Mining
Mineração

Geotechnical aspects of drilling and excavation of volcanic terrain for groundwater exploitation

http://dx.doi.org/10.1590/0370-44672021760027

Juan C. Santamarta[1,5]
https://orcid.org/0000-0002-0269-3029
Luis E. Hernández-Gutiérrez[2,6]
https://orcid.org/0000-0002-9554-809X
Rafael J. Lario-Báscones[3,7]
https://orcid.org/0000-0002-5595-4018
Jesica Rodríguez-Martín[4,8]
https://orcid.org/0000-0003-4457-7760
Noelia Cruz-Pérez[1,9]
https://orcid.org/0000-0003-1279-0823

[1]Universidad de La Laguna - ULL, Departamento de Ingeniería Agraria y del Medio Natural. Tenerife - Spain.

[2]Consejería de Obras Públicas, Transportes y Vivienda, Gobierno de Canarias, Tenerife - Spain.

[3]Universidad Politécnica de Madrid - UPM , Escuela Técnica Superior de Ingenieros de Minas y Energía Departamento de Ingeniería Geológica y Minera, Madrid – Spain.

[4]Universidad de La Laguna - ULL, Departamento Técnicas y Proyectos en Ingeniería y Arquitectura. Tenerife – Spain.

E-mails: [5]jcsanta@ull.edu.es, [6]lhergut@gobiernodecanarias.org, [7]rj.lario@alumnos.upm.es, [8]jrodrima@ull.edu.es, [9]ncruzper@ull.edu.es

Abstract

Heterogeneity of volcanic materials that constitute the Canary Islands (Spain) means that mining work in water galleries excavated on these islands, drilling into the terrain for many kilometres, is very challenging. They are composed of materials that vary significantly in terms of cohesion, ranging from very consolidated to loose and highly unstable. Water galleries have been key in the development of the Canary Islands, in order to obtain drinking water from the aquifer. Generally, aquifers are located in mountainous areas with difficult access, which complicates the drilling work. This article analyses the main geotechnical problems encountered in the construction of subterranean water galleries in the Canary Islands, as well as possible solutions to these problems, so that these can be applied to similar territories. As a general conclusion, the instabilities inherent in volcanic materials affect this type of work, and it is necessary to take specific measures for each type of geotechnical risk, as proposed in this article.

keywords: mines, groundwater, oceanic islands, volcanic rocks, geotechnics.

1. Introduction

The Canary Islands have a great number of subterranean drilled kilometres, due to the need to find underground water. In total, around 2,500 kilometres have been excavated (mines or water galleries). Therefore, knowledge of the subsoil and the geology at the excavation sites can simplify the work and avoid future problems in various situations, for example, in the construction of road tunnels.

The morphological and lithological properties of Canary Islands volcanic rocks are well known from the numerous geological studies that have been carried out on the islands. This has resulted in an extensive bibliography and detailed geological cartography throughout the territory. This contrasts significantly with the very scarce literature regarding geotechnical properties, yet knowing the geology and origin of the land is fundamental to undertaking any underground project. The geology of the Canary Islands is dominated almost entirely by a succession of materials and volcanic structures, such as massive rocks or cinder cones (Dóniz-Páez, 2015). Sequences of lava emissions, as well as pyroclastic deposits of variable composition, form a very singular landscape within the national territory, but on a regional level, they present extreme contrasts from lithological, environmental, landscape and even meteorological perspectives.

In general, water galleries are drillings or tunnels with a single access and an average cross-section of 1.5 x 2 meters or even smaller, although those carried out by public bodies tend to be significantly larger. Drilling works have previously been carried out by mechanical means, although the use of explosives was generalized in the middle of the 20th century. The purpose of a gallery is to reach the aquifer and extract water, drilling at a slightly inclined angle, making it unnecessary to pump water for its use. Normally, when the saturated zone is reached, the amount of water is abundant. There are reserve waters, loaded with salts (Mariucci *et al*., 2008), having remained a long time in the aquifer (Najeeb & Vinayachandran, 2011). Subsequently, the flows tend to stabilise through renewable or recharge waters of a younger age. Gallery lengths can range from 1.5 to 7 km (Santamarta, 2013).

