

Geological-Geotechnical Studies for the Ore Transport Railway Line “S11D—Sudeste do Pará”, Brazil

Priscilla H. P. Oliveira and Mário Quinta-Ferreira 

Abstract

In Brazil, the railway transport of iron ore moves large quantities and needs to overcome huge distances between the mining areas and the shipping harbors. As the Brazilian railway network requires renewal and expansion, sound procedures to conduct suitable engineering geology studies are needed. The objectives, methodology, and study phases are presented, focusing on the geological and geotechnical constraints of the terrains crossed by the railway line. These constraints may increase the costs, cause construction delays, or generate difficulties during construction or operation. The new iron ore railway project, “S11D—Ramal Ferroviário Sudeste do Pará” in Brazil, is used as a case study. It is 100 km in length, connecting the new S11D mine to the existing Carajás railway, and hauls the iron ore to a shipping port, the Ponta da Madeira Maritime Terminal. The geological-geotechnical studies developed for the design, and utilized during construction along the S11D railway branch line, are presented and discussed. Several unusual aspects of the engineering geology studies for an excavation, an embankment, a bridge, a tunnel, and for the location of natural granular materials for sub-ballast and ballast layers are presented. It is concluded that continuous improvement of the engineering geology studies is desirable to increase the efficiency of the design, construction, and operation of a railway.

Keywords

Geological-geotechnical studies • Railways • Iron ore transport

P. H. P. Oliveira
Mining and Geological Engineering, Geosciences Center,
University of Coimbra, Coimbra, Portugal
e-mail: hamada.pri@gmail.com

M. Quinta-Ferreira (✉)
Geosciences Center, University of Coimbra, Coimbra, Portugal
e-mail: mqf@dct.uc.pt

1 Introduction

Ore transport railway lines are designed with the only purpose of transporting ore between the mine and the shipping harbor, presenting significant differences from other railway lines, e.g. high-speed railway lines or mixed passenger and cargo railway lines. Their main characteristics are: usually single track with crossing yards; speed generally not exceeding 80 km/h; horizontal curve radius above 400 m; longitudinal gradient below 2.5%; use of long trains with hundreds of wagons; heavy static loads and high dynamic loads; and a large number of simultaneously circulating trains.

Topographic aspects and the properties and behavior of the geological materials are of the greatest importance, due to the need to adjust the design to the local conditions, requiring construction of large embankments, excavations, and bridges or tunnels. This makes these projects very complex, time-consuming, and costly. A fairly important aspect of a geological-geotechnical investigation is understanding the contribution of geology to ensure the safety of all the engineering solutions related to excavations, embankments, bridge foundations, tunneling, ground treatment, and the location of natural construction materials, mainly for ballast. The railway needs to be adjusted to the encountered geomorphology, geology, and geotechnical characteristics. The possibility of the occurrence of geohazards such as landslides, unstable soils, and flooding, within the railway route corridor, must also be evaluated. For a successful project implementation, it is important to avoid or overcome all the adverse geological and geotechnical aspects, which may increase costs and delays during construction, or generate work stoppages during the railway line operation that would create serious constraints and quite significant costs.

2 The S11D Railway Branch Line and the Carajás Railway

The iron ore mined in Carajás is destined for export and hauled to Ponta da Madeira Maritime Terminal, along 900 km of the Carajás railway, using some of the longest and most heavily-loaded railway trains in the world. The Carajás trains consist of up to 330 wagons and four locomotives of 4,400 hp, totaling 3.3 km in length, carrying more than 40,000 tons of iron ore and imposing individual axle loads of 30 tons onto the railway track, which has a gauge of 1.60 m. The Carajás railway has 35 trains running simultaneously in continuous operation, and carries more than 120 million tons of iron per year.

