Foundations in Venice:

Characteristics and Preservation Challenges in a Unique Environment

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550 km²
Lagoon Area
8% land
92% water and wetlands

1.2 m
Average depth
Range 0.5-21 m

3
Main inlets

Sediment constantly shifting due to tides and human activities

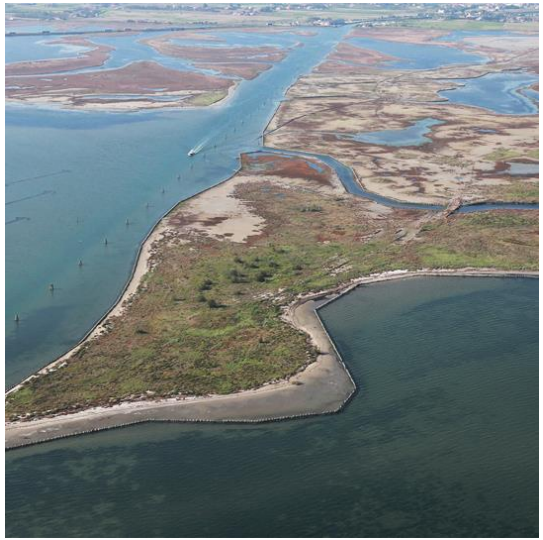
Artificial Canals and Embankments: modified over centuries to support navigation and protect settlements

The Venice Lagoon

The Wooden Pile Foundations

The Frari Bell Tower

A delicate and inherently unstable environment



Salt Marshes



Mudflats

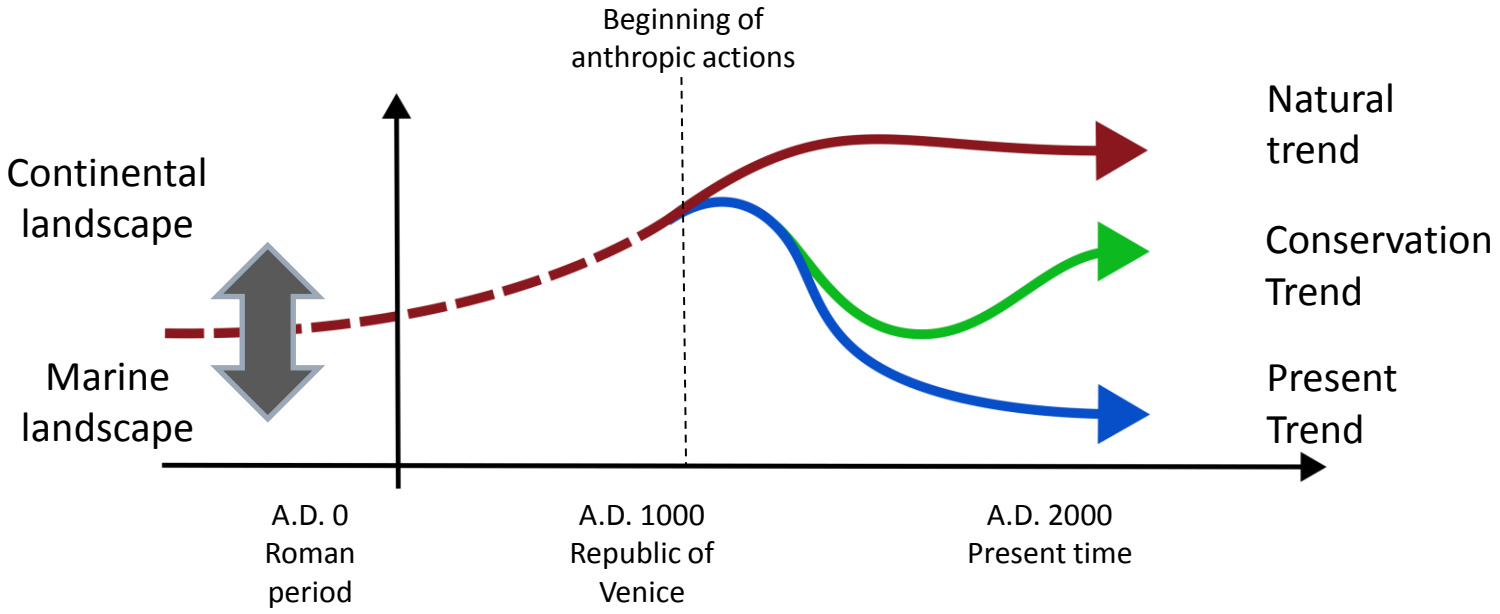


Barrier Islands

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Morphological evolution of the Venice lagoon



from F.M. Falcieri, CNR ISMAR

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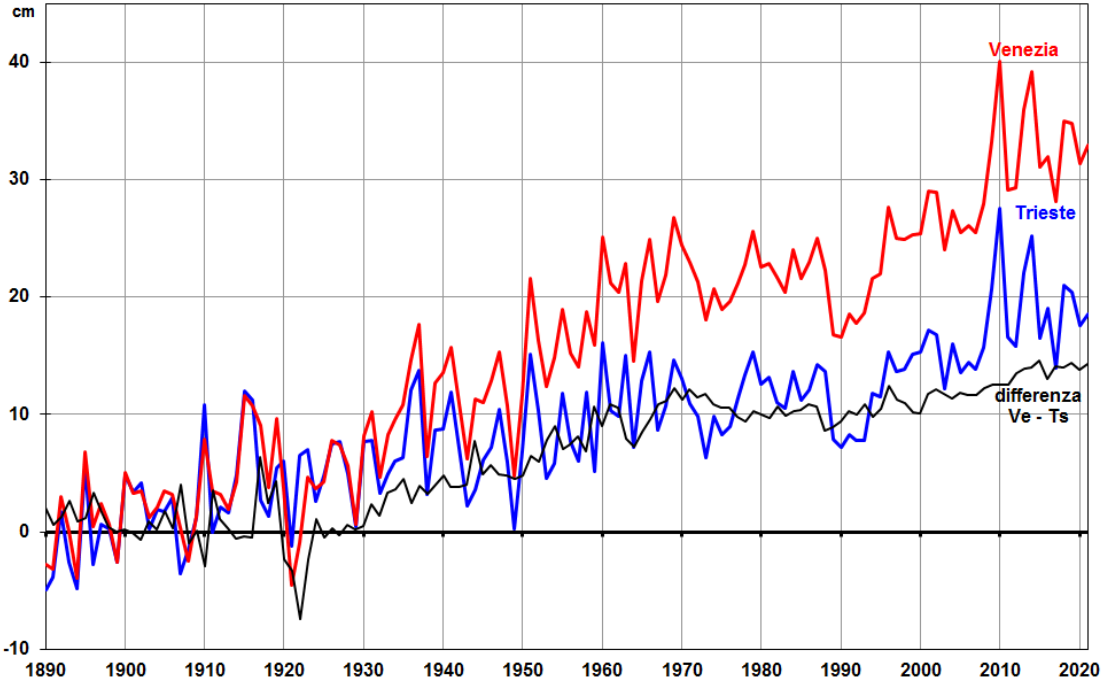
Preservation of low lands by wooden sheet piles



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Land Subsidence and Eustacy



Annual mean sea level trend

from 1890 to 2021

in **Trieste** (stable)
in **Venice** (subsiding)

