The *Crypta Neapolitana*: a Roman tunnel deserving new life

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ABSTRACT

This paper outlines a technical stability assessment for the Crypta Neapolitana, a historic Roman tunnel passing through the Posillipo Hill in Naples. The research emphasizes the importance of functional integrity in heritage preservation, suggesting that a monument's original purpose should inform modern conservation strategies. The work is based a geotechnical analysis of the materials surrounding the 711-m passage, including yellow tuff and a transition pyroclastic layer. Through an examination of the tunnel historical evolution from antiquity to the 20th century, the study tracks structural changes such as lowering the floor level and later backfilling. Ultimately, the work seeks to establish a framework for safely re-opening the ancient corridor by evaluating its static conditions. These findings aim to balance the tunnel's iconic value with practical strategies for material repair and long-term preservation.

Keywords: heritage tunnel, stability assessment, conservation.

INTRODUCTION

In the field of heritage engineering, one often struggles with the definition of "authenticity". To identify the characteristics of interventions compatible with the historical and cultural significance of the works covered by this study, reference can be made to the Restoration Charters. In the Athens Charter (1931) the experts approved the use of all the resources of modern technology for the preservation of ancient buildings, provided that the reinforcement be concealed so as not to alter the appearance and character of the building to be restored; and they recommended their use to preserve the structural elements, avoiding the risks of demolition and reconstruction. The Venice Charter (1964) specified that when the traditional techniques prove to be inadequate, the restoration of a monument can be "*ensured with the aid of all the most modern means of structure and conservation, whose efficiency has been demonstrated by scientific data and guaranteed by experience*". The Italian Restoration Charter (1972), finally, permits "*additions of accessory parts with a static function and restoration of small historically verified parts, carried out, as appropriate, either by clearly defining the outline of the additions or by using different but matching material that is clearly distinguishable to the naked eye, particularly at the points of connection with the ancient parts, and also initialled and dated where possible*". It also permits "*modifications and new insertions for static and conservation purposes in the internal structure or substrate or support, provided that, after completion of the operation, there is no alteration in appearance, either chromatic or in terms of the material, as observable on the surface*". In the context of the Venice Charter (1964) and the more recent Nara Document (1994) and Krakow Charter (2000), the conservation of an old heritage monument is a matter of careful discussion concerning its "authenticity", that often requires a correct definition of its originally conceived life cycle, hence its function. In fact, although the conventional assessment framework usually considers the material, the iconic and the historical integrity as goals for preservation, the functional integrity of the monument, as one of the elements defining the role of the monument in its environment, should be part of it. In this framework, ground reinforcement with new technologies, that can be classified as a "modern renovation" resulting at an intermediate level of iconic integrity (Flora, 2022), should not be excluded, especially if it contributes to keep the built heritage "alive", that is "with the highest functional integrity".

As an example of a possible application of the concept of "functional integrity" to the preservation of a monument, the paper presents the case of a heritage Roman tunnel – the *Crypta Neapolitana* – within the Archeological Area of the Tombs of Vergilius and Leopardi in Naples (Italy), that is currently closed to public access for safety issues, due to ground instability potentially leading to small local rockfalls.

THE HERITAGE TUNNEL: A STRATEGIC ROMAN MASTERPIECE

Commissioned in the 1st century B.C., the *Crypta Neapolitana* was a direct subterranean passage connecting the vital commercial hub of Puteolis (Pozzuoli), at that time the largest port in the western Mediterranean Sea, with the growing town of Neapolis. The tunnel stands as a testament to the brilliance of the Roman engineer Lucius Cocceius Aucto. Its original bore was approximately 4.5 m wide and 3.5 m to 4 m high. Before Cocceius, travellers were forced onto the via Antiniana (the *via per colles*), a route in use since 194 B.C. The tunnel eliminated the punishing climb over the ridges, providing a level, efficient alternative that fundamentally transformed local logistics. The rock layer of the Posillipo hill provided the backbone for this masterpiece, but the subsequent two millennia of human ambition performed a series of radical surgeries on the tunnel's anatomy. In fact, the history of the Crypta is defined by a series of vertical shifts that have seen the floor level lowering into the depths of the hill and then rising again through backfilling. For about 1,500 years, (1st Century B.C. – 15th Century AD) the tunnel remained structurally sound and stable. In the 15th century, Alfonso d'Aragona widened the section and lowered the floor by 3 m. Furthermore, he reactivated the two original Roman aerators ("*occhi di luce*"), which had become obstructed over time. A turning point was reached in the 16th century, under Don Pedro de Toledo, when a radical deepening was carried out. At the Piedigrotta (East) entrance, the floor was lowered by over 11 meters (reaching a total depth of -13m relative to the starting point). This geometrical "*trauma*" triggered the tunnel's first major collapses. Repairs started immediately (17th – 19th century): Pedro Antonio d'Aragona initiated repairs to the walls and flooring. Later, Carlos III de Borbón implemented a massive structural intervention: the construction of pointed masonry arches in tuff, over one third of the tunnel's length. However, the instability phenomenon was not arrested and some of the arches collapsed, until the 20th century when the Naples Municipality raised the floor by 9 meters using anthropogenic fill (Figure 1). Meanwhile, since the tunnel section was not suitable anymore for the growing traffic generated in the city, new modern road and railway tunnels were constructed nearby to provide the transit by also by tram, cars and, later, trains through the hill (Figure 2) and the Crypta was dismissed and finally closed to transit. Recent decades have seen the addition of protective steel ribs to prevent rockfalls at the Western portal and restoration of a few pointed arches on the Eastern portal.