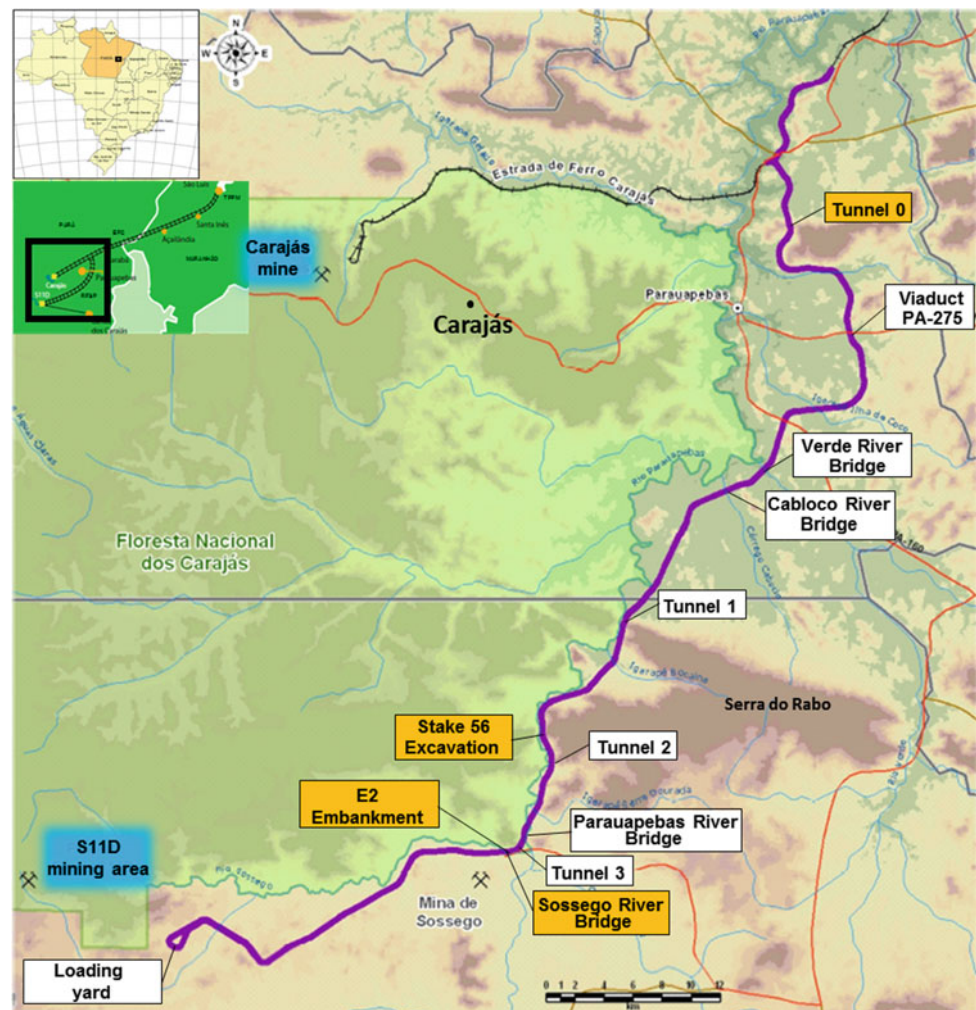
The S11D railway branch line links the S11D project to the Carajás railway, and started operations in 2016, increasing the iron ore production capacity up to a total of 230 million tons of iron ore per year. Other main features of the S11D railway branch are: single line, 100 km long (Fig. 1); one connecting yard with the Carajás railway, six

crossing yards and one loading yard; maximum ramp of 0.4% in the direction of export and 1.0% in the direction of import; minimum curve radius of 859 m; four tunnels, four railway bridges, two railway viaducts and two road viaducts; earthmoving volumes: 14.9 Mm³ of excavation (12.4 Mm³ of soil, 1.5 Mm³ of rippable material, and 1.0 Mm³ of rock material) and 12.0 Mm³ of embankment; sub-ballast: 325,712 m³ and ballast: 496,713 m³; trains with an empty weight of 7650 tons and a loaded weight of 41,970 tons; running speed of 80 km/h empty and 70 km/h loaded; capacity for up to 14 pairs of trains per day.

