Taking care of heritage, a challenge for geotechnical engineers

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ABSTRACT: When dealing with monuments or historic sites, engineers may find themselves out of the comfort zone bounded by balance and congruence, being necessary to have an approach guided not only by technical convenience and cost effectiveness, but above all from the need to preserve at the best whatever is the heritage carried by the specific structure under analysis. Such a lack of comfort has to be the guiding light in sharing the solution with experts from other fields, as clearly suggested by Article 2 of the Venice Charter. This paper reports on three case histories taken from the author's personal experience, related to the heritage of completely different cultural environments (respectively Maya, Greek-Roman and Byzantine-Ottoman), in which these constraints had to be faced from the point of view of a geotechnical engineer. The role played by geotechnical engineering differs from case to case, but the examples presented herein demonstrate that, far from being sufficient, our discipline is most times necessary. It is argued that, even though the best technical solution is always the least invasive one, geotechnical engineers should not be scared *a priori* by the possibility of interacting with historic structures, as long as their intervention is informed, necessary, respectful and above all aimed to contribute in preserving the true essence of heritage, which is not the structure in itself but the role it has in its physical and social environment.

1 THE LEGACY

What is the best possible engineering approach in the protection of monuments? This theme has been debated for a long time, and has seen a significant transformation over time. The current ruling paradigm is the result of the substantial change in the cultural approach introduced in Europe between the end of the nineteenth century and the beginning of the twentieth. Until then, in fact, the predominant tendency was to approach failure or damage of historic structures by reconstruction – total or partial - to (presumedly) make them appear as they once were. Eugène Viollet-le-Duc (1814-1879) is typically taken as an example of this old approach, summarised by the statement: ‘*To restore a building is not to repair or rebuild it but to re-establish it in a state of entirety which might never have existed at any given moment*’.

The new way to look at built heritage that saw the light at the beginning of the twentieth century stems from the original work of many intellectuals, like for instance John Ruskin (1819-1900) and Georg Gottfried Julius Dehio (1850-1932), whose motto ‘*preserve, and do not restore*’ is still often quoted. A decisive contribution to the development of a new culture of preservation in Europe was given by Italian scholars (Brandi, 1963), because of the unique environment in which they were raised and educated. The peculiar and pervasive presence of archaeological sites, historic cities and villages on the Italian territory - whose long-lasting, continuous presence was guaranteed by preservation rules introduced centuries ago – has made local sensibility to the theme always extremely high (D’Agostino, 2022).

Therefore, in the twentieth century in Europe the idea that the legacy carried by a monument did not depend only on its presumed original appearance became largely dominant. Appearance did not necessarily have to be re-proposed, the wounds of time being part of the monument life and contributing to its intangible value. This cultural context explains the highly restrictive position of the Athens Charter (1933) first and of the Venice Charter (1964) subsequently.

The Nara Document (1994), the Krakow Charter (2000) and more recent documents have added complementary information and principles to these original references, recognising that the concept of preservation and even the definition of authenticity and heritage must be referred to considering the different cultural contexts existing around the world.

Is all of this relevant for geotechnical engineering? We have learned that it is. In promoting the Technical Committee on Historic Sites of ISSMGE in 1981, Jean Kerisel and Arrigo Croce made an effort to bring to the attention of the geotechnical community the need to face all the existing cultural constraints, when dealing with cultural heritage. Since then, it has been clearly stated that the principles contained in the fundamental reference documents previously mentioned apply not only to the visible part of the structure but to the whole Ground-Monument System (Jappelli 1991). The relevance of geotechnical engineering in preservation has been highlighted many times (e.g. Jappelli & Marconi, 1997) and nicely summarised in the two previous Kerisel lectures through exemplary case histories (Calabresi, 2013, Viggiani, 2017). Clear definitions of material, iconic and historical integrity have been given (e.g. Viggiani, 2013). Historical integrity, in particular, has been dealt with in terms of authenticity from different points of view (e.g. Iwaski *et al.* 2013), confirming the variety of approaches related to local cultural environments, consistently with the indications of the Nara document.

Fig. 1 schematically summarizes the author's personal view of what we could call the conventional relationship between the different kinds of integrity and some possible engineering actions to be carried out for preservation goals. An insight into the meaning of each action, from conservation to reconstruction, can be found in Petzet (2004). This scheme is a conceptual framework posing constraints that cannot be overlooked, even when dealing with the least visible, underground part of built heritage, and with the subsoil directly interacting with it.

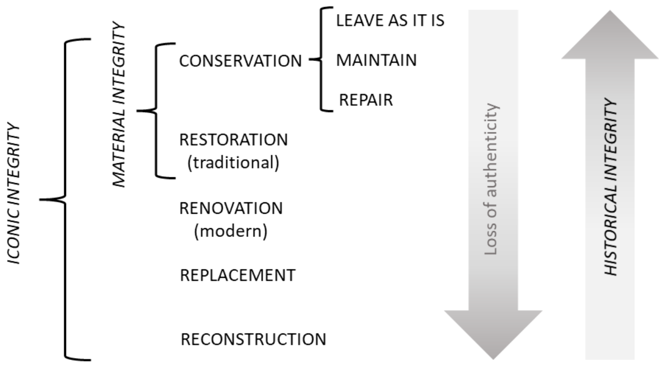


Figure 1. Conventional relationship between iconic, material and historical integrity as a function of different kinds of engineering actions.

Indeed, the scheme reported in Fig. 1 may not be fully satisfactory, because historical integrity and authenticity are somehow elusive concepts, as already mentioned. An enlightening example of such elusiveness can be taken with reference to the conservation of some shrines in Japan (Flora, 2013): up to the mid of the 19th century, several wooden Shinto shrines periodically underwent complete reconstruction ever since the inception of this custom in the 7th century. Such a practice had the character of an important religious ritual, but was probably set forth to answer to the need of substituting spoiled or damaged parts. Later on, in the 19th century, all the Shinto shrines but one (Ise shrine, Fig. 2) stopped the periodic reconstruction because of political changes and economic crisis. Nowadays, while the Ise shrine still keeps its ritual reconstruction every 20 years, all the other shrines are protected by law as architectural heritage, assuming as an indicator of their relevance and integrity the material value, in accordance with Fig. 1.

Actually, the interruption of the periodic rebuilding process was an accident and not the norm, the Iso shrine being the only one to follow its originally conceived life cycle. So, the

Figure 2. Ise shrine (Japan), which still undergoes ritual reconstruction every 20 years ever since the 7th century.

question is: what is authentic in this case? The frozen material situation of the 19th century or the immaterial heritage preserved by the ritual reconstruction of the Ise shrine? The answer is not easy, because such problems often face the lack of unicity of the solution (Viggiani, 2017), which is certainly an uncomfortable situation for engineers.

An attempt to answer may be done complementing the list of material and immaterial values of built heritage, or better overcoming the simple distinction between tangible and intangible values, referring to the role the structure has in its social and physical environment. So, the preservation of the role – intending with it the coherence with the original scope of the construction (considered through what we may call its functional integrity, Fig. 3) along with the importance it has in the perception of the local historic, physical and spatial environment - leads to the need of looking at preservation in a broader sense. Probably, the supreme value to be preserved is the message coming from the past, and therefore *continuity* may be even more important than *authenticity* (Petzet, 2004).

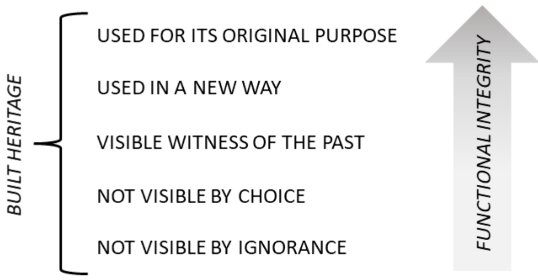


Figure 3. Schematic representation of functional integrity of the built heritage, as one of the elements defining the role it has in its environment.

Far from encouraging arbitrary reconstruction, the concept of functional integrity may certainly be a way to check if the monument or site of interest is in a good shape, alive with wounds, or just dead. In a way, these possible states have to do with the nuanced difference some scholars make between archaeology and architecture, which may seem a semantic dispute but underlays relevant differences in the preservation approach, that could be accepted to be more invasive in the latter case.

A paradigmatic example of built heritage not visible by ignorance is a part of Ercolano, a Greek-Roman town buried by the eruption of Mount Vesuvius in AD 79. Clearly, part of the town (how large? How relevant?) is still buried under modern buildings (Fig. 4), built with no respect - ignorance, in its literal meaning - of the underground heritage constraints.

Figs. 5 to 8 complement the information summarized in Fig. 3 in terms of built heritage functional integrity.

Figure 4. The Greek-Roman town of Ercolano (Italy), still partly buried under low quality modern buildings.

Figure 5. The Samnitic-Roman town of Pompei (Italy), unique witnesses of the past.

Figure 6. Bookstore inside a 13th century Dominican church in Maastricht (Holland). Built heritage used in a new way, with respect of its original conception.

Figure 7. The Roman port of Ventotene (one of the Pontine islands, Italy), still in use (thus at the highest possible level of functional integrity), was entirely excavated in the rock bank, removing some 60.000 m^3 of material, to support emperor Augustus' (63 BC – AD 14) summer residence, as there was no natural harbour on the island.

Figure 8. The Basilica of Saint Peter in Vatican (Rome, Italy), still playing its role of church and centre of the Catholic world (thus being at the highest possible level of functional integrity).

In the framework so far depicted, the case of Ise shrine can be seen as fully respectful of its role and functional value, because able to carry the immaterial, social heritage of the ritual reconstruction.

The consideration of the social role played by the built cultural heritage - well beyond its physical features –indicates that a merely binding preservation culture, as emerging from the strongly conservative constraints posed by the different charts of the twentieth century, may be inappropriate to preserve heritage in its broader sense. Quoting Settis (2018): '*Cities are not museums: they're meant to be lived in, and that's the reason why conservation supervision should not be perceived as a way of leaving everything in a state of hibernation. I don't wish heritage protection to mean hibernation*'.

This is a crucial issue when looking at preservation from the geotechnical engineering point of view. As a matter of fact, our discipline is most often involved in preservation actions when critical mechanisms may affect the Ground-Monument System, with the structure or the site often on the verge of failure. In such cases, geotechnical contribution is typically required to solve critical static problems or to tackle a high seismic risk, often without enough time to explore in depth all the range of technical alternatives. Decisions are easier to take when the geotechnical intervention can be concentrated within the subsoil, i.e. when the action has the goal to remove the cause and not to mitigate the effects on the structure. Soft solutions can overtake on invasive ones in these cases by considering the effect of boundary geotechnical conditions and eventually acting on them, as nicely described for instance by Calabresi (2011) with reference to the Roman Milvius bridge in Rome. In other cases, taking into account the effect of dynamic soil-structure interaction may prevent from useless invasive underpinning interventions (Lancellotta, 2013) or help in better understanding the structural behaviour of monuments (e.g. de Silva *et al.* 2018, de Silva 2020, Flora *et al*., 2021). The well-known case of Orvieto (Italy) (Pane & Martini, 1997) is also worth mentioning as representative of the quite frequent situations of relevant structures or sites above unstable rock cliffs, where the stabilization of the cliff is an effective, fully respectful solution.

The worldwide famous leaning tower of Pisa is another paradigmatic example of good geotechnical practice, as the preservation was successfully obtained by careful under-excavation (Burland *et al*., 2013), i.e. just carefully removing some soil in specific zones underneath the tower, without even touching it, thus keeping the solution in the uppermost part of the conventional integrity scheme of Fig. 1. However, the tower of Pisa may be also seen as a misleading example, in the sense that the successful and fully respectful solution was obtained after almost one century of careful and detailed studies, investigations and monitoring, with no economic constraints, with the support of politics and public opinion, involving in the multidisciplinary study world leading experts. Such an exceptional circumstance is rarely reproducible and cannot be considered as a routine situation, even in the case of extremely valuable historic buildings or sites. In the everyday life of geotechnical engineers, therefore, we know that a compromise is often unavoidable.

If foundation reinforcement with new technologies (to be considered as *modern renovation* only after exploring the possibility of *restoration*, Fig. 1) is the only feasible solution and may solve the problem, for instance, it should not be excluded *a priori*, especially if it contributes to keep the built heritage alive (i.e. with the highest functional integrity, Fig. 3). In fact, often historically valuable structures that still have a good degree of functional integrity are the result of continuous transformations that have taken place in a long time span. Therefore, modifications based on sound cultural and mechanical bases (and thus to be considered necessary) should not scare geotechnical engineers, being possible to consider them as part of the lifecycle of the structure, which should not be necessarily frozen to the present, intrinsically assumed as a reference time out of a still evolving historical pattern. Of course, the first attempt should be to use technological solutions consistent with the original structure, whose characteristics should be known (Roca *et al*., 2019). Apart from the formal distinction between architecture and archaeology that the concept recalls, the solution should be considered case by case, obviously taking into account all possible alternatives and privileging the least invasive ones. Hard interventions in the subsoil (for instance, underpinning) should be possibly avoided, considering that still undiscovered heritage may exist underneath the visible structure to protect.

The lack of a general theory, and therefore of a univocal indication of the best engineering solution to preserve built heritage, imposes the need to be extremely more cautious than with new constructions, and technical convenience or cost effectiveness must not be the guiding light in this case. Engineers have to cope with values usually out of their skills, stepping outside of their comfort zone, and have to agree on the technical solutions with archaeologists, architects, art historians and officials in charge of monuments preservation. Indeed, '*a satisfactory equilibrium between safety and conservation, between engineers and restorers, may be found only in the development of a shared culture*' (Viggiani 2013). Unfortunately, this is still to come in common geotechnical preservation practice, and extremely invasive actions on foundations are often felt acceptable just because they are not visible, with no deeper insight. Then, an effort is needed to go beyond purely academic discussion, if we want to avoid being as '*those people who give good advice if they cannot set a bad example*' (De Andrè, 1967). This is, or at least should be, the role of TC301 of ISSMGE.

The considerations reported in this introductory section clearly warn on the unusually complex task of dealing with the preservation of historic sites and buildings. Before planning any intervention, therefore, this complexity should make engineers aware of the heritage value, no other way being possible to truly perceive it than taking a humble bath into the history of the specific structure of interest, quietly listening to the silent voices of those who have imagined, designed, built, used and eventually modified it during history. Only after this empowering bath (Fig. 9), balance and congruence can take the lead.

The examples reported in the next sections are taken from the author's personal experience, and have been chosen because they show situations in which the lack of unicity of the solution is clear, and the considerations reported may seem questionable and therefore worth discussing. Covid pandemic has dramatically modified the possibility to carry out site investigations in the last two years. The reported case histories have suffered this limitation, and not all the planned activities were performed. Because of this, some of the results must be considered preliminary.

Figure 9. Inner side of the Tomb of the diver's lid (Greek painting, 480/70 BC, Paestum, Italy).

2 INTERFERE WITH THE PAST HELPING TO DISCOVER

2.1 *Copan*

Copan (UNESCO site since 1980) is an ancient Maya settlement located in the extreme western highlands of Honduras, close to the Copan river (Fig. 10). This city-state flourished from the 5th to the 9th century AD - a time-span known as the Classic Maya period - during which it became one of the most important sites of Maya civilization, in that period spread in contemporary southern Mexico, Guatemala, Belize, Honduras and El Salvador. Copan was the intellectual centre of the Classic Maya civilization, where important advances in astronomy and mathematics were achieved (Thompson, 1958). The site was brought to the attention of Europeans in 1576, when Diego Pedro de Palacio visited it and reported on the magnificence of its architecture and sculptures.

