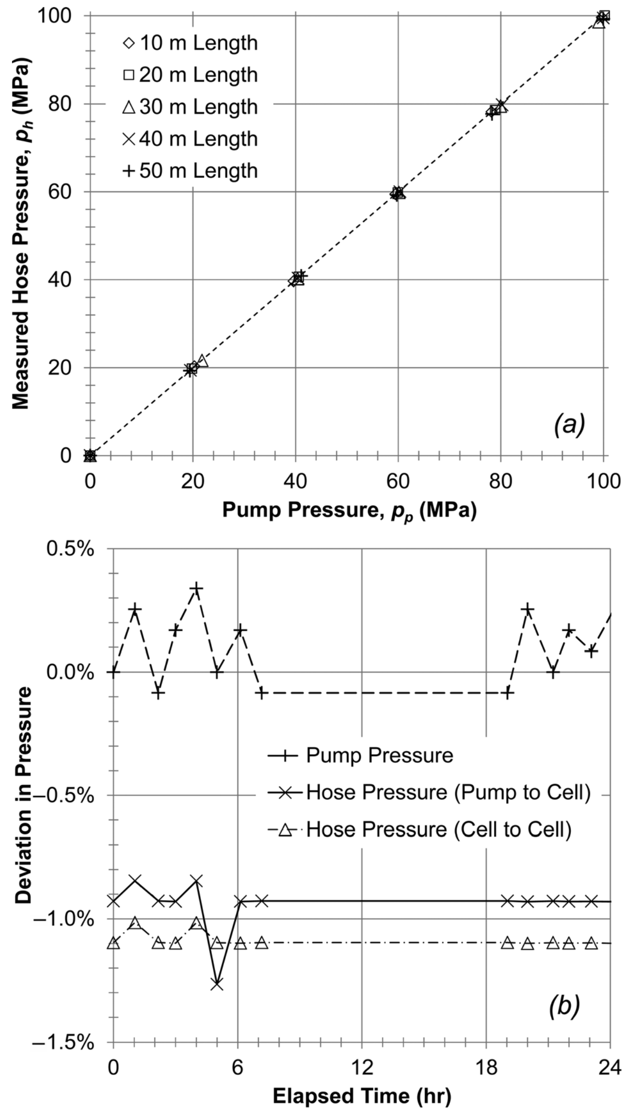


FIG. 4 Calibration and repeatability of new double-acting bi-directional loading cells: (a) results of 14–10 MN load cells, (b) % difference in pressure required to achieve a given load for the 10 MN load cells, and (c) results for the two 20 MN load cells.



Based on these calibration checks on the production-quality components of the high-pressure double-acting loading cell, it appears that the loading cell can support the purpose of conducting project-critical bi-directional loading tests. Its use in practice is demonstrated in the remainder of the paper.

FIG. 5 Pressure tests on supply hoses (a) check on pressure losses along 10 m intervals of 50 m hose, and (b) check on time-rate supply of pressure.



Application of New Loading Cell for Evaluation of Structure Foundation Support

In order to demonstrate the applicability of the new high-pressure double-acting loading cells, two instrumented test shafts (Loading Tests T-1 and T-2) performed at the same site, though with different stratigraphies, are described below. The tests were conducted to establish the load-transfer and load-displacement response of representative drilled shafts proposed to support an 80-story mixed-use high rise building with five basement stories below grade. Loading test T-1 was performed with the loading cell placed at the base of the shaft, whereas loading test T-2 was conducted with the loading cell placed 2 m