3 Geological-Geotechnical Studies

The general objective of geological-geotechnical studies is to understand and quantify the ground conditions and material properties that can affect the feasibility, design, construction, and operation of a project. It is quite important to implement the project according to the geological,

Fig. 1 Location of the S11D railway line, with the main works indicated, and the works analyzed later on in more detail highlighted. Modified from Arcadis (2011)



geotechnical, and geoenvironmental conditions, selecting the most favorable routes, identifying stability problems and geological risks, and determining the geotechnical properties necessary for the design and construction of the structures (Luis et al. 2002). Directing efforts immediately to subsurface investigations at an early stage of a project is not the best approach, because changes in the alignment required by ongoing design inevitably results in wasted site investigation works, requiring additional expensive subsurface investigations. In this way, engineering, geological, and geomorphological mapping are far less expensive and far more productive, because they are more likely to provide relevant information (Baynes et al. 2005). An effective way to implement any engineering project is based on the thorough understanding of the complete geological and geomorphological history of the project area and the associated engineering implications (Baynes et al. 2005). For railways, a reasonable balance between expenditure on the investigations and the resulting benefit of the information obtained is

considered to have been met when the geological mapping is able to generate reliable geological models for all cuts, the embankment foundation conditions are characterized, all sources of construction materials have been located and their performance characterized, all geohazards have been identified, and a reasonable design of the complete rail line is completed, allowing the development of a complete bid package for construction (Baynes et al. 2005).

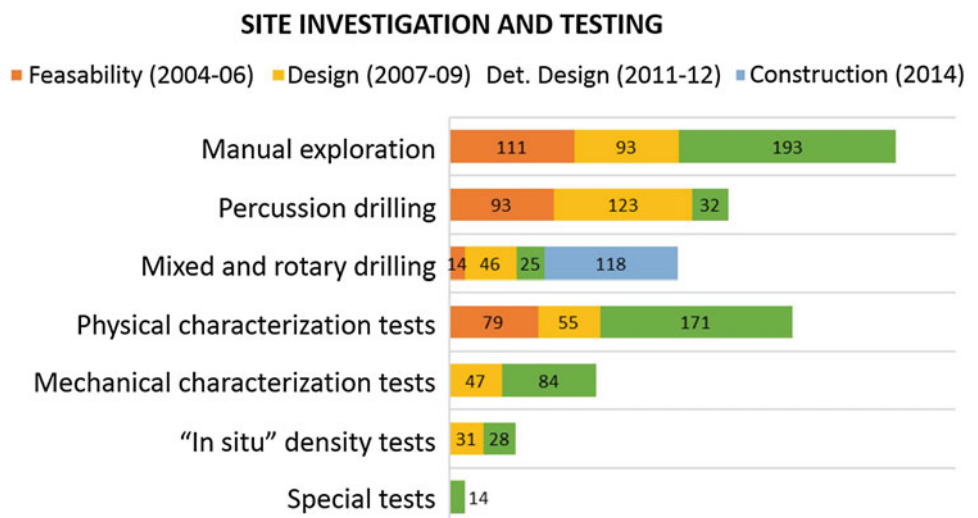
The geological-geotechnical investigations for railway projects are usually done in stages (Table 1). The geological-geotechnical studies of the S11D were carried out over nine years, in distinct stages (Fig. 2). Different companies were involved, being responsible for the Conceptual Phase Minerconsult Engenharia (2004) and for the design and detailed design stages Vega Engenharia e Consultoria (2009, 2012, 2013, 2014a, b; c; 2015).

At the **feasibility stage**, the collection of low-cost information involves desk studies, analysis of aerial photographs, site reconnaissance, general mapping, and site inspection.

Table 1 Summary of geological-geotechnical investigations for railway projects, by stages (Luis et al. 2002; Baynes et al. 2005; Oliveira 1979; Rodrigues et al. 1998)

Stage	Feasibility	Design	Detailed design	Construction	Operation
Objectives	Geological reconnaissance of the possible routes, identify geohazards and sources of construction materials	Design alignment, assess construction requirements, identify engineering geology formations	Engineering geology zoning, constructive solutions for geotechnical risks, construction materials description	Confirm ground conditions and perform necessary adjustments	Ensure the safety and efficiency of railway operation
Activities	Review of existing geological information, aerial photo and satellite imagery interpretation, site reconnaissance	Geo-mapping, geophysical exploration, test pits and boreholes, in situ and laboratory tests	Detailed mapping, test pits, boreholes, in situ and laboratory tests	Collection and registration of excavation and fill works data, additional exploration	Preventive periodic inspection, reduction of risks and accidents
Report	Preliminary report	Interim report	Final report	Complementary report	Operation reports

Fig. 2 Geotechnical investigations and testing along the S11D, by stages. Modified from Vega (2012)



The preliminary geological reconnaissance is important for the initial definition of alternative routes; it provides information on the characteristics and quality of the terrain crossed by the railway, and on the viability of the project.

