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Tunnel, Infrastructure Convergences/ Monitoring and Engineering Role

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Abstract

Worldwide we see that the construction industry is expanding, requiring new directions, new perspectives that can help reduce time, cost, and make transportation easy, safe, and affordable. For decades now, most of the large cities have completed their surface infrastructure. It has become urgent to address their issues for overpopulated cities where nowadays all infrastructure is overwhelmed, these issues must be addressed, solved and have vision to build underground infrastructure. Developed countries are focused on expanding their infrastructure for road systems, subway network, railway, storm, and sanitary systems. The emergency for underground infrastructure development requires more large-scale projects to be built and it is becoming more crucial building tunnels/underground structures for the future than ever before. Engineering focus, scientific searches are looking to develop their ideas for designing and delivering project underground, but government, agencies and engineers are concerned about the safety, durability, functionality, and the lifetime of this structures planned to be functional for decades. To address all this concerns this study provides information of how to identify the risk on tunnels and underground structures by capturing data from the beginning phases of construction, to analyze, evaluate and produce bulletins and engineering reports through convergences and monitoring. Convergences are the key factor on development of infrastructure underground as it is the only way to explore and analyze the rock mass disturbance during excavation. Convergences and monitoring in infrastructure are the safety coefficient for building underground, preventing accidents, and assessing real risks associated with tunnel/mine works and ensuring progress of the construction in underground structures. This study delves into the engineering role of convergence monitoring, during construction activities on project excavated using New Austrian Tunnelling method and Sequential Excavation Method. The primary objective of convergence monitoring is to gather critical information on ground movements and disturbances, thereby enhancing safety measures during tunnel construction. The monitoring process serves as an early warning system offering evidence of the real risks associated with underground infrastructure, bringing results and engineering data to be used for the design as key coefficient for structural design, type of material, type and strength of the concrete, rebars, concrete mix design. By using the convergence and monitoring system on underground infrastructure this study represents information that can contribute to risk assessment, structural analysis, and the lifetime of a project.

Keywords

Tunnel, Infrastructure, Convergence/Monitoring, Underground Monitoring

1. Introduction

Tunnel, underground projects and infrastructure have huge impact on the development of a community, city, country, or state.

From the feasibility studies till the completion of the project are many factors that are considered high risk on a project. Some of influencing factors on selection of excavation method can be mentioned as rock mass properties including intact rock and joint discontinued characteristics, shape and size of tunnel section, underground hydrology *in situ* end induced stressed, regional geology, structural geology, and week zone characteristics. [1]

Including convergences and monitoring (vertical and horizontal) from the preliminary phases to identify, analyze, evaluate, and address all the risks may arise during implementation phases till the project completion, make the project safe, build it on time, on budget, and address all influencing factors through stages for safely building underground infrastructure.

In underground construction, delays are the main challenges we face as many factors contribute to this, always concerns have been raised for bad management, contractual relations, insufficient calculation of the risk in the beginning phases that leads to compromised quality of the project we build, financial lose and failing delivering the project per schedule and plans.

These situations may arise any time and the risk of dispute may be present, contractual agreement may be an issue through this phase where competence and knowledge are crucial for overcoming this situation.

However, infrastructure projects specifically in large scale are managing this through internal systems, different qualified department by engaging participants, resources, methodologies, means and methods, and all through a process accessible from everyone to evaluate, review and see processes during stages of implementation and construction.

Convergences and monitoring hold a significant engineering role as it actively contributes to the infrastructure development objectives through processes such as management, implementation, construction, and commissioning.

Convergence/monitoring on tunnel infrastructure is a basic tool used in today's underground projects for understanding and recording of the rock mass behavior during excavation phase.

NATM, the New Austrian Tunnelling Method (**Figure 1**) is often linked to a patent by Professor Ladislaus von Rabcewicz, who invented the dual linin support for tunnels (initial and final support) [2]. Considering critical the deformation of the structure during drill and blast NATM it is separating the opening in two phases. Monitoring takes place and captures the differences between daily series of measurements. Will be added a second row of devices on the second phase (invert) of the excavation for completing the full template of the tunnel? The initial ground support is provided by shotcrete in combination with fiber or welded-wire fabric reinforcement, steel arches (usually lattice girders), and sometimes ground reinforcement (e.g., soil nails). [3]

SEM, the Sequential excavation method (**Figure 2**) is used in large diameter tunnel where will be incorporated shafts, subway station, under passages, cross passages. Sequential excavation method minimizes the risk of collapse. Monitoring in this case requires devices to be installed in areas where portion been sequent excavated towards front, then decommissioning them and maintaining only the full dome. In any tunnelling project adequate stability during construction is clearly of prime importance, and this is particular in urban environments where consequences of a major tunnel collapse can be catastrophic. The tunnel lining whether will be temporary or permanent must be capable of withstanding all influences on which it may be subject during its design life [4]. SEM has all the required coefficients when it comes to safety and stability, including convergences to handle large diameter Tunnel opening, eliminating risk, and delivering safe product.

Figure 1. NATM (New Austrian Tunnel Method).

Figure 2. SEM (Sequential Excavation Method).

Tunnel convergences are used to determine the conditions of the rock mass to allow engineers identify risk, verify, and capture the shrink excavated area on the underground rock [5]. It is necessary to create convergence and monitoring system in place for the existence of the project itself until the disturbed rock mass creates an equilibrium and the forces will be equal to the resistance of the template shape.