Difference (**black**)
≈ 13-14 cm

Loss ≈ 30 cm

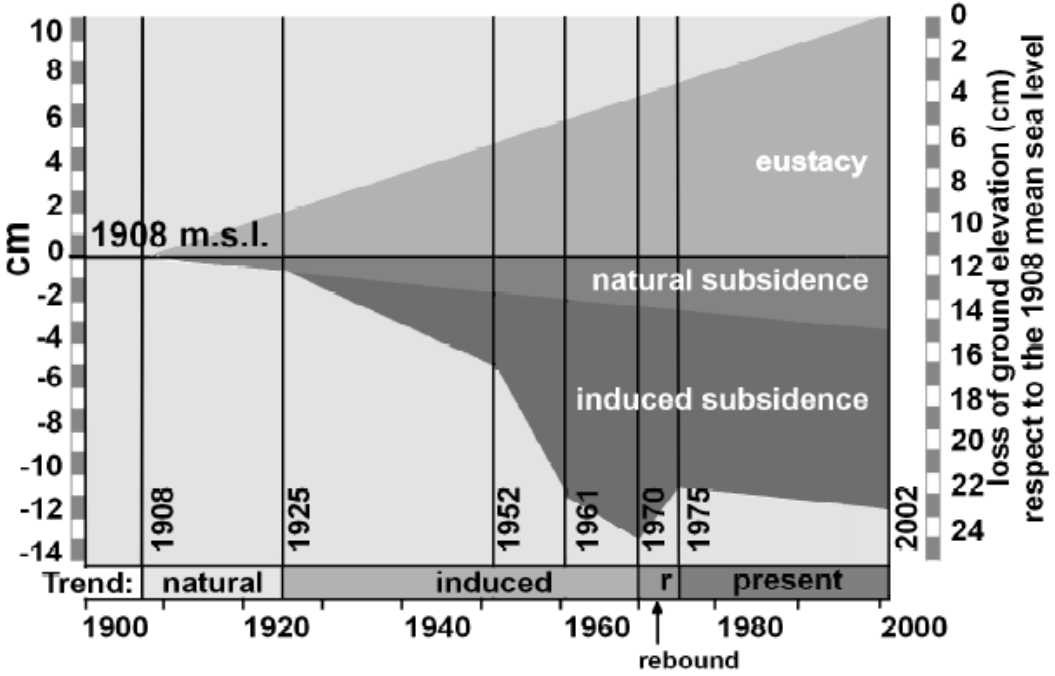
Centro Previsioni e Segnalazioni Maree

CITTA' DI VENEZIA

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Land Subsidence and Eustacy



Graphical representation of the 3 components of the relative ground elevation loss in Venice

from 1908 to 2002

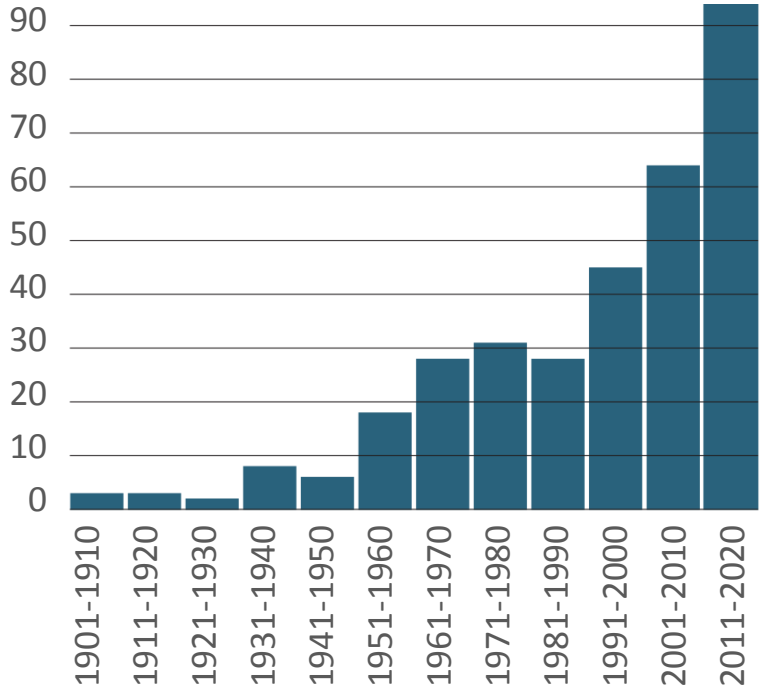
from L. Carbognin et al., 2005

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High tide flooding: *Acqua Alta*

10-year frequency ≥ 110 cm above m.s.l.





04/11/1966
194 cm
above m.s..l



12/11/2019
187 cm
above m.s.l.

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Geological Setting and Stratigraphy

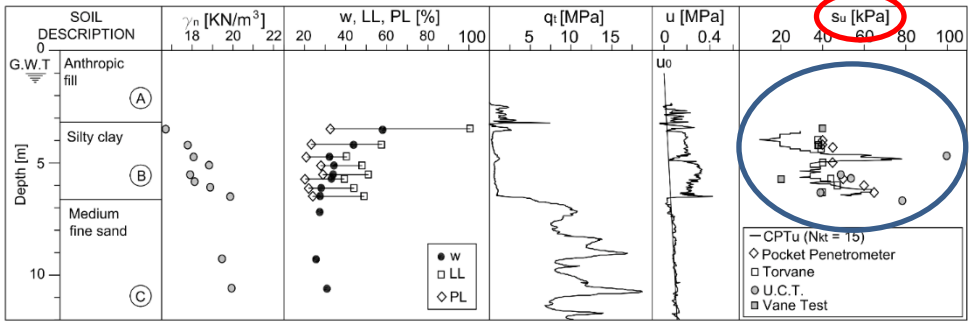
The subsurface up to 50 m deep is characterized by a complex system of sands, silts, and silty clays that accumulated chaotically during the Würmian glaciations and subsequently during the Holocene marine incursion.

10÷50m – Fine sand, silty sand, clayey silt, etc.
Continental deposits

The Holocene subsoil is composed mainly of marine sands with a significant shell content along the coastline, but **finer sediments**, with a significant amount of organic soil, **in the inner part of the lagoon**.

0÷10m – Soft clay and silty clay with organic content
Recent lagoon deposits





The Venice Lagoon

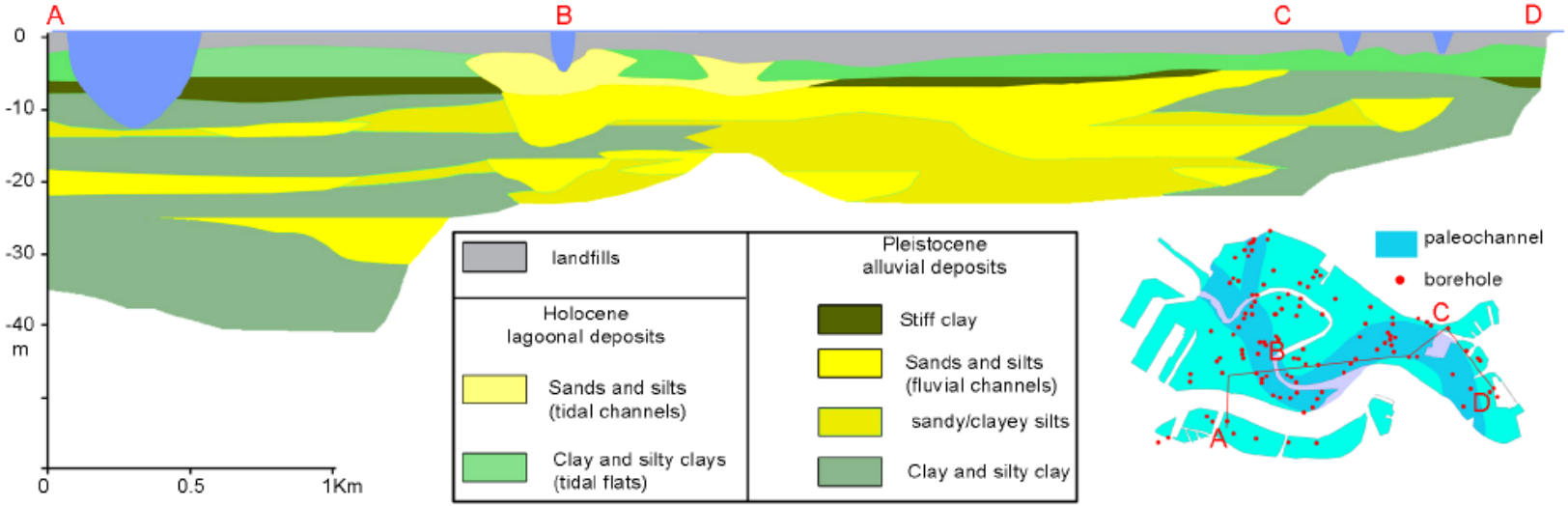
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Geological Setting and Stratigraphy

