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Study on structural monitoring procedures for tunnels

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Abstract

Structural monitoring is a process used to assess stability and performance of structures over time and it consists of a measurement phase followed by a data processing phase. It is mainly applied on infrastructures of significant socioeconomic value, such as transportation networks. In Italy the recent investigation campaign following the legislative actions due to the Morandi Bridge collapse in Genova, has revealed a critical situation nationwide extended, whereby a significant portion of existing post-war infrastructure present such deficiencies that designers and policymakers often must face the decision between their restoration or reconstruction. This situation has made it clear how the almost total absence of monitoring data on the investigated structures, significantly limits the ability to define their effective health status. In such a context, it is essential for each structure, whether new or existing, to be equipped with a monitoring system suitable for the specific boundary conditions and aligned with technological advancements.

In this thesis work, following a review about the most used tools for structural monitoring, attention was focused on the analysis of geotechnical structures behaviour, particularly tunnels. It is believed that the complexity and high degree of uncertainty associated with these structures make the study of an effective monitoring system even more significant. In underground works, boundary conditions can vary over time and space due to numerous phenomena related to the intersection with different geological formations frequently unexpected.

These aspects may require interventions capable to restore the reliability level defined by the original design, but only an adequate monitoring system allows for the recognition of any anomalies and early determination of the most suitable solution. By conducting finite element modelling of tunnels with different imposed boundary conditions, it was possible to analyse the structural behaviour of the linings in terms of displacements and deformations. The results allowed to investigate what is the most appropriate quantities to monitor in order to ensure the safety during construction and operational phases as well. Considering the sensitivity of the most used instruments for structural monitoring, deformation in the linings has proved to be the most sensitive parameter to variations in boundary conditions. Therefore, its measurement is well-suitable for monitoring the structural health status and achieving an effective early warning system.

Further study in this thesis has focused on the potential future scenarios associated with the continuous technological development. Nowadays, sensor components and complex algorithms are becoming increasingly accessible at reduced costs. As a result, there is a noticeable possibility of achieving a substantial automation level that can make measurements and subsequent data processing smarter. A direct consequence of such a monitoring system would be the creation of easily accessible data archives playing a prominent role - even with reference to BIM environment - in decision-making processes associated with the structures lifespan. These innovations would provide valuable cost savings for contracting authorities and/or executive companies, as well as an overall safety enhancement.

Riassunto

Il monitoraggio strutturale è un processo che permette di valutare la stabilità e le prestazioni delle strutture nel tempo e si compone di una fase di misurazione seguita da una fase di elaborazione dei dati. In Italia, la recente campagna di indagine che ha fatto seguito alla spinta legislativa successiva al crollo del ponte Morandi, ha permesso di portare alla luce una situazione critica estesa a livello nazionale, tale per cui buona parte delle infrastrutture esistenti realizzate nel Dopoguerra presentano carenze tali da portare spesso progettisti e decisori politici a dover scegliere tra il ripristino e la ricostruzione delle stesse. Questa situazione ha reso chiaro come la quasi totale assenza di dati di monitoraggio sulle opere indagate renda estremamente più difficile definire il loro effettivo stato di salute. In un tale contesto è importante che ad ogni struttura, nuova o esistente, sia associato un sistema di monitoraggio adatto alle specifiche condizioni al contorno e in linea con i progressi tecnologici.

Nel presente lavoro di tesi, a seguito di una disamina delle tipologie di strumenti utilizzati per il monitoraggio strutturale, è stata posta l'attenzione sull'analisi del comportamento di strutture realizzate in ambito geotecnico, in particolare gallerie. Si è ritenuto che queste ultime, per via della loro complessità e dell'elevato grado di incertezza che le caratterizza, rendano ancor più significativo lo studio di un efficace sistema di monitoraggio. Nelle opere in sotterraneo, infatti, le condizioni al contorno possono variare nel tempo e nello spazio a seguito di numerosi fenomeni legati all'attraversamento di formazioni geologiche

eterogenee e spesso impreviste. Questi aspetti possono rendere necessario intervenire per ripristinare il livello di affidabilità definito dal progetto originario, ma solo un adeguato sistema di monitoraggio permette di riconoscere eventuali anomalie e determinare con il dovuto anticipo la tipologia di intervento più adatta. Attraverso una serie di modellazioni agli elementi finiti di gallerie caratterizzate da diverse condizioni al contorno è stato possibile analizzare il comportamento strutturale dei rivestimenti in termini di spostamenti e deformazioni. I risultati ottenuti hanno permesso di effettuare valutazioni in merito alle grandezze più opportune da monitorare al fine di garantire la sicurezza nella fase realizzativa e nella successiva fase di servizio delle opere. Considerata la sensibilità degli strumenti di misura maggiormente utilizzati per il monitoraggio strutturale, la deformazione nei rivestimenti risulta essere la grandezza più significativa che ben prima di altre risente delle variazioni delle condizioni al contorno e, pertanto, la sua misurazione appare fondamentale per monitorare lo stato di salute e ottenere un efficace *early warning system*.

Ulteriore oggetto di indagine in questa tesi sono stati i potenziali scenari futuri associati al continuo sviluppo tecnologico. Oggigiorno risultano sempre più accessibili componenti sensoristiche e algoritmi complessi a costi ridotti e, pertanto, appare concreta la possibilità di raggiungere un significativo aumento del livello di automazione da sfruttare per rendere *smart* le misurazioni e la successiva elaborazione dei dati. Conseguenza diretta di un tale sistema di monitoraggio potrebbe essere la creazione di archivi dati facilmente consultabili e aventi un ruolo di primo piano - anche in ambito BIM - nelle decisioni che riguardano la vita delle opere. Simili innovazioni garantirebbero un notevole risparmio economico per stazioni appaltanti e/o imprese esecutrici, oltre che un generale miglioramento della sicurezza.

1. BACKGROUND ON STRUCTURAL MONITORING

1.1 Introduction

Structural monitoring is a process for assessing the stability and performance of structures over time. It consists of a measurement phase followed by a data processing phase and is a key step in ensuring the reliability of works, particularly the transportation infrastructure that will be referred to extensively in this thesis work. The latter represents the network of roads, highways, railways, bridges, and tunnels that connect different geographical areas and enable the movement of people, goods and services. Their role is to facilitate mobility and communication, enabling the economic, social, and cultural development of society.

The importance of these infrastructures can be understood by considering the socioeconomic consequences associated with the disruption of one or more of their associated services.

As a result of what has been said, the safety of these works must be considered from the earliest decision-making and design stages, with the drafting of a monitoring plan in which the physical quantities, tools and procedures are defined to assess whether the response of the structures over time follows the behaviors predicted by the design.

Monitoring strategies also provide useful information to optimize maintenance planning for structures in their service phase. To ensure reliable operation and to plan cost-effective maintenance and repair work, it is necessary to continuously monitor and evaluate structural performance and to have an accurate estimate of remaining service life. In this way, the structure can eventually be used beyond its original design life.

To better represent this aspect, which can also be generalized to systems not strictly related to civil structures, reference can be made to Figure 1.1, which shows the trend of a hypothetical structural system health index over time. When a curve intersects the horizontal axis, it means that the system is no longer capable of performing the function for which it was designed. Curve B in Figure 1.1 represents the behavior of an "average" system that follows the design predictions and, therefore, requires replacement or rehabilitation interventions only once its useful life has been reached. Curve A indicates a system that must withstand more severe conditions than those predicted, and Curve C, in contrast, describes a system subject to less demanding conditions than the others. As can be seen in the figure, the absence of a monitoring system leads to two inconvenient situations in opposite aspects: following Curve A, the system is used despite safety risks while, in the case of Curve C, the system will be subject to maintenance without any real need for it.

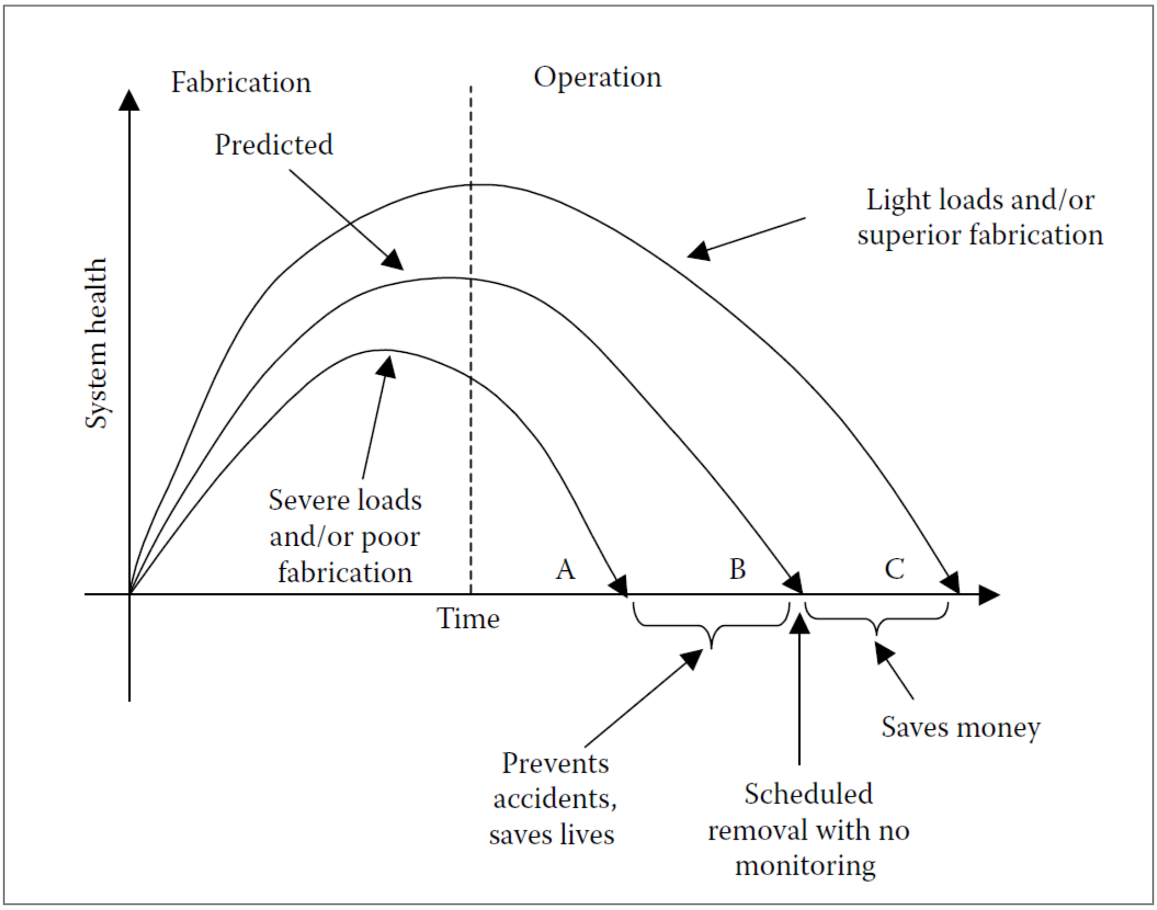

Figure 1.1 Potential utility of system and SHM versus operation without monitoring (Huston, 2010)

With regard to structures built in the geotechnical field, even following thorough investigations, the models developed during design contain uncertainties that, together with the simplifications considered in their realization, result in a residual risk present both during the construction phase and during the operation phase. (Wulf et al., 2014)

In addition, the definition of mechanical and strength parameters for geomaterials is much more imprecise than that for well-known structural materials, as shown in the graph in Figure 1.2.

To still achieve safe and economical designs, the monitoring plan must consider using procedures such as the **observational method**, in which the design is reviewed during the construction phase. In fact, this method allows for optimization of construction and management processes and greatly minimizes risks.

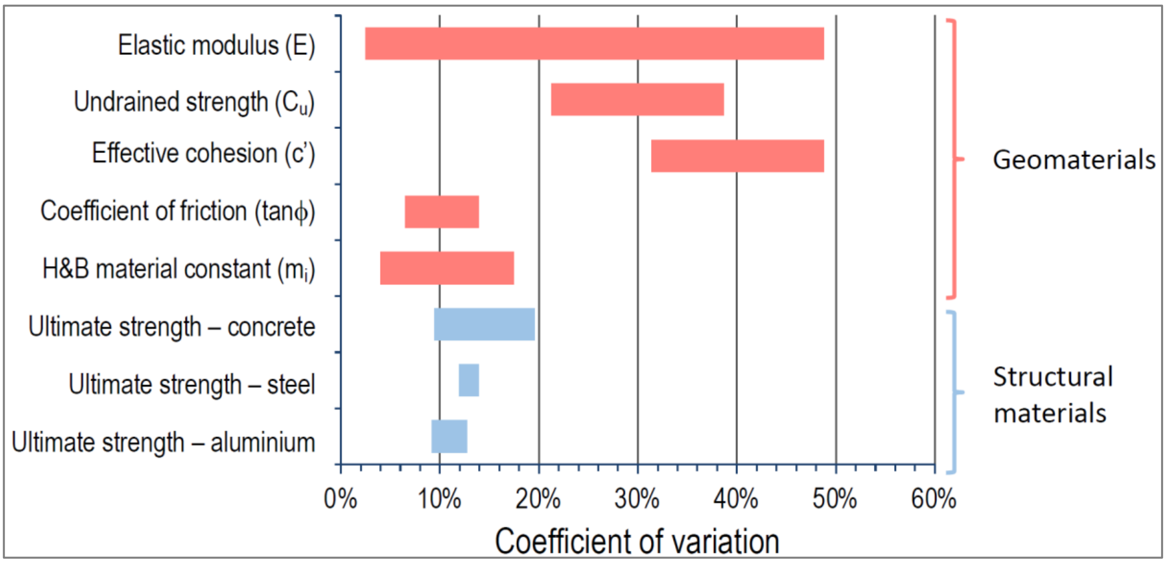

Figure 1.2 comparison between geotechnical and structural parameters

1.2 Sensors and measurements

Structural sensing, structural health monitoring (SHM), structural performance assessment, are all terms that are part of modern structural engineering practice. While in the past the established practice for structural health assessment was visual inspections by qualified engineers, at the present time, thanks to advances over the past two decades, there is a rapidly changing situation with regard to the design, safety management, and maintenance of works. Despite the availability of various sensors for structural monitoring applications, it should be pointed out that considerable uncertainty still exists in choosing the number and locations of devices to be installed in order to obtain optimal information. The first aspect concerns the location of the sensors with respect to the structure. In fact, these can be placed on the surface, embedded within the structure, or placed on it without having any physical contact as shown in Figure 1.3. Cast-in-place or precast linings, for example, are well-suitable for accommodating these devices internally, while in linings composed of steel ribs and spritz beton, a surface installation is preferable. An additional aspect to consider concerns the choice of installation method (bonding, welding, screw fastening), which can be the weak link in the chain by going to interfere considerably with proper measurement. (Huston, 2010)