Copan is most famous for the so-called Main Group (Figure 10), an architectural compound exquisitely decorated with stone sculptures, comprised of a massive elevated royal complex located south, known as the Acropolis, and a series of connecting plazas and smaller structures located north. One of the most famous pieces of stonework is the superb Hieroglyphic Stairway (Fig. 11), the longest known Maya hieroglyphic text, and it's incredibly high relief sculpture, some of the finest ever carved in antiquity (Sharer and Traxler, 2006). Centuries of abandonment left heavy signs on the structures, that were mostly ruined at their rediscovery in the 19th century. In 1830's, Juan Galindo was the first to systematically explore the site, bringing attention from the world to the ruins of Copan and inspiring the first official excavations to begin in the late 1880´s.

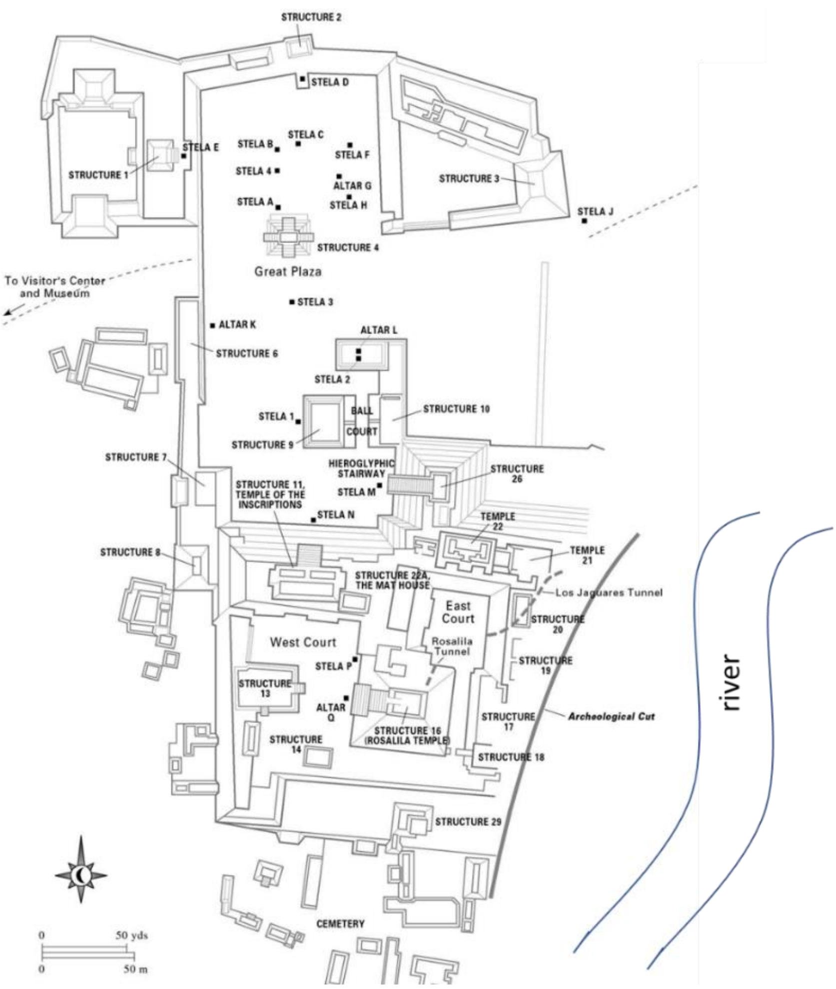


Figure 10. Plan view of the Copan archaeological area, with (sketched, non on scale) the nearby Copan river (modified after Pires, 2020).

When these first consistent explorations took place, the eastern side of the Acropolis had already been partially destroyed because of a large slope failure that involved part of the pyramids (Fig. 12a). Such large collapse was certainly related to the action of the close by Copan river, and the cut - nowadays known as *corte* - is the result of hundreds of years of water action. In fact, at some point of the Classic Period, the Maya artificially diverted the river course. The artificial control of the river path was stopped after the city decline, letting the river meander again. Its widening floodplain eventually became responsible for the undercutting and destruction of the eastern portion of the Acropolis (Bell et al., 2004). Added to centuries of erosion, an earthquake in the 1930's threw the top of three East Court buildings into the river, partially destroying some of the structures recorded by the first archaeologists of Copan (von Schwerin, 2011).

To prevent further catastrophic collapses, in the 1930's the river was diverted again. The large slope failure partially exposed ancient layers of buildings, once hidden in the undergrounds (Figure 12b). This obviously suggested to archaeologists the existence of important buried structures. In fact, the monuments visible in the Acropolis and the enclosed upraised courtyards are just the latest components of a series of additions made by the 400-year dynasty that ruled over Copan, accumulated over the centuries as a result of built layers added by ensuing kings (Fash, 1991). As the relevance of Copan grew, so did the need for Maya rulers of higher and more impressive monuments testifying it and leaving a lasting mark of their reign. The Maya approach to this need was to use the existing pyramids and structures as a core of the new enlarged ones. Therefore, when excavated, the pyramids reveal a series of complete but smaller pyramids, often still with their original coloured stucco decoration. In some cases, individual shrines could be amalgamated into a single bigger complex over time.

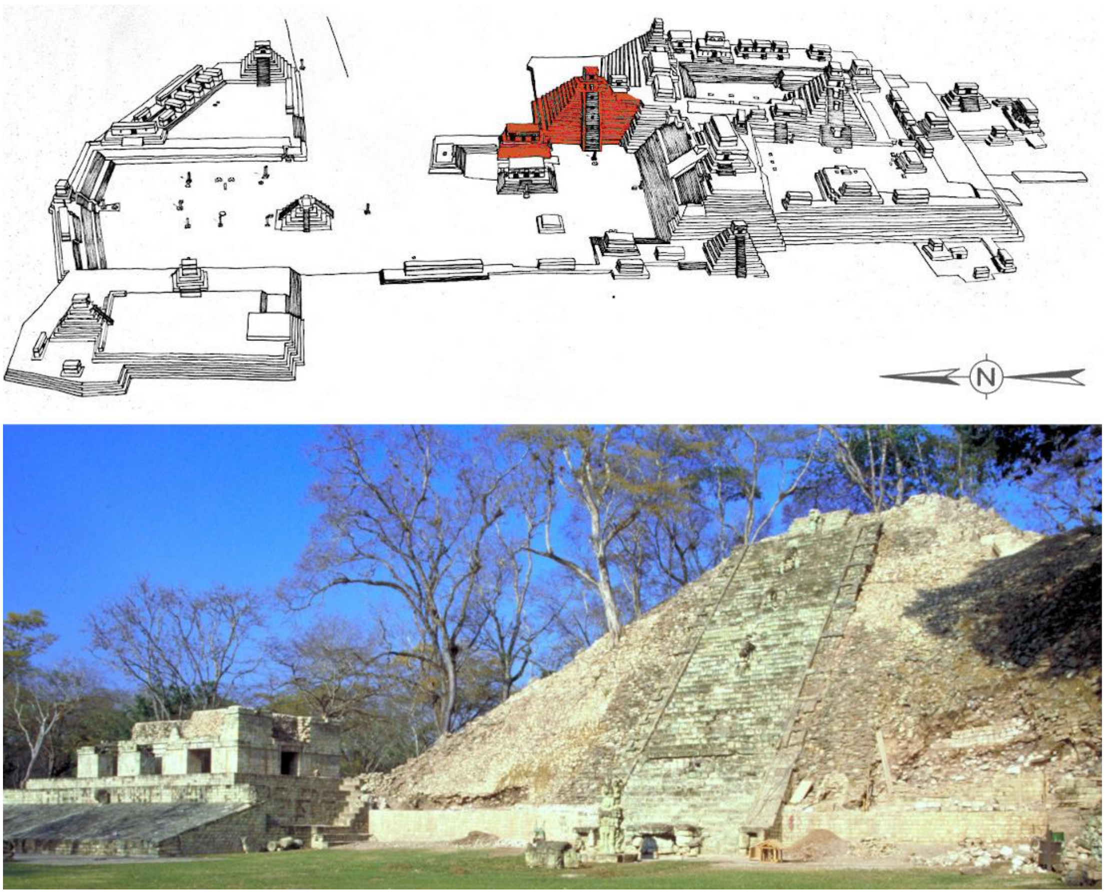
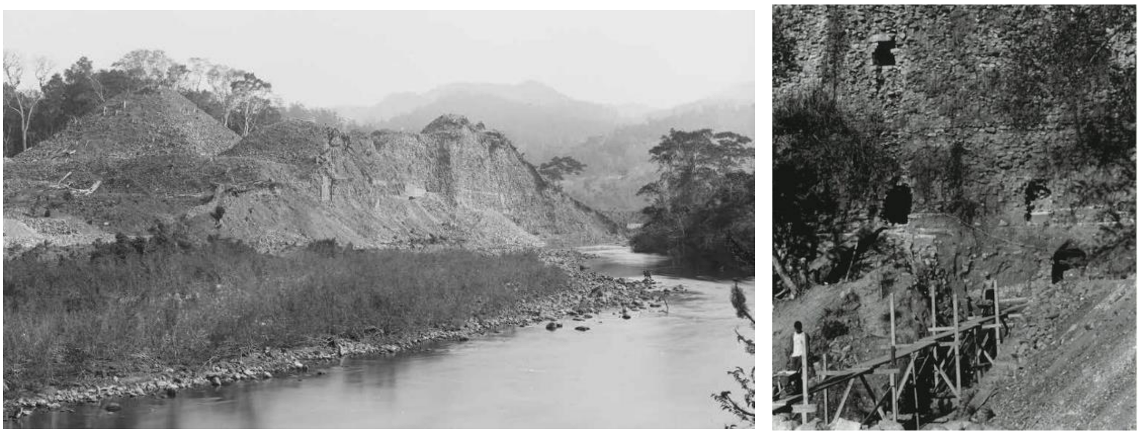


Figure 11. Top: Sketch of the Main Group of Copan with its northern part marked by the low-level plazas, and its southern part constituted by the Acropolis, with emphasis in the Hieroglyphic Stairway Temple (in red) – sketch adapted from Linda Schele's drawing (Schele, 1998); Bottom: Picture of the Hieroglyphic Stairway Court, with the temple at right and part of the Ball Court at left – photo by Linda Schele (modified after Pires *et al*., 2021).



(a) (b)

Figure 12. Left (a): looking north at the river cut (*corte*) into the 120-meter-long masonry eastern wall of the Copan Acropolis, photo by Marshall Saville 1891/92 (Peabody Museum 2004.24.66) – Right (b): a view of different entrances to tunnels in the Acropolis archaeological cut in 1989 – left (modified after Sharer *et al*., 1992).

Once a new and bigger structure had to be built on top of an existing one, the typical erection sequence was the following: first, the ancient superstructure (i.e. the usable building) was dismantled and its construction materials kept for posterior reuse (Abrams, 1994); then, a new and usually larger superstructure and substructure (i.e. the support of the buildings) were built over and around the ancient one. In more dramatic interventions, large platforms (i.e. levelling surfaces) were built. Superstructures were generally made with three-leaf masonry walls, with external leaves composed by dressed tuff stones and an infill core with a sort of "concrete" (Loten and Pendergast, 1984). Substructures were generally composed by a mix of wet-laid earth and stone fill materials, retained peripherally by stone masonry walls.

2.2 *The archaeological tunnels*

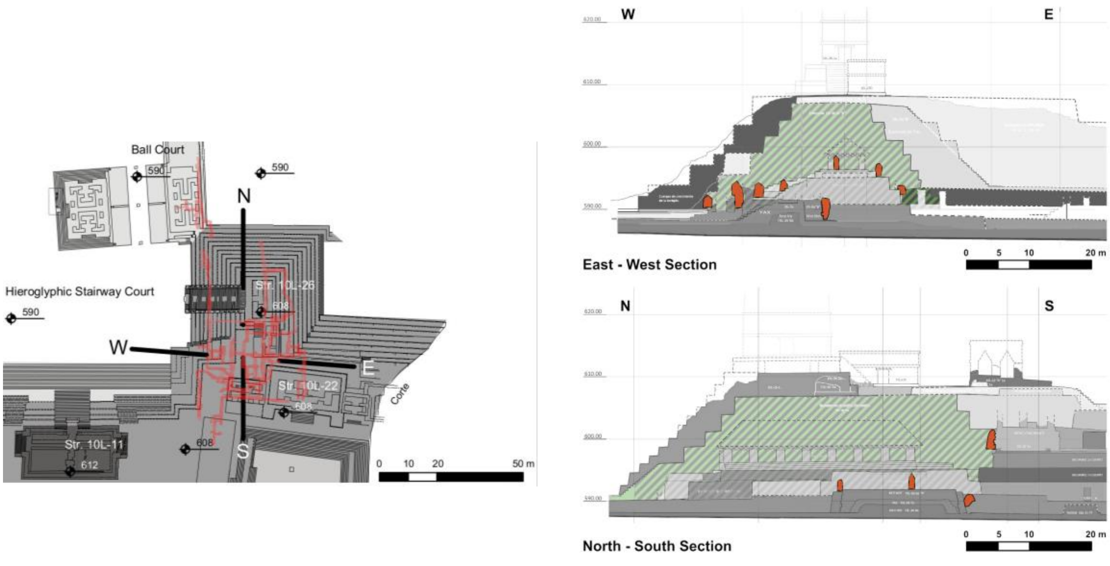
To allow for the archaeological investigation of the buried structures under the Acropolis, the first tunnels were excavated in the 1930's. By the 1980's, a new strategy was established and more complex tunnelling started from the *corte* using the exposed layers as references (Fig. 12b). In time, an incredible 4 km long and complex tunnel system developed within the monumental compound. Fig. 13a reports a sketch of the tunnels network underneath the Hieroglyphic Stairway Temple, in the northern part of the Acropolis. Thanks to this underground investigation approach, extraordinary archaeological discoveries were made. A large number of decorative plasterwork reliefs provided one of the most comprehensive set of information on the origins and development of a Classic Maya complex (Lacombe *et al.*, 2020). At the end of the 1980's, the Copan Acropolis Archaeological Project (PAAC) was established, merging past and new projects under the same direction, and allowing access to part of the tunnels by tourists.