Water production from galleries varies from a few liters per second to two hundred liters per second. For example, the well gallery of Los Padrones on the island of El Hierro (Canary Islands) flows at approximately 80 l/s; thus, it could practically supply most of the island's water demand. Flow decreases and the aquifer drawdown level does not affect different zones equally, although effects tend to be generalized. The galleries form authentic laboratories for the exploration of insular hydrogeology and are part of the geological and mining heritage of the archipelago.

In this study, the different volcanic materials have been ordered and classified according to their geotechnical behavior and the problems they may present. The authors, in their different specialties (civil engineering, mining engineering and geological engineering) and based on their experiences in subway works in the Canary Islands propose different solutions to the support problems affecting subway excavation in the volcanic terrain. This proposal involves a representative spectrum of situations, in which the presence of different volcanic materials is combined, to which a specific technical solution is given, and whose success has been demonstrated by experience.

2. Literature review

Most of the volcanic processes that can occur have taken place in the Canary Islands, and a wide spectrum of volcanic materials and structures can be found there. For this reason, any study or research carried out in the geotechnical field in the Canary Islands can easily be extrapolated to other volcanic regions worldwide. It is evident that it is necessary to know the behavior of the terrain in which the drilling of galleries takes place. However, monitoring excavations on continental terrain has been more exhaustive and complete than that in volcanic terrain. When drilling in volcanic terrain, many volcanic lithotypes can be crossed in a single drill, due to their heterogeneity. Therefore, construction of any type of infrastructure on a volcanic island becomes more complex than on continental terrain and, in the case of tunnelling or other underground work, the heterogeneity of the volcanic terrain makes it very difficult to use the tunnel boring machines (TBM) that are commonly used on continental ground (Santamarta *et al*., 2010). Along the route of the subway works built in volcanic terrain of the Canary Islands, it is common to cross soft and poorly cemented geological formations (pyroclasts), alternating with hard rock massifs (lava flows). TBMs are specifically designed to work in either hard rock or soft terrain. TBMs work crating compressive fractures which, when the head is turning, cuts rock pieces from the face of the tunnel. These rock bits are transferred to a belt conveyor and are thus removed from the tunnel. The hard rock TBM uses a grip system that pushes directly against the rock walls of the tunnel for advancing. Soft terrain TBMs, Earth Pressure Balance Machines (EPB), slurry shield (SS) and open-face types don't use the grip system against the bare rock, since they apply the grip pushing against concrete segments. This working system represents an additional disadvantage in excavating water galleries, as the concrete segments installed behind the cutting head make the tunnel diameter narrower than the cutting head itself, making it very difficult or even impossible for the machine to be recovered backwards if necessary. TBMs are designed to go forward, until they reach the end of the tunnel, which is not the objective of a water gallery. For these reasons, thousands of kilometres of water galleries have been (and are being) excavated in the Canary Islands, and TBMs have never been used.

Another reason for not using TBMs or highly mechanised methods is to preserve, as much as possible, the integrity of the basaltic dikes confining the aquifers. When miners reach a volcanic dike at the excavating front, the perforation depth of the drilling bores for blasting is much shorter than in the excavation of other types of volcanic terrain, going from 3 meters to even 50 cm on basaltic dikes. This technique has two objectives: it controls the thickness of the dike, which will act as a kind of dam in case there is water on the other side, and it will reduce blasting vibrations and the formation of cracks in the dike in the area around the gallery, thus preventing internal water leaks.

TBMs are also not used in tunnels due to the highly heterogeneous geotechnical properties of the volcanic environment that make it impossible to configure a machine capable of excavating extremely hard basaltic massive rocks and clay filled cracks, alternating in a tunnel section of a few tens of meters.

