CASE HISTORY APPROACH TO GEOTECHNICAL DESIGN ON HERITAGE STRUCTURES: MEXICO CITY´S METROPOLITAN CATHEDRAL (1989-2009)

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ABSTRACT

Mexico City´s Metropolitan Cathedral was underexcavated to correct deformations that accumulated previously due to self weight consolidation and regional subsidence. Upon the end of underexcavation, the effects of regional subsidence reappeared and some of the corrections gained were lost. To prevent further accumulation of damage in the future, the very soft clayey soils underlying the Cathedral and the adjacent Sagrario Church were hardened selectively by means of injected mortars. Observational data show that both procedures have been successful. Taking the project for salvaging Mexico City´s

Metropolitan Cathedral as an example, this paper puts forth suggestions for planning a post graduate course on Geotechnical Design focused on heritage structures, based on the study of case histories.

1. INTRODUCTION

Conservation and restoration of historical monuments is a multidisciplinary activity in which, apart from architects, historians or archaeologists, experts from several fields in engineering must frequently participate. Architectural conservation and restoration projects should comply with standards and criteria generally accepted and enforced by governments worldwide. Related engineering activities must not contravene these criteria. In the case of geotechnical engineering, participation of experts in this field in conservation and restoration problems is generally defined in terms of what is customary in "good engineering practice", preferably making reference to statutory regulations, building codes or well established design manuals. There are no specific recommendations or guidelines for applying the principles of geotechnical engineering to these problems although the International Society for Soil Mechanics and Geotechnical Engineering created a special technical committee whose task is precisely drafting a set of guidelines for that purpose. The committee is due to come up with these guidelines shortly.

It can be expected that those guidelines should include the following six basic general topics: a) setting up of the geological and geotechnical environment; b) historical survey; c) analysis and/or diagnosis of the problem; d) identification of solution or intervention proposals taking into account the need to preserve the functional, architectural and historical integrity of the building; e) overview, application and control of the selected solution; f) long term monitoring.

Those six topics can be assembled into a corpus of knowledge to provide civil engineers with the tools necessary to face the geotechnical aspects of a conservation or preservation project. All of them can be incorporated into a course or a series of courses in geotechnical design. The way of integrating these subjects into the curricular activities in university courses can vary depending on many factors. One of them is whether students should be expected to have this expertise as undergraduates or when pursuing higher degrees. In the Authors' opinion those topics can be best included in postgraduate courses.

MSc courses in Soil Mechanics or Geotechnical Engineering generally comprise subjects such as geology, soil properties, rock mechanics, consolidation, seepage, geotechnical analysis, slope stability, geotechnical design, foundation engineering, engineering seismology, etc. The six topics for dealing with the preservation of monuments can all be included throughout the traditional curricular body of a postgraduate course in Soil Mechacnics, i.e those topics can be covered horizontally in all of the traditional courses. Alternatively, specific courses in geotechnical design for the conservation of monuments can be designed. In any case, additional courses or extracurricular lectures in Art History, History of Architecture, Theory of Conservation, would also be of great valuable as well as field trips to the sites of ongoing projects.

Finally, a further approach is the study of case histories in which the six topics put forth above can be discussed in connection to specific well documented projects. It would be a matter of discussion whether studying case histories can indeed substitute other formal, more orthodox courses, bearing in mind that the objective is to train civil and or geotechnical engineers in this kind of work.

In this paper we describe how these topics were applied to the case of Mexico City's Metropolitan Cathedral. The Metropolitan Cathedral in Mexico City was affected with fissures and cracks caused by differential settlements that became alarming in 1989 when the authorities decided to undergo yet another intervention, the fourth in the XXth century, to salvage the monument. In this paper we take cursory look, over the last twenty years (1989-2009), at the most important achievements in Geotechnical Engineering of the project for the conservation and the preservation of that important monument. Detailed discussions and descriptions of the relevant geotechnical aspects of the case have been published elsewhere (Tamez, et al, 1997; Ovando-Shelley and Santoyo, 2001; Santoyo and Ovando Shelley, 2004).

2. GEOTECHNICHAL ENVIRONMENT

As in medicine, the symptoms of a pathology affecting a monument can be normally pointed out with relative ease. Identification of the illness, of the factors causing the pathology cannot always follow straightforwardly. A strategy in going from the symptoms to the actual diagnosis is getting to know the patient first which means learning not only about the history of the building itself but, also, about the geological and geotechnical conditions at the site.

