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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 lies along the side of the hall with small size circular columns supporting a mezzanine level. Two stairwells define both ends of the gallery and lie on either side of the altar.

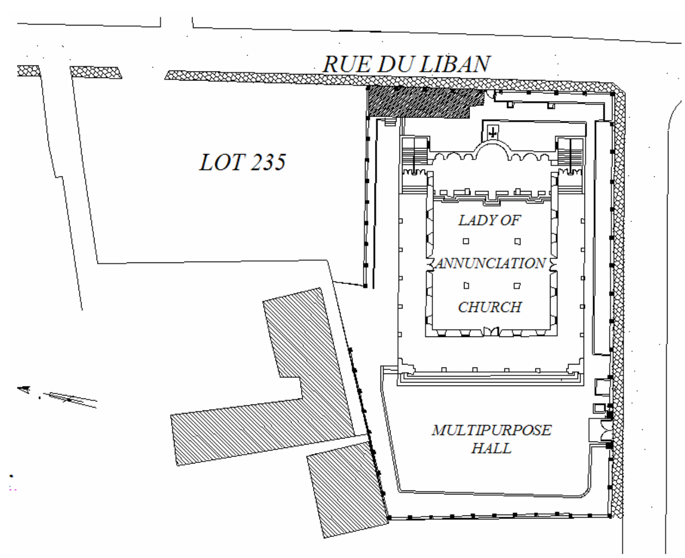

Fig. 1. General plan view of the church and lot 235.

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 ~-15.7m 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 walls 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 ~1.6m to 2.2m c-c and reportedly extending to ~ -17m 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 ~-9m to -12m 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 ~-6.5m 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 -12m. 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 -12m 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 -2.5m 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. In addition, the responsibilities of the assembled panel included 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 remedial underpinning works within the church and the additional shoring works on the lot-235 side.

SUBSURFACE CONDITIONS

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

- A surficial layer of red-brown clayey sand, 2m to 6m thick. The clayey sand layer is loose to dense with SPT values ranging between N=5 and N=7.
- 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.

Water was found in the boreholes at a depth of -12 m to -13 m. It is important to add that during the initial excavation works, water influx into the site was reported at much shallower depths, probably seeping from localized sources, likely broken utilities.

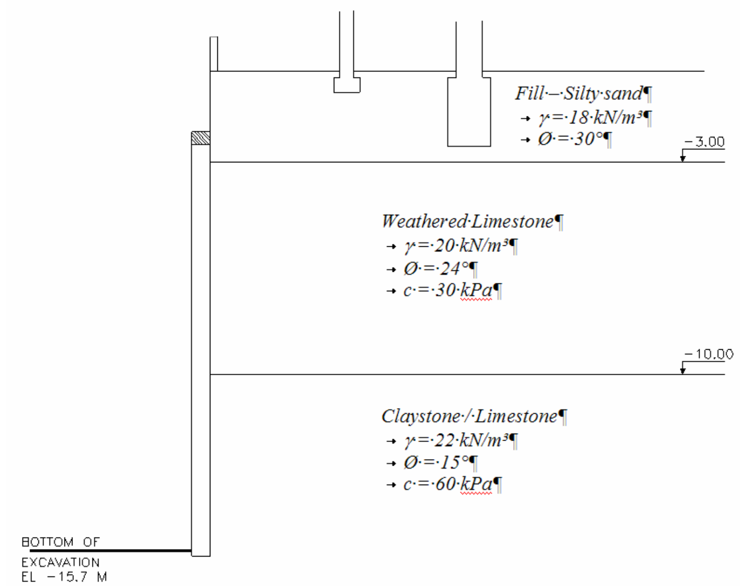

Fig. 2. Typical soil profile and design characteristics

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 loss of support may be associated with lateral deformations of the shoring system at the excavation limit. 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 primary goal of the foundation remedial works was to create a permanent, stable, and uniform bearing support for all foundations. Any approach adopted had also to adhere to a number of constraints namely: the old age of the church, the precarious state of the walls and limitations placed by the religious authorities regarding work in certain areas which may possibly disturb 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 soil-cement columns. This technique is most appropriate where foundations actually rest on cohesionless materials. As the preparatory works proceeded, it became clear that the majority of the foundations were actually bearing on the weathered marl formation, with the exception of the external columns and the staircase well at the north-east corner of the church.

