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Case History — Performance Monitoring Success

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CASE HISTORY - PERFORMANCE MONITORING SUCCESS

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ABSTRACT

The City Creek Center urban redevelopment project in Salt Lake City, Utah involved excavations up to 65 feet deep. Shoring systems included more than 29,000 square feet of anchored diaphragm walls, 100,000 square feet of soil nail walls, and 860 linear feet of underpinning. Detailed performance monitoring alerted the project team to unacceptable performance of an anchored diaphragm wall adjacent to an occupied twenty-five-story building on shallow foundations. This knowledge allowed the team to react quickly, stabilize the excavation, investigate the situation, and develop successful remedial measures. The diaphragm wall was reinforced with additional anchors and subgrade concrete struts, allowing the excavation to proceed with minimal delay and no damage to the adjacent building.

BACKGROUND

The City Creek Center project in downtown Salt Lake City, Utah, involved the redevelopment of two city blocks totaling about 20 acres. The project was located immediately south of the historic Temple Square, headquarters of the Mormon Church and the site of the Salt Lake Tabernacle. Prior to the redevelopment project, the site was occupied by commercial buildings ranging from nine to twenty-five stories in height, a shopping mall with underground parking, a hotel, and other structures.

Plans called for the demolition of the shopping mall and several of the commercial buildings, excavation to a depth of 65 feet below street grade for vastly expanded underground parking, and construction of new high-end mixed-use commercial, residential, and retail space. The site is shown in Fig. 1.

Several of the existing buildings on the site were slated to remain. These included historic masonry structures and a modern, twenty-five-story office building. Busy city streets surrounded the perimeter of the site, and to the east and north, the Utah Transit Authority operated frequent TRAX service on street-level light rail lines.

The subsurface stratigraphy at the site typically consisted of a layer of dense, lightly cemented sand and gravel, overlying a layer of medium-stiff clay and silt, overlying very dense gravel at depth. The excavation would extend into the clay and silt layer in some portions of the site. Groundwater was encountered approximately at the interface between the upper sand and gravel and clay and silt strata, and was cut off with jet grouting performed before commencement of the excavation.

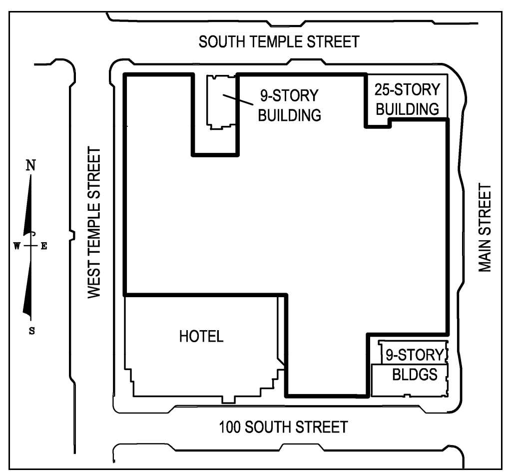

Fig. 1. Site Plan

To maximize the available project space, excavations were to extend laterally to the surrounding streets and abutting structures. This required due consideration for movement control, and the excavation support systems were selected to meet specified displacement and settlement criteria. Underpinning was used in conjunction with temporary soil nail walls where movement control was not critical and foundation loads, if any, were relatively light. Excavations directly adjacent to heavily-loaded shallow foundations dictated the use of structural concrete diaphragm walls with prestressed soil anchors.

Anchored Diaphragm Walls

The diaphragm walls were designed as 24-inch-thick reinforced concrete panels. The walls extended from an elevation a few feet above the top of the existing building footings to 10 feet below the planned subgrade elevation. Average footing surcharges varied from 1,200 pounds per square foot (psf) to 5,000 psf. The exposed wall height ranged from 38 to 48 feet. Three to four levels of anchors at an approximately 10-foot horizontal spacing were used depending on the wall height and surcharges. The anchors were six-strand ASTM A416 prestressing steel, inclined at 10 to 25 degrees from horizontal.

