16 Apr 2004, 8:00am - 9:30am

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Proceedings: Fifth International Conference on Case Histories in Geotechnical Engineering
New York, NY, April 13-17, 2004

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ABSTRACT

An instrumentation program was undertaken to monitor the movements of a multi-story underground parking-structure exhibiting signs of large deformation and severe structural distress including the failure of a column. The structure is a four-story reinforced concrete building with a rectangular footprint measuring 52.42 m by 71.32 m. The building's structural system consists of reinforced concrete waffle slabs supported by rectangular reinforced-concrete columns. The instrumentation plan included the installation of eight vibrating-wire displacement transducers to monitor displacements, and twenty-four electrolytic tiltmeters to monitor inclinations. The instrument data was recorded hourly and read via a remote site modem connected to a datalogger for three years.

Measurements indicate that earth pressure against rigidly framed structures, subject to wide temperature variations, is largely dependent on seasonal variation of temperature and the structural stiffness of the building.

A summary of the instrumentation program and a brief interpretation of typical measurements are presented, along with a discussion of lessons learned and recommendations for similar projects.

INTRODUCTION

Unfavorable land features coupled with financial constraints often result in limiting the options that a design professional may have when preparing a plan for a real estate improvement. For example, structures placed on hillsides often present a number of challenges and a limited amount of economical choices for site design. Figure 1 presents a hypothetical situation where a building structure is located on a hillside requiring a fair amount of cut and fill. Besides gravity and lateral environmental loads, the structure is subjected to a lateral earth pressure applied by the retained hillside-soil. Assuming no seismic activity, a simple linear static analysis of an accurate mathematical model of the structure subjected to an active earth pressure is customarily considered adequate to determine the stresses and deflections due to the earth load. This, however, may only be true if the soil-structure interaction was limited to the lateral movement of the building away from the soil such that the full active earth pressure is mobilized. The latter assumption may not always be true and may be a substantial oversimplification of the problem.

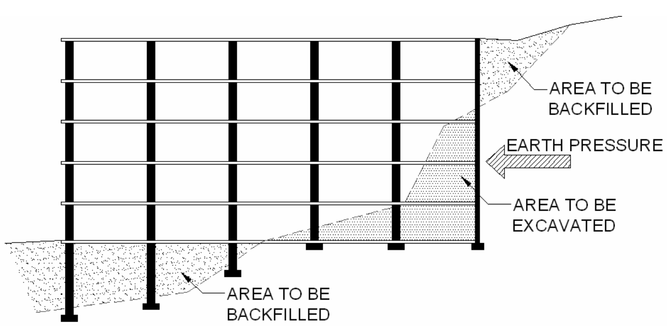

Fig. 1. Example of hillside building

Consider a reinforced concrete rigidly framed structure with a configuration as shown in Fig. 1. The structure will serve as a parking garage open to the elements on three sides and subject to large temperature changes. Volumetric strains, such as expansion and contraction movements, caused by changes in temperature, will result in complex soil-structure interactions. At lower temperatures, the structure is free to contract, and depending on its size, this volumetric contraction may induce further movement of the retained soil in the direction of contraction. On the other hand, at higher temperatures, the volumetric expansion will be partially restrained by the hillside-soil causing the structure to expand in the free direction and preventing it from returning to its pre-contraction condition. This repeated cycle will result in cumulative lateral movements away from the soil, thus producing increasing stress level within the structure.

BACKGROUND

A structural condition survey of a hillside car parking structure revealed the presence of lateral deformations on the order of a few centimeters that lead to severe structural distress. The structure, shown in Fig. 2 and 3 and labeled PG-1 hereafter, is a four-story reinforced concrete building including a full basement, with a rectangular footprint measuring 52.42 m by 71.32 m (172 ft by 234 ft). The building's structural systems consist of reinforced concrete waffle slabs supported by rectangular columns. The north side of the building is a reinforced concrete retaining wall cast against earth at full height with a thickness of 457 mm (18 in) at the base tapering down to 305 mm (12 in) on top. On the southern side, a one-story high, 305-mm (12-in) thick, cast-in-place concrete wall provides enclosure for the basement. Resistance to lateral loads is provided by (1) the northern retaining wall, (2) irregularly placed concrete shear-walls, and (3) the flexural resistance of the rigid frame. The building is open on three sides and is subject to large temperature variations.

An optical survey revealed that, at roof level, the structure underwent a maximum lateral drift of 76 mm (3 in) in the north-south direction, and a drift of 25 mm (1 in) in the east-west direction during its 25 years of service. The amount of deflection measured decreased from the highest to the lowest level, which is typical of lateral deflection of rigid frames. The presence of torsion is associated with the lack of symmetry in the lateral load resisting elements. This lateral-torsional movement induced severe cracking in several columns on the fourth-story level and the failure of one column at the same level.

Adjacent to building PG-1 is a four-story parking-structure (PG-2) of similar construction, but different footprint, which houses the concrete ramps providing access to PG-1. The two buildings are separated by an expansion joint along their lengths. PG-2 was not subject to earth pressure due to the presence of a multi-story building with an excavated basement at its northern edge. No signs of structural distress or lateral movements were observed in PG-2.

Boreholes taken behind the northern wall of PG-1 indicated that the soil consisted of dry miscellaneous granular fill. The ground water table was below the building's foundations.