Although most of the tunnels are apparently stable, local collapses required actions to ensure the safety conditions for researchers and visitors, and also to preserve the material cultural heritage still uncovered by the archaeologists. Moreover, in some cases the change in the environmental conditions of the buried heritage in the tunnels is also leading to the deterioration of valuable decorative materials. Since a comprehensive investigation of the conditions of the tunnels network within the site of Copan had never been carried out, a strategic plan was started by the Copan Acropolis Tunnel Conservation Program from Harvard University (Lacombe *et al.*, 2020), defining investigations, analyses and interventions to be carried out in subsequent steps. At this stage, structural and geotechnical engineers were invited to join the research group. In this framework, in fact, an important task was to obtain an insight into the stability conditions of the tunnels, starting from the available information, which in terms of the geometrical shape and position of the tunnels was well detailed. On the contrary, very little was known on the mechanical properties of the infill material. In this section, the first considerations done on the stability of the tunnels under the Hieroglyphic Stairway Temple (Fig. 13a) and on the preservation ac-

tions to be carried out are reported. Here the tunnels were excavated through Esmeralda (Fig. 13b), a large embankment built around 700 AD, that would later become the supporting platform for the Hieroglyphic Stairway Temple (Sharer *et al*., 1999).
The tunnels of Copan can be described as narrow underground passageways excavated by the archaeologists into the man-made earth fill constituting the core of the pyramids, with the goal of seeking buried structures. Because of this, they have an extremely irregular pattern (Fig. 14), with sharp changes in direction and depth. When buried structures were found, tunnels usually ran aside substructures and superstructures walls (Sharer *et al.*, 1999). From time to time, some of the tunnels have been excavated to go deeper in the embankment (and consequently to an older period of time in the development of the monumental compound). The earth fills within the pyramids have been created in a long time span, to allow subsequent enlargements of the structures. Because of this, they are not made with a homogeneous material, in terms of grain size distribution, density and even of compaction energy. However, for a certain volume related to a specific enlargement of the structure and at a certain depth, the material can be considered homogeneous, consistently with the fact that the workers were taking each time the fill material from the same pit, and were compacting it with the same tools.

Three main filling soils can be found under the Acropolis. The lowermost layers of the earth fills consist of a dark, clayey river mud (*barro*), which was mixed into a slurry to fill the earlier temples when it was time to build a new one on top (Lacombe *et al*., 2020). The barro is a well compacted fine-grained material, and no instability problems are reported in the tunnel stretches excavated into it.

The tunnels' network was mostly excavated immediately above the barro layer, into a layer of dark reddish-brown soil (*tierra café oscuro*) mixed with construction debris, river cobbles and broken lime plaster (Lacombe *et al*., 2020). This is a clayey silty sand with gravel. However, assuming that the larger gravel or boulder inclusions are floating in the finer matrix, the mechanical behavior of this layer corresponds to that of a sand with fines. The uppermost and outer part of the earth fills, the most recent one to be put in place, is made of a fine yellow sand (*girún*), which is the coarsest soil used for the whole earth fill. This sand was used to refine the oldest temples and to complete the latest structures such as Esmeralda. Most tunnel stretches excavated inside the *girún* layer needed to be supported at a later stage with a stone masonry lining, or suffered diffused collapses that required them to be back-filled.



(a) (b)

Figure 13. (a) Detail of the Acropolis plan showing the extension of currently open tunnels under the Hieroglyphic Stairway Temple (in red) – adapted from PAAC drawings; (b) Sections of the Hieroglyphic Stairway Temple showing the approximate positions of tunnels (in red) and the green hatch of the Esmeralda volume – adapted from C. Rudy Larios' PAAC drawings (modified after Pires *et al*., 2021).

Data about tunnels position under the Hieroglyphic Stairway Temple, their internal shape, and the presence of lining, sometimes being parts of original Maya structures, were gathered by a recent 3D dimensional survey. Hence, four typical transverse sections were identified to carry out a parametric numerical analysis of their stability conditions (Fig. 15) (Pires *et al*., 2021). T1 and T2 identify the 'as excavated' tunnel sections, where no lining was applied to the walls; T3 and T4 those structurally retrofitted, that were supported by thick masonry walls as lining at a later stage. Sections T1 and T3 are fully inside the fill material, while T2 and T4 are sections of tunnel excavated adjacent to buried structures, that therefore play a role in their mechanical behavior.

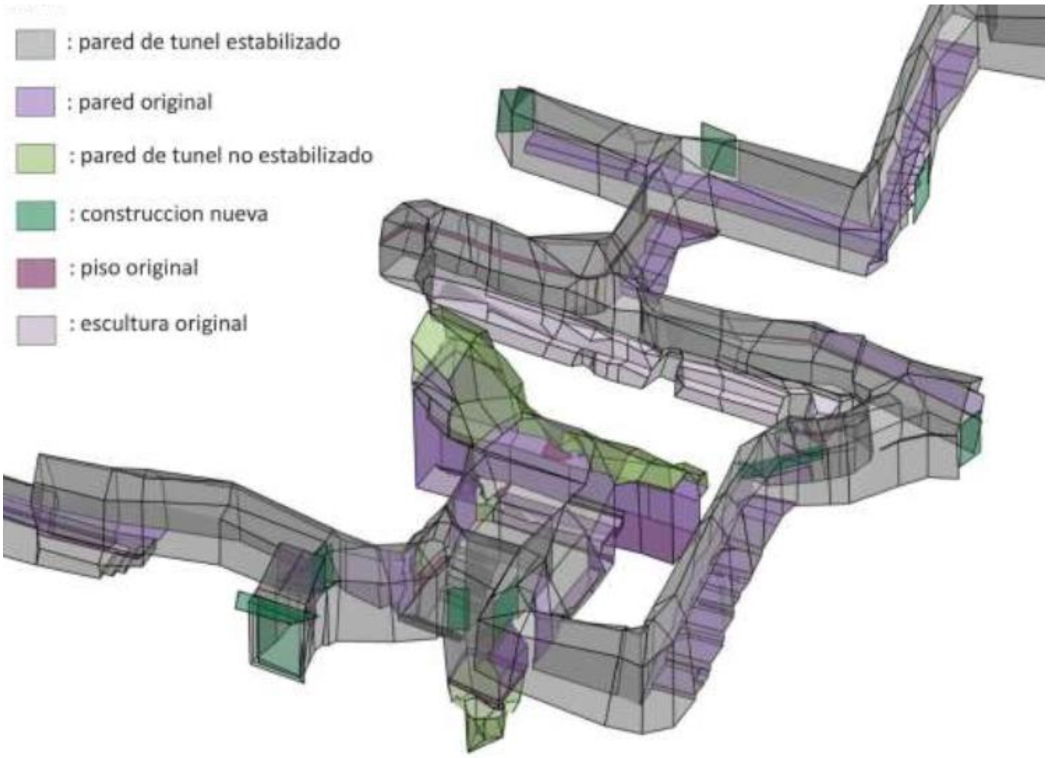


Figure 14. 3D model of part of one of the tunnels in the Acropolis (modified after Lacombe *et al.*, 2020).

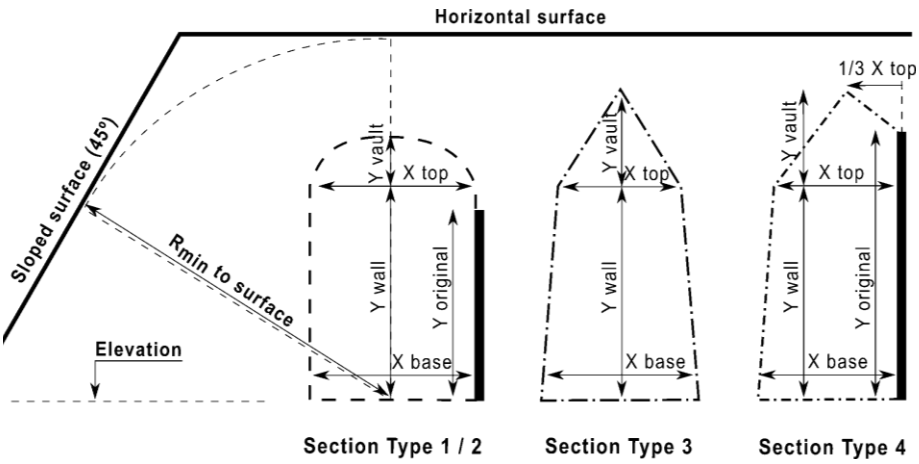


Figure 15. Shapes of typical tunnel sections: Types 1 and 2 (left), Type 3 (center) and Type 4 (right). The difference between type 1 and Type 2 is the presence of a buried Maya structure on one side for Type 2 (indicated as a thick black line) (modified after Pires *et al.*, 2021).

The unlined tunnels in the *tierra café oscuro* layer have a typically stable arched vault (Fig. 16), while the lined ones are vaulted on the top with a triangular corbelled arch. In most lined tunnels the lower walls are slanted. Section T4 is rather irregular and the final shape identified in the figure is just a rough approximation. The dimensions vary within each type but, in general, tunnels are small, serving as pathways for the archeologists, with an average width of about 1.0 m and a height ranging from 2.0 m to 3.0 m. Tab. 1 provides the statistical information obtained from the 3D survey. The distance between tunnels and external surfaces is represented in Fig. 15 by the minimum distance R_{min}. This is measured from the axis at the base of the tunnel to the nearest ground surface.

Figure 16. Unlined stretch of a tunnel excavated in the *tierra café oscuro* (modified afterLacombe *et al.*, 2020).

Table 1. Dimensions of the four typical tunnel sections (for the definition of $Y_{original}$, Y_{wall} and Y_{vault} see Fig. 15; μ=average, s=standard deviation) (Pires *et al.*, 2021).

Section type	Base width (m)		Top width (m)		$Y_{original}$ (m)		Y_{wall} (m)			Y_{vault} (m)	
	μ	s	μ	s	μ	s	median	μ	s	μ	s
T1	1.3	0.2	1.2	0.1	0.0	0.0	1.1	1.3	0.3	0.6	0.2
T2	1.2	0.3	1.2	0.2	2.0	1.1	1.3	2.0	1.1	0.4	0.3
T3	1.0	0.2	0.9	0.2	0.0	0.0	1.6	1.7	0.3	0.6	0.2
T4	1.1	0.2	0.9	0.3	2.6	1.7	1.9	2.5	1.4	0.7	0.2

The full length of the tunnels and the range of distance to the outside surface are summarized in Table 2. Here the surface is classified as sloped or horizontal. The slope of the stepped external surfaces of the pyramid-like structures is about 45º. In total, 360 m of tunnels can be found under the Hieroglyphic Stairway Temple. About 50% of these tunnels have a T3 section, while the other three types of section are equally distributed, as shown in Tab. 2. Most times, collapses occurred at the interface between lined and unlined tunnels or in unlined tunnels, as shown in the photos of Fig. 17.

In 1942, only few years after the excavation of the first tunnels in Copan, stabilization works began by widening the tunnels (except where there were original architectural elements) and putting in place a masonry lining. The masonry walls mimic original structures from Classic Copan, and were made using mortars with Portland cement. The same cement was used also to repoint the ancient walls, making it sometimes hard to discern between additions and the original parts, even though the modern stones are usually smaller and more regularly sized. The preservation methods from the 1990’s changed, keeping stabilization works but also backfilling some stretches. This time, the new masonry walls and arches did not directly touch the original walls, with the installation of plastic tarps between the new masonry and the original when necessary. With time, different local and diffused stabilization works were carried out, unfortunately without a precise strategy (Fig. 18). In many sections, the stabilizing masonry structures are affected by crack patterns indicating a critical stress state.

Table 2 – Total length of the four type of tunnel sections, and distance to the external surface (μ=average, s=standard deviation) (Pires *et al*., 2021).

Section Type	Total Length (m)	R_{min} to external surface (m)					
		μ	s	sloped surface		horizontal surface	
				min	max	min	max
T1	51.0	15.0	7.8	4.0	4.0	15.0	20.0
T2	56.0	17.0	4.4	-	-	8.5	20.0
T3	183.5	10.6	3.8	3.0	10.0	9.5	17.0
T4	66.5	7.7	4.3	2.0	11.0	9.0	12.5

Figure 17. Examples of local collapses: (left) at the interface between lined and unlined stretches; (right) in an unlined tunnel excavated in fine yellow sand (*girún*) (modified after Lacombe *et al.*, 2020).

Figure 18. Different kinds of local stabilisation interventions (modified after Lacombe *et al*., 2020).

2.3 *The contribution of geotechnical engineering: rational maintenance of tunnels*

Fig. 19 shows in red the tunnel stretches where local collapse was observed from 2017 to 2020, and in blue the ones where the main problem was massive water intrusion during the storms of 2017. Clearly, the extension of damage is such to make the use of the tunnels network critical and dangerous. When looking jointly to the history of collapses and heavy rain or storms, a correlation is observed. Furthermore, the critical sections where collapse concentrates are in the unlined part, but close to the lined ones.

Figure 19. Map of local tunnel collapse and of water intrusion observed from 2017 to 2020 (modified after Pires, 2020).

Since the soil was originally compacted in unsaturated conditions, it has to be expected that a change in the degree of saturation has a mechanical effect, obviously more critical in the unlined sections. A main instance, happened after the installation of an impermeable geomembrane over the East Court (Patio Este) in 1998, confirms this observation: shortly after the installation (which was done without proper collection and disposal of rain water accumulated on top of the geomembrane), an hurricane (hurricane *Mitch*) struck the region, bringing intense rainfalls. Three areas along the East Court perimeter suffered tunnel collapse at the time of the hurricane, and three more the year after (Fig. 20).

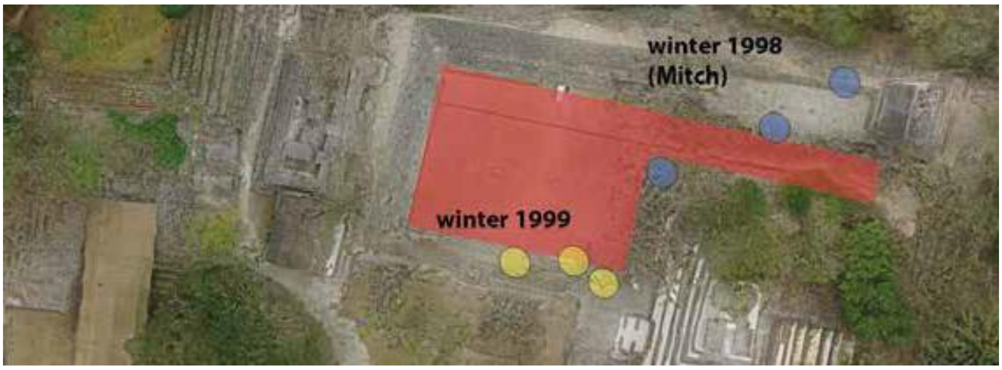


Figure 20. Aerial photo of the Copan Acropolis (east at top) showing approximate positions of tunnel collapses after hurricane Mitch (1998 in blue, and 1999 in yellow), with the position of the East Court membrane marked in red (modified after Lacombe *et al.*, 2020).

In fact, the tunnel sections adjacent to the perimeter of the East Court suffered major infiltration in the earth fill from the edges of the improperly installed geomembrane because of the water build-up at ground level.

To check water effect on the mechanical behavior of tunnels, 2D FEM analyses were carried out with PLAXIS 2D on both lined and unlined sections. The earth fills in which tunnels have been excavated in the considered area is unsaturated *girún*. In this work, the shear strength of this unsaturated granular soil has been simply considered as:

$$\tau = (\sigma - u_a) \cdot tan(\varphi) + (u_a - u_w) \cdot S_r \cdot tan(\varphi) \quad (1)$$

where $(\sigma - u_a)$ is the net normal stress, $(u_a - u_w)$ is the matric suction (s), S_r is the degree of saturation of the soil and φ is the effective shear strength angle. The second term of the second member of eq. (1) is often designated as 'apparent cohesion':

$$c_{unsat} = (u_a - u_w) \cdot S_r \cdot tan(\varphi) \quad (2)$$

Since the apparent cohesion reduces as the degree of saturation increases, water infiltration caused by the frequent heavy rains locally reduces the available shear strength of the unsaturated soil. Therefore, the numerical analyses were carried out considering the cohesive term of the Mohr-Coulomb strength criterion as a state parameter (eq. (2)) (Fig. 21), depending on the relevant soil-water characteristic curve.