The upper part of the Würmian deposits consists of **a layer of highly overconsolidated**, very silty clay, locally called ***caranto*** (a word derived from the Late Latin *caris* = stone).

The *caranto* was subjected to a process of overconsolidation through desiccation during the 10,000 years of the last Pleistocene glaciation and can be found at depths between 6 and 8 m.



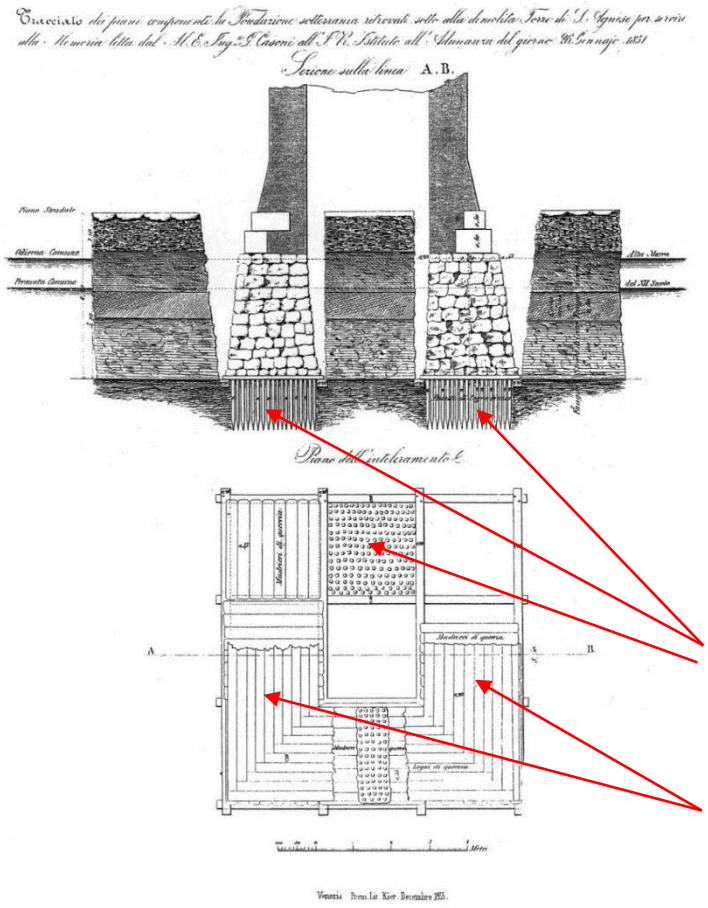
from L. Tosi et al., 2013

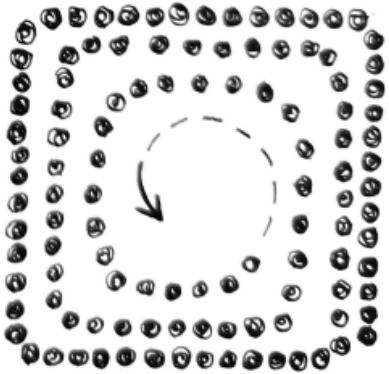
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Sant'Agnese (1851) bell tower foundation





A forest of closely spaced, driven, alder piles
15–20 cm diameter, 2–3 m long

Wooden plank, typically larch
locally called *zatterone,* i.e. floating raft
2–3 m deep, 20-40 cm thick

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San Marco bell tower foundation

A WELL KNOWN CASE HISTORY (1902)

Rebuilt *exactly as it was and where it was…*



San Marco bell tower foundation

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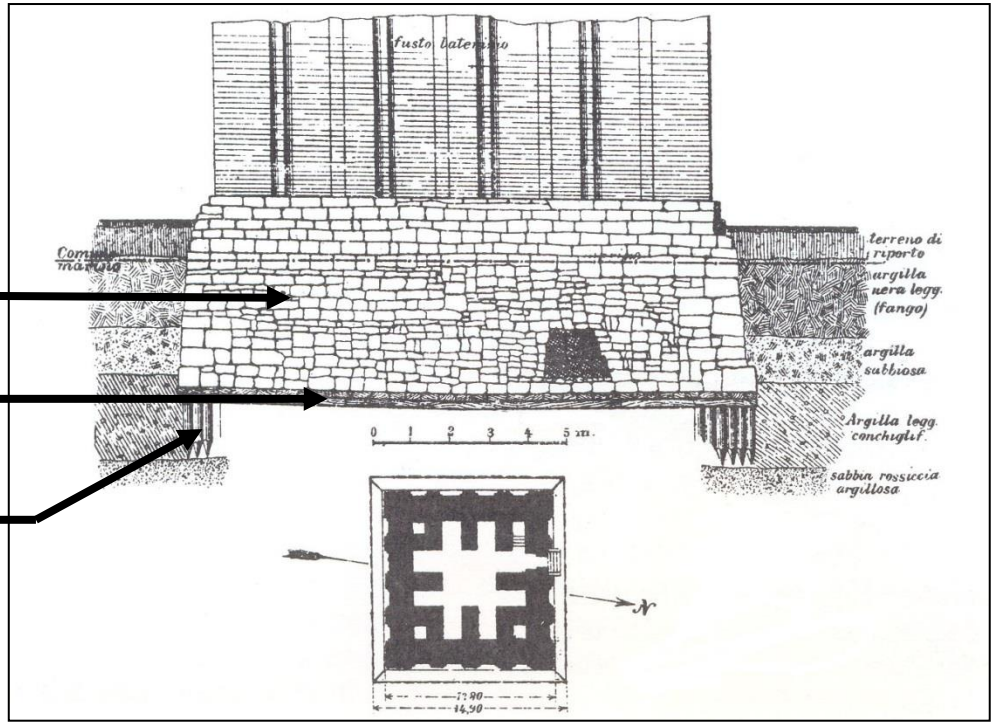
The Frari Bell Tower

A WELL KNOWN CASE HISTORY (1902)

