Drill and Blast Vibration Monitoring: the overpass of A10 Motorway.

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ABSTRACT: Drill and blast excavation produces the propagation of seismic waves with consequent vibration phenomena in the surrounding rock mass, interfering with pre-existing structures or infrastructures. The paper presents the case of Borzoli Erzelli Tunnel (excavation area equal to 120m^2). The tunnel has to overpass two tubes of existing motorway tunnel "Don Guanella" in operation with only 6m gap. In order to predict the short-distance effects due to the excavation and evaluate the actions necessary to ensure the minimum impact on the interference, different predictive models have been adopted, both theoretical and experimental. The processing of the vibration monitoring system data recorded during excavation advancement led to have an accurate prediction of the short-distance effects; this allowed designing the appropriate blast scheme to overpass interfering tunnels. The overpass requires the application of not typical mitigation measures, which request different intervention procedure than the one usually applied for the most common underpass.

1 INTRODUCTION

Drill and blast excavation produces the propagation of seismic waves with consequent vibration phenomena in the surrounding rock mass, interfering with pre-existing structures or infrastructures.

The paper presents the vibration phenomena analysis due to the drill and blast excavation of a road tunnel, which overpass a pre-existing highway tunnel. The minimum gap between the tunnels is equal to 6 meter and the traffic interruption inside the highway tunnel was no necessary during excavation stage.

The drill and blast excavation inducts a stress-strain variation on pre-existing tunnel and on its structural condition. The developed solution considered that. The adopted design solution had to integrate different phases related to design issues, executive problems and assembly aspects. All of them are equally indispensable for the overpass realisation.

The evaluation of inducted seismicity due to the blast is a complex issue. The parameters characterizing the seismic wave propagation inside the rock mass are several. In the most of cases, the procedure to determinate these parameters is costly and the precision of the collected data is not always sufficient.

The commonly adopted approach is to correlate the intensity of the effects produced on the pre-existing structure, by the vibration phenomena, to the vibration velocity and frequency of the particles. Analysing the data measured during the nearing of the excavation face to the interference it is possible to reconstruct the propagation law related to the specific site. The site law allows correlating the distance of the excavation face and the maximum instantaneous charge, to the vibration velocity on site. Using this law is possible not only to predict the effect of the excavation close to the interference from data obtained at greater distances, but also to evaluate the possible interventions on the blast in order to limit the induced effects and ensure the safety of the pre-existing structures.

After a short recall about the predictive models commonly used for the evaluation of the vibration phenomena caused by blasting in rock masses, the paper describes the application of that models to the specific case of the Don Guanella highway tunnel overpass. The design vibrational limits applied and imposed by international rules will be underlined. The paper discusses the design approach and the operational mode applied during the excavation in the proximity of the interference. The comparison between the prediction about the vibrational aspects and the results of the monitoring campaign will close the paper.

2 THE VIBRATION THEORY

The theoretical predictive criteria used estimating the dynamic stress levels produced by blasting as a first analysis.
The literature listed a series of semi-empirical correlations, generally defined "site law. The paper reports only the approaches adopted at the first design stage to estimate the effects and possible critical issues related to vibration in the case of interest.

Scientific considerations and statistical analysis used to develop typical relationships between the variables and the particle velocity and generally represented by formulas such as:

$$v = k \cdot Q^{\alpha} \cdot R^{\beta} \quad (1)$$

where*: v (m/s)* is the maximum particle velocity *k;* α, β are coefficients related to the quality of the rock mass and blast type; *R* is the distance (m) between blast and the measurement station; *Q* is the maximum instantaneous charge (kg); *k* is a coefficient related to blast pattern and rocks mass characteristics; typical values for α e β are 0.5 e 0.75 respectively.

The evaluation of an appropriate k coefficient is complicated. It is commonly adopted a value derived by scientific literature which gives a restrictive reference value such as k = 70 (in case of compact rocks with layers connected to the structure to be defended) and k = 40 (in case of a fractured rock without direct connection between the layers and the structure (Jannello *et al*, 1986).

Another possible predictive approach is the one applied by the German BGR (Bundesanstaltfur Geowissenschaften und Rohstoffe – Federal Bureau for Mine and Raw Material). BGR suggests the following formulas, which have the same form but use different parameters according to the lithology

$$v = 969 \cdot Q^{0,59} \cdot R^{-1,52}, \quad (2)$$

$$v = 206 \cdot Q^{0,80} \cdot R^{-1,30}, \quad (3)$$

sedimentary rock (2) and crystalline rock (3), respectively; original rocks on which there began the metamorphic process is generally considered in case of metamorphic rocks. Each different zone responds to the induced stresses in a specific way and not exactly predictable only on the basis of theoretical considerations. The experimental predictive techniques used instead on the execution of site surveys. The particle velocity values are predicted by the application of the empirical law such as “scaled distance”, which is an approach commonly used by experimenters (Berry & Dantini, 1986)

$$v = k \cdot D_S^{\alpha}, \quad (4)$$

where *k* and α are only empirical dimensionless constants having purely statistical significance.

The formula:

$$D_S = R / Q^{\beta} \quad (5)$$

Defined the scaled distance D_S (m/kg$^{1/2}$ o m/kg$^{1/3}$).