Objectives of the Study

At the onset of the study, the safety and stability of the structure were questionable, and the present rate of movement was unknown. In the absence of definitive knowledge on the amount of movement, the structure was in immediate need of stabilization and additional strengthening. Failed and severely cracked columns were strengthened using 100–150 mm (4–6 in) reinforced concrete jackets. The design of the stabilization scheme against additional lateral movement was based on the results obtained from a linear static 3-dimensional finite element analysis of the structure subjected to conservative estimates of earth pressure. Nevertheless, the possibility of relaxation of earth pressure due to the large movements and the potential redistribution of the forces within the elements of the concrete structure warranted more investigation into the behavior of the building in an effort to minimize the cost of structural retrofit. Thus, instrumentation and monitoring of the building became a viable and economical application.

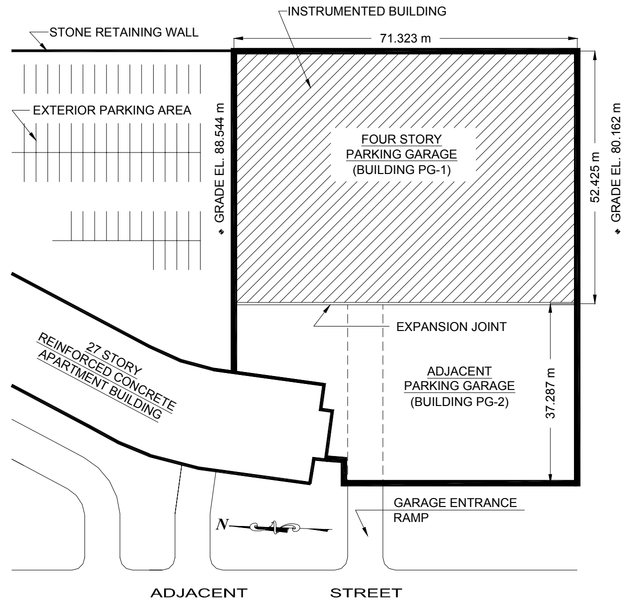

Fig. 2. Site plan

The monitoring program was carried out for three years to measure the present building movements, assess the safety of the building, determine the need for additional strengthening and stabilization, and arrive at a better understanding of the soil-structure interaction. The instrumentation plan and installation procedures are presented by presented by Iskander et. al., 2001, and summarized herein.

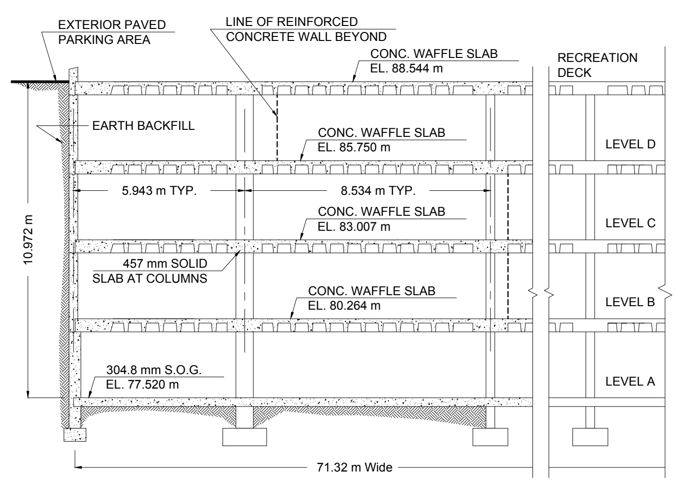

Fig. 3. Partial building section

The data obtained from the instrumentation program lead to a better understanding of the behavior of the building, and prompted a research study of rigidly framed structures subjected to comparable conditions. Selected results of the study are presented herein.

INSTRUMENTATION

Selection of Instruments

The primary purpose of the instrumentation was to monitor the movements of PG-1 in the directions parallel (N-S) and perpendicular (E-W) to the applied earth pressure. The movements were monitored in the E-W direction because the structural survey and subsequent FEM analysis indicate the presence of torsion. The expansion joint separating the two buildings was therefore utilized to mount four pluck-type, vibrating-wire, displacement transducers (VW), used to monitor the displacement of PG-1 in the direction of the earth pressure. This was based on the assumption that building PG-2 is stationary relative to PG-1 in the N-S direction since (1) it was not subject to a lateral earth pressure, (2) it exhibited no signs of distress or lateral drift, (3) the targeted PG-1 movements were relatively large, and (4) the volumetric strains due to thermal variations are theoretically equal given that both buildings are of similar construction and configuration.

The expansion joint was also used to mount four additional VW transducers, used to monitor the relative displacement between the two buildings in the E-W direction.

Tiltmeters were selected for monitoring the tilt of the northern wall in the direction of earth pressure. Additional tilt meters were also installed along the building perimeter to monitor for torsional movements. A tiltmeter is a precision bubble-level that is sensed electrically as a resistance bridge. It is used to monitor changes in the inclination of a structure, which can be used to calculate displacement and curvature using trigonometric rules.

All VW transducers and tiltmeters were equipped with temperature sensors, which recorded the ambient temperature along with displacements and tilts, in order to calibrate measurements for thermal effects.

Vibrating Wire Displacement Transducers (VW)

Locations. Clusters of VW transducers (also known as jointmeters or crackmeters) were mounted at four locations across the expansion joint separating PG-1 and PG-2. Each cluster contained two transducers measuring movement parallel and perpendicular to the joint. The clusters were mounted on the underside of the third and roof level slabs (Levels B & D in Fig. 3), with one cluster on each of the northern and southern sides of the joint at each level.

