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Smart monitoring to aid the safe excavation of a tunnel in an urban area

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This paper illustrates the geological-technical problems encountered in the design and construction of the Küchelberg road tunnel, which constitutes the second completion lot of the Merano bypass in the province of Bolzano, and in particular the characteristics of the specifically developed monitoring system. The tunnel layout runs in an urban environment with low overburden for approximately 2 km in two clearly distinct geological conditions that affect approximately 50% of the tunnel: the Merano side (west) in alluvial soils, the Passirio side (east) in rock. The article describes the type of monitoring system, so-called "active or smart" monitoring, which makes it possible to follow the evolution of significant parameters that are indicators of the potential criticality of the excavation activities on the pre-existing ground with timely updates on a informatic platform.
Keywords: *tunnel excavation, geotechnical monitoring, blast vibrations, rock impedance, site law.*

1. Introduction

In underground works, especially if they are characterized by particular geological complexity and significant interference with pre-existing surface structures, even after the most accurate investigations there remain residual uncertainties about the effective behavior of the underground and the deformation responses induced by the excavation. Acknowledging the impossibility of always providing deterministic solutions, the design defines guidelines indicating the key parameters to be checked during construction with the respective ranges of values within which to apply, and if necessary, adjust the design hypotheses. This is, for example, the division of standard sections according to geomechanically homogeneous sections.

For more than thirty years, this observational design method has taken on even greater importance in urban underground works with low overburdens, depending on both population density and the prestige of the buildings underneath or otherwise interfering with the excavations. In an extreme summary, it proceeds by indicating in advance the limits of acceptability of the values of certain quantities representative of the excavation-structure iteration, with a contextual system of geological verification and geotechnical monitoring during construction such as to allow the adoption of corrective measures if the defined limits are reached.

The evolution of this process, which has been successfully introduced in the project of the second Lot of the Merano ring road by defining it as "smart monitoring", consists in making the processed monitoring data available in real time: the result is the possibility of continuously optimizing even details treated, inevitably, in generic terms during the design (geometry and dimensioning of the flyover schemes, pressures and mixes of the concrete consolidations, ...), preventing risks on the structures and thus focusing one of the primary objectives for this type of work.

2. The Küchelberg Gallery

The Küchelberg (Monte Benedetto) tunnel is a road tunnel of slightly more than 2 km in length, with two lanes and an inner radius of 5.9 m, which underpasses the city of Merano and the 'Küchelberg' mountain. The construction of this work (Lot 2) completes the Merano bypass, which aims to relieve the city of through traffic and improve the connection of Val Passiria and Tirolo to the 'MeBo' Merano-Bolzano motorway (Fig. 1). The underground roundabout along the tunnel creates a direct connection to the future underground garage and offers the possibility of reaching the city centre without driving on city streets, thus avoiding traffic and reducing pollution. The work was commissioned by the Autonomous Province of Bolzano to the San Benedetto Consortium consisting of the contractors: CarronBau – PAC SpA – Mair Josef with Carron Bau Srl a current contract value of Mair Josef & Co SpA approximately EUR 120.000.000. The project was carried out by: Engineer Aribo Gretzer, Engineer Manfred Ebner and Prof. Engineer Konrad Bergmeister. The supervision of the work is being carried out by the professional group: Ingenieurteam Bergmeister Srl – EUT Engineering Srl – Valdemarin Srl – Plan Team Srl – Kauer Ingenieure Srl – Pfeifer Planung Srl – Ingenieurgemeinschaft Ing. Aribo Gretzer & Partner GMK – Sint Ingegneria Srl – Ing. Manfred Ebner – Ferro Studio Ingegneria Srl and the technical consultancy by Pro Iter Srl.

Fig. 1 – Satellite view with overlay of the Küchelberg Tunnel.

3. Geological framework

The tunnel line involves two clearly distinct geological conditions: on the Merano (West side) in alluvial soils, on the Passirio (East side) in rock (fig. 2). The excavation in loose soils, about 1 km below Via Goethe, the main city street, with only 6-8 m of overburden is of high technical complexity due to the risk of subsidence. This section of natural tunnel with associated consolidation and pre-support using jet-grouting and pile umbrella arch is being excavated from both portals: on the Merano side since June 2022, after an initial complex four-lane artificial tunnel with excavation under slab following the "Milan method"; on the Passirio side since July 2022, having completed the advancement of the first kilometer in rock during 2021 (circle in fig. 2). The subject of this note is the approximately one kilometer in rock excavated in the first year of advancement on the Passirio side.

4. Excavation in rock

The main geological peculiarity of the rock part of the tunnel is the crossing of the Periadriatic lineament, here called the Merano-Mules fault, which separates the South Alpine unit of Brixen, consisting of cornubianitic phyllites (contact metamorphism is induced by the nearby Permian granodioritic intrusion), from the Austroalpine Marling fault, with predominantly cataclaseous gneiss and micaschists.

In contrast to the problems encountered with the Brenner Base Tunnel (BBT), in the Meran Periadriatic Tunnel the excavation involved the contact at a greater original depth, when it was subject to metamorphic conditions in amphibolite facies, so that the cataclasites of the fragile Mules environment found during the excavation of the BBT are replaced by recrystallized milonites in ductile conditions (Fig. 3), with greater self-supporting capacity. The entire rock tunnel, in fact, even in the core zone of the Merano-Mules lineament, was always supported by applying the type section envisaged in Class III (Fig. 4), with a first-phase lining consisting only of radial bolts and shotcrete, without ever requiring the adoption of a more rigid, ribbed or pre-supported section.