The *β* range is imposed between 1/2 e 1/3. The correct value depends on two conditions: the shape of the charge and the distance from the stress point. The spherical propagation condition adopted the lower value, while for a similar cylindrical conditions *β* is set equal to 0.5. Furthermore, the short-distance (< 6 m) usually employed the value of 1/3 while greater distance (exceeding 31 m) adopted the value of 1/2 is generally. The induced vibration velocity values recorded during blast with different charges at different distances let to collect the measurement necessary to estimate the parameters α and k. To obtain the site calibration line it is necessary to interpolate the data obtained from the tests. The “specific site law”, defined by this way, is usually a good predictive tool during excavations, also in short-distance conditions. Considering the properties of logarithms appears evident the advantage of using bi-logarithmic scale

$$v = k \cdot D_S^{\alpha} \Rightarrow \log(v) = \log\left(k \cdot D_S^{\alpha}\right), \quad (6)$$
$$= \log(k) + \alpha \cdot \log(D_S) = q + m \cdot \log(D_S)$$

Seismic law can be represented in this plane by a straight line of the form y = mx + b where α represents the angular coefficient (m), while log (k) is the term known.

As for the regulatory framework, currently in Italy there is no specific legislation to correlate the impulsive vibration phenomena to the possible damage on buildings. Standards UNI 9916 and 9614 provide the measurement criteria, the evaluation of vibrations on buildings and the caused disturbance, but do not indicate the acceptable vibration limits. The regulations above for those contexts refer to various European and American standards withholding proven.

The European context commonly refers to German legislation DIN4150. The latter provides thresholds of vibration velocity and frequency. The values are different for different types of construction and ensure, in accordance with the proposed limits, the statistical absence of damage to the buildings. The DIN 4150 fixes the tolerability limits in the maximum value of one of the three components of the vibration velocity, measured at the level of the foundation, as a function of frequency and structure type.

The civil structures are categorized into three types: industrial buildings, residential civil buildings, historical buildings or buildings with sensitive structure. The Figure 1, extracted from the above-cited DIN1450, shows 3 polylines (Line 1, 2 and 3). The lines represent the maximum thresholds of vibration values correlated to the specific tolerable frequencies for the three types of buildings. The Line 1 is the industrial buildings, the Line 2 residential civil buildings and Line 3 historical buildings and/or sensitive structures.

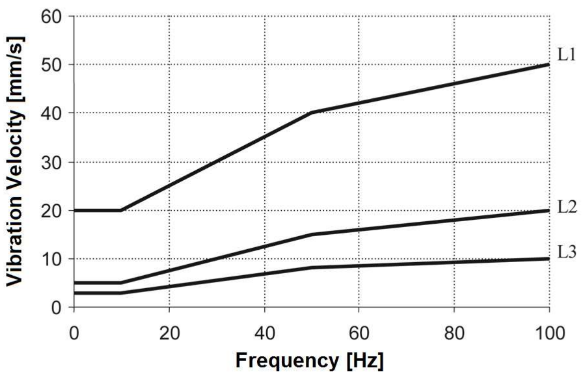


Figure 1. Allowable velocity in function of the Vibration frequency (DIN 4150-3)

3 THE SURVEY PHASE

3.1 *Project overview*

The project consists of a link between an existing road, in Borzoli area close to municipal sports complex, with Erzelli town. The link road includes a new tunnel, which overpasses an existing A10 highway double tube tunnel, called "Don Guanella. The project lies entirely within the municipality of Genoa (see Figure 2). The road facilities include two tunnels, the Borzoli side and the Erzelli side: the first has a length of 138.5 m and develops in single curve, while the second constituted by three sections, one of which is rectilinear, for a total length of 809.5 m.

Figure 2. Project overview

The road section has two carriageways (3.50 m width) and two lateral platforms (1.25 m width). The internal radius of tunnel crown is 6.0 m (See Figure 3).

From a geological point of view, the tunnel excavated inside Metabasalt formation. The rock mass has different fracturing level. The new tunnel overpasses the A10 double tube tunnel at the chainage PK 0+870, with a minimum gap between the existing tunnels and the new one equal to 6.0 m.

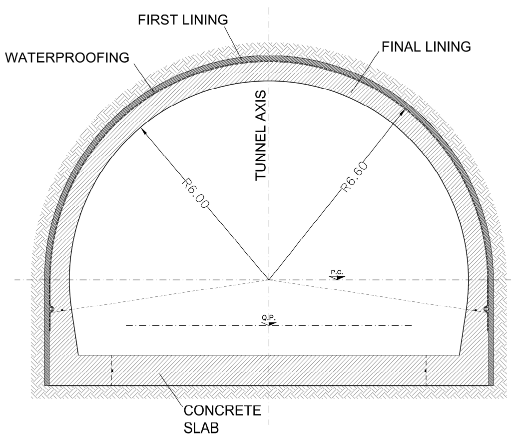


Figure 3. Standard tunnel section

In this section geological and geotechnical survey, underlined several highly weathered passages at the depth of the designed interference between the new tunnel and the existing tunnels. The geophysical surveys carried out confirmed worsening condition in the tested section compared to the neighbouring investigated one. The data set allow to qualitatively defining the rock mass from normally to heavily fractured with local areas of limited thickness completely weathered.