Convergence/monitoring requires specific measurements procedure as the process itself, require accuracy capturing data from targets (devices) installed and require daily measurements and reports. Results and accuracy of the reports of the monitoring often relies on 1) well trained personnel, 2) strict installation procedure, 3) Sustainability during the monitoring period, 4) existence of device, 5) instrument with high precision.

In construction the classification of the rock it is defined in the geological mapping and bore holes drilled along the profile of the tunnel Soil properties have been investigated by means of numerous geotechnical surveys which were carried out both from the ground surface and from within the tunnel. Boreholes drilled on the alignment of the tunnel body are providing all characteristics of the rock mass and this will provide us evidence for the tolerance of the movement will be considered normal for this type of rock [6]. In case the convergence values are higher, this may be a red flag warning on excavation phases.

When a tunnel in soil is planned, ground movements are an important topic to be considered for the tunnel design. Depending on SEM, urban tunnelling is aimed at ground deformation to a minimum tolerance when projects take place in underground urban areas.

2. Methodology

The data of this study were obtained from surveying instrument conducted inside of the tunnel while construction was taking place in different stages of the tunnel opening. Objectives are the targets installed on the tunnel section. The template was determined by the engineering department, survey engineers, geological engineers, and consultants. Conventional tunnel excavation methods are typically NATM and SEM where both have convergences and monitoring system in place.

Convergences/monitoring process has main tool surveying network which is extended along the project from beginning to the end of the project alignment. It has been agreed that for the tunnel it is required a network to be attached to surface network which is used by surveying instruments to capture coordinates and elevation representing the values for the final monitoring results.

Geodetic measurements can use curvature of the earth through geoid model coefficient as the network will be measured underground and geodetic calculations must be accurate related to general network of the project.

The geotechnical coefficient of the rock mass movements is defined by geotechnical studies for the minimum and maximum tolerances related to geological mapping/cores captured along the tunnel plan.

On geology and mining, the vertical gravity force G of this underutilized rock body is the product of its mass "m" in kg. and the action of gravity g = 9.81 m/s^2; so, we can write G = m × g (in N). Giving the mass of the rock per 1 m^3 of its volume, thus giving its density ρ = m/V (in kg/m^3). The pressure exerted by a vertical rock column of height h (in m), on a surface of A = 1 m^2 can be determined by the equation: p = h * ρ * g (in Pa). From the estimate $\gamma = \rho$ * g = 25,000 kg/m^3 × 9.81 m/s^2 ≈ 2500 kg/m^{2}s^2, we can get in SI units for force 1 Newton = 1 N = 1 kg m/s^2 and for pressure - 1 Pascal = 1 Pa = 1 N/m^2 [7].

An approximate calculation for the normal pressure exerted by the underutilized rock mass at a depth h (in m) can be done with the equation: $\rho \approx \gamma$ * h ≈ h/40 (in MPa) where the force of the specific weight (gravity) ρ = G/V = 0.025 MN/m.^{3} For example, we accept the pressure of the undercut rock, derived only from the weight of the rock mass, without considering the mining influence, approximately 20 MPa in a depth 800 m, which means 20 N/mm^2 = 2000 N/cm^2, or in the previous units – 200 kp/cm^2 (200 bar) [8].

Tunnel surveying nowadays is a one of the highly used practices in infrastructure and underground industry for the construction of tunnels to capture data for convergences and monitoring process. Methods and procedure of tunnel surveying are well developed, and all the existence of the project depends on that from the beginning phases to delivery, commissioning, and maintenance through existence. Special instructions on the type of survey and the equipment used in the tunnel surveying procedure/construction are initially given by the planners based on the design and tolerances defined in project specifications. The basic procedure of tunnel surveying is to create the structure design in digital alignment line, longitudinal, sections and transfer that to the tunnel. This also involves levelling the surface of the ground and the internal of the tunnel. Ground surface settlement and building movements are classically related to volume loss [9], captured on surface from level monitoring, underground through device (target) measurement.

Establishing the survey network underground has its difficult characteristics as it is a fast environment where activities take place one after other, from the beginning to the completion of the project.

Underground environments may have limited visibility, limited access through stages of work, and communication. However, with proper planning gaining time through phases of shifts rotations till mobilization, you can implement, construct and measure survey controls with high accuracy that ensure tolerances require from project specifications and maintain to have reliable data collection. Monitoring and measurement are usually carried out using a total station, with reflective signs at the measuring points [10].

The specific geodetic controls network will depend on the underground environment and the survey objectives.

In this study case is represented the best option of evaluation information for different methodologies taken in consideration through underground monitoring. In our case the Network has been used for convergences and monitoring for tunnel displacement monitoring, which includes wall convergence (horizontal displacement) and crown settlement (vertical displacement) [11].

Methodology used represent quality measurement and practical implementations of the process by investigating the functional scope of current data quality tools. In construction industry has been identified many ways of measuring, calculating, and providing monitoring data on tunnels, from which we evaluated five of them with respect to data collecting through devices, quality measurement in terms of metrics, and continuous data quality monitoring during construction. A) Laser Scanning, B) Extensometer, C) Bassett System, D) Shape array (accelerometer), E) Total Station (Geodetic Network) the chosen one in this case.