Specifications. The VW transducers have a measuring range of 100 mm (4 in), with a resolution of 0.025 mm, and a precision of ±0.5 mm. They are equipped with built-in temperature sensors with a range of – 45 °C to 100 °C. The transducers are connected to the datalogger using 22-gauge shielded cables.

Installation procedure. Anchors were installed on opposite sides of the expansion joint, on the underside of the concrete slab, using a high-strength, fast-setting, non-shrink epoxy. The transducers mounted across the joint were connected to the anchors by means of ball joints as shown in Fig. 4. A different setup was used to install the transducer parallel to the joint. A 152-mm (6-in) long steel angle was mounted across the joint by means of an expandable-bolt, mounted on one side of the joint. On the other side of the joint, the vertical leg of the angle was threaded to receive one end of the transducer, and the other end was connected to an anchor placed at the same side of the joint, as shown in Fig. 4.

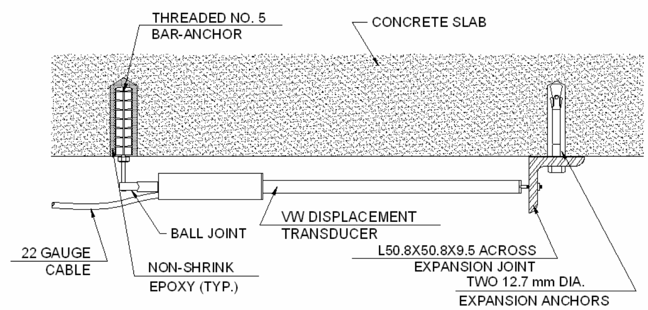

Fig. 4. Schematic of VW transducer along expansion joint

Electrolytic Tiltmeters

Locations. A total of 24 tiltmeters were installed. Twelve sensors were mounted on the northern retaining wall of the building. Each level was monitored using three tiltmeters installed near the western, eastern, and center portion of the wall. These sensors were connected to the datalogger and recorded hourly. The remaining twelve sensors were installed on the exterior columns along the eastern and southern sides of the building, and were used to monitor the tilt of the structure in the east-west direction and verify the readings of the tiltmeters installed on the northern retaining wall, respectively. These twelve sensors were read at weekly intervals using a manual readout unit.

Specifications. The tiltmeters are capable of measuring inclinations within a ±40 arc-minutes range, with a resolution of 1 arc-second or better when read with the datalogger or 2 arc-seconds using the manual readout unit. The sensors measurement repeatability is ±3 arc-seconds. They operate in a temperature range of –20°C and +50°C and are equipped with built-in temperature sensors. The tiltmeters were connected to the datalogger via 24-gauge shielded cables.

Installation Procedure. To install a tiltmeter, a 127 mm (5 in) horizontal hole was drilled into the concrete. The hole was cleaned and filled with fast-setting, high-strength, non-shrink epoxy. A 12.7-mm (0.5-in) diameter stainless steel threaded anchor was then placed in the cleaned hole. The anchor was adjusted to form a 90-degree angle with the face of the wall. After hardening of the epoxy, the tiltmeter was affixed to ballpoint hardware machined at the end of the anchor (Fig. 5). Next, the anchor was leveled and an initial reading was recorded.

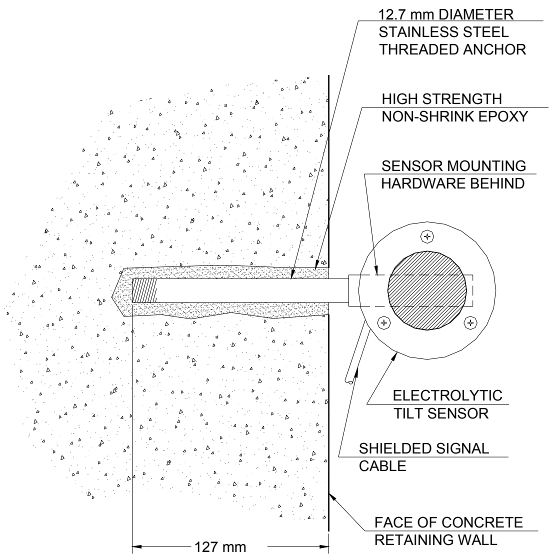

Fig. 5. Schematic of electrolytic tiltmeter

Data Collection and Management

Data collection from the sensors was performed using two data-acquisition systems. A datalogger programmed to record data hourly was connected to eight VW displacement transducers, and the 12 tiltmeters installed on the retaining wall. In addition to the datalogger, the acquisition system was comprised of two multiplexers, a vibrating wire interface, and was powered using a battery connected to on-site AC power. Communication with the datalogger was established via a telephone line and an on-site modem. Communication was initiated by a personal computer equipped with datalogger support software. A computer program was written to automate data retrieval and control the datalogger.

A manual readout unit capable of storing 8,000 time-and-date stamped readings was used to record data from twelve tiltmeters, at weekly intervals. Data was downloaded to a personal computer equipped with interface software.

Instrumentation Limitations

The measurements obtained from the VW displacement transducers were limited to providing information on the relative movement between the two parking structures along and across the construction joint, with the assumption that one building was stationary.

The calculated tilt-sensor translations were relative to the base of the wall at the basement slab elevation, with the assumption that this point was fixed due to soil reactions on all sides.

Due to their placement in a fully functional facility, the sensors were susceptible to tampering or vandalism in-spite of continuous effort to notify the building users to refrain from unauthorized interference with the equipment.

