George Massey Tunnel Pile Load Test Program

Dave Siddle, M.Eng.
Operations Manager, Golder Associates Ltd., Vancouver, BC.

Pierce Bakker, P.Eng.
Associate, Senior Geotechnical Engineer, Golder Associates Ltd., Vancouver, BC.

Keith MacKay, B.ASc, EIT.
Construction Engineer, Golder Associates Ltd., Vancouver, BC.

Muthucumarasamy (Yogi) Yogendrakumar, Ph.D., P.Eng.
Principal, Senior Geotechnical Engineer, Golder Associates Ltd., Vancouver, BC.

ABSTRACT As part of the George Massey Tunnel (GMT) Replacement Project, Golder was retained by The Ministry of Transportation and Infrastructure (MoTI) to perform a full scale, instrumented static pile load test adjacent to the George Massey Tunnel's southern portal. The aim was to obtain site specific measurement data on the effects of pile driving on sensitive adjacent structures and site-specific measurement data on pile load-deflection response, displacement and pile load transfer during execution of the static pile load test which would potentially reduce uncertainties and risk for a future design-build contractor for the proposed replacement bridge. The work included design and implementation of automated noise, displacement, settlement, vibration and robotic survey systems to monitor the effect on the adjacent structures and existing tunnel to pile driving in real time. Five large diameter (2.0 m) steel pipe piles were installed to a depth of approximately 67m, followed by the construction of a load test reaction frame weighing over 100 metric tonnes, which was used to conduct a static load test capable of exerting over 60MN of axial load by way of 12 synchronized large capacity hydraulic rams. The final deliverable was a factual report associated with the static load test, pile driving dynamic response, construction monitoring, and adjacent structure monitoring. This paper provides an overview of this technically challenging project.

Test Site Location and Project Description

The location of the Test Site is directly adjacent to the south portal of the Massey Tunnel on Deas Island in Delta, BC, as presented in figure 1 on the following page. The existing George Massey Tunnel is a four-lane structure, approximately 1.5 km in length that extends beneath the south arm of the Fraser River from south Richmond to Deas Island. A short four-lane bridge connects the south end of Deas Island to the Delta mainland. Current land-use adjacent to the Test Pile site consists of recreational and undeveloped land on Deas Island. In general, the existing site topography at the Test Pile site is relatively flat and ranges in elevation from approximately +1 m to +4 m geodetic, with the higher elevations generally related to the previous flood-protection (diking) works. It was a requirement that the existing GMT remain fully operational during all of the site work and specialized monitoring and construction procedures were required to minimize potential effects to Highway 99 traffic and the GMT and south approach structures. MoTI provided a clear outline on vibration and deformation thresholds and construction procedures that needed to be implemented to mitigate effects due to pile installation should they be required. Key project team members included All-Span Engineering and Construction Ltd., Fraser River Pile and Dredging Ltd., RST Instruments Ltd. Underhill Geomatics Ltd., and Hymac Industries Ltd. The entire Static Load Test was designed, set-up and executed in general accordance with the requirements set out in the contract documents and ASTM D1143M-07 – "Standard Test Methods for Deep Foundations Under Static Axial Compressive Load".