Distance formula,

$$D = \sqrt{(x2 - x1)^2 + (y2 - y1)^2}$$

Angle formula.

tga(a – b) = Yb – Ya/Xb – Xa arctan(a – b) = tan – 1 a(a – b) = Degrees (°), minutes ('), seconds ('') where a = 360*-arc tg

Measurements are captured with Total Station with high accuracy, setting up on the created network and data extracted are coordinates and elevation, the next stage is the evaluation and calculation of this data [12].

Has been selected the best methodology regarding pre-defined criteria to ensure that they are real evidence, precision, accuracy, large data collecting, efficiency, ability to review and transmit, save, and produce convergence bulletins in a time frame with construction and excavation phases -independent, that provide the required/expected results. This survey methodology reveals potential for their functional enhancement on engineering departments collecting and evaluating convergences. Monitoring becomes a pragmatic tool to manage the uncertainties and the risk [13], values are considered for construction stages and design processes.

The results obtained through survey measurements allow a critical discussion on concepts of convergence/monitoring for underground structure to highlight importance of the risk assessment through data evaluation.

3. Result and Discussion

As we know, on infrastructure projects it is always required Geodetic Network, representing coordinates and elevations to be used from the feasibility studies to commissioning process.

Network build in this case study for coordinates capture data by using Trimble RTK GPS from the global position system using UTM measuring in fast static mode for the coordinates of the network.

Also, for elevations are taken the benchmark of the government created, in the nearest location of the project and transmitted along the network using digital level. Engineers are creating and maintaining the project network on tunnels through control points with known coordinates, and it is managed in two phases which are critical for the project progress/completion.

In both phases survey data/measurements are the information/coordinates used to calculate convergences on the Mine/Tunnel/Underground project.

Engineers and their expertise are important as all preparatory work, establishment of the overall project network including ground control points, measurements, calculation for whole alignment of the project.

Formulas are used for distance and angles for the coordinates of the network and distance calculation, data extracted from instruments are calculated and adjusted on StarNet software to maintain the network in tolerance and accuracy.

Digital design is created for the tunnel, related to structural design itself and values are added on specific software as TCP, Amberg, to complete alignment, longitudinal section (lines-curbs-radius-vertex), section are created including multiple templates as umbrella, excavation line, iron arch line, shotcrete line, final line, inverts, sidewalks, layers for aggregate, asphalt etc.

This design is used on Alignment Solver for defining change of the target, distance from center line. First measurements and data received are considered baseline for monitoring.

In this practical of convergences Alignment Solver has been used and the values are extracted from its results.

Values are analyzed, added to diagram corresponding to certain chainage and specific location on the tunnel section template.

The template itself represents all targets (devices) installed on the shotcrete phase.

Diagram provides information how the numerical results were compared with the monitoring data from levelling points [14], including their location, coordinates, elevation (**Figure 3**) and the movements/convergences in three dimensional as per height (**Figure 4**), centerline of the tunnel, and vector towards chainage directions (**Figure 3**).

	TARGET No.5 (Point at the right side of axis)				
DATE	X	Y	Chainage	Dcl	H
2011/11/25	4413202.8260	4564259.2900	15817.6250	5.3860	448.5400
2011/11/26	4413202.8260	4564259.2940	15817.6250	5.3860	448.5390
2011/11/27	4413202.8260	4564259.2940	15817.6250	5.3860	448.5390
2011/12/2	4413202.8270	4564259.2950	15817.6252	5.3846	448.5390
2011/12/3	4413202.8270	4564259.2950	15817.6252	5.3846	448.5390
2011/12/5	4413202.8270	4564259.2960	15817.6247	5.3838	448.5390
2011/12/7	4413202.8270	4564259.2960	15817.6247	5.3838	448.5380
2011/12/9	4413202.8280	4564259.2960	15817.6255	5.3832	448.5380
2011/12/12	4413202.8280	4564259.2960	15817.6255	5.3832	448.5380
2011/12/14	4413202.8280	4564259.2960	15817.6255	5.3832	448.5380
2011/12/16	4413202.8290	4564259.2950	15817.6269	5.3835	448.5390
2011/12/20	4413202.8310	4564259.2930	15817.6297	5.3839	448.5390
2012/1/7	4413202.8310	4564259.2940	15817.6291	5.3831	448.5380
2012/1/12	4413202.8310	4564259.2930	15817.6297	5.3839	448.5380
2012/3/18	4413202.8150	4564259.2900	15817.6183	5.3956	448.5190
2012/3/27	4413202.8160	4564259.2910	15817.6185	5.3942	448.5180
2012/3/28	4413202.8170	4564259.2920	15817.6188	5.3928	448.5180
2012/3/29	4413202.8170	4564259.2920	15817.6188	5.3928	448.5180
2012/3/30	4413202.8170	4564259.2920	15817.6188	5.3928	448.5180
2012/3/31	4413202.8170	4564259.2930	15817.6182	5.3920	448.5180
2012/4/2	4413202.8180	4564259.2930	15817.6190	5.3914	448.5180
2012/4/5	4413202.8180	4564259.2930	15817.6190	5.3914	448.5180
2012/4/10	4413202.8180	4564259.2930	15817.6190	5.3914	448.5180

Figure 3. Data, coordinates, elevations, chainage, cl.