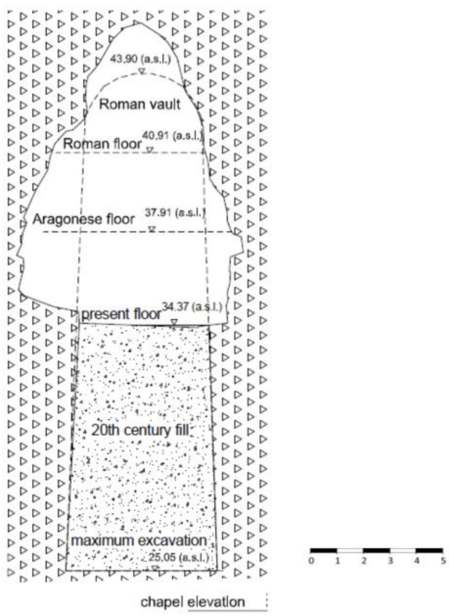

Figure 1. *Cross section of the Crypta Neapolitana 20 m inside the eastern entrance: current state and reconstruction of the different elevations of the floor in time (modified after Amato et al., 2000).*

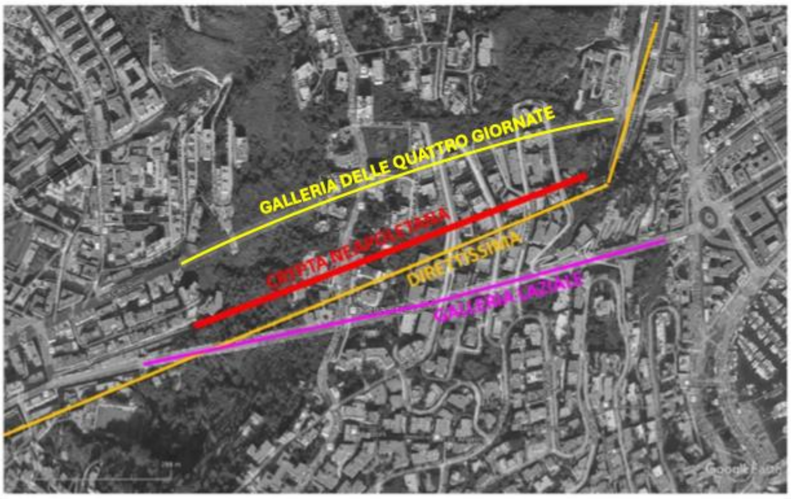

Figure 2. *Modern tunnels around the Crypta Neapolitana. The "Galleria 1894", later named "Galleria delle Quattro Giornate" was the first to be constructed in substitution of the Crypta.*

