Design and construction of tunnels in zones subjected to high convergences

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ABSTRACT: The economic development of a region depends on the speed that people and goods can travel. The reduction of people and goods travel time can be achieved by planning smooth road layouts, which are obtained by crossing natural obstacles such as hills, by tunneling at great depths, and allowing the reduction of the road alignment length. The stress state in rock masses at such depths, either because of the overburden or due to the tectonic conditions of the rock mass induces high convergences of the tunnel walls. These high convergence values are incompatible with the supports structural performance installed in the excavation stabilization. In this article it is intended to evaluate and analyze some of the solutions already implemented in several similar geological and geotechnical situations, in order to establish a methodological principle for the design of the tunnels included in a highway section under construction in the region influenced by the Himalayas, in the state of Himachal Pradesh (India) and referenced by "*four laning of Kiratpur to Ner Chowk section*".

1 INTRODUCTION

The Kiratpur – Ner Chowk section of NH-21 roadway Project, to be executed in the state of Himachal Pradesh (India), comprises 5 two lane tunnels, designated from T1 to T5 (Figure 1).

Figure 1.Kiratpur – Ner Chowk section of NH-21 Project general layout.

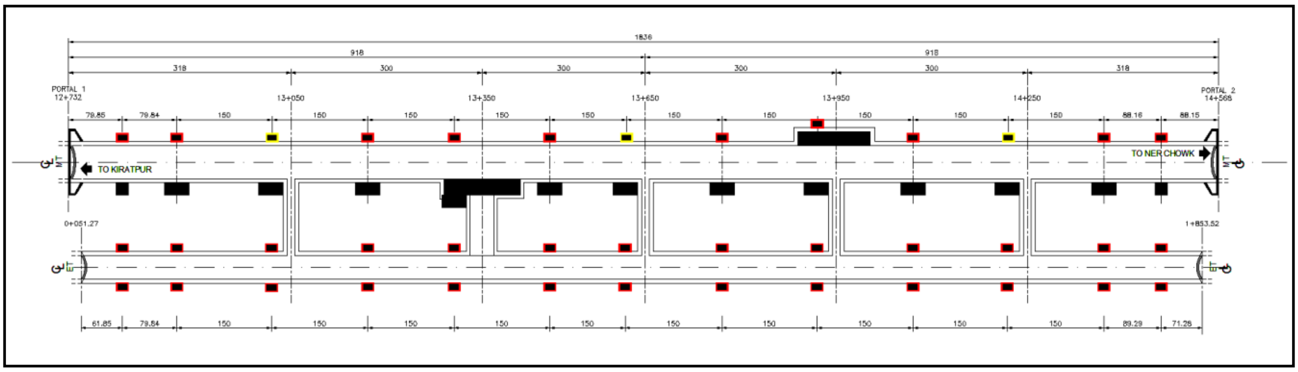
All five tunnels are bidirectional, complying different lengths and overburdens, based on their location along the alignment (Table 1).

Table 1.Tunnels general characteristics.

Tunnel	Extension (m)	Overburden (m)
T1	1836	300
T2	494	130
T3	584	120
T4	1254	180
T5	744	100

Concerning the safety during the operation, all tunnels are provided with suitable devices to fulfill the minimum safety requirements during the tunnel operation, in accordance with international references and the *Guidelines for Road Tunnels* (IRC:SP:91-2010). Therefore, based in their lengths, the tunnels will be provided with emergency galleries, lay-by for vehicles stoppage inside the tunnel, niches and mechanical ventilation systems (Figure 2).

From this group of tunnels one can stand out T1, with a total length of 1836 m, from which 36 m are executed with the "*cut and cover*" technique. Beyond being the longest tunnel, is also the tunnel that has the biggest overburden.



LEGEND

▭ – Pedestrian emergency exit

▨ – Vehicular emergency exit

▬ – Tunnel LAY–BY

– Ventilation Building

🟦 – Emergency stations (niche in the side wall equipped with an emergency telephone and two extinguishers)

🟩 – Fire Niche (niche in the sidewall with a fire hydrant)

🟥 – Cleanout Niche (niche in the sidewall for inspection and maintenance of the drainage systems)

🟨 – Electrical and Cleanout Niche (niche in the sidewall for electrical systems enclosures and inspection and maintenance of the drainage system)

Figure 2.Kiratpur – Ner Chowk section of NH-21 Project general layout.