VECTORS							EXCAVATION CHAINAGE		CONVERGENCE						
D1	D2	D3	D4	D5	D6	D7	LEFT	RIGHT	dD1	dD2	dD3	dD4	dD5	dD6	dD7
	3.5617		6.7234	6.2415	10.9831		15834.8	15641.5	0.0	0.0	0.0	0.0	0.0	0.0	
	3.5615		6.7229	6.2421	10.9825			15645.5	0.0	−0.2		−0.5	0.6	−0.6	
	3.5610		6.7241	6.2410	10.9833		15838.8			−0.7		0.7	−0.5	0.2	
	3.5625		6.7234	6.2406	10.9819			15659.2		0.8		0.0	−0.9	−1.1	
	3.5614		6.7229	6.2395	10.9813		15846.8	15665		−0.3		−0.5	−2.0	−1.7	
	3.5622		6.7236	6.2388	10.9813		15847.8	15669.5		0.5		0.2	−2.7	−1.7	
	3.5624		6.7229	6.2390	10.9808		15854.8	15680		0.7		−0.5	−2.5	−2.3	
	3.5619		6.7229	6.2386	10.9802		15861.9	15691.3		0.2		−0.5	−2.9	−2.9	
	3.5606		6.7236	6.2381	10.9810		15863.2	15692.8		−1.1		0.2	−3.4	−2.0	
	3.5611		6.7241	6.2381	10.9810		15867.4	15704		−0.6		0.7	−3.4	−2.1	
	3.5609		6.7248	6.2371	10.9812					−0.8		1.4	−4.4	−1.8	
	3.5620		6.7243	6.2379	10.9817					0.3		0.9	−3.6	−1.3	
	3.5616		6.7241	6.2370	10.9809					0.0		0.7	−4.5	−2.1	
	3.5602		6.7241	6.2366	10.9817					−1.5		0.7	−4.9	−1.3	
	3.5599		6.7298	6.2362	10.9853					−1.5		0.7	−4.9	−1.3	
	3.5580		6.7277	6.2353	10.9817	3.4571				−3.3		−1.4	−5.8	−4.9	
	3.5584		6.7277	6.2341	10.9803	3.4570				−2.9		−1.4	−7.0	−6.3	
	3.5576		6.7284	6.2334	10.9803	3.4570				−3.7		−0.7	−7.7	−6.3	
	3.5571		6.7277	6.2331	10.9803	3.4570				−4.2		−1.4	−8.0	−6.3	
	3.5570		6.7272	6.2324	10.9789	3.4580				−4.4		−1.9	−8.7	−7.7	
	3.5564		6.7255	6.2318	10.9776	3.4580				−5.0		−3.6	−9.3	−9.1	
	3.5564		6.7255	6.2318	10.9776	3.4580				−5.0		−3.6	−9.3	−9.1	
	3.5564		6.7255	6.2318	10.9776	3.4580				−5.0		−3.6	−9.3	−9.1	

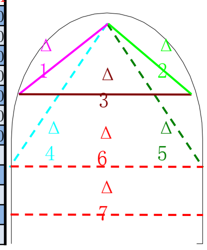

Figure 4. Vectors distances and convergences.

Between targets, distance formulas are used during each measurement to provide the (dD) convergences (**Figure 4**) and the real movement/stress the section had during excavation period.

All measurements of the devices/targets following the first baseline provide three-dimensional movement of the devices along the chainage, elevation differences, and on plan toward center line of the tunnel.

Diagrams contain values for each target measured on the section of the tunnel and they represent date and time of the measurement, northing and easting of the target, elevation, chainage of the target in the tunnel alignment, distance from center line of the center of the tunnel (**Figure 3**). The diagram include also Station (CP) where the instrument has been set and the station of orientation (closure error to), measured vectors (distances) created between targets D1 to D7 (**Figure 4**), excavation of the chainage (front line) to know the distance of it as we have two parallel tunnels and during blasting front lines of both of them has to be known as per safety standards, teams have to be evacuated on the other tunnel during blasting. Also, on this diagram are reported convergences dD (**Figure 4**), which are the real movements of the measured section for the two phases of the tunnel.

Measurements are captured with base instruments far from the active area of the construction to represent only the movement of the rock mass. It is important to set up instruments always on decommissioned area where we have stabilized underground, 0.00 values of the movement of the rock mass.

Reporting and representing displacement are required to create and maintain diagram and schemes as they will visualize values and results of the measured/data captured. Comparison between measured data and calculated surfaces, subsurface, ground, ground displacements has been reported. Measured settlement through the ground surface above the tunnel is also compared with predicted ones [15].

Below are represented displacements and they are shown on the section of tunnel (full cavern) for their direction and visualizing differences d-h (**Figure 5**) vertical displacement provide the differences in elevation certain target had during process or monitoring from first moment of the baseline, for the completion of the project and d-cl (**Figure 6**) horizontal displacement on plan view provide the difference in location considering the distance from target to center line of the tunnel, d-ch (**Figure 6**) displacement along the tunnel (through chainage) provide the difference in location towards the alignment of the project + or – from the baseline (first registered data).

During construction of the project and with this monitoring information, geological department predicted the movements and tolerances based on the rock specifications and their final report provided data for the structural engineers for future calculations. Structurally these convergences are used for designing the thickness of the structure concrete, walls, arches, concrete formula, rebar, and other calculations for structural resistance for the lifetime of the tunnel/project.

Convergences and monitoring provide critical information to be used on the design and implementation of the project itself for its existence, and functionality for its design purpose.