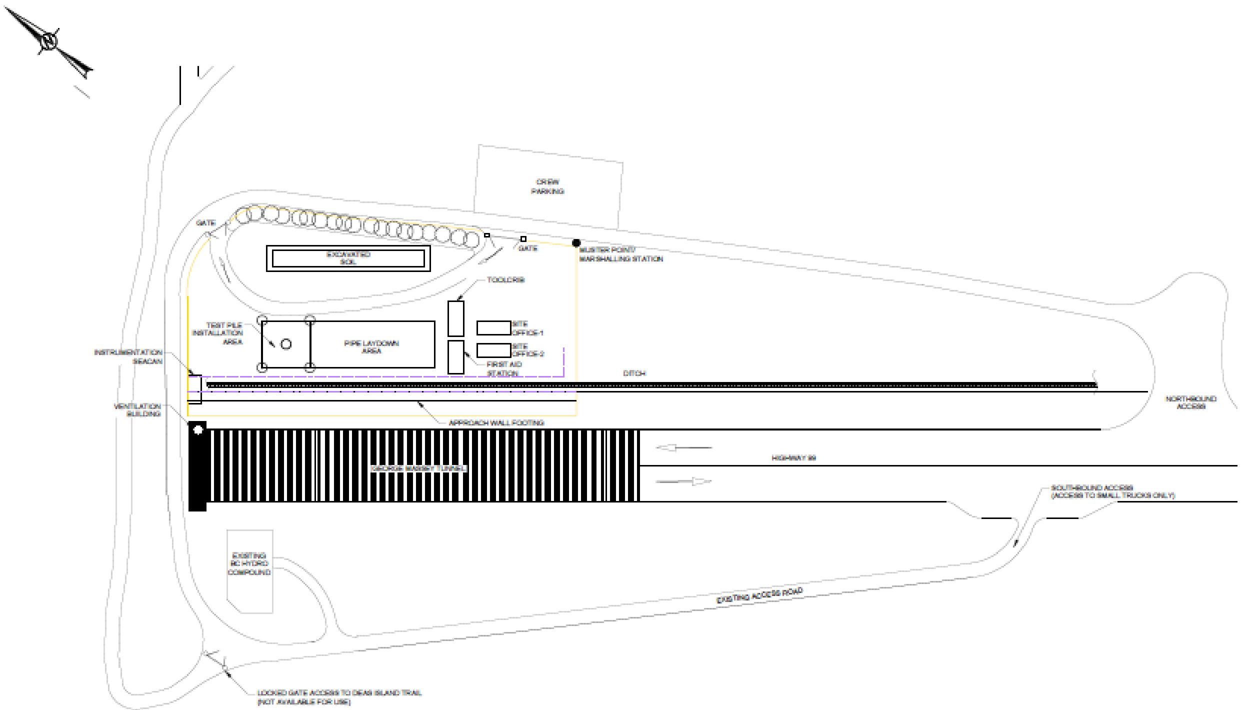
Adjacent Structures monitoring

In order to record the effects of pile driving adjacent to the GMT, adjacent structures and surrounding atmosphere, and more importantly in order to assure the safety of the GMT and adjacent structures during the test pile program, several different types of monitoring were undertaken both on and around the GMT. These included Noise Monitoring, Vibration Monitoring, Joint Displacement Monitoring, Deep Settlement Gauge Monitoring, Ground Surface Monitoring and Survey Displacement Monitoring.

Noise monitoring

Ten Noise monitors were installed in total, with three located on Deas Island, six on the Delta side of the Fraser River, and one on the Richmond side of the Fraser River. The noise meters recorded Lmax and Leq values in A-weighted decibels at eight of the locations, and Lpeak in A-weighted decibels at two of the locations. Where Lmax and Leq values were recorded, Casella 246 noise meters were utilized, where Lpeak values were recorded Casella 620 noise meters were utilized. Lmax measurements were recorded between about 99 and 121 dBA, Leq measurements were recorded between about 73 dBA and 97 dBA, and Lpeak measurements between 122 dBA and

Fig. 1. Test Pile Site Location on Deas Island



134 dBA were recorded. The largest increases in noise levels during pile driving using the diesel hammers were generally recorded at the measuring locations directly adjacent to pile driving activities.

Vibration monitoring

Six vibration monitors were installed in total, with four installed along the top of the GMT sidewalls at the south portal, and two installed inside the ventilation building. The vibration monitors consisted of a geophone, attached via cable to Instantel Pro4, Pro6 or Micromate recording devices. The vibration monitoring was conducted continuously during the pile driving portion of the project, and peak particle velocities were recorded every 120 seconds. Initially a threshold limit for the Peak Particle Velocity (PPV) was set to 15 mm/s. After the initial driving of piles and monitoring of the tunnel performance, this limit was raised to 30 mm/s as directed by MOTI. Vibration Monitoring measured PPV between about 1 mm/s and 27 mm/s at various locations on the existing tunnel structure. In general, the maximum PPV values were recorded during installation of the second segment of each pile using the APE D138-42 diesel hammer.

Survey Monument monitoring

Five robotic total stations were connected as part of a system to monitor deformation of the GMT, adjacent structures, and deep settlement gauges. Leica GMP104 mini-prisms were installed on points for monitoring and measured by the robotic total stations. The system was configured such that the x-y-z position of the approximately 40 installed prisms was measured once every 120 seconds during pile driving. The Survey Monument Monitoring measured absolute displacement between about 1 mm and 10 mm. Higher displacement values were recorded by the survey instruments during pile installation activities due to vibration of the total stations while measurements were occurring; however, the survey readings generally stabilized to values close to the original readings once pile driving stopped. Overall, the displacements recorded by the survey equipment did not appear to directly correspond to the pile installation activities and, based on review of the survey measurements, it is considered likely that the survey monument displacements were more related to external temperature and/or tidal effects in the adjacent Fraser River.

