MICROPILE PERFORMANCE AND DURABILITY AFTER 15 YEARS UNDER LOAD

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ABSTRACT

The data presented in this paper provide a history of micropile performance and durability under static load in a corrosive environment. The data are compiled from a group of 536 micropiles over a 15 year period. Two monitoring systems measured forces in the piles at the surface and at discrete depths throughout their lengths. A third monitoring system measured ground deformations within the soil profile from the tops to tips of the piles. The data demonstrate a close correspondence between compressible soft soil intervals and forces carried by the micropiles in these intervals. The data also revealed that load has redistributed along and between the piles over the years. The tops of the piles are exposed in an enclosed and uncontrolled humid environment. Steel has corroded and scaled off the load transfer frames in sheets. Galvanized conduits have disintegrated. Wire connections have corroded. By September 2012, 210 of 1072 Vibrating Wire Strain Gauges (VWSG) had corroded to failure. Terminals were cleaned restoring data quality and a program to replace failed VWSG's on the tops of the micropiles was initiated.

INTRODUCTION

The site is located in the Las Vegas Valley of southern Nevada, USA. The geologic setting and representative soil properties are described in a paper published in the proceedings of the Ninth International Conference on Piling and Deep Foundations, (pp 131-138), Nice France, in June 2002. That paper describes, in detail, the micropiling methods, drilling technique, rate of advance, pile and grout materials, plastic grout properties, grouting technique, grout strength, and load test results. That paper should be reviewed for the details of the instrumented micropile group construction.

The structural frame for the 44 story building was complete and partially skinned in June 1998 when it was recognized that unanticipated settlements were jeopardizing the completion of the resort complex. The owner and the governing agency required that a method to control the movement be implemented for work to continue. Within a three week period; a plan was developed; and the structural engineer determined the method would not further compromise the structure; a contractor was mobilized; and one micropile was constructed to a depth of 200 feet (61m) to demonstrate that the concept was constructible. The first 6 inch (152mm) diameter by ½ inch (12.7mm) wall, production micropile (N30) was installed on July 16, 1998. The last micropile was installed on October 9, 1998.

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A quality assurance plan was developed, submitted, and approved before production began. The plan required; continuous inspection of; drilling; grouting, and grout sampling; load testing every micropile; paired VWSG's mounted at the top of each pile; and sister bar strain meters (SBSM) embedded in at least 10 percent of the micropiles between the tops and tips. The duration of the monitoring is at the discretion of the governing agency, (Figure 1).

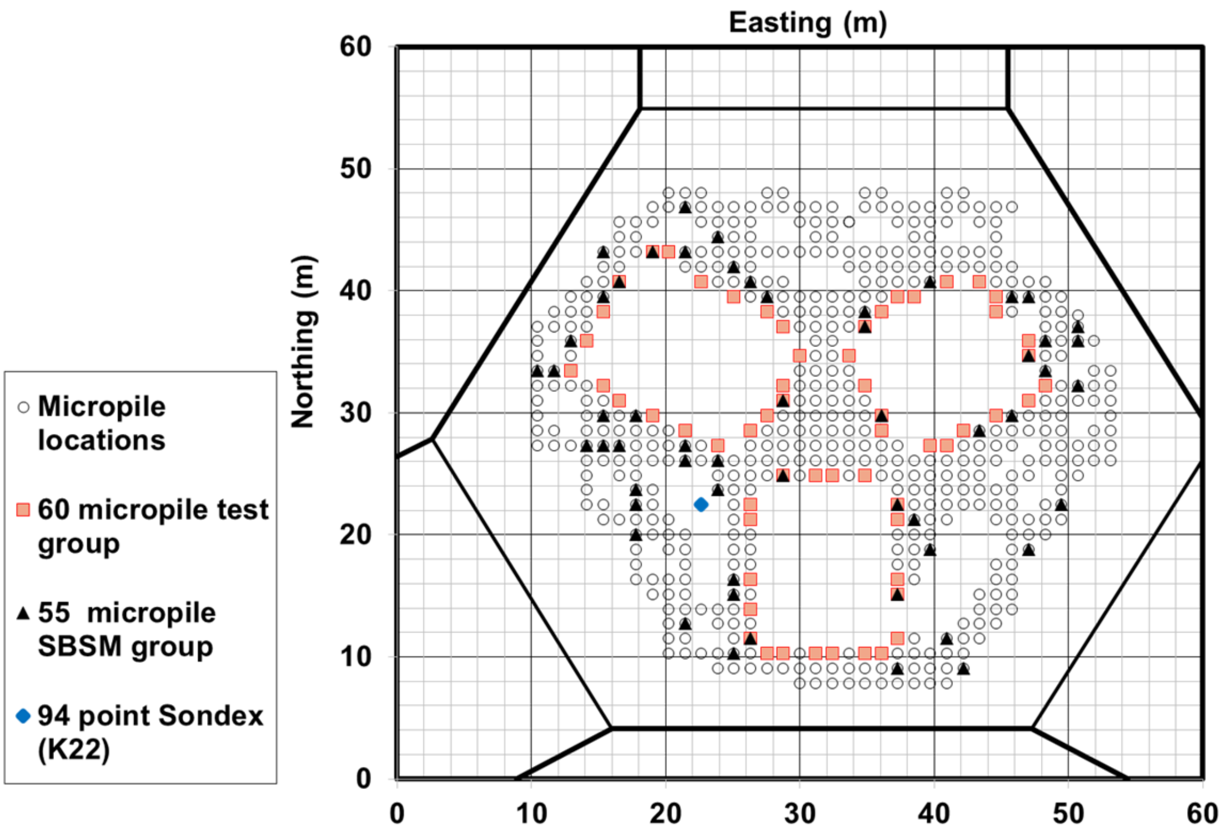

Figure 1 - Micropile plan grid 1.2 x 1.2 meter

Figures 2 and 3 are representative of site conditions during the installation near the completion of the work. Load testing and the quality assurance testing are described in the 2002 paper[2].

Fifty eight micropiles were instrumented with SBSM's placed inside the casing and grout at depths of 28.5 to 200 feet (8.7 to 61 meters) below the tops of the micropiles. Ten SBSM's in three micropiles were lost to construction work. Four additional SBSM's failed between 1998 and 2012. By 2012 corroded gauges and wiring

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[2] MICROPILE PERFORMANCE VARIABILITY, A FUNDAMENTAL CASE STUDY, Ninth International Conference on Piling and Deep Foundations, Nice FR, pp131-138, June 2002, WE Vanderpool, DA Bruce, EE Rinne, FH Kulhawy

connections destroyed 210 VWSG's and degraded data from other instruments, (Figure 4).