In the case of the Mexico City's Metropolitan Cathedral, preliminary studies performed in 1989 included 21 cone penetration tests (CPT tests) as well as two borings with continuous undisturbed sampling. In the course of the construction of 32 shafts in 1993, 29 additional CPT tests were made. Analysis of these borings and previous knowledge accumulated over the years in and around central Mexico City led to establishing the stratigraphical characteristics at the site. The profile shown in Figure 1 was produced from the results of three CPT borings performed in the atrium in front of the Cathedral and of the Sagrario. As seen there, the soil at the boundary between both churches is stronger because it corresponds to the zone that has received the heaviest load transmitted by the Aztec temples, by an archaeological fill, and by the two heavy Colonial structures. Towards both ends of the profile penetration resistance reduces almost by a half. This condition induced the tilting of the southern part of the Cathedral towards the west whereas the Sagrario is inclined to the east. The same figure also shows the thickness and depth of the most relevant strata found in the soil sequence at the site.

The soft soils with low CPT strengths are lacustrine clays which are the product of the hydration and degradation of volcanic effusions: clastic materials transported from upper parts of the basin by water currents, glaciers and directly from the volcanoes, by eolic action. These soils are geologically very young and are notorious for their extremely high water content and compressibility. Layers of coarser materials are also present, ashes and pumices, the product of volcanic eruptions that occurred during the Upper Pleistocene, as well as various forms of organic matter and microfossils.

The depth of the contact plane between the natural shallow crust and the soft clays was defined from information derived from the CPT tests. That surface was originally flat but as a result of the consolidation induced by the Aztec pyramids it underwent depressions as deep as 10 m. This is why the site was leveled with artificial fills to shape a new initial plane before the construction of the Colonial churches. One-dimensional consolidation tests demonstrated that the loads applied by the former pre-Hispanic constructions were removed at some parts, although in other areas they were subsequently increased by the weight of the Cathedral and of the Sagrario, as illustrated in Figure 2. This complex load history brought about the heterogeneity in soil conditions and properties.

Pore-water pressures at different depths were measured in a piezometric station installed at the southern atrium of the Cathedral. It can be observed in Figure 3 that between 0 and 20 m in depth, pore pressure is nearly hydrostatic; beyond this last depth a pressure loss of about 180 kPa was noted at the First Hard Layer, 38 m deep, and of 200 kPa at the Deep Deposits, 53 m deep. Pore pressures will slowly decrease in the future due to the extensive exploitation of the deep aquifers that underlie the city, which brings about regional subsidence. Estimations of the future evolution of pore pressure show that pore water may eventually define a hung aquifer formed by the infiltration of rainwater and by seepage from potable water and sewage mains

3. HISTORICAL SURVEY

The Metropolitan Cathedral was built on an area covered originally by the main Aztec Ceremonial Precinct (Ovando- Shelley and Manzanilla, 1997). Remains of structures corresponding to this pre-Hispanic site can still be seen under its foundation (Figure 2).

Construction of the Metropolitan Cathedral started in 1573 at the apse, under the direction of Master Builder Claudio de Arciniega, who already knew of the problems brought about by the underlying soft clays, based on his own previous experience. The vaults were erected next and were completed around 1667 and the façade in 1675. Damián Ortiz de Castro finalized the towers in 1791 and Manuel Tolsá, who completed the building in 1813, profiled the dome and joined the complex with a balustrade and pinnacles.

The subsoil was initially reinforced by driving about 22,500 wooden stakes, 3 to 4 m in length. On top of them a masonry platform was built over an area of 140x70 m. This area is larger than the one actually occupied by the Cathedral because it was originally conceived as a seven nave temple with four towers, one in each corner. The platform is 90 cm thick on average but it is thicker towards the south which suggests that the first builders added thickness at that particular zone to compensate differential settlements that became apparent since the earliest stages of its construction. A grid of masonry beams was placed on top of the platform, 3.5 m in height, 2.5 m wide and as much as 127 m long, to receive the walls, pilasters and columns, as illustrated in Figure 4. The top part of the platform had the same level as the Plaza Mayor (main square) and the grid of inverted beams was 3.5 m above this elevation suggesting that Master Builder Arciniega expected large magnitude settlements to occur.

