Geotechnical intervention techniques in the preservation of monuments

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Introduction

• A necessary first step towards restoring and preserving a monument is to identify the factor or factors that bring about damage.

• Structural damage can be usually related to either stress or strain concentrations which are the result of the accumulation of unwanted deformations. The latter may result because supporting elements are undergoing deformation caused by stress and strain changes in the ultimate supporting element, the soil.

• Solutions to geotechnical problems in architectural monuments have almost entirely been drawn from the field of Foundation Engineering so that the resulting intervention techniques constitute applications of that branch of geotechnics giving due consideration to the notions of preservation and conservation.
Before acting on a monument it is useful to have a conceptual framework with which geotechnical engineers will gain insight into the nature of the problem and within which the applicability and efficacy of plausible intervention techniques to solve the problem under consideration can be assessed qualitatively.

The study of soil conditions must also aim at the reconstruction of the effective-stress-history at the site. In this context historical research must not be limited to the building, it must also include the soil. Historians and archaeologists can provide useful data and information. Documentary research is also required in this respect.

Example: the Metropolitan Cathedral in Mexico City
Geological background
Historical and archaeological considerations, evolution of construction

Fig. 5 Description of the Foundations
Follow up during the life of the structure
the first photograph of the Cathedral circa 1841
Incidents and behaviour after construction.

Fig. 10 Regional Subsidence

a) Regional subsidence of Tica reference at the Cathedral

b) Settlement distribution between March 23, 1991 and May 4, 1992

Note: Numbers indicate the settlement rate in cm/year; asterisks (*) indicate average values also expressed in cm/year.
Conceptual framework

0-1 Initial consolidation
1-2 Self weight secondary consolidation
2-3 Construction of pyramids
3-4 Construction of the Cathedral
4-5 Deep well regional pumping
5-6 Injection of mortars (short term)
6-7 Dissipation of excess pore pressures produced during injection of mortars
7-8 Effect of regional subsidence in the future

\[ P' = \frac{1}{\left( \sigma' + 2 \varphi' \right)} \]

\[ q = \varphi' - h' \]

\[ M = 6 \sin \varphi' \]

\[ \varphi = \varphi' - h' \]

\[ \text{virgin consolidation line} \]

\[ \text{modified by the injection of mortars} \]

\[ \text{virgin consolidation line} \]

\[ \text{modified by the injection of mortars} \]

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<table>
<thead>
<tr>
<th>Origin or source</th>
<th>Influencing factors</th>
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<tbody>
<tr>
<td>Design errors</td>
<td>1. Architectonic, geotechnical, structural (combinations of any of these)</td>
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<td></td>
<td>2. Inability to obtain verticality or right angles in walls, ceilings, etc.</td>
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<td>3. Alteration (remoulding) of soil at foundation level</td>
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<td>Construction errors</td>
<td>4. Increase of dead weight</td>
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<td></td>
<td>5. Flooding of basements</td>
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<td>6. Architectural or structural alterations</td>
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<td>Changes in buildings</td>
<td>7. Removal of trees</td>
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<td>8. Dam impoundment</td>
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<td>9. Flooding</td>
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<td></td>
<td>10. Water penetrating into open fractures or fissures in soil mass</td>
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<td></td>
<td>11. Breakage of sewage or water supply lines</td>
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<td>12. Leakage from cisterns or water depositories</td>
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<td>Increase in water content or humidity in the soil mass</td>
<td>13. Construction of underground structures (car parks, shafts, structures for hydropower projects)</td>
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<td>14. Tunnelling (mines, railways, roads, sewage or water supply)</td>
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<tr>
<td>Existence or construction of underground structures</td>
<td>15. Buried structures</td>
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<td>16. Erratic distribution of compressibilities</td>
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<td>17. Variations of thicknesses of soil strata</td>
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<tr>
<td>Geotechnical peculiarities at the site</td>
<td>18. Introduction of vegetation (mainly trees)</td>
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<td>19. Removal of water from flooded basements</td>
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<td>20. Local influence of pumping wells</td>
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<td>21. Regional subsidence</td>
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<tr>
<td>Extraction of water from soil mass, soil drying</td>
<td>22. Excavations near the monument, mainly in urban areas</td>
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<tr>
<td>Excavations</td>
<td>23. Obliteration of archaeological evidence</td>
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<tr>
<td>Construction of new buildings</td>
<td>24. Unwanted effects on existing monument</td>
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<tr>
<td>Slope instability</td>
<td>25. Cuts to modify slope inclination</td>
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<td>26. Humidity at slope feet along rivers, seafront, lakes</td>
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<td></td>
<td>27. Leakage from sewage or water supply systems</td>
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<td>28. Deforestation leading to erosion</td>
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<td>29. Slope subjected to long term geological processes (creep)</td>
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<td>Earthquakes</td>
<td>30. Accumulated tilt</td>
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<td>31. Low bearing capacity</td>
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<td>32. Low factor of safety in slopes</td>
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<tr>
<td>Method</td>
<td>Advantages/disadvantages</td>
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<td>------------------------</td>
<td>------------------------------------------------------------------------------------------</td>
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<tr>
<td>Underexcavation</td>
<td>Effects may be difficult to predict or estimate. Relies heavily on observational method. Adaptable to a large variety of conditions. May require auxiliary works (trenches, shafts) or specialized drilling equipment. Non obtrusive. Rate of induced corrective settlements may be controlled.</td>
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<td>Jacking from pile heads</td>
<td>Piles must first be installed or cast in place. Major structural modifications required in the monument’s foundation system. Superstructure must be adapted and/or reinforced to tolerate imposed movements. Rate and magnitude of corrective vertical displacement can be accurately controlled.</td>
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<tr>
<td>Control piles</td>
<td>Piles connected indirectly to the building by means of a frame. May be used to regulate loads applied at the pile heads or to directly control settlements. Modifications at foundation and at the superstructure level required. Permanent maintenance required.</td>
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<td>Piles at selected sites</td>
<td>Special and very specific geotechnical conditions must be met in order to use this technique, e.g. at sites undergoing regional subsidence.</td>
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<td>Local injection of water</td>
<td>Intended to restore pore pressure at selected locations in sites undergoing regional consolidation. Induced corrective settlements are difficult to control.</td>
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<td>Electro-osmosis</td>
<td>Put forth to induce water flow and changes in effective stress and, hence, corrective settlements. Difficult to control</td>
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</table>
## Intervention techniques to *prevent* the detrimental effects of differential settlements