3. Study area and geotechnical units

The Canary Islands are made up of eight islands and five islets, covering an area of approximately 7.500 km^2. Geologically, the most recent hypothesis on the origin of the archipelago of the Canary Islands (Hernán Reguera & Anguita Virella, 1999) emerged in 2000. This hypothesis proposes the existence of hot spots under the Canary Islands (Herrera & Custodio, 2014), associated with a residual thermal plume, active since the beginning of the opening of the Atlantic, 200 Ma ago. From a geochemical point of view, the volcanic rocks of the Canary Islands belong to the alkaline igneous series, in this case associated with intraplate volcanism. This igneous series is formed by a sequence of rocks whose composition evolves from undifferentiated (represented by basalts,) intermediate (represented by trachybasalts) and, finally, more differentiated or evolved (represented by trachytes and phonolite). The following geotechnical units of a volcanic nature have been defined in the Canary Islands (Hernández-Gutiérrez *et al*., 2015). Each unit has been assigned the values of RMRb (Rock Mass Ratio, basic) by Bieniawski (1989), commonly used in excavations and supports in underground works:

• Basal complexes: these are represented by Cretaceous sediments, underwater lava and plutonic rocks (gabbros and syenites). This group is crossed by a multitude of dikes with such a high density of intrusion that they often leave no trace of the encasing rock. Usually, they have a high degree of alteration. They are considered soft and fractured rocks, generally presenting RMR values of less than 40.

• Salic massifs and lava flows: highly resistant rocky materials of a salic nature (trachytes and phonolites), appear in two forms of outcrops. 1) Very thick casts, usually with a horizontal disposition or as thick tabular packages with not very pronounced slopes and high horizontal extension. Sometimes, these packages can be formed by very compact breccias of fragments of a similarly salic nature 2) Domes, rocky masses of large vertical dimensions rooted in the subsoil and of more limited horizontal extension. Both have hard rock characteristics and RMRb values between 75 and 90.

• Altered basaltic masses: formed by basaltic flows of small thickness (around 1 m or less) and moderate to high alteration. They present vertical alternation of levels of basaltic compact (basaltic rock) and levels of scoria (granular material) that generally appear in a self-brecciation form due to the degree of alteration. There are also pyroclastic mantles and areas with frequent rubefaction, which sometimes correspond to levels of paleo-soils that have been calcined by the heat of the overlying lavas. They generally present soft dips that can vary between 10º and 30º. They usually present RMRb values between 40 and 60.

• Fresh basaltic lava flows: the types "pahoehoe" and "aa" can be distinguished. Pahoehoe lavas are characterised by the presence of a large number of vacuoles or small, more-or-less spherical holes, which give them great porosity, and by volcanic tunnels or tubes that can stretch kilometres in length and have diameters of several metres. The "aa" lavas or scoriaceous lavas have a vertical section consisting of a central band of dense rock furrowed by a network of diaclases or fissures, formed by retraction when the melt cools and solidifies, limited at the bottom and top by two irregular scoriaceous bands. The massive levels of basalt rock, in general, present RMRb values between 60 and 85. The scoriaceous layers behave as granular soils and require consolidation treatments in underground excavations.

• Pyroclastic materials: this unit can be further subdivided into two 1) Welded ignimbrites and tuffs -- these are hard or semi-hard rocks that correspond to very compact pyroclastic or cineritic deposits such as ignimbrites, with or without eutaxitic texture or compact cineritas. They have RMRb values between 60 and 75 2) Loose or weakly cemented pyroclastic materials -- they are usually not very compact and are easily collapsible. The larger ones are called scorias which, in some cases, acquire rounded shapes when spun in the air (pumps); the lighter, clearer and more porous trachytic and/or phonolithic ones are the pumice deposits, also known as plinia or pyroclastic rain deposits. They are low-density pyroclastic deposits, with average dry apparent weights usually between 7 and 13 kN/m^3. They have RMRb values between 0 and 25.