The level of knowledge should progressively increase throughout the development of the **design**, using progressively more elaborate and time-consuming methods and techniques (Luis et al. 2002; Baynes et al. 2005; Oliveira 1979; Rodrigues et al. 1998) to obtain information that is adequate to support the decisions that must be taken. Investigations involving detailed mapping, test pitting, drilling boreholes, and laboratory testing are far more expensive and would be done when the route has been selected and greater detail is required for design. During the design stage, it was necessary to perform changes to 35% of the route length, due to occupations by the Movement of the Landless (MST) or because of a lack of permits from the Brazilian environmental agency (IBAMA) to perform site investigations in protected Amazon forest areas.

The **detailed design** is based on engineering geological mapping, in situ geophysical prospection, mechanical exploration investigations, and in situ and laboratory tests. The work is divided into several projects in order to optimize the design for the excavations, embankments, bridges, viaducts, and tunnels. The work specifications and the preparation of the technical reports with all the geological and geotechnical information of the project, suitable for construction, are prepared.

In the **construction stage**, special attention should be paid to the engineering geological model validation, in order to carry out the engineering geology mapping of the exposed surfaces to verify the ground conditions and identify possible differences with respect to the design. This is needed in order to be able to perform the necessary adjustments, especially in tunnels where the discrepancy between the data obtained in the design studies and those obtained during the construction stage may be large. During construction of the S11D railway branch, it was also necessary to perform complementary site investigation for four bridges, one viaduct and one tunnel, and adaptations of the project based on the encountered conditions. Most of the mixed and rotary drilling were completed during the construction stage, because the site investigation for a long viaduct was insufficiently developed during the design. All the project surveys would represent an average of one survey location for each 200 m of the railway line.

Table 1 presents the proposed methodology for the geological-geotechnical studies and in situ investigations, summarizing the objectives, the main activities, and the type of report issued in each project stage. A comprehensive approach is intended to be tailored to the specificities of each

type of work (excavations, embankments, bridges, or tunnels). All the activities carried out during the geological-geotechnical studies must be aimed at avoiding the occurrence of geotechnical problems, which affect the safety of workers and infrastructure, the construction time, and the operation costs of the railway.

As the studies and projects were developed by several companies, which in turn subcontracted the surveys and tests, the information is dispersed among many different sources. There was no systematic information processing, such as a database that could gather all project information, maps, and profiles incorporating the results of the several site investigation and testing campaigns. If the information generated during the studies were included in a single database and represented in a GIS environment, such as the work done by the Geological Survey of Brazil for the High Speed Train project, there would be greater efficiency due to easier access to information, and a better use of all data and information for decision making. Despite this, the data obtained was fundamental and quite useful for the development of the project.

4 Geological-Geotechnical Units

The tropical humid climate (Arcadis 2011a) with an annual precipitation around 1800 mm, average temperature range from 23 to 24 °C, with a maximum of around 30 °C, where the S11D railway branch line is located, significantly influences the geotechnical properties of the terrain, mainly outcropping soils developed by the weathering processes.

The extensive office and field work, and laboratory testing, allowed eight geological-geotechnical units crossed by the S11D railway branch to be defined (Arcadis 2011a; Vega 2009):

- **Granitic Suites:** comprises the Anorogenic Granite Formations and Plaquê Suite. At the surface they mainly present as sandy-clay and silt-sandy saprolite. They weather down to 15 m. The soils are highly susceptible to erosion and have suitable bearing capacity. The Anorogenic Granite occur from the beginning of the railway branch until Tunnel 0. The Plaquê Suite are elongated bands interspersed in the Xingu Complex, from Sossego Mine until the end of the railway line. This is the only unit that has the right conditions for the installation of quarries;
- **Rio Novo Unit:** this is an amphibolite enclave in the Xingu Complex, composed of volcano-sedimentary rocks, with a predominance of metabasic/amphibolite, schist, and associated iron formations. The outcrops are

red residual clay soils, sometimes with fragments of hard relic rock, with medium to high expansiveness. The susceptibility to erosion is medium and has low to medium bearing capacity. This unit occurs from Tunnel 0 (km 4.7) to the vicinity of the viaduct over the PA-275 (km 16.1);