Given the tunnel length and in order to respond to the international recommendations for emergency situations it is also planned an emergency tunnel, which will develop in parallel to the main tunnel gallery and connecting to it by several linking galleries (Figure 2).

The highway layout where the tunnel is integrated, with elevation levels ranging between 680 and 715 m, crosses tectonic zones, whose altimetry elevations of natural terrain vary between 700 m on portals and 1000 m in the area of greatest terrain overburden.

Under these conditions, the depths of tunnel excavation occur with variable overburden, with maximum values of around 300 m (Table 1).

2 MAIN CHARACTERISTICS OF THE TUNNEL T1

The main tunnel consists of a single gallery for bidirectional circulation, which in its section bears the clearance profile of 8.0 m width and 5.5 m height. Each traffic lane has 3.5 m width.

In accordance with the “Guidelines for Road Tunnels” (IRC:SP-91-2010), were also considered an edge strip width of 0.5 m and a sidewalk of 0.75m wide (minimum) on each side of the tunnel. Each sidewalk features a constant height of 0.18 m above the pavement.

The cross section contour of the tunnel is formed by a guideline in a three centers arch, with radius of 5.54 m and 7.06 m on the sidewalls and 4.92 m for the crown, allowing the clearance profile to the vertical axis of the tunnel to have greater height, satisfying the needs of ventilation with the ventilation ducts installation.

On figure 3, is presented the main tunnel cross section, to apply in favorable geotechnical conditions (ZG1 and ZG2).

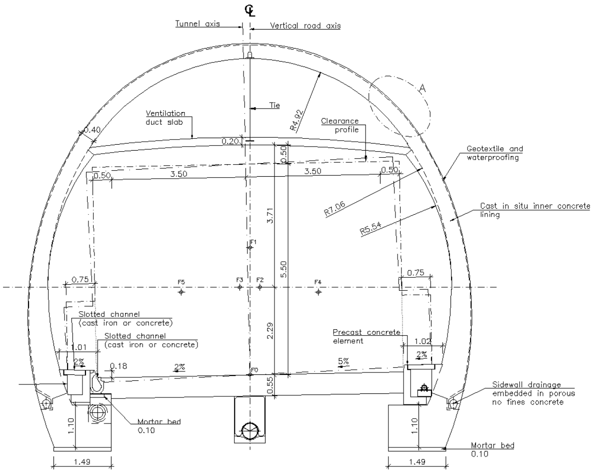


Figure 3.Tunnel 1 cross section – without invert arch.

For unfavorable geological and geotechnical conditions of the rock mass (ZG3), the cross section of the tunnel will be provided with an inverted arch threshold (Figure 4).

The invert arch will be executed with a radius of 21.0 m, resulting in an additional centre arch for the tunnel.

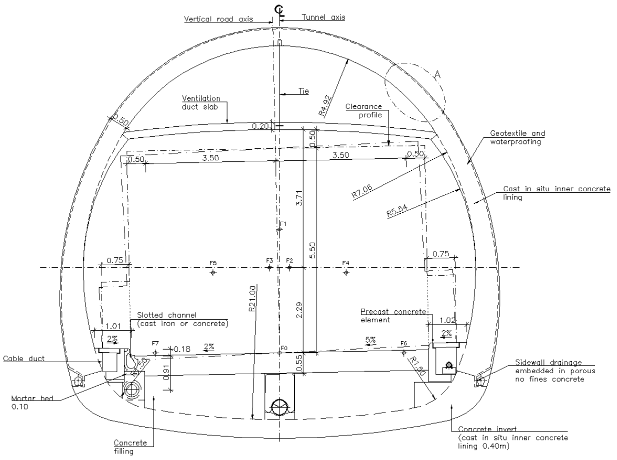


Figure 4.Tunnel 1 cross section – with invert arch.

3 GEOLOGICAL AND GEOTECHNICAL CONDITIONS

3.1 *Geomorphological and Geological Aspects*

The Himalayas are characterized by a great complexity and variety of geological formations, which represent several phases of the tectonic events resulting from the collision between the Eurasian and the Indian plates (Figure 5).