A group of 60 micropiles was loaded to 300 kips (1334 kN) each on September 4, 1998. This load was sustained for 70 days until all of the 536 micropiles had been load tested.

Figure 2 –Micropile installation completed October 9, 1998.

A permanent 50 kip (222 kN) load was applied to each micropile and mechanically "locked-off" between November 10 and 13, 1998. A jack remains on each micropile to permit load adjustments in the future, if warranted. The facility was completed and occupied in March 1999. There has been no significant change in the building load since March 1999.

Seepage infiltration from utility lines developed at some unknown date after the area was enclosed (Figure 5). Maintenance between November 1998 and March 2012 consisted of cutting shallow sumps and installing pumps into the top of the mat foundation (Figure 6). Infiltration is currently approximately one gallon per minute based on the sump volumes and the pump cycle rate.

Figure 3 – Between grid lines 27 and 28. Micropile H28 in foreground.

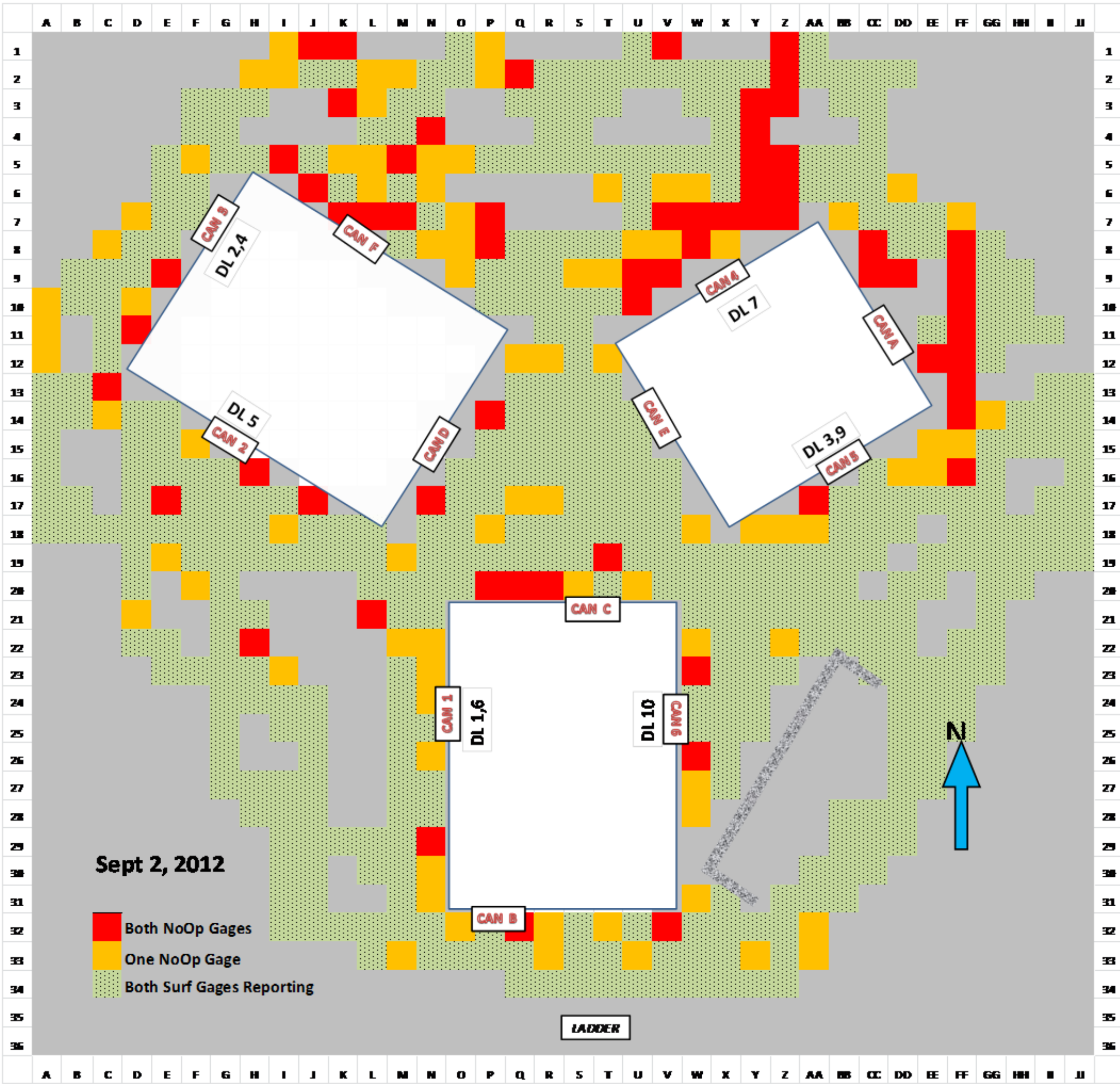

Figure 4 – Micropiles with one (82) or both (64) gauges corroded beyond repair September 2, 2012

Figure 5 - Seepage and staining, from leaking utility lines.

Figure 6 - Sump and pump operating at approximately 1-minute cycle.

MONITORING SYSTEMS

Signal cables from the 1072 VWSG's and the 119 SBSM's that survived the construction were routed to nine data loggers. The loggers were mounted on elevator walls at convenient locations around the micropiled area, (Figures 4 and 7).

Data were collected sequentially, each hour, and temporarily stored on site. Initially, data were recovered and processed weekly until the structure was occupied. The data processing frequency was subsequently modified to monthly, quarterly, and now annually. One of the nine data loggers failed in the fall of 2010. The problem was detected in January 2011 and this data logger was replaced.

Figure 7 - Steel conduit consumed by corrosion (12/12/2013). Data logger-5 mounted on the south wall of the west elevator.

Vibrating Wire Strain Gauge (VWSG) pairs

The VWSG pairs mounted at the tops of the micropiles are exposed to a humid, uncontrolled environment. Water from undetermined sources, (excess irrigation, leaking water lines, or drains) has been seeping through walls and electrical conduits into the micropiled area since the facility was occupied. Corrosion has been aggressive in some areas, (Figures 8, and 9). The corrosion shown in Figure 10 is more representative of the general conditions.

Figure 8 - Micropile J19, 12/12/2013

Figure 9 - Micropile E14, 12/12/2013

The VWSG's were protected by PVC covers, (Figure 10). By 2012, data from at least one of the VWSG pair on 146 micropiles were corroded beyond repair or data were unreliable, (Figures 11). A maintenance program was initiated to clean terminals and replace failed gauges, (Figure 12).

