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EXCAVATION SHORING FAILURE THREATENS A HISTORIC CHURCH: EXPLORATION OF CAUSES AND REMEDIAL MEASURES

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ABSTRACT

The city of Beirut is home to a very large number of historic monuments. Given the recent development boom following the years of civil strife, modern projects have begun to encroach on the spaces afforded older monuments.

Recently, excavation works adjacent to the Lady of Annunciation Church resulted in severe cracking and deformations within the walls and floors of the stone and brick structure. The shoring provisions which were executed within the excavated lot consisted of contiguous bored piles with pre-stressed anchors. The failure occurred when the excavation works had progressed to a level of about 12m below original grade. Faced with the imminent catastrophic collapse of the church, the Municipality of Beirut ordered the immediate backfilling of the site in order to limit further movements. The case study presented in this paper includes the details and results of the geotechnical forensic investigation which included an array of measures and efforts, all implemented in an environment of urgency, given the need to find the cause of the failure, and propose and implement remedial measures which would spare the church. The analyses, monitoring measures and actual remedial works adopted and successfully completed at the site are presented and discussed.

INTRODUCTION

The church of the Lady of Annunciation is one of Beirut's oldest active religious centers. The church lies today in the heart of a residential neighborhood that has grown to completely surround it. Up until recently, turn of the century houses lined the streets adjacent to the Church.

As the civil strife in Lebanon came to an end, the real-estate market in Beirut witnessed a real boom, driven in part by the need for additional modern housing and by the scarcity of land available for development. As a result, old structures have been systematically torn down and replaced by multi-story high rises. Such a project "Beirut Arc angels" was to be erected on Lot 235 adjacent to the existing church.

The Lady of the Annunciation church is a sandstone-block structure, built along classical architectural features as shown in Fig. 1. A central hall covered by a dome resting on massive pillars and external bearing walls form the bulk of the space. A peripheral gallery or roofed-walkway runs along the side of the hall with small size circular columns supporting a mezzanine. Two stairwells define both ends of the gallery and lie on either

side of the altar.

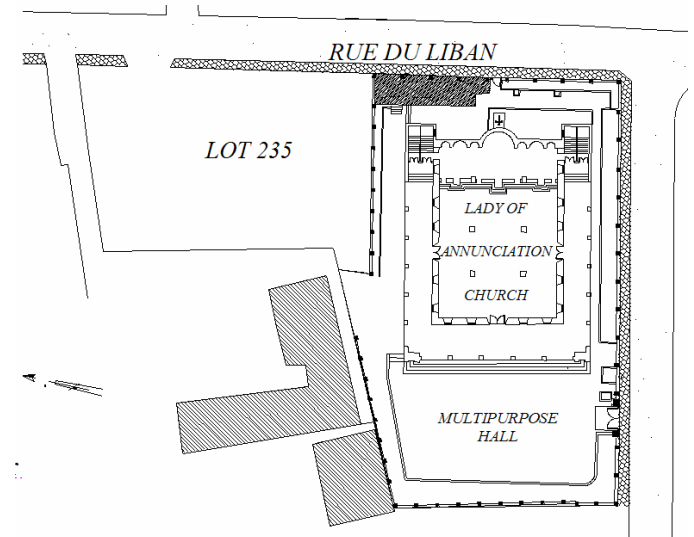


Fig. 1. General plan view of the church and lot 235.

CHRONOLOGY OF EVENTS

The development project on LOT-235 adjacent the church, included the provision of a number of basements which required the site to be excavated to ~ 15.7 m from the existing grade. The original design adopted by the contractor consisted of a mixed support system including two levels of pre-tensioned anchors and three lower levels of soil nails. As the work proceeded on the first anchors in the uppermost row, signs of distress were reported in the floor and wall of the church, namely some heaving and hairline cracking.

Following the reports of movements in the church and at the insistence of the municipal authority, the shoring system was changed and pre-bored cast in situ concrete piles 60cm in diameter, spaced at ~ 1.6 m to 2.2m c-c and reportedly extending to ~ -17 m were executed. Lateral support would be provided by three rows of anchors.