MONITORING RESULTS

VW Transducer Data

Selected results of nearly 30 months of monitoring are presented in Fig. 6 and 7. The sensors are designated as follows: **VW-LSD,** where **VW** = **V**ibrating **W**ire Transducer, **L** = building **L**evel where the sensor is installed (A, B, C or D); **S** = building **S**ide where the sensor is installed, N for North and S for South; and **D** = **D**irection of sensor with respect to expansion joint, P for Parallel and N for Normal.

The movements recorded by the vibrating-wire transducers are those describing the relative movements of Buildings PG-1 and PG-2.

Movements Parallel to the Expansion Joints. If both PG-1 and PG-2 moved in unison, the VW transducers will record no movement. For instance, if the building's expansion or contraction movements due to temperature variations were the same, as it theoretically should be, then the thermal movement of one relative to the other is zero. However, if PG-1 was restrained from expansion by the retained soil, then the recorded movement near the restrained end will indicate the additional movement underwent by PG-2 compared with PG-1. This is an indication of the amount of restraint that PG-1 is subjected to. On the other hand, the recorded movement at the free end indicates the additional movement underwent by PG-1 compared to PG-2, given that the volumetric expansion of PG-1 that was restrained on one end will eventually occur at the free end. Moreover, If PG-1 underwent a lateral movement due to earth pressure, while PG-2 did not, then the recorded movement will be exactly equal to the movement of PG-1

The measurements of the VW transducers, installed along the length of the expansion joint located on Level D are shown in Fig. 6. The top graph is that of the transducer installed at the northern end (restrained end) and labeled VW-DNP, and the bottom graph shows the recorded movements of the transducer installed at the southern end (free end) and labeled VW-DSP. A positive movement indicates shortening of the transducer, or the expansion movement underwent by PG-2 compared to PG-1. A movement in the negative direction indicates an increase in length of the transducer, and a negative displacement indicates that PG-1 have moved laterally more than PG-2.

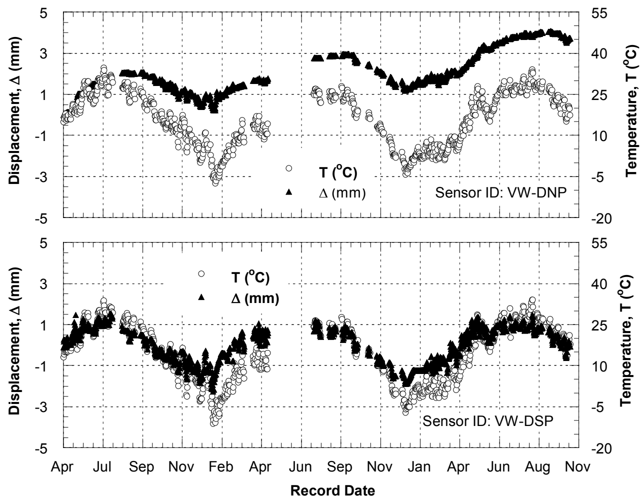

Fig. 6. VW measurements at D-level along expansion joint

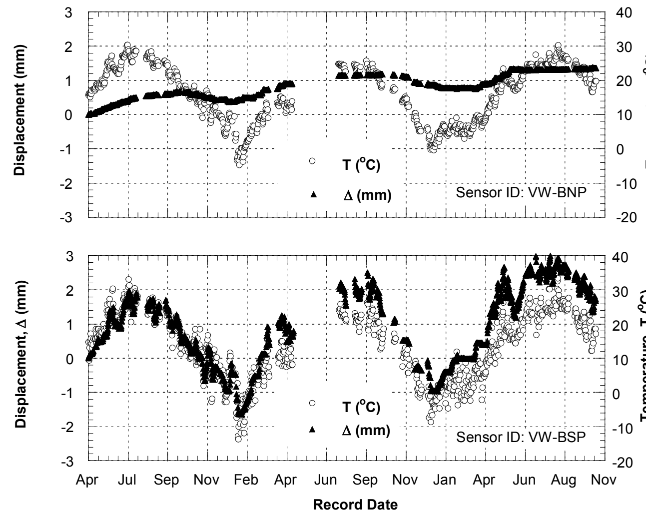

Fig. 7. VW measurements at B-level along expansion joint

VW-DNP recorded an initial decrease in length corresponding to an increase in temperature during the first three months of April, June and July, indicating that PG-2 expanded more than PG-1. As the temperature dropped during the winter months, the transducer's length returned to nearly its starting position in January, with a 0.2 mm residual shortening. This indicated that the two buildings nearly returned to their starting positions. At the next full cycle from January to the next December, the transducer recorded a similar behavior ending the cycle with a residual shortening of nearly 1 mm. Again, similar behavior is recorded during the following cycle, though the residual shortening continued to increase arriving at nearly 3 mm in the middle of the second half of the cycle. This indicates a cumulative shortening of the transducer, or a permanent deformation of building PG-1 relative to PG-2.

VW-DSP, on the other hand, recorded an initial shortening of the transducer indicating that PG-1 expanded more than PG-2. As it would be expected, the amount of shortening in the sensor was equal to that at the restrained side, demonstrating that the volumetric strain at the free end was larger by the amount restrained at the other end. Subsequent cycles show a movement inline with temperature changes, but larger than that at the restrained end, and nearly free of residual deformation. The movements indicate that with increase in temperature, PG-1 expands more than PG-2 and with decrease in temperature PG-1 contracts more than PG-2. This is indicative of the presence of a permanent lateral deformation at the free end of PG-1 toward the southern side of the building. By contracting a larger distance than PG-2, PG-1 is returning to its normal contracted position through a movement that increases as the permanent deformation increase. This clearly shows that the presence of the retained soil mass at the northern edge of the building interferes with the thermal movements of the entire structure through a complex soil-structure interaction.