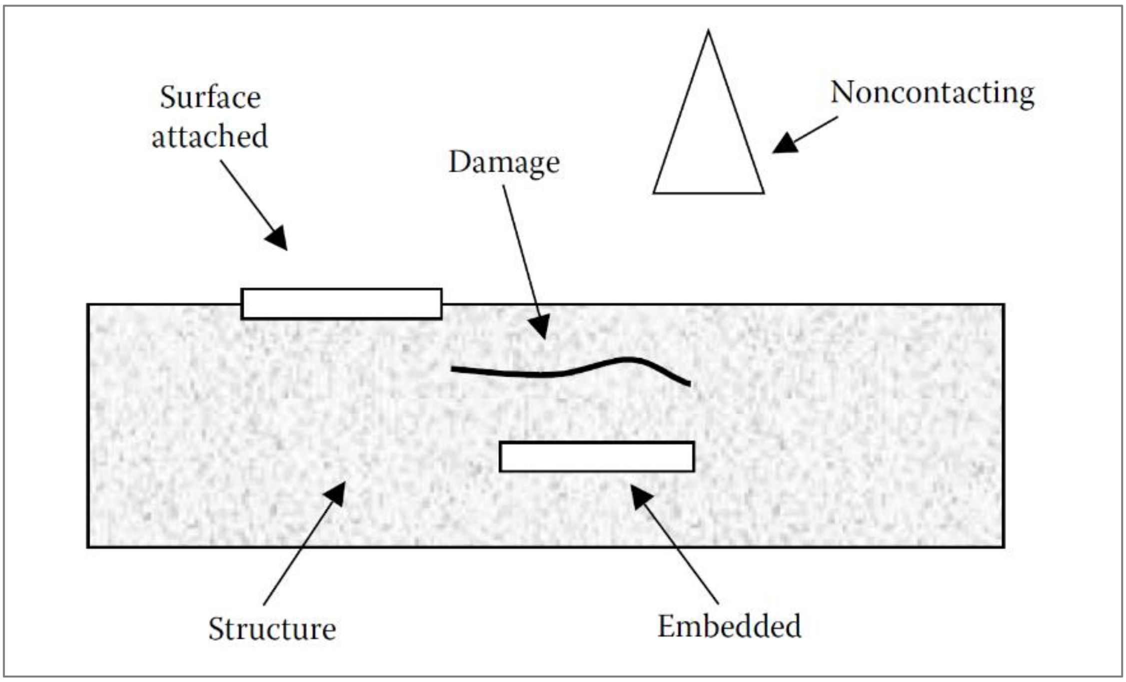

Figure 1.3 Sensor location relative to structures (Huston, 2010)

The most widely used measurement techniques and types of sensors for structural monitoring are presented in Table 1 (Strauss et al., 2020a)

Table 1: Measuring technics and types of sensors used in monitoring of tunnels (Strauss et al., 2020a)

Measured quantity	Measuring techniques and sensors
Linear displacement	Geodetic techniques Mechanical sensors Inductive sensors Vibrating wire sensors Capacitive sensors Eddy current sensors Fiber optics sensors Laser techniques Radar techniques Extensonleters Hydraulic sensors
Angular displacement	Inclinometers Fiber optics sensors MEMS sensors
Strain/stress	Electrical resistance gauges Load cells Fiber optics sensors Vibrating wire sensors Hydraulic piezometers MEMS sensors
Vibration velocity and acceleration	Piezoelectric sensors Capacitive sensors Inertia sensors Inductive sensors Radar techniques Laser techniques Geophysical seismic testing MEMS sensors
Crack opening	Mechanical sensors Inductive sensors Fiber optics sensors Vibrating wire sensors
Degradation processes	Acoustic emission sensors Chloride level sensors Sensors of pH level Corrosion sensors

Due to an extensive literature review, the fundamental quantities for assessing the health of a structure resulted definitely strain variations and displacements. The latter can be associated with phenomena such as increases or decreases in acting loads and temperature variation.

For this reason, tools and measurement methods related to these parameters will be described in the following. Typical methods used for measuring strains include (Wulf et al., 2014)

- resistive strain gauge
- vibrating wire gauges
- fibre optic sensors

Resistive strain gauges are electrical sensors for detecting variation in the quantities just mentioned. These are inexpensive, compact, and reliable devices, and they guarantee a stable output signal. Their operation is based on the change in resistance associated with deformations in the elements of the circuit that compose them, and the latter can be designed to be sensitive to some effects, such as elongation, and insensitive to other effects such as variation in temperature.(Das & Saha, 2018; Huston, 2010)

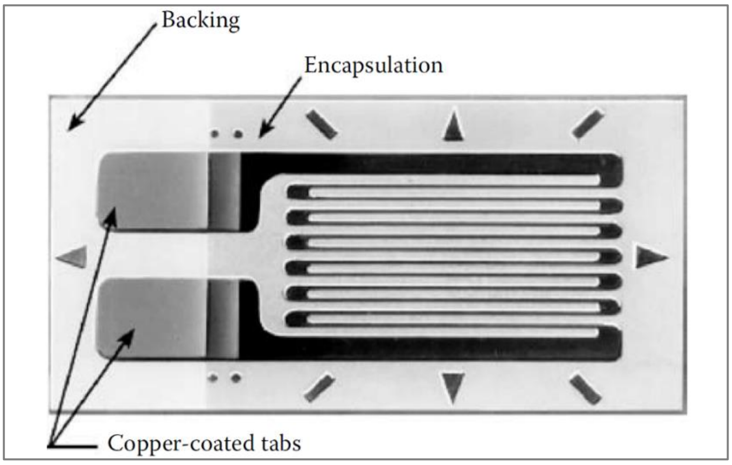

Figure 1.4 Resistive strain gauge (Huston, 2010)

Although they allow for optimal measurements, these sensors are susceptible to corrosion of electrical connections and, therefore, are not ideal for long-term monitoring or in harsh environmental conditions unless appropriate measures are taken to increase their durability.

(Chen & Ni, n.d.)

Vibrating wire strain gauges have become popular in structural monitoring mainly because of their measurement sensitivity. The device consists of a steel wire constrained at the ends and placed under tension, hermetically sealed and coupled with an electromagnetic coil, as shown in Figure 1.5.

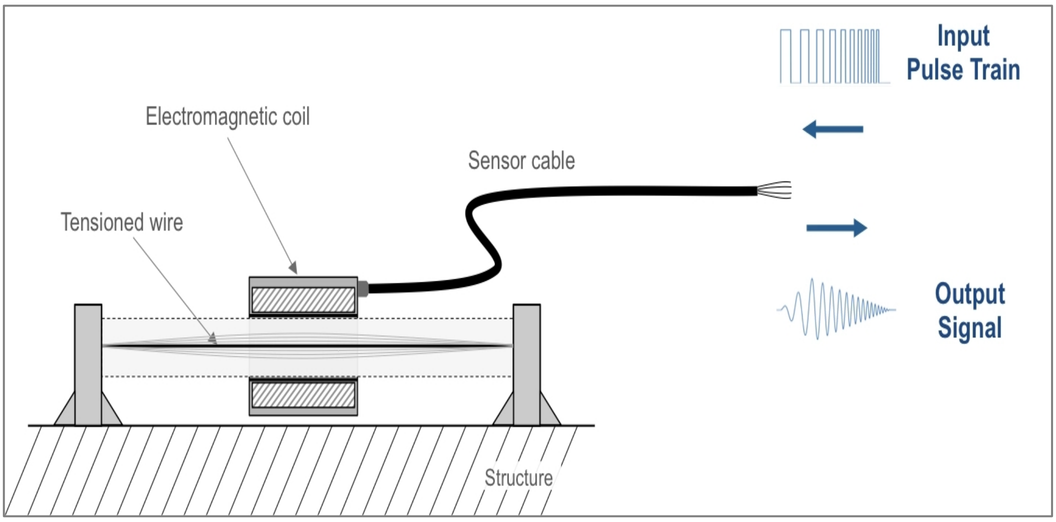

Figure 1.5 vibrating wire strain gauge (ni.com)

The operating principle is based on the link between the resonant frequency and the length of the metal wire. More precisely, using electromechanical induction, the vibration of the wire is induced until it reaches resonance frequency.

The disadvantage of these devices lies mainly in their cost, which can be justified only in special situations. (Chen & Ni, n.d.)

For the sake of completeness, a description of fiber-optic sensors is given, which originates from a technology that has been studied for many years but has not yet found stable application in structural monitoring of civil works. Effectively, this type of sensor has many advantages such as insensitivity to external perturbations and the possibility of realizing distributed deformation monitoring especially in large structures. The principle of operation is based on light reflection that is a function of the length traveled within the fiber.

(Das & Saha, 2018)

Optical fiber is composed of a core of thin glass fibers coated with a flexible stainless-steel sheath, which confines light inside so that it can propagate.

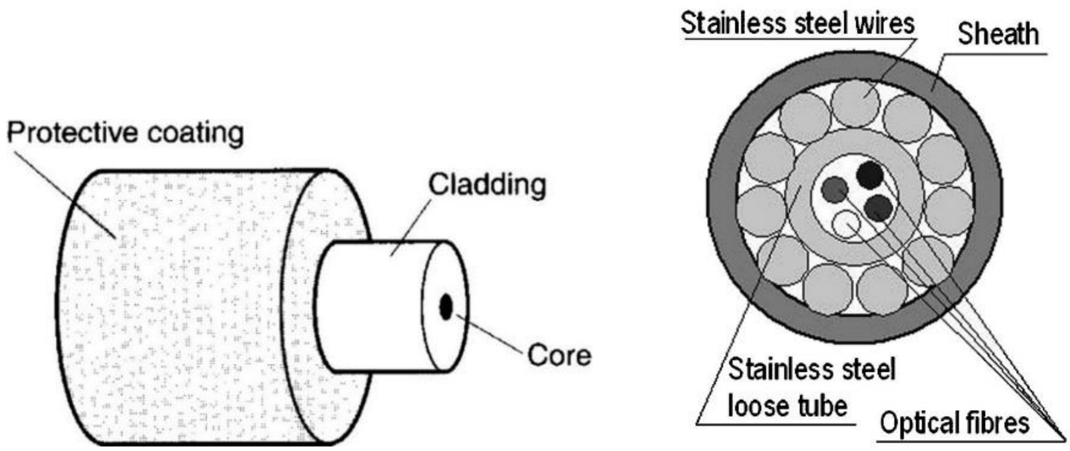

Figure 1.6 Fiber optic wire (Das & Saha, 2018)

The most recent innovation in the field of sensors involves Micro Electro-Mechanical Systems (MEMS), which allow miniaturization of measuring devices. MEMS technology has revolutionized the electronics industry in that it has allowed mechanical components to shrink to a size similar to that of electronic components.

The Smart Steel System (S3) device, recently developed by Prof. Francesco Tondolo of the Polytechnic University of Turin, makes use of this new type of component to determine strain variations in the steel bar in which the sensor itself is installed. As can be seen in Figure 1.7, in fact, the measuring sensor is placed inside a cavity created within the reinforcing bar, which will then be sealed with a welding operation.

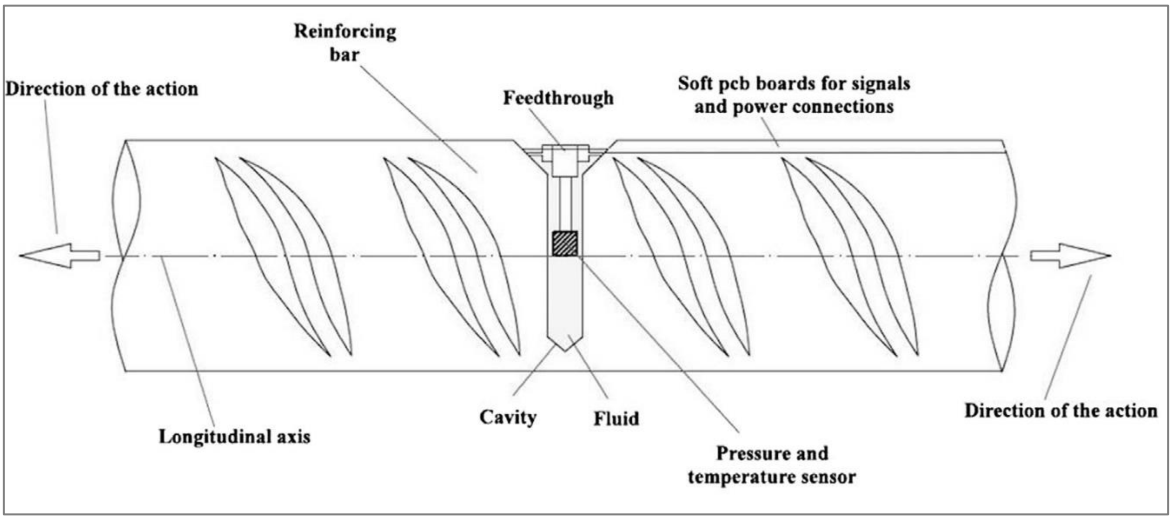

Figure 1.7 smart steel system (Tondolo et al., 2018)

As shown in Figure 1.8, the sensor can communicate measurements to the outside world through connection with a PCB, which in turn can exchange information with the data acquisition system.