The excavation by blasting involved rocks of moderate geomechanical quality (RMR ~45÷55, GSI ~50÷60, intact rock resistance up to 200 MPa), characterized by medium-low overburdens (50÷70 m) and studded on the surface with valuable and very delicate buildings (Fig. 5), such as castles, medieval towers and Liberty villas from

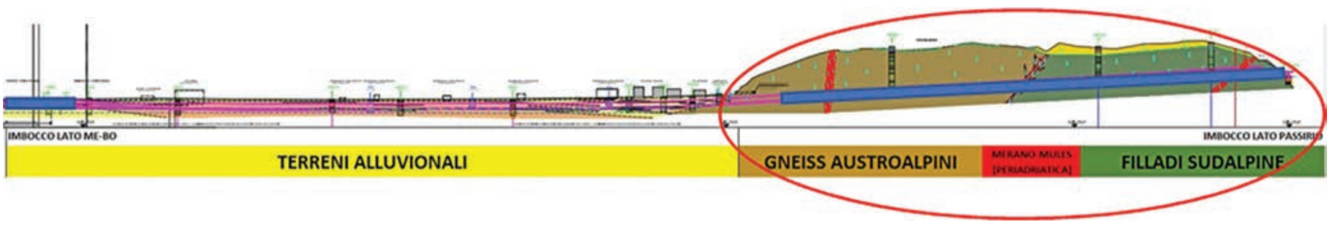

Fig. 2 – Schematic geological profile.


Fig. 3 – Photograph of the tunnel excavation face (near the crossing of the Merano-Mules Lineament).

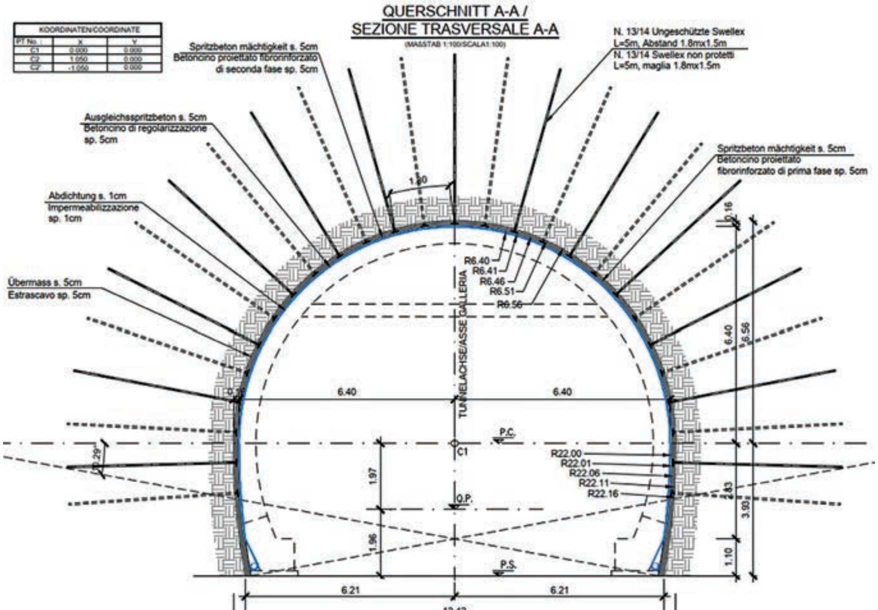

Fig. 4 – Section type class III.


Fig. 5 – View of the Küchelberg (Monte Benedetto) crossed by the homonymous tunnel.

the early 1900s. The risk that excavation with explosives could interfere to an unacceptable extent with these pre-existing buildings had led to the hypothesis of alternative rock felling solutions, in particular the use of a roadheader, a hypothesis that later proved to be incompatible with the need to reduce the time required to complete the work as much as possible.

4.1. The smart monitoring

Traditionally, geotechnical measurements in tunnels are used, in application of the 'observational method', as indicators of rock behavior at excavation, to be compared with the design behavior expected. However, tunnel advancement proceeds autonomously, and monitoring takes action during construction only if some parameter (convergence, extrusions, stresses, rock quality indexes, etc.) exceeds the expected limit value of attention and/or alarm. In the case of the excavation of the Küchelberg tunnel by blasting, on the other hand, the feed-back of the vibrometric monitoring constituted a necessary constraint for the dimensioning of the firing pattern of each blasting.

The most usual and also adopted normative reference for vibration control is the German DIN4150 standard (fig. 6, with recordings referring to a delicate construction), which reports:

- The peak vibrometric velocity of the maximum component (Peak Particle Velocity = PPV in mm/s, on the ordinates of the diagram),
- The respective main vibration frequency (Hz, on the abscissa)
- The building typology, identifying three threshold curves for progressively more conservative conditions: V1 (industrial buildings), V2 (reinforced concrete dwellings) and V3 (monuments and delicate constructions).

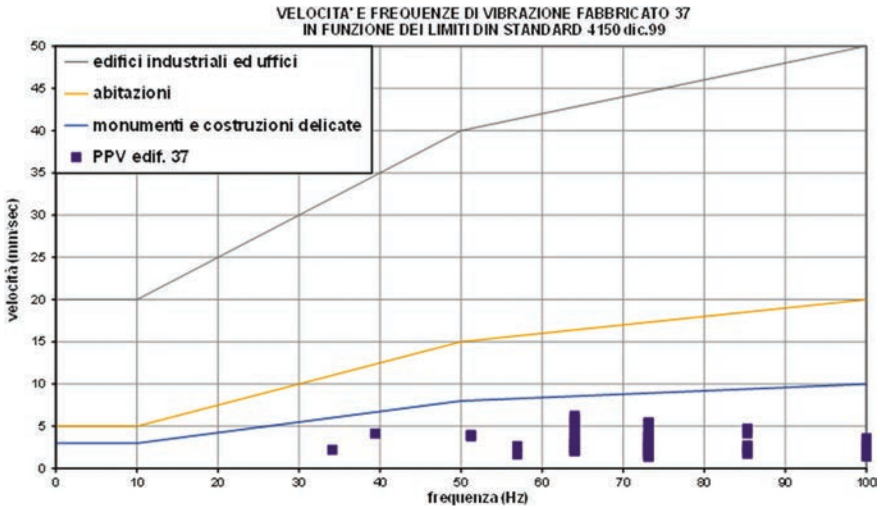

Fig. 6 – Building no. 37: measured PPV as related to the vibration limits in the frequency and speed diagram (DIN4150).