Given the above, the underpinning system was modified to include low-capacity vertical and inclined micro-piles installed in a relatively dense array around the church foundation piers and footings. The micro-piles were designed provide support for the applied the vertical loads while at the same time consolidating the subsurface soils. Pre-jacking was not considered since it would have tended to increase the rigidity of the system and possibly resulted in upward movements within the structure, which could have compounded the damage. The layout of the micro-piles and typical details are presented in Figures 3 and 4.

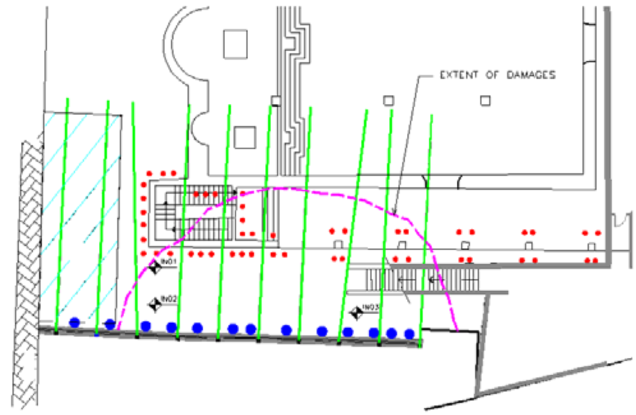

Fig. 3. Extent of 'failed zone" and micropile layout

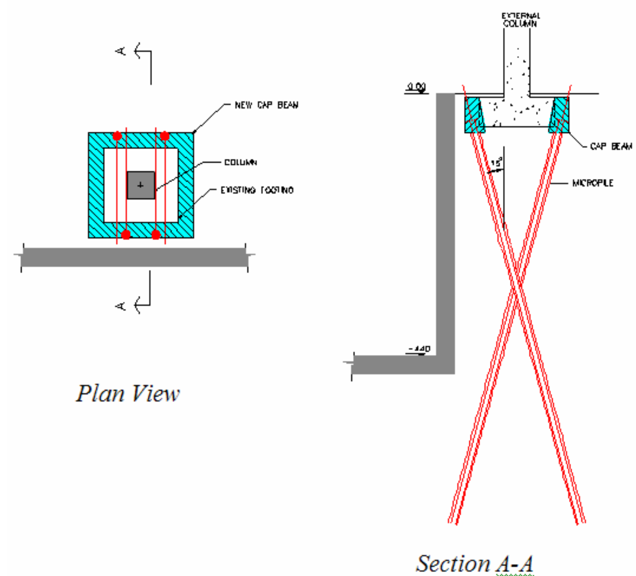

Fig. 4. Detail of micro-piles used for underpinning

The service capacity of the micro-piles used for the project was 19 t, designed to be developed by friction in the weathered marl formation. The frictional capacity developed within the upper sand formation was conservatively ignored. The micro-piles were designed for a service life of 100 years and the section of steel used was modified/increased to accommodate this requirement.

The layout of the micro-piles is presented in Fig. 3. It is basically comprised of two schemes. Four battered micro-piles are installed in an "X" pattern around the external 30-t columns, at a 15 degree to the vertical, as shown in Fig. 4. The micro-piles were positioned outside the walls of the staircase given the extremely tight space inside. The top of the micro-piles were tied through a cap beam which connects through "finger" beams (openings made through the external walls) to an internal mat constructed inside the staircase. The layout of the micro-piles was finalized in such a way as to minimize any interference with the future pre-stressed 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 (Fig. 1.). The required excavation was 5.5 m deep and the boundaries of the excavation reached the main bearing walls of the church. In order to minimize any potential deformation, the foundations of the front columns of the main entrance had to be treated through in-situ stabilization works.

For the case of the bearing walls, the excavation was stabilized by micro-piles and lateral pre-stressed anchors as shown in plan in Fig. 5. Special care was taken at the salient corners in order to avoid interference between two cross-anchors. The shoring system was designed with a maximum tolerance on the deformations at the top of less than 5 mm. The shoring works were also designed in a fashion to optimize the anchoring system with respect to the very strict space constraints around the columns.