Istrian limestone basement

Wooden plank

«Compaction» piles



from D. Donghi, 1913

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Wooden pile driving technique, 18th century



from M. Piana, 2023



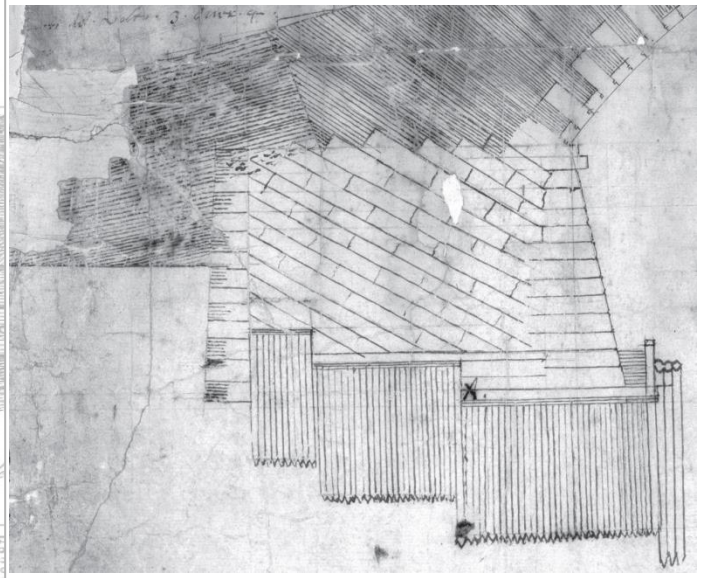
Typical manual post driver

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Foundation of **Rialto bridge** (1588)
11652 piles, 16.5 per square metre

from A. Lazzarini, 2018

Construction sequence typically used by Venetians

- ✓ a possibly dry construction site was prepared by driving **wooden sheet piles** (*palada*) all around the foundation soil, to prevent or reduce water seepage
- ✓ soil inside was first **removed** to the maximum possible depth and then the **foundation wooden piles** (*batudo*) were installed with a manual pile driver
- ✓ a horizontal surface was prepared by leveling the heads of the piles (*a gualivo*) and laying **a wooden plank** (*zatterone*)
- ✓ the **Istrian limestone blocks** were placed as foundation basement, while the excavation was backfilled laterally, up to the ground level

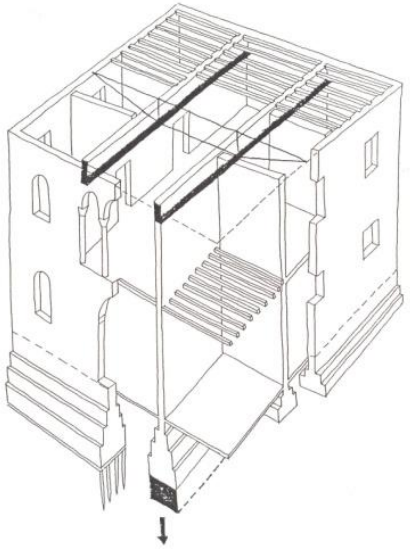
⇨ the final outcome was a deeper shallow foundation made up of wood and compressed soil

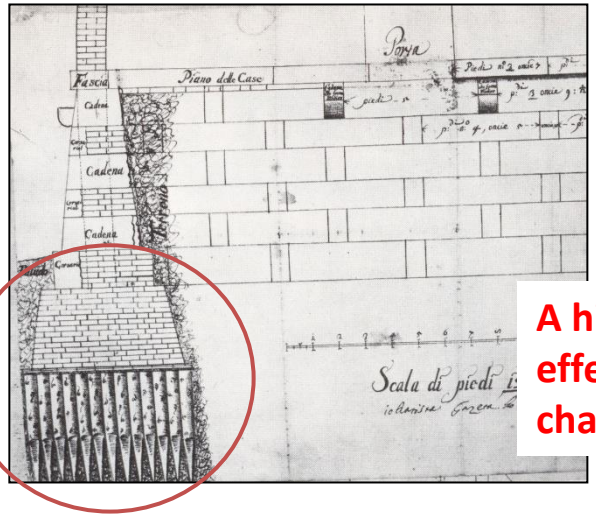
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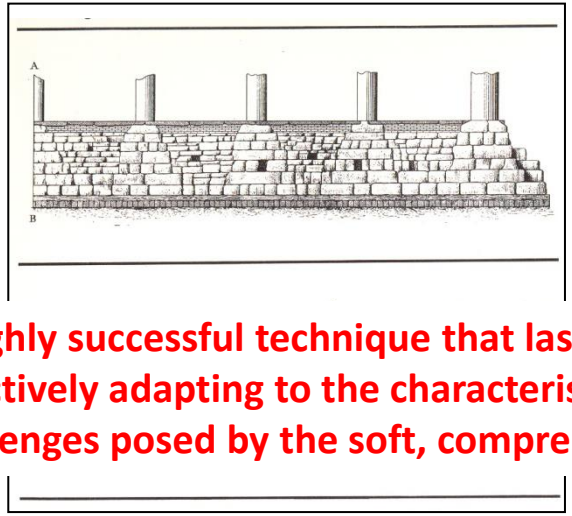
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Wooden piles were frequently used, especially for **external** masonry walls, such as those bordering the canals, and for highly stressed foundations, like in the case of bridges, bell towers or major buildings; while **rafts without underlying piles** were mainly used for **internal** walls and minor buildings





from G. Zuccolo, 1975



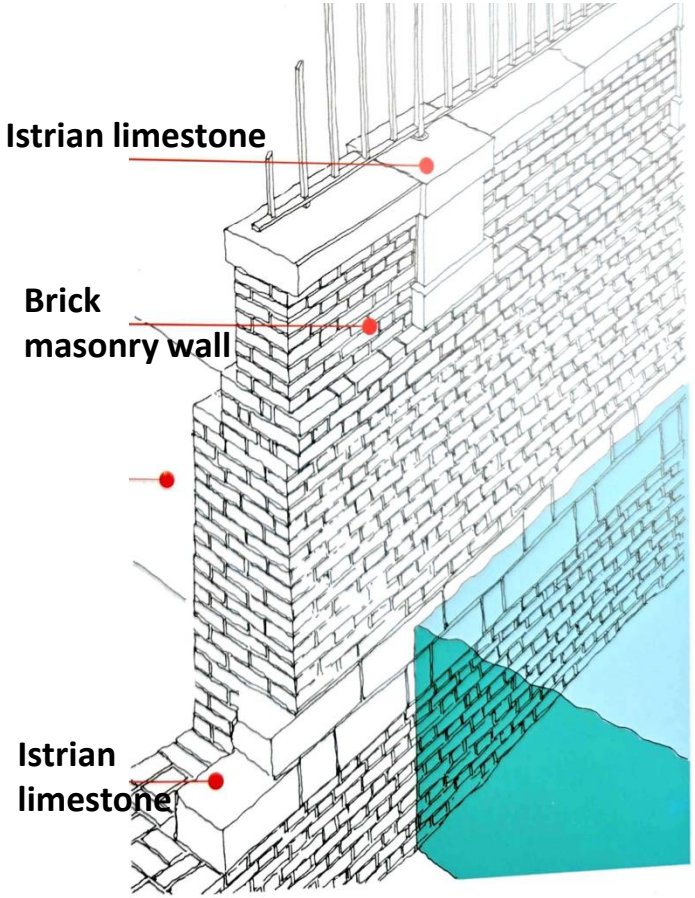
A highly successful technique that lasted for centuries, effectively adapting to the characteristics and to the challenges posed by the soft, compressible lagoon subsoil

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Main preservation issues of ancient Venetian foundations

- Possible continuous (secondary) settlements and consequent movements and damages of the structure
- Severe environment (high humidity, salt water, pollution, etc.)
- Material degradation
- Wave-induced bank wall erosion
- **Land subsidence and Eustacy**

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The Basilica of Santa Maria Gloriosa dei Frari

The Basilica is a classic and most splendid example of **Franciscan Gothic style**