A period of three months had elapsed from the initiation of the works in June 1999 to the completion of the cast-in-situ piles in September of the same year. Excavation works started again and once the excavation reached depths of ~ -9 m to -12 m in December significant cracks appeared in the main walls of the church and around the dome. Again the municipality ordered a halt to all work on site and the excavation was backfilled to ~ -6.5 m along the side contiguous to the church in order to allow for the execution of additional shoring provisions, namely extra anchors. The additional anchors were completed in February 2000 and the excavation continued and reached a depth of -12 m. New cracks within the church continued to appear, to the great concern of the church caretakers. On the fourth of April, 2000 and as excavation works were being extended below -12 m along the church side, a very important and extensive set of new cracks involving the totality of the North-Eastern corner of the structure appeared. Some of the anchors in the uppermost row were reported to have failed and the observations made of the newly opened cracks indicated an accelerated rate of slip and movement. The same day, the Beirut municipality ordered the backfilling of the totality of the site. Backfilling operation continued until a depth of about -2.5 m from the original grade and the movements in structure appeared to stabilize. The total loss of the historic monument was averted once again.

A panel of experts was appointed to evaluate the causes and extent of the damages. The responsibilities of the assembled panel included also, the supervision of the remedial works in the church itself and the shoring works which were to be re-executed in lot-235. The authors represent the parties involved in the process, including the panel of experts, the geotechnical consultant representing the church (Turba Engineers) and the geotechnical specialties contractor (Edrafor) given the charge of executing the underpinning works within the church and the

shoring works on the lot-235 side.

SUBSURFACE CONDITIONS

A comprehensive site investigation campaign was initiated and a report prepared by Turba Engineers in May 2000. In total, seven boreholes and a number of test pits were executed within the church premises alone. The deduced stratigraphy at the site is presented in Fig. 2 along with the soil parameters used for the remedial works design. The soil profile consists of:

- A surficial layer of red-brown clayey sand, 2m to 6m thick, in loose to dense state (SPTs between 5 and 27).
- A layer of creamy white weathered marl, moderately firm to firm, 3m to 8 m thick.
- Green-gray claystone and creamy white limestone firm to very firm.

The above formations appeared to have a slight dip parallel to the boundary with Lot 235 which does not appear to affect the stability of the excavation. Water was found in the boreholes at a depth of -12 m to -13 m. However, during the initial excavation works, water influx into the site was reported at much shallower depths, probably seeping from localized sources, likely broken utilities.

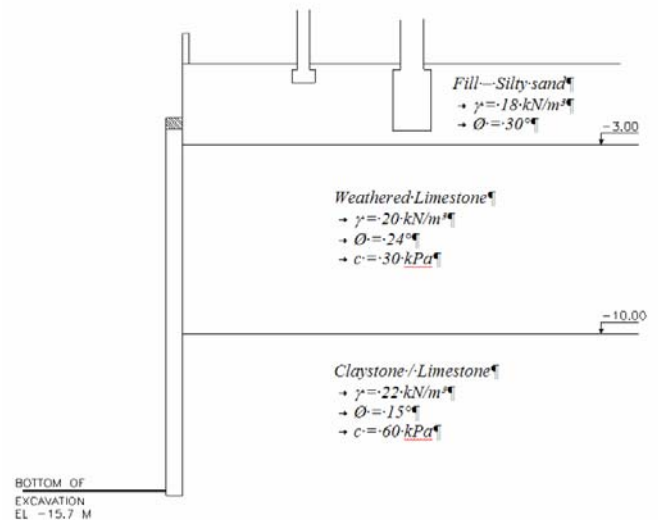


Fig. 2. Typical soil profile and design characteristics

UNDERPINNING OF THE CHURCH STRUCTURE

Based on the comprehensive damage survey prepared for the structure, the areas of extensive damage appeared to be concentrated in the zone identified in Fig. 3. The damage patterns and the established subsurface conditions strongly suggest that the distress to the structure is due to a loss of soil and bearing support beneath the church foundations. The foundation system in this case consisted simply of shallow (1-2m) “piers” built with sandstone blocks and bearing on the sand layer for some and the underlying marl for others. As such, the remedial solution adopted for the church itself was to consolidate/strengthen the bearing soil and then strengthen the church walls.