The safety factor for the unlined section with an ancient wall on one side (T2) is 10% to 30% higher than for the section with no wall (T1) for low to medium degrees of saturation (Fig. 22). However, approaching saturation the values converge, resulting into failure for S_r>80%.

Clearly, FS increases passing from unlined to lined sections. As long as drainage is ensured (i.e. there is no or little water pressure on the lining), the lining provides high safety margins to the tunnel, whatever the soil saturation degree, and ensures stability with high margins even in fully saturated conditions. But drainage has to be granted, which is not always the case on site. Real safety conditions can therefore be significantly lower, and have to be analyzed case by case.

The numerical results obtained (including those not reported here for the sake of brevity, see Pires *et al.* 2021) confirm how relevant the role of the degree of saturation in the compacted earth fill is for the stability of the unlined parts of the tunnels excavated in the Acropolis. Clearly, in the lined sections, the degree of saturation is locally higher than in the unlined ones because of the reduced exposure to draining surfaces. This explains why most collapses have taken place at the interface between the two kinds of section, where the gradient of saturation degree caused by the different boundary conditions triggers a water flow towards the closest outcome, which is the first unlined section. Eventually, this will locally result into a degree of saturation higher than in other unlined sections, further from the lined stretch, and thus in lower safety factors that may trigger the collapse of blocks.

To confirm these preliminary results, more extensive survey of the complex 3D tunnels geometrical layout is however needed, along with an adequate experimental characterization of the earth fill and of the tunnels lining masonry materials.

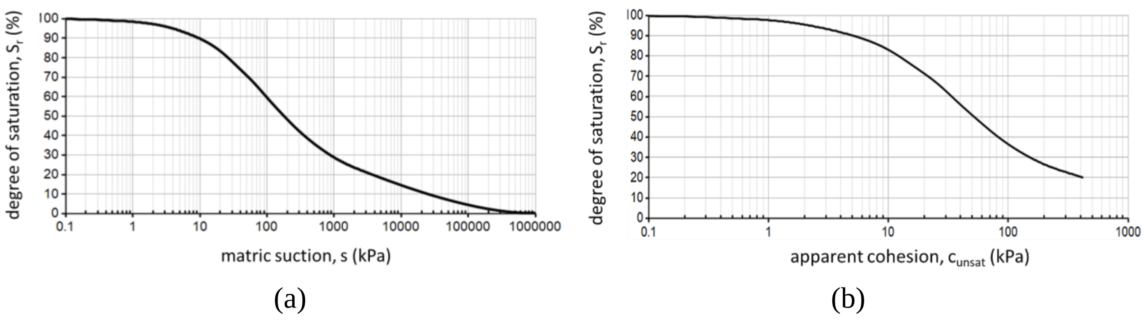


Figure 21. (a) Soil-water characteristic curve and (b) apparent cohesion versus saturation, for the silty sand infill (*'girùn'*).

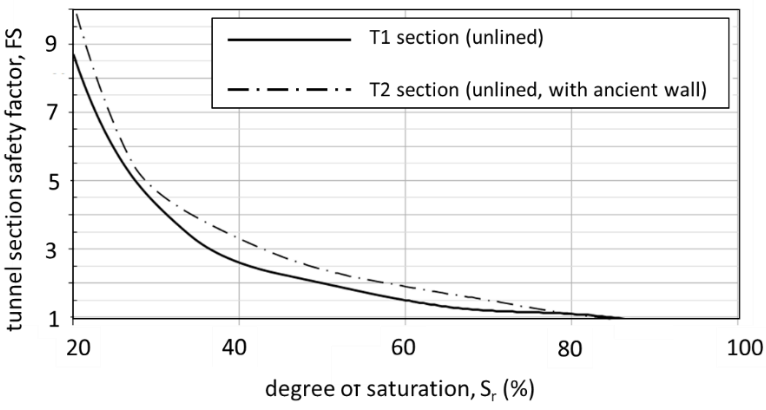


Figure 22. Safety factors for the unlined tunnel sections T1 and T2 at a depth of 20 m as a function of soil degree of saturation of soil (modified after Pires *et al*., 2021).

These activities were planned in 2020 but never carried out because of the Covid pandemic, that dramatically reduced the possibility to operate on site and, for the author, to travel to Copan.

Based on the preliminary results herein summarized, the following recommendations have been made for the short term: correctly collect and dispose rain water at ground level, minimizing infiltration; carry out a constant monitoring of the water content in the soil around tunnels, especially at the transition between lined and unlined sections, to anticipate safety issues (instrumentation still to be put in place); ensure drainage in the lined tunnel sections to minimize water pressure on the lining; avoid the addition of new tunnels too close to the existing ones, continuously updating the 3D map of the tunnels system.

From a strategic point of view, the preservation of the invaluable heritage existing deep inside the Copan Acropolis (Fig. 23) would ask for a massive application of these preservation actions.

In the medium to long term, new lining should be installed where necessary, respectful of the critical chemical conditions of the buried Maya stuccos, and possibly new tunnel stretches connecting to the outside or to other tunnels should be added as escape paths for safety reasons, to avoid extremely long blind parts. A complete lack of interaction (either mechanical or chemical) between the Maya buried structures and the new lining should be also ensured.

However, because of the length of the tunnels network and of the critical lack of funding, this whole program is unfeasible, at least in the short period. Therefore, backfilling of some parts in critical safety conditions will be required, after a more detailed analysis of the different parts of the network, sharing the decision among archaeologists, art historians and engineers (geotechnical, structural and chemical). Backfilling will in fact make not accessible sites of possible interest, and will not allow further investigations along those directions.

Figure 23. Examples of parts of the buried Maya structures discovered in Copan through archaeological tunnelling (modified after Lacombe *et al*., 2020).

3 INTERFERE WITH THE PAST OUT OF NECESSITY

3.1 *The Crypta Neapolitana*

This tunnel has a long-lasting story, that goes along with the development of the town of Napoli (Italy), and has been already dealt with from a geotechnical point of view in the recent past (Amato *et al*., 2001, Viggiani, 2017). Its conception is attributed to Lucio Cocceio Aucto, a Roman architect (in a broad sense, being him a fine engineer as well) of the first century BC, highly appreciated by the emperor Octavianus Augustus and designer of the Temple of Augustus (later turned into the catholic church of San Procolo) in Pozzuoli and of the other two long Roman tunnels (Seiano Grotto and Cocceio Grotto) in the area around Naples. The Crypta Neapolitana runs close to the east-west direction, and crosses the Posillipo hill, that separates the Gulf of Pozzuoli from that of Naples (Fig. 24).

According to some recent studies of the Roman tunnels in the Neapolitan area (Escalona, 2022), the hypothesis that a smaller tunnel along its longitudinal axis already existed before Cocceio's work is also considered. Well before the Romans took the area, information reported in the Odyssey of Homer (11.14) and interpreted by historians indicate that the mysterious population of Cimmerians lived in the area around the Lake Avernus (close to the later Cocceio Grotto, see Fig. 26 on the left) during Ulysses peregrination on the Italian coasts. The Cimmerians were an old nomadic Indo-European people coming from the Caspian steppes, on the northern shores of the Black Sea, who probably settled in the Campania Region (as also referred by Strabo and Plinius the Old) between 1000 BC and 800 BC. During their migration, they had previously settled in Cappadocia, where they learned to excavate and live in underground spaces. Ever since they have been known as the people of darkness, living in underground houses, connected among them with tunnels. In the Phlegrean Fields, they had an oracle (a Sibyl, a sorority sister) that was venerated by the pre-Hellenic native populations. Those who lived about the oracle had an ancestral custom, that no one should see the sun, but should go outside the caverns only during the night.

Escalona (2022) claims that the existence of a small chapel within the Crypta Neapolitana may indicate a deeply seated room, originally conceived for burial (Cimmerians used to bury their Kings or leaders in the deepest heart of mountains) or religious reasons, to be reached through a small tunnel coming from the western side of the hill. Even though this is still a matter of scientific discussion, it would somehow justify the mediaeval legend claiming that the

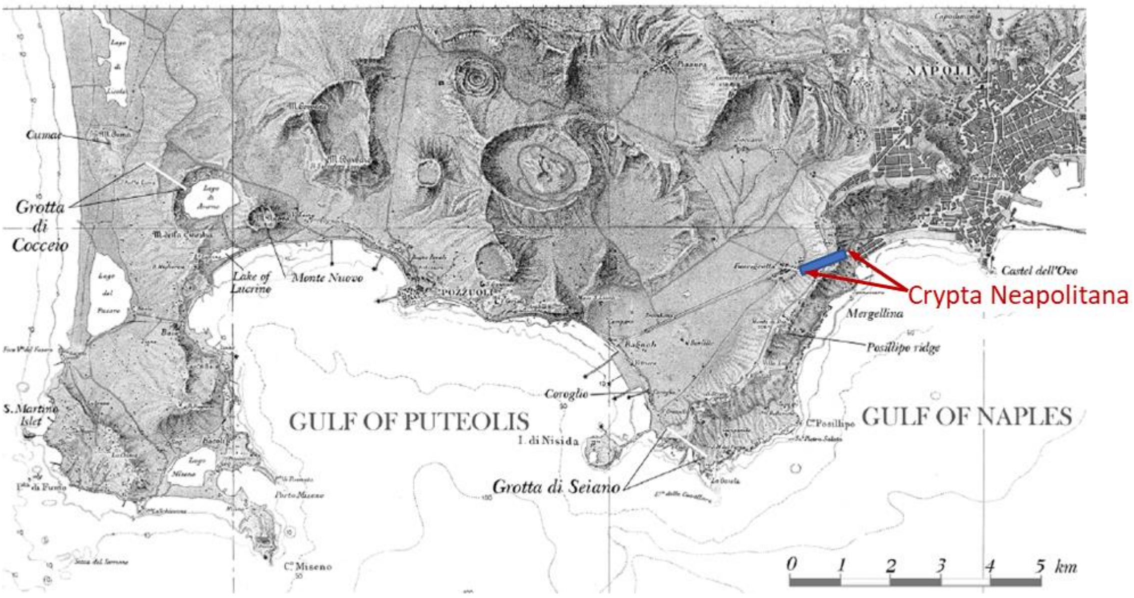


Figure 24. Map of the coastal region called *Phlegrean Fields* with in evidence the location of the Crypta Neapolitana through the Posillipo hill (The old town of Naples is on the East side). The topography refers to the second half of the XIX century, while nowadays the whole area on both sides of the tunnel is densely urbanized, the two towns of Napoli and Pozzuoli merging into a unique built environment.

tunnel was excavated by the poet Virgil in a single night: in fact, this myth could reflect a rather fast construction of the tunnel, corresponding to a possible renovation or enlargement of an originally existing one, and not to a completely new excavation. Just an hypothesis, certainly fascinating.

In any case, the Roman tunnel excavated (or enlarged) in the first century BC had the clear goal to enhance and simplify the communication between the very active town of Puteolis (nowadays Pozzuoli), where the largest commercial harbour of western Mediterranean sea was located, and the growing town of Neapolis (Napoli), and was part of a large number of public works constructed in the area under the coordination of Marcus Vipsanius Agrippa, who was a close friend and son-in-law of the emperor Augustus (Ferrari & Lamagna, 2015). The Aqua Augusta (Serino) aqueduct was built later, crossing the Posillipo hill in parallel to the Crypta Neapolitana and far only a few meters from it, letting the water flow from the far Serino springs to Puteolis. The original Roman cross section of the tunnel was between 4 and 5 m large, and likely no more than 4 m high (may be even less), with a curved vault and vertical side walls. Its shape is mostly lost, because of subsequent reshaping carried out for centuries. The tunnel is 711 m long, with two inclined ventilation shafts on the two sides of the hill. A longitudinal section with the recent shape of the tunnel is reported in Fig. 25.

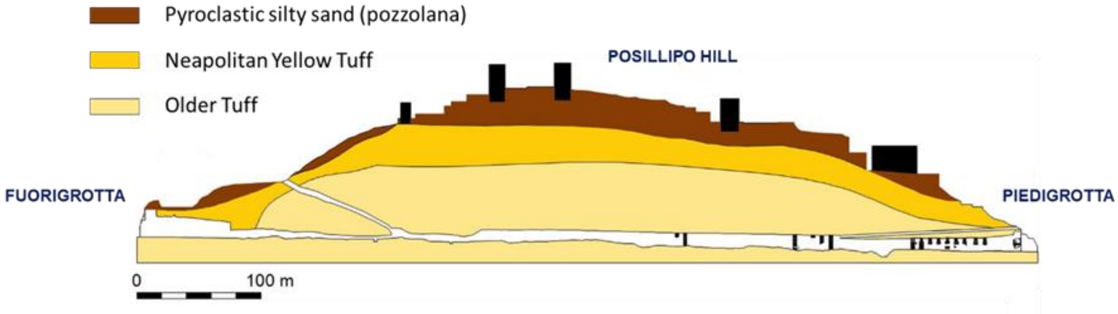


Figure 25. Cross section of the Posillipo hill along the *Crypta* longitudinal axis, with indication of the geological units.

As schematically sketched in the figure, the tunnel crosses different pyroclastic formations. The deeper one is a weakly cemented old tuff, with poor mechanical properties, that can be considered a transition material between an uncemented pyroclastic silty sand (*pozzolana*) and a tuff, with some specific sections in which cohesion is close to zero. Because of the uncomplete cementation process, this formation is not affected by the typical syngenetic cooling fractures observed elsewhere in town in well cemented tuff. Neapolitan Yellow Tuff covers the old tuff in the hill of Posillipo. As well known, it is a soft, light rock with a good degree of cementation, with a number of subvertical and sub-horizontal cooling fractures. The Crypta Neapolitana crosses the Neapolitan Yellow tuff formation only in the first 100 m on the western side, and only for few meters on the eastern one. So, most of the tunnel is excavated in the old tuff. Because of this, the eastern and western parts of the tunnel were unlined, while the central part was lined with masonry, with only few parts of *opus reticulatum* still visible.

The first documented intervention into the tunnel was carried out in 1445 by the king Alphonse of Aragòn to lower the eastern entrance. A century later, the Spanish viceroy Pedro de Toledo further lowered this part of the tunnel, paving the roadway. Other retrofitting works were done under Pedro Antonio d'Aragona (XVII century), Charles III Bourbon (1748), the Municipality of Naples (1893, with the insertion of a number of strengthening masonry arches in the eastern part of the tunnel), till 1917 when, because of ongoing local collapses and of the diffused risk of collapse of blocks, the Crypta Neapolitana was closed, its crucial connecting role between the two sides of the hill being taken from the newly built and close by rail and car tunnels.

In 1930, the eastern part of the Crypta was partly filled, and the floor raised back as much as 9 m, to accommodate the entrance to an outside green area where the supposed tombs of Virgil and of the Italian poet Leopardi are placed. Fig. 26 show a reconstruction of the changes in time of floor elevation (Amato *et al*., 2001).