The Cathedral has five naves: the central one bounded by 16 columns and divided by the choir; the two processional aisles running along the length of the church; and the two lateral ones occupied by chapels, that are in turn bounded by the peripheral and perpendicular walls. The great central dome, 65 m high, is supported by four columns. The two huge and heavy towers are 60 m in height. The church is 60.40 m wide, about 25 m high along the central nave and 126.67 m long with a total weight of 12,700kN and an average contact pressure of about 166 kPa.

Other religious buildings were built around the Cathedral, like the parish church known as the Sagrario which was constructed on top of the pyramid of the Aztec sun god, Tonatiuh. In the Sagrario, Lorenzo Rodríguez used the same foundation system as in the Cathedral. The soil was reinforced with short woodpiles and a masonry platform was built on top of them but with lesser quality materials. The Sagrario, built from 1749 to 1768, was partially founded on the Cathedral`s foundation platform and its western wall is common to both structures. It covers a square area of 47.7 m by side, weighs about 3,000 kN and the average contact pressure is about 132 kPa. The Bishopric was erected later, as well as All Souls Chapel (Capilla de las Ánimas) and the Seminary which was demolished in the nineteen forties.

Consolidation of the subsoil induced by Aztec temples and structures pre-existing at the site produced differentials in the compressibility of the clay strata which in turn, caused differential settlements in the Cathedral since the beginning of its construction. Structural misalignments caused by these deformations were compensated as construction progressed by modifying the heights of columns and walls in order to level the springing of the vaults. Architectural contrivances as the introduction of variable heights in the cornices and wedged quarried blocks at the two towers were used to disguise some of the visual effects of settlements. After analyzing the geometrical details of the monument it was demonstrated that during construction of the Cathedral, and prior to the completion of the vaults a maximum differential settlement of 85 cm with respect to the plinth of a pilaster the apse (Figure 5).

4. DIAGNOSIS

The maximum differential settlement in the Cathedral over 419 years, until the end of 1989, was 2.42 m, between the apse and the western tower (points B-11 and C-3 in Figure 6). This is the sum of two factors: a) consolidation induced by the weight of the pre-existing Aztec temples and of the subsequent Colonial structure; and b) regional subsidence of the city. The latter has been the most important factor for the development of differential settlements over the last 150 years; between 1907 and 1989 it induced a differential settlement of 87 cm in the west tower. The plinth of pilaster C-3 at the apse has traditionally been considered the zero reference, as seen in Figure 6.

The effect of regional subsidence on differential settlements at the structures was followed with precision topographic leveling surveys carried out at the Cathedral and the Sagrario during the stage of preliminary studies. The levelings were performed at the plane of the plinth of the columns supporting the Cathedral therefore allowing continuity in the leveling of this surface that have been carried out since 1907. As seen in Figure 6, the western tower used to settle 12 mm a year with respect to the central part of the nave; the southeastern corner of the Sagrario was settling 16 mm with respect to its central part, and the vertical deformation of the museum building was of 26 mm taking as a the bolt in pilaster C-3.

A forecast of long-term settlements was carried out using traditional soil mechanics methods assuming that the churches would be left as they were in 1989. As mentioned before, future settlements at the Cathedral and the Sagrario depend on the evolution of the pore-water pressures in the clay deposits. These estimations showed that future differential settlements brought about by water pumping would endanger seriously the cathedral should no actions were to be taken to correct accumulated damage or to prevent it in the future. It was also concluded that a large magnitude earthquake such as the one that occurred in 1985 could induce a stress condition that could seriously compromise the stability of the churches, particularly that of the western tower. Hence it was necessary to reduce the magnitude of both accumulated and future differential settlements.

5. SOLUTION PROPOSALS

The following five possible solutions for correcting historic differential settlements and to reduce future differentials were studied:

Piles supported on the Hard Layer. Their aim was to uniform settlements by driving 1500 point-bearing piles to the First Hard Layer, capable of supporting through negative skin friction, the total weight of the surrounding ground and of the Cathedral itself.

Shafts supported by the Deep Deposits. With this solution, the settlement of the structure would not depend on the sinking of the two clay formations. Shaft tips would be supported by the Deep Deposits and would be connected to the foundation by means of mechanical devices to correct existing tilts and to avoid the accumulation of tilting in the future.