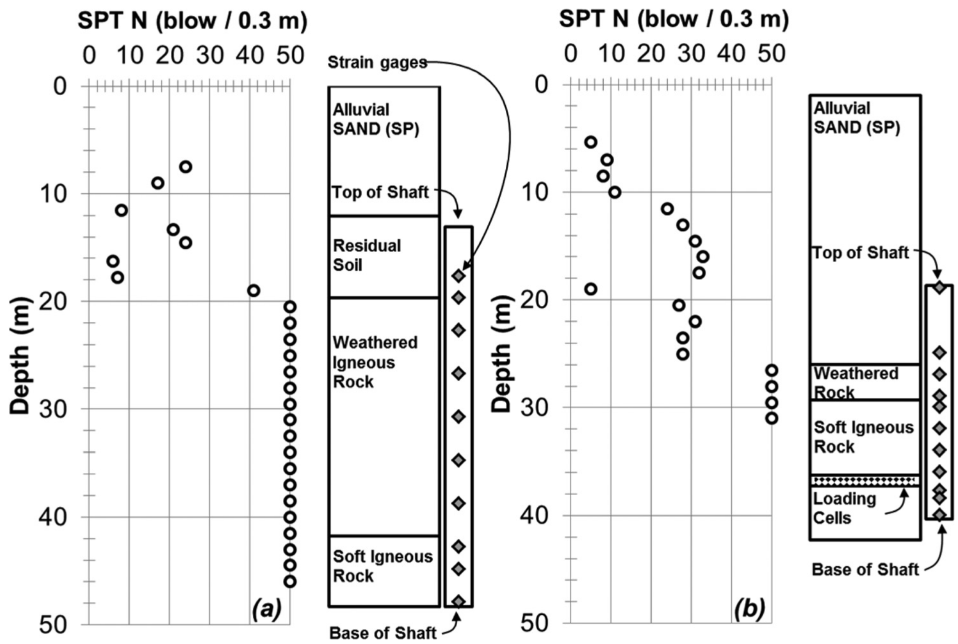


FIG. 6 Soil and instrument profiles for (a) drilled shaft test T-1, and (b) drilled shaft test T-2.

above the base of the shaft. Both loading tests were performed in general accordance with ASTM D1143.

LOADING TEST T-1

Loading test T-1 was performed on a 34.5 m long, 2.5-m diameter drilled shaft. Fig. 6(a) provides a representative subsurface profile of the geologic conditions, which includes a 12 m thick layer of poorly-graded, loose to medium dense alluvial sand overlying 7.5 m of highly variable residual soil, overlying 22 m of weathered igneous rock, underlain by soft igneous rock of unknown thickness. Intact specimens of the soft rock indicated unconfined compressive strengths of 50 MPa. Shaft T-1 was installed and tested following excavation of the basement parking levels, such that the top of the shaft was located at a depth of 13 m below adjacent grade. To achieve the target uniaxial test load of 80 MN, four 20 MN capacity high-pressure double acting loading cells were arranged symmetrically at the base of the test shaft as shown in Fig. 7(a). Displacements exhibited by each of the two loading plates were observed using three independent telltales set within casings (Fig. 7(a)). Two pairs of strain gages were distributed along ten elevations to observe the load-transfer distribution with bi-directional displacement (Fig. 6(a)). Following placement of the reinforcement cage and instrumented loading plates, structural concrete was tremied to the base of the shaft through one of several access ports and grouted in a bottom-up sequence. The loading test was initiated following adequate strength gain of the concrete, confirmed after 28 days.

Generally, loading tests are performed until one of three limiting criteria are met: the pre-determined maximum test load has been achieved, the maximum travel of the loading cell has been reached, or the maximum cell pressure has been realized. Initially, the loading of shaft T-1 was performed using 5 MN increments held for 30 min. The project team then changed the loading protocol so that loading increments were applied after a one hour hold or when the rate of movement dropped to 0.25 mm per hour, whichever came first. Although the foundation design required a capacity of 60 MN, the test was concluded upon reaching the maximum cell pressure (i.e., cell capacity) of 150 MPa, corresponding to a uniaxial load of 80 MN. The load-displacement response for the upper and lower test plates of drilled shaft test T-1 is shown in Fig. 8(a), whereas the load transfer along the shaft is shown in Fig. 8(b). Upward and downward displacements at the 80 MN test load were 21 and 32 mm, respectively. The benefit of bi-directional

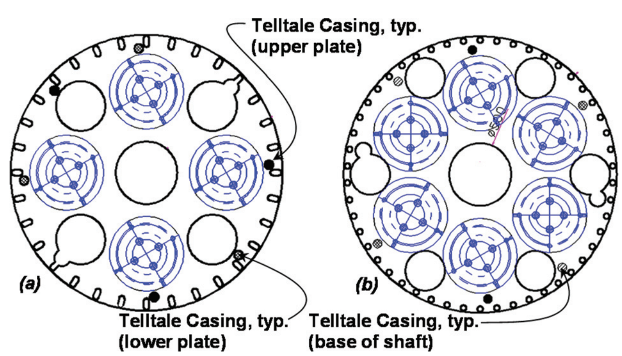


FIG. 7 Distribution of high pressure, double-acting loading cells, and various telltale casings on 2210 mm diameter loading plates for (a) test shaft T-1, and (b) test shaft T-2.