3.2 *Preliminary survey on the pre-existing structure*

The investigations carried out had the purpose to investigate the status, the strength and the thickness of the existing tunnels final lining. The stress level condition of the structures and the one of the rock mass around the tunnel after the new tunnel excavation, have been also analysed. The following list summarizes the performed tests:

- Continuous core sampling within the final lining and uniaxial compression tests
- Continuous coring radially run into the rock masses with a length of 6m and dilatometry tests.
- Overcoring test with CSIRO or USBM load cells in order to determine the stress level on the final lining
- Investigations by flat jack in order to check the state of stress on the final lining.

The tests performed directly from the Don Guanella Tunnel led to obtain in-depth analysis on the local geological condition, on the thickness of the first lining and its internal stress level. The average thickness varying from 50 cm to 60 cm and a maximum stress level equal to 2 MPa has been recorded as the ones acting on the final lining (see Figure 4).

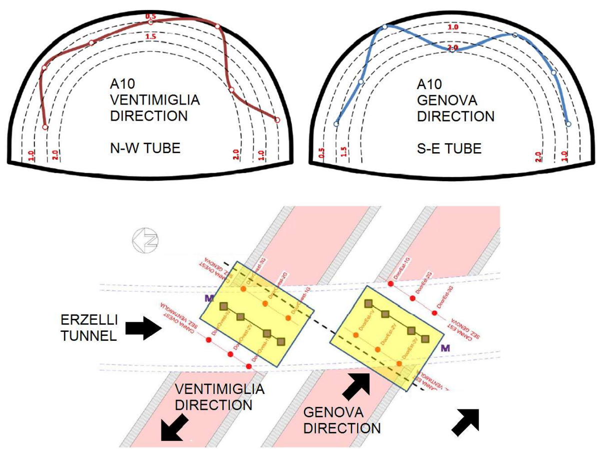


Figure 4. Stress level inside the final lining

The geophysical survey underlined a not predictable critical issue: the presence, between final lining and the rock, of cavities characterized by not regular shape and metric size along the longitudinal direction of the tube.

The detected cavities have been located close to the excavation of the new tunnel. The possibility that vibrations cause the fall of unstable rock portions, in addition to a non-uniform distribution of the stress increases identified the highest risks.

Referring to the first lining structure status, the survey campaign underlined a non-optimal conservation status, confirming what had been highlighted by the first visual inspections.

The uniaxial compression tests carried out inside the tunnel revealed several damaged concrete zones, characterized by a compressive strength around 5MPa (see Figure 5).

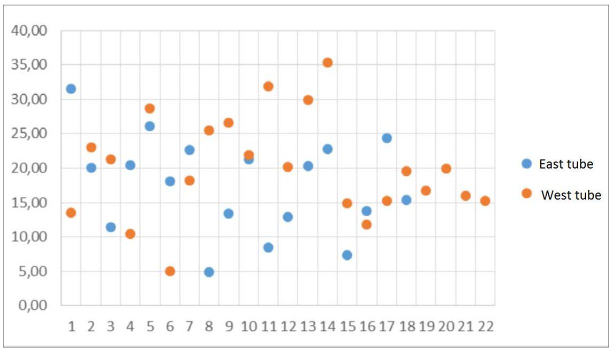


Figure 5. Don Guanella concrete compressive strength

4 DESIGN STAGE

4.1 *Evaluation of stress-strain aspects*

The complexity of the analysed situation, with the crossing of two existing tunnels with an angle of incidence of approximately 36°, has necessarily required a three-dimensional finite element calculation model.

The excavation phases of the Don Guanella double tube tunnel and the ones of the new road tunnel have been modelled. The model considers the pre-existing stress level, defined on the survey campaign carried out, has been used to properly define the effect inducted by the excavation of the Erzelli Side Tunnel within a correct stress-strain condition (see Figure 6). The results of job site test confirmed the model results.

After the construction of the Erzelli Side Tunnel, numerical analysis highlighted a stress level increase up to 5MPa in correspondence of Don Guanella side wall. This increase is not compatible with the structure state highlighted by the surveys. Don Guanella Tunnel had to be operating during the construction of Borzoli Tunnel. In such operating condition, it was not possible to accept any breakage of permanent lining, and the material detachment had to be avoids.

These findings imposed the study of a specific tunnel intervention section; which on one-hand confines the deformation phenomena and the consequent stress effects induced on pre-existences, on the other hand takes into account the vibrational aspects minimization, as described below.