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The Frari's Basilica in Venice



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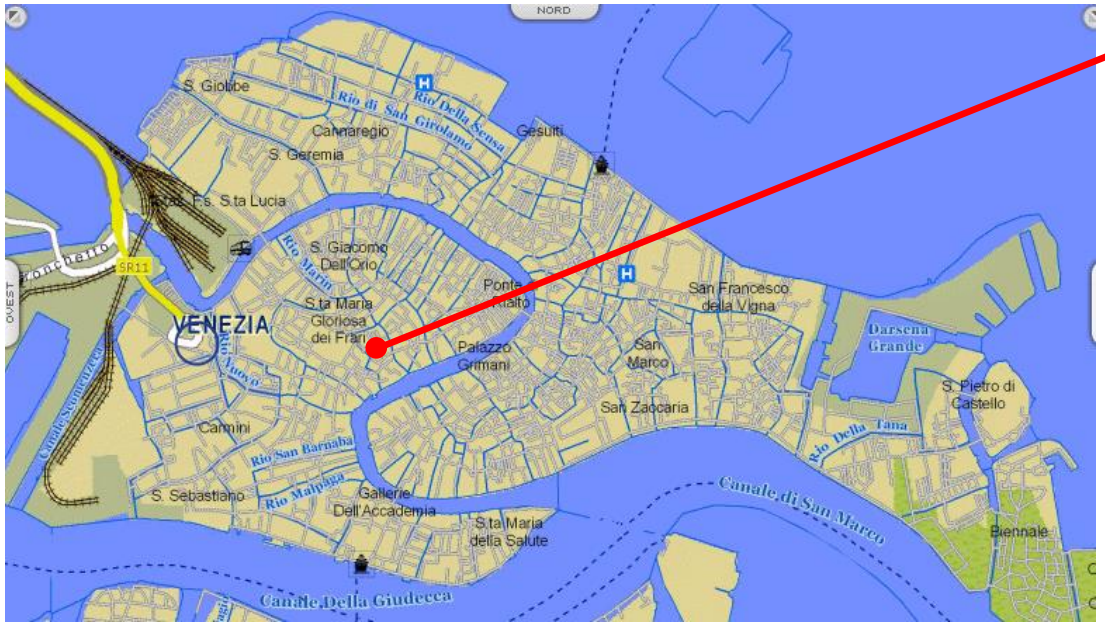
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The Frari's Basilica in Venice

- ✓ Style: Romanesque
- ✓ Architect: Jacopo Celega and son
- ✓ Period of construction: 1361-1396





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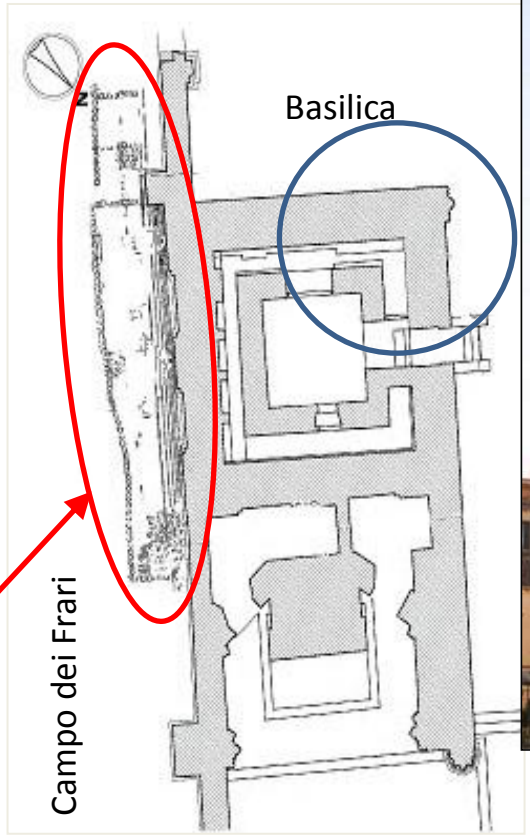
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The Frari Bell Tower

GENERAL INFORMATION

- ✓ Double brick masonry structure
- ✓ Height: **65 m**
- ✓ Base width: **9.2 ÷ 9.4 m**
- ✓ South-West corner of the bell tower incorporated in the masonry walls of the Basilica
- ✓ V (weight) = **57 MN**
- ✓ M = **30 MNm**
- ✓ Inclination (2000) = **0.7°**

Main strengthening intervention - 1904



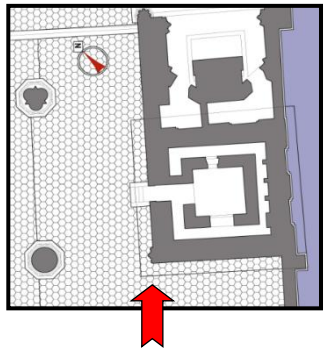


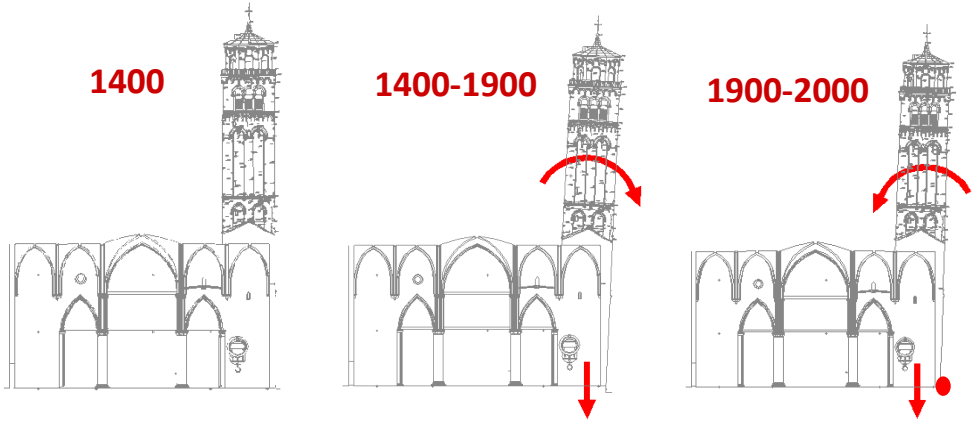
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Past movements of the tower