The majority of the structures undercrossed by the Küchelberg tunnel require the containment of PPVs within the V3 line. In view of this constraint coupled with the short distance between the blasting sources and the sensitive receptors, the permissible unit charges of explosives were, at least in some sections of the tunnel, at the limit of feasibility during the preliminary dimensioning.

For this reason, work was carried out on two fronts: on the one hand, an accurate study of the firing patterns, limiting the depth of each blast and using the maximum number of delays to reduce the unit charge, and on the other hand, setting up a monitoring system that would not only give immediate and continuous feedback at each blast, but whose feedback would also be a necessary condition for the dimensioning of each subsequent firing patterns and blasts. In this sense, the term "smart monitoring" is an integral and necessary part of the advancement.

The approach initially followed traditional criteria: the execution, at the end of March 2021, of a vibrometric monitoring test field with in-hole blasting of small, growing charges for the preliminary determination of the "site law", i.e. the mathematical expression describing the attenuation of vibrations in the rock mass through the correlation between unit charge, distance of the receptor from the blasting source and vibration velocity (PPV). In this case, the most common regressions were adopted: the 'quadratic law' of Duvall-Petkov (1959), the 'cubic' of Ambraseys-Hendron (1968) the formulation of Langefors-Kihlstrom (1973) (examples in fig. 7).

As can be seen from the examples in Fig. 7, however, these formulations show low correlation indices; moreover, they vary at each blasting, as they depend on the seismic transmissivity of the rock medium crossed, which in turn changes as a function of the geomechanical parameters (fracturing, joint opening and filling, strength and elasticity characteristics of the rock mass, ...). The site law is then also a function of the drilling geometry and the explosive charge-rock coupling: even if executed with a latest-generation robotic jumbo, it is inevitable that some holes will not be perfectly aligned with respect to the exact position foreseen by the

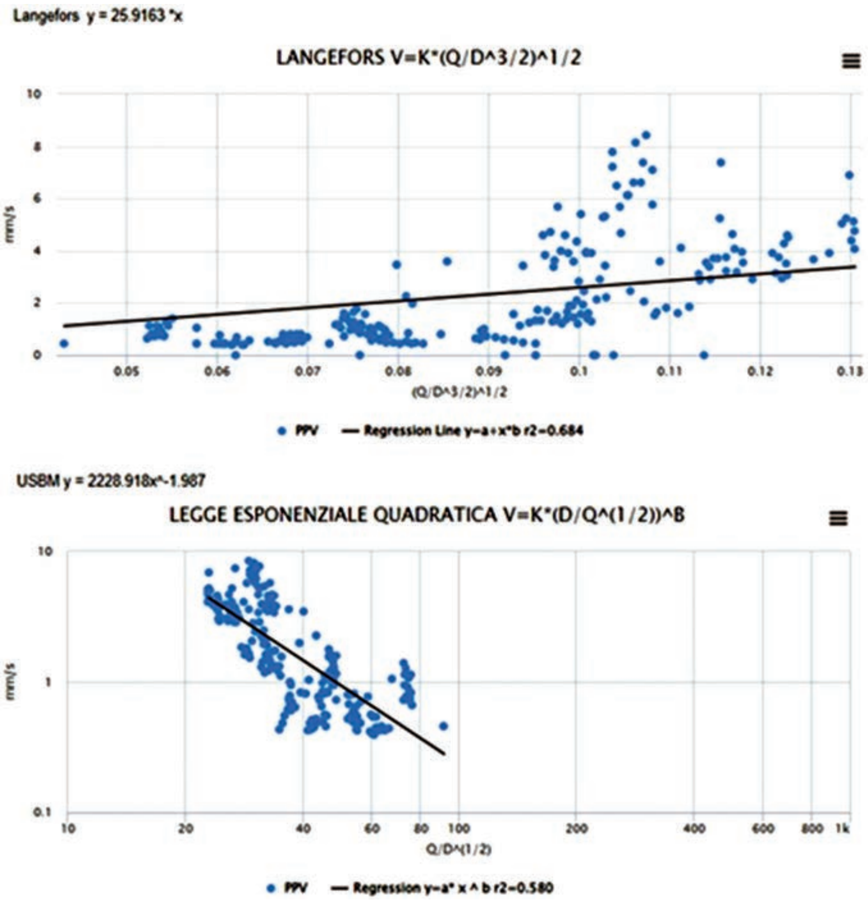

Fig. 7 – Regression examples of actual measured vibrometric data.