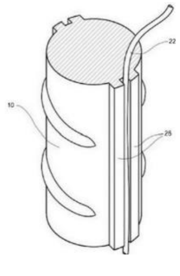

Figure 1.8 Soft PCB hosted in the bar lug (Tondolo et al., 2018)

The idea behind this instrument is to simultaneously measure variations in pressure and temperature, which are quantities that can be directly correlated to the change in cavity volume through the perfect gas law.

The advantage of this instrument is mainly related to its low cost, measurement sensitivity and robustness. With reference to the latter, it is worth pointing out that the device is specifically designed to tolerate significant mechanical stresses that make it particularly suitable for construction sites.

2. MONITORING OF TUNNELS

2.1 Introduction

Tunnel monitoring involves numerous aspects that only partially affect the health of the supporting structures. Geotechnical measurements, both at the boundary and at the excavation face, are essential to understand the evolution of soil behavior, environmental ones to ensure the safety of workers and limit phenomena such as fires, explosions, and chemical risks. Further surveys concern the productivity of the machinery used, which allows the time and cost of carrying out operations to be kept under control. Figure 2.1 shows the configurations that can be considered in setting up tunnel monitoring.

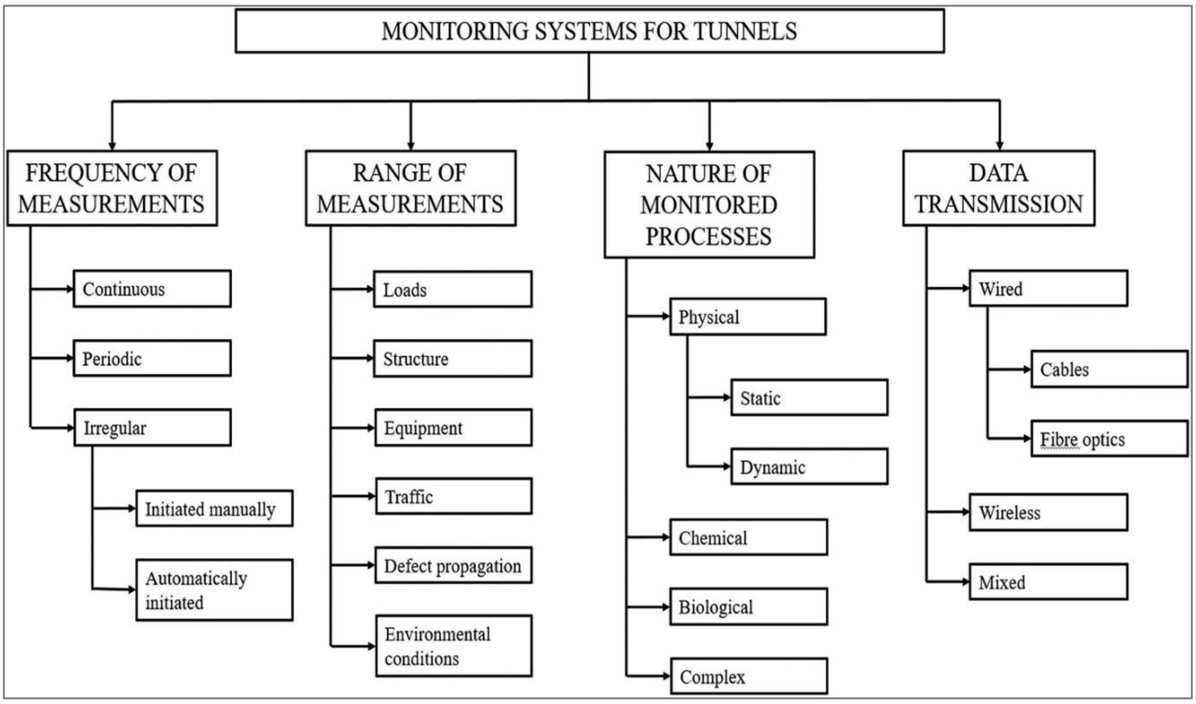

Figure 2.1 Basic parameters of monitoring system for tunnels (Strauss et al., 2020a)

As follows, Table 2 shows the measurable quantities and corresponding monitoring methods.

Table 2 Observation variables and applicable observation methods (Wulf et al., 2014)

	Absolute 3D displacement monitoring	Face displacement monitoring	Levelling	Extensometer	Load cell	Tilt meter	Hydrostatic levelling system	Borehole inclinometers	Piezometers	Water level gauge	Strain gauges	Invert probe	Geological compass-clinometer	Digital ground mapping	Visual inspection
Surface Settlements	■	-	■	■	-	-	□	■	-	-	-	-	-	-	-
Structures and utilities deformation	■	-	■	■	-	■	□	■	-	-	-	-	-	-	-
Lining displacements	■	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Lining strains	■*	-	-	-	-	-	-	-	-	-	■	-	-	-	-
Anchor loads	-	-	-	-	■	-	-	-	-	-	-	-	-	-	-
Invert integrity	■	-	-	■	-	-	-	-	-	-	■	■	-	-	■
Water level	-	-	-	-	-	-	-	-	■	■	-	-	-	-	-
Pore pressure	-	-	-	-	-	-	-	-	■	-	-	-	-	-	-
Face displacements	-	■	-	-	-	-	-	-	-	-	-	-	-	-	-
Ground structure	-	-	-	-	-	-	-	-	-	-	-	-	■	■	■
Ground displacements	-	-	-	■	-	-	-	■	-	-	-	-	-	-	-
Qualitative inspection of lining integrity	-	-	-	-	-	-	-	-	-	-	-	-	-	■	■

■ very valuable
□ limited value
- no value
* - possible with computer-based interpolation and evaluation methods

Detailed procedures and requirements for monitoring are generally defined by the standards and national regulations and specific guidelines.

In the Italian case, for example, the main agencies involved in the design and management of road and rail networks on behalf of the state (e.g. ANAS, RFI), have provided documents detailing how monitoring must be carried out. Table 3 effectively summarises the operational procedures to be followed. (Capitolato Speciale di Appalto ANAS)

Table 3 Tunnel monitoring procedures

Station	Location	Reading	Reading time
Tunnel entrances	Each entrance	Daily	Duration of construction site
Shallow urban tunnels	< 100 m	Daily or less	Duration of construction site
Shallow extra-urban tunnels	< 250 m	Daily or less	Duration of construction site
Fundamental	< 1000 m	Daily or more	Up to final acceptance certification
Primary	< 500 m	Daily or less	Up to 5 diameters far from tunnel face or up to final lining installation
Secondary	< 50 m	Each work operation	Up to 3 diameters far from tunnel face or up to final lining installation
Face	Each work operation	Each 10 m	Up to final lining installation

In particular, the following is the list of instruments required for in-progress monitoring of the Fundamental, Principal, and Secondary stations, which most closely mirror the numerical modeling in Chapter 3 below.

Key stations:

- No. 6 removable optical targets;
- No. 3 multi-base strain gauges
- No. 2 hydraulic load cells installed below the foot of the ribs;
- No. 5 radial pressure cells;
- No. 6 strain gauge bars;
- No. 1 advancing continuous coring survey

Main stations:

- No. 6 removable optical targets;
- No. 2 hydraulic load cells installed below her foot of the ribs;
- No. 5 radial pressure cells;
- No. 6 strain gauge bars.

Secondary stations:

- No. 6 removable optical targets

With regard to monitoring during operation phase, the same documents do not consider the installation of Secondary stations, while they consider the installation of four flat jacks at the Fundamental stations (possibly in addition to the instrumentation already in place during operation) and twelve concrete strain gauges at the Main stations.

2.2 Structural monitoring of new tunnel linings

The term "tunnel" in this thesis work has been used explicitly to refer to road and rail tunnels. In this section the focus is on the deformation and displacement behavior of the linings installed to support the contour of such tunnels. Recent investigations have established that more than 83 percent of existing tunnels have a final lining with reinforced or unreinforced concrete. In new construction, on the other hand, the first-phase lining assumes a crucial role in ensuring the safety of users and the success of the project. (Strauss et al., 2020b)

The monitoring strategy for these structures appears to be influenced by the tunnel construction methods, but the tools used for measurements are actually similar. A further difference can be related to the in-process and in-service monitoring since lower gradients are generally expected in the latter. (Bilotta et al., 2022)

In the excavation phase of conventional tunnels, the main objectives of monitoring are to evaluate stress trends in the first-phase lining and to have information on the extrusion of the face.

Strain measurements on the steel ribs that generally make up the linings are made through sensors welded to the flanges of the beams themselves. Currently, the most widely used devices for this purpose are the vibrating strain gauges (Figure 2.2) already introduced in the previous section. To make measurements on the final lining during operation of the structure, the same instruments can be welded to the reinforcement and embedded within the concrete casting (Figure 2.3).

The monitoring of the displacements of the linings themselves is carried out with the help of total stations (Figure 2.4) for the purpose of measuring the convergence of cross-sections-that is, the reduction of the minimum distance between pairs of points positioned symmetrically with respect to the tunnel axis-or the absolute displacement of certain points on the tunnel contour. (Bilotta et al., 2022)

Convergence curves can be represented as a function of time or distance from the excavation front.

For both deformations and displacements, the initial reading taken immediately after the installation of the linings is followed by further readings with time intervals defined by the monitoring plan or by the conditions actually encountered during excavation. In this regard, standard reading frequencies are defined in line with past experience. However, it is emphasized in each case that these measurements should be adapted to the on-site conditions. (LUNARDI, 2016)

The measurement of displacements can be manual or automatic depending on the characteristics of the total station used, and it requires specialized technicians. In fact, the procedure is the same as a topographic survey whereby the instrument is installed on a georeferenced point (tripod or pillar) from which reflective target positioned at the internal surface of the linings (usually 5 or 7 pairs) are pointed.

In newly constructed tunnels, the main objective of monitoring is to highlight any anomalies in behavior compared with design predictions, in the spirit of the observational method already introduced in Section 1.1, while in the existing tunnels the focus is on assess the current structural health of the structures.

Figure 2.2 vibrating wire gauges bolted to the rib. (Bilotta & Russo, 2016)

Figure 2.3 Vibrating wire gauges embedded in RC (gestecno.it)

Figure 2.4 Optical monitoring operation with total station (Bilotta et al., 2022)

As for mechanized tunnels, displacement monitoring is limited by the massive machinery operating to make the borehole and, therefore, the most appropriate measurement is the measurement of deformations within the precast segments lining. Due to the construction process by which these elements are made (Figure 2.5), it is very easy to insert measuring instruments such as vibrating strain gauges inside the segments.

Figure 2.5 precast operation of segments (www.ferrovie.it)

This type of installation allows a zero reading to be taken both before and after installation, depending on the effects to be monitored. For example, a critical phase for these segments is when the TBM (Tunnel Boring Machine) pushes against them to allow the excavation to advance (Figure 2.6)

One disadvantage of embedded tools is that they cannot be easily repaired and/or replaced, so that more studies should be carried out in this direction; therefore, durability is definitely a key aspect to focus on in their design.

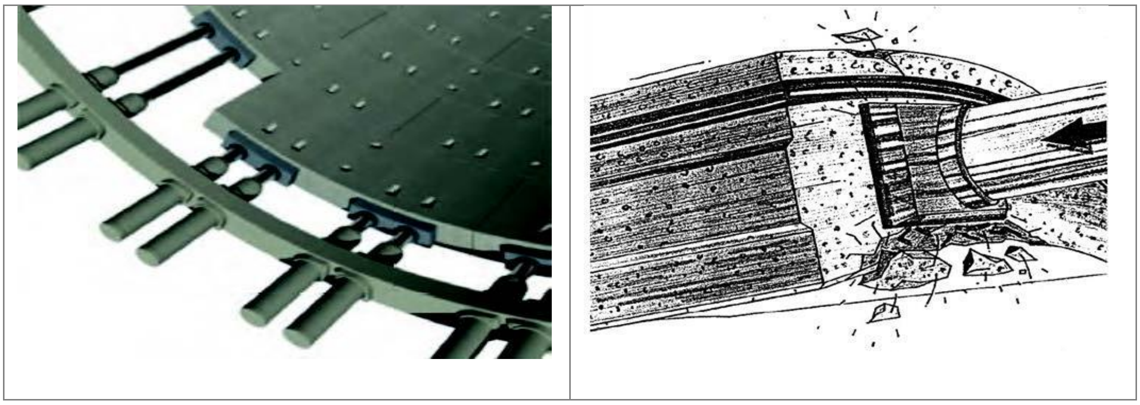

Figure 2.6 Trust jacks pushing on segmental linings (ITA Working Group 2 - Research, 2019)

2.3 Structural monitoring of existing tunnel linings

The issue of monitoring existing tunnels is more complex because of additional uncertainties due to the usual lack of basic information concerning the original design and life of the work.

The objective differs from that set out in the previous paragraph since, in these cases, the key issue is to determine the current state of the linings especially in terms of thickness and quality of materials: in fact, it is not uncommon to be faced with major unevenness in these aspects.

The mapping of these parameters is the basis for the interpretation of subsequent measurements. In effect, the final parameter to be evaluated is the stress state in the final lining, knowledge of which allows assessments to be made regarding possible interventions to be put into practice for structural rehabilitation.

At this point, it should be pointed out that the calculation of the stress state always passes through strain measurements in the elements considered. This is why it is so important to associate the mechanical and geometric parameters of the linings with them. From deformation, knowing the modulus of elasticity, it is possible to calculate the stress, and knowing the geometry it is possible to determine the internal stresses.

To solve the problem regarding the initial unknown, current practice is to resort to a specific type of testing through which it is possible to trace the level of deformation achieved in the linings up to the time of testing.

