Reinforcement of Transportation Infrastructure, The Cable Car Network of La Paz (Bolivia)

Freddy Lopez
Friedr. Ischebeck GmbH, Ennepetal, Germany
lopez@ischebeck.de

Racquel Nottingham
Friedr. Ischebeck GmbH, Ennepetal, Germany
nottingham@ischebeck.de

Abstract

The metropolitan area of the neighboring cities of La Paz and El Alto has an approximate population of 2 million people. Due to its abrupt topography and limited geographical extension, the rapid growth of La Paz caused a massive urban development on and nearby steep slopes. In order to satisfy the transportation requirements of the city, a cable car network has been successfully implemented to interconnect the different districts. However, as a result of complex geological and geotechnical conditions, several landslides occur periodically in densely populated and built-up areas, causing considerable damage and increasing the risks to life and infrastructure. This paper discusses a particular failure mechanism that affected one area of the city, and the possible implications on the stability of vital elements of the cable car network. Based on the results of the carried-out analysis, a reinforcement solution by using Ischebeck TITAN self-drilling soil nails is proposed.

1 INTRODUCTION

La Paz is the seat of the government and the financial centre of the *Plurinational State of Bolivia*. The Metropolitan Area of the neighbouring cities of La Paz and El Alto has a population of approx. 2 Million people. The valley of La Paz has a very abrupt topography, with a longitudinal slope of approx. 5% (1km in 18.5km) and a transversal slope of approx. 16% (0.5km in 3km) (Figure 1):

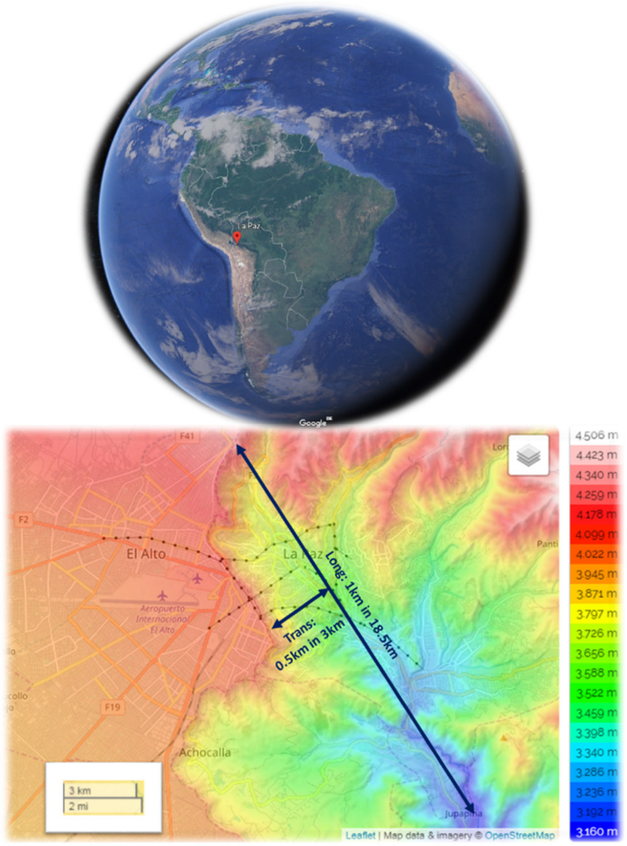

Figure 1. Location and topography of La Paz, Bolivia after Lopez et al (2019)

Due to the topography and the limited geographical extension of La Paz, the urban development of the past few decades occurred within regions, characterized by the presence of steep slopes. To connect these highly populated and built-up areas, a cable car network was successfully implemented since 2014.

Operating at about 4000m above sea level and with a transportation rate of 3000 passengers/ hour, the implementation of the cable car network has a major influence in the urban development, changing quintessentially the public transportation.