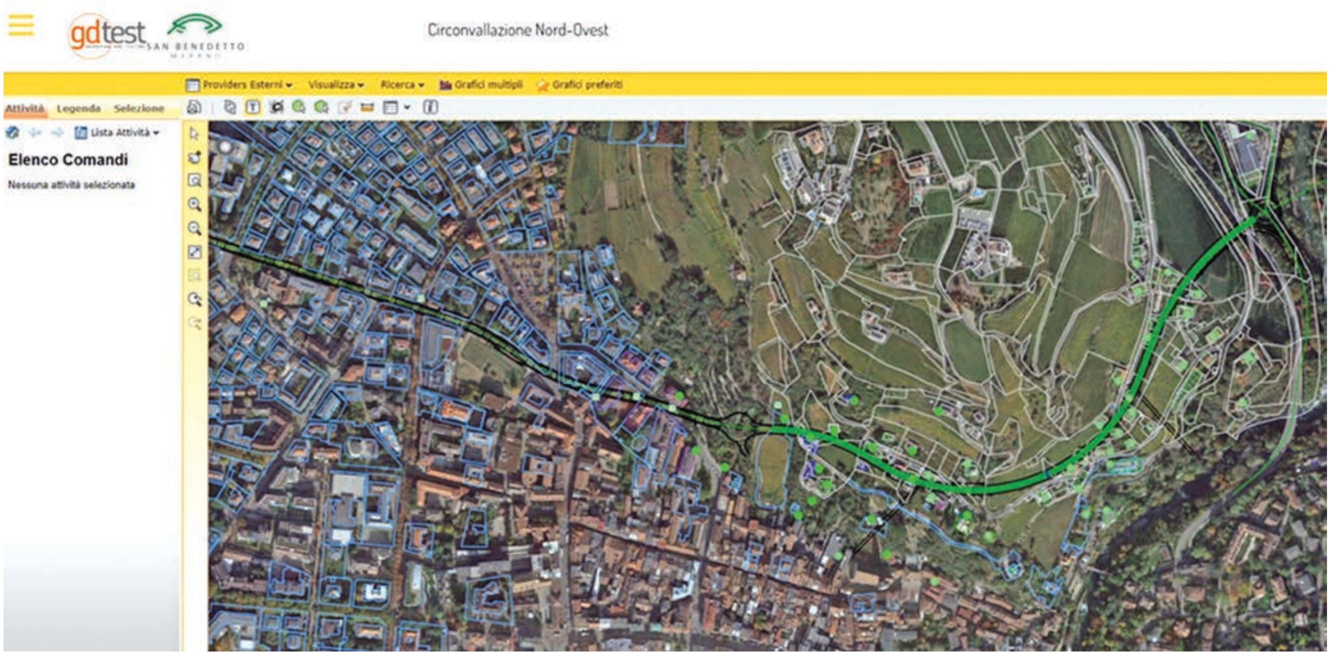

Fig. 8 – Areal distribution of triaxial vibrometers.

shot pattern. Lastly, the imperfect synchronization of the detonators also supports uncertainty in the vibrometric response.

In view of these considerations, improved smart monitoring procedures compared to traditional vibration control practice, some of them even innovative, have been put in place to ensure compliance with DIN4150 at all times:

a) *Vibrometric monitoring carried out with an areal distribution*, by the installation of triaxial measuring instruments not only on all the most delicate receptors, but also on the less critical ones if they are located in poorly covered areas. A total of 51 fixed measuring points were monitored, indicated with the green dot in Fig. 8, of which 18 vibrometers were simultaneously active with automatic remote transmission of data (updated every 20 minutes) on the GDTMS web-GIS platform developed by the company GD Test of Turin.

b) *Continuous updating of the site law after each individual* blast in order to plan and optimize the maximum permissible unit charge for the next blast. In the example in Fig. 9, to ensure a maximum PPV of 5 mm/s, 6.5 kg of explosive per delay is permissible on a receptor placed at 55 m from the blasting source.

c) *Map display of vibrometric iso-velocity curves.*

Despite the refinement of the vibrometric control obtained with the two previous points, in particular with the updating of the site law after each blast (on avera-

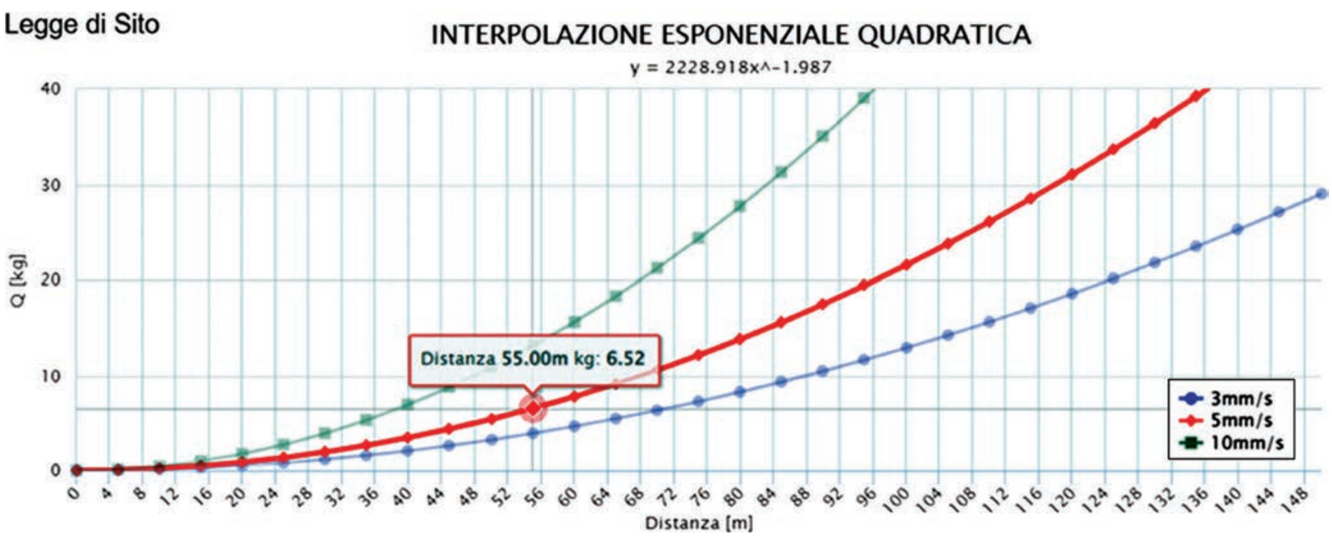

Fig. 9 – Site law calculation updated after blast no. 405.

ge, two blasts per day were shone each with an average net advance of about 2 meters, for 5 days/week plus a single advance on Saturdays, therefore with an average production of about 20-25 m/week for a total of 560 blasts), it became evident that applying the law to all receptors *tout court* would be inadequate, both because each surface point has a different vibrometric response and because not all receptors have the same vulnerability.

For the optimization of the firing scheme, an additional piece of information had to be acquired: the refinement of the site law also according to the planimetric location. With this in mind, GD Test developed the 'vibro-contour' SW application, which allows peak iso-velocity curves to be displayed and automatically updated directly on the GDTMS platform map.

In Fig. 10, for example, relating to blast no. 405 at pk 2+380.7 on 8 February 2022, with 10.7kg of maximum explosive charge per delay and drilling depth 2.0 m, it can be seen that two receptors slightly exceeded 7.0 mm/s. One of the two, named V6, is placed on a sensitive building: although still well within the permissible limits of the L3 curve, it was deemed precautionary to take corrective action.