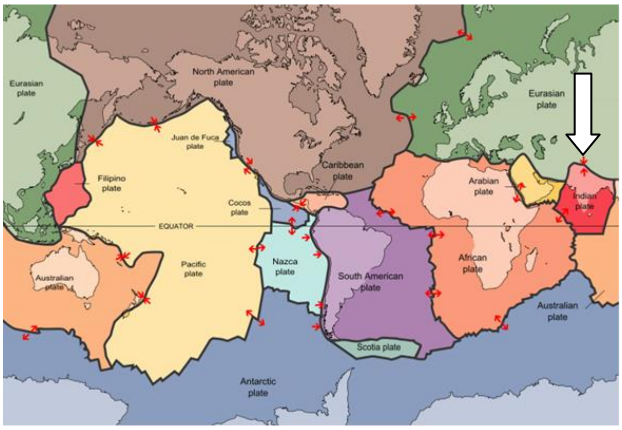


Figure 5.Tectonic plates of the world.

The Himalayas can be divided into six primary lithotectonic zones that occur in parallel belts. These zones consist of the Trans-Himalayan batholith, Indus-Tsangpo suture zone, Tethyan (Tibetan) Himalaya, Higher (Greater) Himalaya, Lesser (Lower) Himalaya, and Sub-Himalaya.

The lithotectonic zone in which our Design area is inserted is the Sub-Himalaya zone. This foreland zone consists of clastic sediments that were produced by the uplift and subsequent erosion of the Himalayas and deposited by rivers. These rocks have been folded and faulted to produce the Siwalik Hills that are at the foot of the great mountains.

With an average height of about 1000 meters, they are generally covered with thick forests and comprise the youngest rocks in the Himalayan range, dated from Pliocene. The soft, loose and easily erodible rocks comprise sandstones, siltstones, claystones and conglomerates.

Water penetrates into these rock masses along the fractures and joints and sometimes creates flowing ground conditions.

The main geological outcrops in the Design area are dated from Tertiary and Quaternary.

In Figure 6 it can be observed a simplified map of the NW part of Himalayas, showing the lithotectonic and longitudinally thrusts. The location of tunnel T1 is marked with an arrow.

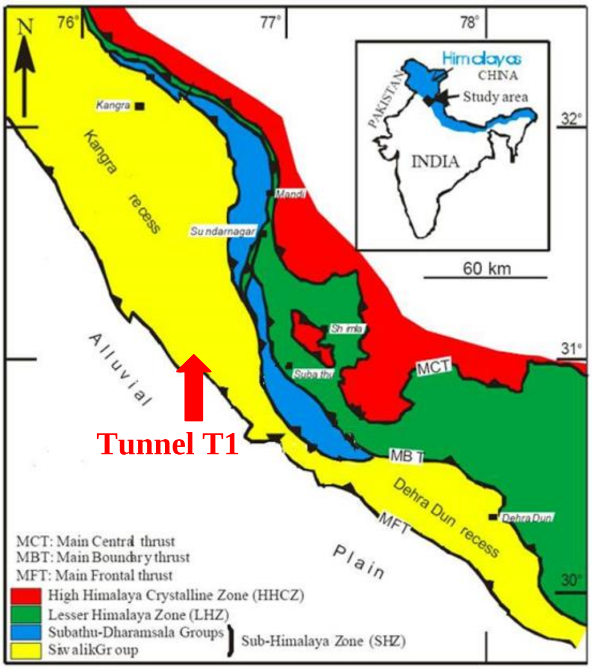


Figure 6.Intervention zone of the tunnel 1. Simplified geological map.

3.2 *Geotechnical Zoning*

The rock mass geotechnical zoning was defined based on the "*Austrian Guideline for the Geotechnical Design of Underground Structures (Austrian Society of Geomechanics, 2010)*", taking into account the Geotechnical Investigations held during December 2012 to

April 2013, according with the following sequence:

1. Determination of Rock Mass Types (RMT) with a description of the basic geological model and definition of the geotechnically relevant parameters for each rock type;
2. Determination of Rock Mass Behavior Types (RMBT), evaluating the potential rock mass behavior considering each rock mass type;
3. Selection of construction concept, based on the rock mass characteristics and the determined rock mass behavior (excavation method, sequence of excavation and support);
4. Evaluation of behavior in the excavation area, in which the potential behavior in the excavation area is analyzed (face and perimeter stability);
5. Determination of the excavation and support type and evaluation of behavior in the supported area;
6. Geotechnical Zoning, based on the previous steps the alignment is divided into sections with similar support types;

The rock masses along Tunnel 1 are represented by a sequence of argillaceous and arenaceous rocks, forming a series of interbedded of sandstones, siltstone/claystone beds.