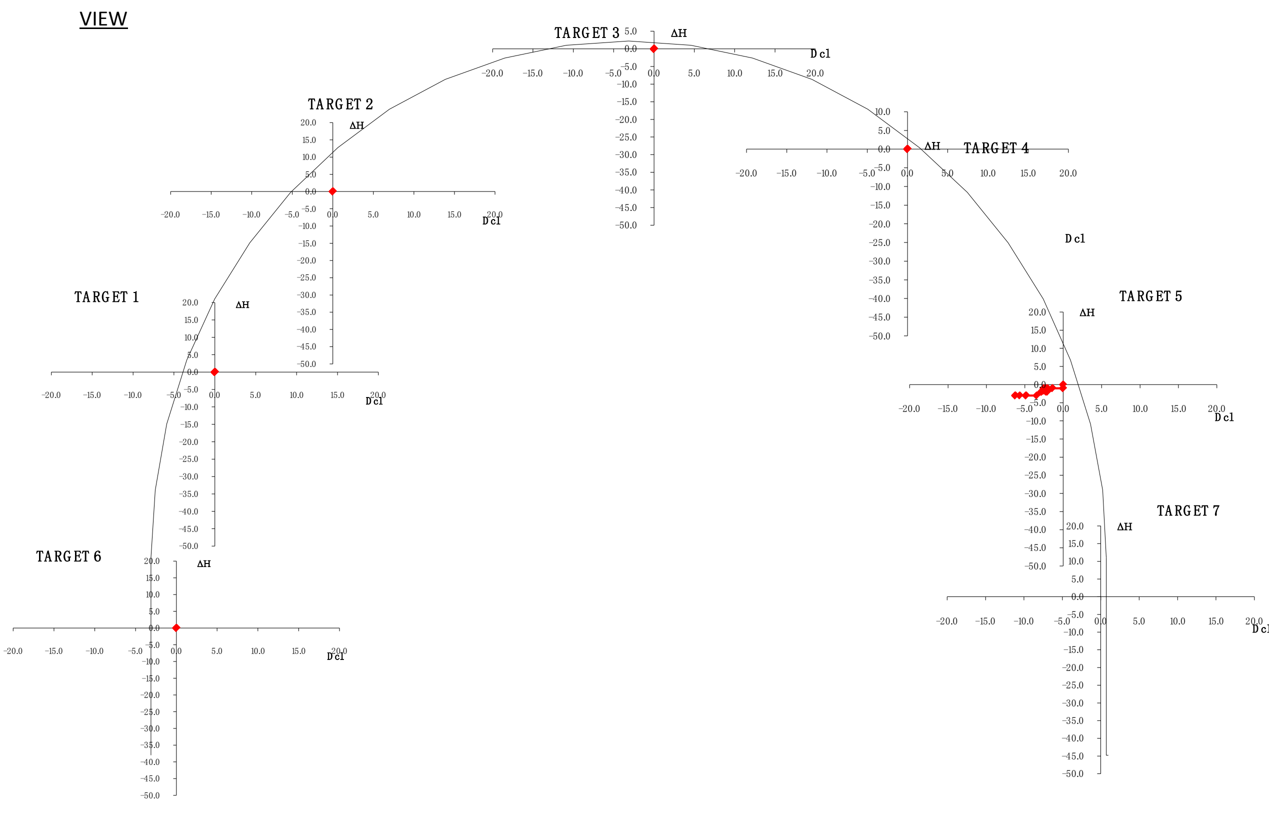

Figure 5. Deformation of tunnel.

Displacements are the real values that are the product of all activities and calculations during monitoring process including all details, coefficient, and project requirements (Figure 5). The large amount of geodetic data permits us to estimate the absolute displacements of the targets and the final deformed profile of the sections. However, this detailed analysis of the monitoring data provides substantial information on the kinematics of the support system due to the imposed stresses on the excavation procedure (Figures 7-10) [16].

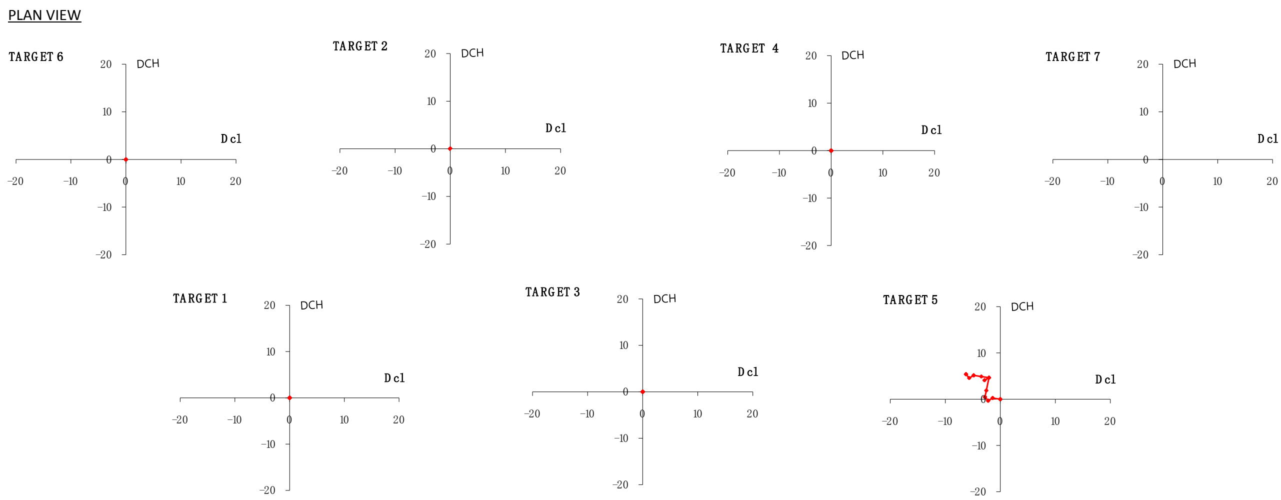

Figure 6. Deformation chainage-centerline.