- **Gneiss Complexes Unit:** this covers the lithologies of the Xingu Complex and the Estrela Granitoids, and is composed of granoblastic gneisses, migmatites, and anisotropic granite-gneisses, with milonitized bands. It has weathering soils of 15 to 20 m, showing high susceptibility to erosion and satisfactory bearing capacity. This unit occurs: (a) from the viaduct over the PA-275 highway (km 16.1) to the vicinity of the Verde River (km 30.9); (b) from the Sossego River (km 65.75) to the loading yard (km 96.2), interspersed with the unit Granites Suites (Plaquê Suite);
- **Águas Claras Unit:** this is composed of conglomerate metarenites, siltstones, and rhythmic subordinate argillites. The resulting soils have small thickness, and are silty sand and occasionally gravel and clayey soils. This unit occurs from the vicinity of the Verde River (km 30.9) to Tunnel 1 (km 45.4);
- **Parauapebas unit:** this consists of intensely fractured metabasic, metadacite, metariorite, and amphibolitized rocks. The relief is strongly undulating to hilly. The soils produced by weathering are clayey silts, often covered by laterized clayey soils and crusts. Soils are poorly susceptible to erosion, and have low bearing capacity. This unit occurs from Tunnel 1 (km 45.4) to the Sossego River (km 65.75) and constitutes the segment with the greatest restrictions on the implementation of the railway;
- **Lateritic-detritic unit:** this is the soil covering the other units, and is composed of iron concretions and carapaces in an arenaceous matrix, oolites and ferruginous pisolites,

pebbles, and reworked quartz gravel. The relief has smooth, undulating surfaces. The soils are only 2 to 3 m thick, silty sand with gravel and concretions (A-1-b). It is susceptible to erosion and has a good to optimum bearing capacity, and is easily compacted. This is the unit that can supply the stabilized soils required for the sub-ballast layer of the railway and the primary coating of service roads;

- **Alluvium unit:** composed of sandy sediments, with few intercalations of clay lenses and rare occurrences of organic matter. It has low susceptibility to erosion and good bearing capacity when associated with surface drainage. It is associated with the Águas Claras and Gneiss Complex units (after the Sossego River at km 65.75);
- **Colluvium unit:** composed of residual soils occurring in the Serra do Rabo and in less rugged terrain, as in the Granitic Suites, Gneiss Complexes and Águas Claras units, confused with the surfaces of the lateritic-detritus unit.

Table 2 presents a statistical summary by soil groups along the S11D railway branch, showing the predominance of clayey soils of type A-7-5 and A-7-6, represented by plastic clays with the presence of organic matter (high compressibility) and A-6, represented by medium plastic silty clays with little or no expansible material (low compressibility). According to the American Association of State Highway Transportation Officials (AASHTO) classification, these clayey soils have a weak to poor behavior; however, by the Departamento Nacional de Infraestrutura de Transportes (DNIT) specification (2015), these soils can be used in the embankment bodies, as they have a California Bearing Ratio (CBR) > 5, and expansion $\leq 2\%$. They can also be used in the reinforcement of the subgrade (last 60 cm), because they have CBR ≥ 8 and expansion $< 2\%$.