• Brechoid materials: chaotic and brechoid masses formed by blocks of diverse nature, generally very angular, with great variation in size, encompassed in a fine matrix, more or less cemented, and occasionally very hard. They form packs of great thicknesses (up to hundreds of metres) and have gentle slopes of compact and chaotic breccias of a mono- or polymictic nature. They can present characteristics of hard and, in some cases, semi-hard rock. They present RMRb values between 60 and 75.

With respect to the hydrogeology of the islands, each island is different, and they have distinct water demands, defined by the main water uses on each island (Santamarta & Lario-Bascones, 2015). We can find studies which refer to the fact that the heterogeneity of the subsoil facilitates higher recharge rates, compared to soils with homogeneous properties (Hartmann *et al.*, 2017). In the Canary Islands, water resources come from the subsoil and this is why so many horizontal tunnels (water galleries) have been built, as well as vertical works (wells) that have been excavated with mining technology (Custodio *et al.*, 2016). The main objective has always been to reach the large masses of water retained in aquifers, which are often found behind dyke barriers that safeguard these water reserves (Izquierdo, 2014).

The geological history of the Canary Islands has also been linked to landslides (Hürlimann *et al.*, 1999; Kimura & Kawabata, 2015; Rodríguez-Losada *et al.*, 2009) and seismic activity, which must be considered when guaranteeing the stability of drilling (Feng *et al.*, 2016). The most recent seismic events in the archipelago occurred in 2011 on the island of El Hierro (Taracsák *et al.*, 2019), and before that, there was an earthquake on the island of La Palma in 1971. Microseisms are noted almost daily in the archipelago.

4. Geological heterogeneity: a case study from Canary Islands

Geotechnical aspects are some of the most complicated issues when designing or carrying out an underground project in volcanic terrain. Volcanic materials are extremely heterogeneous, discontinuous and difficult to predict. The usual configuration of the terrain in insular volcanic environments consists of the accumulation of different successions of lava emissions, the product of effusive eruptions, mostly of a fissured nature, which make up a landscape dominated mostly by lavas and pyroclastic deposits. Depending on the effusive rate, the explosiveness of the eruption and the rheological characteristics of the materials emitted, these can be spatially distributed in a chaotic and disordered manner, which leads to the heterogeneous character mentioned above.

As an example, the following is a summary of the description of a 3,700-meter-long gallery at an elevation of 1,500 m above sea level in the Orotava Valley (Tenerife Island):

(1) The gallery is filled with basaltic lavas with intercalated pyroclasts, crossed by unconsolidated polymictic breccia deposit, with subangular syenites. In addition, as the gallery deepens along the main tunnel and branches, fine dispersion basaltic pyroclasts of an older series are crossed. Occasionally olivine basalts can be seen assimilating to porphyric types

(2) As progress is made, pumice materials are found combined with compact deposits and other vacuoles accompanied by a certain degree of almagrization (or annealing) until reaching an area of alternate lava levels (basalts, trachybasalts and phonolites)

(3) At a greater depth, the lava layers correspond to highly crystallized basalts, with augite phenocrystals and olivine. The lava scoria is loose and filled with materials of fine granulometry (4) It is anticipated that the gallery will produce new water sources as it approaches the dorsal axis and the philonian density increases (Izquierdo, 2014).

As can be seen, a wide variety of volcanic terrains can be found in a single gallery, each with its own geotechnical peculiarities. Thus, regarding geotechnical risks, the main problems that usually occur in the galleries of the archipelago are that the waters are not related to large geological structures but to features associated with the filling of cracks, volcanic tubes, and natural caverns. Special attention should also be paid to possible cavities in the ground, which can lead to collapses while drilling (Figure 1) (Jordá-Bordehore *et al*., 2016). This is why stability and safety are the two main factors to consider when drilling in volcanic terrain (Sakuma *et al*., 2008).

Figure 1 - Collapse during drilling in a water gallery in the Canary Islands.

5. Problems analysis and proposal of technical solutions

Table 1 analyzes the different geotechnical problems that were experienced during underground works of the gallery studied, as well as the possible solutions proposed. This is a series of constructive measures to contain the terrain, due to the different layers that can be found when penetrating volcanic terrain (more compact material followed by other disaggregated, for example). They are constructive measures that arise from the accumulated experience of the authors in this type of work in the Canary Islands.