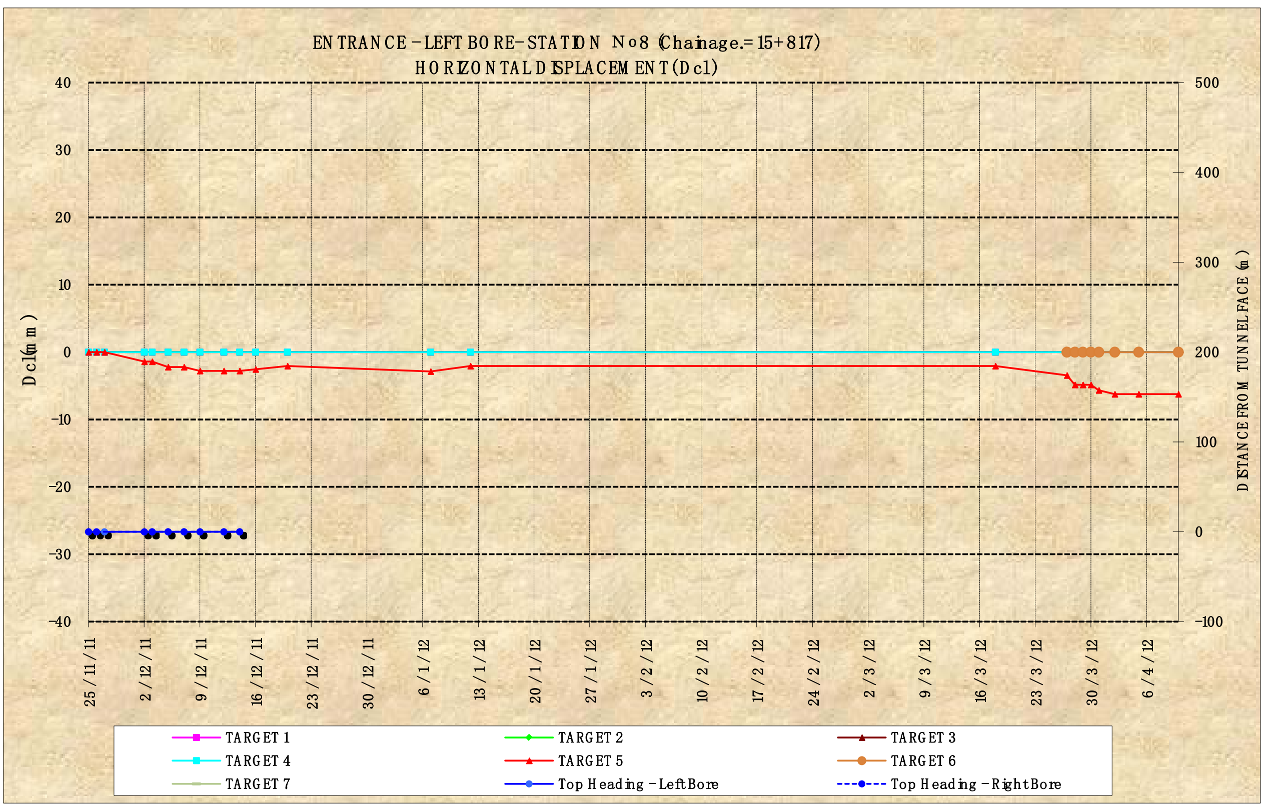

Figure 7. Displacement through chainage dch.