Underexcavation in soft clays. It would require excavating small diameter micro-tunnels that would close due to plastic deformation of the soft clays; successive opening and closure of the tunnels would gradually induce corrective settlements until reaching the deformation targets fixed according to structural considerations.

Pore water recharge. The artificial recharge of water into permeable subsoil strata was studied making reference to a brief experience gained with this technique at the National Palace. This would control 69% of the settlements provided water injections remained permanently; otherwise settlements would inevitably start accumulating again.

Underpinning with micropiles. "Pali radice" or inclined and vertical small-diameter micro-piles were also studied. Intertwined inside the clays, these elements create hard blocks that transfer loads to the deeper strata. This solution would require an enormous amount of such elements.

Analyses of the five options were presented to associations of architects and engineers as well as to soil mechanics specialists. The solutions were evaluated on the basis of the opinions gathered thence, with reference to the following factors: structural goals, interference for the usage of the temples, time of execution, budget, and probable contingencies. Bearing that in mind, it was concluded that the best solution was the Underexcavation Method.

6. UNDEREXCAVATION AT THE CATHEDRAL AND THE SAGRARIO

The purpose of applying this technique was to reduce differential elevations and tilting induced by differential settlements. The method involved lowering the high parts with respect to the low points through the slow and controlled extraction of soil from the bearing strata. Three specific tasks were necessary to apply the method in our case: a) the construction of access shafts; b) the punctual drawdown of the phreatic level; and c) underexcavation or controlled extraction of small portions of soil until removing a pre-established volume. The two first operations are preliminary; the third one constitutes the corrective geotechnical procedure itself. Underexcavation trials in a masonry structure whose architecture is similar to the Cathedral's were performed at the temple of San Antonio Abad which is a comparatively small church.

Preparatory work began by excavating 32 access shafts whose number and distribution were determined applying analytical and numerical methods. Their bottom was taken down to top of the Upper Clay Formation, between 14 and 25 m. A pumping system was applied during the excavation to gradually drawdown the phreatic level and to prevent bottom failure; it operated throughout the whole soil extraction process.

Soil was extracted from the soft clay located at the boundary of the Upper Clay Formation, the morphology of which is illustrated in Figure 7. In each shaft a maximum of 50 radial borings penetrated into the soil in lengths ranging 6 to 22 m. Boreholes, 10 cm in diameter, were inclined 20º and a remolding tool was sometimes used to accelerate their closure.

The targets to be achieved were derived from the results of graphic-analytic and numerical structural analyses. The correction targets derived from these analyses were: a) to close and rotate the lateral walls in order to strengthen the “confining belt” formed by the walls along the perimeter of the temple and along the sides of the chapels; b) to lower the Cathedral’s apse 80 to 95 cm, in a rigid body movement, c) to lower the Sagrario’s north side 30 cm in a rigid body movement.

In the process of underexcavation, the weight and the moisture content of the material extracted were accurately and rigorously monitored; samples for laboratory testing to obtain their mechanical properties were also retrieved. Soil extraction began in August, 1993, and finished in June, 1998; 4,220 m^3 were removed in about 1,500,000 extraction operations. The procedure was controlled by a technical committee that met every other week to analyze the results of precision levellings, records of electronic plumblines, convergence gauges, tiltmeters and temperature gauges. The committee, applying the Observational Method, decided upon the actions to be taken during the following fortnight. Underexcavation stopped once the structural targets of the project were achieved and, thus, the religious complex was once again exposed to the action of regional subsidence.

Precision topographic surveys were made by measuring 246 control points distributed over the whole area covered by the monument. These levellings were carried out every two weeks from October 1991 to the end of 1999; it was subsequently decided to schedule them monthly. 2000. Three levellings per year were done afterwards from 200 to 2004. Two levellings were made in 2005 and none in 2006; the last two levellings we made in December 2007 and December 2008.

7. GEOMETRICAL CORRECTION ACHIEVED

When underexcavation ended in June 1998, differential settlements that had accumulated over the previous 65 years as a result of regional subsidence were basically eliminated.