Figure 10 - VWSG's on Micropile L33 with PCV covers.

Figure 11 - Micropile E14, 12/12/2013

Figure 12 - Micropile J19, 12/12/2013 with replacement VWSG's

Embedded Sister Bar Strain Meters (SBSM)

One hundred twenty nine SBSM's were embedded in the fluid grout of 58 micropiles during construction. Ten instruments in three micropiles did not survive the construction. One to four instruments were installed per micropile at depths of 28.5 to 200 feet (8.5 to 61 meters) below the top of the micropile. Few data were collected during the construction phase due to the congested work area. However, small clips of data were collected between installation and load test at eight micropiles on four to seven dates.

Two SBSM instruments were installed in pile N31 at depths of 70 and 80 feet (12.2 and 15.2 meters). Data were collected on five dates from these instruments in N31 after it was constructed on July 24, 1998 and before it was load tested on August 4, 1998. Data from pile N31 between July 24 and July 30, 1998 are presented in Figure 13. These instruments were logged at 15 second intervals from August 11th to the 18th, 1998 and from August 21st to the 25th, 1998, (Figure 14). Micropile N31 was one of the 60 micropiles loaded to 300 kips (1335 kN) as a group on September 3, 1998. These instruments were not logged during this period of sustained 300 kip (1335 kN) load from September 3 to November 13, 1998 when the 50 kip (222 kN) load was applied to each micropile and the long-term monitoring system was commissioned.

The pattern of daily increasing compressive load was common for each of the micropiles where data were collected. Initially (7/25–7/30) micropile N31 was accumulating load at approximately 15 kN/day. By August 30, 1998 the rate of accumulating load on N31 had decreased to approximately 11 kN/day. Two hundred and four micropiles had been installed and 82 of these piles had been load tested by August 30, 1998.

Throughout the remainder of the paper data are presented as sequential daily observations. Data presented in Figures 15 to 20 have been parsed from the hourly collection rate to the midnight data set for each day from November 13, 1998 to January 1, 2014.

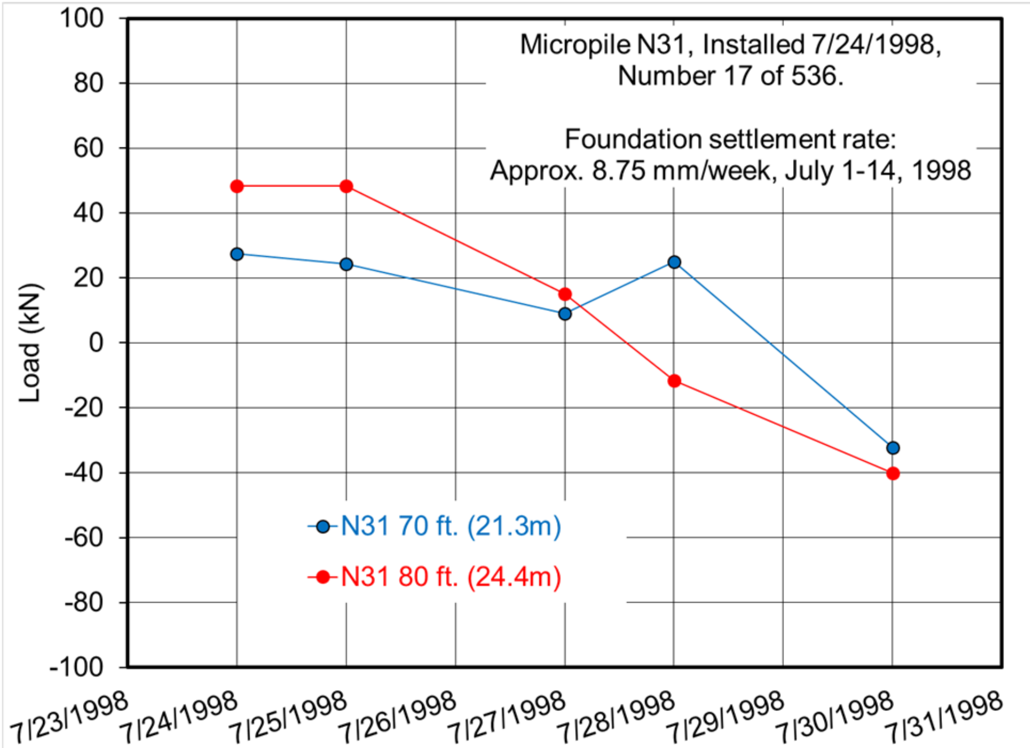

Figure 13 - Embedded SBSM data from period between installation and load test

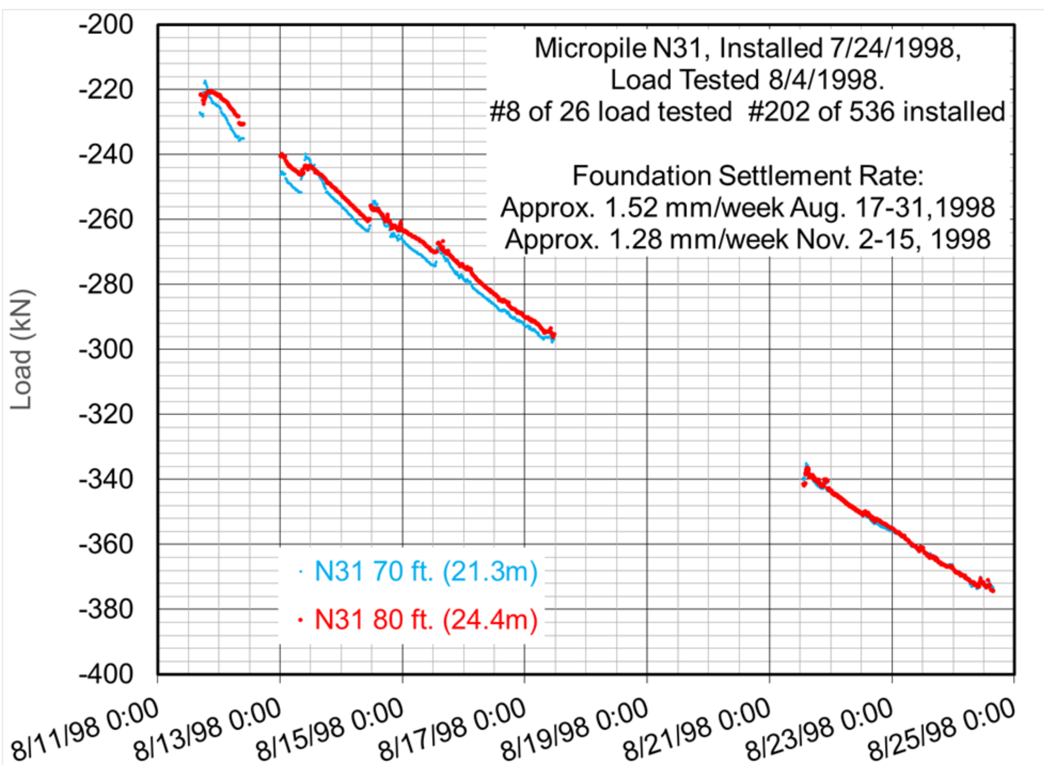

Figure 14 - Embedded SBSM data from the period between load test and 60-micropile group load application.