Joint Meter monitoring

A total of five crack/joint meters (RST Instruments VWCM1000) were installed on the eastern wall of the exposed tunnel approach structure at several locations. The purpose of the joint meter installations was to directly monitor relative movement between the six adjacent segments of the south approach structure that adjoin to the Ventilation Building. Each end of the joint meters were securely fastened (doweled) into the top of the concrete approach wall on either side of the designated joint and adjusted so that the meters could detect both compression and elongation (100 mm total movement range, 50 mm movement in either direction). Joint Meter Monitoring measured joint movement between about 1 mm and 5 mm. In general, the maximum displacements recorded by the joint meters did not correspond directly with the pile driving activities and, based on review of the joint monitoring displacement data, it is considered likely that the measured joint meter displacements were more related to external temperature and/or tidal effects in the adjacent Fraser River.

Deep Settlement Gauge monitoring

A total of five deep settlement gauges were installed approximately 8 m east of the eastern wall of the exposed tunnel approach structure. The purpose of the deep settlement gauge installations was to directly monitor below-ground settlement at and near the approach wall footing elevation. Deep Settlement Gauge Monitoring measured vertical (downward) displacement between about 10 mm and 25 mm. The maximum displacements in the deep settlement gauges were generally recorded during installation of the reaction piles closest to the deep settlement gauges (the deep settlement gauges adjacent to the two south reaction piles recorded the highest displacements).

Reaction Pile installation

Four 2000 mm diameter by 25 mm thick steel reaction piles and one 2000 mm diameter by 32 mm thick steel test pile were installed to approximately 67 meters depth as reaction piles. The actual pile installation activities occurred between March 12, 2016 and May 31, 2016, with test pile cleanout and final cut-off occurring shortly thereafter. Three pieces of pile driving equipment were used to install the reaction piles to the required elevation including an APE 200-6 vibratory hammer, an APE D138-46 diesel hammer and an APE D180-46 diesel hammer.

Test Pile installation

The test pile was comprised of seven sections of open ended structural steel pipe with nominal dimensions of 2000 mm by 32 mm, welded at designated splice locations. The steel sections were approximately 11.9 m in length (except for one approximate 3.6 m section) and contained both longitudinal and transverse production welds. A total of six 11.9 m long sections were delivered to the site along with a shorter 3.6 m section (76 m approximate length of steel pipe pile prior to pile driving). The test pile was installed between May 16, 2016 and May 31, 2016. Pile Driving Analyzer (PDA) testing was carried out on the test pile on May 31, 2016 (End of Initial Driving, EOID), June 1, 2016 (One Day Restrike) and June 7, 2016 (Seven Day Restrike).

Strain Gauge and Tell-Tale Installation

The test pile was required to have a series of vibrating wire strain gauges installed on the perimeter of the pile as well as two telltale rods and housings installed on the perimeter of the pile. Due to the open-ended pile design and necessity to clean the upper portion of the test pile out following installation for placement of concrete, the strain gauges and portions of the telltale instrumentation had to be installed on the outside of the test pile prior to the test pile being driven below the ground surface.

The vibrating wire strain gauges (strain gauges) and associated cables were to be installed on four axis, evenly distributed at approximately 90 degrees around the circumference of the test pile. A total of eight levels of strain gauges, with seven levels located below ground, were required starting at approximately 2 m above the tip of the test pile, then distributed at intervals ranging between about 8.4 m and 13 m along the length of the pile. Each strain gauge level was assigned a number, starting a Level 1 near the bottom of the test pile to Level 8 near the top of the test pile. A minimum of six strain gauges were installed on each below-ground level (Levels 1 through 6), with eight strain gauges installed on Level 7. Only four strain gauges (one on each of the four axes) were installed on Level 8 with no redundant gauges since these gauges were installed after the pile driving was completed.

Fig. 2. Test pile sections being spliced together while strain gauge cables being installed above.

The strain gauges were installed with the fixed, or grooved, end of the gauges facing in the upward direction and the adjustable end facing in the downward direction. This was recommended by the manufacturer based on previous case studies of vibrating wire strain gauge failures during pile driving. The adjustable end of the strain gauges was equipped with additional anchoring nuts to provide added protection against loosening during pile driving. The strain gauge cabling was securely tied to tie-down bolts that were pre-welded onto the test pile and, where required, the strain gauges and cabling were wrapped with protective fire-resistant cloth.