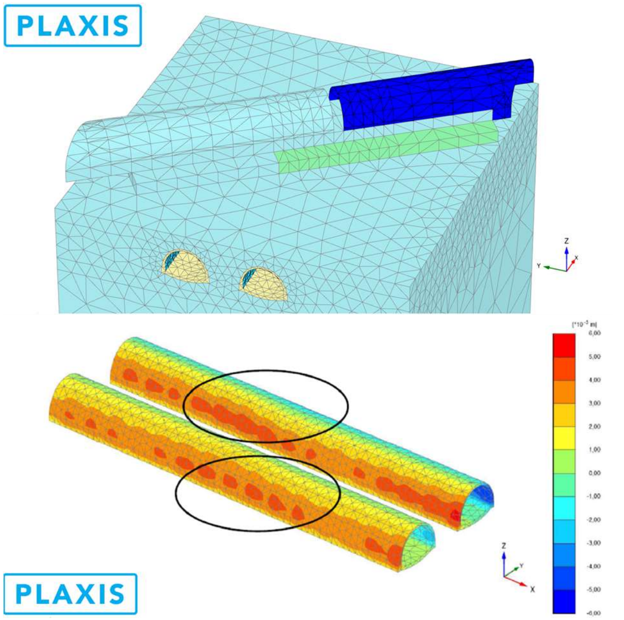


Figure 6. Plaxis 3D numerical modelling

The installation of a properly section type during the overpass led to limit the convergence of the cavity and the final lining stress level increase to only 3 MPa.

4.2 *Vibrational issue: predictive theoretical model*

The Figure 7 reported the curves obtained for the case in question by means of the two approaches mentioned above (see. par.3); The preliminary design during the design stage uses these curves due to absence of in situ data. Considering the discussed situation (the interfering tunnel has been operating during the construction of Erzelli Side Tunnel; the sensitivity of Don Guanella final lining highlighted by the investigations) the standards reference for typical excavation frequencies (greater than 50Hz) specified extremely reduced maximum velocity, with a limit value lower than 10 mm/s. The Don Guanella tunnel structural reinforcements was necessary in order to limit the sensitivity of permanent lining and accept higher speed, up to 20mm/s.

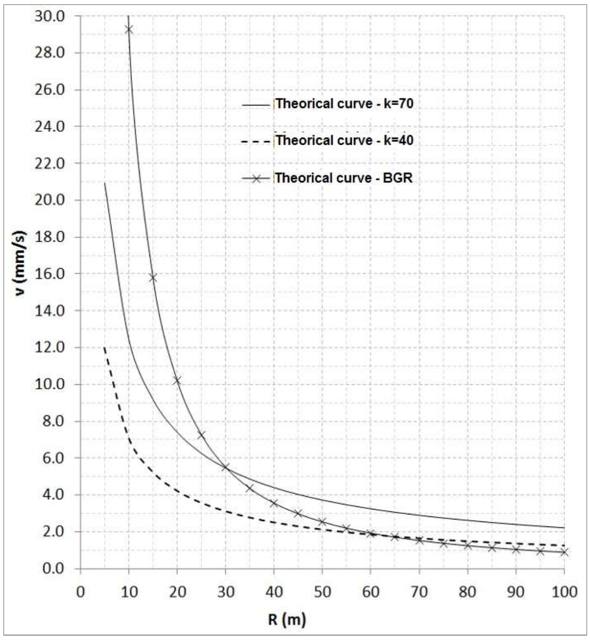


Figure 7. Predictive theoretical curve considering 1kg of Q (maximum instantaneous charge)

The identification of the following possible solutions was necessary to limit the maximum velocity to values comparable to those imposed by regulatory limits: to limit (to 1-2kg) the maximum instantaneous charge or to provide solution for damping of the seismic waves (pre-cutting, etc). The limitation of the explosives amount emerged from the theoretical considerations is restrictive in terms of production, and requires the study of particular blast with a limited material volume removed. The excavation of neighbouring Borzoli Side Tunnel, performed in the same geotechnical context, proceeded with a maximum instantaneous charge between 10 and 20 kg (we consider contemporary blasting all the charges in a time delay lower than 10ms). The theoretical curves also provide information on the influence on the civil works. The theoretical maximum velocity adopting for high quantities of explosive far away from the source (>100m) are few mm/s. The interference band can be extended between 30 and 50m from the interference.

The indications obtained from the theoretical curves represent only a first estimation of the vibration velocity. The curves did not take into account the specific characteristics of the site, the relative positions between the source and the interference, the geometric arrangement of the charges etc. During the design stage, an appropriate vibration monitoring system to be installed during the construction has been defined, in order to calibrate experimental models on the specific site law and eventually adapt the designed interventions.

4.3 *Advancing mode at the overpass*

The numerical analysis and the problems related to the vibrational aspects let to define a specific advancing tunnel section, close to the interference, (See Figures 8, 9, 10). The division in two parts of the section, crown side and bottom part, allows to reduce the explosive quantities adopted and to increase the distance from the tunnel. The maximum breakdown progressed of 1.20m by installing a preliminary lining constituted by 2-IPN 160 profiles and 20cm of shotcrete.

The excavation of the bottom tunnel section and the cast of the base slab must to be realized within a limited distance from the excavation face (less than 15m) to allow the immediate closure of the cavity to control the deformation. Finally, a grouting intervention of the bottom tunnel section has been considered in case a fractured rock mass is encountered. The grouting intervention has been evaluated step-by-step during the excavation progress and applied, just in case, before the tunnel invert excavation. The results obtained from geophysical surveys calibrated by exploring drilling performed in progress define the need of intervention.