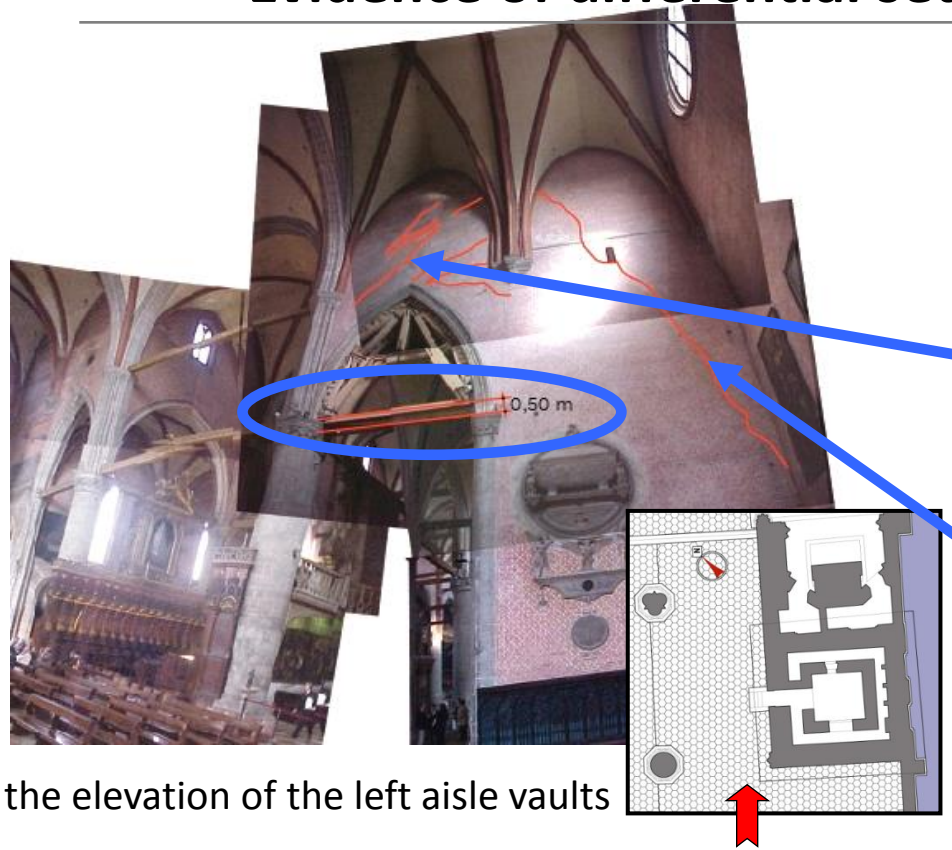
1) Initial situation, with the bell tower incorporated in the masonry walls of the Basilica
2) Over the centuries the tower showed a differential settlement relative to the Basilica structure and an out-of-plumb towards South-East. At the beginning of the XX century a differential settlement of **about 40 cm** was recorded
3) After the strengthening intervention carried out in 1904, the tower started tilting **in the opposite direction, towards the Basilica,** with an average settlement of **1 mm/year (10 cm/100 years)** in the West corner of the tower





Evidence of differential settlements

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View of the elevation of the left aisle vaults

Cracks on the left aisle vaults

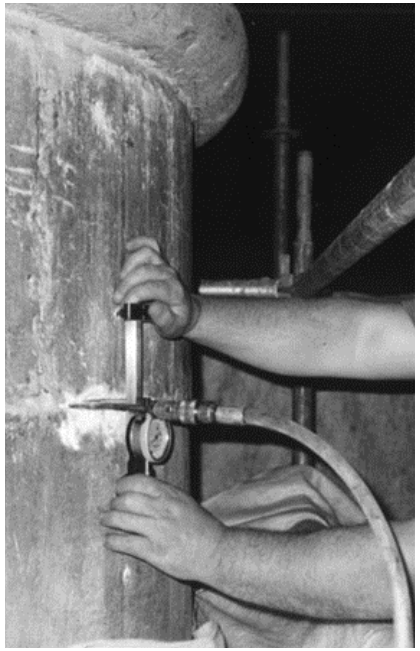
Main diagonal crack on the brick masonry structure of the bell tower

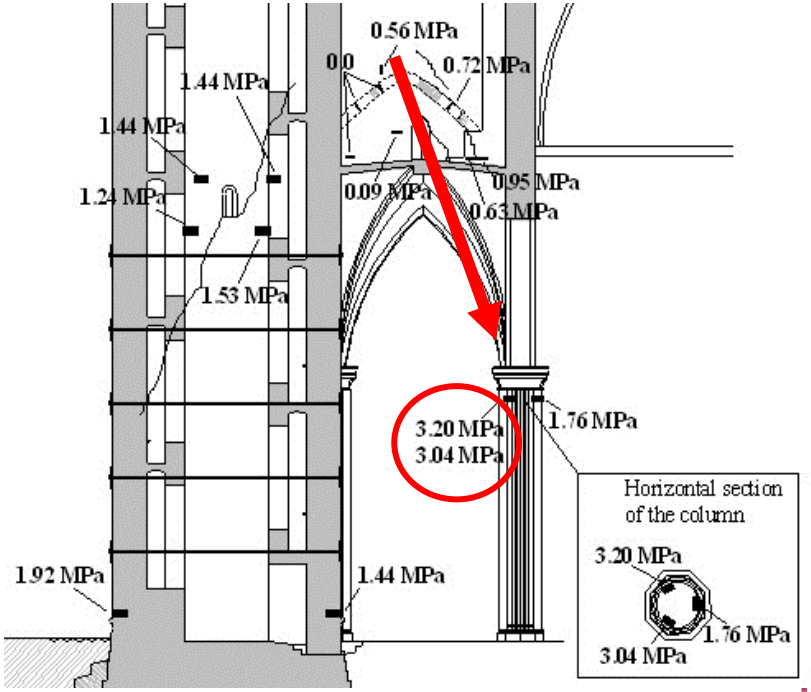
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State of stress caused by differential settlements

Flat-jack measurements showed the presence of a **thrust line** going from the bell tower to the structures of the Basilica





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Aims of the strengthening intervention

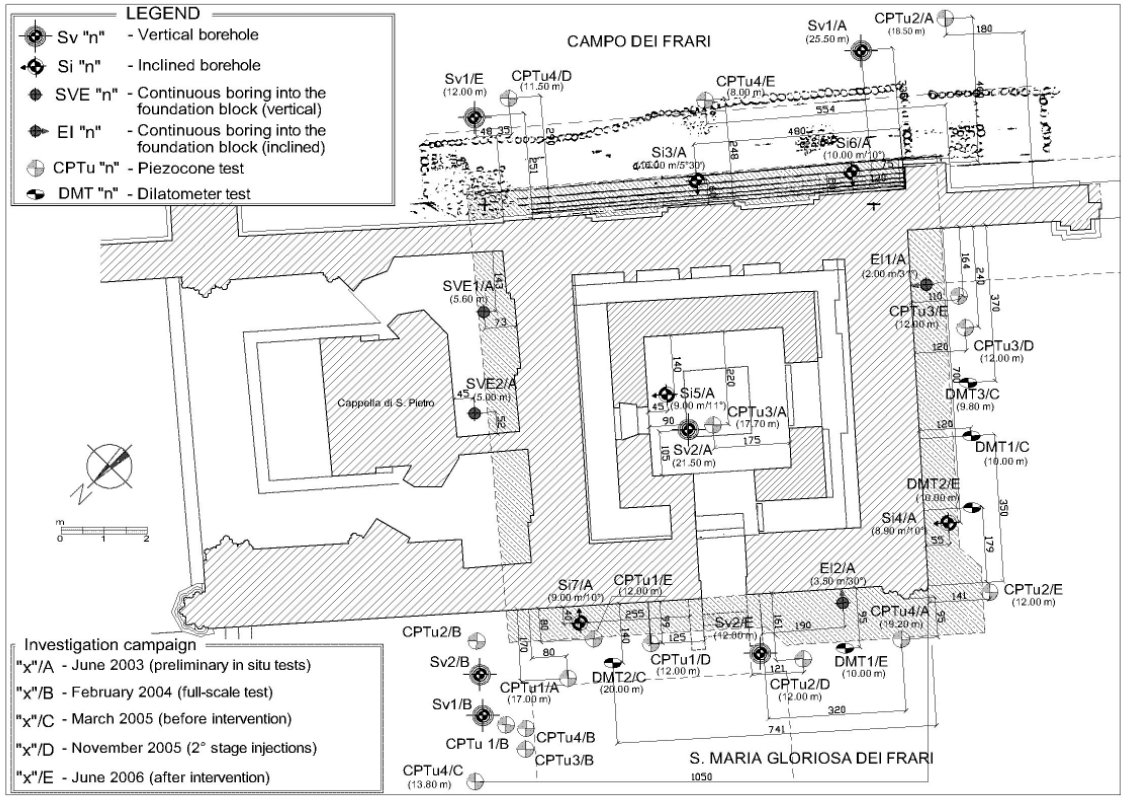
1. Making compatible the remaining settlements of the complex basilica-bell tower, limiting **differential settlements**
2. Preserving as much as possible **the original foundation structure and the current stress distribution**
3. Avoiding to propose a **rigid foundation system** for the bell tower
4. Enabling a **flexible and modular** intervention, according to the outcome of a suitably implemented real-time monitoring

