

INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING



This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

<https://www.issmge.org/publications/online-library>

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

The paper was published in the proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering and was edited by Mizanur Rahman and Mark Jaksa. The conference was held from May 1st to May 5th 2022 in Sydney, Australia.

Milagres tunnel instrumentation (Pernambuco-Ceará, Brazil)

Instrumentation du tunnel Milagres (Pernambuco-Ceará, Brésil)

Leonardo Ferreira

*M.Sc, Geotechnical Civil Engineer at the Ministry of Regional Development, PUC-Rio, Rio de Janeiro, Brazil,
leonardoferreira.engenheiro@gmail.com*

ABSTRACT: This paper summarizes the excavation works of the 818m long Milagres Tunnel, excavated in rock (Phyllite), between the municipalities of Salgueiro (Pernambuco) and Penaforte (Ceará). This tunnel is part of the São Francisco Transposition Project (PISF), under construction since 2007, and planned to be concluded in 2021. The 10m high, 10m wide tunnel has an arc rectangular shape. This paper briefly reviews the tunnel excavation techniques and presents details of the geotechnical instrumentation in this project. Displacement data from five instrumented sections of the tunnel are discussed. Convergence and settlement results are noted to be interconnected. Moreover, stabilized displacements in all monitored sections were noted 60 days after installing the support system.

RÉSUMÉ: Cet article résume les travaux d'excavation du tunnel Milagres, long de 818 m, creusé dans la roche (Phyllite), entre les municipalités de Salgueiro (Pernambuco) et Penaforte (Ceará). Ce tunnel fait partie du projet de transposition de São Francisco (PISF), en construction depuis 2007, et qui devrait être achevé en 2021. Le tunnel de 10 m de haut et de 10 m de large a une forme rectangulaire en arc. Cet article passe brièvement en revue les techniques d'excavation du tunnel et présente les détails de l'instrumentation géotechnique dans ce projet. Les données de déplacement de cinq sections instrumentées du tunnel sont discutées. Les résultats de la convergence et de l'établissement sont considérés comme interconnectés. En outre, des déplacements stabilisés dans toutes les sections surveillées ont été notés 60 jours après l'installation du système de soutien.

KEYWORDS: Milagres Tunnel; tunnel instrumentation; convergence; settlements; São Francisco River.

1 INTRODUCTION

Brazil is a country of continental dimensions and has abundant water resources. However, the distribution of these resources is irregular. It is verified that the largest share of available water is in the Amazon Region, North, while the Northeast region suffers from periodic scarcity. The water deficiency of the Sertão Nordestino is known to all Brazilians. The Northeast region currently has almost 60 million people, that is, about 28% of the Brazilian population, with water availability of only 3% of the country's total according to data from the Ministry of Regional Development (MDR, 2019). Despite the scenario of northeastern water scarcity, there is the São Francisco River, which holds 70% of the region's water supply. With more than 2,800 km of extension, the São Francisco River is called the National Integration River, because it is the natural connecting path of the Southeast and Northeast regions of Brazil. From the springs in the Serra da Canastra, in Minas Gerais, to the mouth in the Atlantic Ocean, on the border of Sergipe and Alagoas, the river receives the contribution of 99 perennial tributaries and 66 others with a periodic regime. The periodicity is due to the irregularity of annual rainfall indices, ranging from 1,900mm in the springs to 350mm in the northeastern stretch. The annual evaporation rates vary inversely, from 500mm at the head to 2,200mm annually in Petrolina (PE), according to RIMA (2004). According to the National Water Agency (ANA), the average flow of the São Francisco River is 2,846 cubic meters per second. According to official data (MDR, 2019), the São Francisco River Basin covers an area of about 640,000 square kilometers in the states of Goiás, Minas Gerais, Bahia, Pernambuco, Alagoas, Sergipe, and the Federal District, with more than 18 million inhabitants (IBGE, 2010).

At the end of the 19th century, between 1877 and 1879, the Brazilian Northeast experienced the saddest period in its

history, with the Great Drought, a devastating calamity that devastated crops and herds and caused the death of 400,000 people and the mass migration of flagellates to other regions of the country. It was three years in a row without rain and water for the northeastern population.