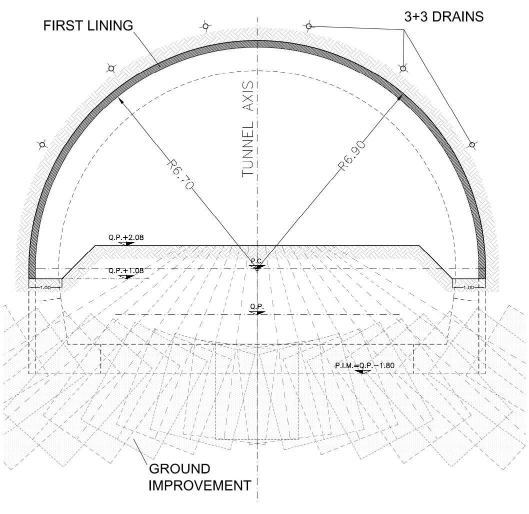


Figure 8. Advancing section type in the vicinity of the interference – transversal section

The accurate and conservative interpretation of the adopted criteria and the analysis of the available measures, confirmed the compliance of the safety limits with the vibrations effects, up to a safe distance of 100 meters between the excavation faces and the motorway tunnels. The activation of the vibration monitoring was immediate. 8mm / s and 10 mm/s values defined the attention threshold and the alarm threshold respectively.

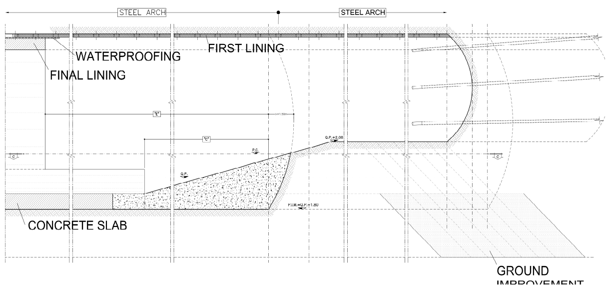


Figure 9. Advancing section type in the vicinity of the interference – longitudinal section

The velocity propagation systematic collection and direct readings processing related to the tunnel approach, as well as the reassuring data value, led to validate the empirical correlations giving a good background for more effective future interpretation. A specific recovery intervention for Don Guanella double tube tunnel has been planned from this distance, before proceeding with the work progress.

Figure 10. Divided advancing section type – Picture taken during interference overpass

4.4 *Reinforcement intervention on the pre-existing tunnel*

The preliminary analysis underlined some critical issues, which require the definition of two different interventions. First was necessary to fill the cavities.

The holes drilled in the concrete lining were useful to inject expansive polyurethane resins at the crown level. This procedure reduced the disturbance on the pre-existing tunnel. Polyurethane resins have a considerable expansive capacity. The injected volume is a function of the adopted resin characteristics.

The applied solution guarantees several advantages, not only with reference to the operational stage, but also in terms of structural behaviour of the concrete lining (i.e. which will no overload due to an additional weight at the crown level). The visual investigations performed by inspection cameras monitored and confirmed the effectiveness of the intervention.

The section T1 was the one with the highest interference level. The identification has been a direct consequence of the performed analysis considering the stress level increase, the vibrational effects and the consistency state of the structure. This section required the application of steel ribs with sliding joints and electro-welded mesh and shotcrete layer. The ribs installation required a pre-cuts executed by hydro-demolition into the lining. This type of ribs allows an easier installation of the ribs themselves and a more effective adaptation to the real shape of the tunnels (see Figure 11). The section T2, which is adjacent to both side of T1 and external to the theoretical interference zone, required the installation of an electro-welded mesh as a prudential intervention.

The detailed survey of the current internal layout of the existing tunnel let to verify the feasibility of the intervention. The intervention had to fit the inner existing tunnels shape. This clause was a mandatory request of the Highway Managing and Designing Department.

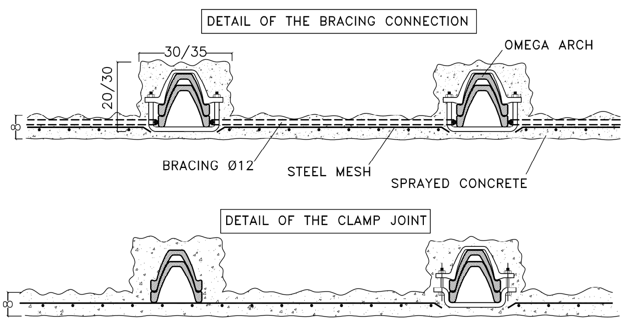


Figure 11. Structural reinforcement at the extrados.

The intervention will contribute however to stabilize the current geometric shape of the final lining, to remove and to reconstitute the outermost part and possibly flaking of the permanent lining itself. The designed solution has been constructed during night-time by 6 hours of traffic interruptions through the tunnels per day and an overall time around six months has been necessary to complete the intervention.

4.5 *Vibration monitoring system layout*

The vibration effects on "Don Guanella" tunnel have been by No. 2 vibrational sensors for each tube, added to the ordinary stress-strain monitoring system, assessed the vibration effects on "Don Guanella" tunnel (see Figure 12).