Based on this procedure it was developed the geological and geotechnical profile shown in Figure 7.

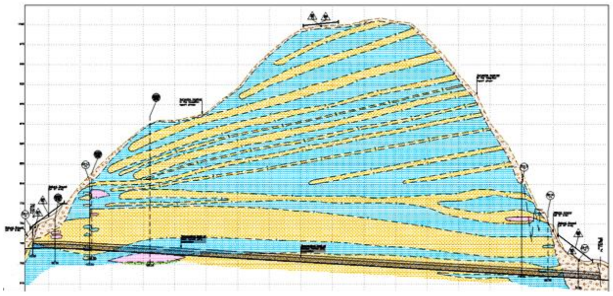


Figure 7.Tunnel 1 geological and geotechnical profile.

Sandstone (in blue), predominantly gray with coarse, medium and fine grained. Low to moderately weathered.

Interbedded Siltstone (in yellow) *and Claystone* (in pink), the siltstones are fine grained, often Micaceous. The Claystone are fine grained, soft to fairly hard, sometimes highly friable. The claystone interbedded appears in the field totally incoherent, due to high fracture zones and high rate of weathering.

Top soil (in brown), sands, silty sands, clay, cobbles and boulders.

The rock mass behavior (RMBT) was determined for each rock mass type by evaluating the effect of the influencing factors on the response of the rock mass with the full excavation geometry (*Austrian Society of Geomechanics*, 2010).

The Bieniawski Geomechanical Classification (1989) or the Rock Mas Rating (RMR) was also applied in the definition of the zoning and geomechanical characteristics of each geomechanical zoning, as well as the *NATM Rock Mass Classes* (ÖNORM B 2203) for establishing the tunnel support classes.

The three Geotechnical Zones are the following:

- ZG1 – RMBT 3/1;
- ZG2 – RMBT 3/2;
- ZG3 – RMBT 5/11 and 8/11.

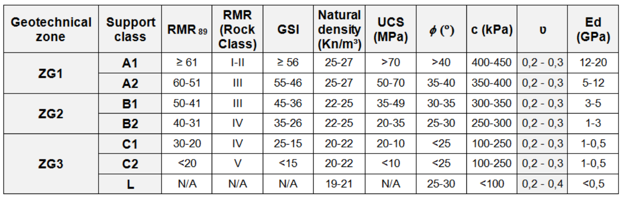
It was established a correlation between the three geotechnical zones and the tunnel support classes. Also it were added the following support sub-classes, according to the overburden and the geotechnical characteristics of the rock mass.

- C1-A – Support class C1, with H ≤ 200 m;
- C1-B – Support class C1, with H > 200 m;
- C2-A – Support class C2, with H ≤ 200 m;
- C2-B – Support class C2, with H > 200 m;

The estimated Geomechanical Parameters of Rock Mass were based on the geotechnical investigations, laboratory tests and the RMR. The calibration of these parameters was made using the software program RocLab, for determining rock mass strength parameters based on the generalized Hoek-Brown failure criterion.

The parameters calibration has led to the following Geomechanical Parameters (Table 2).

Table 2.Geomechanical parameters.