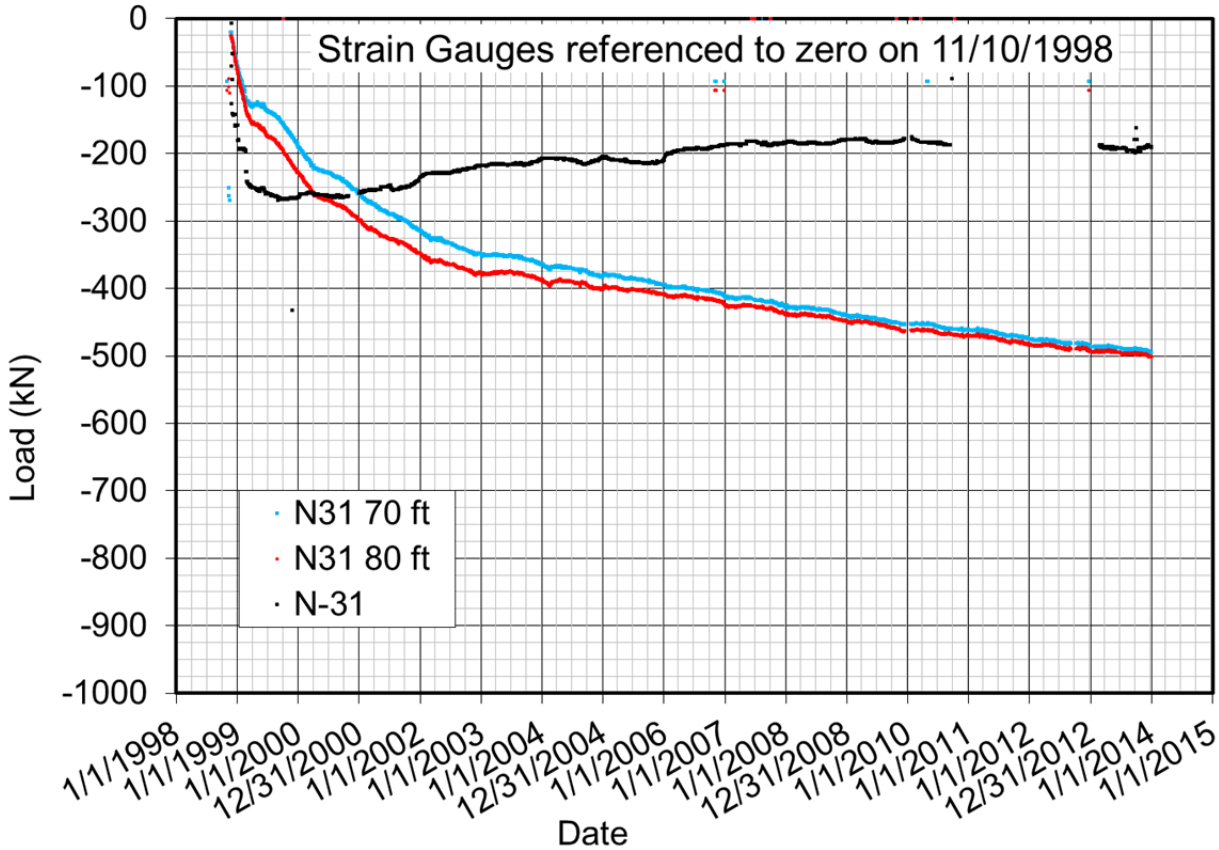

Figure 15 - Micropile N31 VWSG and SBSM data since 11/13/1998.

LONGTERM MONITORING

The top ten feet (3 meters) of each micropile were isolated from the mat foundation by a ten inch (0.25 meter) diameter PVC pipe to provide isolation between the grout and the mat concrete. The mat provided the reaction during load tests and for the permanent load applied in November 1998. Load tests confirmed the bond was yielded during each test. Data infer that this bond has yielded between the mat or micropile and the PVC sleeve multiple times over the past 15 years. The bond yield has appeared as an abrupt change in load within the 24 hours between observations. The limit state residual bond stress appears to be on the order of 0.62 to 0.65 psi (4.3 to 4.5 kPa) for micropile P15 (Figure 16, 2/28/02 and 2/12/08).

Close examination of the gauge values for the pair at the top of micropile P15 and others reveal that the loads are not constant and small changes occur daily. Both increasing and decreasing patterns of changing load over periods of months to years are common.