From the analysis of the vibrogram of V6 corresponding to the previously mentioned blast (fig. 11), it is also possible to put in evidence that the peak velocity (PPV = 7.51 mm/s) was recorded on the vertical component with a delay of 870 ms from the '*zero*' time detonation, i.e. at the ordinary detonator #9. The subsequent blast No. 406, which was characterized by a reduction in the charge of the detonators used for time #9, recorded PPV = 5.41 mm/s (Fig. 12), which was achieved even without a reduction of the advance excavation (2.0 m).

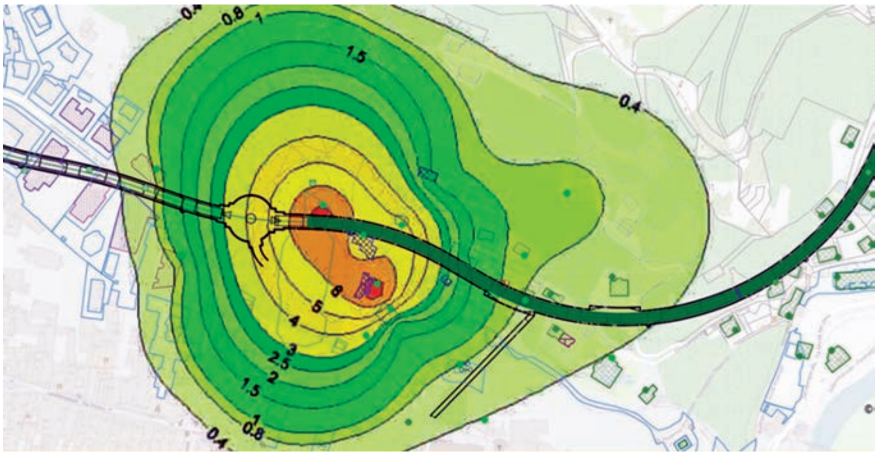

Fig. 10 – In-plant distribution of the vibrometric response following blast No. 405 of 8/2/22.

By actively working with this criterion on each single blast, it was possible to guarantee the V3 limit of DIN4150 and prevent potential damage as a result of excessive vibration levels.

Correlation between RMR and PPV: an ongoing issue

Fig. 13 shows the synoptic diagram with the peaks of the vibrometric velocities (PPV, left-hand Y-axis) recorded on the surface

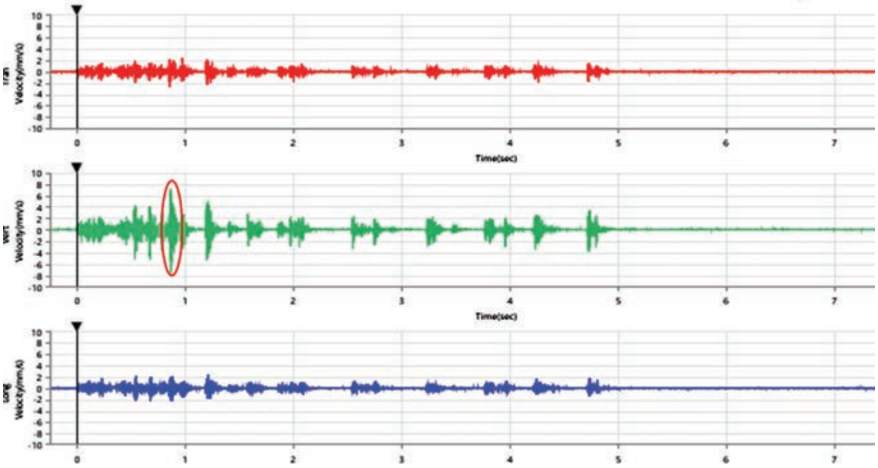

Fig. 11 – V6 building vibrogram induced by blast No. 405 of 8/2/22.

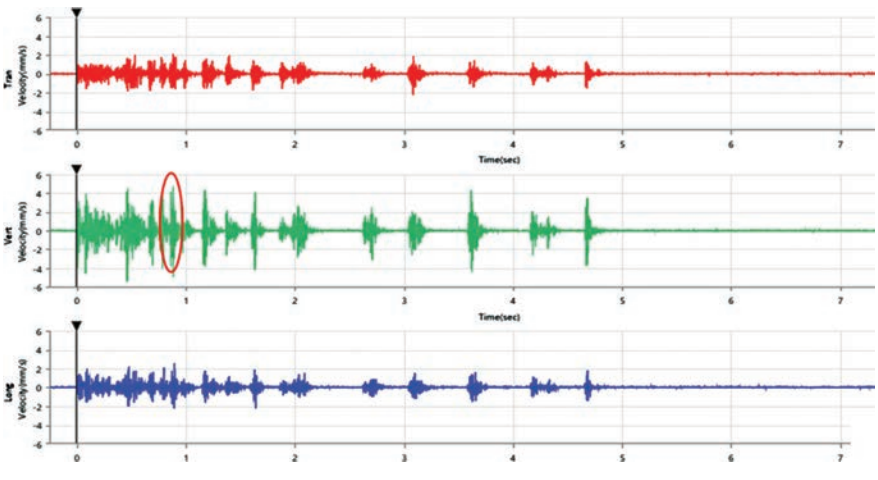

Fig. 12 – V6 building vibrogram induced by blast No. 406 of 8/2/22.