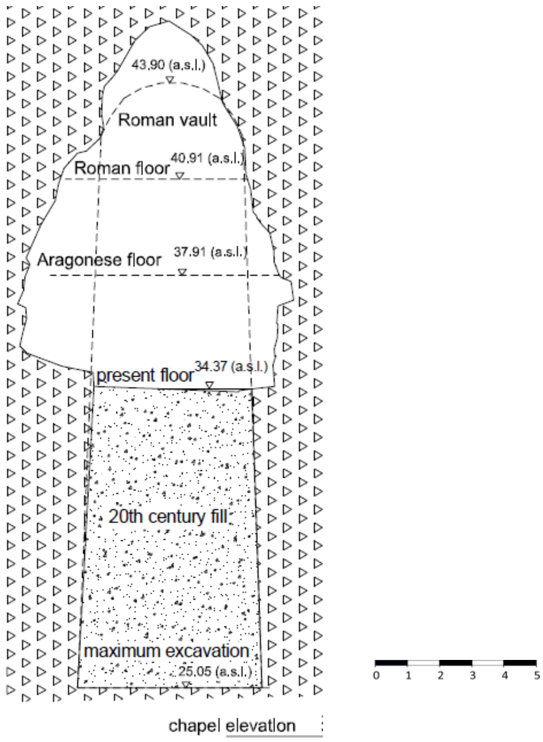


Figure 26. Cross section of the Crypta Neapolitana at 20 m from the eastern entrance in its current state, along with the reconstruction of the different elevations of the floor in time (modified after Amato *et al*., 2001).

Figs 27 and 28 show the two entrances of the tunnel. Recently, bolted steel arches were placed to support the vault in the first 30- 40 m on the western side (Fig. 27).

The tunnel is actually in very bad static conditions, with diffused collapse of large blocks along its axis, especially in the central part, where site survey is now almost impossible for safety reasons. The Roman masonry lining has collapsed along the whole lined stretch, with only few parts, with no static role, still standing. A large part of the masonry supporting structures placed in the 19th century collapsed. Figs. 29 and 30 show some photos of a recent survey (January 2022) from both entrances of the tunnel, giving a clear idea of the widespread state of instability.

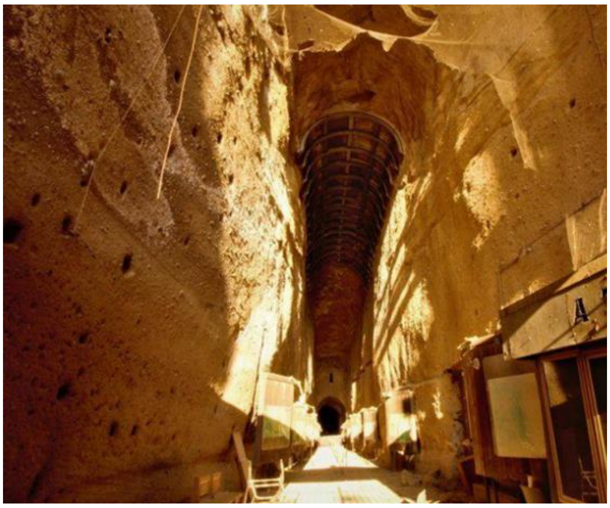


Figure 27. Western entrance of the Crypta Neapolitana in a recent photo. On the vault, the recently placed bolted steel arches.

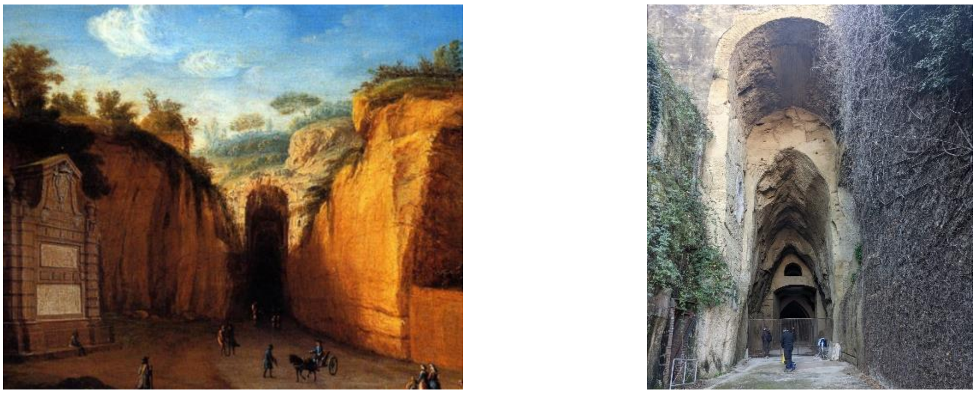


Figure 28. Eastern entrance of the Crypta Neapolitana in a painting (van Wittel, XVIII century, oil on copper) and in a recent photo.

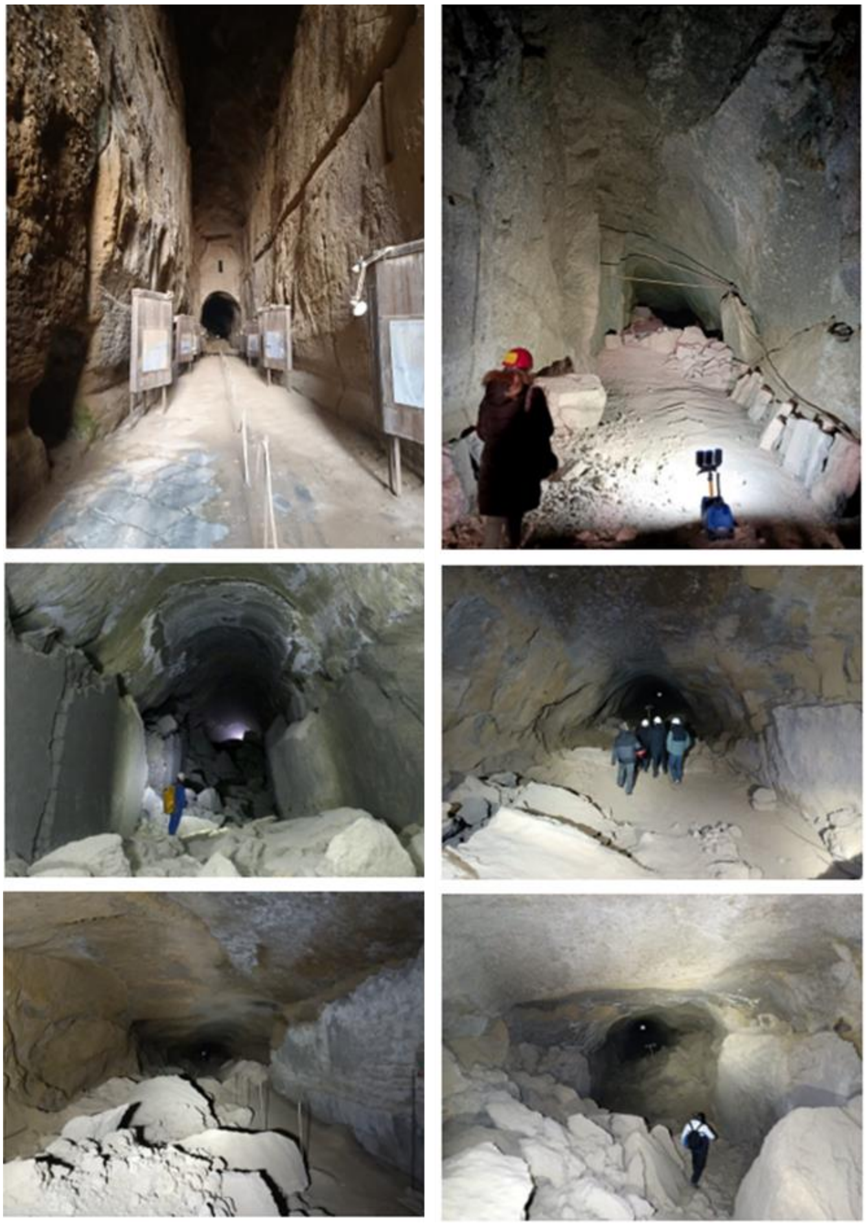


Figure 29. From top left: pictures from the western entrance till ca. progressive 350 m. Collapse of blocks, tension cracks and collapse of masonry lining are clearly visible;

Figure 30. From top left: pictures from the eastern entrance till ca. progressive 150 m. Masonry arches well preserved in the first part, with complete collapse of side walls in the final part. Large subvertical rectangular blocks sometimes on the verge of instability failure.

3.2 *The contribution of geotechnical engineering: tunnels reinforcement and reuse*

To check the static conditions of the tunnel, an in situ investigation was carried out about 20 years ago. Boreholes from the ground surface and core drills from within the tunnel were executed. Samples retrieved during coring were tested to get the uniaxial compressive strength σ_c, while flat jack tests were carried out in some sections of the tunnel to quantify the in situ vertical stress (Fig. 32). In the old tuff, i.e. for most of the tunnel length but the parts close to the two entrances, the compressive strength values are in the range 0,5 MPa<σ_c<2 MPa, while in the Neapolitan Yellow Tuff σ_c is as high as 6 MPa. The comparison between σ_c and the vertical stress estimated with flat jack indicates that, for distances from the western entrance between 100 m and 200 m, the rock around the tunnel is locally on the verge of failure, consistently with the evidence of diffused collapse.

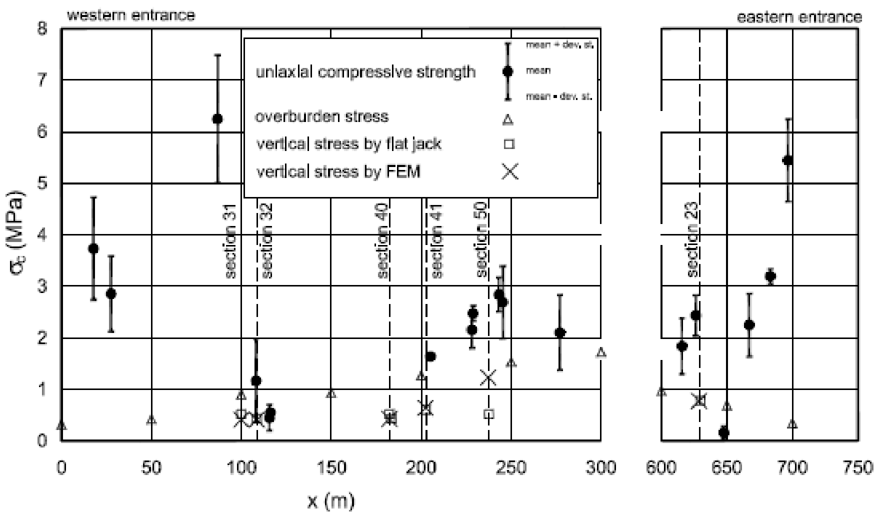


Figure 31. Values of the uniaxial compressive strength of tuff and in situ stress along the axis of the Crypta. Distances taken from the western entrance (modified after Amato *et al*., 2001).

A detailed geometrical survey of the tunnel was also carried out with a laser scanner (Fig. 32). The characterization of the rock mass was done using the Hoek & Brown failure criterion (Bilotta, 2022), then converting the parameters into the ones (c, φ) of the Mohr-Coulomb failure criterion, to be used in elastic-perfectly plastic 2D analyses carried out with Plaxis. Fig. 33 briefly summarises the results in terms of plastic stress points (red and white points corresponding respectively to shear and tension failure), reporting also the values of the safety factor corresponding to a mechanism of local collapse (blocks failure). As expected, the most critical situation is in section C (see Fig. 33) (FS<1), in the part of the tunnel with the worst mechanical properties, while the other sections are globally stable, with the exception of section F (FS≈1).

Assuming that yielded volumes progressively collapse, the numerical analyses indicate that most times the critical mechanism is the creation of tension cracks on the sides and the subsequent collapse of blocks, consistently with the experimental evidences. Since this mechanism could be perverse (i.e. local collapses, and subsequent reshaping of the sections, may trigger further collapses and reshaping, and so on), the overall indication is that the preservation of this Roman tunnel asks for a diffused reinforcement.

This brings the discussion to the constraints posed by the relevance of the historic site. The wounds of time are in this case clearly visible, and there is no reason to try and replicate the original Roman cross section, whose traces are mostly lost. The largest part of the tunnel has been naturally reshaped as a result of a stress redistribution within the rock mass or later human interventions. Then, the question arises about what should be preserved. In this case, it seems that the strongest legacy is linked to the role of the Crypta Neapolitana, which is the connection of two neighbourhoods separated by the hill, as demonstrated by their names: *Fuorigrotta* (literally, *out of the grotto*) the one on the west side, and *Piedigrotta* (literally, *at the entrance of the grotto*) the one on the east side, the grotto obviously being the Crypta Neapolitana. This path has been a living part of the city for at least two thousand years, and still keeps traces of this long lasting life (Fig. 34).

Therefore, according to the author's opinion a hard interference with the iconic integrity may be justified in this case to let the Crypta Neapolitana return to its role of a connecting path. In particular, it should become a pedestrian tunnel that would correspond to the best possible preservation of its functional integrity. This is actually a matter of discussion with local authorities. Interventions should include: a new lining in the central part of the tunnel, with new materials and local openings to show details of the old masonry lining or of local connections with the close-by Aqua Augusta aqueduct; a retrofitting and underpinning of the masonry arches on the eastern side; bolting of potentially instable blocks, and bolted nets in the unlined western part of the tunnel excavated in the Neapolitan Yellow Tuff.

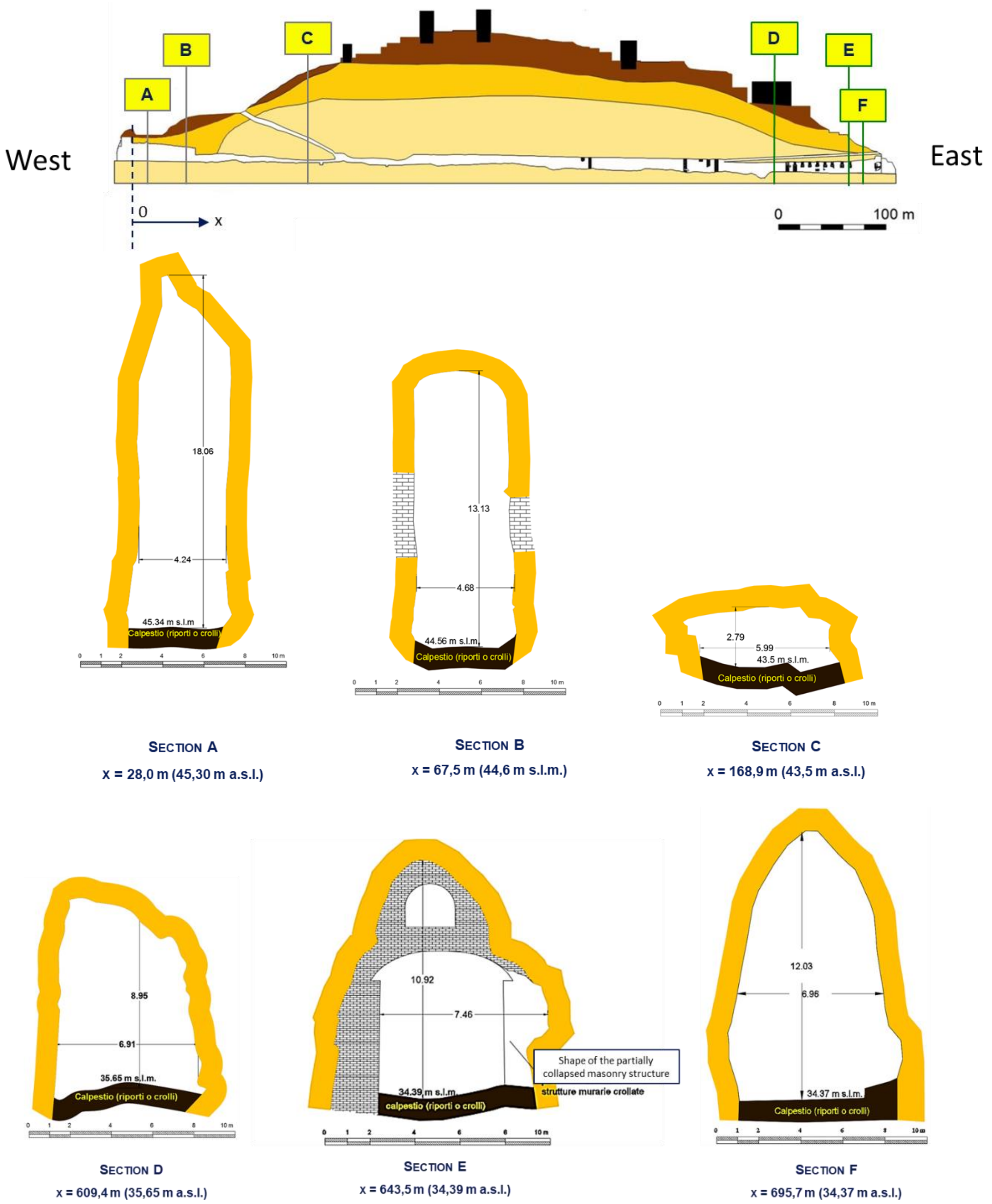


Figure 32. Cross sections (obtained by laser scanning) of the Crypta Neapolitana considered in the numerical analyses, with indication of their position (distance from western entrance) along the tunnel axis.