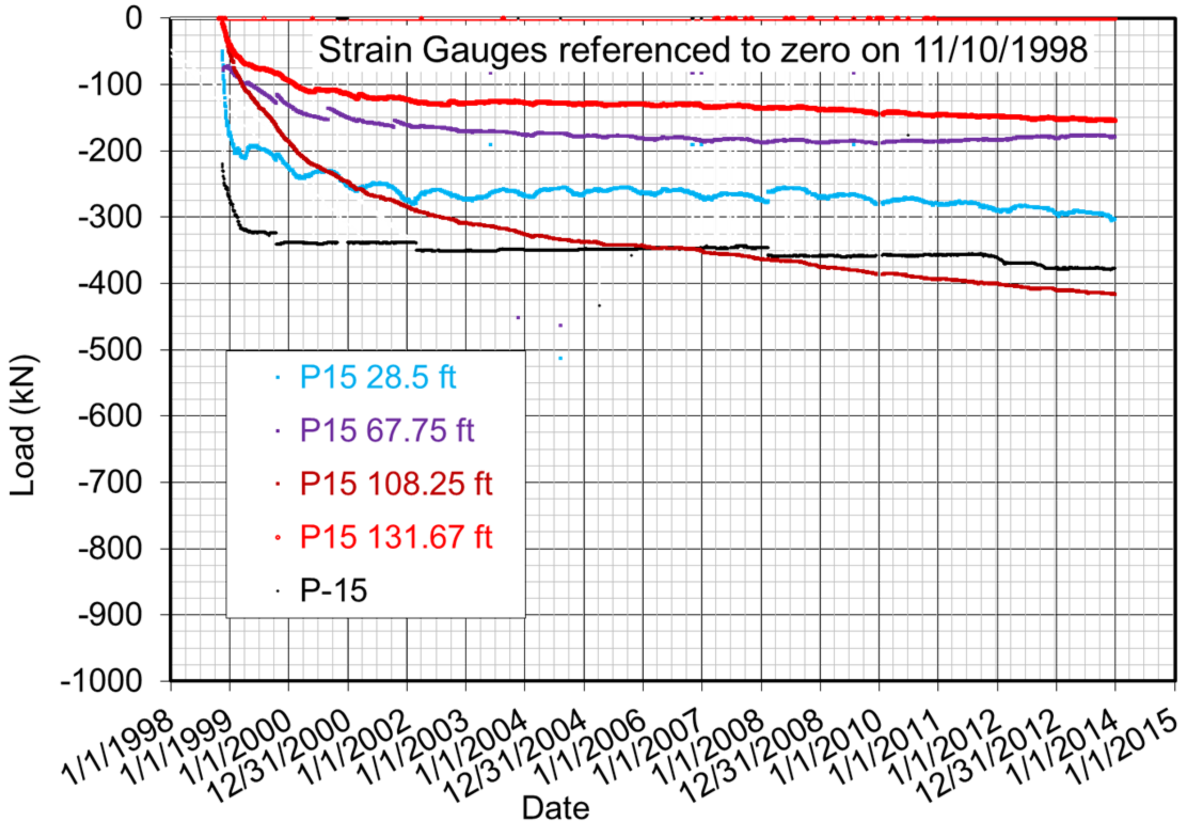

Figure 16 - Load changes 2/28/2002 and 2/12/2008 represent PVC bond yield.

Annual cyclic excursions from the nominal compressive load for many SBSM's located up to approximately 70 feet (21 meters) below the tops of micropiles have been observed. The pattern is more pronounced in SBSM's located in members of the group of 60 piles loaded to a 300 kip (1334 kN) load for 70 days. Annual fluctuations in soil temperature to a depth of 70 feet (21 meters) have been observed locally, however the range at this depth is typically 1 to 3 degrees (F) peaking in the fall and lowest in the spring. The fluctuation in the groundwater head locally has been approximately +/-1 foot (300mm) annually, also peaking in the fall. This cyclic response is not explained.

By January 2001, time dependent events, and soil profile properties were clearly not uniform or static with respect to time or depth below the tops of the micropiles. The building load at the tops of the micropiles has been nearly constant since March 1999. The load within the micropiles migrated deeper in the first year and has increased in compressible layers over the past 15 years. Large excursions of the load, both decreasing and increasing, have occurred at discrete depths (Figures 17, and 18).

The data from the embedded SBSM's have been grouped into 14 depth intervals with four to 15 of the total 114 to 119 reporting SBSM instruments per interval. The data from the VWSG pairs at the tops of the micropiles and the data from each grouped depth interval have been averaged to reduce the complexity of the data set. This data set still preserves 5083 daily sets of data for the surface mounted VWSG pairs and each of the 114 SBSM strain meters at the 14 depth intervals. Fifty of these averaged data sets for load in the depth domain from selected dates between November 13, 1998 and January 1, 2014 are presented in Figure 19. There are unreported additional similar data sets. One for each day since the system was commissioned.