Figure 7 shows the measurements recorded by the transducers installed along the expansion joint on Level B. The graphics show similar behavior of the building as presented above. However, the range of movements is smaller for the lower level sensor, consistent with the fact that thermal volumetric strains of rigidly framed buildings are smaller on the first unrestrained level than the rest of the levels above.

<u>Movements Normal to the Expansion Joint</u>. The measurements recorded from VW sensors DSN and BSN (i.e. those sensors installed at the southern side of the building, perpendicular to the expansion joint, on levels D and B respectively) are shown in Fig. 8. These measurements clearly show a close relationship between the joint movements and temperature. A detailed analysis of the volumetric movement of the expansion joint is presented by Aboumoussa and Iskander (2002), and showed that the apparent presence of

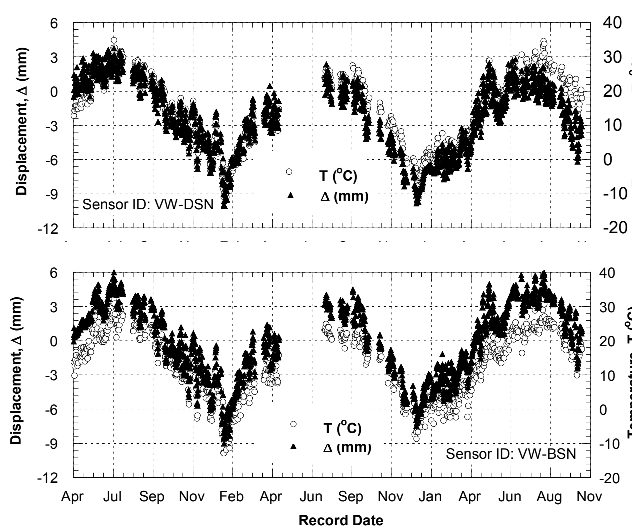

Fig. 8. VW measurements at D and B levels normal to joint

torsion in the building is also due to temperature movements in the E-W direction. This was concluded when it was found that the expansion joint movements at the northern end were greatly restrained by the presence of the concrete wall running along the transverse direction of the building, and were in the order of one-tenth of a millimeter, whereas the joint movements at the southern end had a range of over 15 mm. There was no indication of permanent deformation occurring during the monitoring period in the E-W direction.

PARMETRIC FINITE ELEMENT ANALYSIS

To obtain a better understanding of the behavior of rigidly framed earth-retaining structures subjected to large temperature variations, a parametric study of 2-dimensional finite element models of structures with various numbers of bays, stories, and frame stiffness was performed. The analysis was performed using the commercial finite element analysis software *Plaxis*. The structures were restrained on one side by an elasto-plastic Mohr-coulomb soil model, the stiffness of which was also varied as an additional parameter. The results of selected FEM analysis are presented herein.

Structure No. 1

The first structure is a single story rigid frame, 3.05 meters in height, with three 3.05 meters bays, and a relative column to beam stiffness of 1. The structural members are simulated with elastic concrete beam elements. The soil properties are as follows: $\phi = 30^o$, c = 0 MPA, $\gamma = 1602$ kg/m^3, E = 13.8 MPA, $\nu = 0.3$.

The first analysis stage simulated the addition of the backfill behind the structure and is designated with the subscript "a" in the graphics. The subsequent stage was an increase in temperature of 27.8ºC (50ºF), designated as expansion cycle 1 with a subscript "ec1". The following stages simulated alternate temperature cycles starting with a decrease in temperature of 55.5ºC (100ºF), designated with subscript "cc1" for contraction cycle 1. The analysis was carried for several cycles, with similar subscript designations, until strain equilibrium is reached in the soil model.

The parameters obtained from the analysis and presented in Fig. 9 are the earth pressure variations with temperature cycles, and the change in (1) the retaining wall movements, (2) the end column movements, (3) the retaining wall moment and (4) the end column moment. The graphics are discussed below starting by the top graphic and continuing downward.

The top graphic in Fig. 9 shows that the earth pressure variation with temperature is quite minimal for the size of structure analyzed. A slight increase in earth pressure at the top of the structure is noticed during the expansion cycles (denoted with subscript "ec") due to the movement of the structure towards the soil.