The Doorstopper method shown in (Figure 2.7) involves making a probe hole in the lining. A special cell (Figure 2.8) that incorporates 4 resistive strain gauges (Figure 2.9) such as those described in section 1.2 arranged at 45° to each other, are then bonded to the bottom of the hole which has been previously flattened using a special diamond tool. At this point, overcoring is performed, which generates a stress release associated with a change in strain instantly measured by the device.

The determination of stress through this method involves performing a triaxial test on the specimen that is extracted following overcoring, so as to obtain the actual elastic modulus of the concrete.

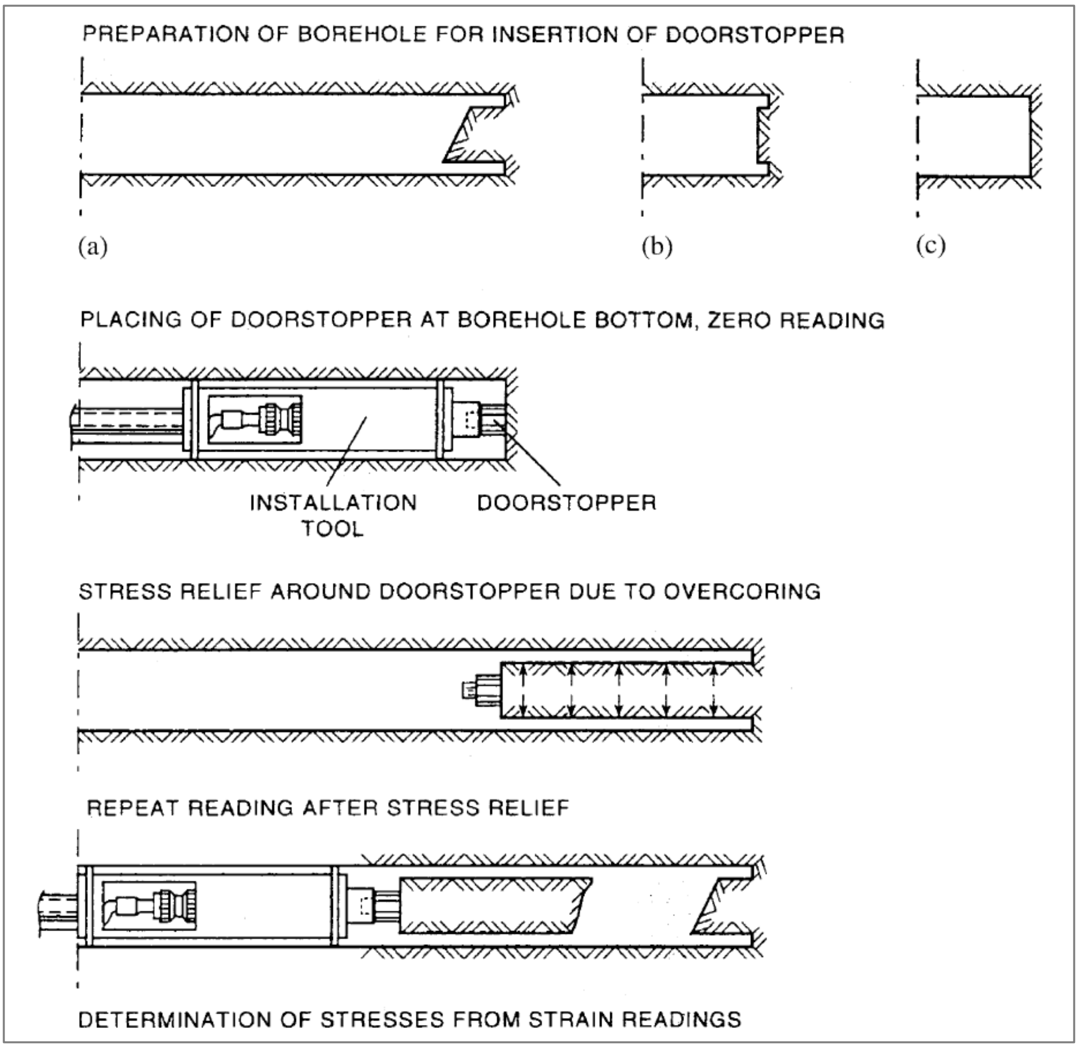

Figure 2.7 Doorstopper test procedure (Ljunggren et al., 2003)

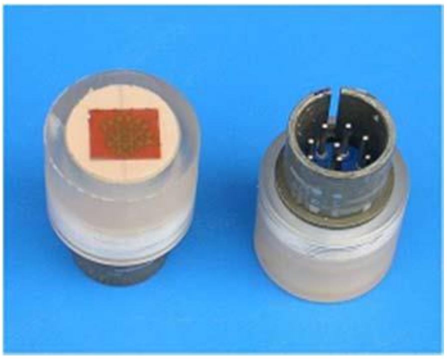

Figure 2.8 Doorstopper Cell

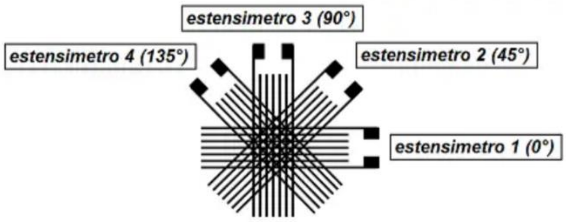

Figure 2.9 Doorstopper strain gauges (www.sialtec.it)

Figure 2.10 Doorstopper application in tunnel lining (Guido et al., 2021)

A method almost similar to the one just given is the flatjack test (Figure 2.11). A flatjack consists of two steel plates welded at the perimeter and filled with oil that can be pressurized (Figure 2.12).

Figure 2.11 Flat-jack test (www.sisgeo.it)

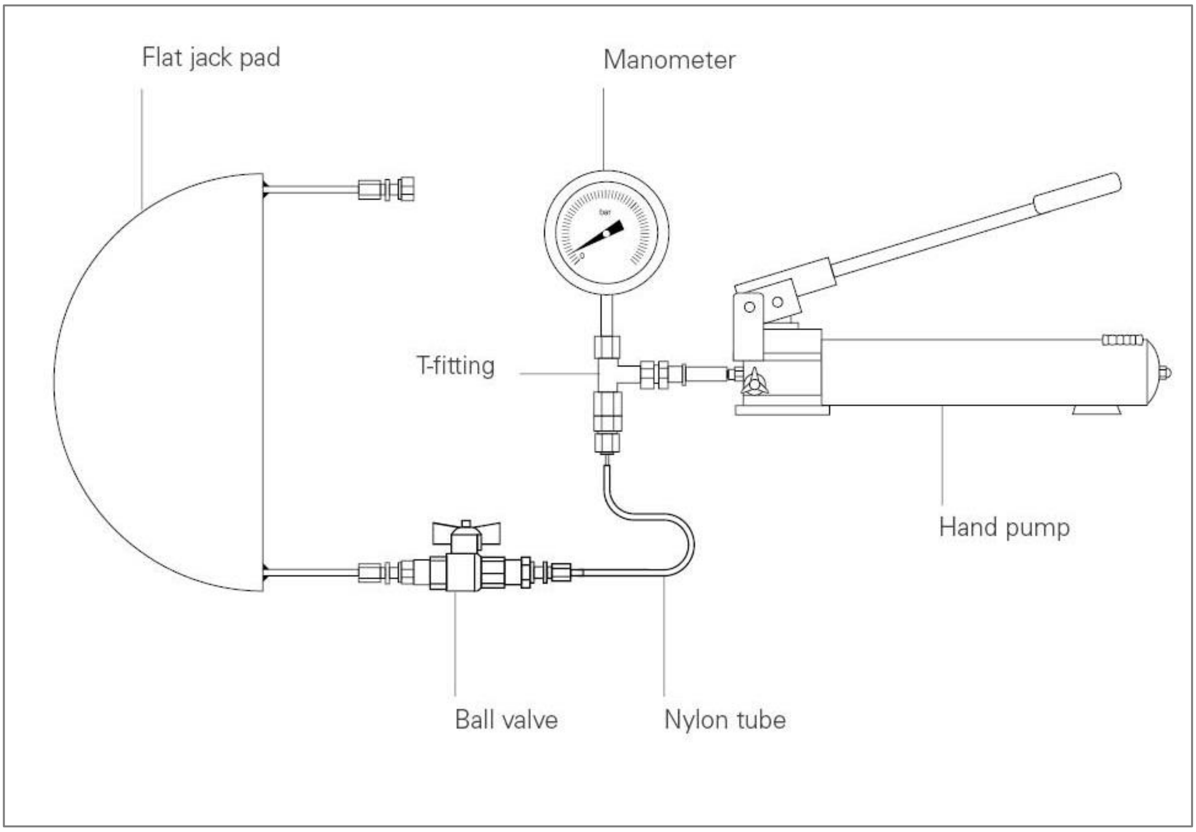

Figure 2.12 Flat-Jack device (www.sisgeo.it)

The test can involve four steps (Figure 2.13) to arrive at the pre-existing stress state:

- Installing reference pins and measuring distances.
- Drilling overlapping hole to create a slot and measuring the corresponding pin distances.
- Installing the flat jack and fixing it in place with neat cement grout.
- Pressurizing and depressurizing the flat jack while measuring corresponding pin distances

(Bobrowsky & Marker, 2016)

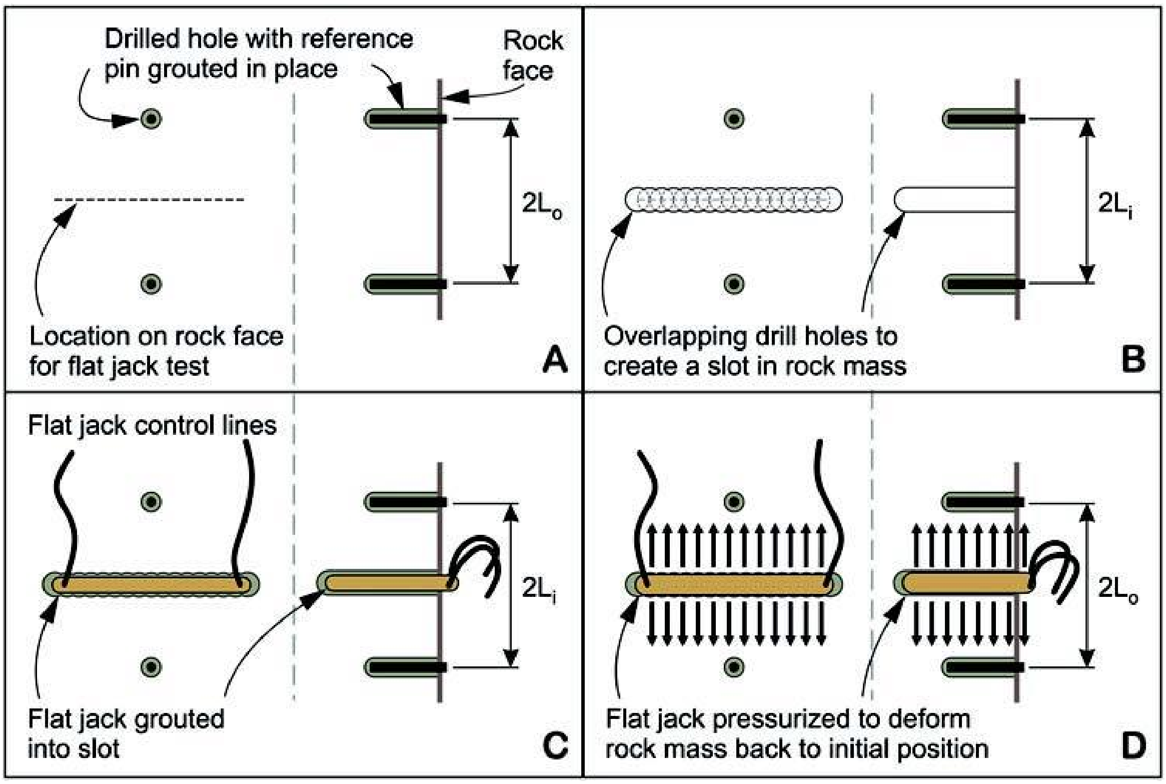

Figure 2.13 Jacking Test (Bobrowsky & Marker, 2016)

3. NUMERICAL ANALYSIS

3.1 Modelling

This chapter discusses a series of FEM modeling performed with Rocscience's RS2 software (*RS2 Documentation*, n.d.)in order to simulate the structural response of the linings of seven ideal tunnels subjected to different boundary conditions. Through the processing of the numerical results performed with Excel software from the Microsoft Office365 suite, it was possible to study the trend of displacements and deformations, which, as seen in the previous chapters, are the quantities most considered in the structural monitoring of linings.

To facilitate the reading and interpretation of the results given in the next paragraph, reference can be made to Figure 3.1 in which notable points arising from a homogeneous subdivision of the tunnel geometry are depicted.

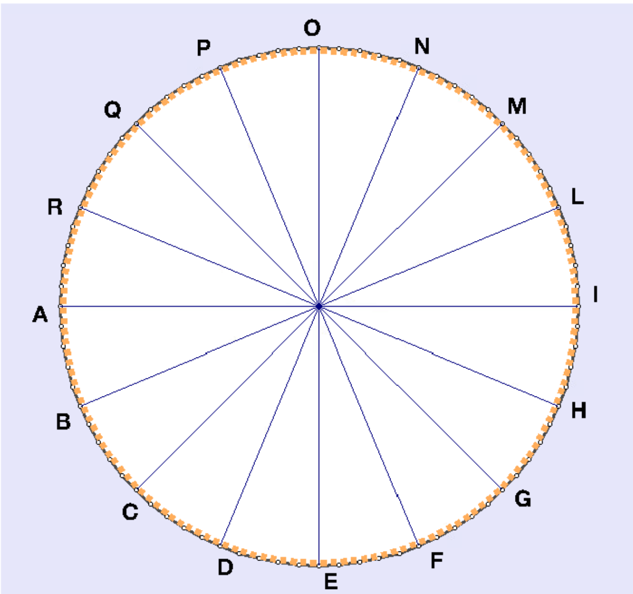

Figure 3.1 Geometric subdivision tunnel contour

The support structures were modeled through predefined "beam elements" available in RS2, since in these cases it is not of interest to know the actual stress distribution, for which it would have been necessary to model the thickness of the linings in finite elements, but it is more appropriate to directly obtain the average values of the acting stresses (normal action and bending moment). In this way, the contour was automatically discretized with 160 "beam elements" so that, placing this numerical subdivision alongside the geometric one introduced earlier, 10 ten measurement points between two successive letters of Figure 3.1 result.