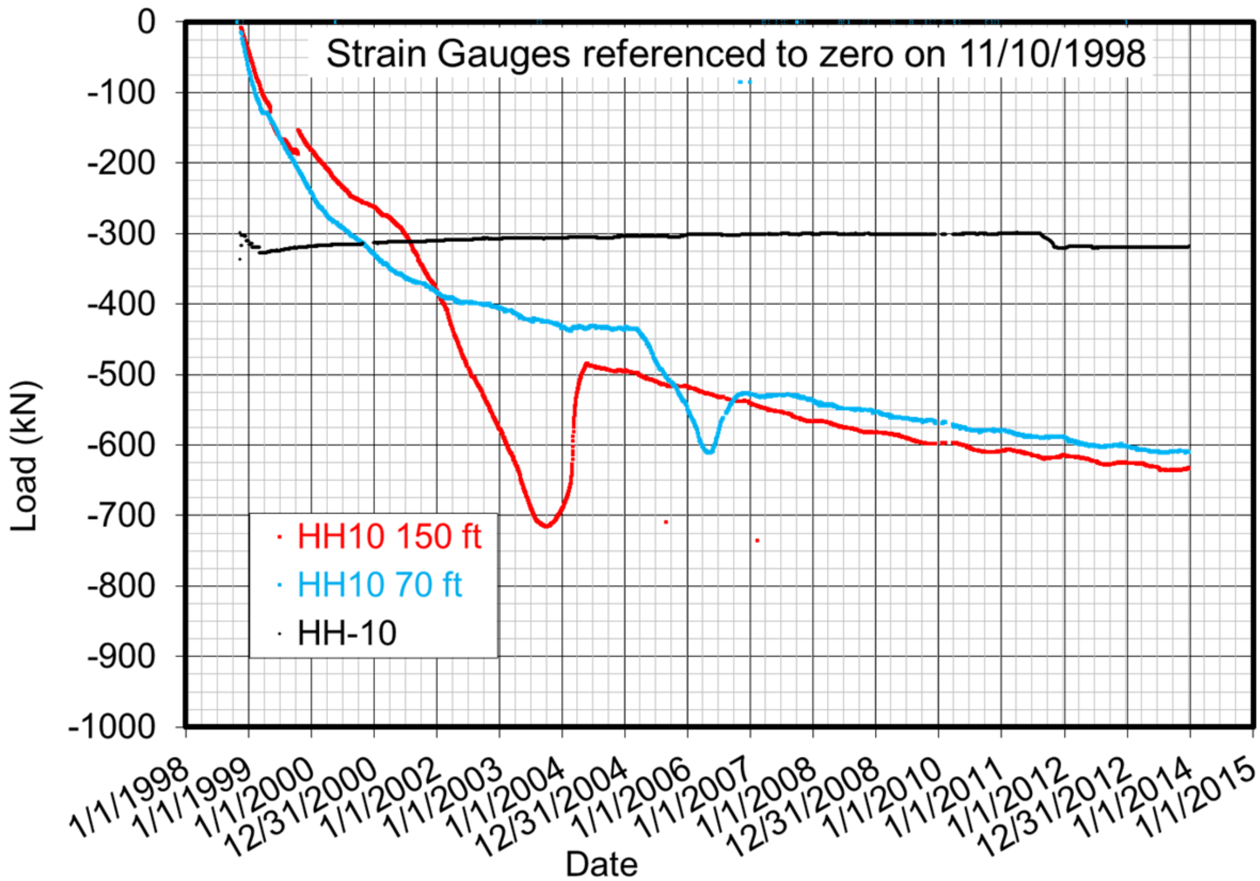

Figure 17 – Micropile HH10

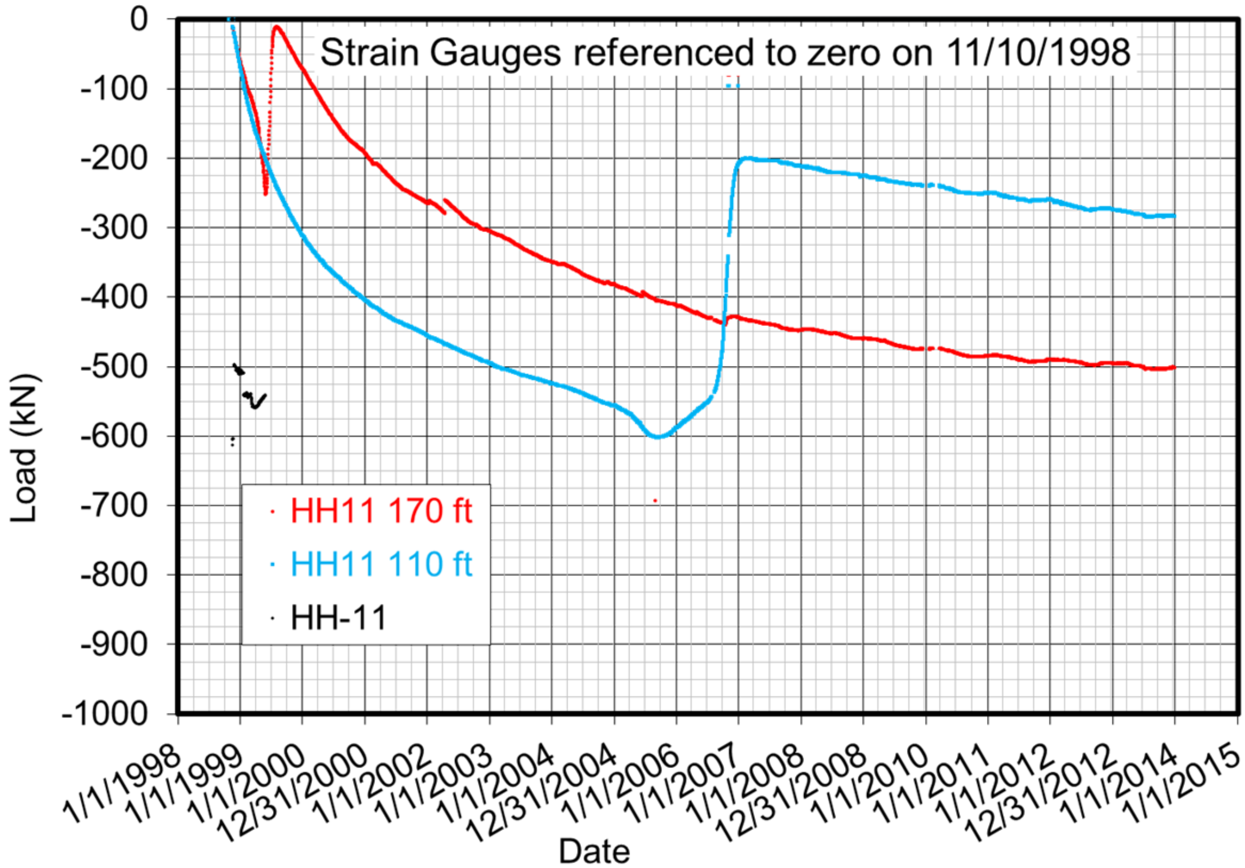

Figure 18 – HH11 located 4 feet (1.2m) from HH10

The data sets in Figure 20 represent the daily depth to the point of neutral compressive load for the group of 536 micropiles. This depth is the point where the cumulative load above and below this depth are equal, as measured by the average value for the VWSG pairs at the tops of the micropiles and the average values for the SBSM's at the 14 depth intervals 5.6 to 61 meters below the tops of the micropiles. Total structure load over the micropiled area has been nearly constant since the structure was occupied in March 1999.