Touched by the tragedy, Emperor Pedro II began to give priority to the theme of drought in his official speeches delivered in Parliament, known as the "Lines of the Throne". In 1878, amid the tragedy of the Great Drought in the Northeast, Pedro II declared: "The scourge of drought has ravaged for almost two years a considerable part of the North of the Empire, deeply afflicting my heart. To mitigate the consequences of such calamity, the government has employed the means at its fingertips" (Senado Federal, 2017). The "Lines of the Throne" did not deal with the transposition of the São Francisco River, but the monarch was already working with measures to combat drought. In 1852, the German engineer Henrique Halfeld was hired to propose a project to divert water from the São Francisco River to the Semi-Arid Northeast. In April 2005, more than a century after the São Francisco transposition plan, requested by Pedro II, the construction of the São Francisco Integration Project (PISF) was finally authorized (IBAMA, 2005). The PISF was the most consistent structural plan for the water supply of the Semi-arid Northeast. Evaluations and technical studies, covering the environmental impact and technical and economic feasibility, were carried out according to the Decennial Plan of the São Francisco River Basin, prepared by ANA (National Water Agency, an agency of the Brazilian government that deals with the regulation, planning, monitoring and application of the Brazilian Water Law, approved in 1997). The PISF is the largest infrastructure project under implementation in Brazil, defined as part of the National Water Resources Policy. With about 700km of total length, the project has two main axes (East and North), to ensure the water safety of 12 million people, living in the states of Pernambuco,

Ceará, Rio Grande do Norte, and Paraíba, where severe droughts are frequent. The two axes of the project involve the construction of varied infrastructure works: 13 aqueducts, 9 pumping stations, 27 dams with reservoirs, 9 substations, 4 tunnels, and 270km of transmission lines in high voltage. The 15km long Cuncas tunnel is the largest in Latin America for water transport. Human supply is the priority of the project, which is also considered as a means of regional development of metropolitan regions and the interior of the four favored states (Ceará, Rio Grande do Norte, Pernambuco, and Paraíba). The project also aims at economic progress, with the use of reservoirs for local irrigation and tourism projects. The São Francisco River should guarantee the water supply of large urban centers (Fortaleza, Campina Grande, Caruaru) and important medium-sized cities in the interior of northeastern Brazil. The Project will not cause damage to the flow of the São Francisco River. Results of hydrological analyses of ANA show that, even in periods of drought, the project can divert $26\text{m}^3/\text{s}$ from the flow of the river that would be dumped into the sea. In the rainy season, the catchment can reach $127\text{m}^3/\text{s}$, without harming the flow of the river, as indicated by the Prior License (IBAMA, 2005). Figure 1 shows the two axes of water transfer, subdivided into six segments of works, called Goals 1N, 2N, 3N, 1L, 2L, and 3L, being N and L indicative of the North and East Axes, respectively. In March 2020, the project had about 97% average progress, 96% in the North Axis, and 100% in the East Axis. The present work aims to present an analysis of the geomechanical behavior of the Milagres Tunnel, included in the Goal 1N of the North Axis. The structure was excavated in metamorphic rock (filite) with varying degrees of change, resulting in convergence deformations from despicable to significant, and contributing to the risk of rupture in the tunnel. The analysis used was the instrumentation data established for behavior monitoring during the excavation and execution of reinforcements/supports of the tunnel, represented by convergence pins and tassometers. Sections with different mass classifications and supports were defined. With the data, analyses were elaborated to verify and compare the magnitudes of convergence and settlements, as well as the evolution of both with time.

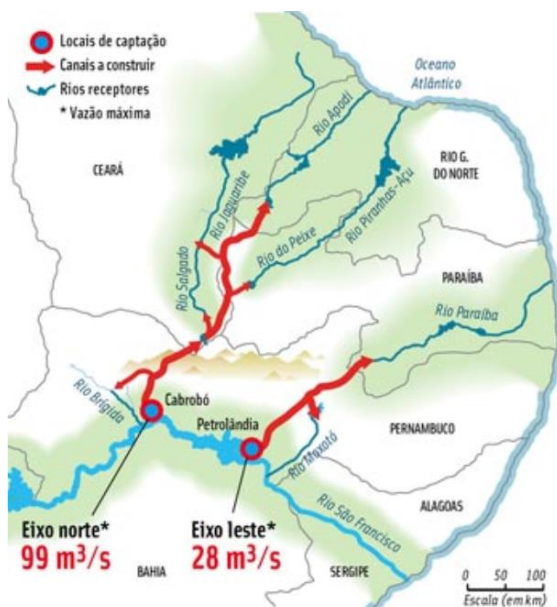


Figure 1. Location of PISF Axes (Espaço ET, 2020).