According to official information, more than 200 Million passengers have used the cable transportation system until June 2019 (Mi Teleférico, 2019). The network has currently ten operative lines with an extension of approx. 30.5km. The Golden Line (Línea Dorada) is in the final design stage (Figure 2):

Figure 2. Metropolitan Cable Car Integration Network of La Paz and El Alto, after Mi Teleférico (2019)

2 LANDSLIDES IN LA PAZ

The city of La Paz has an area of approx. 472km^2. Deep valleys and steep slopes characterize most of the urban area, which is prone to landslides. According to official information, the urban sprawl area is primarily covered by slopes:

Table 1. Land area distribution acc. to DEGIR-GAMLP (2011)

Terrain	Grade [%]	Area distribution [%]
Steep slopes	> 50	35
Moderate slopes	10-49	28
Small slopes / flat terrain	< 10	37

The combination of steep slopes, torrential rainfall (around 600mm/year) and intense superficial erosion contributes to potential instability problems and the corresponding periodical occurrence of landslides, especially in the districts located and /or nearby steep slope areas, which have been identified as high-risk zones (red marked areas) by the official integral risk management report, published by DEGIR-GAMLP (2011), as depicted in Figure 3:

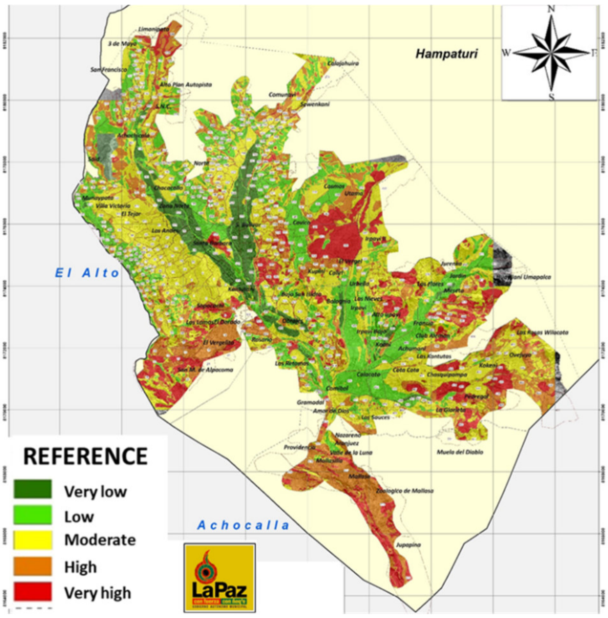

Figure 3. Risk map for the city of La Paz (modified after DEGIR-GAMLP, 2011)

In the past 24 years, at least eight catastrophic landslides have been recorded in the seven Macro-districts of La Paz, as summarized in Table 2:

Table 2. Major landslides recorded since 1996

Landslide	Date	Aftermath
Cotahuma	04/1996	60 collapsed houses 18 human casualties
Retamani II	02/2009	50 collapsed houses
Huano Huanuni	01/2010	61 collapsed houses
Sta Rosa de Callapa	02/2011	1188 collapsed houses
Las Lomas	02/2012	11 collapsed houses
Hoyada 23 de Marzo	02/2012	10 collapsed houses 1 human casualty
Auquisamaña	02/2017	8 collapsed houses
Kantutani	02/2019	66 collapsed houses 2 human casualties

As presented in Table 2, it can be observed, that the events took place between the months of January and April, which correlates with the typical rainy season (December – March). This condition usually points to instability due to an accumulation of pore water pressures and superficial erosion, associated with heavy rainfall. However, the records of one particular landslide: *Auquisamaña* (02/2017) have shown particularly abnormal dry conditions.

This paper will discuss possible reasons for instability in this particular case, since it presents possible implications on the stability of the infrastructure of the cable car network.

3 THE AUQUISAMAÑA LANDSLIDE

At 16:00 hours (local time) on February 15 2017, a 40m-tall, massive clayey cliff collapsed, destroying at least 8 houses in the quarter of *Auquisamaña* (District of Calacoto, Macrodistrict South) as presented in Figure 4:

Figure 4. Aerial views of the *Auquisamaña*-Landslide

3.1 SITE CONDITIONS

The geology of the area corresponds to the extended *La Paz-Formation*, which is characterized by the presence of over-consolidated, low to high plastic clays acc. to DEGIR-GMLP (2011). These clays offer very good resistances for the foundation of structures; however, they can be susceptible to instability in areas with intense erosion and abrupt topography, due to the possible development of joints and defined slip planes. The geotechnical properties of the La Paz-Formation scatter throughout its extension, as presented in Table 3:

Table 3. Characterization of the La Paz-Formation acc. to Sangueza, O. and Prudencio, M. (2016)