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Geotechnical investigation campaigns



Position of in-situ tests (CPTu and DMT) and boreholes at various stages of the intervention

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Inclined boreholes





Inclined borehole Si3

between 0.00 m and 8.00 m depth

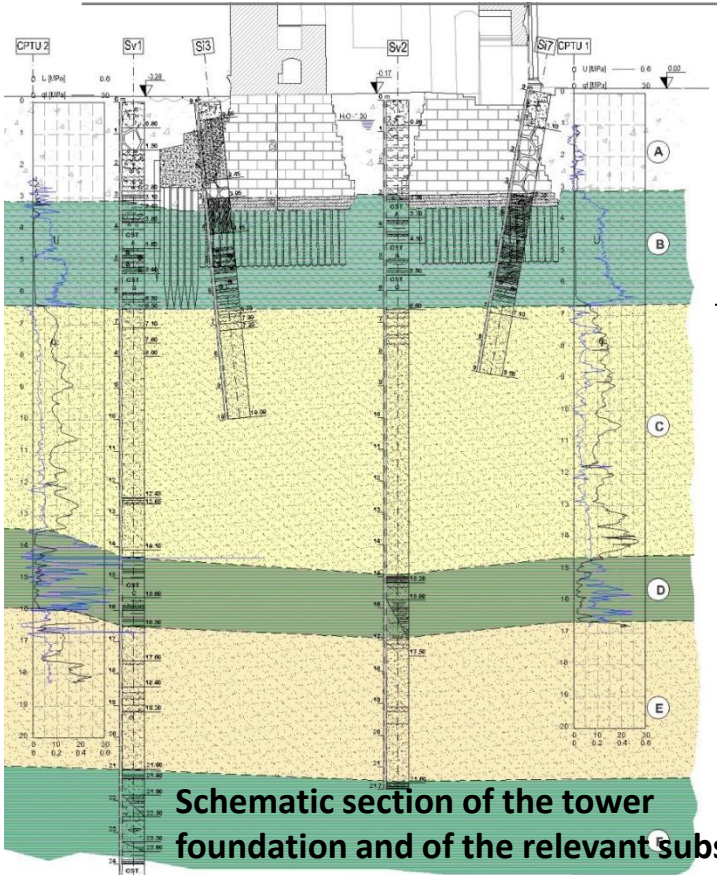
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Foundation soil profile



Schematic section of the tower foundation and of the relevant subsoil

UNIT A: between 0.0 m and about -3.20 m
Anthropic fill

UNIT B: between - 3.20 m and about - 6.70 m
Silty clay, NC or slightly OC

UNIT C: between - 6.70 m and about – 14.5 m
Medium fine sand, from dense to very dense

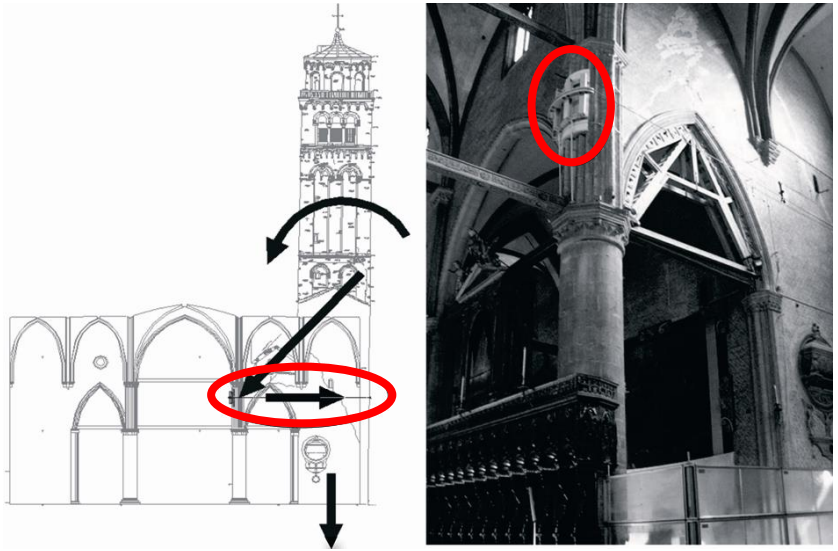
UNITS D, E, F: between – 14.5 m and about – 25.5 m
Alternation of soft **clayey silt** and **medium-fine dense sand**

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The Intervention Strategy

Phase 1: Provisional strengthening intervention



Temporary intervention via a steel cable supporting part of the horizontal thrust acting on the column of the Basilica

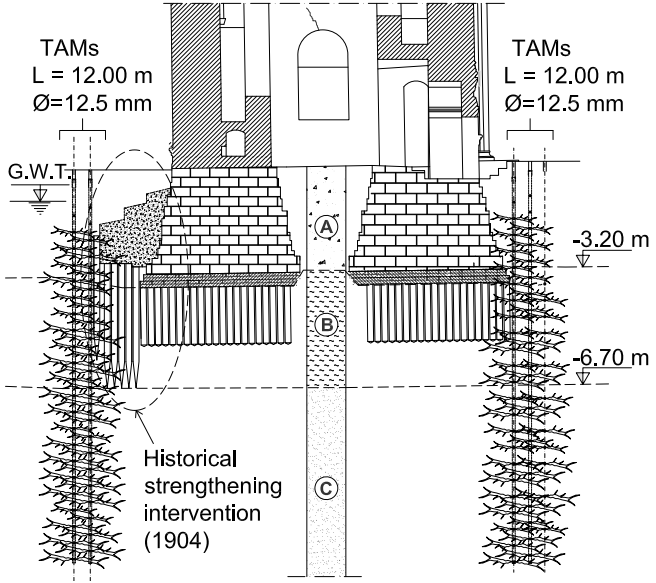
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The Intervention Strategy

Phase 1: Provisional strengthening intervention

Phase 2: Soil strengthening *via* soil fracturing



Improvement of the soil - foundation system

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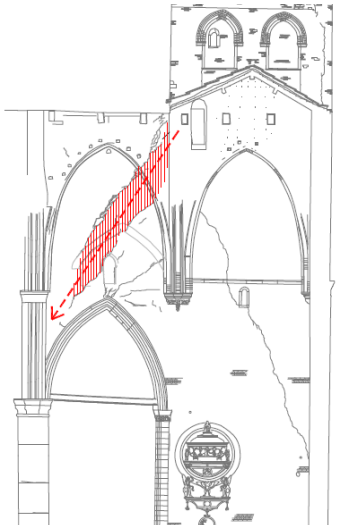
The Intervention Strategy

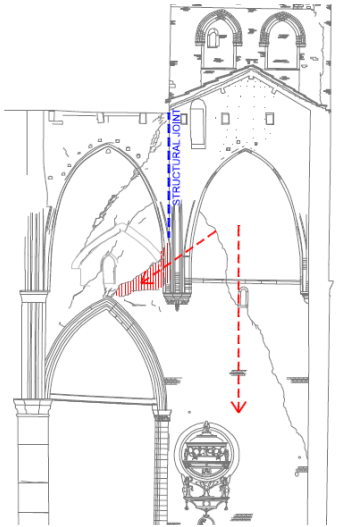
Phase 1: Provisional strengthening intervention