2 MILAGRES TUNNEL

The Milagres Tunnel is inserted in the North Axis of the PISF, with tunnel entrance in the municipality of Salgueiro, State of Pernambuco, and tunnel exit in the municipality of Penaforte, State of Ceará. The main access routes to the tunnel are the federal highways BR-232 and BR-116, which serve the city of Salgueiro. The works on the Milagres Tunnel covered the services of excavation and treatment of the transition sections of the tunnel entrance, tunnel exit, and internal perimeter of the tunnel. It has an arch-rectangle shape and flat base with an internal height of 9.6m and a maximum width of 10.0m. Due to the geomechanical characteristics of the filite rock massif traversed by the tunnel, two typical sections were considered for the analyses:

- Section S1: Corresponds to the sections of the initial and final sections, close to the ambush and unblock of the tunnel, with the treatment of the massif using injected enqueues, installed around the vault. The inner lining is represented by engineered concrete with a minimum thickness of 0.30m in the dome and walls. In the vault, trussed boots and a support shoe 1.0 m wide were implanted. The floor of the tunnel section is flat and coated in conventional concrete with 0.20m thickness;
- Section S2: Corresponds to the typical sections along the tunnel, except ambush and unblock, with the treatment of the massif using internal coating executed in reinforced concrete reinforced with metal mesh and systematic anchors, on the walls and vault, in addition to barbacás drains and deep horizontal drains (HpD's). The floor of the section is flat and coated in conventional concrete with 0.20m thickness.

The reinforcement treatments of the tunnel sections were defined considering the concept of Equivalent Diameter (D_e) as a function of the maximum span divided by the excavation support index (ESR), as proposed by Barton et al. (1974). The calculation of the Tunnel Equivalent Diameter adopted a minimum tunnel span equal to 10.17m (for the project flow) and $ESR = 1.3$. The methodology of Barton et al. (1974) was considered for the definition of the limits of each support category of the executive project according to the Equivalent Diameter. It should be emphasized that the Milagres tunnel was excavated in class III and IV filite, resulting in the treatments defined for the typical sections S1 and S2. The influence of the quality of the rock massif on the magnitude of the convergence and settlements values, through the continuation of the excavation front, was analyzed considering the immediate installation of the supports in each section.

2.1 Geological- Geotechnical Investigations

According to Barton et al. (1974), in 77% of the tunnel excavations, support category VI predominated, followed by category VII with 17% and in lower percentages of mass category VIII (4%) and IV (2%). There was no significant percentage of support in category V (Figure 2).

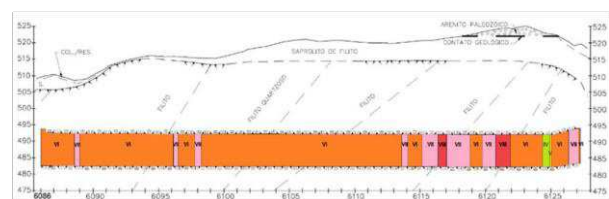


Figure 2. Longitudinal profile of the Milagres Tunnel with the support categories throughout the excavation (MDR, 2019).

2.2 Tunnel execution

In the excavation of the Milagres Tunnel, the NATM method was used (Bieniawski, 1989). The tunnel excavation cycle corresponded to the following 7 phases, illustrated in Figures 3 to 7: (i) Topography; (ii) Drilling with a diameter of 45mm; (iii) Load and fire about 250 kilograms of explosive per feed; (iv) Ventilation; (v) Rock removal; (vi) "Bate Choco" (detection of loose blocks) in the excavated front, dome and walls; (vii) Containments with 21 and 25mm diameter, steel, and projected concrete.



Figure 3. Excavation cycle with drilling of the tunnel fire plane (MDR, 2019).



Figure 4. Removal of loose blocks in front of tunnel excavation (MDR, 2019).



Figure 5. Application of projected concrete on walls and vaults (MDR, 2019).



Figure 6 - Drilling for the installation of the tiles (MDR, 2019).



Figure 7. Installation of metal camats in the tunnel entrance (MDR, 2019).