FIG. 8 Performance of test shaft T-1: (a) load-displacement curves of upper and lower steel plates, and (b) load transfer observed above loading plates for selected load increments.

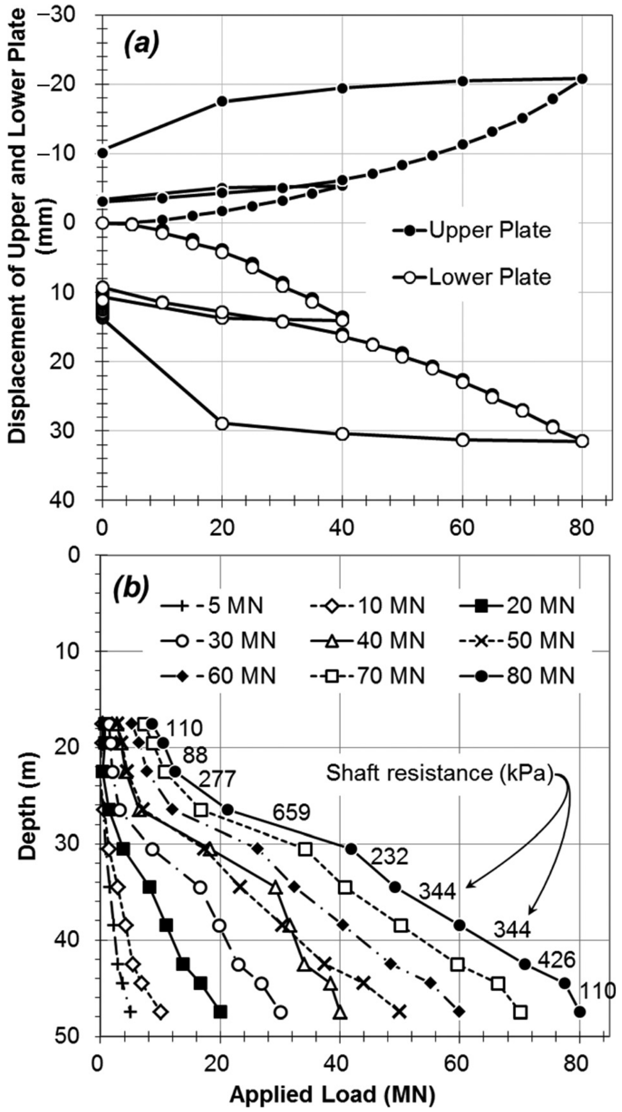
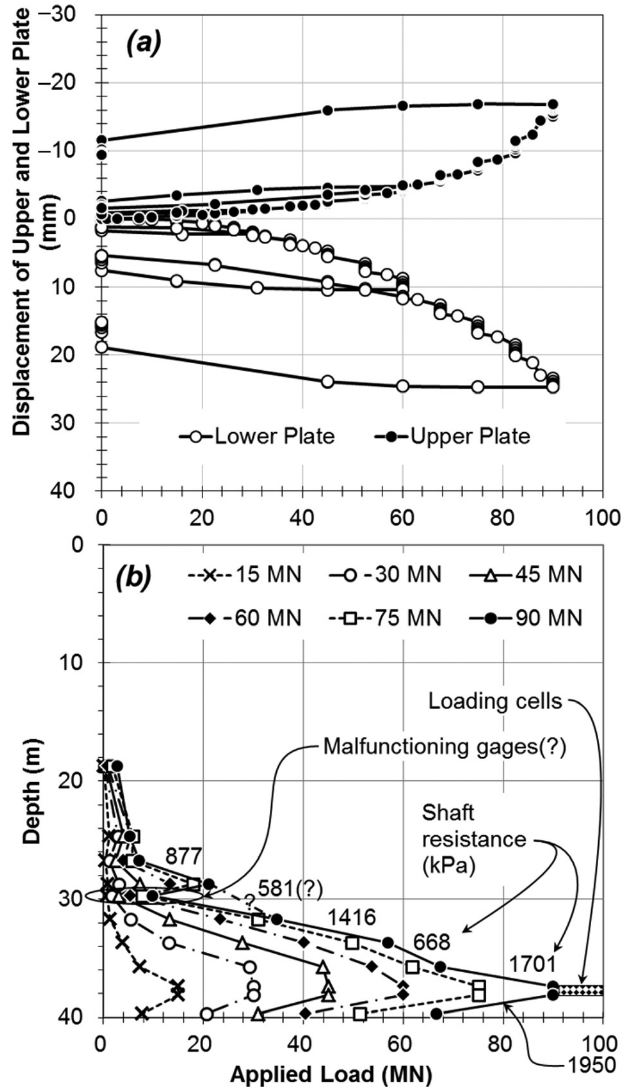