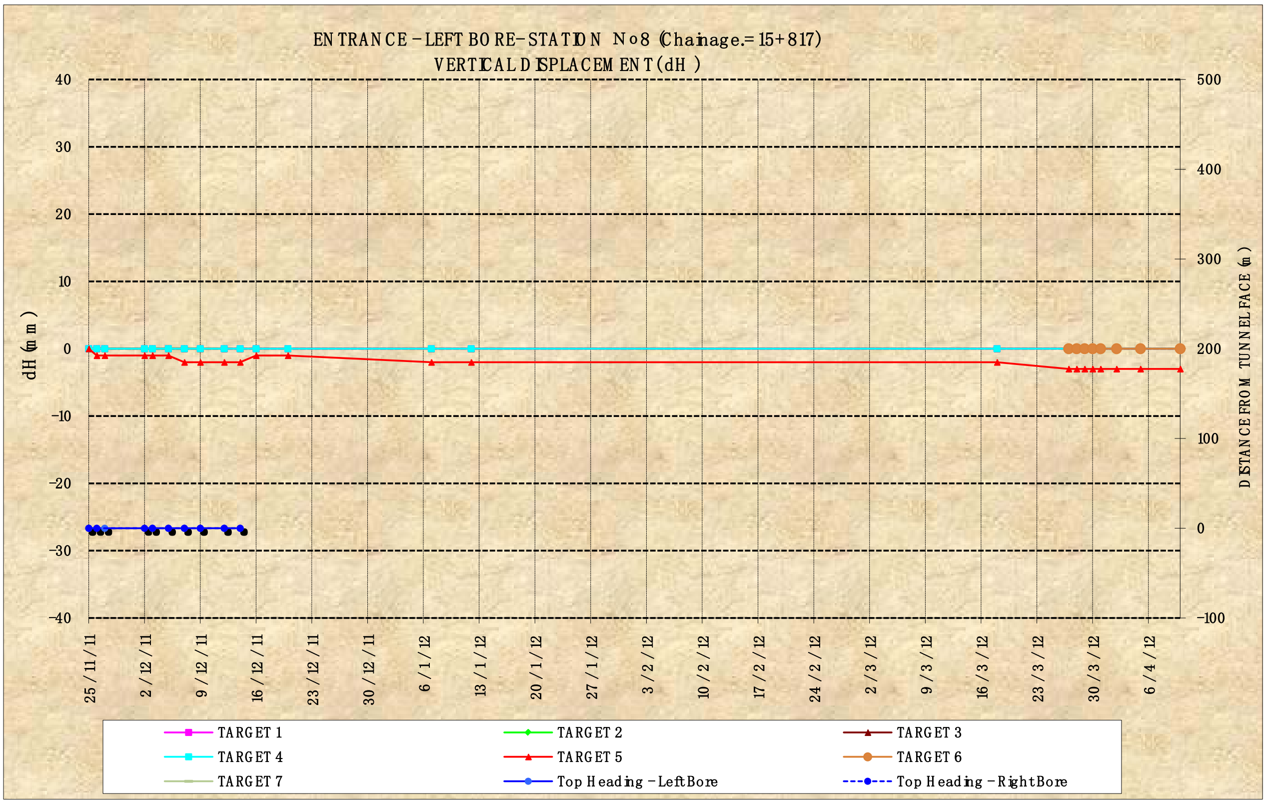

Figure 8. Horizontal displacement, dcl.

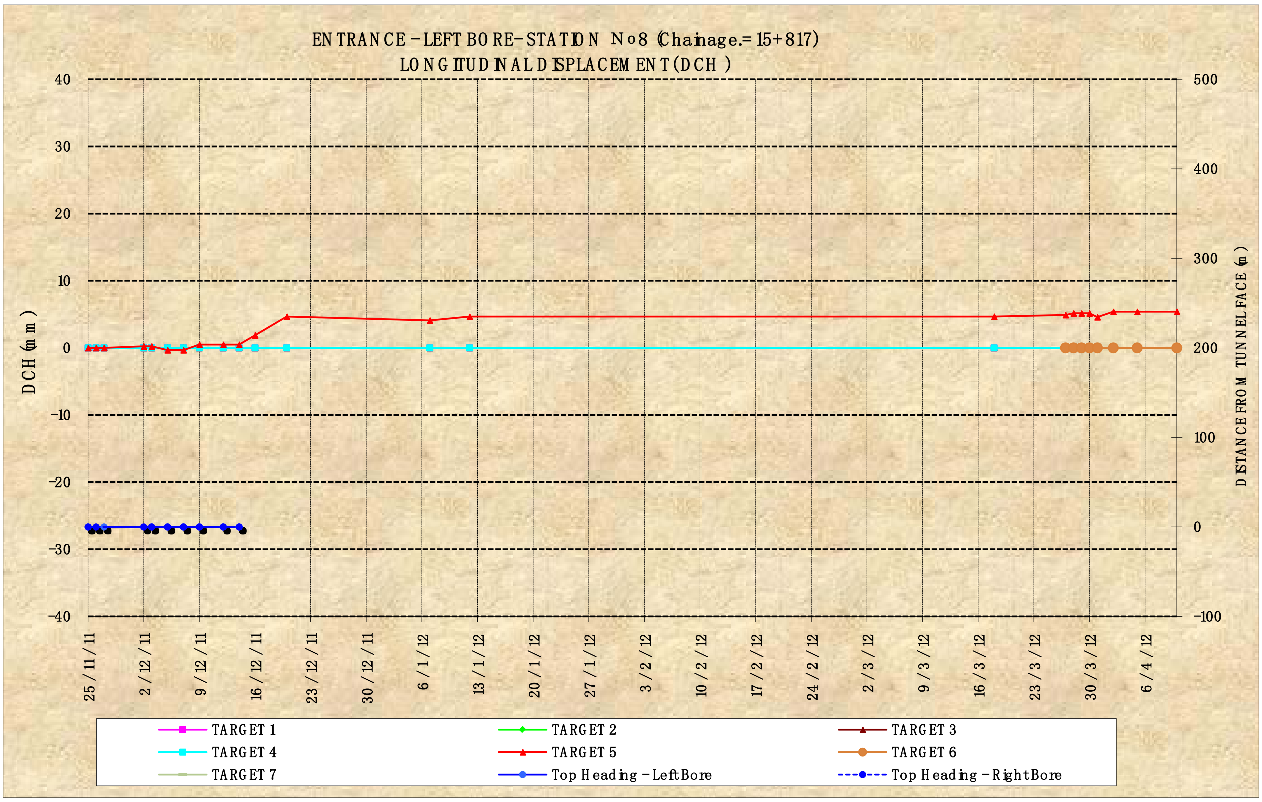

Figure 9. Vertical displacements dh.