2.3 Instrumentation

The Milagres Tunnel has instrumentation sections composed of 5 surface landmarks and 3 tassometers installed in the massif and convergence pins (3 bases) in the excavation internal perimeter (Figure 8), in 17 sections distributed in the 818m extension of the tunnel. It is noteworthy that the convergence bases used to perform this work are those represented by pins P1, P2, and P3, resulting in 3 bases for each instrumented section.

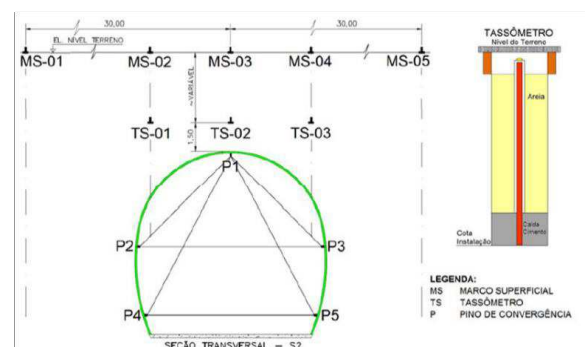


Figure 8. Instrumentation of the sections of the Milagres Tunnel (MDR, 2019).

To measure the displacements in the tassometers, topographic levels of GEODETIC, model DSZ2, with nominal accuracy of 1.0mm/km or 0.5mm using the micrometer, with a minimum focal length of 1.6 m were used. In the convergence readings, OBRK meters, model JSS-30 A, with measuring range 0.5 to 30m and accuracy of 0.01mm were used.

3 RESULTS AND ANALYSIS OF CONVERGENCE AND SETTLEMENTS MEASURES

Displacement and deformation analyses were performed considering 5 instrumented sections, covering classes III and IV of rocky massif present in the Milagres Tunnel and indicated in Table 1.

Table 1. Sections adopted for convergence and settlements analyses.

Section	Location	Class	Convergence basis	Tassometer
S1	16m of the tunnel entrance	III	1-2, 1-3 e 2-3	1, 2 e 3
S2	36m of the tunnel entrance	IV	1-2, 1-3 e 2-3	1, 2 e 3
S3	66m of the tunnel entrance	IV	1-2, 1-3 e 2-3	1, 2 e 3
S6	236m of the tunnel entrance	IV	1-2, 1-3 e 2-3	1, 2 e 3
S17	40m of the tunnel exit	III	1-2, 1-3 e 2-3	1, 2 e 3

Figures 9 to 13 show the results of monitoring convergences and settlements of the 5 sections S1, S2, S3, S6, and S17.

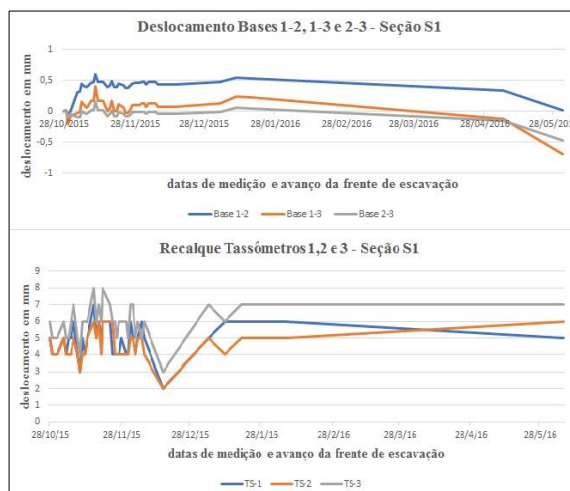


Figure 9. Comparison between convergence and time-based measures - Section S1, Massif Class III (Ferreira, 2020).

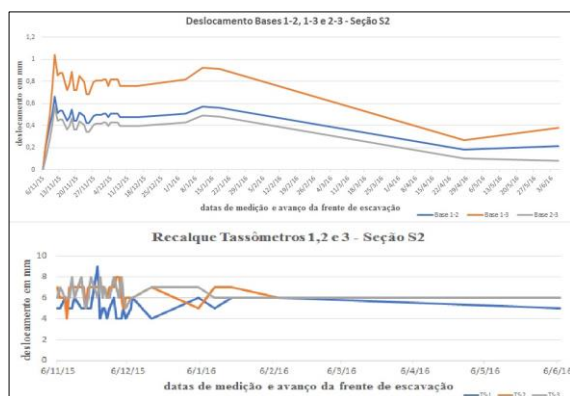


Figure 10. Comparison between convergence and time-based measures - Section S2, Massif Class IV (Ferreira, 2020).