Classification	Friction Angle [°]	Cohesion [kPa]	Unit weight [kN/m^3]	E-modul [MPa]
Over-consolidated, low plastic clays CL	18 – 23 (20)	50 – 75 (60)	17 – 19 (17)	11 – 25 (23)
( ) indicate the values for the district of *Calacoto*				

3.2 LANDSLIDE ANALYSIS

A digital model of the slope was developed using the available official planimetry and altimetry of La Paz (GAMLP, 2012) and the software GGU-Stability. Slope stability analysis were carried out to determine the factor of safety and the risk of sliding. For the analysis, the *General Wedge Method* acc. to DIN 4084 (1981) was used, in combination with a Mohr-Coulomb constitutive model, using with the values listed in Table 3.

The *General Wedge Method* consists of the analysis of polygonal slip surfaces, comprised by rigid slip bodies, which are limited by "external" and an "internal" slip planes, defined by the borders to the neighbouring slip bodies (Figure 5).

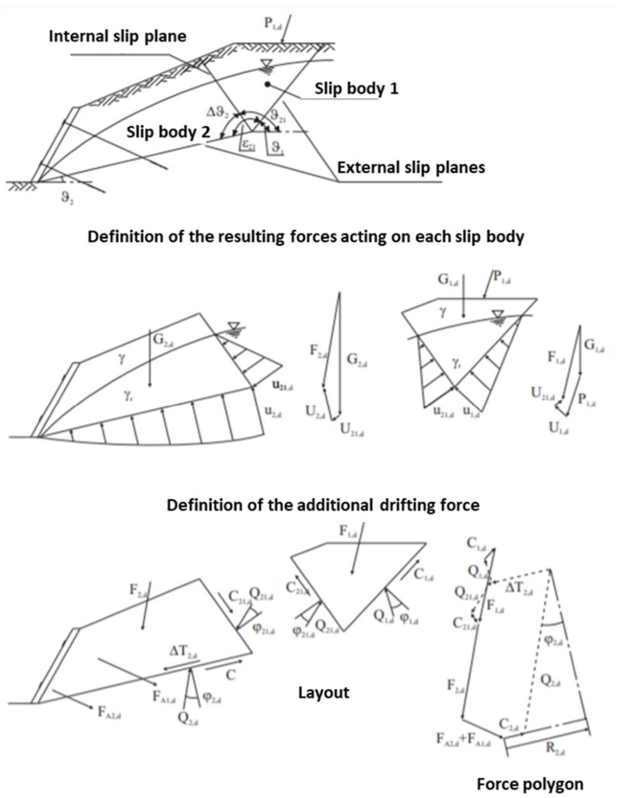

Figure 5. Failure mechanism with the General Wedge Method, modified after Katzenbach (2011)

The analysis of polygonal slip planes is recommended for slopes in over-consolidated soils and/or with predefined potential slip planes (Katzenbach, 2011).

The analysis of the *Auquisamaña-Landslide* resulted in a global safety factor of η = 1.6 (Figure 6), although the clayey cliff clearly collapsed.

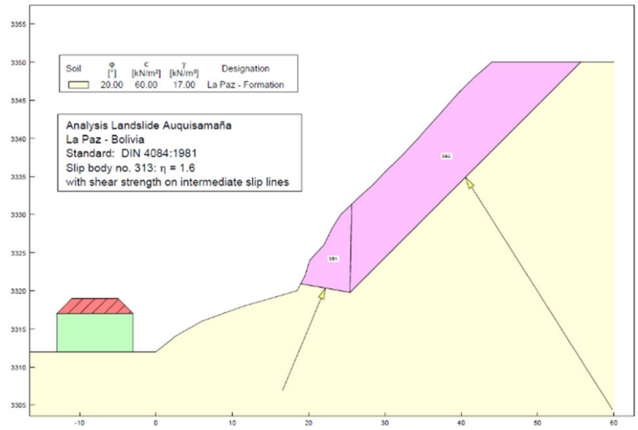

Figure 6. Critical slip body (No. 313) / Safety factor η = 1.6

One clue was decisive to understand the failure mechanism: one day after the landslide, the Risk Management Office (DEGIR) informed that the landslide occurred under abnormally hot and dry weather conditions, and that the collapse was caused by the "drying and contraction" of the clays (Tierra Plus, 2017).