Phase 2: Soil strengthening *via* soil fracturing

Phase 3: Structural joint

with the aim of eventually reducing the damaging interaction among the different masonry structures, induced by differential settlements





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Design of the soil fracturing intervention

MAIN FEATURES

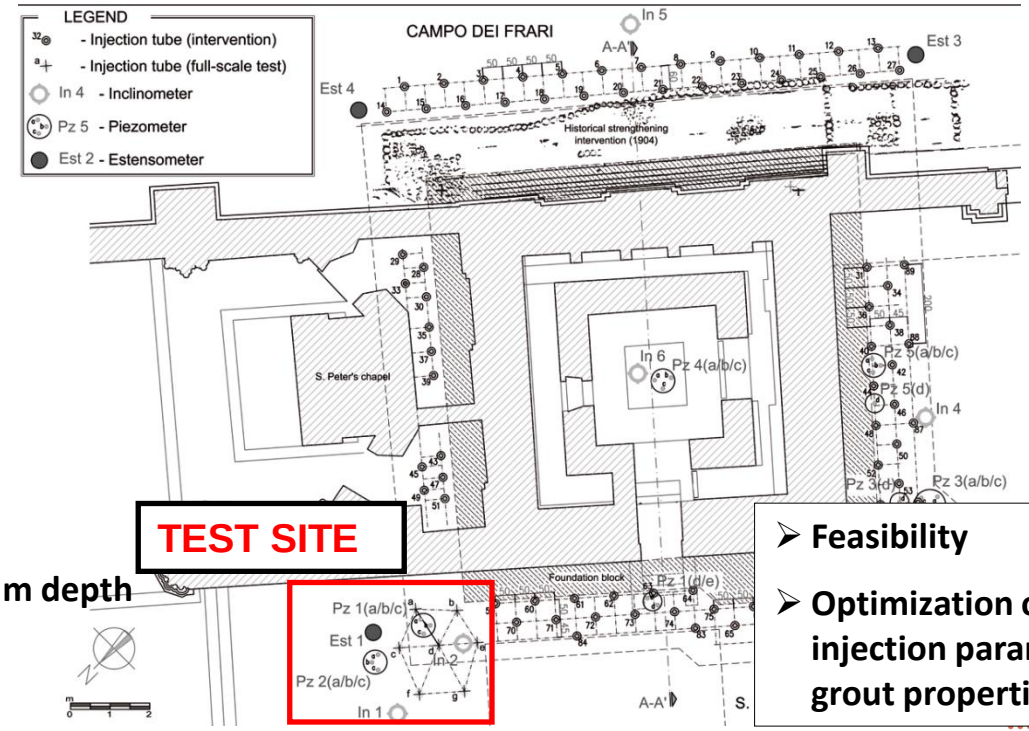
INJECTION PIPES

- ✓ **88 pipes (TAMs)**
- ✓ **external Ø: 88.9 mm**
- ✓ **length: 12 m**

- ✓ **2 or 3 rows**
- ✓ **row spacing: 50 cm**

VALVES

- ✓ **21 valves each pipe**
- ✓ **between -2 m and -12 m depth**
- ✓ **valves spacing: 50 cm**



- ➢ **Feasibility**
- ➢ **Optimization of the injection parameters / grout properties**

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Final investigations and Monitoring

Real-time monitoring during the intervention

- ✓ **of grout injection parameters**

  real time control of injection *pressure* (less than 5 bars) and injected *volumes* (more than 100 m^3 overall)

- ✓ **of the soil behaviour and response**

  vibrating wire piezometers, multibasis extensometers and inclinometers

  in situ geotechnical investigations (boreholes, piezocone and dilatometer tests) at various stages of the intervention

- ✓ **of the bell tower**

  precision levelling and direct pendulum measurements

  measurement of the state of stress and deformation of the structure during injections, before and after the execution of the structural joint (crack gauges, long base extensometers and flat jacks)

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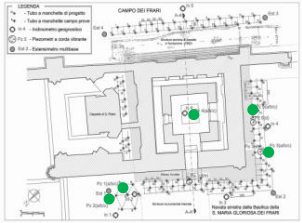
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Final investigations and Monitoring





- ✓ pore pressure peaks induced by adjacent grout injections
- ✓ relatively quick consolidation rate

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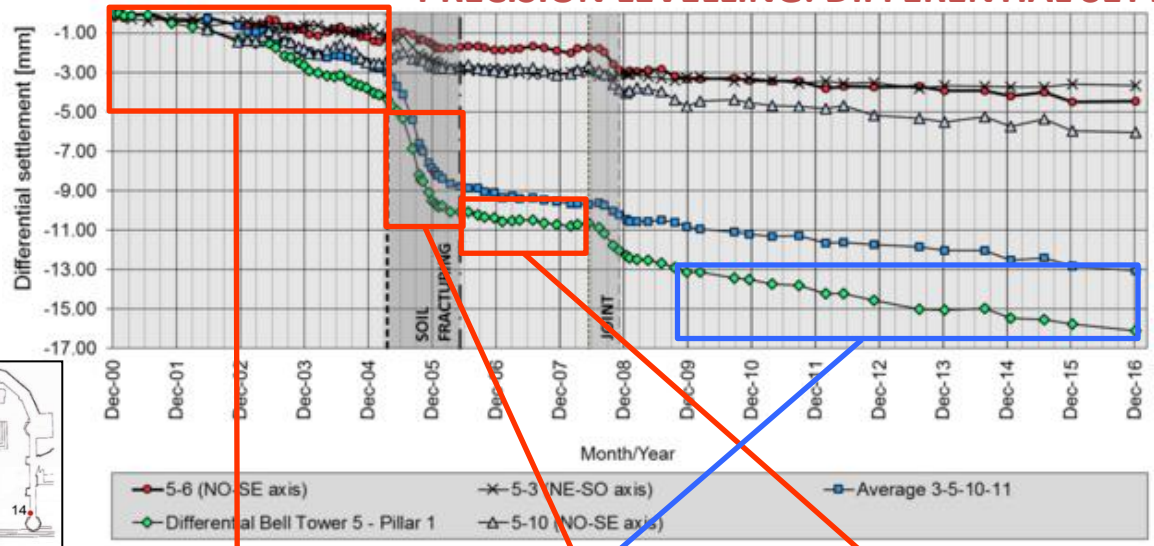
The Venice Lagoon

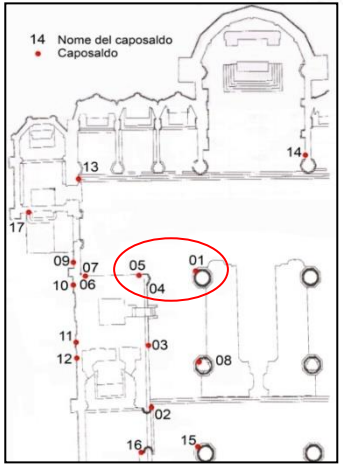
The Wooden Pile Foundations

The Frari Bell Tower

Final investigations and Monitoring

PRECISION LEVELLING: DIFFERENTIAL SETTLEMENT





Differential settlement between bell tower (BM 05) and Column (BM 01):

1.01 mm/year before | ***5.04 mm/year during*** | ***0.27 mm/year after*** ***soil fracturing***

0.4 mm/year after ***the structural joint execution***

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Many thanks for your attention!