The main objective of the soil consolidation works was to create a long-term, stable, and uniform bearing support for all foundations. The system had also to abide by certain constraints namely, the old age of the church, the precarious state of the walls, limitations placed by the religious authorities regarding work in certain areas and possibly disturbing existing shrines etc. In summary, the limitations controlling the choice of the adopted consolidation works were the following:

- ❑ Minimizing disturbance to structural elements.
- ❑ Avoiding any methods which would involve undesirable levels of vibrations and which would compromise the very sensitive structure.
- ❑ Avoiding/minimizing works from within the church itself, particularly in and around the altar area.
- ❑ The need to work in relatively tight spaces.
- ❑ Incorporating a system with a rigidity similar to that of the existing foundations.

Initially, the most appropriate solution was found to be the double jet grouting technique which would replace the existing upper sands with columns of soil-cement grout. This technique is most appropriate where foundations rest on cohesionless materials. However, during the preparatory works, we realized that the majority of the foundations were bearing on the weathered marl formation, except for some external columns and for the staircase at the north-east corner of the church.

As a result, the underpinning system was modified to include low capacity vertical and inclined micropiles installed in a dense array to act as root piles for the church. The micropiles are designed to both absorb the vertical loads and to consolidate the subsoil. Pre-jacking was not considered since it tended to increase the rigidity of the system and possible cause upward movement of the structure, which could have compounded the damage. The layout of the micropiles and typical details are shown on Figures 3 and 4.

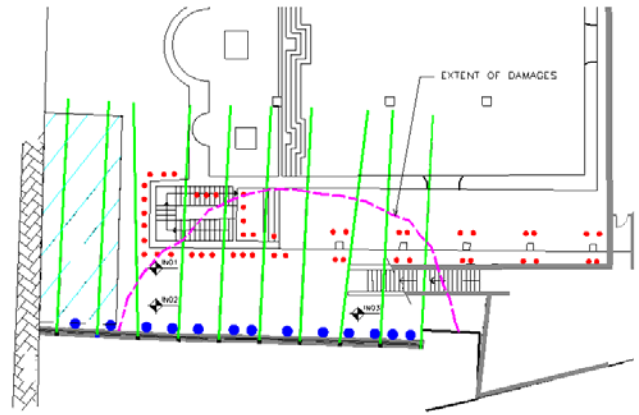


Fig. 3. Extent of 'failed zone' and micropile layout

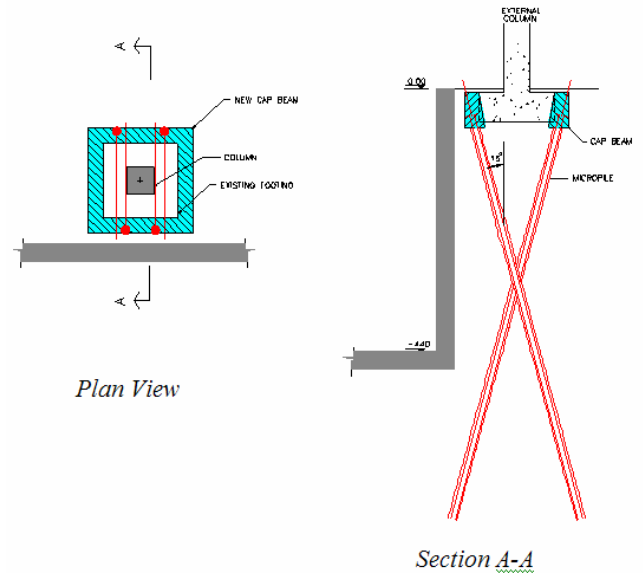


Fig. 4. Detail of micropiles used for underpinning

The micropiles used for the project have a service capacity of 19 t designed to be developed by friction in the weathered marl formation, the friction in the sand being conservatively ignored. The micropiles were designed for a service life of 100 years and the section of steel used was over-thickened to accommodate this requirement.