This condition suggests the occurrence of a "degradation process", reducing the shear resistance of the constitutive materials.

A sensitivity analysis was conducted to evaluate potential factors that might have affected the cliff. The main focus was set on evaluating the presence of possible joints or gaps, which can occur as a result of the repeated exposition of the clays to humidity-dryness-cycles over the time, and the subsequent differential erosion along the joints. Evidence of this process jointing can be found in other locations (Figure 7). Table 4 presents the joint parameters adopted for the analysis.

Table 4. Definition of the adopted joint parameters

	Friction Angle [°]	Cohesion [kPa]	Hor. inclination [°]
Joints	20	0	30 – 90

Figure 7. Evidence of jointing in the La Paz-Formation: Outcrop in Rosaspampa, DEGIR-GAMLP (2011)

The results of the sensitivity analysis are presented in Figure 8. A global safety factor $\eta < 1.0$ was obtained for a joint (horizontal) inclination between 50° - 53°.

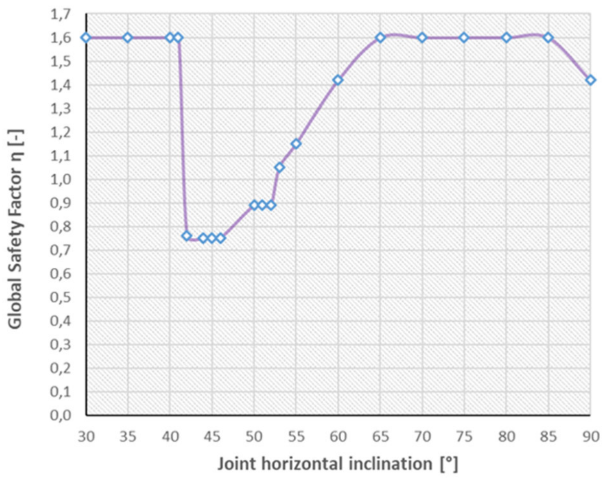

Figure 8. Global safety factor Vs. Joint inclination

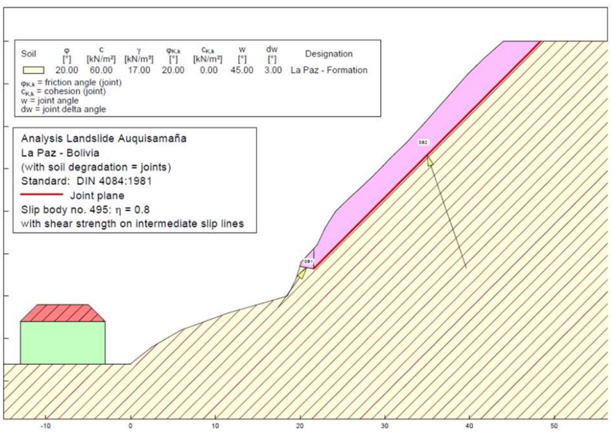

Figure 9. Critical slip body (No. 495): Joint inclination = 45° and correspondent safety factor $\eta = 0.75$

Under these conditions, if was possible to calibrate the model and to obtain the critical slip body, for which the failure was verified, showing a good agreement with the collapsed cliff (Figure 9).

4 IMPLICATIONS FOR THE INFRASTRUCTURE OF THE CABLE CAR NETWORK

Several of the towers (pylons) in the network are located in areas, characterized by the same conditions discussed in this paper:

- On and / or nearby steep slopes
- Founded on the *La Paz-Formation*

Figure 10. Some examples of towers for the Cable Car Network (Left: Yellow Line / Right: Purple Line)

Following the above-mentioned methodology, a slope stability analysis was conducted for the Tower 24 of the Green Line, located on a 43m-tall steep clayey cliff (Figures 11 and 12):

Figure 11. Plan view of the Tower 24 (Green Line)