Table 1 - Geotechnical problems encountered and proposed solutions.

Problem of gallery support	Technical solution
Scoria	Metal truss
	Steel rounds
	Rear stones > 45 cm
Volcanic cone material	In order to advance with the perforation, it is necessary to stabilize the front by means of cement grouts
Entrance of gallery in piedmont	Metal plating and profiles
	Reinforced concrete type voussoirs
Pyroclasts	Metal truss
	Cement slurry with bolts
	Gunitem
	Steel rounds
Presence of pumice, plastic materials	Plastic-coated siphon pipe
	Lining of the borehole by means of segments
Phreatomagmatic chamber materials	Lining perforation with blocks and concreting; if only the blocks are left collapses by pushes of plastic material
Materials in slabs	Sheet metal
	Trusses
Retraction prisms	Difficult solution
	Determine the unstable sections and act on them

Source: prepared by authors.

Obtaining geological information on the underground works to be carried out is sometimes complicated because one would generally have to resort to vertical soundings of great depth (more than 500 meters). A common solution to evaluating water in the tunnel trace is the drilling of a horizontal borehole of about 50 meters in front of the excavation. This is mainly to estimate the heights of the sheets of water raised by dykes, to avoid flooding problems and ensure the safety of workers. The properties of the terrain can also be estimated, and the geological materials to be traversed can be identified by consulting the bibliography of works carried out in similar materials (Del Potro & Hürlimann, 2009).

Regarding the geotechnical characteristics of the terrain to be excavated, generally the massive terrain does not present stability problems. In the granular parts (scoria and pyroclasts), a more rounded section is usually produced, and it is sometimes necessary to resort to support systems (trusses, gunite) to reinforce the terrain in these sections. With these conditioning factors, construction of the tunnel and galleries must be considered as a complete section, though in most of this section no reinforcement measures may be necessary. If any of these premises is not met, we can resort to different types of support for this infrastructure. Table 2 shows different types of support, depending on the type of rock mass and the RMR value, obtained from the accumulated experience of several decades of construction of subterranean works in the Canary Islands.

Table 2 - Recommendations for support according to the characteristics of the terrain.

DESCRIPTION AND RMR CLASSIFICATION OF THE VOLCANIC ROCK MASS	SUPPORT COMPONENTS		
	Concrete	Bolts	Trusses
Compact of massive lava or with occasional intercalation of scoria and pyroclasts of reduced thickness. RMR > 70	Projected and reinforced with fiber Thickness: 10 cm	10 Tn L=4 m Bolting pattern: 1.5 x 2.0 m	Not required
Massive lava compacts with some intercalation of scoria or pyroclasts of metric thickness, but that does not affect the crown or the floor. RMR between 60 to 70	Projected and reinforced with fiber Thickness: 15 cm	10 Tn L=4 m Bolting pattern: 1.0 x 2.0 m	Not required
The same rock mass (RMR: 60-70), but with the metric intercalation of scoria or pyroclasts located at the level of the floor.	Projected and reinforced with fiber Thickness: 20 cm	10 Tn L=4 m Bolting pattern: 1.0 x 2.0 m	1 TH-29 / 1.5 m with bracings
The same rock mass (RMR: 60-70), but with the metric intercalation of scoria or pyroclasts at crown level; or presence of blocks delimited by discontinuous planes, at crown or side walls.	Projected and reinforced with fiber Thickness: 20 cm	10 Tn L=4 m Bolting pattern: 1.0 x 2.0 m	1 TH-29 / 1.0 m with bracings
Massive and welded deposits of scoria and pyroclasts or with some occasional interleaving of massive lava compact RMR between 50 to 60	Projected and reinforced with fiber Thickness: 25 cm	10 Tn L=4 m Bolting pattern: 1.0 x 2.0 m	1 HEB-160 / 1.0 m with bracings
Soft deposits of scoria and pyroclasts or with some occasional interleaving of massive lava compact RMR between 40 to 50	Projected and reinforced with fiber Thickness: 35 cm	10 Tn L=4 m Bolting pattern: 1.0 x 1.5 m	1 HEB-180 / 1.0 m with bracings
Very soft or loose deposits of scoria and pyroclasts or with some occasional interleaving of massive lava compact RMR <40	Projected and reinforced with fiber Thickness: 40 cm	Not recommended	1 HEB-180 / 1.0 m with bracings

Source: Prepared by authors.