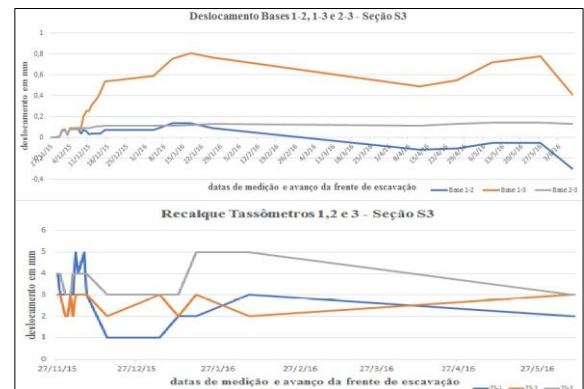


Figure 11. Comparison between convergence and time-based measures - Section S3, Massif Class IV (Ferreira, 2020).



Figure 12. Comparison between convergence and time-based measures - Section S6, Massif Class IV (Ferreira, 2020).

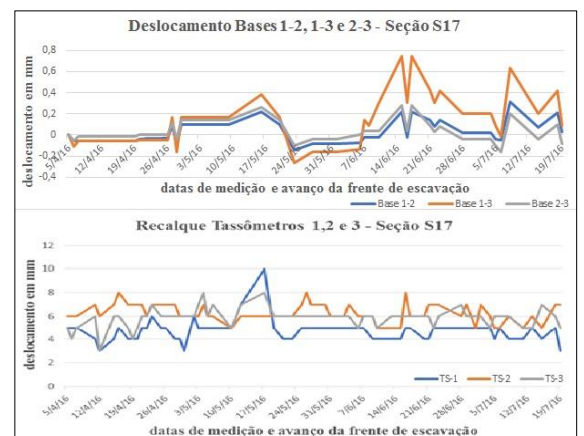


Figure 13. Comparison between convergence and time-based measures - Section S17, Massif Class III (Ferreira, 2020).

The convergence monitoring of the sections in classes III and IV showed that the displacement curves of the three bases present very similar behaviors, with successive disturbances for 30 days after the beginning of the measurements, due to the advance of the excavation front. The tendency of temporary stabilization after 30 days is observed, followed by an increase in displacements until they again reach stabilization, possibly due to the distance of the tunnel mirror, as well as the execution of the supports. It is worth mentioning that the stabilization of the convergence curves occurs after approximately 60 to 70 days at the beginning of the monitoring. The settlements

curves of the three tassometers have behaviors very similar to those observed in the convergence curves, showing periods of disturbances and stabilizations, which coincide with the periods observed in the convergence measures. It is emphasized that the periods of measurement of the settlements are identical to the periods of monitoring the convergence of the sections. The monitoring periods of the studied sections ranged from 104 to 217 days. Kontogianni et al. (1999) warn about the behavior of sections that present temporary stabilizations of displacements and that, after days or even months, they move again and then reach a new level of stabilization with high displacements, causing the instability of the work. This was not observed in the instrumented sections of the Milagres Tunnel, since the displacement curves over time showed a tendency of stabilization at values below 1.2 mm. Also, the deadline for stabilization of curves was between 60 and 80 days. It should be noted that the measurement periods of the sections varied between 104 and 217 days, with advances of the excavation front of up to 580m ahead of the monitored site. The deformations measured in the convergence sections were lower than the values corresponding to the levels of attention and alert defined in the project. The warning limit adopted was equal to 10-3 of the tunnel span. The attention limit was 70% of the alert limit. Thus, for the Milagres Tunnel, the Attention Limit is 7.2mm and the Alert Limit is 10.3mm. It is noteworthy that in none of the analyzed sections it was observed the achievement of the limits of attention and/or alert, with convergence displacements of a maximum of 1.2 mm and settlements of a maximum of 10 mm. The internal (convergence pins) and external (tassometers) instrumentation of the tunnel played a fundamental role in making work decisions, such as the confirmation of the type of support to be used, the number of explosives from the plane of fire, the depth of advancement of the tunnel mirror and even the correct time for the application of the support elements. All these management measures are closely linked to the classes of massifs and geological structures found on the excavation fronts. It is noteworthy that the superficial landmarks, because they present inexpressive displacements, were not part of the analyses of this research. However, without the aid of internal and external instrumentation, the success of the tunnel execution, without major problems, would be practically unfeasible. The instrumentation sat in confirming the stabilization period of the convergence measures of the excavation, which, in the literature, is indicated after 60 days, and which in the Milagres Tunnel occurred between 60 and 80 days. It is important to highlight the sensitivity and timing of the internal and external instrumentation of the Milagres Tunnel, which can be observed by comparing the convergence and settlement curves over time. As expected, the highest displacement values, both convergence, and settlements were verified in the less competent massifs of the excavation. It was also evidenced that, as the excavation fronts move away from the instrumented sections and the supports are installed, the rebalancing of stresses of the massif and the stabilization of the displacements occurs. Besides, it was also noted that Section S17 with less conservative coating than that of the other instrumented sections (S1, S2, S3, and S6), presented higher oscillations of the convergence and settlements curves by time (Figure 13).