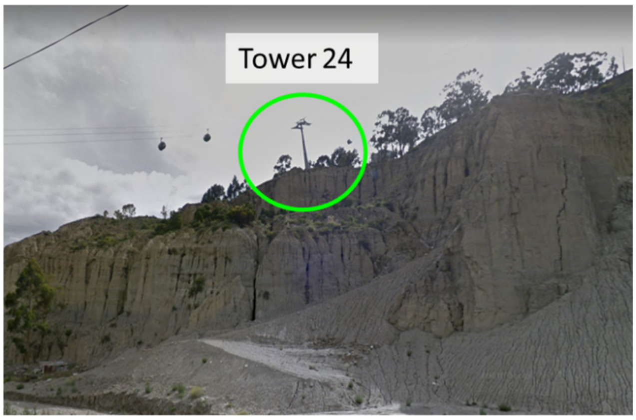

Figure 12. Lateral view of the Tower 24 (Green Line)

The geotechnical parameters presented in Table 3 were used for the calculations, since they were considered to be representative enough for the location. Figure 13 presents the result of the calculations, with a more than satisfactory global safety factor of $\eta = 1.5$.

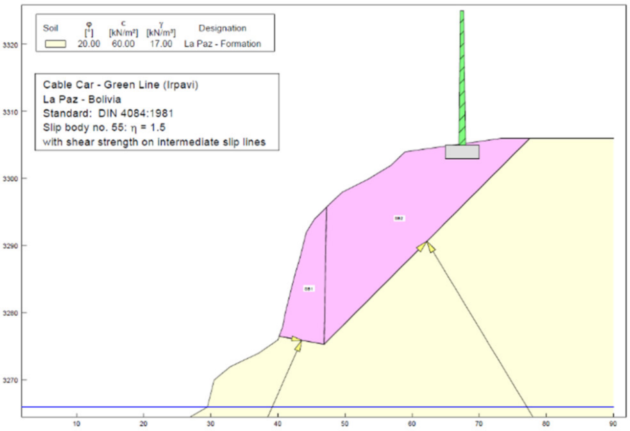

Figure 13. Critical slip body (No. 55): Safety factor $\eta = 1.5$

The results of the sensitivity analysis are presented in Figure 14.

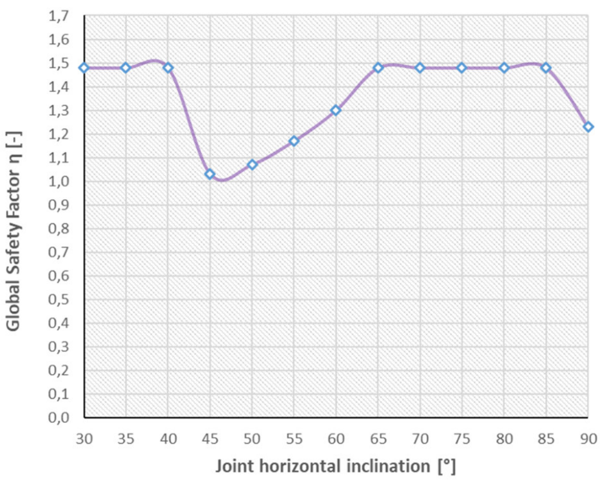

Figure 14. Global safety factor Vs. Joint inclination

The results of the study show that, as a general case, a global safety factor $\eta > 1.0$ could be obtained for every analysed joint inclination, verifying the overall stability of the clayey cliff; however, a significant reduction of the global safety factor was observed for joints with (horizontal) inclinations between 45° - 60° (i.e. Figure 15).

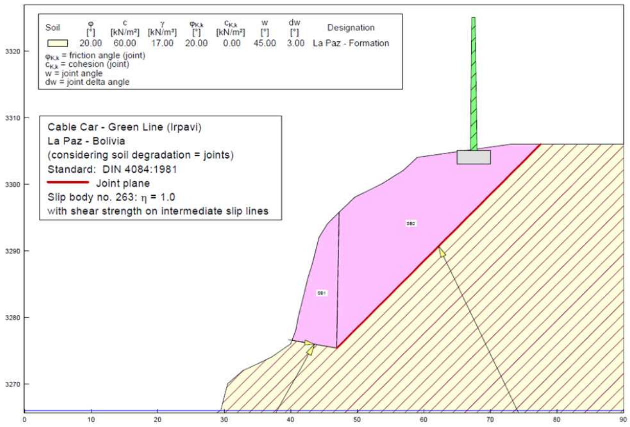

Figure 15. Critical slip body (No. 263): Joint inclination = 45° and correspondent safety factor $\eta = 1.03$

5 PROPOSED REINFORCEMENT

To increase the overall stability of the analysed slope, the reinforcement with soil nails was evaluated. Soil nails allow tensile forces to be accommodated, tie-backing the critical slip bodies to the passive zone. The load is transferred to the surrounding soil via the bond resistance at the interface grout-soil (skin friction). An ultimate skin friction value of $q_s = 150$kPa was adopted for the analysis. Several calculations were performed until a minimum factor of safety of 1.4 was achieved.