The configuration of the site and the buildings slated to remain created several reentrant corners in the shoring alignment. This required detailed consideration in the design and careful control during construction, as anchors from adjacent perpendicular walls were drilled into the same space under the existing buildings. It was essential to prevent the anchors from intersecting each other in order to avoid damage and loss of support for the walls.

Performance Monitoring Systems

Two complementary performance monitoring systems were used on this project.

The first performance monitoring system consisted of conventional slope inclinometer casing installed in each segment of the excavation support wall alignment. Readings were taken by lowering an inclinometer probe into the casing and measuring the deviation relative to a fixed point at the bottom of the casing. Slope inclinometers provided a detailed displacement profile over the full height of the wall with a high degree of precision. The readings were taken manually, typically once per week during the mass excavation phase of construction, although the frequency of readings could be adjusted as required.

The second performance monitoring system used automated total stations to measure and record the movement of the excavation support walls and adjacent structures. An array of optical prism targets was installed on the buildings around the project site prior to the start of excavation. Two automated total stations were installed to provide line-of-sight to all of the planned target locations and to fixed reference points located away from the zone of influence of the excavation. Additional prism targets were installed on the face of the soil nail and diaphragm walls as the excavation progressed. Readings were taken continuously and reported to a centralized server. A web-based interface allowed all members of the project team to access the monitoring data at any time and create customized reports. Additionally, automatic alerts were set to notify key personnel if any readings exceeded predetermined values.

An example of a report from the automated monitoring system is presented in Fig. 2. Small cyclical variations and occasional spurious readings are evident in the graph, and these are typical of optical survey measurements, but the trend in the data is also apparent. Specific events, such as an excavation stage or the installation of an anchor, can be tied to changes in the readings that lie outside the normal variation or deviate from the long-term trend.

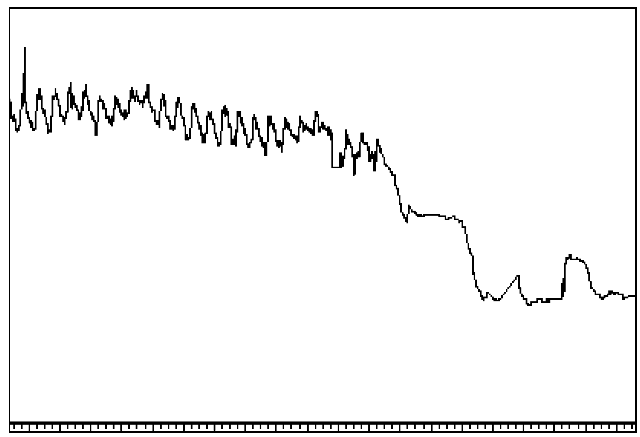

Fig. 2. Automated Survey Plot

The advantages of the automated system were continuous real-time reporting and the small marginal cost to add additional monitoring points. The optical survey methods did not permit extreme precision in the measurements, especially considering the long sight distances involved - up to about 800 feet, so the inclinometer readings were used to calibrate and confirm the displacements reported by the automated system. Additionally, movements occurring below subgrade could not be measured by the automated system, so the inclinometers filled in that portion of the monitoring program.

DIAPHRAGM WALL MOVEMENT

The initial phase of the project involved the demolition of the existing structures, including two levels of underground parking, and the installation of soil nail wall shoring to support the excavation and expose the footings of the buildings slated to remain. Diaphragm wall panels were excavated, steel reinforcing cages were installed, and concrete was placed by tremie. Excavation continued, and anchors were drilled and installed through pre-positioned blockouts in the concrete panels.

Automated survey and inclinometer readings were taken throughout this time, and the wall performance followed expectations. Small displacements were observed, consistent with the excavation depths and anchor installation sequence. In the northeast corner of the site, adjacent to the twenty-five-story office building, three of four levels of anchors had been installed in the diaphragm wall below the building's mat foundation. During stressing, two anchors failed to meet the specified test load and were locked off at a lower design load; supplemental anchors were installed to provide the required total anchor capacity. In retrospect, it was realized that this was the first indication of a potential problem with the diaphragm wall.