Table 4 Geometrical and numerical discritization

Geometrical discretization	Numerical discretization
A	Point 1
B	Point 11
C	Point 21
D	Point 31
E	Point 41
F	Point 51
G	Point 61
H	Point 71
I	Point 81
L	Point 91
M	Point 101
N	Point 111
O	Point 121
P	Point 131
Q	Point 141
R	Point 151

For each finite element, the software returns stress and displacement values that can be seen as the result of a monitoring campaign.

The differences between the boundary conditions of the various modeled tunnels obviously resulted in linings with different characteristics from each other. To make a more congruous comparison, all sections were calibrated so that the acting stresses, at the final stage, were near the limit of the interaction diagram.

The graphical and tabular results presented in the next section summarize what was obtained from the FEM analysis and subsequent processing.

The software directly returns displacement values at the centerline of each finite element. Regarding this aspect, it is emphasized that the total displacements at each point were considered, starting from the first stage of linings installation.

Deformations, on the contrary, were derived from the moment and normal stress values of the same points, using the equations proper to the elastic calculation of reinforced concrete sections (Cosenza et al., 2019)

3.2 Results

Model 1

Tunnel excavated in very high-quality rock mass

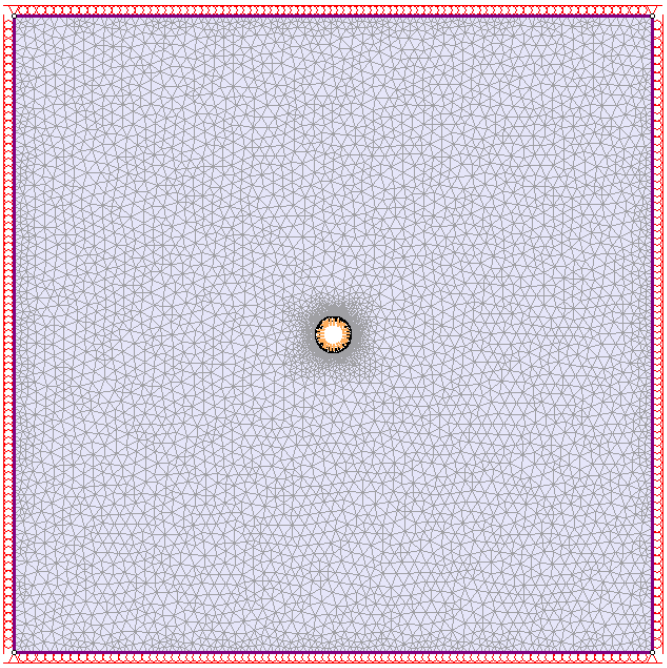

Figure 3.2 Overview of model 1

Table 5 MAIN FEATURES OF MODEL 1

Type of model	$symmetric$
Tunnel shape	$circular$
Tunnel depth	$400\ m$
Elastic modulus of rock mass	$10\ 000\ MPa$
Preliminary lining	$35\ cm$
Fina lining	$-$

Model 1 – main results for preliminary lining

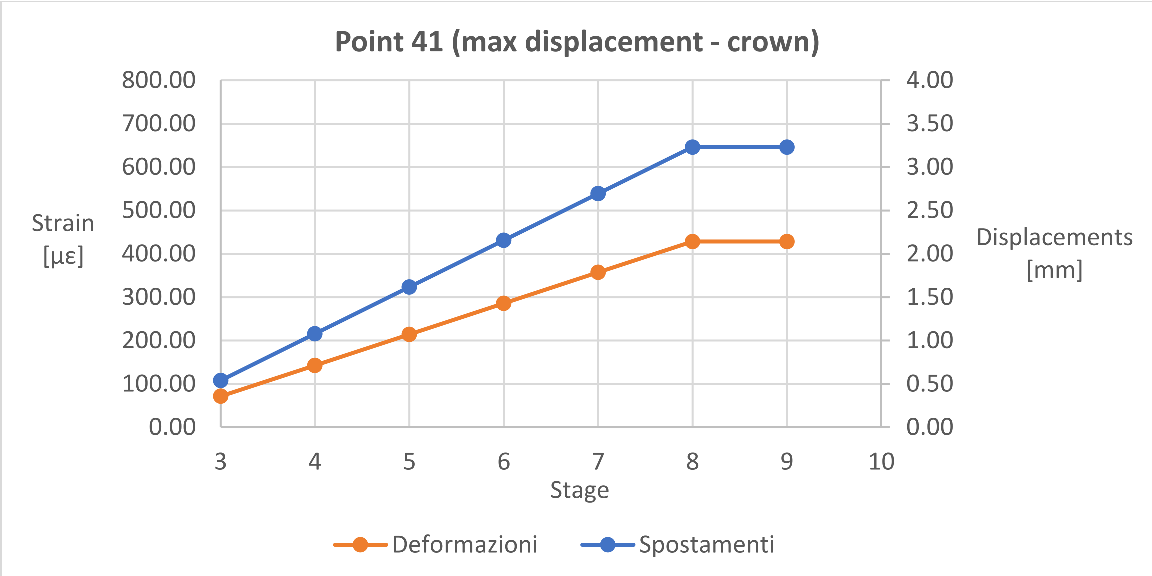

Figure 3.3 maximum displacement and associated strain

Table 6 Numerical results of model-1

MAX DISPLACEMENT	$3.23\ mm$
Associated strain	$428.3\ \mu\varepsilon$

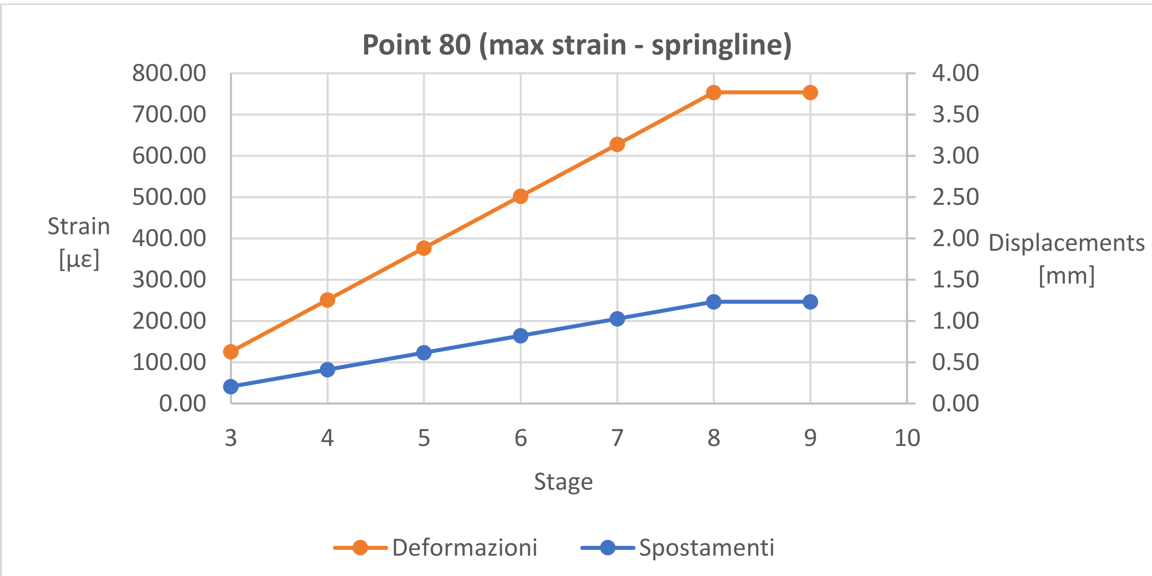

Figure 3.4 maximum strain and associated displacement

Table 7 Numerical results of model-1

MAX STRAIN	$753.8\ \mu\varepsilon$
Associated displacement	$1.23\ mm$

Model 2

Tunnel excavated in heterogeneous media (soil, rock)

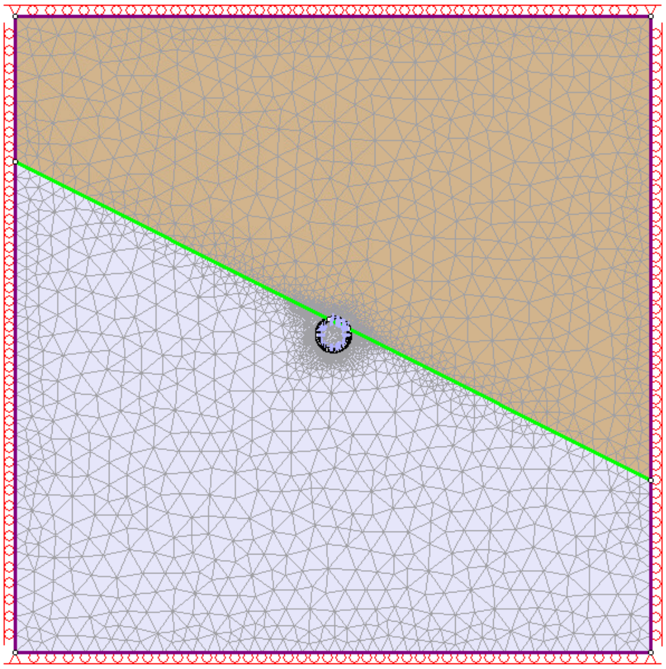

Figure 3.5 Overview of model 2

Table 8 MAIN FEATURES OF MODEL 2

Type of model	$Asymmetric$
Tunnel shape	$circular$
Tunnel depth	$400\ m$
Elastic modulus of soil	$1\ 000\ MPa$
Elastic modulus of rock mass	$200\ MPa$
Preliminary lining	$50\ cm$
Fina lining	$40\ cm$