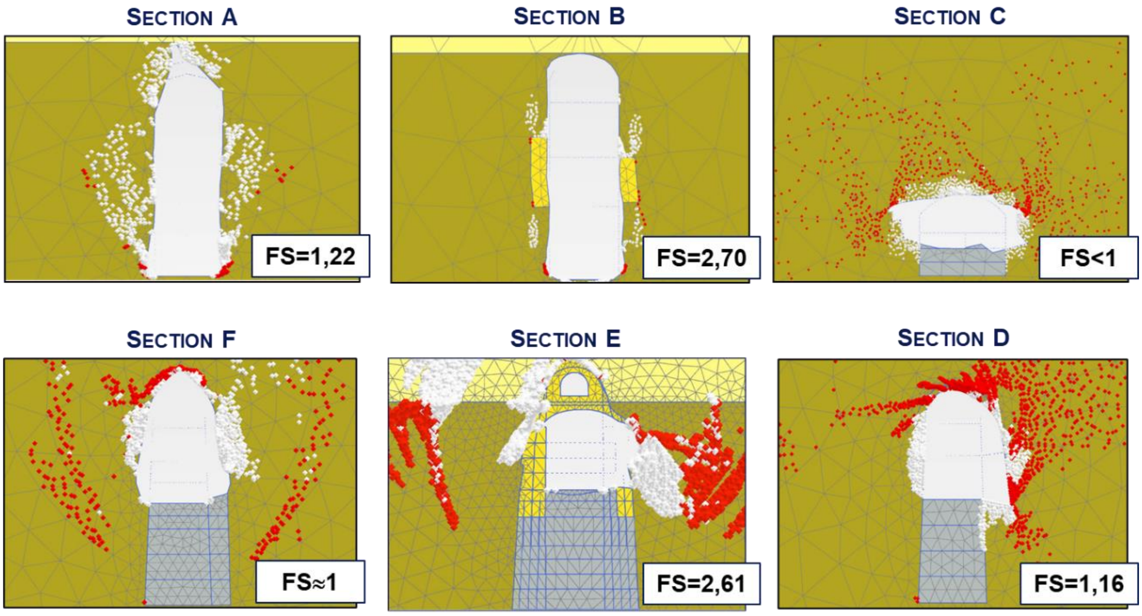


Figure 33. Results of the numerical analyses in terms of plastic stress points (red and white points corresponding respectively to shear and tension failure). FS is the safety factor corresponding to a mechanism of local collapse (blocks failure) (Bilotta, 2022).

Figure 34. Painting of the Persian God Mithra, depicted as the sun, within the Crypta Neapolitana (courtesy of L. Amato). In Napoli, Mithraism dates back to the Hellenistic period, and spread during the 5th century A.C. through prisoners and slaves coming from Cilicia. In some basements in the old town, bas-reliefs depicting the Persian God while sacrificing a bull can be still admired.

4 INTERFERE WITH THE PAST LEARNING FROM IT

4.1 *The Theodosian walls of Constantinople*

The city of Byzantium was relatively unimportant during the early Roman period, but when the Roman influence in the east grew, its strategic position was recognized, and the need to defend it became a priority. Such a need became even more urgent when the Roman emperor Constantine the Great (AD 272-337) gave a sharp impulse to its development, building a new imperial residence in the city and renaming the city Constantinople after himself. In AD 328, the city eventually became the capital of the empire, keeping this role for more than a thousand years. This move, and in general the age of Constantine, conventionally marks the transition from classical antiquity to the Middle Ages.

Since the city was initially located on the European side, it was naturally protected by the sea on the north, east and south, the major problem being to protect it from possible attacks from the inland, on the west side. Constantine arranged a wall to be built (Fig. 35) from the Golden Horn to the Sea of Marmara. As the city grew, however, this confine had to be overcome to accommodate all the people attracted from the new status of the city. An impressive double line of walls was then built on the land side during the reign of Emperor Theodosius II (408–450 AD), after whom they were named, about 2 km to the west of the old Constantinian Wall. The protective system, completed in AD 423, is the result of the skills and dedicated work of Anthemius, a Praetorian Prefect of the East, who did not see his work completed as he died in 414. In their final configuration, the Theodosian walls had a length of about 7 km, completely surrounding the city (Fig. 35), thus creating a barrier not only on the west side but also along the whole coastal perimeter.

On the land side the system consisted of two closely spaced defensive lines (Fig. 36): an inner wall, with a maximum height of 12 m, and an outer wall, with a lower height, each one fortified by towers placed at some tens of meters apart. The inner towers are as high as 24 m, while the outer ones are ca. 10 m high. The ground level on the terrace (*peribolos*) between the two walls is some meters (ca. 5 m) higher than that (*parateichion*) outside the outer wall, thus giving a dominant position to the defenders in case of attack. The *parateichion* is confined on the outside by a moat, originally filled with water supplied by a sophisticated system, as a first defensive means.

Figure 35. Map of Constantinople at the beginning of the Ottoman Period, with the location of the first defensive wall of Constantine and the location of the outer, much longer Theodosian walls (http://romeartlover.tripod.com/Murter.html). Tower T19, dealt with in this section, is indicated in the south reach of the latter wall.

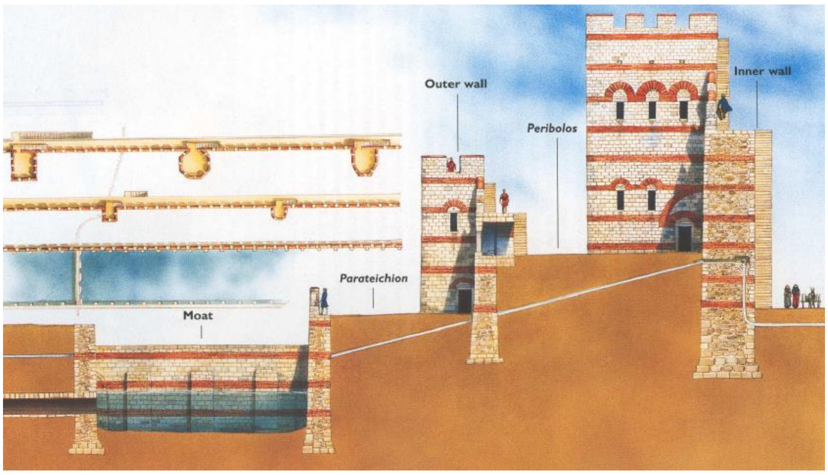


Figure 36. Typical cross section and plan of the Theodosian walls and towers. On the top left of the plan, the different shapes of the towers (modified after Turnbull, 2004).

Each tower had a battlemented terrace on the top. Its interior was usually divided by a floor into two chambers, not communicating with each other. The lower chamber, opened through the main wall to the city, was used for storage, while the upper one could be entered from the wall's walkway, and had windows for viewing and battling. Access to the wall was provided by large ramps along their side (Turnbull, 2004). The lower floor could also be accessed from the *peribolos* by small posterns.

This defensive system became legendary in the Middle Ages, deemed invincible and considered impregnable for any medieval besieger. The only exception was the sack of 1203-1204 during the fourth Crusade, that was a turning point in medieval history because of the decision of the Crusaders to attack the world largest Christian city. Before and after it, the Theodosian walls saved Constantinople - and the Byzantine Empire with it - during many sieges, even though with the sack of 1203 the city decadence began, and large parts of the empire were lost. The Ottomans unsuccessfully attempted to take the city in 1396 and 1422, eventually succeeding on 29 May 1453 under the guidance of sultan Mehmed the Conqueror, after a six-week siege in which a crucial role was played by the 8 m span cannons used by the besiegers. Parts of the walls were largely damaged by the gunpower, and then restored by the Ottomans.

The walls were largely maintained intact during most of the long Ottoman period (1453-1922). Sections began to be dismantled only in the 19^{th} century, as the modern city outgrew its medieval boundaries. Despite the subsequent decadence and lack of maintenance (Fig. 37), many parts of the walls and towers survived and are still standing today.

Despite all the sieges they had to face throughout their history, the Theodosian walls were damaged much more by earthquakes and floods than by enemies' attacks. Earthquakes, in particular, were a major source of damage. Fig. 38 reports the epicentres and years of the main his-

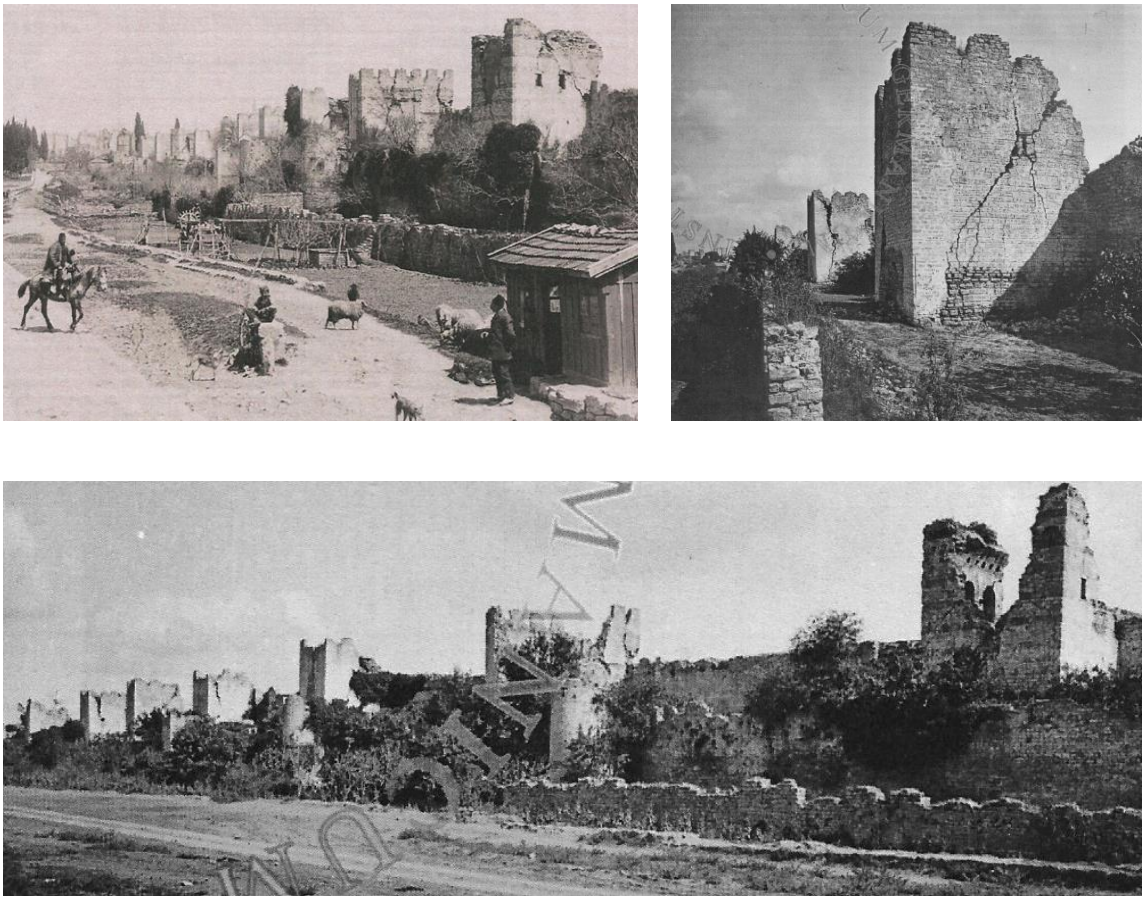


Figure 37. State of decadence of the Theodosian walls in the early 20th century, with clear evidence of unrepaired seismic damages to the towers (German Archaeological Institution, 1939).

torical earthquakes around the Marmara region, showing the extremely high seismicity of the area. The strong Kocaeli-Adapazari earthquake of AD 447 (only 24 years after walls completion), for instance, resulted in the partial collapse of 57 towers and large sections of the walls, and also subsequent major earthquakes (1509, 1719, 1754, 1766 and 1894) caused significant damages to the walls and towers (Ispir et al., 2014). Repairs were therefore undertaken on numerous occasions, as testified by the inscriptions commemorating the emperors or their servants who undertook the restoration works, and most of the surviving towers of the main wall have been rebuilt either in Byzantine or in Ottoman times.

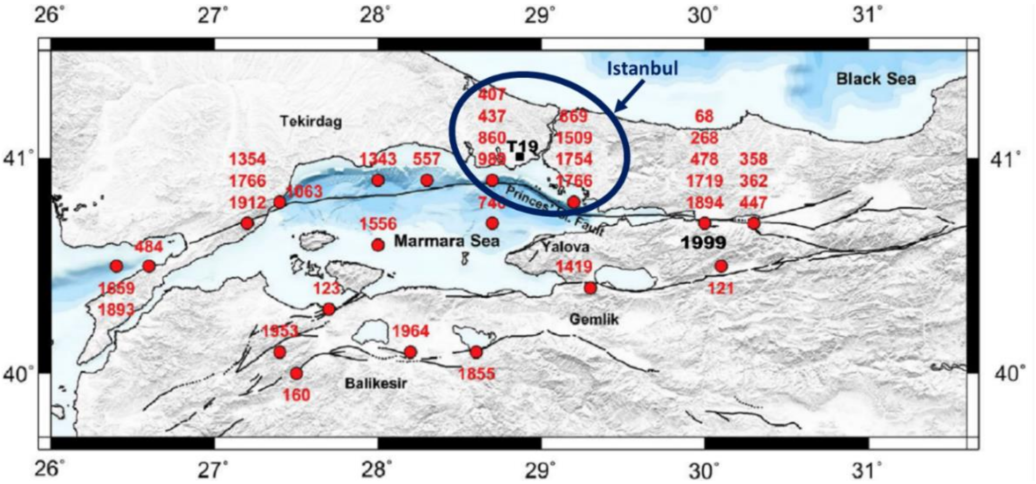


Figure 38. Historical earthquakes in the Marmara region (modified after Ambraseys, 2002), indicated with epicentral position and date. The degrees on the frame indicate North parallels (on the vertical sides) and meridians (on the horizontal sides). The area of modern Istanbul is highlighted, with the position of tower T19.