The layout of the micropiles is shown on Fig. 3 and incorporates

two general schemes. Around the external 30-t columns, four inclined micropiles are installed in an “X” pattern as shown in Fig. 4. For the staircase walls, inside space was extremely tight and the micropiles were positioned outside the walls. A capping beam ties the top of the micropiles and connects through “finger” beams (openings made through the external walls) to an internal mat constructed inside the staircase. The micropiles were distributed in such a way to minimize interference with the future prestressed anchors of Lot 235.

NEW MULTIPURPOSE HALL

As the rehabilitating works were proceeding, the Church decided to take advantage of the already created disruption to add an underground multipurpose hall in the front yard of the church (Fig. 1.). The required excavation was 5.5 m deep and the boundaries of the excavations reached the main bearing walls of the church. As such, the front columns of the main entrance required in-situ stabilization work that would not induce any deformation.

For the bearing walls, the excavation was stabilized by micropiles and lateral prestressed anchors as shown in plan in Fig. 5. Special care was taken at the salient corner to avoid interference between two cross-anchors. The shoring system was designed to limit top estimated deformations to less than 5 mm and to optimize the anchoring system with respect to the very strict space constraints around the columns.

For the external 30-t columns away from the central walls, the adopted system was developed in close collaboration with the Architects. The main objective of the underpinning was to implement a scheme that would guarantee negligible displacements. The requirements of such a system were to meet the following criteria:

- ❑ Maintain the wedge of soil beneath each column in an at-rest condition during the entire duration of the operations.
- ❑ Apply least amount of vibrations to existing columns.
- ❑ Respect architectural constraints.

SHORING OF LOT 235.

Once the church underpinning and structural repair works were completed, the excavation and shoring works for lot-235 were given the approval to resume by the municipality. About one year had passed since the near-catastrophic failure. The geotechnical specialty contractor submitted a design which incorporated elements of the already executed shoring system.

The already existing system comprised 60cm diameter bored cast in situ concrete piles spaced at 1.6m to 2.2m on center and extending to 0.5m to 1.0m below the projected final excavation level. The piles would be incorporated in the new shoring design. However, as was noted earlier, many of the already installed anchors had failed and only two rows at a depth of -4.5m and -12 m could be considered as useful in any measure.

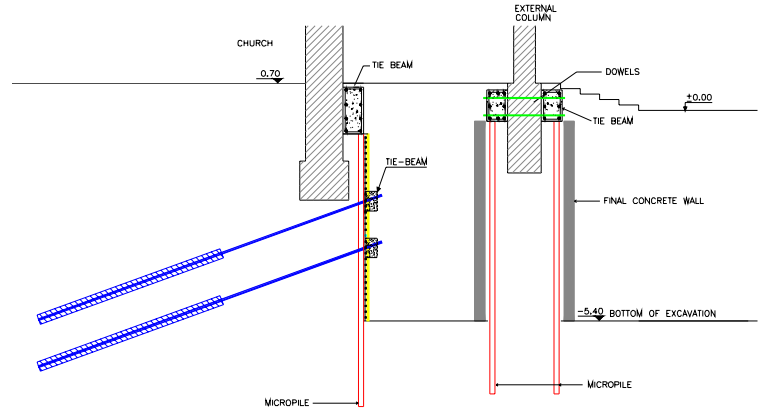


Fig. 5. Shoring and underpinning for the multi-purpose hall

After some discussions and re-designs, the adopted design incorporated all existing piles and the second row of anchors (at -12m) to a partial extent. The reliability of the row of anchors executed at -4.5m was deemed to be very low, given its proximity to the failed mass and the time elapsed since its completion. The analysis and design of the shoring system was performed using a finite element, elasto-plastic spring model, WALLAP by Geosolve. The program takes into account all external loads, the rigidity of wall, the stiffness of the soils, and all relevant construction phases. The new rows of anchors were distributed vertically to meet the following criteria:

- ❑ Maximum permissible deformations of 5 mm at the top of wall and 20 mm along the pile shaft.
- ❑ Maximum service moments in the piles of 418 kN.m per pile, as back-calculated from data communicated by the general contractor.
- ❑ Location of future basement slabs.