FIG. 9 Performance of test shaft T-2: (a) load-displacement curves of upper and lower steel plates, and (b) load transfer observed above loading plates for selected load increments.



testing is apparent in consideration of the weathered igneous rock providing the majority of load transfer. Use of standard penetration tests or unconfined compression tests of rock cores would likely produce significantly lower, as well as less reliable, rates of load transfer than that revealed during the instrumented loading test. For example, the shaft resistance observed in the weathered igneous rock, which is difficult to sample, was observed to range from approximately 230 to 650 kPa. Following completion of the test, the loading cells were retracted from the base plate to eliminate the voids within the cells and provide easier and more uniform post-test grouting between the base plate and the cells (**Fig. 1**). Following retraction of the loading cells, the newly created annular space was grouted to maintain the structural integrity of the shaft, with grout pressures ranging from 0.4 to 1.0 MPa (depending on the depth of the loading cells and grout stage) and 28-day compressive strengths greater than 60 MPa.

LOADING TEST T-2

The second loading test was performed on a 21.6 m long, 2.5 m diameter drilled shaft, shown in **Fig. 6(b)** and constructed within a slightly different stratigraphy as that of test shaft T-1. At this location, a 26 m thick deposit of poorly-graded sand overlies a relatively thin, 3 m thick layer of the weathered igneous rock, underlain in turn by the deep soft igneous rock layer. The base of the shaft was embedded approximately 11 m in the soft rock layer. Six high-pressure double-acting 20 MN loading cells with a maximum uniaxial capacity of 120 MN were arranged on steel loading plates as shown in **Fig. 7(b)**, and were placed 2 m above the base of the shaft. Two pairs of strain gages were positioned at 12 elevations to observe the load transfer distribution as shown in Fig. 6(b).

Based on the observed load transfer of test shaft T-1, load increments were reduced to 3 MN for the testing of T-2 in order to better observe the development of shaft resistance. These smaller loading increments, which were held for the shorter duration of 1 h or upon reaching a settlement rate of 0.25 mm per hour, were applied until achieving the target maximum test load of 90 MN. Although the test load could have continued to 120 MN with regard to the high pressure cell capacity, the test was terminated at the lower load to minimize the potential for damage to shaft T-2, which was going to be used as a working foundation to support the 80-story high-rise. Peak upward and downward displacements of 17 and 25 mm were observed at the maximum test load as shown in Fig. 9(a), and these displacements reflect a 1 h hold, over which 1.8 and 1.3 mm creep displacement occurred for the upper and lower plate, respectively. Fig. 9(b) shows the load transfer distribution for test shaft T-2. The load transfer deduced from the strain gages indicated relatively similar rates of load shedding in the soft rock layer above (∼1700 kPa) and below (∼1950 kPa) the double-acting loading cells. Owing to the relatively loose density of the alluvium at the location of test T-2, significantly less load-transfer was shown to occur in the uppermost soil layers as compared to T-1, of which the upper portion of the shaft was constructed in the residual soil. Loading test T-2 also illustrated the significant variation in rock quality over small distances in the footprint of the building site, typical of igneous formations. Following conclusion of the loading tests and verification of design assumptions, the contractor proceeded with the high-rise construction. The high-pressure and double-acting loading cells were shown to successfully perform their intended function.

Summary and Conclusions

Drilled shaft foundations represent significant investments in civil infrastructure, and efforts to improve their construction quality are welcome to owner, engineer, and contractor alike. This paper describes the development of a new, high pressure double-acting loading cell for use in bi-directional pile loading tests (BDPLT). The use of higher pressures (up to 150 MPa) in the double-acting loading cell leads to the development of higher capacities at a given cell diameter than a typical loading cell, which typically uses a maximum target pressure of 70 MPa. The use of a double-acting loading cell is also advantageous, as the cells can be retracted from the base plate following testing, again allowing a higher degree of confidence in the distribution of post-test grouting and minimization of grout voids.