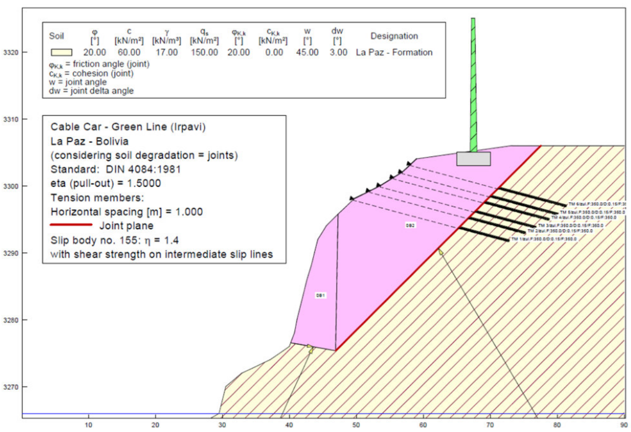

Figure 16. Reinforcement with soil nails. Critical slip body (No. 155): Joint inclination = 45° and correspondent safety factor $\eta = 1.4$

Figure 16 shows the slope reinforced with six (6) soil nails, set up with a center-to-center distance of 1m in both horizontal and vertical direction. The details are presented in Table 5.

Table 5. Soil Nail details, including length (L), diameter of grouted body (D), safe working load (R_{adm}) and inclination (α_{hor})

N°	TITAN	L [m]	D [mm]	R_{adm} [kN]	α_{hor} [°]
1	40/16	24	150	350	15
2	40/16	24	150	350	15
3	40/16	24	150	350	15
4	40/16	24	150	350	15
5	40/16	24	150	350	15
6	40/16	24	150	350	15

R_{adm} = safe working load with a safety factor = 1.5

Due to the abrupt topography on the site, the reinforcement was placed only on the more accessible areas at the top of the slope.

The analysis was carried out considering the use of Ischebeck TITAN self-drilling soil nails.

Self-drilling soil nails consist of continuously threaded hollow bars, made out of seamless steel pipes, installed via rotary percussive drilling. During the drilling process, the soil nails are continuously grouted (dynamic injection), building a rough interlocking at the interface grout-soil, increasing the skin friction (Lopez and Severi, 2017), as presented in Figures 17 and 18.

These soil nails fulfil the requirements of different execution guidelines and standards, such as the FHWA (2003) and the EN 14490 (2010), correspondingly.

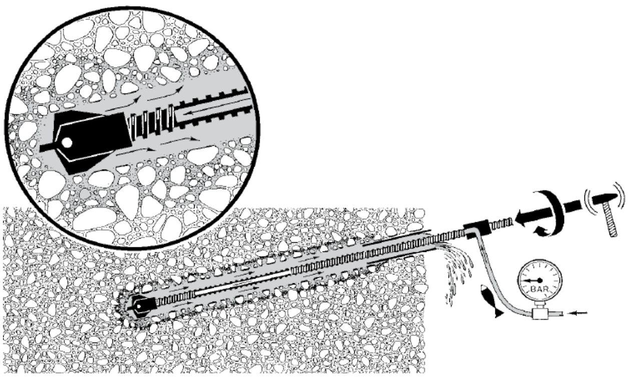

Figure 17. Rotary percussive drilling with flushing grout (w/c = 0.7-0.8) after Friedr. Ischebeck (2019)