THE GEOLOGICAL SETTING

As mentioned, the Crypta Neapolitana is located inside the Posillipo hill. The latter, based on geological studies, has a highly uniform structure and consists of a core of yellow tuff, known as Neapolitan Yellow Tuff (NYT), a material with moderate mechanical characteristics and a low degree of fracturing and alteration. The NYT originated from the Fuorigrotta eruption, it is overlaid by a blanket of loose pyroclastic materials and rests on a base material consisting of fine-grained grey cineritic materials with the presence of pumice. Immediately in contact with the NYT is the presence of a very fine material that is highly diagenised to the point of resembling a stone rock (Nicotera, 1950). The presence of this diagenised pyroclastic material, which has very poor mechanical characteristics, has always been overlooked, attributing to it the same nature as the deeper tuff of the Chiaia eruption, while in this study it has been identified as a "transition layer" among the two tuff formations. The Crypta Neapolitana develops precisely in the band of lithotypes composed of soft rocks (NYT) and diagenised pyroclastic materials (transition layer). In particular, at the portals, the tunnel is dug into the NYT, whose roof slopes steeply down the sides of the hill. By cross-referencing the data provided in the literature and the geotechnical investigation performed in more recent years, it was possible to better define the ground conditions in the longitudinal section, as shown in Figure 3. In the figure, the presence of the transition layer with an irregular altimetric trend can be noticed, that affects the Western stretch of the Crypta in particular. The result of backfilling can be also noticed in the Eastern part.

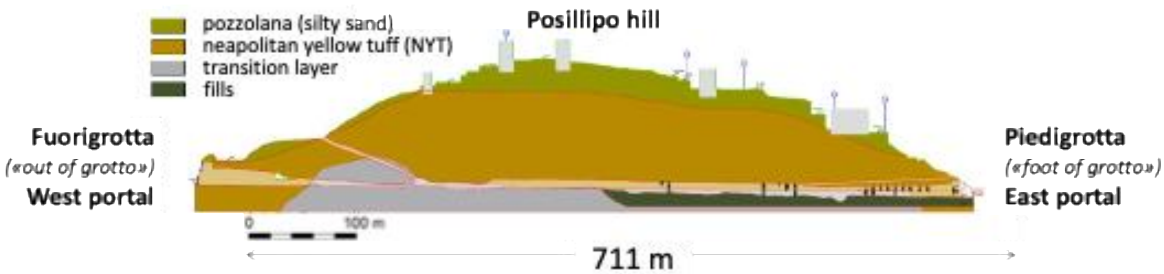

Figure 3. Longitudinal section of the Posillipo hill along the Crypta longitudinal axis, with indication of the geological units

STABILITY ASSESSMENT

Geotechnical investigation

All the data available from previous in-situ investigations were gathered to check the static conditions of the tunnel. The investigations campaign consisted in boreholes from the ground surface and core drillings from within the tunnel, as well as geo-structural survey to rate the rock mass and flat jack tests carried out in some sections of the tunnel to quantify the in situ vertical stress. The uniaxial compressive strength, σ_c, of the rock surrounding the cavity was measured on intact specimens from cores. While σ_c up to 6 MPa, and around 3 MPa on average, was found around both portals, for most of the tunnel length the compressive strength is on average 2 MPa, being even lower (around 0.5 MPa on average) along a stretch about 70 m long. Such variability can be attributed to the different layers of rock (NYT or transition) that are found along the tunnel axis. The geo-structural survey led to assess values of RMR_{76} generally ranging between 50 and 70, with some local drops. GSI was assumed equal to RMR_{76} (Hoek 1994). The results are summarised in Figure 4. The comparison of the measured σ_c values to the vertical stress level in the rock, estimated with flat jacks, indicates that, for distances from the Western entrance between 100 m and 200 m, the rock surrounding the cavity is locally yielded, consistently with the evidence of diffused collapse. It is worth noting that a stretch of about 300 m (from x = 300 m to x = 600 m) is missing in the plot in Figure 4, due to the inability to move boring rigs on a largely disrupted floor.