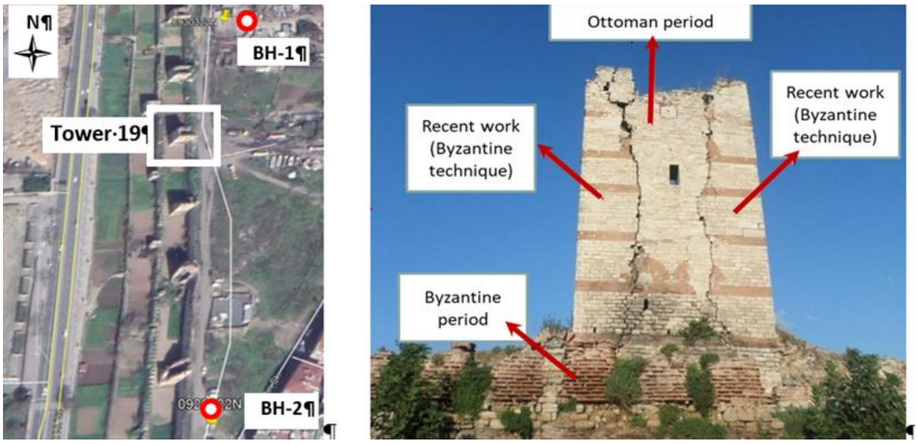
The inner wall, which is connected to the taller towers, has a thickness of ca. 5.00 m and is made of a rubble core confined between two shells built of nicely shaped squared blocks, having a thickness of 30-50 cm (Ahunbay and Ahunbay, 2000). The original, 5th century Byzantine masonry is of a fine quality, with brick bands - approximately 0.40 m high - laid at regular intervals of dressed stones. These bands run through the entire thickness of the wall, binding the structure firmly at different levels. The blocks used for the inner towers and wall in the original fifth-century construction are made of sandstone, quarried close by. The original mortar was a mixture of lime, crushed bricks and bricks powder. In subsequent restoration works, lime-based mortars were used as well.

While until the end of the 12th century the reconstructions largely replicated the original model, later modifications introduced a clear change, from both the formal and the construction point of view, and the strengthening brick bands were not used any more. Since the nearby quarries run out in the Byzantine period, after the 12th century the blocks used to restore walls and towers had different origin and had a much more irregular shape. Because of all these reasons, the resulting masonry structure was less refined and certainly less stiff.

UNESCO’s designation of this defensive system as a World Heritage site in 1985 resulted into an extensive, large-scale restoration and conservation program, still under way. On the towers, the restoration works consisted in cleaning them from the vegetation and rebuilding the masonry structure, trying to replicate wherever possible the original Byzantine style. Most times, the walls and towers were over-restored and refaced rather than being repaired, possibly destroying many historical evidences.

The strong 1999 Kocaeli earthquake, whose epicentre was located about 80 km south-east of Istanbul, caused major damages to parts of the walls and to some towers. Interestingly, in some cases the damages were larger on the towers that had already undergone restoration works. As quoted by Turnbull (2004), prof. Zeynep Ahundbay (chair of Historic Preservation at Istanbul Technical University) said after the 1999 earthquake: ‘*The restoration campaign of the 1980s has been criticised due to its resort to the reconstruction of ruined towers and gates instead of* *stabilising and consolidating dangerous structures. The performance of the 20th century repairs during the recent (1999) earthquake …omissis… constitutes a good lesson for future restoration*'.

Indeed, words to be reminded. Because of the symbolic heritage carried by this impressive, iconic defensive system, a contribution to interpret the dynamic behaviour of the walls and towers was recently attempted (Flora *et al.*, 2021, Somma *et al*., 2022) with the precise goal to plan better preservation actions for the future, cooling down what seems to be an endless game between men and nature. The attention was initially focused on one rectangular tower (tower T19), located on the south side of the land walls, close to the Marmara Sea and between the Belgrade and Golden Gates (Fig. 35). It is one of the tallest towers connected to the inner walls, restored in the early 1990's, thus before the 1999 Kocaeli earthquake struck Istanbul. Different construction and restoration techniques are now superimposed on it (Figs. 39 and 40) (Sarimese, 2018): the lower part is still made of original Byzantine masonry, while the upper part is only partially (in the centre of the west side) made of the Ottoman one. The recent restoration works completed the tower in the original Byzantine style. As a consequence, the brick bands do not completely bound the structure. The earthquake largely damaged the tower, causing the opening of cracks at the connection between the reconstructed and the Ottoman masonry (Fig. 39b) on the west side, typical diagonal cracks on the windows on the south side and the collapse of the whole east side and of upper corners wedges.



(a) (b)

Figure 40. (a) Position of tower 19 with indication of nearby bore holes (BH-1 and BH-2) and (b) recent picture of the west side of the tower. The different, superimposed construction techniques can be clearly seen: the original Byzantine one (before 12th century) in the lower part, the later Ottoman one in the central part, without brick bands, and on the sides the restoration works carried out with the Byzantine technique, using the brick bands (Sarimese, 2018). The damages caused by 1999 Kocaeli earthquake are clearly visible.

Figure 40. Recent views of all sides of tower 19. The damages caused by 1999 Kocaeli earthquake are clearly visible.

4.2 *The contribution of geotechnical engineering: avoid preservation mistakes*

Clearly, all the restoration work was lost in what cannot be considered an unexpected natural event. To carry out a simulation of what has happened in 1999, detailed laboratory and in situ investigation was carried out (Figs. 41 and 42), and the closest recorded outcrop motion (Fatih station, 4.8 km away) was deconvolved at the bedrock, using the soil profile and properties at the Fatih station site (Ince, 2008), and then considered as the seismic input at the bedrock of the tower T19 site (Flora *et al*., 2021).

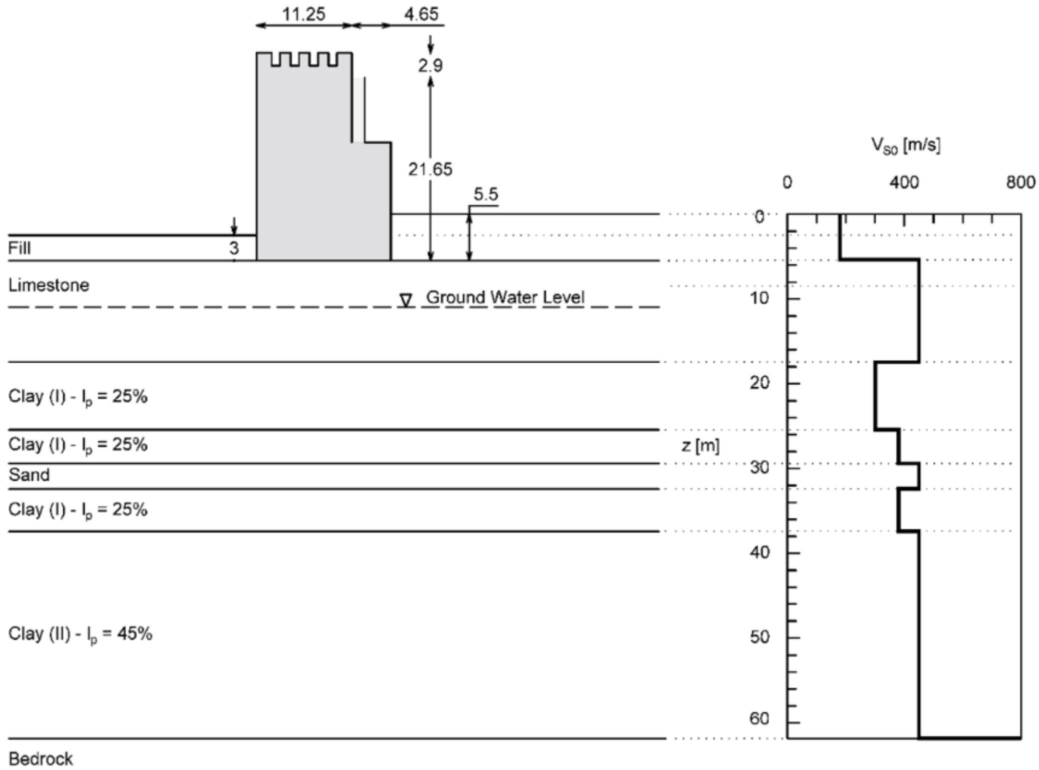


Figure 41. Soil and V_s profiles at the site of tower 19 (modified after Somma *et al*., 2022).

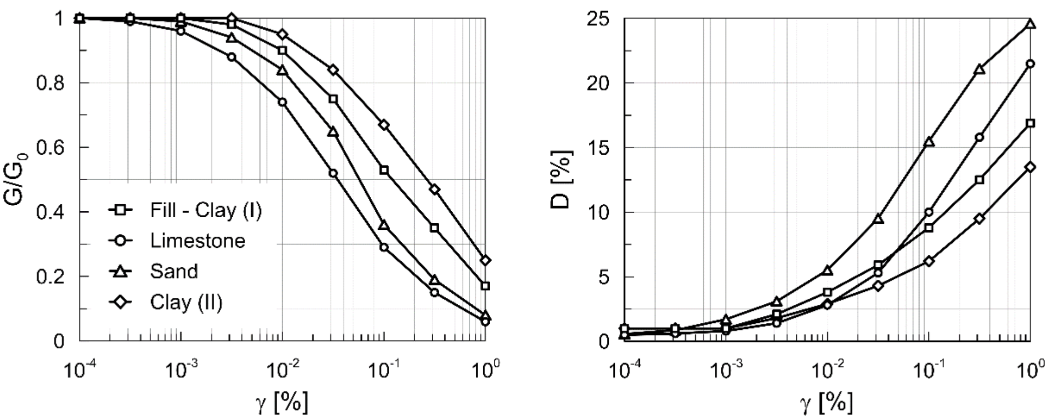


Figure 42. Shear modulus and damping ratio curves for the different soil layers (modified afterFlora *et al*., 2021).

Seismic site response analysis shows a relevant amplification effect, with a fundamental frequency of the subsoil of 1.55 Hz (Fig. 43a), close to the predominant frequency of the Kocaeli signal (1,85 Hz, Fig. 43b), indicating the occurrence of resonance. Thus, the remarkable amplitude of the Fourier spectrum close to this frequency is not a startling result, with a value of the calculated PGA as high as 0.34 g.

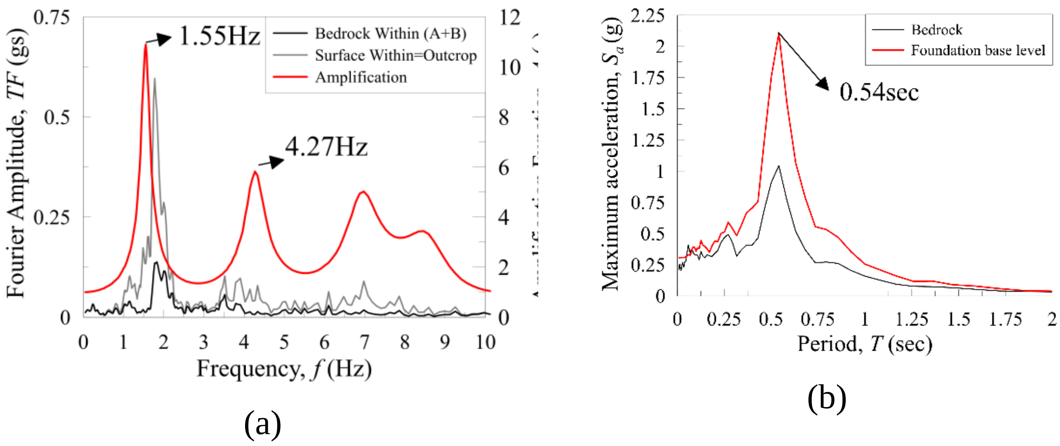


Figure 43. Fourier (a) and acceleration (b) response spectra compared with the input motion applied at the base (bedrock) of the soil profile (Somma *et al*., 2022).

3D dynamic numerical analyses were carried out to interpret tower T19 behaviour during the 1999 earthquake (Figs. 44 and 45), considering soil-structure interaction (SSI) or a fixed base, an equivalent linear elastic or a non-linear elastic-plastic behaviour for the subsoil and the tower. The tower was modelled considering two extreme scenarios, i.e. a less stiff Ottoman style masonry (M1) and a stiffer Byzantine style masonry (M2), being the real structure composed of both. The seismic input was separately applied in the x or y directions, defined respectively as the longitudinal and transversal axes of the wall (Fig. 44).

The details of the analyses are reported in Somma *et al*. (2022). Fig. 46 indicates that the existence of a relatively stiff layer of limestone underneath the foundation reduces the effect of dynamic soil-structure interaction; therefore, the natural period T of the tower shows relatively small increments considering the more realistic, compliant scenario (i.e. with SSI). However, being on the raising part of the response spectrum, even a small increase of T may correspond to a relevant increase of the seismic demand, as extremely evident in the x (less stiff) direction for the Ottoman (M1) masonry (top left of Fig. 46), for which the seismic demand is the highest possible (peak of the spectrum). Therefore, this is a typical case in which neglecting SSI would not be conservative and would lead to an underestimate of the seismic action on the tower even if the tower is founded on a relatively stiff material.

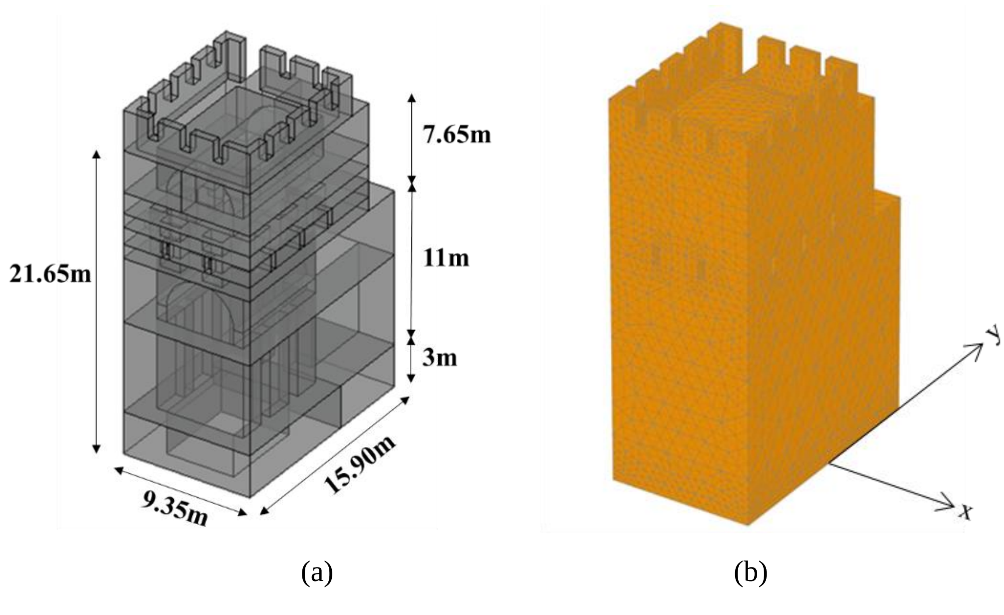


Figure 44. Tower 19: (a) geometric model and (b) Plaxis3D mesh (x=wall’s longitudinal axis; y=wall’s transversal axis).