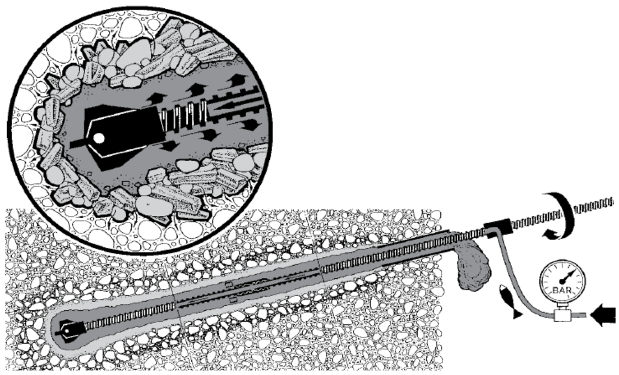

Figure 18. Dynamic pressure grouting (w/c = 0.4-0.5) after Friedr. Ischebeck (2019)

The proposed reinforcement was chosen, due to the advantages of the system:

- Suitable for use in areas where working space is limited or challenging (Figure 19)
- Varying soil conditions do not pose a threat for this system and the soil nails can be adapted for every possible scenario
- Permanent corrosion protection by means of grout cover is provided, in accordance with DIBt (2020)

Figure 19. Execution self-drilling soil nails in areas with restricted space, after Friedr. Ischebeck (2019)

6 CONCLUSIONS

This paper discusses a particular failure mechanism that affected one area of the city of La Paz: the *Auquisamaña-Landslide.*

The results of the analysis suggest that the collapse of the 40m-tall clayey cliff was triggered by a “degradation process” of the constitutive materials, as a result of the repeated exposition to humidity-dryness-cycles over the time. This condition might have caused the presence of joints in the over-consolidated clays, with the correspondent reduction of the shear strength.

Based on the obtained results, a study was conducted to evaluate the possible implications of this degradation process on the stability of vital elements of the cable car network: the towers.

Several calculations were carried out to evaluate the stability of one tower of the Green Line (Tower 24), located on a 43m-tall steep slope, with similar conditions as the presented in the *Auquisamaña-Landslide*.

It could be concluded that although the overall stability of the slope was verified, significant reductions on the global safety factor could be expected. Based on those results, a reinforcement solution by using Ischebeck TITAN self-drilling soil nails was proposed, in order to re-establish the required safety level, providing the slope with additional resistance reserves. These preventative measures can be implemented to limit or eliminate the risk to life and infrastructure.

7 REFERENCES

DEGIR-GAMLP (2011). "*Memoria Indicativa y Mapa de Riesgos de los Distritos Urbanos del Municipio de La Paz*". Report. La Paz

Deutsches Institut für Bautechnik-DIBt (2020). "*National Technical Approval: TITAN Micropiles*". Berlin

DIN 4084 (1981). "*German Standard: Subsoil; Calculations of terrain rupture and slope rupture*". Berlin, Beuth Verlag

EN 14490 (2010). "*European Norm: Execution of special geotechnical works – Soil Nailing*"

Federal Highway Administration FHWA (2003). " *Geotechnical Engineering Circular No. 7: Soil Nail Walls*". Maryland

Friedr. Ischebeck GmbH (2019). *"Technical Documents*". Ennepetal

GAMLP (2012). *"Mapas del Municipio de La Paz*". La Paz

Katzenbach, R., (2011). "*Böschungs- und Geländebruch*" Studienunterlagen Geotechnik, Technische Universität Darmstadt: VII-1 to 47. Darmstadt

Lopez, F., Saucedo, M., and Gonzalez, D. ,(2019)."*The Cable Car network in La Paz*". Proceedings of the 14th International Workshop on Micropiles. Goldcoast, August 21-23.

Lopez, F., Severi, G., (2017). "*Micropiling in Urban Infrastructure: Advantages, experience and challenges*". Proceedings of the DFI-EFFC International Conference on Deep Foundations and Ground Improvement. Rome, June 5-8.

Mi Teleférico (2019). "*Los números de Mi Teleférico*". Report. La Paz

Sangueza, O., Prudencio, M., (2016) "*Caracterización Geotécnica de la formación La Paz, Sectores Curva de Holguín y Alpacoma*". Thesis for Civil Engineering Degree, Catholic University of Bolivia. La Paz

Tierra Plus (2017). "*Press release: https://www.tierraplus.com.bo/Internacional/Social/Sequedad-y-calor-han-ocasionado-el-deslizamiento-en-Auquisamaa* ". Online Newspaper