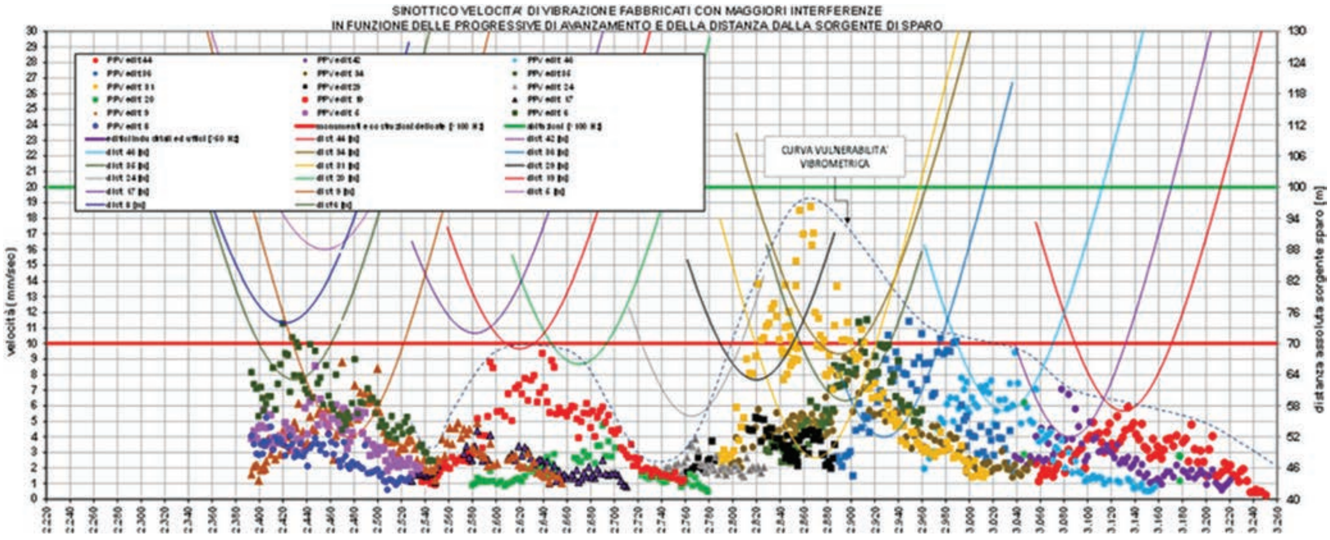

Fig. 13 – Vibration peaks (PPV) of the most interfering buildings as a function of distance.

preexistences most interfering with the advance, as a function of the tunnel progressions (X-axis). Each dot represents the vibrometric peak of each blast, with the lower horizontal line indicating the most conservative limit V3 of DIN4150 (delicate buildings and monuments) and the upper line the intermediate limit V2 (civil buildings). The right-hand Y-axis also shows, again as a function of the progressives, the absolute distance between the buildings and the shot source, with equal colours for the same receptors for both PPV values and distance curves. It is evident the growth/decrease evolution of the vibrometric impact as a function of approach to/from the building.

Thanks to the constant refinement of the shooting patterns during construction on the basis of smart monitoring, the V3 limit was complied with, except for sporadic and insignificant slight overstepping. The building corresponding to the yellow points is a reinforced concrete structure that allows vibration levels within the V2 limit (up to 20 mm/s >100 Hz).

The diagram in Fig. 14 shows, again as a function of the progressions X-axes, the trend of RMR and GSI surveyed during excavation (with a comparison of the same indices forecasted by the executive design). The vertical pink bands represent fault and/or pervasive cataclastic zones (the most extensive, of course, in the central position the Merano-Mules periadriatic lineament). Six 'vibrometric classes' have also been identified on the right-hand Y-axis, corresponding to zones in which the vibrometric risk increases with the same distance between source and receptor. A certain qualitative correlation can be observed between the rock quality indices (RMR and GSI) and the variation of the PPV values measured at the surface (not only due to the different distances). A detailed analytical study is being conducted to search for possible mathematical formulations of correlation between these parameters.

5. *Excavation in loose material*

After approximately one kilometer of rock excavation, in August 2022 the advancement from the Passi-

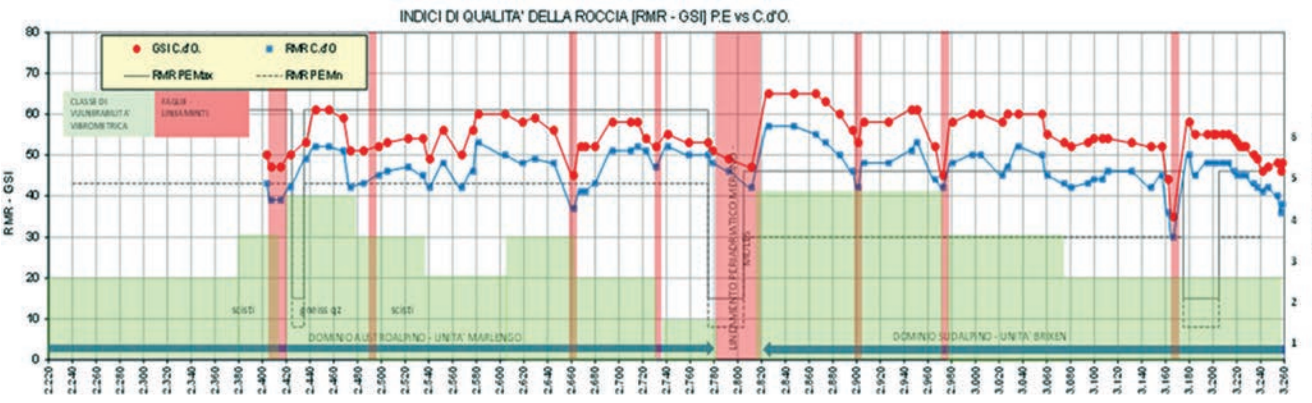

Fig. 14 – Quality indices (RMR and GSI) predicted by P.E. and found during construction and vibration classes.