To elaborate, the geotechnical units have been classified in different ranges of RMR values, from less than 40 to more than 70. The geological description that most frequently corresponds to these RMR values, has been attributed to each range, as a result of the authors' experience over several decades of work in subway excavations in the Canary Islands. Based on this experience and the solutions adopted in each case, the support recommendations are based on the combined application of three components: concrete, bolts and trusses. In the case of geotechnical units corresponding to very soft or loose deposits of scoria and pyroclasts, the application of bolts is not recommended, since it has been observed that during the drilling process, over-excavations and worsening of the material occur. For this reason, application of a 40 cm shotcrete lining and placement of trusses are considered sufficient.

In continental terrain, tunnel supports are generally essential to avoid collapse of the infrastructure. In volcanic territory, the massive areas of lavas are self-supporting, and it is necessary to use cladding only in a few cases; for instance, due to ground overloads (Figure 2) or lateral ground thrust (Figure 3).

Figure 2 - Overloaded arch in gallery section.

Figure 3 - Lateral ground thrust in gallery section.

If claddings are to be used in the tunnel, the following technical parameters must be checked: pressure exerted by the ground on the lining; tension in the lining; deformations of the lining; displacement of joints; and interstitial pressures in the soil.

The first conditioning factor when assessing the geotechnical problems of water mines in the Canary Islands is their accessibility. Normally, in the field of large public works and mining, the surroundings must be adapted so that it is possible to access the site with the necessary human resources and machinery. In the case of the galleries of the Canary Islands, the location of these in protected landscapes or terrains, or with very difficult access, make it impossible to use many investigative techniques that are considered normal or usual. A vast majority of galleries are not electrified, and the machinery used depends exclusively on diesel engines.

Although they represent a relatively minor problem, the frequent micro-spills that occur in most galleries can represent a great risk for workers, as they can cause derailment of transport convoys. These micro-spills can occur in different forms and are not always associated with the release of ground pressure during excavation. The most typical are those produced by alteration of the rock when it meets the atmosphere. An apparently competent terrain during the excavation phase can quickly weather in a matter of weeks in contact with the atmosphere of the gallery.

In the case of galleries, great emphasis has been placed on better illustrating the different geotechnical problems that occur in groundwater catchment works, and also, because they represent the greatest length and volume of drilled land in the Canary Islands archipelago. The problems described are also easily extrapolated to traditional Canary Islands wells. These are vertical works of large diameter (up to 5 m) and great depth (up to 650 meters), most of them with galleries inside. Vertical perforations drilled from the surface must also deal with the problem of the heterogeneity of volcanic terrain. To date, the only effective methods for drilling are those of percussion and rotopercussion, with relatively low rates of progression when traversing basaltic layers.

6. Conclusions

Groundwater catchment works in volcanic terrain have unique geotechnical characteristics. The most relevant factors when defining geotechnical problems in drilling and in geotechnical support, when facing works with these characteristics, are typology and accessibility of the works, heterogeneity of terrain, variability of atmospheric conditions after drilling, and geometry and drilling methods.

Works developed inside galleries and wells require substantial knowledge of the geological conditions. In addition, they are conducted in areas that have little accessibility and where it is difficult to count on the most advanced technology, thus making it necessary to advance drilling work in a more traditional way. The heterogeneity of volcanic materials creates situations of vulnerability while drilling in underground terrain. This makes it necessary to have identified the different problems that may arise, in order to minimize potential dangers during the excavation process.