The new high pressure double-acting loading cells were subjected to a number of calibration checks to illustrate their production-level quality. Calibrations of the target load and pump pressure for 10 and 20 MN cells show a high degree of linearity, with very little deviation in required pumping pressure between replicate tests. The typical high pressure pump, hoses, and hydraulic fluid synchronization lines used with the bi-directional loading cells were shown to maintain approximately 116 MPa of pressure over 24 h hold periods. Finally, the use of the new high pressure double-acting loading cells were illustrated through a case history of a high-rise building project, where two instrumented test shafts, 2500 mm in diameter and 34.5 and 21.6 m in length were tested. The bi-directional loading cells were shown to satisfactorily displace the upper and lower loading plates of each test shaft, and illustrate the load transfer possible in the weathered and intact igneous rock. Optimization of the building foundation lengths was then possible based on the results of these loading tests. Use of the high pressure double-acting bi-directional loading cells is now common in Korea and its use worldwide should continue to grow.

References

ASTM D1143/1143M-07, 2013: Standard Test Methods for Deep Foundations Under Static Axial Compressive Load, ASTM International, West Conshohocken, PA, www.astm.org

Choi, Y. and Nam, M. S., 2012, "Case Study of Load Capacities for Bi-Directional Pile Load Tests," *Int. J. Geo-Eng.*, Vol. 4, No. 1, pp. 5–10.

Hayes, J. A., 2012, "The Landmark Osterberg Cell Test," *Deep Foundations*, Nov/Dec 2012, pp. 45–49.

Iskander, M., Roy, D., Kelley, S., and Ealy, C., 2003, "Drilled Shaft Defects: Detection, and Effects on Capacity in Varved Clay," *J. Geotech. Geoenviron. Eng.*, Vol. 129, No. 12, pp. 1128–1137.

Lee, C.-S., Lee, M.-H., Kim, S.-I., and Choi, Y., 2007, "Study on Development of the Bi-Directional High Pressure Pile Load Test (BDH PLT) and Its Application," *Kor. Geotech. Soc.*, Vol. 23, No. 6, pp. 23–36.

LoadTest, 2005, "Report on Drilled Pile Load Testing (Osterberg Method), TB-1 (DSSB), New Songdo City Project, Incheon, Korea," *Data Report*, Daewang E & C Co., Buk-Gu, Busan, Korea.

Nam, M. and Choi, Y., 2007, "Structural Resistance Factors for Shear Loading in Drilled Shafts With Minor Flaws Based on Experimental Study," *KSCE J. Civ. Eng.*, Vol. 11, No. 5, pp. 243–252.

O'Neill, M., Tabsh, S. W., and Sarhan, H., 2002, "Response of Drilled Shafts With Minor Flaws to Axial and Lateral Loads," *Eng. Struct.*, Vol. 25, No. 1, pp. 47–56.

Osterberg, J. O., 1986, "Device for Testing The Load Bearing Capacity of Concrete-Filled Earthen Shafts," U.S. Patent No. 4,614,110.

Osterberg, J. O., 1998, "The Osterberg Load Test Method for Bored and Driven Piles – The First Ten Years," *Proceedings of the 7th International Conference and Exhibition on Piling and Deep Foundations*, Vienna, Austria, June 15–17, 1998, DFI, Hawthorne, NJ, pp. 1–17.

Petek, K., Felice, C., and Holtz, R., 2002, "Capacity Analysis of Drilled Shafts With Defects," *Deep Foundations 2002*, GSP No. 116, ASCE, Reston, VA, pp. 1120–1135.

Schmertmann, J. H., Hayes, J. A., Molnit, T., and Osterberg, J. O., 1998, "O-Cell Testing Case Histories Demonstrate the Importance of Bored Pile (Drilled Shaft) Construction Technique," presented at the *4th International Conference on Case History in Geotechnical Engineering*, St. Louis, MO, March 9–12, 1998, Missouri University of Science and Technology, Rolla, MO, Missouri University of Science and Technology, Rolla, pp. 1103–1115.

Tse, K., Kwok, K., and Tamura, Y., 2012, "Performance and Cost Evaluation of a Smart Tuned Mass Damper for Suppressing Wind-Induced Lateral-Torsional Motion of Tall Structures," *J. Struct. Eng.*, Vol. 138, No. 4, pp. 514–525.