Model 2 – main results for preliminary lining

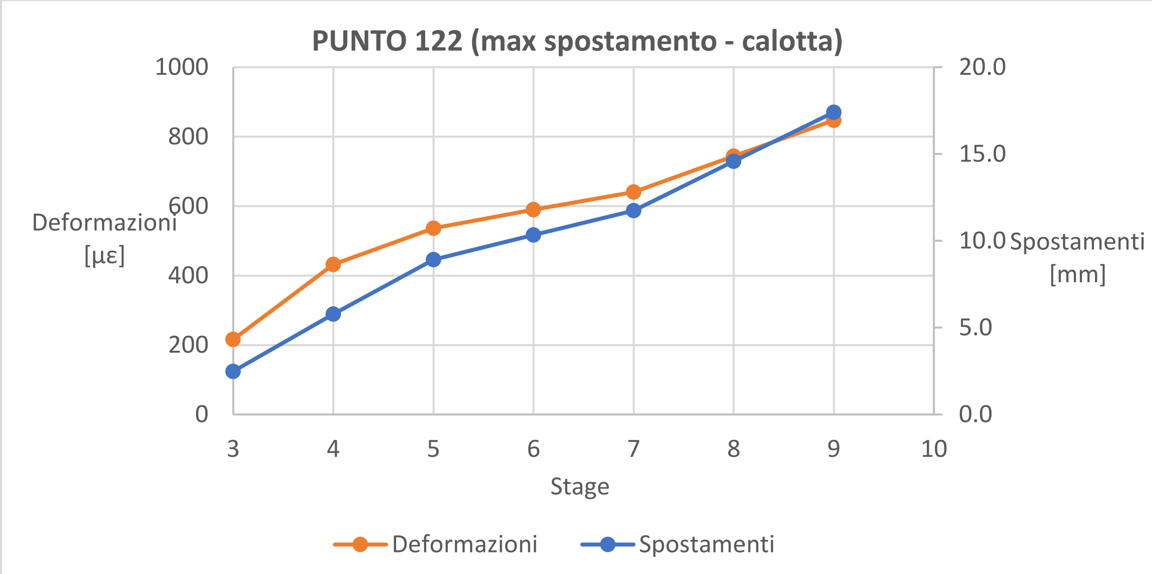

Figure 3.6 maximum displacement and associated strain

Table 9 Numerical results of model-2

MAX DISPLACEMENT	$17.4\ mm$
Associated strain	$847.2\ \mu\varepsilon$

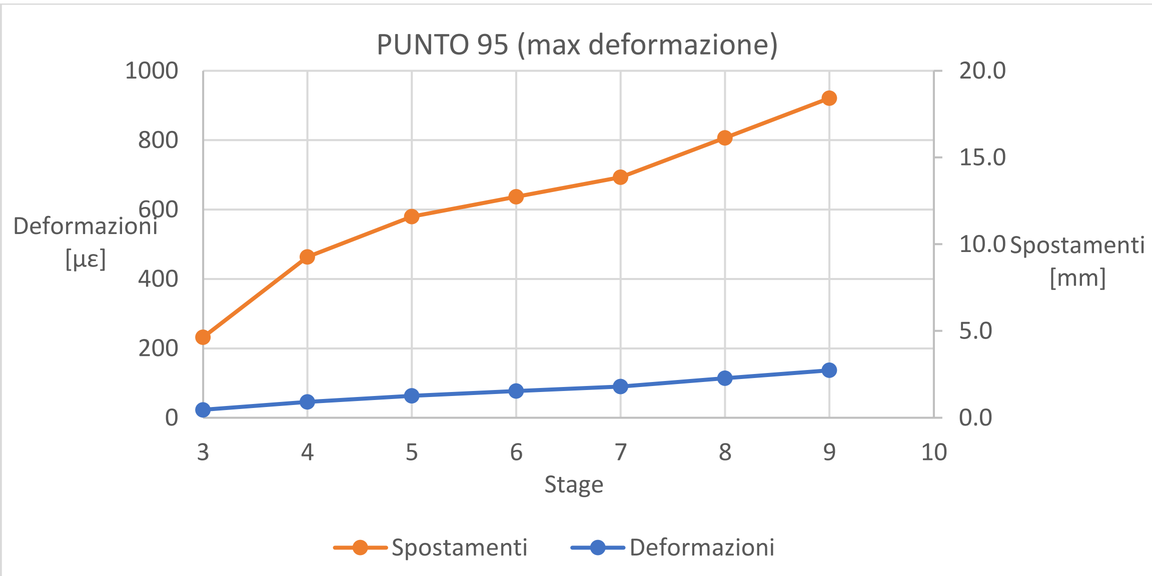

Figure 3.7 maximum strain and associated displacement

Table 10 Numerical results of model-2

MAX STRAIN	$921.2\ \mu\varepsilon$
Associated displacement	$2.73\ mm$

Model 2 – main results for final lining

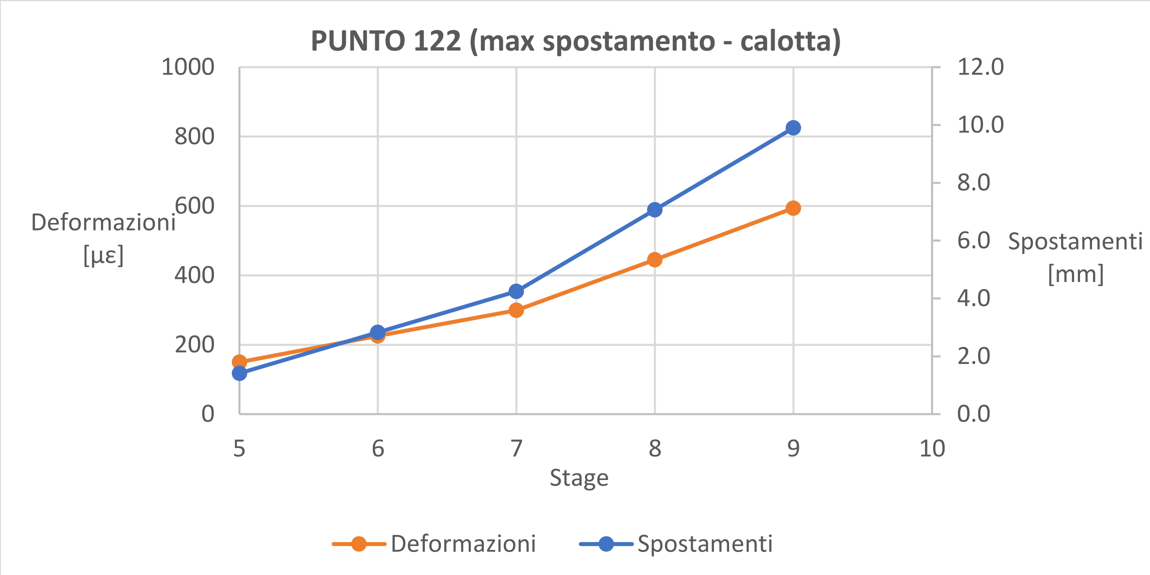

Figure 3.8 maximum displacement and associated strain

Table 11 Numerical results of model-2

MAX DISPLACEMENT	9.90 mm
Associated strain	543.6 $\mu\varepsilon$

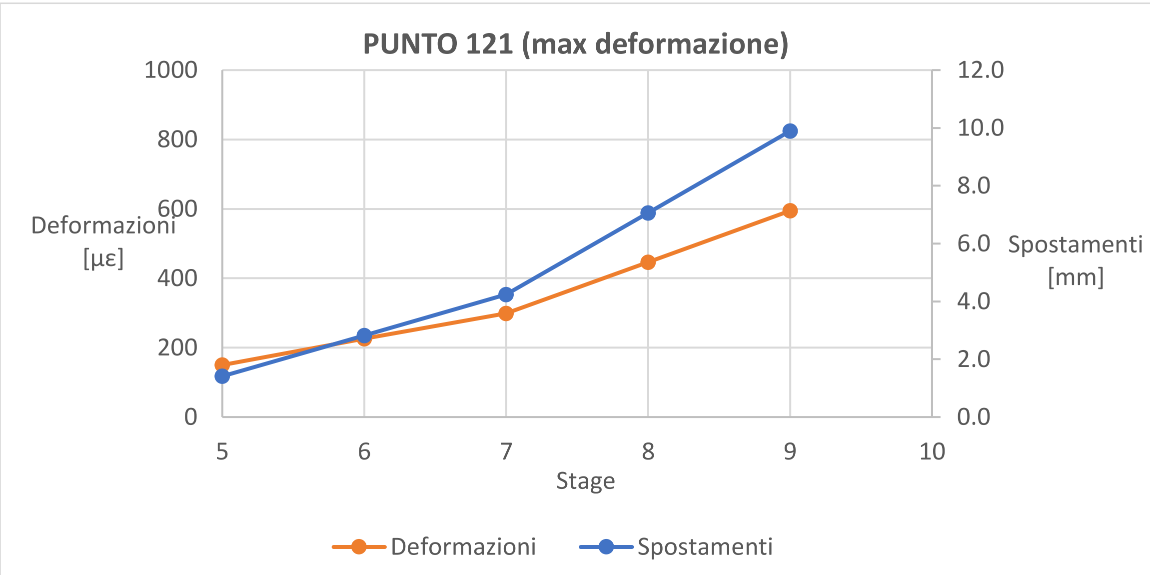

Figure 3.9 maximum strain and associated displacement

Table 12 Numerical results of model-2

MAX STRAIN	594.6 $\mu\varepsilon$
Associated displacement	9.90 mm

Model 3

Tunnel excavated in medium quality rock mass

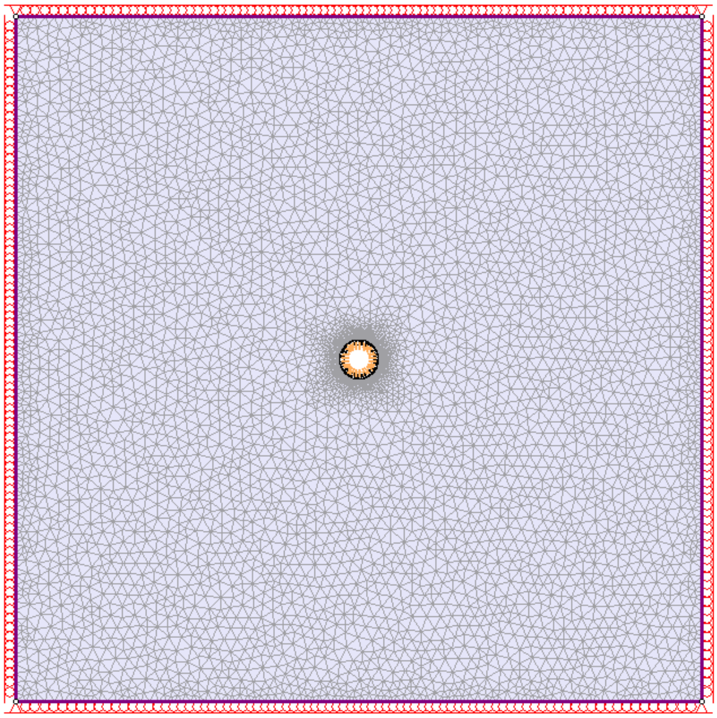

Figure 3.10 Overview of model 3

Table 13 MAIN FEATURES OF MODEL 3

Type of model	$symmetric$
Tunnel shape	$circular$
Tunnel depth	$400\ m$
Elastic modulus of rock mass	$1\ 000\ MPa$
Preliminary lining	$-$
Fina lining	$35\ cm$