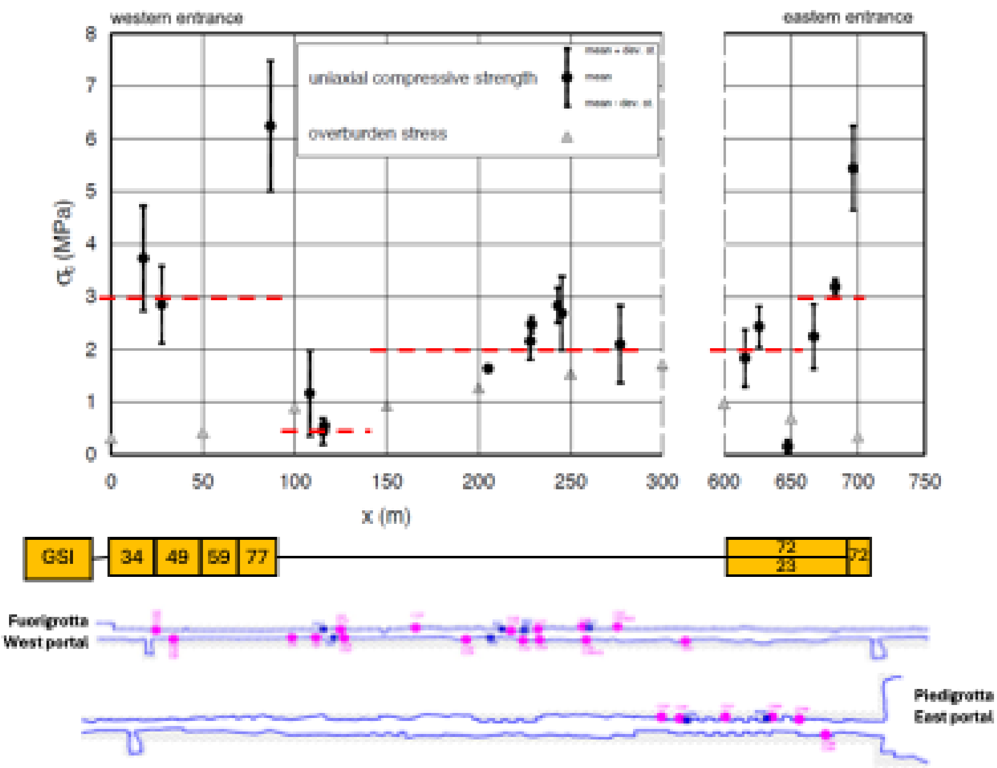

Figure 4. *Values of rock uniaxial compressive strength and in situ stress along the axis of the Crypta. Distances taken from the western entrance (modified after Amato et al., 2001).*

The strength of the rock mass was modelled using the Hoek & Brown (H&B) non-linear failure criterion, according to the values of $\sigma_{c,i}$ (uniaxial compressive strength for intact rock) shown in Figure 4, assuming the constant m_i (for intact rock) equal to 13 and using suitable values of *GSI*. An equivalent Mohr-Coulomb linear failure criterion was also defined, converting the H&B parameters into equivalent cohesion, *c*, and friction angle, φ. Young's modulus E values were also obtained by using empirical correlations [(Hoek and Brown, 2019).

Numerical procedure

Elastic-perfectly plastic 2D analyses were carried out with the 2D Finite Element code Plaxis (2024) in a number of transverse sections representative of the variable geometrical configuration along the tunnel.

The history of excavation, further lowering and backfilling has been simulated to establish, as better as possible, the current state of stress around the cavity sections and to back-analyse the value of GSI representative of the rock conditions before the collapses occurred (in fact, this may differ from the current rock conditions). Hence, the safety level has been assessed by a “strength reduction” analysis, that is a common numerical procedure that consists in progressively reducing the original shear strength of the materials. A typical result is shown in Figure 5.