Excavation for the fourth level of anchors proceeded as scheduled. Within a few days, the automated optical survey system began to show anomalous displacements, as can be seen in Fig. 3. A weekly inclinometer reading on a Tuesday showed a significant acceleration of movement in the lower part of the wall, including the section below subgrade, which had displaced approximately ¼ inch over a period of about four days.

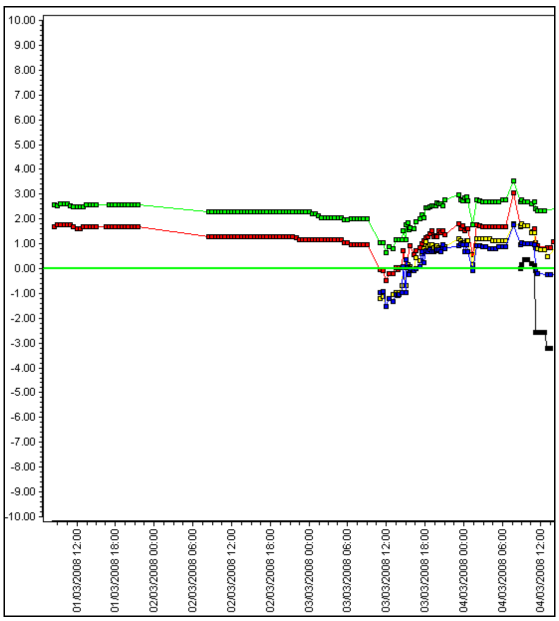

Fig. 3. Diaphragm Wall Displacement Plot

Follow-up readings on Wednesday and Thursday confirmed the trend of continuing movement, as shown in Fig. 4. Analysis of the monitoring data led the project team to conclude that the excavation support system was at a point near failure, and that movement would continue unless appropriate action was taken. Considering the proximity of the occupied twenty-five-story office building and the obvious consequences of failure, emergency measures were immediately implemented.

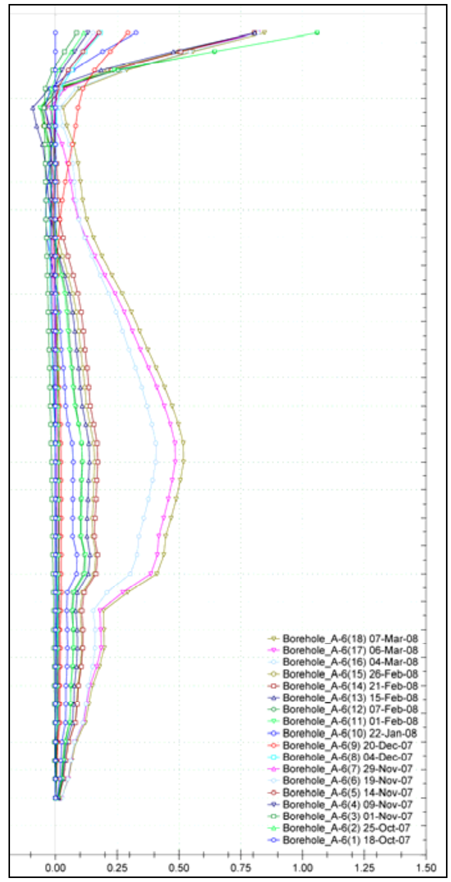

Fig. 4. Inclinometer Plot

The excavation support subcontractor met with the general contractor, explained the situation, and developed a plan to bring movement of the diaphragm wall under control using a stabilizing berm. On Friday, construction commenced on a compacted soil berm 10 feet high and 35 feet wide in front of the diaphragm wall. The berm was complete by Saturday, as shown in Fig. 5. Subsequent inclinometer readings and automated survey system measurements showed that the diaphragm wall movement had effectively been stopped.