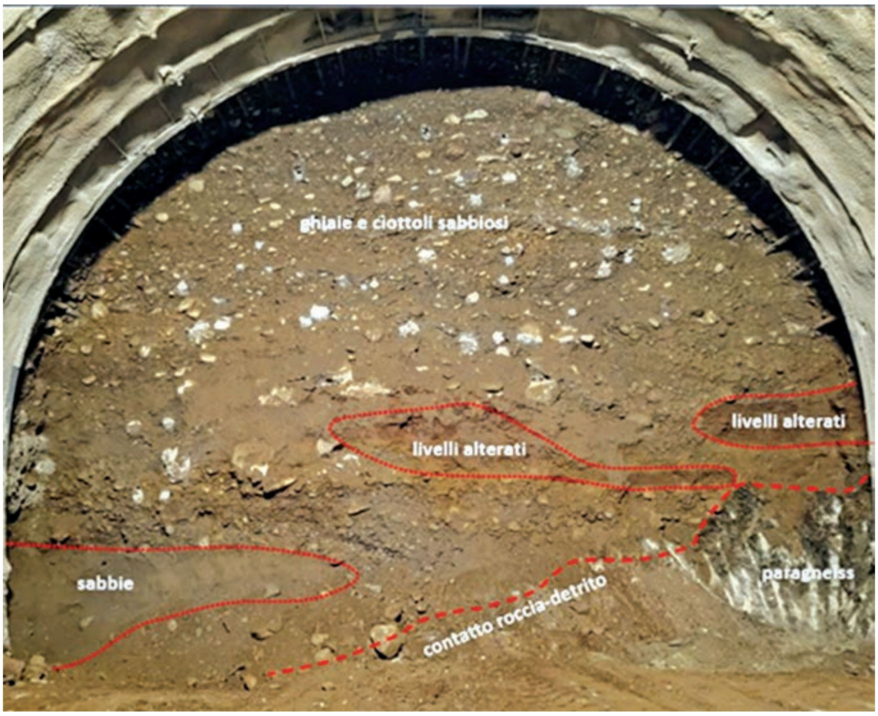

Fig. 15 – Excavation face in loose material.

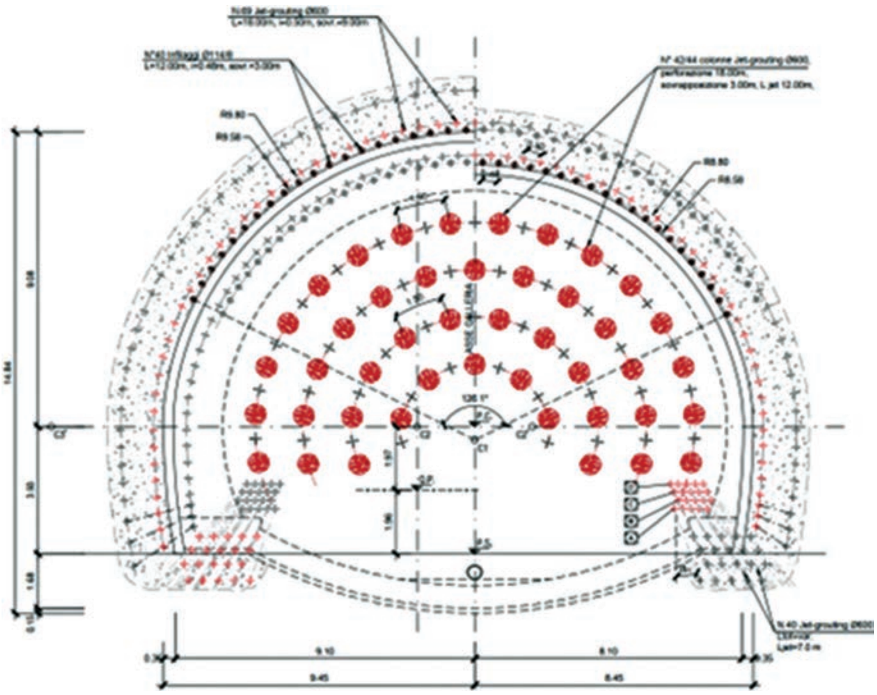

Fig. 16 – Standard section in loose soil with fields L = 9 m.

rio side entrance also reaches the alluvium of the Adige River, consisting of very constipated sandy gravel with pebbles and blocks of even metric dimensions, in a sparse silty matrix (Fig. 15 – note the contact with the rock substratum on the right foot).

The average tunnel overburden is about 6-8 m below the main road but, in some sections under buildings, a minimum distance of about 4 m is reached between the basement floors of buildings and the excavation profile (1.5 m relative to the extrados of the consolidations).

In order to consolidate the ground and counteract subsidence, the project includes a crown of sub-horizontal micropiles (umbrella arch) and jet-grouting at the extrados, while additional jet-grouting columns consolidate the excavation core and the foundations of the ribs (Fig. 16); along the sections which underpass the buildings the consolidations are reinforced with additional jet-grouting and a double crown of micropiles. Each consolidation operation involves 18 m of soil in front of the tunnel face. Excavations are then carried out in modules ('fields') of 9 m length: this results in a 100% consolidation overlap. The first-phase lining consists of profiled ribs and fiber-reinforced shotcrete.

5.1. First Monitoring Findings

Figures 17 and 18 show the plan view and cross-section of the tunnel section from rock to loose soil with subsequent undercrossing with minimal overburden of a historic masonry building and a school complex. At the end of 2022, the first 7 fields are excavated, so the excavation is under the school (consolidations have already passed it).

The smart monitoring of this section is mainly aimed at the continuous control of subsidence and 3D displacements based on an automated optical survey with two remote total stations that detect: a series of optical prisms positioned along the roads both transversally and longitudinally with respect to the advancement, a series of optical prisms positioned on the buildings and, where it is not possible to apply prisms a series of significant points detected in reflectorless mode. In order to integrate the automatic optical monitoring, WSD (Wireless Smart Datalogger) type instruments