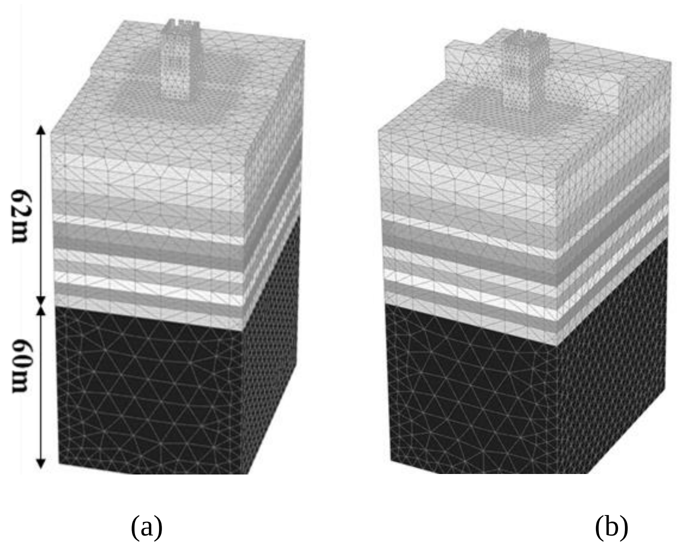


Figure 45. Plaxis3D model of the subsoil with Tower 19 considering (a) or neglecting (b) the inner wall.

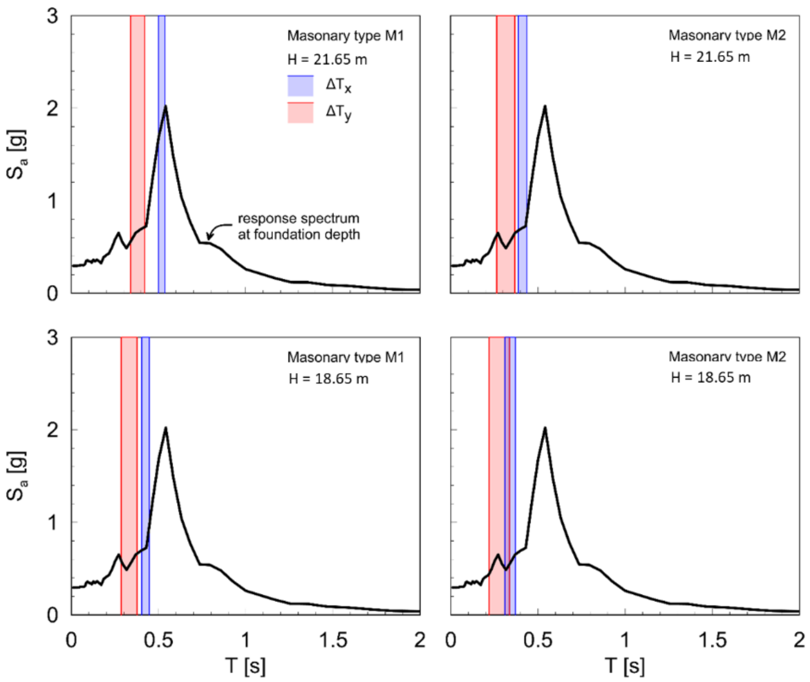
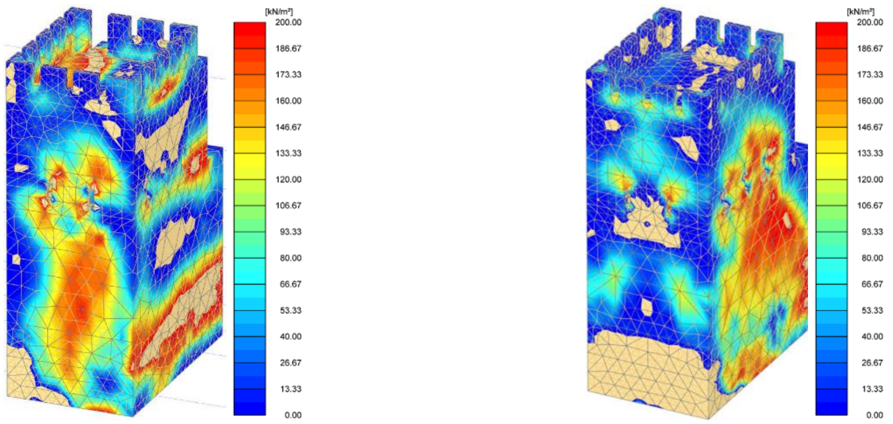


Figure 46. Equivalent elastic analyses: tower 19 seismic demand considering or neglecting dynamic soil-structure interaction in the two directions x and y, for both types of masonries (M1 and M2) and for different ways to consider the height of the mass centroid: at the foundation level (H=21.65 m) or at ground level (H=18,65). Period elongation indicated by the coloured bands (see legend on top left) (modified after Somma et al., 2022).

However, Fig. 46 also shows that the seismic demand of tower T19 is for the Kocaeli earthquake always very high, whatever the considered scenario and earthquake direction.

The effect of seismic shaking is also shown for the non-linear analyses in terms of maximum principal tensile stress shadings in Fig. 47, indicating that tensile strength (200 kPa) is reached in large areas, the red shading suggesting possible critical failure mechanisms, mostly concentrated below the first floor and at the first floor itself. These mechanisms are certainly consistent with the ones that took place in 1999 and largely damaged the freshly restored tower (Fig. 40). Despite unavoidable uncertainties and simplifications (taken into account considering different



(a) (b)

Figure 47. (a) Contours of principal maximum tensile stresses for tower 19 (compliant base, masonry M1): (a) seismic action in the x direction; (b) seismic action in the y direction.

scenarios), all the results demonstrate that the partial collapse of tower T19 during the Kocaeli earthquake is not a surprise, being just the repetition of an event happened several times since Theodosian walls construction in the fifth century. Similar considerations could be done on the other towers damaged during the same earthquake, with differences among them linked to different site amplification effects on the seismic demand.

Then, the question to ask is what to do to step out of this reconstruction and destruction game between man and nature. From the geotechnical engineering point of view, the idea of using a Geotechnical Seismic Isolation (GSI) solution is intriguing, because it is the best way to avoid touching the structure to be protected, thus limiting to a minimum the interference with the heritage carried out by it. GSI technologies may aim to either reduce or increase soil rotational and translational stiffnesses, to increase damping or to add some soil mass to the system. All these actions modify soil-structure interaction, either reducing or increasing the natural period of the structure (the choice therefore depending on the response spectrum of interest and on the original structural period T), and can be achieved with a number of technologies (e.g. Flora *et al.* 2018). However, because of the high seismicity of the Istanbul area and of the poor structural qualities of tower T19 (and of the others as well), GSI by itself would not be sufficient.

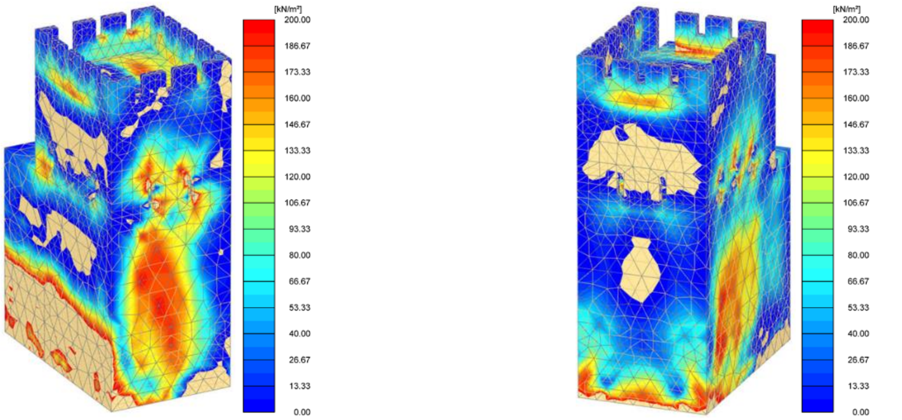
This is confirmed by the results of the analyses carried out considering two simple and opposite GSI interventions: (i) lateral disconnection of the structure from the soil to the foundation base; (ii) stiffening of the soil around the tower, to be obtained with partially overlapped jet grouted columns. The previous approach is extremely simple and respectful, and has the goal to reduce the rotational stiffness of the soil-foundation system (with the trade-off of reducing also radiation damping); the latter has the opposite goal of increasing the rotational stiffness. Tab. 3 reports the results of the visco-elastic analyses, clearly indicating that for the Kocaely earthquake only a stiffening GSI intervention would have been of some help for the structure, be-

Table 3. Results of the visco-elastic analyses considering the effect of 2 GSI interventions. The variation of spectral pseudo-acceleration Δa is referred to the fixed base scheme (Somma *et al.*, 2022).

model SSI conditions	earthquake direction	masonry M1 T (s)	masonry M1 a(T) (g)	masonry M1 Δa (g)	masonry M2 T (s)	masonry M2 a(T) (g)	masonry M2 Δa (g)
fixed base	x	0.49	1.60	-	0.39	0.69	-
compliant base	x	0.50	1.75	+ 0.15	0.41	0.72	+ 0.03
foundation lateral disconnection	x	0.56	1.86	+ 0.26	0.46	1.19	+ 0.50
lateral soil stiffening	x	0.40	0.70	- 0.90	0.31	0.50	- 0.19
fixed base	y	0.33	0.58	-	0.26	0.54	-
compliant base	y	0.36	0.63	+ 0.05	0.31	0.55	+ 0.01
foundation lateral disconnection	y	0.38	0.68	+ 0.10	0.33	0.56	+ 0.02
lateral soil stiffening	y	0.29	0.54	- 0.04	0.24	0.50	- 0.04

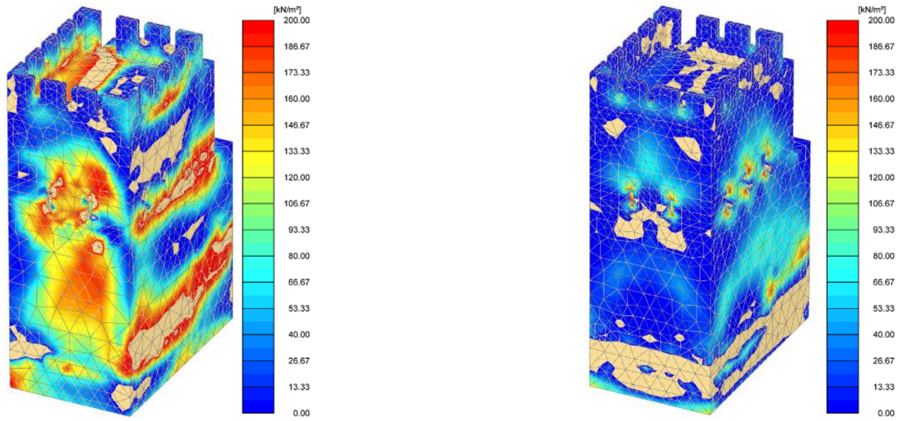
cause in this case (very shallow foundation, stiff layer underneath) the lateral disconnection is not sufficient to increase the period T in such a way to pass over the peak of the response spectrum, reducing the seismic action.

Similar considerations can be done looking at the results of the non-linear analyses in terms of the maximum principal tensile stress shadings on the tower, considering the two possible GSI solutions (Figs. 48 and 49). Soil stiffening is beneficial, but not sufficient.



(a) (b)

Figure 48. (a) Contours of the principal maximum tensile stresses in the laterally disconnected tower in x-direction at 5.60 s; (b) Contours of the principal maximum tensile stresses in the laterally disconnected tower in y-direction at 7.05 s.



(a) (b)

Figure 49. (a) Contours of the principal maximum tensile stresses in the laterally stiffened tower in x-direction at 7.92 s; (b) Contours of the principal maximum tensile stresses in the laterally stiffened tower in y-direction at 6.72 s.

Then, in this case there is no alternative to some strengthening of the structure. From a methodological point of view, after investigating less invasive possibilities, this is certainly consistent with preservation principles, as also explicitly suggested by Brandi himself (1963) with reference to the mitigation of seismic risk for built heritage. There are many literature indications on the best way to do so (e.g. Cosenza & Iervolino, 2007), and possible alternatives will be taken into account in the future (mitigation of the pushing effect of the vaults, improved interaction between orthogonal walls, improved connection of wall portions built in different periods, strengthening of the weaker portions), discussing about them with structural engineers but also with experts from other disciplines. Obviously, when passing from the back analysis of a single event to the design of future preservation interventions, a probabilistic approach will have to take the place of the deterministic calculations herein reported to back-analyse the effects of the 1999 Kocaeli earthquake.

5 FINAL CONSIDERATIONS (FAR FROM BEING CONCLUSIONS)

The tumultuous development in the last decades of the investigation and monitoring instruments, as well as of the theoretical and numerical tools, has certainly widened the range of options in the hands of engineers when dealing with the preservation of built heritage. When the structure shows wounds of geotechnical origin, these arrows in the quiver should inform the approach, that should concentrate as a first step on the subsoil itself, to understand the causes and possibly to restore equilibrium conditions in the soil or rock mass, lost for a number of possible changes of the boundary conditions. Only if such solutions are not available should the engineer touch the structure to protect. No action should be undertaken without thorough understanding, and the principle of necessity should always be the guiding light. This is possible only if monitoring and surveying, that should be considered as mandatory prevention measures, keep feeding information and alert against critical events.

New technologies should not be considered as enemies of cultural heritage, but their implementation should be taken into account only after a hierarchic analysis of all possible alternatives, that should start by considering the adoption of the original technological choices, consistently with the indications given in Fig. 1. In any case, dogmatism should be avoided, being important to save what can be saved in the range of our possibilities, with the highest possible attention to regional traditions of preservation (Petzet, 2004).

In the examples reported in this paper, different geotechnical solutions could be found with the goal of preserving heritage. Partially or highly invasive interventions were also taken into account, when considered necessary. While the reductionistic approach in which civil engineers have been raised is a powerful tool in the solution of most practical problems, the examples show that it may not be suited to face built heritage, for which more sophisticated investigations and analyses are necessary to better catch details that may inform the solution. If it is certainly true that there is no specific geotechnical engineering of monuments and historic sites, we may conclude that there should be a specific need of consistent complexity in the approach to their preservation, for which cost effectiveness should not be the main concern.

Engineers should always face the preservation of built heritage with reference to a principle of responsibility - or rather to an imperative of responsibility, according to Hans Jonas (1984) -, which represents an updated version of Kant's categorical imperative '*act so that the consequences of your actions are compatible with the permanence of an authentic human life on earth*'. Paraphrasing this categorical imperative, we could say to the civil engineer: act in such a way that the consequences of your actions are compatible with the permanence of an authentic life of the historic structure or site on which you operate. When in doubt, we may add, do nothing; and if you have to exceed, exceed in caution, intended not as safety but as preservation.

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