The configuration of corrective settlements is given in Figure 8. The maximum correction induced was 92 cm then, between the apse and the southwestern corner. However, in September 1999 it reduced to 88 cm and to 30 cm at the Sagrario. The difference from 92 to 88 cm is due, as discussed previously, to the return of the effects of regional subsidence upon the end of underexcavation and the stoppage of the pumping operations.

Historical differential settlement between points C-3 and B-10 changed from 243 cm in 1989 to 156 cm in June 1998. The average angular correction between these two points was 23' 06" and of 25' 33" between points D-1 and A-12.

Underexcavation initially induced movements to recover the confinement provided to the vault by the walls. The sequence of soil extraction was later adjusted to produce rigid body displacements towards the northeast. Corrective settlements contributed to the closing of the cracks and to reducing tilts in columns. Nonetheless, some new cracks developed and others that already existed widened. Plastering fell off at some points as well but damages were considerably smaller than those expected at the beginning of the project.

Analyses showed that the safety conditions of the churches were at no time at all in the course of the project in a situation of risk. The shoring, the confinement reinforcing at the columns (splints), and the turnbuckles that were installed at the roof protected the structures against possible damage. The most critical aspect regarding the safety of both churches concentrated on the columns, and it was therefore decided to grout them to achieve long-lasting improvements in their safety factors.

8. MORTAR INJECTIONS

A means to prevent or avoid the detrimental effects of regional subsidence on the Cathedral at the end of underexcavation was sought and found: hardening selectively the underlying clays to attain a uniform or fairly uniform distribution of compressibility. Before applying this concept in the Cathedral an important precedent case was studied, that of the Palace of Fine Arts (Palacio de Bellas Artes).

Differential settlements at the Palace of Fine Arts, were first noticed in 1906 when its foundation slab was being constructed. This prompted the injection of grouts into the soft underlying clays, from 1910 to 1925. Those injections were aimed to arrest radically the settlements, although to no avail. However, it should now be acknowledged that grouting achieved a great success because, although the settlements were not stopped, they became uniform. The same procedure had been applied in 1881 at a railway station and in an orphanage in the nineteen forties (Santoyo et al, 1998).

Regarding the Cathedral, theoretical and experimental research into the effect of mortar grouts injected into soft clays began in 1997. The technique was evaluated from the results of field trials and with complementary laboratory tests and numerical simulations. Mortars injected under pressure into the soft soils produces hydraulic fracturing, a phenomenon that has been investigated in extensive theoretical and practical research in many countries, but never in the Mexico City clays.

Field tests showed that fluid mortar injected into the clay produces fissures and cracks along planes whose orientation depends on the initial in situ stress state. In this case mortar penetrates in the fissures forming vertical or nearly vertical sheets since Mexico City Clay is normally consolidated (the major principal stress is vertical). Trials on the formation of rigid inclusions were also performed opening 23 cm boreholes stabilized with slurry generated during the perforation. A permeable polyester fabric is then introduced into which fluid concrete was then cast. Exploratory excavations performed afterwards revealed that the mean diameter in the inclusions was 29 cm, which implies a 26% radial expansion in the borehole diameter. Rigid inclusions as well as the associated vertical mortar sheets are illustrated in Figure 9.

An *in situ* clay hardening test took place between November, 1997 and January, 1998 out side the southwest corner of the Cathedral which comprised casting 18 rigid inclusions and injecting 179.5 m^3 of mortar. The test was followed with: a) settlement measurements at different time intervals, within a grid of control points; b) monitoring the hydraulic conditions within the clay mass before, during and after the test; c) measurements of wave propagation velocities with a seismic cone and lateral stresses with a Marchetti dilatometer. The grout was made with a mixture of cement, bentonite, pumitic sand and admixtures. Reductions of deformability depend on the stiffness of the mortar and on the percentage of grout injected. This last concept is the ratio between the volume of mortar and the volume of soil to be improved.

Borings to carry out the injection crossed the archaeological fills and the superficial crust and went through the Upper Clay Formation, that was grouted down to its contact with the First Hard Layer. Figure 10 shows the areas where the Upper Clay Formation under the Cathedral and the Sagrario was hardened reduce the accumulation of additional large differential settlements and to try to improve their behavior. Grout percentages varied from 2 to 7% at the Cathedral and from 1 to 5% at the Sagrario. Deformable mortar was injected at 571 inclusions with their respective clusters of lateral sheets. 419 inclusions were formed at the Cathedral, 111 at the Sagrario, and 41 at the museum building. This distribution was decided in terms of the zoning determined for the subsoil compressibility and was adjusted applying the Observational Method.