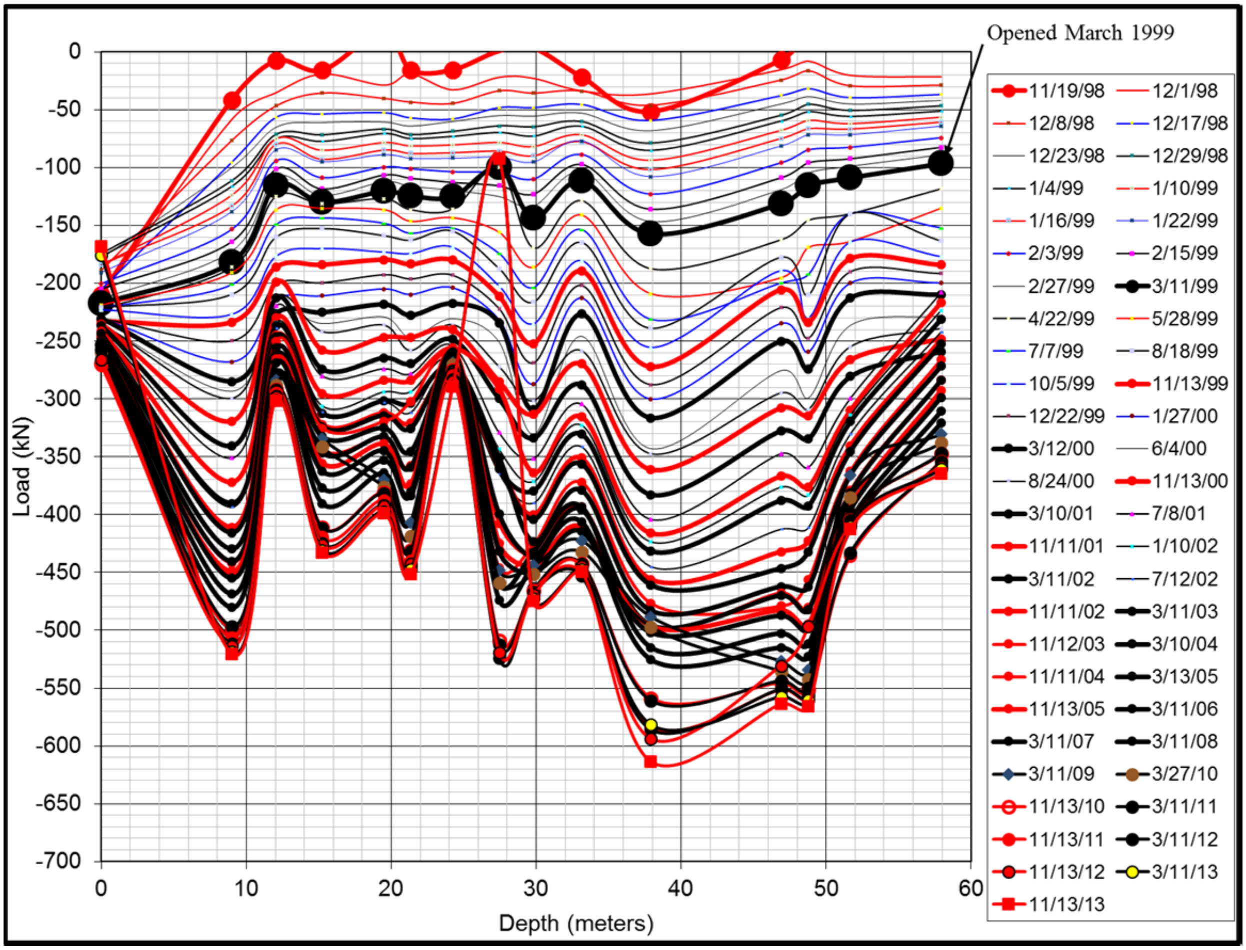

Figure 19 – Average micropile compressive load by depth interval.

The change in neutral depth describes the downward migration of micropile load over time as soft/weak strata drain, consolidate, creep, and pile/soil bond interface deforms while stronger/cemented layers absorb the stress yielded by the consolidation and creep in the softer/weaker strata.

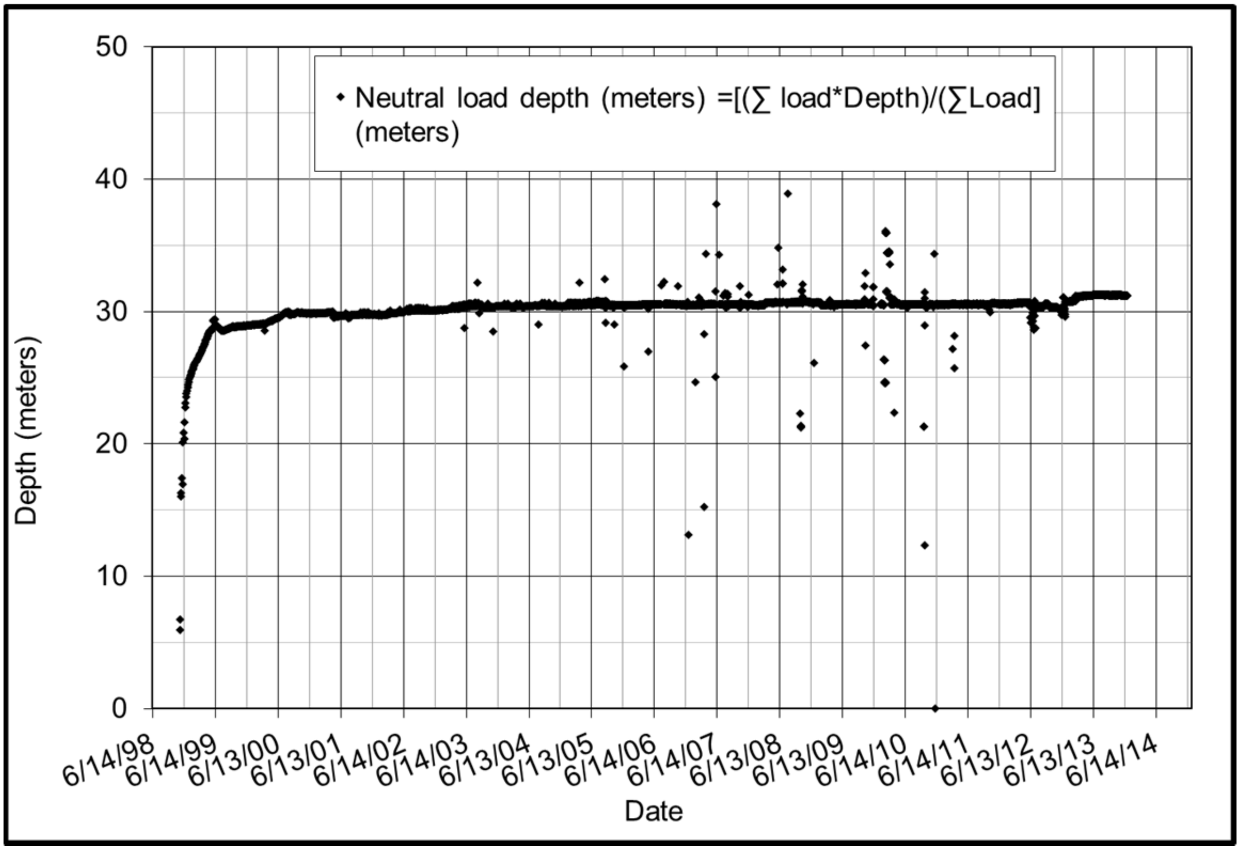

Figure 20 – Steady state achieved after approximately 18 months

This depth centroid initially approximately 18 feet (5.6 meters) below the top of the micropile group in November 1998 descended to a depth of approximately 30 meters by July 2000. This depth centroid has remained nearly constant (+/- 1 meter) from July 2000 through December 2013.

SONDEX System

On July 25, 1998 an inclinometer pipe with a corrugated PVC sleeve was installed to a depth of 210 feet (64 meters) at grid location K22 (Figure 21). Initial baseline data were collected between July 26 and August 5, 1998. Six additional data sets were collected between November 12, 1998 and May 30, 2001. Interpretation of the data sets is presented in Figure 22.

Figure 21 - SONDEX ground deformation monitoring location. Grid point K22 Total depth 210 feet with 94 settlement monitoring depth levels.