Table 2 Statistical summary by soil groups of the S11D railway branch (Vega 2012)

AASHTO classification	Frequency (%)	% passing n° 200#	Max. dry density (kgf/m)	Expansion (%)	CBR (%)	Natural moisture (%)	Optimal moisture (%)
A-7-5	44.0	64.0	1635	0.8	14.4	16.9	20.8
A-6	20.9	62.9	1662	1.3	8.6	17.5	14.4
A-7-6	13.3	59.8	1638	0.7	13.9	16.9	19.2
A-2-4	9.4	28.4	1881	0.1	18.2	7.4	11.2
A-4	4.3	46.8	1736	0.6	15.0	–	15.7
A-1-b	3.6	20.4	2028	0.1	27.9	–	9.9
A-2-6	2.5	29.3	1915	0.6	22.1	15.0	12.4
A-2-7	2.5	33.2	1722	0.2	21.2	15.7	19.2

5 Comments on a Cut, a Bridge, an Embankment, and a Tunnel

In the analysis of some specific examples of the geological-geotechnical studies of the S11D, a cut, a bridge, an embankment, a tunnel and the occurrences of natural materials for sub-ballast and ballast were selected to be commented upon. A few proposals for improvement and omissions to the extensive and successful work carried out are summarized below.

- In the **stake 56 excavation** (km 56.00) the execution of mixed drill reaching the bedrock, only in the construction stage, implied the loss of previously developed projects based on quite short drills only intersecting superficial soils. For the new design, other methods could be used for evaluating the shear strength parameters of the terrain, such as laboratory tests (direct shear and triaxial) and in situ tests (e.g. Standard Penetration Test - SPT), or using geomechanical classifications like the Rock Mass Rating (RMR) (Bieniawski et al. 1989) and the Slope Mass rating (SMR) (Romana and Serón 2003) for better guidance on the stabilization methods.
- For the **Sossego River bridge** no geological-geotechnical longitudinal section was available at the time of construction, nor any test reports that would allow the strength and deformability of the soil to be defined, nor any explanation of why some piles were of the continuous auger type. The foundation ground was also simplified in the finite element modeling, and no static load tests were performed on piles to check the failure load.
- In the **embankment of the bridge over the Sossego River**, it would be advisable to include in the design specification an allusion to the need to perform experimental embankments to define the constructive aspects of the rockfill embankment, such as the cord deposition technique, and to the construction quality control method, macro testing, and precision leveling.
- The early identification of geological-geotechnical problems in the **southern portal of tunnel 0** and the modification of the design allowed an increase in stability in the portal construction and in the first meters of the tunnel excavation. The quality of the geological-geotechnical profile, the cartography of the excavation fronts, the use of the RMR and Q geomechanical classifications, and the instrumentation ensured the success of the excavation by the NATM method, without any

substantial difference in relation to the design (Vega 2016);

- In the study of the occurrence of natural materials for the sub-ballast layers, the standards used for characterization should be mentioned, and the characteristic values of the Liquidity Limit (LL) and the Plasticity Index (PI) of tested samples should be presented. For the stone material for ballast, the only suitable lithology was granite.

6 Final Considerations

The primary objective of the engineering geology studies is to understand the nature and the geotechnical behavior of the terrain that will receive the new railroad, a linear infrastructure, crossing diverse geological formations and variable topography, where, in addition to the earthworks, it will be necessary to build special works requiring specific studies, which must be quite detailed and diversified.

All the activities carried out during the engineering geology studies must be aimed at avoiding the occurrence of geotechnical problems, increasing safety, and optimizing the construction schedule and costs, as well as the efficient operation of the railway.

As the railway was completed in December 2016, it is now very important to ensure the safety and efficiency of the operation of the railway. To achieve this objective, it is necessary to carry out periodic preventive inspections and to propose solutions to problems or anomalies that may develop and generate risks or accidents. Monitoring and interpretation of the instrumentation installed along the railway line must be systematically carried out, and the trends assessed to evaluate the stability of soil and rockfill embankments, cuts, and structures.

For the rockfill shoulder of the Sossego River bridge, it is recommended that the settlements be periodically measured, and that the behavior of the embankment be monitored, as it is located in a region with high and concentrated rainfall that can induce deformations in the rockfill (Oliveira 2017).

Adequate compilation and additional interpretation of the site investigation, of the design, of the construction and of the operation of the railway can improve the geotechnical knowledge and behavior of the railway, allowing the investments made to be optimized, a good performance of the infrastructure to be ensured, and to serve as a basis for more efficient development of new ore transport railway projects.