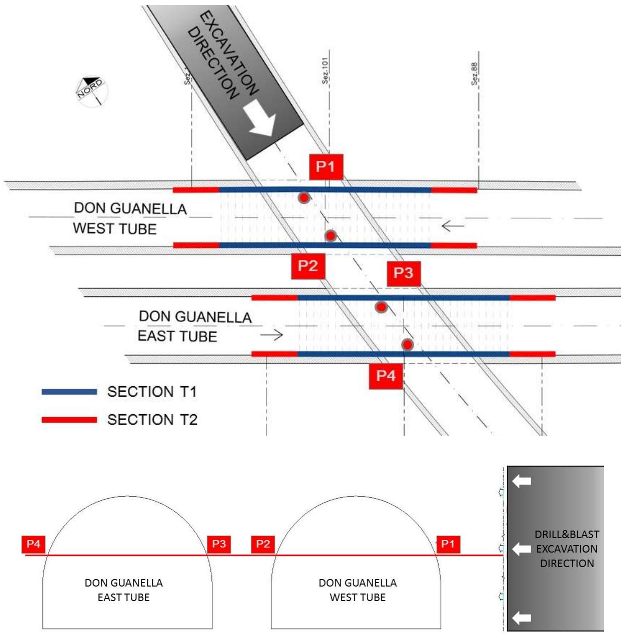


Figure 12. “Don Guanella” tunnel vibrational sensors positioning

The different location of the vibration source respect to the tunnel lining defined the sensors position. Furthermore, the three dimensional analysis, from the tensional point of view, underlined the most demanding situations in correspondence of the side wall. The installed sensors allowed recording the characteristics of the vibrational motion in terms of frequency and vibration velocity along the three directions, transverse, longitudinal and vertical, with respect to the direction of motion propagation.

The vibration monitoring, conducted in compliance with the specific regulations, recorded the following parameters: vibration velocity peak, v (mm / s) and dominant motion frequency, f (Hz). Each sensor recorded data, for each excavation unit of the tunnel under construction (see Figure 13).

5 OPERATIONAL STAGE

5.1 *Results of the tension monitoring*

The following paragraph describes the main results obtained by the stress monitoring within the Don Guanella double tube tunnel during the excavation phases (see Figure 14). The steel arches structural reinforcement and the concrete lining have one and two monitoring sections installed respectively. N°3 pairs of strain gauges characterized each section. The recorded data underlined the compliance with the numerical modelling: the permanent lining stress increases have been recorded on the side wall medium and bottom level, with a maximum compression increased value close to 3MPa. The steel ribs had a maximum compression value around 15 MPa.

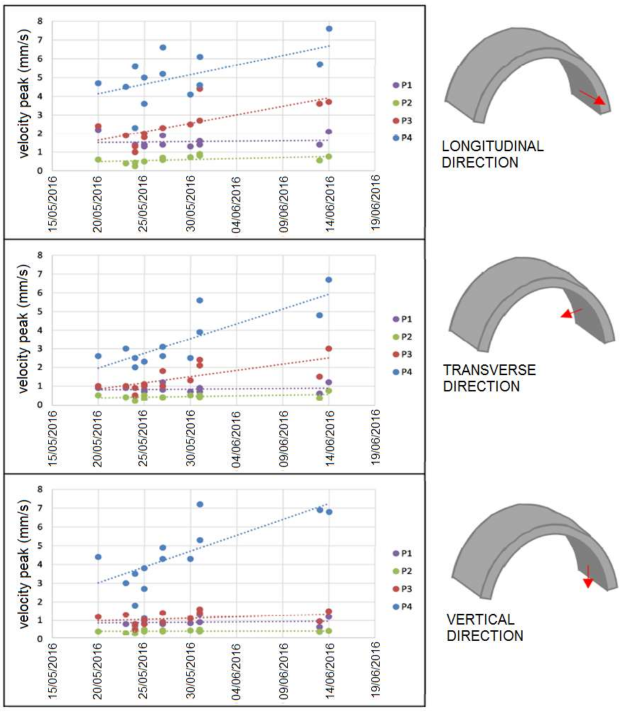


Figure 13. Vibrational monitoring system data

5.2 *Results of the vibrational monitoring: the application of experimental approach*

This paragraph summarizes the experimental data processing obtained by instrumental monitoring aimed to evaluate the vibration effect caused by drill & blast excavation of the "Don Guanella" double tube tunnel as an integral part of the New Link Road (GNSB).

The instantaneous charge Q (kg) and the sensor distance equal to R, characterized the blasts. Each excavation unit required to record four pair of *v* and *f* values; each pair related to specific values of Q and R, where the value of R varies for each sensor. Figure 15 shows the recorded frequency and velocity maximum values up to an interference distance of 50m.