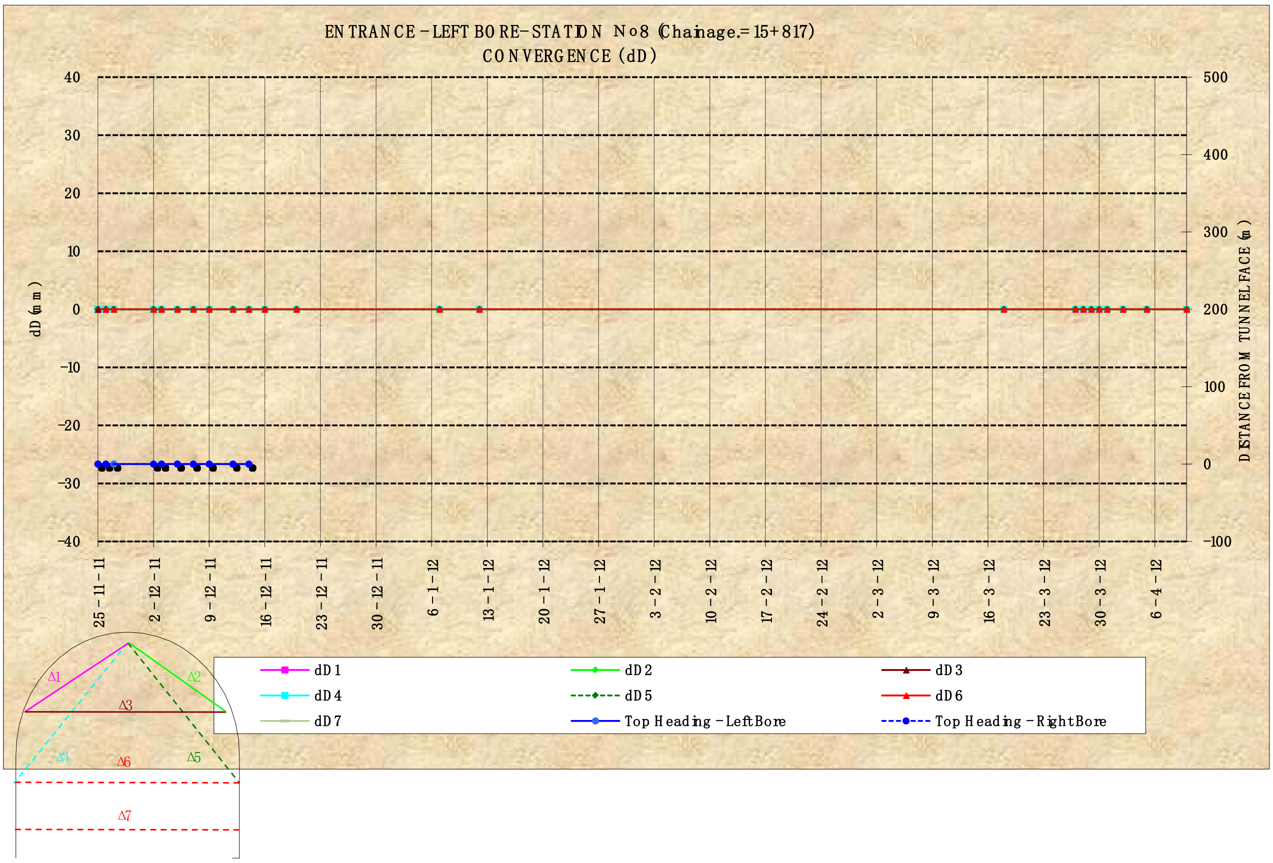

Figure 10. Convergence, dD.

4. Conclusions

The convergence and monitoring used in tunnel and infrastructure industry have rapidly changed in the last years where companies, consultants, designers, government, and agencies are considering this as a safety coefficient and risk management tool.

During years and years of building, underground infrastructures were opened without knowing the risk factor, real disturbances of the rock mass during excavation.

As a fact, years before convergences and monitoring were used during construction for subway lines, railways and metro tunnels, engineers were building on soft grounds under the cities and this brought catastrophic situation that tunnels collapsed as there were no system in place for calculating convergences and monitoring to bring in light the real movements of the disturbed ground to be analyzed, evaluated and address the problems they cause.

The role of engineering in underground infrastructure is to use convergences and monitoring as a tool from preliminary to project finalizing, addressing the risk and build safely.

Convergences and monitoring have a significant impact on underground infrastructure and tunnel projects by eliminating risk, preventing collapse during construction, making the work environment safe and delivering projects for generations to use.

There are important and significant differences between today's methods using convergences and monitoring on underground structures by eliminating risk of any collapse and the times prior using this method, by reducing accidents and preventing catastrophes.

These differences are pushing engineers to design and build larger projects and expand the area of the underground infrastructure industry. Build for our future.

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Companies that used means and method statements for infrastructure tunnel projects, dedicating a monitoring department on the project for the safety, measurements, analysis, collecting data, and making risk analysis to prevent collapse during construction, making each single member of their project team return healthy and safe home each day.

Engineering is amazing, it is the change and progress through knowledge and science for good in our life.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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