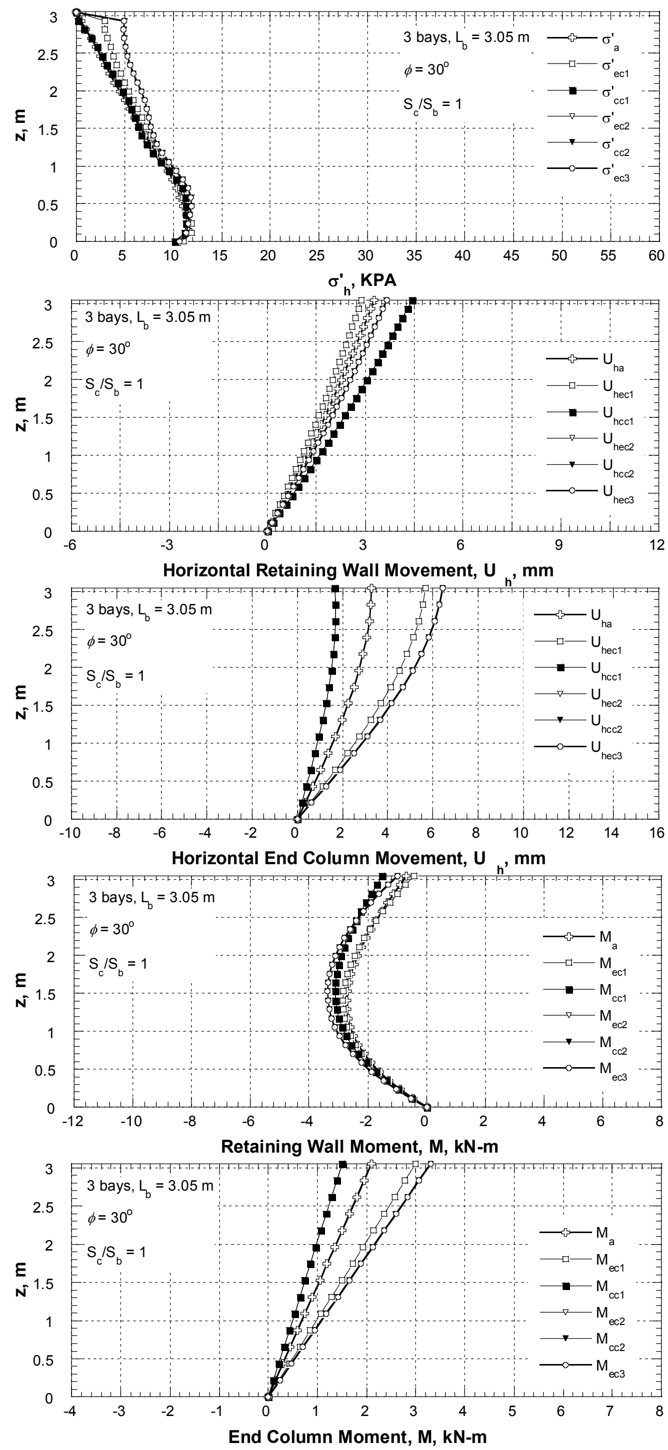

Fig. 9. Finite element analysis results for Structure No. 1

The retaining wall lateral movement during the thermal cycle is compared to that of the wall subjected to active earth pressure only (U_{ha}). In the first analysis stage where the backfill was added to the frame, the structure deflected 3.29-mm at the top. At the first expansion cycle, associated with a temperature rise of 27.8ºC, the top of the wall moved into the soil about 0.39 mm. This is nearly 1 mm less than the expansion of an unrestrained structure, or only 28% of the total unrestrained expansion of 1.39 mm. During the next cycle, which simulates the contraction of the building under a temperature change of 55.5ºC, the top of the wall movement indicated a contraction of 1.55 mm, or 50% of the unrestrained contraction movement. At the next expansion cycle, the structure expanded 0.79 mm at the top of the wall, which again amounts to only 28% of the total expansion should the structure be free of restraints. The remaining cycles were similar with a relative 28% contraction and expansion. The final position of the top of the wall during a contraction cycle, after strain equilibrium is reached, shows that the structure contracted 0.88 mm only from its original position at the backfill stage, reaching a 3.65 mm total lateral deflection. Should the structure be free of restraints, however, it would have undergone a contraction of 2.78 mm at the top of the wall, equal to the total deflection of the wall.

It is therefore clear, that the presence of a soil restraint at one end the structure introduces a complex soil structure interaction when coupled with thermal movements due to large temperature variations.

On the other end of the structure, the end column graphic shows that the frame expanded substantially more at the free end than at the restrained end. In fact, the expansion and contraction movement was equal to the movement of an unrestrained structure plus the balance of movement restrained by the soil. Thus, at strain equilibrium, the structure expands and contracts nearly 4.76 mm, or nearly 172% of the unrestrained-structure movement. Furthermore, the final deflection of the structure during an expansion cycle was nearly twice that of the structure subjected to earth pressure only. On the other hand, the contracted position of the structure does not bring the end column into the structure as it would be typical of the contraction movement of a frame free of restraints.

These behaviors of the wall and the end column under thermal changes are qualitatively in-line with the data recorded by the VW transducers in the instrumented building presented earlier.

The last graphic in Fig. 9 shows the change in the moment diagram for the end-column with the change in temperature. During the expansion cycle, at strain equilibrium, the maximum moment in the column is 57% larger than the maximum reached when the structure was subject to earth pressure only. Thus, not including the effect of the soil-structure interaction due to temperature changes could result in unsafe design of the structural members.