As far as the external 30-t columns away from the central walls were concerned, the adopted system was developed in close collaboration with the architects. Here again, 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 a quasi at-rest condition during the entire duration of the operations.
- Induce the 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 was comprised of 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.

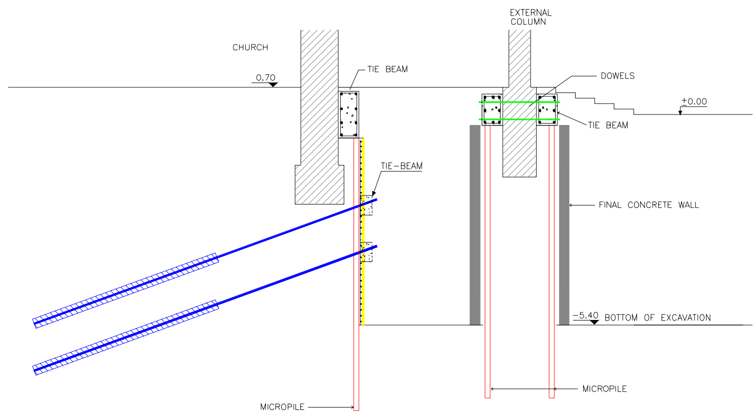

Fig. 5. Shoring and underpinning for the multi-purpose hall

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.

In total, five rows of anchors were executed 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 insufficient pile embedment. A decision was taken to accept the calculated toe-level deformations at the design stage with the provision that the piles would be locally examined and treated once the final excavation level is reached.

A new concrete wall was constructed above the existing piles and the first row of anchors placed through it as shown in Fig. 6. This row was provided as a key element in controlling top deformations.

The temporary pre-stressed anchors were designed in accordance with "Recommandations TA95". For a borehole size of 120 mm, the working shaft resistances used to determine the bond length of the anchors were 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.

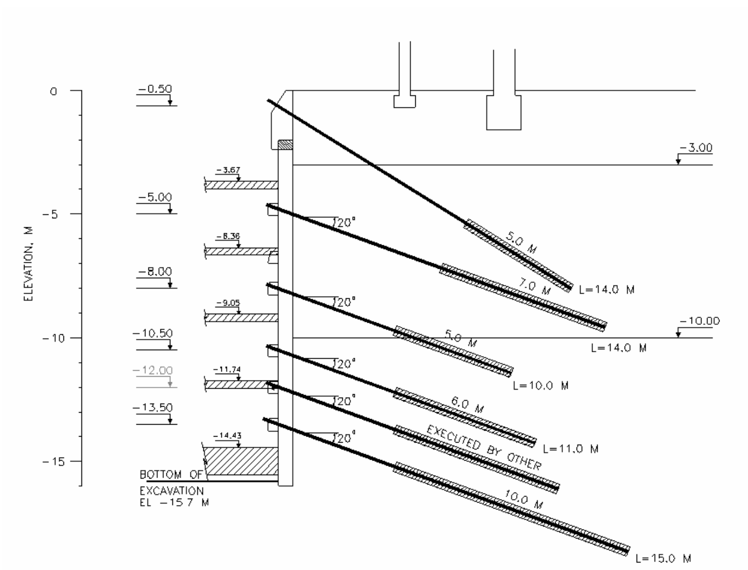

Fig. 6. Layout of the re-designed shoring system along lot-235

EXCAVATION MONITORING

Inclinometers were installed to monitor deformations during excavations. This was the first use of inclinometers in Lebanon! 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 and 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 installation, and anchor stressing.