Along each of the four axis that the strain gauges were mounted on, a steel protective cover was provided over top of the strain gauges and cabling. The protective cover consisted of a steel 3.5 inch by 3.5 inch by 0.25 inch (88 mm by 88 mm by 6 mm) angle section that was typically pre-welded (continuous welding) onto each of the individual test pile sections prior to hoisting and stacking for splice welding. Selected sections of the protective cover were left off the test pile segments, generally at strain gauge and splice locations, until immediately prior to driving below ground. This allowed for final testing, adjustment, or repair of the strain gauges prior to driving underground (and becoming inaccessible). Where required, the protective cover plate was welded over the gap sections immediately prior to driving underground such that the cover plate extended continuously along each axis from about 1 m above the test pile tip to the ground surface. A 0.6 m long tapered section of cover plate was provided at/near the pile tip to reduce drag resistance during pile driving.

Please see figure 2 on the opposite side of the page for a picture of the test pile installation in progress.

Static Load Test preparation

As part of the Static Load Test, a load frame had to be assembled on site in order to transfer the reaction forces between the Test Pile and Reaction Piles. A complex jacking system was installed between the load frame and the test pile in order to apply the required loads to the test pile. Additionally, the Static Load Test had a component of installation and monitoring of geotechnical instrumentation on the Test Pile and reaction piles including vibrating wire strain gauges, telltale rods/housings and LVDT sensors, load cells, liquid level settlement monitoring system and laser tracking survey system.

Load Frame preparation and installation

The load frame used for the static load test was the same load frame that was used for pile load testing on both the recent Pitt River Bridge and Port Mann Bridge Replacement Projects. Due to the different test pile, reaction pile and load frame sizes/configurations used for those projects, the load frame, in its previous configuration, did not meet the minimum spacing dimensions required for the George Massey Tunnel Replacement Project Pile Load Test. As such, the load frame required some structural modification to meet the minimum spacing dimensions consistent with ASTM D1143M-07 specifications (a minimum of 5 pile diameters needed to be maintained between the test pile and each of the reaction piles for this Static Load Test).

The previous loading history of the load frame was confirmed prior to structural re-design. Based on the previous pile load test results obtained at both the Pitt River Bridge and Port Mann Bridge sites, it is understood that the load frame had previously been loaded to at least 44.9 MN and 53.7 MN reaction forces, respectively. The load frame pieces were transported to the Massey Tunnel Replacement Project Test Pile site on July 5, 2016 and assembly started on July 6, 2016. The load frame was assembled using a mobile, 200 tonne crane.

Jacking System

The jacking system was designed to apply the test loads at the required loading intervals while not overstressing any of the structural elements (including the test pile). The jacking system was also designed to optimize the useable stroke capacity of the jacks (about 123 mm each) and shimming plates (about another 300 mm thickness) for an overall stroke capacity of about 423 mm. Various combinations of loading cycles were considered in the jack shimming, pumping and sequencing design to account for various loading/deflection scenarios that could potentially occur during the Static Load Test. A total of twelve hydraulic jacks were used in the jacking system that were aligned in a symmetrical, circular layout between the test pile and load frame and twelve load cells were placed immediately below the hydraulic jacks and a steel spacer place. To maintain stability of the jacking and load cell arrangement and to adequately reduce bearing loading on the load frame and test pile, three - 2.34 m diameter solid steel load plates were provided including areas between the load cells and test pile (152 mm thick plate), the load cells and the hydraulic jacks (38 mm thick plate) and the hydraulic jacks and load frame (152 mm thick plate). The hydraulic jacks and load cells were arranged in a circular pattern at/near the outside of the steel plates at 30 degree intervals.

The hydraulic jacks were connected to a variable pumping and valve system which allowed simultaneous jacking and draining of up to six jacks at a time (this allowed for quick shimming process below 30 MN load) and allowed for jacking of up to 10 jacks at a time (for loading above 30 MN). Shimming at the higher loads, where needed, required test loads to be held constantly while draining/shimming two pumps at a time (a process that needed to be repeated five times each time shimming was required above 30 MN).

Load Cells

Twelve (12) load cells were mounted directly on top of the test pile load plate, in line with each of the hydraulic jacks. The load cells were mounted evenly around the circumference of the test pile, at 30 degree intervals, approximately in-line with the wall of the test pile.