Geotechnical zone	**Support class**	**RMR_{89}**	**RMR (Rock Class)**	**GSI**	**Natural density (Kn/m^3)**	**UCS (MPa)**	**ϕ (°)**	**c (kPa)**	**υ**	**Ed (GPa)**
ZG1	**A1**	≥ 61	I-II	≥ 56	25-27	>70	>40	400-450	0,2 - 0,3	12-20
	A2	60-51	III	55-46	25-27	50-70	35-40	350-400	0,2 - 0,3	5-12
ZG2	**B1**	50-41	III	45-36	22-25	35-49	30-35	300-350	0,2 - 0,3	3-5
	B2	40-31	IV	35-26	22-25	20-35	25-30	250-300	0,2 - 0,3	1-3
ZG3	**C1**	30-20	IV	25-15	20-22	20-10	<25	100-250	0,2 - 0,3	1-0,5
	C2	<20	V	<15	20-22	<10	<25	100-250	0,2 - 0,3	1-0,5
	L	N/A	N/A	N/A	19-21	N/A	25-30	<100	0,2 - 0,4	<0,5

3.3 *Geology Influence over Underground Works*

Several published references about the geological and geotechnical conditions in the regions of the Himalayas, alert for the risks of the behavior that underground works show in that geological environment (*Goel*, *Sainie et al.*). These risks are related with the occurrence of problems in the excavation face collapse, chimney formations, overbreaks, water inrush, squeezing, etc.

In its communication, through the survey of several events, *Goel* refers that in the region of the Main Frontal Thrust (Sub-Himalaya or Shiwaliks) and until maximum overburdens of about 1000 m, where tunnel T1 will be located, there is the possibility to occur the previous stated problems.

According with the Norwegian recommendations (Shrestha, 2005), the squeezing phenomena can occur, in formations consisting by sandstones, shals and siltstones, for depths over 250 m (Figue 8).

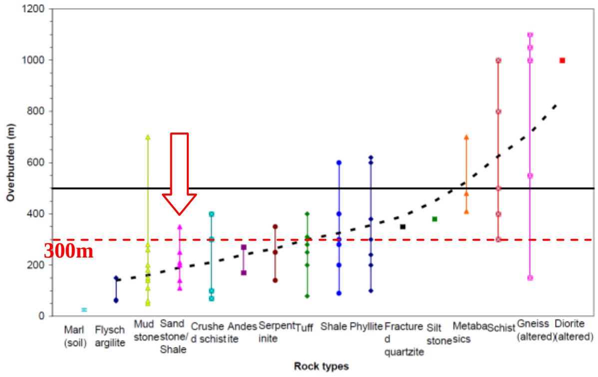


Figure 8.Relations between the various rock types and the overburden (*Shrestha, 2005*).

Singh et al (1992) proposed a method to distinguish the zones more likely to occur the squeezing phenomena, based on the analysis of various events during the construction of tunnels in the Himalayas region, using Equation 1.

$$,H > 350\,Q^{\frac{1}{3}} \tag{1}$$

where Q is Barton quality index and H is the tunnel depth or overburden.

This methodology has allowed to evaluate the depth (H), for each geotechnical zone, from which the squeezing phenomena may occur (Table 3).

Table 3.Critical depths for the occurrence of squeezing.

	CLASS	RMR	GSi	Singh et al H (m)	SQUEEZING
ZG1	A1	80	75	1625	NS
	A2	55	50	452	NS
ZG2	B1	50	45	350	NS
	B2	40	35	210	S
ZG3	C1	30	25	126	S
	C2	25	20	95	S

Hence the Tunnel 1 has a maximum overburden of 300 m, one can observe that there is the possibility of occurring squeezing for ZG2 (Support Class B2). Based on the results, for ZG3, there is a likely possibility of occurring squeezing.

The expected tunnel sidewalls deformations (convergences) due to squeezing and the probable plasticizing zone radius of the cavity surrounding were estimated using the semi-analytical models of *Kovari* (1998) and *Hoek and Marinos* (2000).

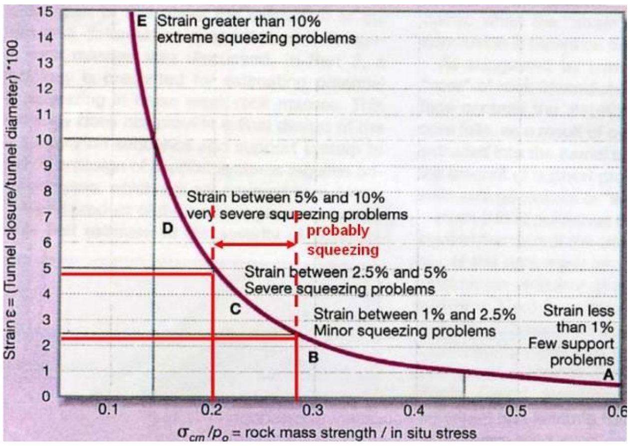


Figure 9.Classification of squeezing behavior (*Hoek and Marinos, 2000*).