Based on the combination of three support systems (concrete, bolts and trusses), different technical solutions are proposed for the most frequent types of volcanic materials present in the excavation face. These have been proven through several decades of work and hundreds of kilometres of subway works.

Acknowledgments

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

References

BIENIAWSKI, Z. T. ***Engineering rock mass classifications.*** John Wiley, 1989. p. 1-251.

CUSTODIO, E.; CABRERA, M. del C.; PONCELA, R.; PUGA, L. O.; SKUPIEN, E.; DEL VILLAR, A. Groundwater intensive exploitation and mining in Gran Canaria and Tenerife, Canary Islands, Spain: hydrogeological, environmental, economic and social aspects. ***Science of the Total Environment***, v. 557-558, p. 425-437, 2016. Disponível em: https://doi.org/10.1016/j.scitotenv.2016.03.038

DEL POTRO, R.; HÜRLIMANN, M. A comparison of different indirect techniques to evaluate volcanic intact rock strength. ***Rock Mechanics and Rock Engineering,*** v. 42, n. 6, p. 931-938, 2009. Disponível em: https://doi.org/10.1007/s00603-008-0001-5

DÓNIZ-PÁEZ, J. Volcanic geomorphological classification of the cinder cones of Tenerife (Canary Islands, Spain). ***Geomorphology,*** v. 228, p. 432-447, 2015. Disponível em: https://doi.org/10.1016/j.geomorph.2014.10.004

FENG, Y.; BIAN, W.; GU, G.; HUANG, Y.; QIU, J.; SUN, A.; WANG, P. A drilling data-constrained seismic mapping method for intermediate-mafic volcanic facies. ***Petroleum Exploration and Development,*** v. 43, n. 2, p. 251-260, 2016. Disponível em: https://doi.org/10.1016/S1876-3804(16)30028-3

HARTMANN, A.; GLEESON, T.; WADA, Y.; WAGENER, T. Enhanced groundwater recharge rates and altered recharge sensitivity to climate variability through subsurface heterogeneity. ***Proceedings of the National Academy of Sciences of the United States of America,*** v. 114, n. 11, p. 2842-2847, 2017. Disponível em: https://doi.org/10.1073/pnas.1614941114

HERMÁN REGUERA, F.; ANGUITA VIRELLA, F. El origen de las Islas Canarias: un modelo de síntesis. ***Enseñanza de Las Ciencias de La Tierra***: Revista de La Asociación Española Para La Enseñanza de Las Ciencias de La Tierra, v. 7, n. 3, p. 254-261, 1999.

HERNÁNDEZ GUTIÉRREZ, L. E.; RODRÍGUEZ LOSADA, J. A.; OLALLA MARAÑÓN, C.; SANTAMARTA CEREZAL, J. C.; MARTÍN RODRÍGUEZ, J.; POMARES RODRÍGUEZ, M. J. Unidades geotécnicas y problemas asociados en terrenos volcánicos. ***Ingeniería Geológica en Terrenos Volcánicos.*** Madrid: Ilustre Colegio Oficial de Geólogos, 2015. p. 95-112. Disponível em: https://doi.org/10.13140/RG.2.1.3161.6884

HERRERA, C.; CUSTÓDIO, E. Groundwater flow in a relatively old oceanic volcanic island: the Betancuria area, Fuerteventura Island, Canary Islands, Spain. ***Science of the Total Environment,*** 496, p. 531-550. Disponível em: https://doi.org/10.1016/j.scitotenv.2014.07.063

HÜRLIMANN, M.; LEDESMA, A.; MARTÍ, J. Conditions favouring catastrophic landslides on Tenerife (Canary Islands). ***Terra Nova,*** v. 11, n. 2-3, p. 106-111, 1999. Disponível em: https://doi.org/10.1046/j.1365-3121.1999.00233.x

IZQUIERDO, T. Conceptual hydrogeological model and aquifer system classification of a small volcanic island (La Gomera; Canary Islands). ***Catena,*** 114, P. 119-128, 2014. Disponível em: https://doi.org/10.1016/j.catena.2013.11.006