Liquid Level Gauges

A liquid level system consisting of two transducers capable of measuring water pressure (head) in a common liquid reservoir was installed to precisely measure pile head deflection during the Static Load Test. The precision of the system was approximately 0.1mm. One of the liquid level gauge transducers was mounted directly on the north side test pile at/near the existing ground surface with another reference liquid level gauge transducer mounted on the reference H-pile located near the test pile. A small, 0.5 m deep localized excavation was provided immediately below the transducer mounted on the test pile to accommodate pile/liquid level gauge movement during the Static Load Test. The liquid level reservoir connecting the transducers consisted of a 75 mm diameter flexible polyethylene pipe that covered with mineral soil between the test pile and the reference H-pile to reduce potential temperature change effects. The liquid used in the system was 100% water and completely filled the reservoir piping system.

Laser Tracking Survey

A precision laser tracking system was used to monitor and record absolute movement of the above ground portions of the test pile and reaction piles during the Static Load Test. The system included a Leica Absolute Tracker AT402 with laser reflectors installed on each of the five piles. In addition, a control network consisting of an additional six reflectors mounted on concrete pedestals and/or portions of the GMT was installed around the pile test area to establish/maintain survey control of the laser tracking system during the test. The laser tracking system included its own data logger which was time synchronized with the main automated data acquisition system so that the time-stamped laser tracking data acquired during the test could be aligned with the other instrumentation data acquired during the Static Load Test. The system had a precision of approximately 0.1mm in both vertical and horizontal directions.

Vibrating Wire Strain Gauges

A series of vibrating wire strain gauges was installed on the test pile and reaction piles to measure strain in these piles prior to and during the Static Load Test. In addition to below ground strain gauges on the test pile installed during pile driving, a single row of strain gauges was also provided at 0.3 m above the ground surface on each of the test and reaction piles. Each of the above ground levels included vibrating wire strain gauges mounted directly on the pile sidewall(s) at 90 degree intervals (a total of four above ground strain gauges on each level for each of the five piles). The pre-test elevation of the above ground strain gauges was approximately +1.2 m on each of the piles. On the test pile only, seven levels of below ground strain gauges were provided, with six strain gauges mounted at 90 degrees apart on each level, except on Level 7 (elev. -9.1 m) where eight strain gauges were mounted. The below ground strain gauge levels were located at approximately elev. -64.1 m, -55.7 m, -47.7 m, -38.9 m, -30.5 m, -22.1 m, and -9.1 m. In total, 64 strain gauges were installed, including 44 below ground strain gauges on the test pile and 20 above ground strain gauges on both the test and reaction piles.

Of the forty-four below ground strain gauges that were installed on the test pile, only thirty-two strain gauges remained functional immediately prior to the Static Load Test. The functionality of the below ground strain gauges was monitored at regular intervals during installation of the strain gauges and pile driving. It was observed during pile driving that many of the strain gauges became non-functional and/or could not be read with handheld monitoring equipment. The functionality/readability of the strain gauges appeared to be inversely proportional to their exposure to pile driving with the APE D180-42 diesel hammer (i.e. the strain gauges that were located in closest proximity to the impact point and exposed to the highest amount of impact repetitions appeared to lose functionality/readability first).

Telltales and LVDTs

Two 9.5 mm diameter, solid stainless steel, telltale rods were installed within 25 mm square steel tube housing(s) that were welded directly onto opposite sides of the test pile. The telltale rods were installed following installation of the test pile, cleanout and placement of the concrete plug. Two Linear Variable Differential Transducers (LVDTs) were mounted directly onto the test pile above the top end of each telltale housing to precisely measure the telltale rod movements during the Static Load Test. Each of the LVDTs were clamped onto mounting blocks that were welded onto the side of the test pile. The mounting blocks also contained guide holes to stabilize the telltale rods and reduce jitter in the LVDT readings. The measuring end of the LVDTs was directly clamped to the telltale rods.

Fig. 3. Jacks and load cells on top of test pile, with strain gauge instrumentation installed.

Static Load Test

The Static Load Test was carried out in three individual phases on different days including an initial loading and unloading phase, a second loading and unloading phase, and a third loading and unloading phase. The following sections present the specific details of the overall Static Load Test.