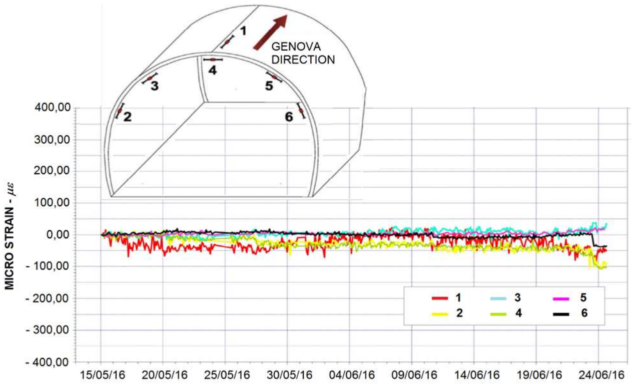
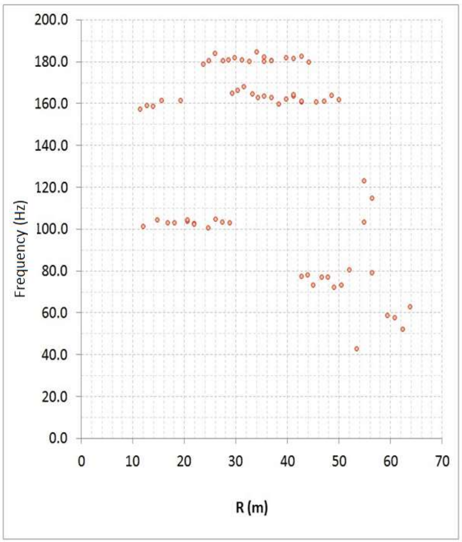
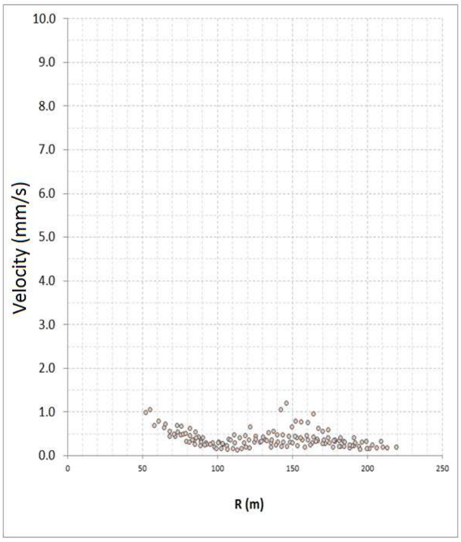


Figure14. Stress level detected on the east tube tunnel lining.



a)



b)

Figure 15. Recorded a) frequency and b) maximum velocity (up to R = 50m)

The decrease of the quantity of explosives used in the excavations starting from a distance of 100m caused an increase of the recorded frequencies. This is a further advantage from the induced vibration effects point of view: the standards reference indicates greater eligible velocity limits at higher frequencies.

The measured data processing led to calibrate the provisional curves of the vibration velocity as a function of the distance R between the blast point and the measuring point.

In order to determine k and α coefficients provided by the formulation of the experimental model, the data values measured v, R, Q have been plotted by bi-logarithmic log (v) - log (Ds) plane. The values of the so determined coefficients are equal to:

$k = 10^{1.119} = 13.16$; $\alpha = -0.873$ per $\beta = 1/3$
$k = 10^{1.525} = 33.47$; $\alpha = -1.199$ per $\beta = 1/2$

The experimental model in the scaled distance Ds investigated range well interpolated the vibration velocity v measured data (see Figure 16).

The plotted curves provide the effects of vibrations with the excavation proceeding with respect to limited distances allow confirming or modifying the designed explosives amount. This procedure has been repeated iteratively for each break-down executed, in order to improve the experimental results confidence on the source distance decreasing (see Figure 17).

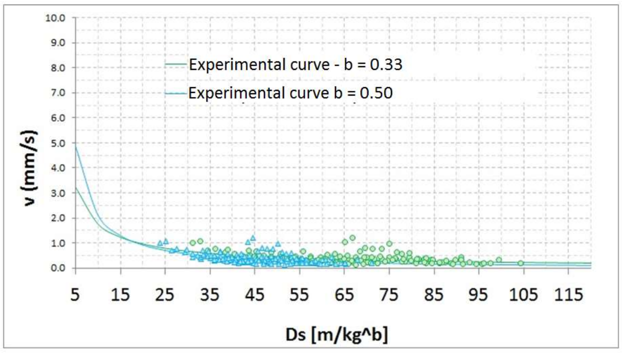


Figure 16. Monitoring data processing

The Figure 17 graph highlights the vibration effects underestimation of the experimental curves in case of measures absence under 50m. The predictive model is efficient for a distance around 25-30m. The Figure 18 shows the vibration monitoring data recorded at the end of the excavation, considering all the installed sensors. During the overpass the maximum instantaneously charge was equal to 0.8kg, but variable in the previous section and in any case less than 5kg (see Figure 17). The maximum velocity recorded was 11 mm / s for a 10m distance between the excavation and the vibrometer. The new plot of the site law updated with the results obtained by short distance completes the analysis. Figure 19 shows the comparison between theoretical and experimental curves.

The formulations in the literature indicate a maximum velocity value generally greater than the one related to the distance of interest with respect to the law of the site experimentally obtained. This issue is particularly evident by distance decreasing from the interference, although at 10 m distance the experimental value coincides with the theoretical one assuming k equal to 70. Moreover, in this case the curves obtained for different values of β are substantially the same.