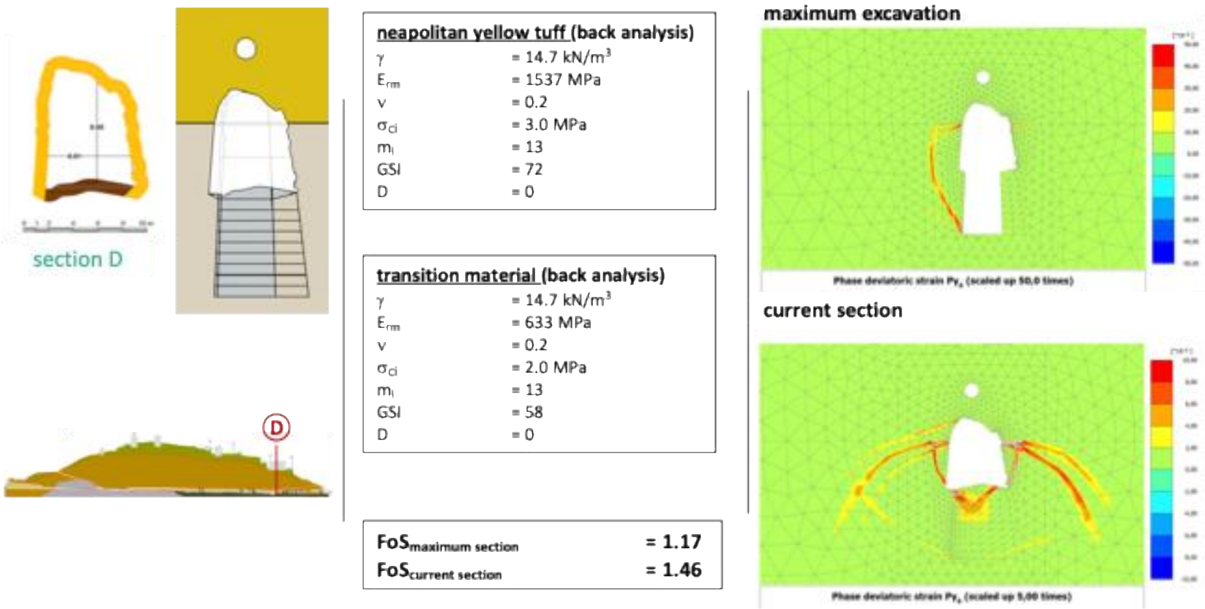

Figure 5. *Typical results: the geometrical changes of section D along time (including rock block falls) summarised in the scheme of Figure 1 were simulated. The value of the Factor of Safety (FoS) of the cavity at its maximum size and in the current configuration are obtained.*

A summary of the calculated values of FoS in five sections of the tunnel, with linear (MC) and non-linear (HB) yielding criterium is shown in Figure 6. It may be noticed that the two sets of FoS are consistent with each other. The highest value of FoS corresponds to a section at the Eastern portal, where the tunnel is entirely excavated within the NYT with high values of both $\sigma_{c,i}$ and *GSI*. Otherwise, FoS ranging between 1 and 1.5 have been calculated in most sections, indicating stable to barely stable conditions. It is worth noticing that a significant stretch of the tunnel is excluded from this assessment, which suffered significant disruption and is not yet characterized (see x= 300 m to x= 600 m in Figure 4).

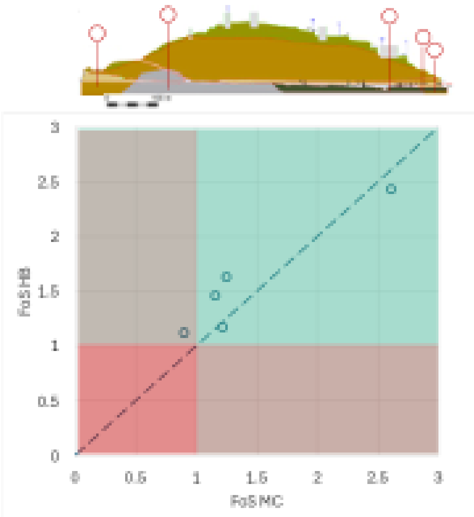

Figure 6. *Calculated safety factors (MC vs. HB) in five representative sections*

CONCLUSIONS

Since the Roman age, the Crypta Neapolitana played a key role in the development of Naples, achieving iconic status in the urban landscape during centuries. It is currently closed to the public for safety reasons due to locally unstable ground conditions. A preliminary assessment of its static conditions provided a clear indication of the need for extensive reinforcement to allow the tunnel to be reopened and reused to connect the two parts of the city across the Posillipo hill. In fact, 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.

Of course, the relevance of the historic site poses several constraints to the restoration of the monument since the conventional assessment framework usually considers the iconic, the material and the historical integrity as goals for preservation. Nevertheless, in the case of the Crypta, largest part of the tunnel has been naturally reshaped because of stress redistribution within the rock mass or later human interventions. This resulted in a loss of the traces of the original Roman cross section that is now mostly lost. Therefore, it seems difficult, if not pointless, to try and replicate the original tunnel in order to restore it to its original use as a connecting route. On the contrary, the respect of its functional integrity should guide its preservation.

The study presented in this paper indicated that most times the critical issue for the stability of the tunnel section is the creation of cracks on the walls and in the vault and the subsequent collapse of blocks. This is consistent with the evidence: local collapses and subsequent reshaping triggered further collapses. It has been shown that it is possible to assess the level of risk of several cross sections along the tunnel and that the safety conditions are quite variable along its length, due to the variable geometrical configuration and the heterogeneous rock conditions.

It looks that the only possible strategy for the preservation of this Roman tunnel requires diffused reinforcement where critical mechanisms may be activated. This can only be justified at the cost of a hard interference with the iconic integrity of the Crypta Neapolitana to respect its functional integrity and return to its role of a mainly pedestrian path.

Should the respect of functional integrity prevail, future interventions may be aimed at removal of small unstable blocks, bolting of large unstable blocks, partial reshaping and insertion of a lining in the central part of the tunnel and supporting the existing masonry arches, in accordance with the most widely recognized restoration guidelines.

ACKNOWLEDGEMENTS

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