Phase 1 Sequence

The initial stage of the Static Load Test was carried out to approximately 300 mm of vertical pile head deflection, which was defined as the maximum pile head deflection criteria by MoTI for the Static Load Test. The maximum test load achieved during the initial loading sequence was 26.2 MN and this test load was held for 15 minutes between approximately 280 mm and 297 mm pile head deflection. The unloading phase immediately followed the 15 minute hold period at 26.2 MN.

Phase 2 Sequence

A maximum test load of 26.7 MN was achieved during the second loading sequence at 413 mm pile head deflection. The Phase 2 loading sequence was terminated at this pile head deflection as the maximum stroke of the jacks was realized. The second unloading phase immediately followed a 6 minute hold period at 26.7 MN.

Phase 3 Sequence

In preparation for the Phase 3 portion of the test a few special adjustments were incorporated:

- The upper portion of the test pile was completely filled with concrete.
- Additional shims and spacer plates were required to extend the range of the jacking system. A layer of twelve – 350 mm high, 200 mm diameter solid steel shims was provided immediately above the load cells at the exact same spacing/location as the load cells. An additional 2.20 m diameter, 25 mm thick spacer plate was provided between the new shim layer and jack layer. All the jacks, shims and load cells were

placed at 30 degree spacing and 910 mm diameter offset from the centre of the pile.

- Other adjustments to the instrumentation, including liquid level system, were necessary to extend the measuring range of the instruments.
- The surficial materials located immediately surrounding the test pile were locally excavated to approximately 0.4 m below the Phase 1 and Phase 2 loading sequence ground elevation to allow the side mounted instrumentation to extend below the surrounding ground surface.

All twelve hydraulic jacks were utilized with the test loads applied by alternating sets of six jacks. Three hydraulic pumps were utilized concurrently to achieve the maximum test load of 29.1 MN during the third loading sequence at 257 mm pile head deflection. It should be noted that the vertical pile head measurements were zeroed at the start of the third loading sequence and, therefore, do not represent the full pile displacement for the three combined loading sequences. The Phase 3 loading sequence was terminated at this pile head deflection with the approval of MoTI. The unloading phase immediately followed a 15-minute hold period at 29.1 MN. A picture of the Load frame sitting on top of the piles, along with associated jacks, pumps, load cells and other instrumentation on the first day of the static load test, is presented in the figure 4 below:

Fig. 4. A view of the Load Test Frame on the piles on the day of the Static Load test.

Conclusion

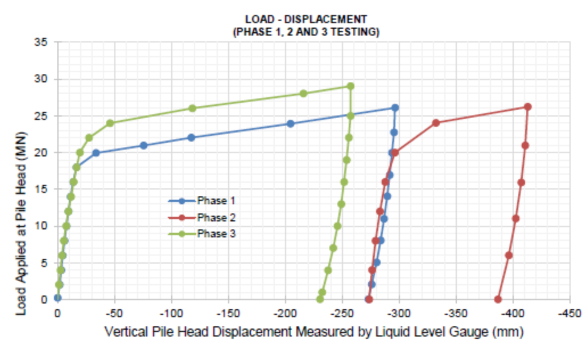
The three phases of the Static Load Test were completed successfully. A summary chart displaying the load vs. displacement curves obtained during the three phases of the Static Load Test is presented in figure 5 on this page.

No visible damage due to construction activities was observed to the structural elements based on comparison of the pre and post condition surveys that were carried out. Some ground surface subsidence was observed between the Massey Tunnel and the Test Pile site during pile installation when the vibratory hammer was used.

The Static Load Test was carried out in three separate loading/unloading phases including:

- An initial loading and unloading phase on August 18, 2016 carried out on the original Test Pile configuration to 26.2 MN maximum applied load and 296 mm vertical pile head displacement.
- A second loading and unloading phase on August 19, 2016 carried out on the original Test Pile configuration to 26.7 MN maximum applied load and 413 mm vertical pile head displacement (total combined displacement including the first loading and unloading phase).
- A third loading and unloading phase on August 31, 2016 carried out on a modified configuration of the Test Pile where the concrete plug was extended to the top of the Test Pile (the bottom of the lower load plate). The third phase of the Static Load Test was taken to 29.1 MN maximum applied load and 257 mm vertical pile head displacement (644 mm combined vertical pile head displacement for all three phases of the test).

Fig. 5. Load Displacement Graph from Static Load Test



Additional information on this project and the load test results, can be found on the MoTI project web page.

We would like to acknowledge and thank the MoTI for their involvement in the execution of this project and for their permission to publish this paper.

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