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages/disadvantages</th>
<th>Important examples</th>
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<tbody>
<tr>
<td>Underpinning: broadening of footings, restoration of original foundation elements</td>
<td>Used to restore or improve condition of existing foundation. Effective, depending on proper identification of originating factor and on good knowledge of geotechnical conditions.</td>
<td>Has been used in many monuments and historical buildings around the world.</td>
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<tr>
<td>Addition of piles, micropiles or other deep foundation elements.</td>
<td>Can usually eliminate the originating factor giving rise to differential settlements. Can disrupt, damage or even completely destroy archaeological data.</td>
<td>Has been used in many monuments and historical buildings around the world.</td>
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<tr>
<td>Soil improvement: jet grouting, deep mixing,</td>
<td>Can be difficult to implement; it is sometimes intrusive (can produce damage to archaeologically rich deposits or ancient buried structures).</td>
<td>Mortar injection by hydrofacturing Cathedral</td>
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<td>Injection of mortars by hydrofracturing in soft soils</td>
<td>Can be difficult to implement; it is sometimes intrusive (can produce damage to archaeologically rich deposits or ancient buried structures). Overall intended effect: to attain a more uniform distribution of settlement or vertical deformation fields.</td>
<td>Used successfully at the Metropolitan Cathedral and the San Agustín Church in Mexico City.</td>
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<td>Compensation grouting</td>
<td>Can be difficult to implement; it is sometimes intrusive (can produce damage to archaeologically rich deposits or ancient buried structures). Overall intended effect: to induce corrective vertical deformations to compensate other non wanted movements</td>
<td>Used in the Jubilee line in London.</td>
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<tr>
<td>Rigid inclusions</td>
<td>Can be difficult to implement; it is sometimes intrusive (can produce damage to archaeologically rich deposits or ancient buried structures). Overall intended effect: to attain a more uniform distribution of settlement or vertical deformation fields. Rigid inclusions are not connected to structure.</td>
<td>Not proven in Architectural Monuments. Several projects have been put forth in several ancient structures in Mexico City.</td>
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<tr>
<td>Isolation or separation trenches.</td>
<td>Slurry trenches can be used to separate or isolate displacement fields of two or more structures. Non setting gels may be also used.</td>
<td>Used at the Capilla de las Ánimas and the Casa de Los Azulejos, Mexico City. Results are still being evaluated. Suggested as a means to correct the inclination of the Tower of Pisa.</td>
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</tbody>
</table>
Design and/or construction errors

Casa de los azulejos
(House of Tiles, Mexico City)
Many important architectural monuments are located on or near sloping grounds that can eventually be subjected to unwanted deformations…

…standard stabilization procedures will in general be applicable for deep seated failure mechanisms; local failure mechanisms affecting the monument may require special attention.
Possible slope instability caused by an excavation

Excavations near monuments: open pit mine in Cerro de San Pedro, San Luis Potosí, Mexico
Other factors may also induce differential settlements:

Vegetation
Water leakage from:
• Cisterns
• Sewage pipes

Localmente han causado problemas severos!
SOME NON CONVENTIONAL INTERVENTION TECHNIQUES
Control piles
a) Arco de soporte
Arremate de empotramiento
Pilote

b) Espárrago

\[ \angle = 2^\circ \]

Banco de concreto

Arco de soporte
Rótula


c) Espárrago

Banco de concreto

Pilote

Láminas galvanizadas

Arco de soporte
Rótula


d) Tuerca

Puente

Banco

Pilote

Cubos de madera

Láminas de separación

Rótula

Placa
Segmento de pilote

Acero de refuerzo

Tubo de lámina

Corte A-A'

D= 40, 50 y 60 cm
H= 100 cm
h= 10 a 15 cm
PROJECT FOR INSTALLING CONTROL PILES AT THE METROPOLITAN CATHEDRAL, MEXICO CITY (1976)
Interpretación esquemática del estado de los pilotes de control

- Pilote largo
- Pilote corto
- Pilote que penetró
- Pedraplén
- Capa dura
- Relleno
- Costra superficial
- FAS
- Capa dura FAI

Profundidad, m
Levelling with underexcavation
- Settlement rates can be controlled.
- May be adapted to a wide variety of conditions.
- Its effects are difficult to estimate or predict beforehand, observational method must be used.
  requerir de trabajos auxiliares o equipo de perforación especial.
- It can be devised as a non-obtrusive technique.
Hanging Steeple of Wybunbury, Chesire, (1751); underexcavation performed in 1832 by Charles Trubshaw.

Data and figures courtesy of G. Johnston & Prof. J. B. Burland
Other historical precedents:

THE STABILISATION OF THE CHURCH TOWER AT NIJLAND
(province of Freisland in the Netherlands) (1866)

The Chimney (100 m tall!!) of the Bochum Cast Steel Works in Germany (1866)

Terracina’s 1962 proposal for straightening the Tower of Pisa

Several buildings underexcavated in Mexico City after the 1985 earthquakes
View on Nijland. Drawing in Indian ink by Friedrich Wilhelm Graebe, circa 1750 (Jonston, 2002).
Chimney (100 m tall!!) of the Bochum Cast Steel Works in Germany (1866) (Johnston, 2002).
Fig. 2 Proposal for correcting the Tower of Pisa (Terracina, 1962)
Metropolitan Cathedral
Mexico City
Profundidad media 20 m

Subexcavación
**Fig. 16 Underexcavation at the Cathedral and the Sagrario**

- **a)** Shafts for the underexcavation process
- **b)** Location and volume of soil extracted at each shaft

Process of plastic deformation of 10 cm diameter borings during underexcavation

Average depth: 20 m

Top left: An access shaft to the soft soils can be observed

Top: Safety tubular structure to support the arches, as well as splints placed at two columns

Left: Access “windows” through which the pressure-driven underexcavating pipes are introduced.
NOTES:
1. Contour lines in cm
2. Contours were defined assigning the zero value to point C-3
3. Elevation of point C-3 is 2233.083 m above sea level
4. New coordinate system

Differential correction between levelings 1 and 203 performed by TGC (25/oct/91 - 20/sep/99)

Geometry of corrected settlements

Correction as of August 2000

Isometric mesh of differential settlements and induced corrections

Isometric mesh of corrections referred to a horizontal plane

Reconstruction of the path followed by the dome

Fig. 17 Archieved Corrective Settlements
Reconstrucción de la trayectoria del desplomo de la cúpula
The Tower of Pisa

Fig. 15 Geometric correction for the Tower of Pisa
Fig. 3 Soil profile under the Tower
Grouting with hydro-fracturing

Grouting in normally consolidated soils and in overconsolidated materials
Compensation grouting (schematic)
Grouting in normally consolidated soils,

Palace of fine arts, Mexico City

Grouting took place from 1907 to 1922
ESTADO DE ESFUERZOS
Geometría de las láminas de mortero inyectado

FRACTURAMIENTO HIDRAÚLICO
Pipe for radial expansion of the mortar core

Mortar sheet

Geotextile

Geotextile cover

Sleeve pipe for lateral injection

Assembly of sheets
Fig. 19  Mortar Injection Under the Cathedral and the Sagrario Church
a) Measurements from January 7, 1991 to September 2, 1991

b) Measurements from 29 May 2009 to 24 October 2012
Isolation and separation trenches

Modern building with point bearing piles in a site undergoing regional subsidence shows a relative emergence with respect to its surroundings.
The former temple of Corpus Christi
Mexico City
Fig. 19  Recimentación del Templo de Corpus Christi
For your attention, thank you!