4 CONCLUSIONS

The analysis of the results of the monitoring of 5 sections with internal (convergence) and external (settlement) instrumentation scans along the excavation of the Milagres Tunnel allows the following conclusions:

1. In four of the five sections analyzed, displacement stabilization occurred eighty days after the beginning of the monitoring of the sections;
2. The displacements in the convergence pins occurred while the excavation front was in the vicinity of the analyzed section and after the distance of the excavation front and installation of the supports, the displacements showed a tendency of stabilization at values lower than the measured peak values;
3. The largest convergence measures occurred in the less competent massifs, represented by Class IV;
4. At no time did convergence measurements threaten the limits of attention and/or alert defined in the project;
5. The reduced values of convergence are attributed to the efficiency and speed of application of the supports, to mobilize the self-support of the massif;
6. Convergence and settlements measures are linked, representing the behavior of the massif as a function of the advance of the excavation fronts, that is, the trends of disturbance and stability coincide in position and time;
7. The analyses confirm the timing and redundancy of internal and external measurements in all sections;
8. The measurement deadlines for convergence and distance from the tunnel mirror to the monitored section proved to be sufficient for the monitoring of the work.

5 ACKNOWLEDGMENTS

The author thanks to the Ministry of Regional Development (Brazil) for the information of the PISF and the Milagres Tunnel for graduate studies at PUC-Rio. The author thanks PUC-Rio and CAPES for granting a scholarship to an exemption from school fees during the Master's period.

6 REFERENCES

- BARTON, N.R.; LIEN, R.; LUNDE, J. (1974). Engineering classification of rock masses for the design of tunnel support, *Rock Mechanics and Rock Engineering*, 6(4), pp. 189-239.
- BIENIAWSKI, Z.T. (1989). *Engineering rock mass classifications: A Complete Manual for Engineers and Geologists in Mining, Civil, and Petroleum Engineering*, New York, John Wiley & Sons, 272p.
- Espaço ET (2020). *Espaço em Transformação, Transposição do Rio São Francisco*. (https://espacoemtransformacao.wordpress.com, acesso em 2020)
- FERREIRA, L.A. (2020). *Análise da Instrumentação do Túnel Milagres, obra Integrante da Transposição do Rio São Francisco, Dissertação de Mestrado, Depto. Eng. Civil, PUC-Rio, Brasil*, 132p.
- IBAMA (2005). *Instituto Brasileiro do Meio Ambiente e dos Recursos Renováveis. Licença Prévia nº 200/2005, 04p.*
- IBGE (2010). *Instituto Brasileiro de Geografia e Estatística. Censo 2010*. https://censo2010.ibge.gov.br
- KONTOGIANNI, V.; TESSERIS, D.; STIROS S. (1999). Efficiency of geodetic data to control tunnel deformation. 9th International Symposium on Deformation Measurements, Olsztyn, Poland, pp. 206-214.
- MDR (2019). *Ministério do Desenvolvimento Regional. Relatório Final de Acompanhamento Técnico das Obras do Túnel Milagres, Volume VII, RT e RETN*, 339p.

RIMA (2004). Relatório de Impacto Ambiental do Projeto de Integração do Rio São Francisco com Bacias Hidrográficas do Nordeste Setentrional. Ministério da Integração Nacional, 137p.

SENADO FEDERAL (2017). Transposição do Rio São Francisco. <https://www12.senado.leg.br/noticias/materias/2017/06/05/senado-do-imperio-estudou-transposicao-do-rio-sao-francisco>