JORDÁ-BORDEHORES, L.; TOULKERIDIS, T.; ROMERO-CRESPO, P. L.; JORDÁ-BORDEHORE, R.; GARCÍA- GARIZABAL, I. Stability assessment of volcanic lava tubes in the Galápagos using engineering rock mass classifications and an empirical approach. ***International Journal of Rock Mechanics and Mining Sciences,*** 89, p. 55-67, 2016. Disponível em: https://doi.org/10.1016/j.ijrmms.2016.08.005

KIMURA, J. I.; KAWABATA, H. Geochemistry, geophysics, geosystems. ***Geochemistry Geophysics Geosystems,*** v. 16, n. 1, p. 267-300, 2015. Disponível em: https://doi.org/10.1002/2014GC005684.Key

MARIUCCI, M. T.; PIERDOMINICI, S.; PIZZINO, L.; MARRA, F.; MONTONE, P. Looking into a volcanic area: an overview on the 350 m scientific drilling at Colli Albani (Rome, Italy). ***Journal of Volcanology and Geothermal Research,*** v. 176, n. 2, p. 225-240, 2008. Disponível em: https://doi.org/10.1016/j.jvolgeores.2008.04.007

NAJEEB, K.; VINAYACHANDRAN, N. Groundwater scenario in Lakshadweep Islands. ***Journal of the Geological Society of India,*** v. 78, n. 4, p. 379-389, 2011. Disponível em: https://doi.org/10.1007/s12594-011-0095-3

RODRÍGUEZ-LOSADA, J. A.; HERNÁNDEZ-GUTIÉRREZ, L. E.; OLALLA, C.; PERUCHO, A.; SERRANO, A.; EFF-DARWICH, A. Geomechanical parameters of intact rocks and rock masses from the Canary Islands: implications on their flank stability. ***Journal of Volcanology and Geothermal Research,*** v. 182, n. 1-2, p. 67-75, 2009. Disponível em: https://doi.org/10.1016/j.jvolgeores.2009.01.032

SAKUMA, S.; KAJIWARA, T.; NAKADA, S.; UTO, K.; SHIMIZU, H. Drilling and logging results of USDP-4 - penetration into the volcanic conduit of Unzen Volcano, Japan. ***Journal of Volcanology and Geothermal Research,*** v. 175, n. 1-2, p. 1-12. Disponível em: https://doi.org/10.1016/j.jvolgeores.2008.03.039

SANTAMARTA, J. C. ***Hidrología y recursos hídricos en islas y terrenos volcánicos.*** Colegio de Ingenieros de Montes. Tenerife, 2013. Disponível em: https://doi.org/10.13140/RG.2.1.4464.5608

SANTAMARTA, J. C.; LARIO-BASCONES, R. J. Improving training in the hydrogeology of volcanic islands by visiting the Water Galleries of the Canary Islands (Spain). ***Procedia - Social and Behavioral Sciences,*** 191, p. 1317-1322. Disponível em: https://doi.org/10.1016/j.sbspro.2015.04.521

SANTAMARTA CEREZAL, J. C.; HERNÁNDEZ, L. E.; RODRÍGUEZ-LOSADA, J. A. Volcanic dikes engineering properties for storing and regulation of the underground water resources in volcanic islands. *In*: OLALLA *et al.* (ed.) ***Volcanic Rocks Mechanics.*** London: Taylor & Francis Group, p. 95-98. Disponível em: https://doi.org/10.1201/b10549

TARACSÁK, Z.; HARTLEY, M. E.; BURGESS, R.; EDMONDS, M.; IDDON, F.; LONGPRÉ, M. A. High fluxes of deep volatiles from ocean island volcanoes: Insights from El Hierro, Canary Islands. ***Geochimica et Cosmochimica Acta***, 258, p. 19-36, 2019. Disponível em: https://doi.org/10.1016/j.gca.2019.05.020

Received: 20 April 2021 - Accepted: 5 January 2022.