Five rows of anchors were used at the project as shown in Fig. 6. The moment capacity of the piles was verified but large deformations remained at the pile toe despite increasing the number of anchors and lowering the last row of anchors. The reason for these large deformations was attributed to the inadequate pile embedment. Nevertheless, these deformations were tolerated in the design with the assumption that the toe

would be locally examined and treated once the final excavation level is reached.

The first row of anchor was installed on a new concrete wall constructed above the existing piles. This row was considered a key element in controlling top deformations.

The temporary prestressed anchors were designed in accordance with "Recommendations TA95". For a borehole size of 120 mm, the working shaft resistance used to determine the bond length of the anchors was 0.23 MPa and 0.35 MPa for the weathered marl and limestone formations respectively. Anchor capacities varied between 300 kN and 640 kN. A quality assurance plan was implemented for the anchors in the form of two destructive pull-out tests and conformity checks for each anchor to 20% above working load.

installation, and anchor stressing.

In general, the obtained data confirm the results predicted by the analyses. Fig. 7 and 8 present typical sets of data for inclinometer IN02. The following observations may be made with reference to the inclinometer readings:

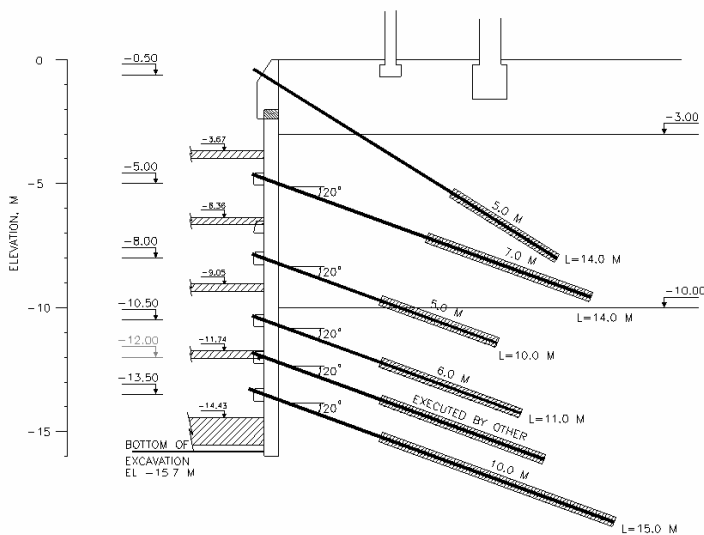


Fig. 6. Layout of the re-designed shoring system along lot-235

EXCAVATION MONITORING

For the first time in Lebanon, inclinometers were installed to monitor deformations during excavations. Three inclinometers were installed at locations shown on Fig. 3. Inclinometers IN01 and IN02 were positioned along the most critical section at 4 m interval, whereas IN02 and IN03 were installed along a line parallel to the property limit to cross-check verify data.

The inclinometer casings were installed in vertical boreholes and grouted along their entire lengths. For proper referencing, the inclinometers were extended 2 m below excavation level. Measurements were taken on a regular basis and at each construction stage corresponding to soil excavation, anchor