Additional geotechnical borings were made along the wall alignment. The borings indicated the presence of a 20-foot-thick layer of interbedded silt and clay with numerous sand seams overlying the medium-stiff clay and silt. This layer had not been detected in the original geotechnical exploration program and was not observed in other portions of the site. A review was made of the diaphragm wall panel installation records and anchor drilling logs and test reports. This review corroborated the presence of the interbedded silt and clay stratum. This layer imposed much greater lateral pressures on the diaphragm wall than the dense sand and gravel that had been expected, and additionally provided lower ultimate bond stresses for the anchors supporting the wall. Significant remedial actions would be required to address the presence of this layer, protect the existing twenty-five-story building, and allow the redevelopment project to proceed.

Fig. 5. Stabilizing Berm

REMEDIAL ACTIONS

An analysis was made of the excavation support system considering the revised stratigraphy and the measured diaphragm wall performance. Knowing that the wall had reached the point of incipient failure, that is, a geotechnical factor of safety only marginally greater than 1.0, the analysis could be calibrated to the observed performance. This allowed the engineering properties of the various strata, particularly the interbedded silt and clay, to be determined with a relatively high degree of confidence.

Along the south side of the existing building, a remedial action plan was implemented that involved the installation of additional, longer soil anchors. The anchors were sized to resist the increased lateral pressures, and the lengths were chosen to ensure adequate bond in the weaker soils. Considerable effort was made in the design and installation process to ensure that none of the new anchors would intersect any of the existing anchors installed from the perpendicular wall. A three-dimensional CAD model was created to help visualize the anchor configuration and determine the required layout. As additional anchors were installed, the stabilizing berm was excavated in controlled lifts and the diaphragm wall was closely monitored.

Along the west side of the existing building, an alternative approach was taken. Approximately 50 feet west of the diaphragm wall, beyond the toe of the stabilizing berm, a concrete mat foundation for a new building was being completed. In coordination with the structural engineer, it was determined that the mat could be used to resist lateral loads from the diaphragm wall. A series of subgrade cast-in-place concrete struts were designed to transfer the load from the wall to the mat. In order to minimize additional wall movements, the stabilizing berm was excavated in small sections, a prefabricated reinforcement cage was lowered into the trench, concrete was placed, and the berm was restored. A schematic of the subgrade strut installation is shown in Fig. 6. Each strut was completed in a single shift. When all of the struts were completed and the concrete had reached sufficient strength, the berm was removed.

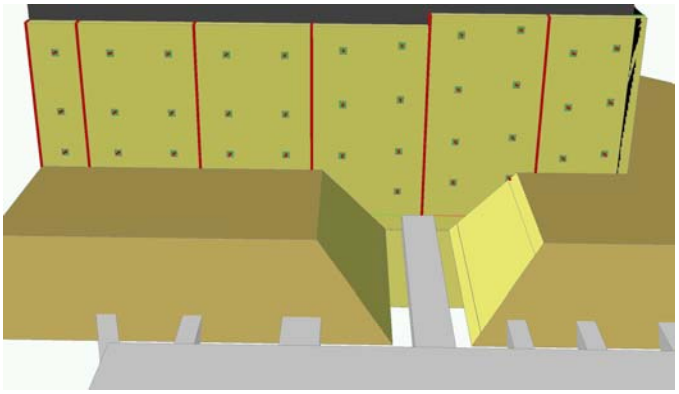

Fig. 6. Subgrade Strut Installation

Continued performance monitoring throughout the installation of the additional soil anchors, construction of the subgrade struts, and removal of the stabilizing berm indicated that there was no significant additional movement of the diaphragm wall or the adjacent building.

CONCLUSION

Performance monitoring was essential to the success of this project. The combination of real-time automated optical survey and conventional slope inclinometer readings provided the information required to identify and react to a problem, understand the situation, and develop a solution, allowing the project to proceed with minimal schedule interruption and no damage to the adjacent structures.