In general, the data obtained 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:

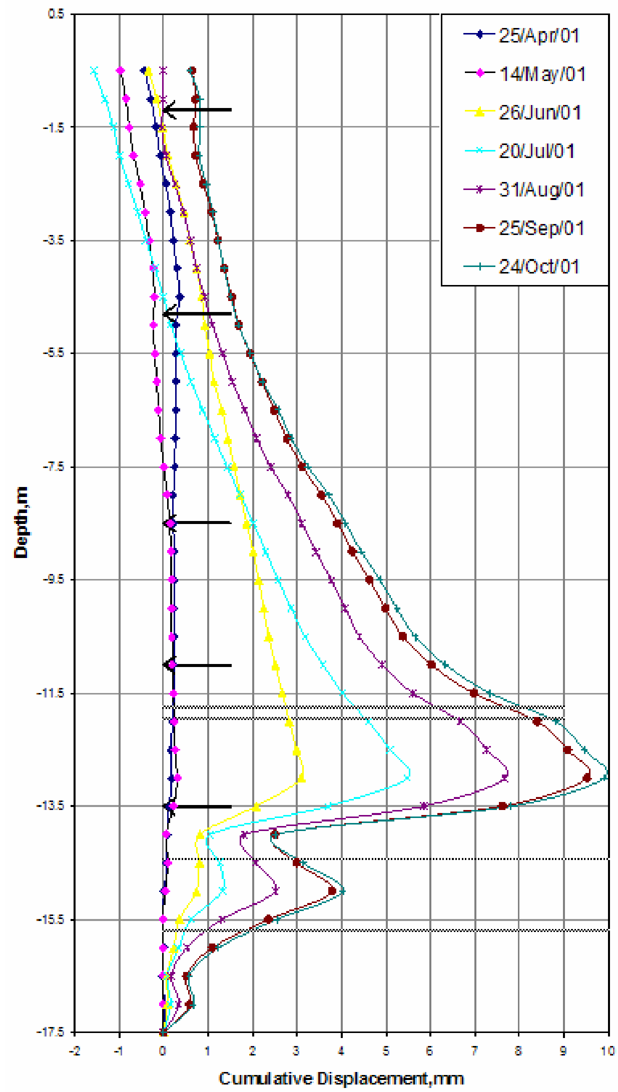

Fig. 7. Cumulative displacements at IN02

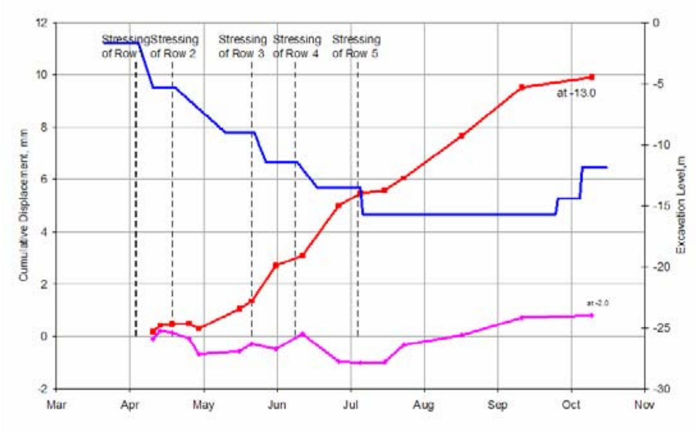

Fig. 8.Time displacements at IN02

- 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 anticipated based on the design. However, it is interesting to note that deformations continued even after a stable level of excavation was reached. Although the observed values were still smaller than predicted, the observed behavior was 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 soils in which the anchors are secured.

CONCLUSIONS

In this paper the case of the near total failure of the Lady of Annunciation Church is presented along with the possible causes of the observed distress. The successful rehabilitation of the structure and adjacent lots is documented in detail along with the design constraints and considerations. The paper also describes the shoring system and the monitoring system put in place to allow for close and reliable measurement of deformations and insure a safe excavation of Lot 235.

Inclinometers proved to be a very useful tool to monitor deformations of the excavations with remarkable accuracy. Results were analyzed immediately after measurements were taken allowing for rapid intervention on site if and when necessary.

The continued deformations measured along the excavation walls after the completion of the excavation and for a duration of weeks to months was unexpected. This was attributed to the nature of the subsurface strata and long term creep and relaxation of the anchors. All in all the deformations remained well within the levels anticipated.

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.

PS- As an interesting side note, after the re-excavation works were completed, the long standing legal disputes and costs incurred during the months leading to that point, the main contractor faced grave financial difficulties. Works on building the basements superstructure could not proceed and the lot was backfilled, again!, and serves now as much needed parking area for the neighborhood Fig. 9.

Fig. 9. View of the backfilled lot.