Acknowledgements The authors would like to thank VALE mining company for the authorization to publish the data from the S11D project (Ramal Ferroviário do Sul do Pará). This work was supported by FCT (Fundação para a Ciência e a Tecnologia, I.P.), through Portuguese funds, in the research project UID/Multi/00073/2013 of the Geosciences Center of the University of Coimbra.

References

- Arcadis. Environmental impact report of the southeast railway branch of Pará, São Paulo: Arcadis Tetraplan S.A., 112 pages. (2011). (In Portuguese)
- Arcadis. Environmental impact study of the southeast railway branch of Pará, São Paulo: Arcadis Tetraplan S.A., 1,280 pages. (2011). (In Portuguese)
- Baynes, F.J., Fookes, P.G., Kennedy, J.F.: The total engineering geology approach applied to railways in the Pilbara, Western Australia. *Bulletin of Engineering Geology and the Environment* **64** (1), 67–94 (2005). <https://doi.org/10.1007/s10064-004-0271-4>
- Bieniawski, Z.T.: *Engineering rock mass classifications*. John Wiley and Sons (1989)
- DNIT. *Railway Service Instruction: Geotechnical Studies*. Brazil: Directorate of Railway Infrastructure (DIF), ISF-207, National Department of Transport Infrastructure, 44 pages. (2015). (In Portuguese)
- González de Vallejo, Luis, I., Ferrer, M., Ortuño, L., Oteo, C. *Ingeniería Geológica*. Madrid: Pearson Educación (2002)
- Minerconsult. Report on geological and geotechnical studies. Belo Horizonte: Minerconsult Engenharia Ltda (currently SNC-Lavalin), Memorial describing the conceptual phase, 38 pages. (2004). (In Portuguese)
- Oliveira, R.: Engineering geological problems related to the study, design and construction of dam foundations. *Bull. Int. Assoc. Eng. Geol.* **20**, 4–7 (1979)
- Oliveira, P.H.: Geological-geotechnical studies of railway cargo works. The Southeast of Pará Railway Branch (Brazil). MSc Thesis in Mining and Geological Engineering. University of Coimbra, Portugal (2017). (In Portuguese)
- Rodrigues, R., Lopes, J.A.U. *Rodovias.*: In: Oliveira, A.M.S., Brito, S. N.A. (eds.) *Geologia de Engenharia*. São Paulo: ABGE, cap. 25, 419–430. (1998). (In Portuguese)
- Romana, M., Serón, J., Montalar, E.: SMR Geomechanics classification: Application, experience and validation. *ISRM 2003–Technology roadmap for rock mechanics*, South African Institute of Mining and Metallurgy, 4 p (2003)
- Vega. Containment project for the cut of the 56 km massif. São Paulo: Vega Engenharia Ambiental S.A., railway branch southeast of Pará, Technical report, 292 pages. (2015). (In Portuguese)
- Vega. Execution of landfill in material of 3rd category. São Paulo: Vega Engenharia Ambiental S.A., railway branch southeast of Pará, Technical report on earthworks, 3 pages. (2014c). (In Portuguese)
- Vega. Geological and geotechnical studies of the southeastern railroad branch of Pará, São Paulo: Vega Engenharia Ambiental S.A., descriptive memorial of the detailed project, 153 pages. (2012). (In Portuguese)
- Vega. Geotechnical studies of the southeastern railway branch of Pará, São Paulo: Vega Engenharia Ambiental S.A., Descriptive memorial and justification of the basic project, 55 pages. (2009). (In Portuguese)
- Vega. Memories of calculation of the stakes of the bridge on the river Sossego, São Paulo: Vega Engenharia Ambiental S.A, southeast railway branch of Pará. (2014b). (In Portuguese)
- Vega. Technical report on surveys. São Paulo: Vega Engenharia Ambiental S.A., Railroad southeast of Pará, 13 pages. (2014a). (In Portuguese)
- Vega. Tunnel 0—Topographic plant and geotechnical profile. São Paulo: Vega Engenharia Ambiental S.A., Railway Branch Southeast of Pará, Drawing of As Built. (2016). (In Portuguese)
- Vega. Tunnel Project—Tunnel 0. São Paulo: Vega Engenharia Ambiental S.A., Memorial descriptive of the detailed project, 51 pages. (2013). (In Portuguese)