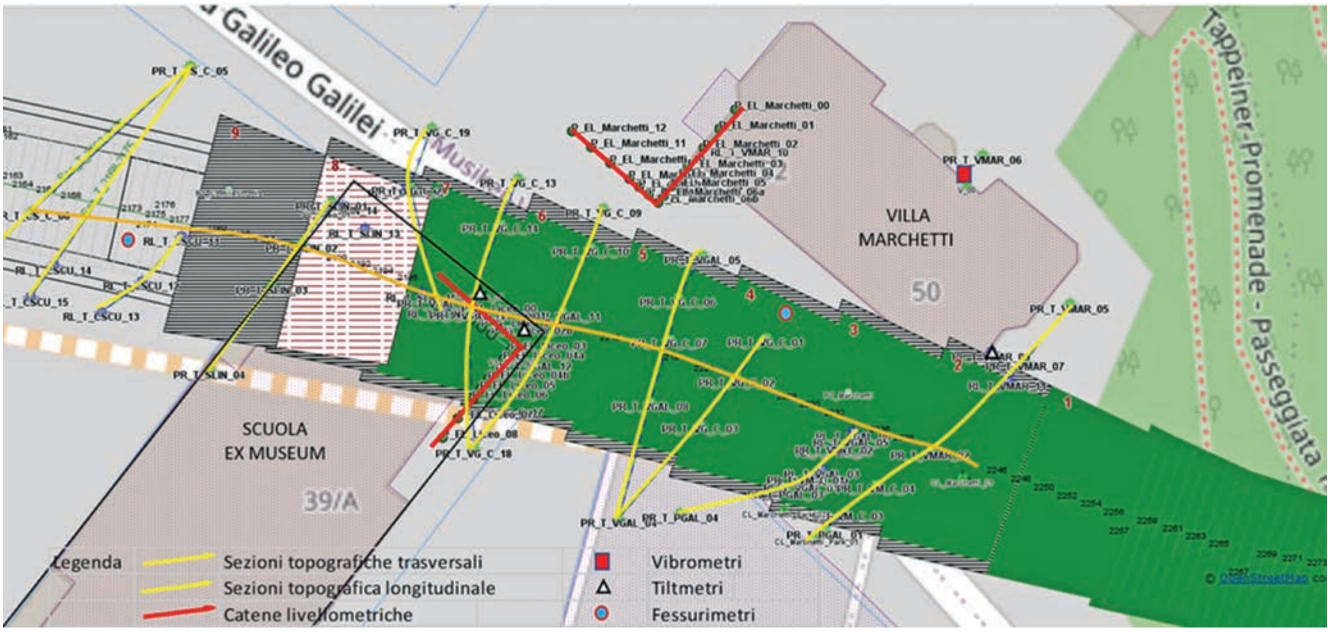

Fig. 17 – Plan view with projection of the tunnel under excavation. The green background indicates the advancement fields excavated of length 9 m.

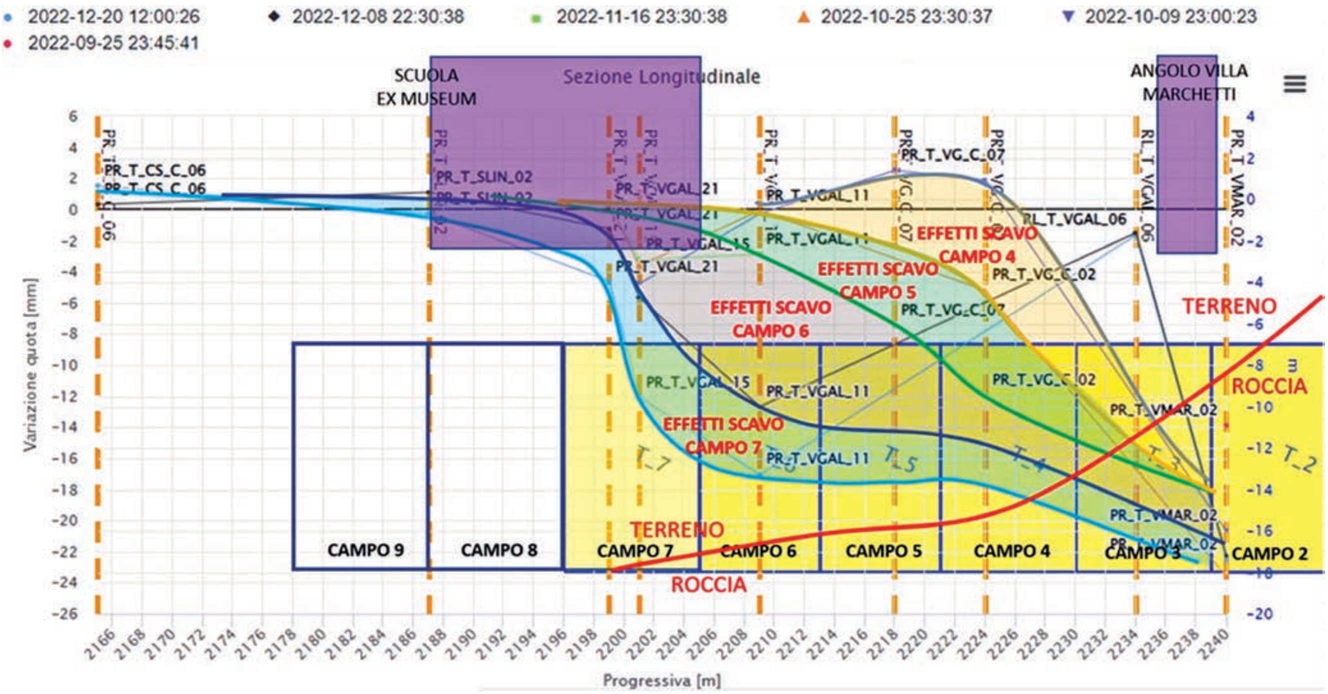

Fig. 18 – Longitudinal section with the subsidence curves and the respective contribution for each field (left Y-axis); also schematically represented are the advancing 'fields', the interfering buildings and the axial trend (downward line) of the soil-rock contact.

were installed, managed through a specific WSN (Wireless Sensor Network): wireless electrolevels beam sensors, surface tiltmeters, crack-meters and vibrometers on the buildings, to monitor any deformation effects induced directly on the structures, and automatic piezometers for continuous control of the possible influence of the underground work on the water table.

The results of these initial advances were favorable, with no lesions observed on the school and only the presence of aesthetic cracks in Villa Marchetti in particular (Fig. 18):

- The subsidence at the front at the end of the 7th field is of the order of 3 mm against the 10 mm of the attention threshold.
- The subsidence away from the front is of the order of 24 mm with a tendency to exhaustion and in accordance with the calculation values.

- The maximum distortion recorded by electrolevel beams installed in the school, 1/333, is in accordance with the attention threshold away from the front.
- In tunnels, the convergence and levelling values are almost zero.

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