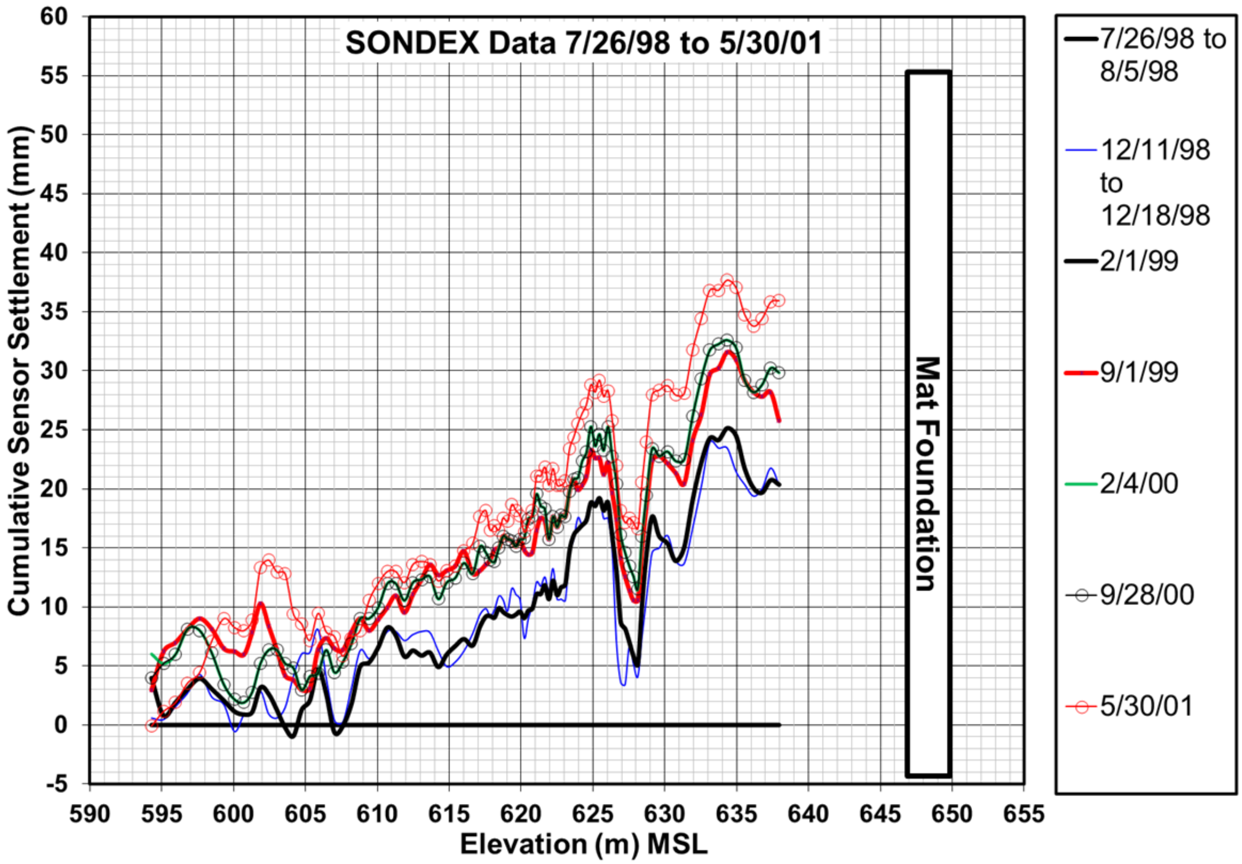

Figure 22 – Interval and cumulative profile compression.

Ninety four sensors were mounted on the PVC sleeve at one to ten foot (0.3 to 3 meter) depth intervals. The borehole was backfilled by tremie with a soft bentonite/Portland cement grout. The inclinometer pipe was surveyed and found to be plumb within one diameter of the borehole (254 mm) from the surface to the total depth.

The precision of the data was found to be observer sensitive, relying on the sensing of the peak sound volume and the observed depth measured by cable calibrated in 0.1 foot (3mm) increments. Repeated data sets by multiple observers were collected between July 26 and August 5, 1998 to establish a statistical baseline from interpretation of data sets. Subsequent observations were collected as three or more sets of observations evaluated for accuracy and averaged to improve precision and then referenced to the baseline.

Data from the instrumented micropiles and a fluid level monitoring system confirmed that settlement of the micropiled area was nearly complete by the middle of 2000.

CONCLUSIONS

1. Comparing Figure 19 and Figure 22, it becomes apparent that depth intervals where the greatest change in compressive load is indicated from SBSM data generally correspond with depth intervals where the greatest compression was measured in the inclinometer/SONDEX.

2. The micropiles began to collect load, slowing the settlement rate from the first day following installation (Figures 13 and 14). The stiff pile element began attracting load from the softer compressible surrounding soil. Stiffness attracts load.

3. The application of the 18000 kip (80,000 kN) load to the group of 60 micropiles early in the work helped to reduce the effects of ground disturbance and stress relief caused by the drilling and grouting work.

4. The SBSM response in data from micropile P15 (Figure 16) is typical of data from 9 micropiles with SBSM's in the group of 60 micropiles loaded to 300 kips (1334 kN) for 70 days. The load has been nearly constant or even decreasing at the tops of these micropiles. The SBSM loads (Figure 16) have been more constant that those in micropiles not subjected to the sustained "pre-stressing" load (Figures 17 and 18).

5. The annual cyclic load pattern for SBSM's in the depth interval from 28,5 feet (8.7m) to approximately 70 feet (21 m) appears in many piles but is most pronounced in piles from the group of 60 micropiles loaded to 300 kips (1334 kN) for 70 days.

6. The pattern of changing load in micropiles HH10 and HH11 (Figures 17 and 18) was repeated in 16 of the 55 micropiles with SBSM's. However, the excursions from the typical constant or slowing increasing Micropile load pattern are not reflected in data from other depths in the same micropile or at the same depth in adjacent micropiles during the same time period.

7. Neither the load in the micropile nor the stress in the ground are truly static. Drainage and fluid pressure dissipation continued for months after the micropiles were installed and loaded. Micropile/soil bond creep and yielding have redistributed load to the soil and this increased stress in the soil profile has reappeared as increased load in adjacent piles.

8. Average load on the tops of the micropiles decreased from the applied 50 kips/pile (222kN/pile) during the first 5 weeks following the initial load application and reappeared over the following 70 day period (Figure 19). This is attributed to the sequential micropile load application reacting against the mat over a three day period. Approximately 18000 to 20000 kN of additional micropile load has accumulated on the tops of the piles as the mat contact pressure has decreased during the past 15 years.

9. Although the precision of the SONDEX data is poor, there is a reasonable correspondence between the shortening of the soil column (36 mm) between August 1998 and June 2001 and the elastic shortening of the 200 foot (61m) micropile compressed by an average May 2001 load of approximately 54 kips/pile (240kN).