Model 3 – main results for preliminary lining

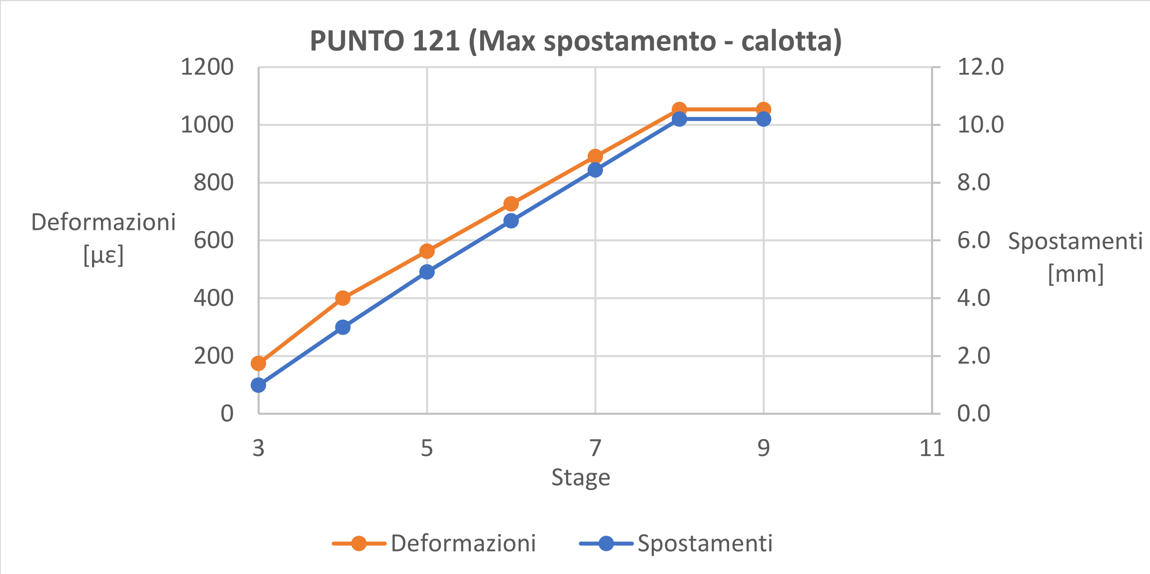

Figure 3.11 maximum displacement and associated strain

Table 14 Numerical results of model-3

MAX DISPLACEMENT	$10.2\ mm$
Associated strain	$1053.6\ \mu\varepsilon$

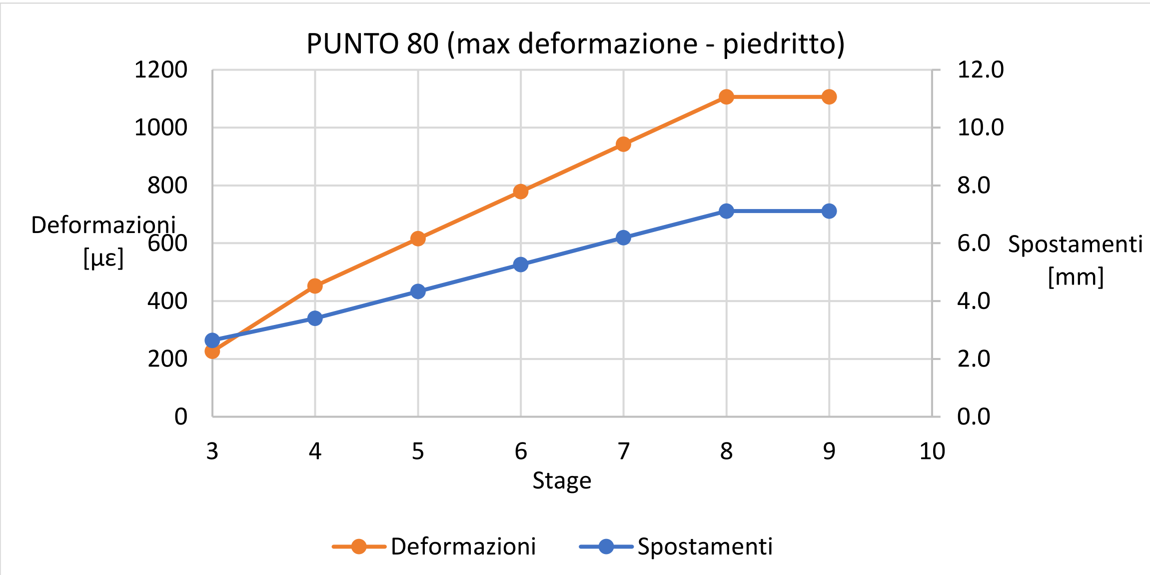

Figure 3.12 maximum strain and associated displacement

Table 15 Numerical results of model-3

MAX STRAIN	$1106.2\ \mu\varepsilon$
Associated displacement	$7.12\ mm$

Model 3 – main results for final lining

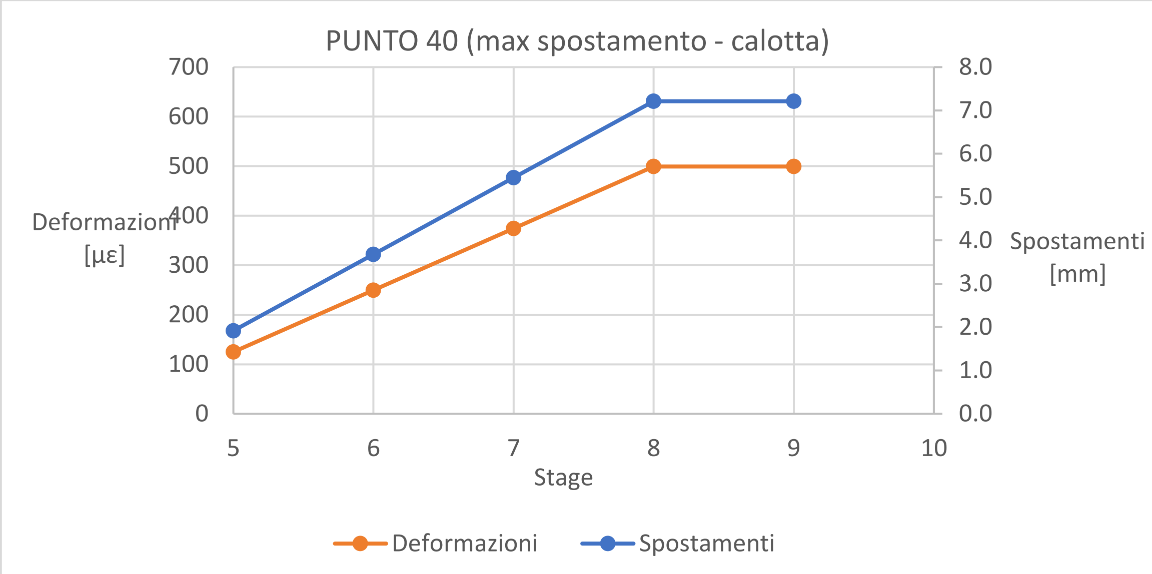

Figure 3.13 maximum displacement and associated strain

Table 16 Numerical results of model-3

MAX DISPLACEMENT	$7.21\ mm$
Associated strain	$499.2\ \mu\varepsilon$

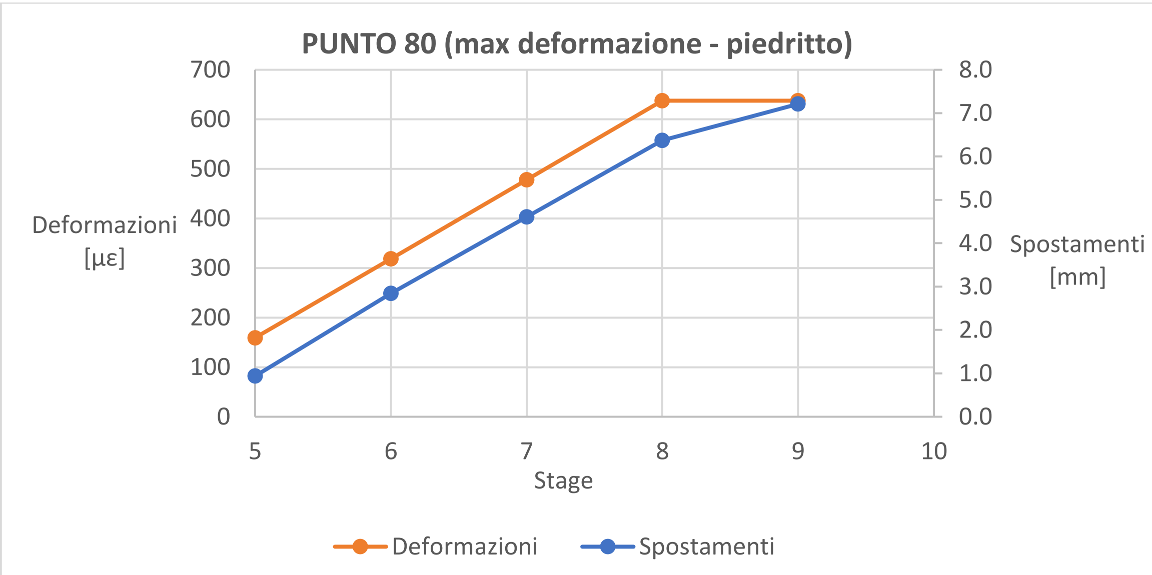

Figure 3.14 maximum strain and associated displacement

Table 17 Numerical results of model-3

MAX STRAIN	$1106.2\ \mu\varepsilon$
Associated displacement	$7.12\ mm$

Model 4

Tunnel excavated in medium quality rock mass

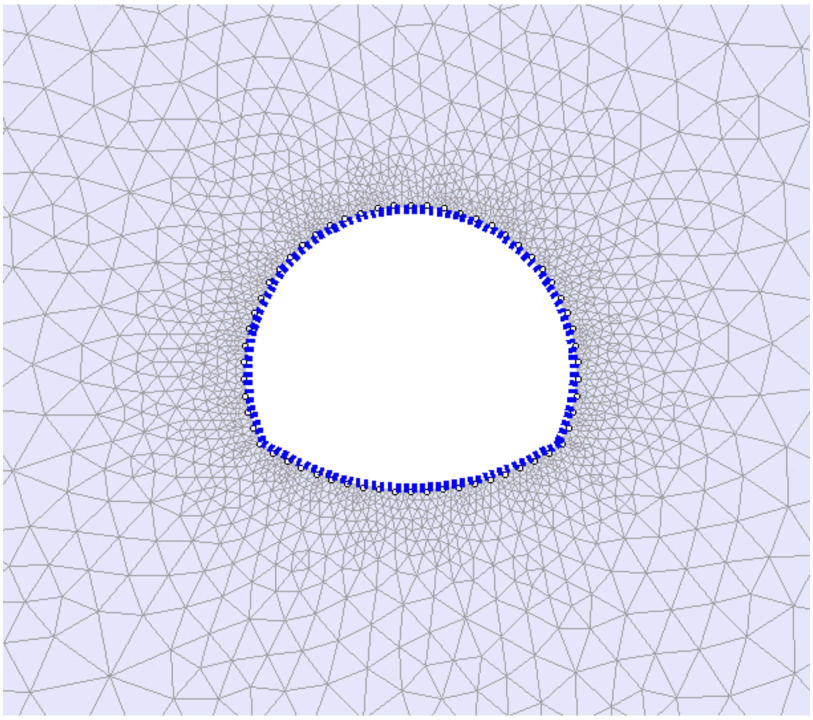

Figure 3.15 Overview of model 4

Table 18 MAIN FEATURES OF MODEL 4

Type of model	$symmetric$
Tunnel shape	$not\ circular$
Tunnel depth	$400\ m$
Elastic modulus of rock mass	$1\ 000\ MPa$
Preliminary lining	$30\ cm$
Fina lining	$-$

Model 4 – main results for preliminary lining

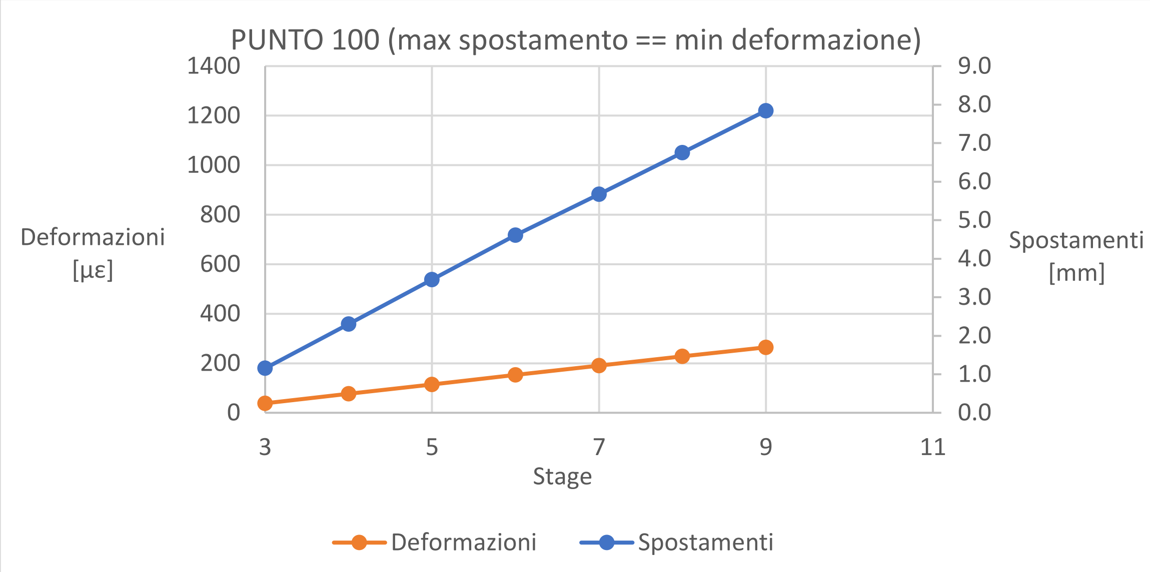

Figure 3.16 maximum displacement and associated strain

Table 19 Numerical results of model-4

MAX DISPLACEMENT	$7.843\ mm$
Associated strain	$264.3\ \mu\varepsilon$

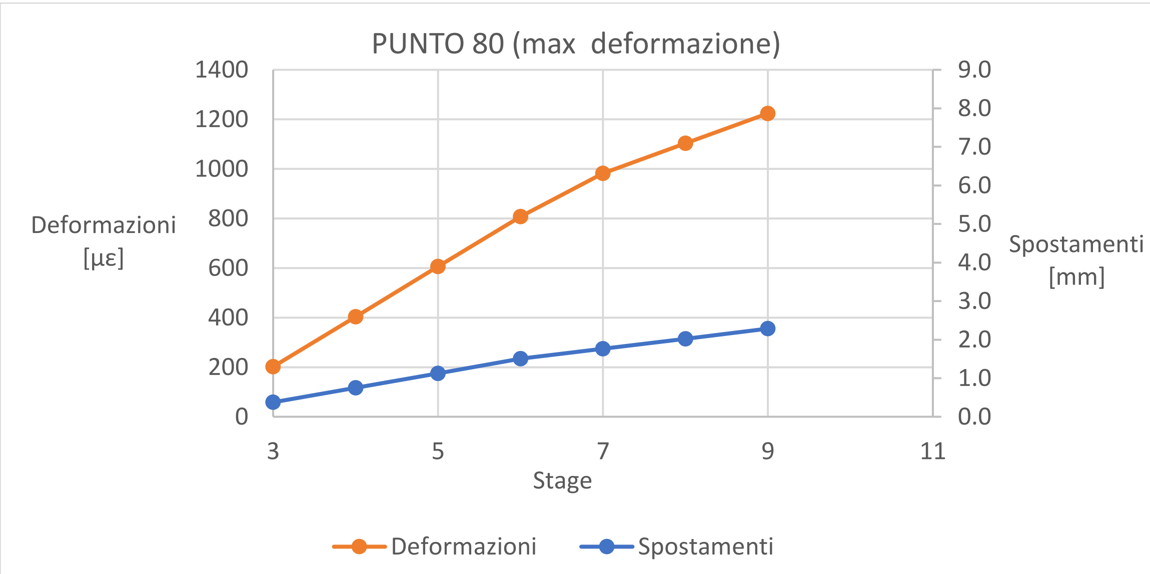

Figure 3.17 maximum strain and associated displacement

Table 20 Numerical results of model-4

MAX STRAIN	$1224\ \mu\varepsilon$
Associated displacement	$2.286\ mm$

Model 5

Tunnel excavated in swelling rock mass

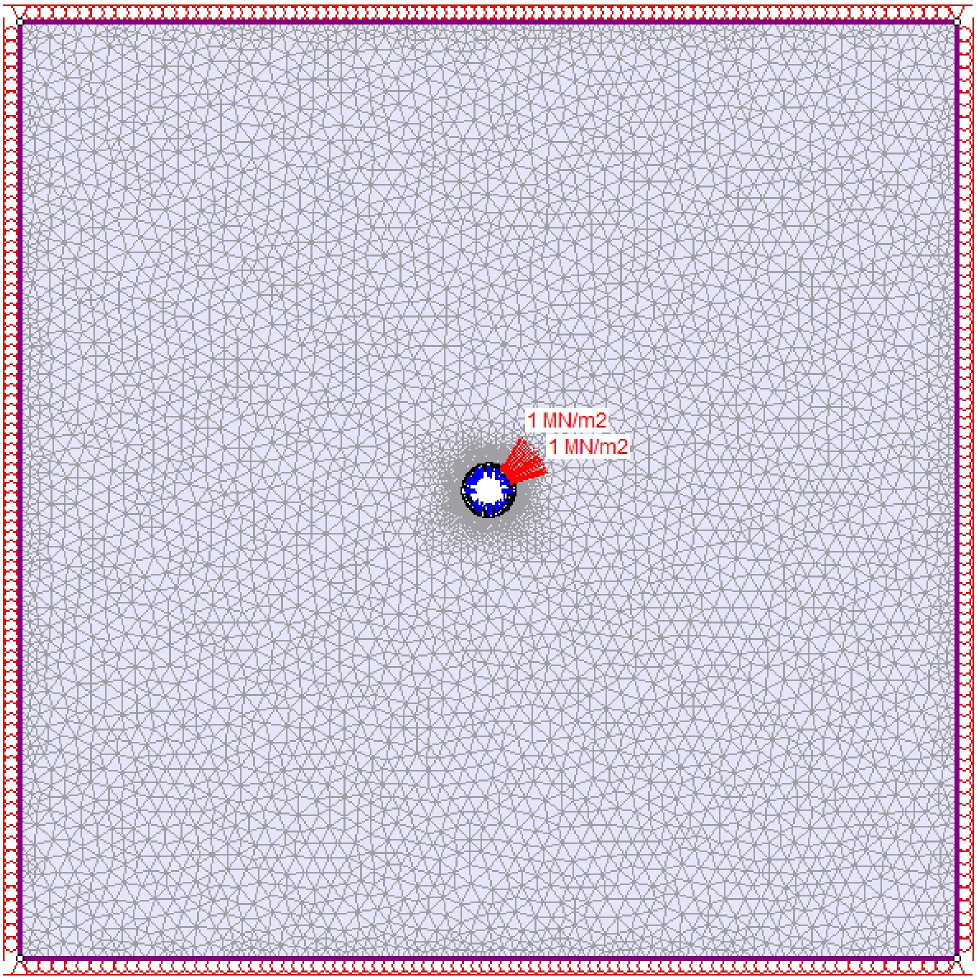

Figure 3.18 Overview of model 5

Table 21 MAIN FEATURES OF MODEL 5

Type of model	$Asymmetric$
Tunnel shape	$circular$
Tunnel depth	$400\ m$
Elastic modulus of rock mass	$1\ 000\ MPa$
Preliminary lining	$35\ cm$
Fina lining	$35\ cm$