From September 8, 1998 to June 4, 1999 the southwestern part of the Cathedral was grouted as well as the northeast and southeast corners of the Sagrario from June 7 to September 9, 1999 the south zone was grouted with 2%; finally, in December 2000 the same thing was done at the northeast corner, although the volume of grout was only a fraction of the total planned. The grouting job was complemented in the northwest corner from November 2001 to January 2002. The total volume of mortar injected was 6934 m^3.

9. BEHAVIOR AFTER GROUTING

Comparing settlement rates at the Cathedral and the Sagrario before and after injecting mortars proves that subsoil grouting was indeed successful. Figure 11 shows the initial behavior expressed graphically in terms of settlement rates observed between January 7 and September 2 of 1991. The central part of the Cathedral emerged with respect to its northeast corner, at a rate of 16 mm/year, and with respect to the western bell tower at 12 mm/year. The maximum differential rate of 18 mm/year developed between the center and the northeast corner. The Sagrario shows a maximum settlement rate at its southeast corner of 16 mm/year with respect to point C-3, located close to the apse of the Cathedral, and 20mm between the southeast corner and the northwest columns.

As seen in Figure 11, the Cathedral was still sinking in December 2008 but it did so almost uniformly, as expected. From the direct comparison of the graphs in that figure, two conclusions can be derived: 1) injection of mortar grouts into the subsoil modified positively the pattern of settlement rates; and 2) this modification was beneficial for the structures because it achieved a substantial decrease of differential settlement rates. For example, relative differential settlement between point C3 and the southwest corner passed from 12 mm/year in 1989 to 4 mm/year in 2007.

10. FINAL COMMENTS

The participation of engineers in patrimonial conservation projects complements the task of architects, historians, archaeologists and conservationists. The case of the Metropolitan Cathedral provides an excellent example of how the specific activities of geotechnical engineers were of paramount importance for providing innovative, effective, solutions to the problems affecting this important monument.

As shown here, underexcavation was successfully applied at the Metropolitan Cathedral in Mexico City. It can also be adapted to a large variety of conditions as in the Tower of

Pisa (Jamiolkowsky et al, 1999). Mortar injections have been used in other geotechnical environments as a means to compensate surface settlements induced by underground works (Harris et al, 2001). Both methods, as applied in this case, are innovative and are now being used in Mexico City to prevent the effects of differential settlements in a variety of buildings, mainly modern structures.

The successive application of underexcavation as corrective measure followed by mortar injections as a means to prevent further damage to the Cathedral relied heavily on applying *ab initio* the Observational Method which depends on (Peck, 1969): a thorough knowledge of both geotechnical conditions and soil characteristics; the estimation of probable working conditions and extreme case scenarios; selection of the variables to monitor and the monitoring of those variables during the course of the intervention; periodical assessment of the structural response; the adjustments or modifications of the design assumptions or of the actions required to achieve the expected goals; the continued reassessment of the structural response.

In terms of didactic values, case histories as the one presented here are not always readily available. Still, it is usually possible to build up reasonably good cases based upon published materials. Literature on the subject, specifically on Geotechnical Engineering applied to the conservation of monuments has grown steadily over the last decades. Specialty sessions on the subject have been present at international conferences for more than 15 years, as well as seminars, *colloquia* and conferences.

The paper presented here outlines the subject matters, the six topics mentioned previously, that can be examined closer, perhaps exhaustively, via examples like the Cathedral, in a course on Geotechnical Engineering and/or Geotechnical Design applied to heritage structures. The authors propose a post graduate course based mostly on discussing the actions taken on emblematic case histories, following them stepwise and complemented by lectures and field trips. Learning from first hand experience is also most desirable. So, invited lecturers having that experience would be great complements in such a course. Finally, non engineering complements are also desirable, through outside courses, through other external lectures, in History, Art History, History of Architecture and Theory of Conservation.

The course we propose implies that most of the typical curricular activities in a MSc course in Geotechnical Engineering would be maintained. The course would add up that knowledge with the aim of applying it to heritage structures, through the detailed study of one or more case histories.

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