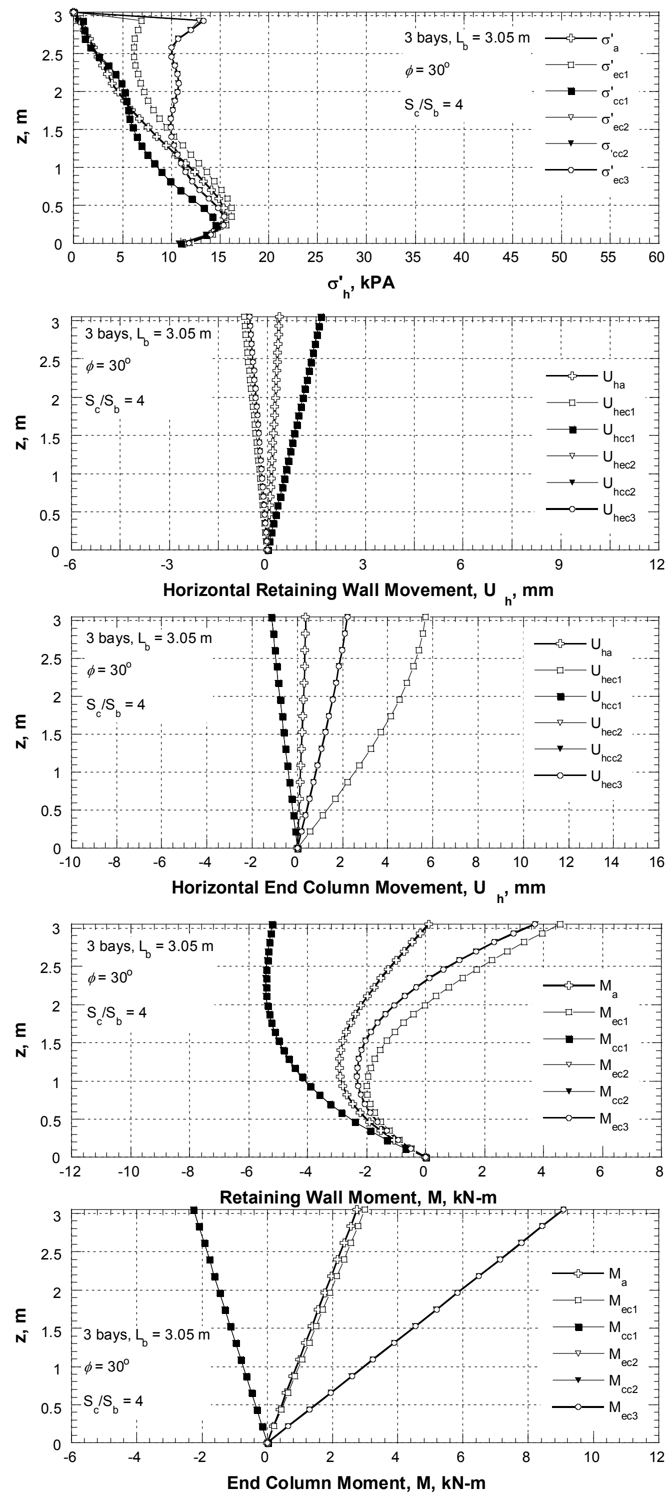

Fig.10. Finite element analysis results for Structure No. 2

<u>Structure No. 2</u>

The second structure is identical to the first, but with a relative column to beam stiffness of 4, simulating a stiffer rigid frame. The analysis stages were also identical. Figure 10 presents selected analysis results.

The top graphic in Fig. 10 shows that the earth pressure variation with temperature is quite substantial at the top one half of the structure during the expansion cycles. This could be explained by the fact that, although the expansion force is equal for both structures, the rigid frame of Structure No. 2 is much stiffer laterally than that of Structure No. 1, and is capable to expand into the soil as shown in the retaining wall movement graphic. At about 2.45 m (8 feet) in height, the

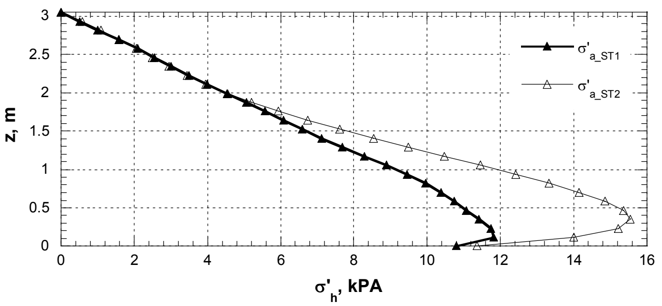

Fig.11. Lateral earth pressure for Structures No. 1 and 2

earth pressure is nearly 400% larger during the last expansion cycle when compared to the pressure in the absence of thermal movements.

To examine the frame-stiffness parameter, Fig. 11 compares the earth pressure behind the wall after the backfill stage for both Structures 1 and 2. The earth pressure is quite equal for both frames for the top half of the wall, but is larger behind the stiffer frame in structure No. 2 for the bottom half of the wall. This indicates that the initial mobilization of active pressure is not the same for both structures. This, however, could be expected since the lateral deflection of the frames is not equal, and the stiffer frame undergoes less deflection. Thus, since the mobilization of active pressure is directly related to the amount and nature of the movement of the retaining structure, stiffer rigid frames will result in less mobilization of active pressures. Furthermore, the stiffer frame capability of a higher lateral load resistance will result in larger expansion movement toward the retained soil. The stiffness of the structure and that of the soil will both affect the behavior of the structure.

The retaining wall and end column horizontal movement graphic indicate that the expansion and contraction movement at strain equilibrium were 40% of the unrestrained-structure movement for the wall and 60% for the end column. This is a significant difference when compared to the percentage movements of Structure No. 1.

<u>Structure No. 3</u>

The third structure is modeled with the same parameters as Structure No. 1, but the number of bays is increased to 20, thus increasing the length of the structure from 9.14 m to 60.96 m. The analysis stages remain identical. Figure 12 presents selected analysis results.