On zone ZG3, support class C2, for overburdens over 200 m it is expected the occurrence of big sidewalls deformations (Figure 9), due to squeezing, that can be characterized between “minor squeezing problems”, with about 1.8% strain, and “severe squeezing problems” with a strain of about 4.7%, matching the zone C of the previous curve.

It is expected that the tunnel sidewalls may reach deformations values in proportion to the tunnel radius, with values between 94 mm and 236 mm. The total convergence values will be about double these values.

The application of the *Kovari* (1998) model has shown a close agreement with the above values.

The reports and papers presented at numerous international forums on underground works, undertaken in recent years in the Himalayas, reveal a frequent occurrence of squeezing phenomena which may present high deformation values.

It should be noted that in recent works, excavated in formations of the same nature, the convergence values that were observed during the construction are below the estimated values, in the other tunnels of Himalaya Region.

Nevertheless, even assuming that the actual values may be lower than those obtained by calculation, the design foresees mitigation measures to prevent the effects of large deformations.

These measures include the implementation of compensatory over-excavation and the use of support elements capable to accommodate large displacements, type Lining Stress Controllers (LSC) systems (Dywidag-systems international) (Figure 10).

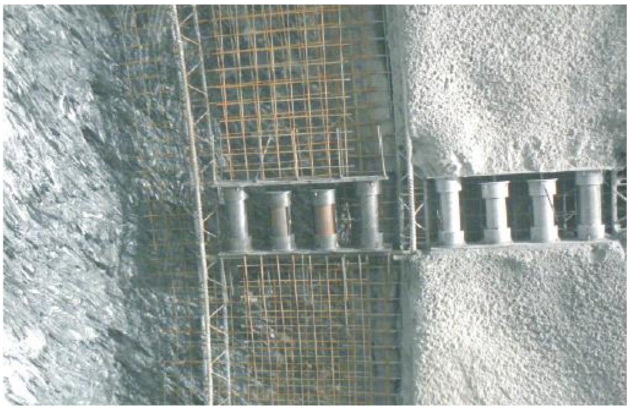


Figure 10.LSC yielding elements with four deformation pipes (*Radoncic, N. et al, 2009*).

The use of this procedure to prevent the effect of large deformations requires a close monitoring of the excavation face in gauging the geological and geotechnical conditions, the daily review of data obtained from the observation of the the excavation behavior and defining the type of LSC to apply.

4 TUNNEL DESIGN

The tunnel design was carried out with the analysis of the adopted construction sequence, by applying the Convergence Confinement Method (CCM) and the Finite Elements Method (FEM), through the software PLAXIS.

The sequence of excavation and installation of supports for various geotechnical conditions along the tunnel alignment was simulated with the previous methods, being estimated for the tunnel sidewalls convergence deformations, for the plastification radius of the tunnel surrounding rock mass and also for the behavior of the support to install.

For example, on Tunnel 1 – Main Tunnel, the calculation by applying the CCM and FEM has shown high convergence values, that are presented in Table 4.

Table 4.Tunnel 1- Main Tunnel. Convergence values.

Geotecnical zone	Support class	H (m)								
		100			200			300		
		CCM	*MEF*	*Semp*	*CCM*	*MEF*	*Semp*	*CCM*	*MEF*	*Semp*
ZG1	*A1*	----	----	----	----	----	----	*6,7*	*8,2*	----
	A2	----	----	----	----	----	----	*26,0*	*32,3*	----
ZG2	*B1*	----	----	----	----	----	----	*37,7*	*46,7*	----
	B2	----	----	----	----	----	----	*68,5*	*79,4*	*70,6*
ZG3	*C1*	----	----	----	*69,5*	*73,7*	*77,4*	*149,5*	*184,6*	*178,1*
	C2	----	----	----	*187,5*	*202,2*	*98,9*	*455,9*	*463,5*	*223,2*

These methods allowed estimating the primary support solutions concerning the constructive methodology, namely the excavation sequence, the assignment of the support classes to each geotechnical zone and, given the case that large displacements may occur, the use of LSC.