Model 5 – main results for preliminary lining

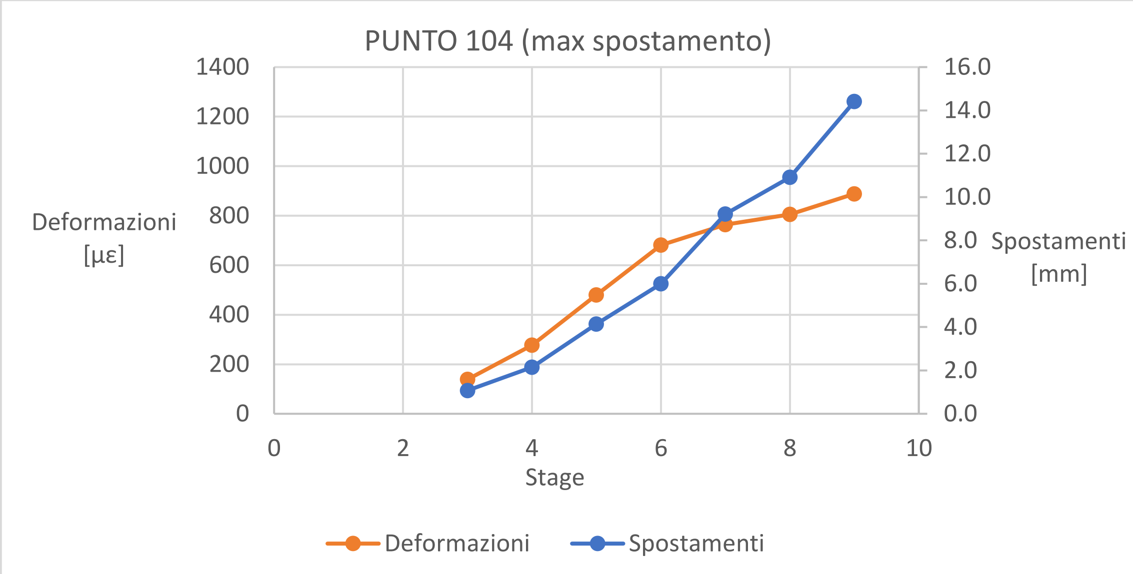

Figure 3.19 maximum displacement and associated strain

Table 22 Numerical results of model-5

MAX DISPLACEMENT	$14.411\ mm$
Associated strain	$888.32\ \mu\varepsilon$

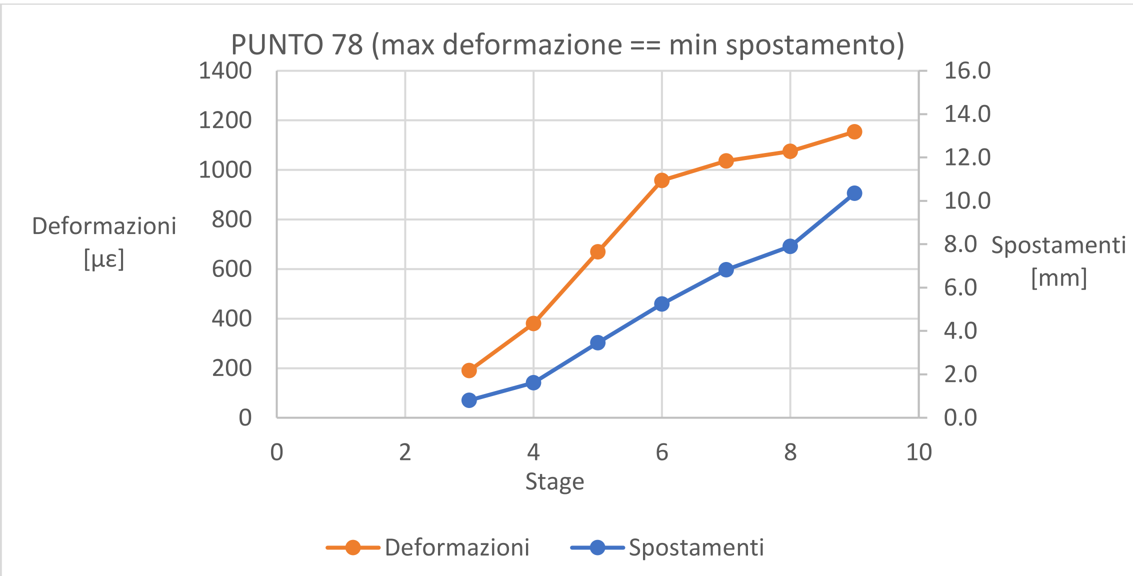

Figure 3.20 maximum strain and associated displacement

Table 23 Numerical results of model-5

MAX STRAIN	$1153.85\ \mu\varepsilon$
Associated displacement	$10.347\ mm$

Model 5 – main results for final lining

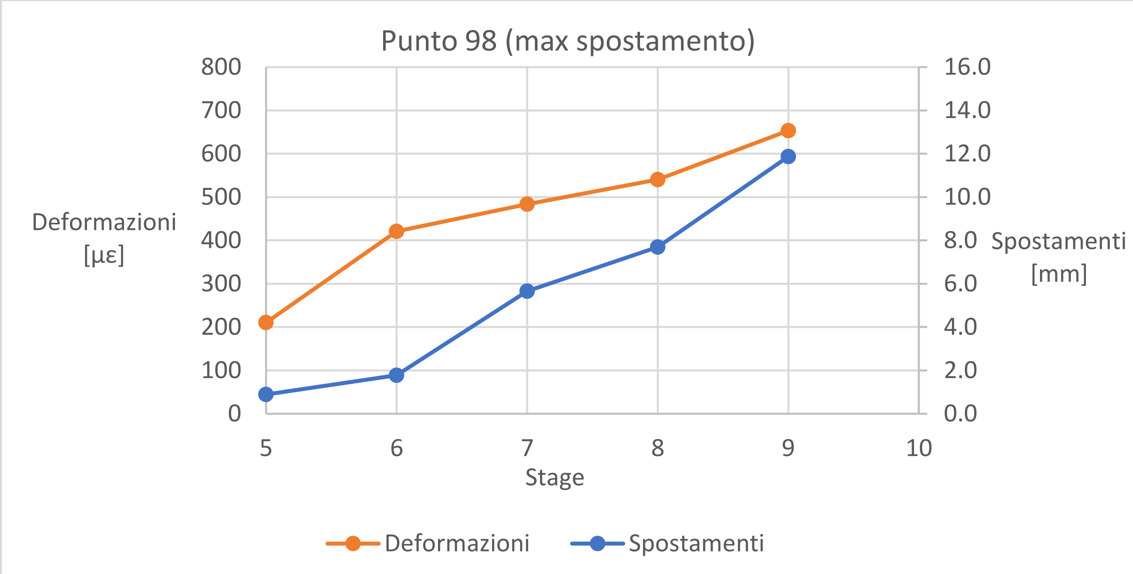

Figure 3.21 maximum displacement and associated strain

Table 24 Numerical results of model-5

MAX DISPLACEMENT	$11.869\ mm$
Associated strain	$653.24\ \mu\varepsilon$

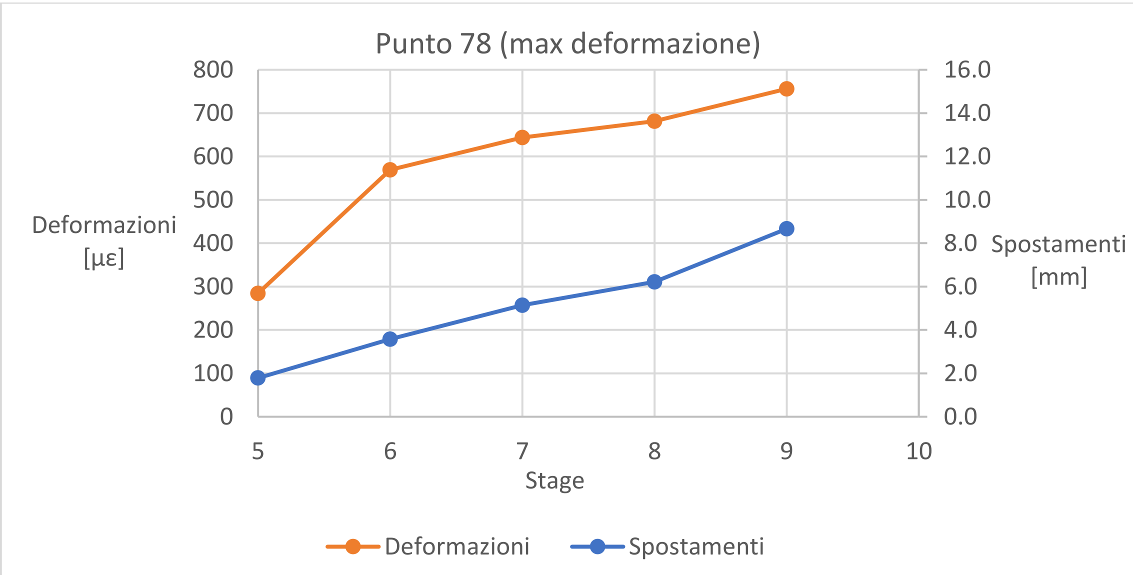

Figure 3.22 maximum strain and associated displacement

Table 25 Numerical results of model-5

MAX STRAIN	$756.13\ \mu\varepsilon$
Associated displacement	$8.665\ mm$

The study made it possible to show the deviation between displacement and strain values of points placed in corresponding sections. Although these quantities have different units of measurement, some conclusions can be drawn by referring to the accuracy of the instruments with which they are measured.

For example, a high-level total station with angular accuracy of 0.15 mgon and distance accuracy of 0.6 mm + 1 ppm achieves a final accuracy in the measurement of differential displacements that is between ±1 mm and ±5 mm.

Strain measurement devices have sensitivities ranging from 1με to 5 με.

Considering the results reported in the previous pages, strain measurements should ensure a significantly more sensitive warning system to changes in boundary conditions. (Bilotta et al., 2022)

4. CONCLUSIONS

Most civil structures are well designed, and it is well known that currently the probability of failure is minimized by a design approach that can rely on careful studies regarding the safety coefficients to be adopted.

The use of a monitoring system in such a context might seem totally inappropriate because it would not bring benefits in the short term, especially from an economic point of view.(Huston, 2010)

Currently, the most common way to check the reliability of civil structures is to carry out inspections and maintenance at prescribed intervals that do not follow well-defined rules and depend on regulatory requirements.

A time-based approach has obvious shortcomings, since critical events can occur at any time or, in any case, develop in the time between two successive inspections. Conversely, it may happen that the time set for inspections is extremely conservative compared to the actual stability conditions achieved at the site. It is therefore understood that this type of approach is primitive compared to the technologies that can be relied upon today.

According to what was mentioned before, apart from affecting human safety, has a direct impact on inspection and maintenance costs. Often, in fact, even replacements of certain components and maintenance work are performed with the same time-based approach, and this implies a large economic impact that can be limited especially if the structure is in good health. An automatic structural monitoring system provides a solution to both problems and, in addition, allows constant monitoring of those parts of the structure that are difficult to access (cables, bolts, poles) that may be overlooked in a routine inspection.

Most research on SHM strategies-as is commonly the case in civil engineering-has been motivated by disasters such as bridge collapses (e.g., the Morandi Bridge in Genoa, Italy) (Strauss et al., 2020a).

Failures of tunnel support systems during construction can also mobilize a large portion of the underground space, causing a series of chain events, such as large volumes of soil inflow or flooding of the excavated tunnel, substantial sinking or collapse of nearby and aboveground structures, and significant delays in delivery. During operation, the interaction between tunnel and soil is often considered to be a relatively stable and therefore reliable load bearing capacity system. However, the consequences of failure are still of great significance as highlighted above.

Transportation infrastructure, as reported in previous chapters with particular reference to tunnels, has considerable uncertainties. Load conditions, especially in structures that span hundreds of meters, can undergo significant changes over time that directly affect the supporting structures.

While critical episodes are limited, careful consideration must be given to the fact that without adequate monitoring during the useful life of the works, one is faced with undesirable situations that are difficult to manage without having the appropriate information available. These conditions are related to the continuous and inevitable degradation of materials (e.g., corrosion of steel, carbonation of concrete), which can be even more facilitated in underground environments. (Chen & Ni, n.d.)

SHM should rely on advanced sensors and real-time measurements in order to offer great potential for informed and effective infrastructure management.

Sensors should be inexpensive and easy to implement so that they can be applied to existing civil structures with little effort. It is generally expected that the sensor system will work for the lifetime of the civil structure, which can be up to 50 or 100 years. Therefore, a robust sensor system that maintains reliability over the life of the structure is required.

Such a monitoring strategy provides continuous information that allows the maintenance plan to be updated, providing a clear understanding of the remaining useful life of the structure, which could be longer or shorter than originally defined in the original design.

Structural health monitoring has the potential to improve the design and management of civil structures in several ways:

- Design assumptions and parameters can be validated when necessary.
- Inspections can be scheduled more rationally based on monitoring data, bringing cost savings and improved safety.
- Performance levels can be accurately defined to provide warning when prescribed limits are violated, such as for load anomalies due to pushing phenomena and crevice pressures.

- Real-time safety assessment can be performed during normal operations or during and immediately after disasters and extreme events (e.g., fire, earthquake, slope instability).
- Fosters a better understanding of structural response, which is necessary for the development of new models and design methods.

However, there are still few examples where structural state monitoring (SHM) technology has successfully moved from the research phase to practical application, which is typically limited to the following situations:

- Infrastructure with innovative structural solutions and/or materials.
- Structures of great strategic importance belong to the transportation network.
- Damaged structures awaiting rehabilitation or replacement.
- Reference structures representative of the national heritage, monitored for the creation and verification of degradation models.

Although in the field of civil engineering the field of structural condition monitoring (SHM), as understood above, is still in its infancy, its development would generate innovations in the design and maintenance of civil structures, leading to the development of modern smart infrastructure. (Strauss et al., 2020a)

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