By increasing the number of bays to 20, the expansion length of the single story frame increases substantially. This causes significantly larger expansion movements causing a significant increase in earth pressure behind the retaining wall. At about 2.45 m in height, the earth pressure at the backfill stage was amplified nearly 10 during the expansion cycle. This increase in earth pressure, coupled with the movement of the wall into the soil cause the maximum moment in the wall

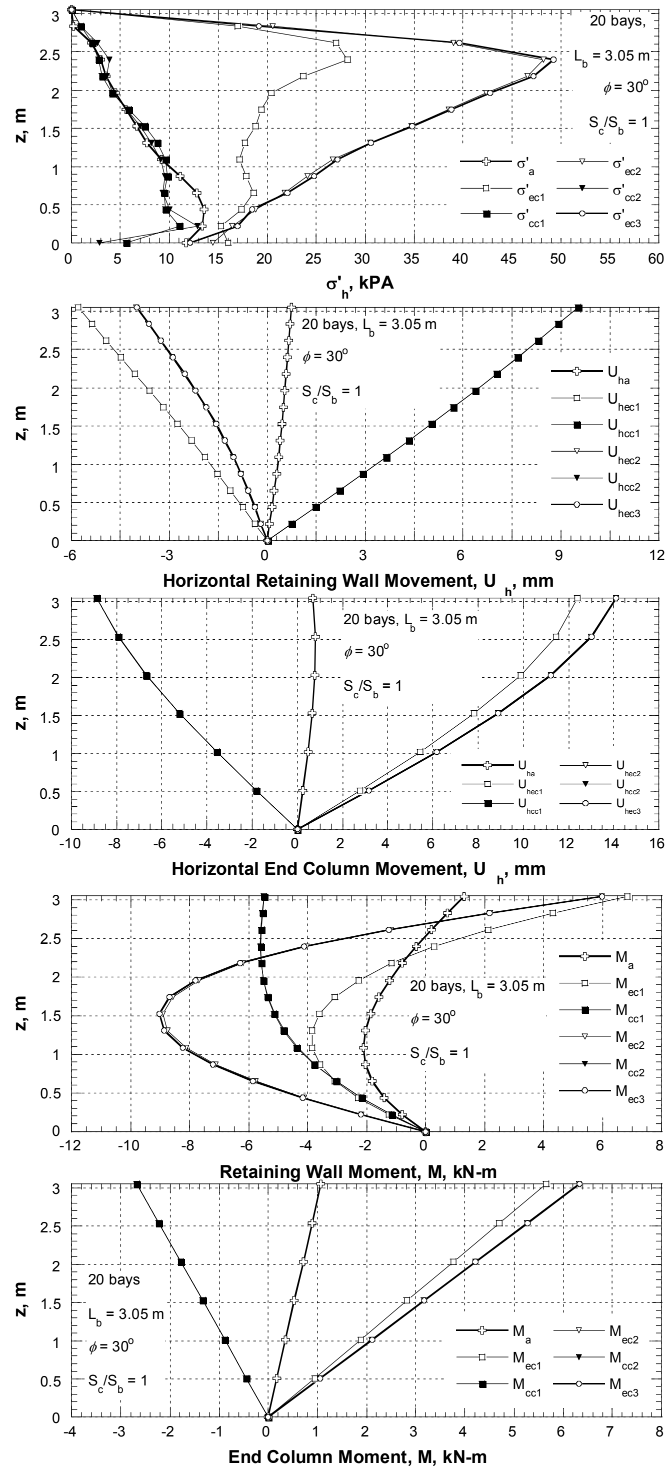

Fig.12. Finite element analysis results for Structure No. 3

to nearly double, as shown in the Retaining Wall Moment graphic. Furthermore, the lateral pressure distribution behind the wall is considerably different from the classical triangular lateral earth pressure for retaining structures. Moreover, the moment change in the end column moment due to the expansion movement is nearly 575% compared with the backfill stage moment.

CONCLUSION

The instrumentation and monitoring of a four-story reinforced concrete parking structure retaining earth on one side and subjected to large temperature changes were presented in this paper. The monitoring data revealed a complex interaction between the structure and the retained soil during the expansion and contraction cycles. The soil restraint curtailed the expansion of the structure at the retaining wall, and caused the structure to expand more at the free (opposite) end. The contraction movements were also affected by the soil restraint.

A parametric finite element analysis was performed to further study the behavior of rigidly framed earth retaining structure subject to large thermal movements. The results of three different analyses were presented. It was found that the temperature induced movements of the structures can substantially vary depending on the soil and frame stiffness. The stresses and deflections of the structure were significantly increased at times, that a conventional structural analysis that ignored the effect of the soil-structure-temperature interaction could lead to erroneous results and unsafe basis for design.

It was also shown that the amount of mobilization of active earth pressure behind the retaining wall of the structure was dependent on the structural stiffness of the rigid frame. Additionally, the earth pressure distribution is considerably different from the classical triangular distribution in the case of large expansion movements towards or into the soil.

Given the lack of studies and literature on the subject matter, the authors are conducting a research study of structures similar to those presented herein in an effort to better qualify and quantify the following:

- The relationship between the structural stiffness (and lateral-load-resisting behavior of structures) and the mobilization of active earth pressure in the retained soil.
- The effect of the soil and frame stiffness on the temperature movement of the structure, and the relationship between the two.
- The behavior of the retained soil during expansion and contraction cycles.
- The stresses and deformations within the structure due to the soil-structure interaction.

ACKNOWLEDGEMENTS

The work presented herein was funded through Antonucci & Associates (A/E) and an industrial matching grant to NSF CAREER Grant No: CMS 9733064. Slope indicator Inc. provided instruments and significant in-kind support. The writers gratefully acknowledge the support of the three sponsors. The writers also wish to thank Dr. Andrew Whitle, Pierre Gouvin, and Robert Antonucci, for their valuable input throughout this study. Thanks are also extended to Frank Calfa of SCS, Inc., for his assistance in equipment installation.

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