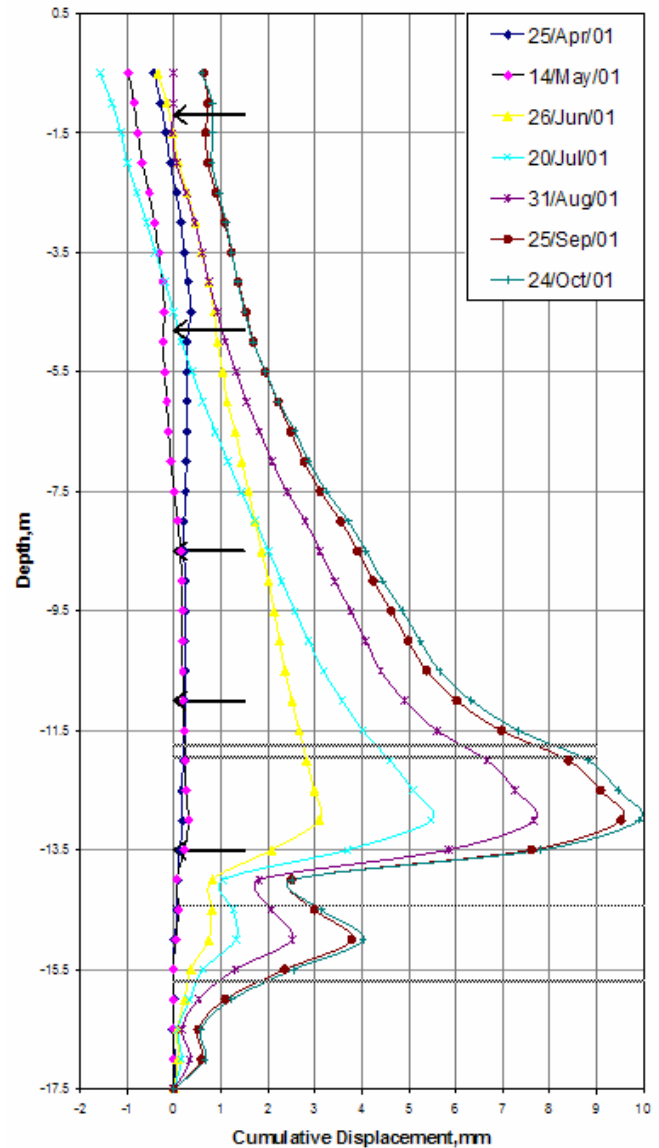
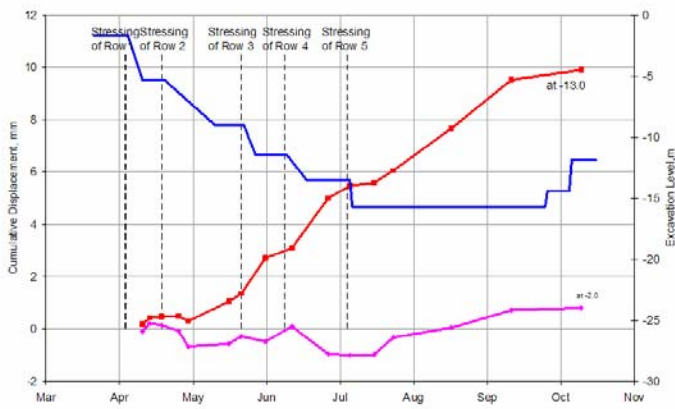


Fig. 7. Cumulative displacements at IN02



The use of inclinometers proved to be a very useful tool to monitor deformations of the excavations with excellent accuracy. Results were analyzed within hours of their measurements allowing rapid intervention on site, if necessary.

An unexpected behavior was noted in the deformation pattern of the excavation wall where deformations continued to take place for a few months with no additional excavation activity.

The need for close monitoring and constant evaluation of the expected design performance of such works cannot be underestimated in an environment where developers constantly push for deeper basements in a denser and more urbanized city undergoing rapid, and in ways, unchecked growth like Beirut.

- ❑ Deformations at the top remained small and less than 1 mm.
- ❑ Deformations at the bottom of the pile are relatively large, reaching a maximum of 10 mm.
- ❑ Deformations usually increase during excavations and either regress or stabilize after anchor installation.
- ❑ Deformations at top anchors are not affected by subsequent excavation stages.
- ❑ Once the final excavation depth was reached, deformations continued to evolve but at a slightly slower rate than during excavation.
- ❑ Once construction of the building foundations and slab started, the rate of deformations decreased significantly to become almost nil.

The above findings were generally expected by design. However, it is interesting to note that deformations continued when reaching a stable level of excavation. Although the observed values were still smaller than anticipated, the observed behavior is unusual and may be associated with one or a combination of the following:

- ❑ Lack of pile embedment, which gives rise to an unstable toe; or
- ❑ Delayed reaction of the shoring system due to a natural long-term relaxation of the cohesion.

CONCLUSIONS

This paper documents the successful rehabilitation of the Lady of Annunciation Church after the near total failure triggered by the excavation of an adjacent lot-235 slated for development. The paper also describes the shoring system and the monitoring system put in place to allow a safe re-excavation of Lot 235.