Associated to this methodology, were also planned compensatory over-excavation of the tunnel necessary in order to accommodate the potential convergence deformations inside the tunnel construction line.

Thus, the excavation line was considered on a surrounding of the theoretical section in a value equal to the expected deformation. Nevertheless, the final values will be reevaluated during the execution of work through behavior models in back analysis.

The tunnel primary support will include shotcrete with wire mesh, rock bolts type “swellex” and, according with the support class, steel ribs and forepoling. In the assumption of large convergence displacements, due to squeezing, will also be applied LSC (Figure 11).

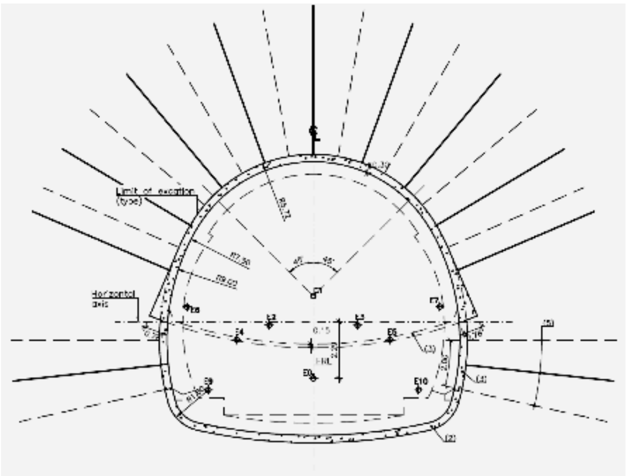


Figure 11.Tunnel 1 – Main Tunnel. Typical primary support.

5 CONCLUSIONS

The existing theoretical models to evaluate the behavior of the underground excavation, with theoretical approaches of reality, give us results that should be confronted with the data obtained during the execution of the works. This information is often replicated into empirical models and/or reported incidents during the works executed in similar conditions.

The innumerable published references on recent excavations in the Himalayas report the occurrence of numerous situations in which are observed and registered large displacements by convergence within the tunnels, which are responsible for breakage or collapse of the supports applied. Thus, given the current conditions of the project and in order to timely prevent the possibility of undesirable situations on the tunnel supports, the design foresees the use of devices for energy absorption by deformation, type LSC, to install in the primary support.

Thus, given the dispersion of geotechnical data of the materials to excavate, the decision on when and where to use the LSC will result from the close monitoring of the excavation, through the implementation of the observational method and assignment to the excavation work front of technical staff with large professional experience.

For that purpose, the tunnel design contains the appropriate criteria to set the limits of the technical staff, in order to adjust or choose a particular solution.

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REFERENCES

Dywidag-systems international, *AT-LSC, Lining Stress Controllers*, www.alwag.com;

Goel, B.K. ; 2000. *Challenges of tunneling in fragile rocks of Himalaya*, GeoEng 2000.

Indian Road Congress ; 2010. IRC:SP:91-2010. *Guidelines for road tunnels*.

Goel, B.K., Dwivedi R.D., Viswanathan, G., Rathore, J.S.; 2013. *Monitoring of tunnel through mixed geology in the Himalaya*, World Tunnel Congress 2013, Genève, pp 2115-2122;

Palomba, M., Russo, G., Amadini, F., Carrieri, G., Jain, A.R.; 2013, *Chenani-Nashri Tunnel, the longest road tunnel in India: a challenging case for design-optimization during construction*, World Tunnel Congress 2013, Genève, pp 964-971.

Radoncic, N., Schubert, W, Moritz, B., 2009. *Ductile support design*, Geomechanics and Tunnelling 2, No. 5;

Saini, G.S., Dube, A.K., Singh, B., *Severe tunneling problems in young Himalayan rocks for deep underground opening*, (*www.undergroundspace.in*).

Shrestha, G.L., 2005, *Stress induced problems in Himalayan tunnels with special reference to squeezing*, *Thesis* (PhD in doctor engineer), Norwegian University of Science and Technology, Trondheim, 195p.

Singh, B., Goel ,R.K. 2011. *Engineering rock mass classification*, Elsevier Inc.