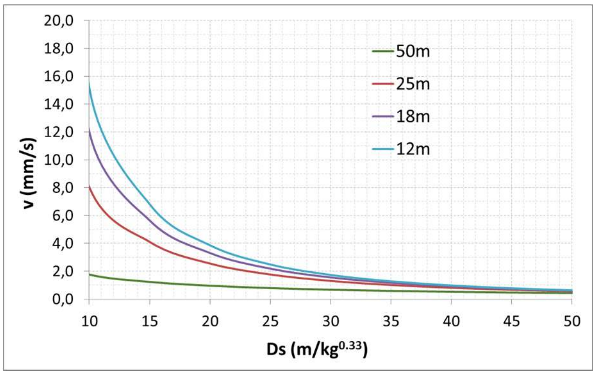


Figure 17. Interpolation curves for the excavation advancing variation.

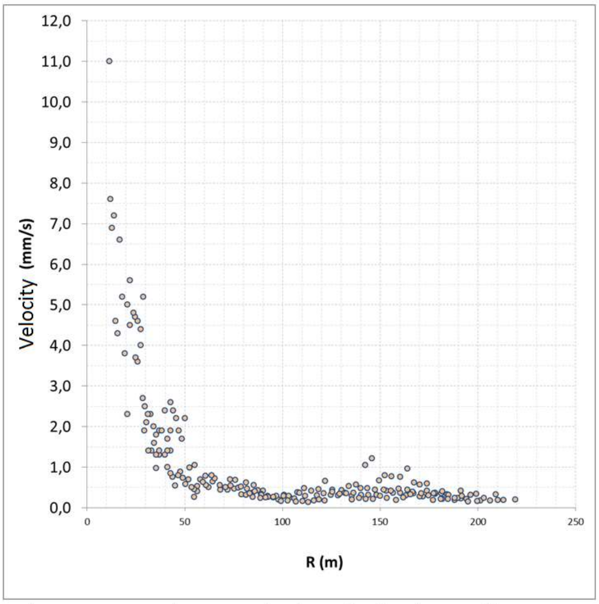


Figure 18. Maximum velocity obtained as a distance R function

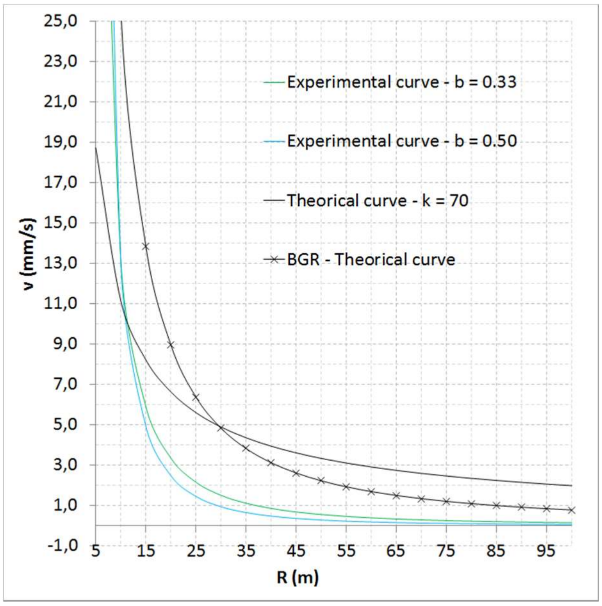


Figure 19. Comparison between theoretical and experimental curves

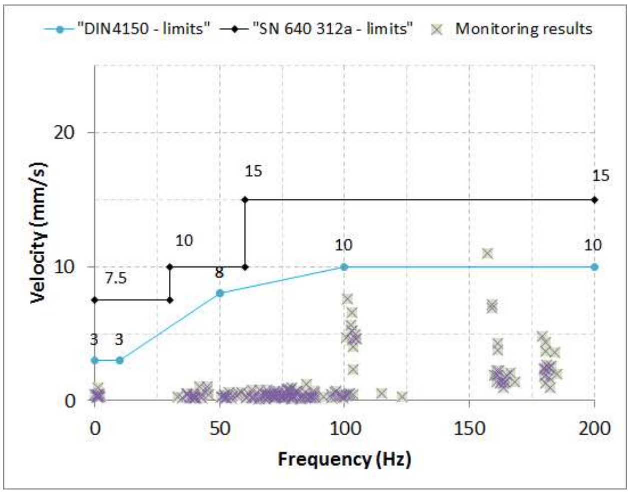


Figure 20. Monitoring results compared with international codes.

6 CONCLUSION

The paper presented the results obtained during the overpass of the Don Guanella tunnel by the excavation of the Erzelli side tunnel belonging to Borzoli-Erzelli road link, which is a part of the new high-speed railway line Milan-Genoa.

The paper retraces the critical issues of the overpass, mainly related to the vibrational aspects and the applied design approach.

The theoretical predictive methods provided a starting point for the case under study. The literature suggestions led to obtain conservative results for the applied solution compared to the ones collected by the experimental data.

The survey campaign and monitoring data acquisition performed during construction stage led to calibrate the design choices. By this way has been possible to overcome the critical issues with excellent results and keeping in operation the existing highway tunnels.

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