

GEOLOGICAL AND GEOTECHNICAL CONDITIONS OF HUMAN INTERVENTIONS IN NATURAL VOLCANIC CAVERNS: THE OUTFITTING OF “LOS JAMEOS DEL AGUA” AUDITORIUM, LANZAROTE, CANARY ISLANDS, SPAIN

C. Olalla

Escuela de Ingenieros de Caminos. Universidad Politécnica de Madrid. Madrid. Spain

A. Cárdenas

ENAC Ingenieros, Lanzarote Canary Islands. Spain

A. Serrano

Escuela de Ingenieros de Caminos. Universidad Politécnica de Madrid. Madrid. Spain

E. Pradera

ICYFSA, Tres Cantos (Madrid). Spain

D. Fernández de Castro

ICYFSA, Tres Cantos (Madrid). Spain

ABSTRACT: The possibility of using volcanic caverns associated with lava tubes is analysed according to their geological and geomorphological configuration and their dimensions. Each particular risk is defined and studied by considering its threat. The different natural risks are grouped into four categories: Group I: Structural instability zones due to hanged strata or extremely low width levels at the top of the cave. Group II: Medium and large block instabilities. Group III: Small block instabilities. Group IV: Surface weathering and instabilities in rock particles (sand or gravel)

In this paper this methodology is applied to the well-known auditorium of “Los Jameos del Agua”, located in Lanzarote. This volcanic island forms part of the Canary archipelago. This volcanic tube is visited by more than 800,000 people per year.

After an analysis of the different alternatives, the proposed technical solutions for each level of risk are described and the results of some calculations are shown.

1 INTRODUCTION

The auditorium located within the naturally-formed arch which is part of the “Jameos del Agua” complex to the north of the island of Lanzarote was closed for several years due to the instability observed in the solid rock mass of which the covering arch is comprised.



This arch forms part of a recent volcanic tube, originating in the La Corona mountain the origin of which is located at approximately 10 km from the

location of the object being studied. “Jameo del Agua” is located in the northern part of the island of Lanzarote at approximately 25 km from the city of Arrecife very close to the coast. The nearest town is Punta Mujeres approximately one kilometre away.

This is a unique landscape of exceptional natural beauty with a capacity for approximately 500 people. It is suitable for holding a wide variety of public events in the inside and boasts excellent acoustic conditions.



Given these circumstances, the Town Council of Lanzarote decided to commission a group of experts to study the problem and provide a report accordingly. The objective, from the point of view of the feasibility of the facilities for public use of the auditorium, was:

- to analyse the situation and possible evolution of Los Jameos del Agua,
- to identify the possible technical solution which would enable a reopening of these facilities in safe conditions for such use.

The conclusion reached was that the auditorium had various problems which were affecting its stability to a different extent. All of those, however, required undertaking specific action to considerably reduce the natural process contributing to its destabilisation and to allow opening it to the public whilst ensuring an adequate level of safety. The considerable patrimonial value of the complex required these actions to be defined and implemented whilst observing restoration and renovation requirements in

such a way as to preserve the natural environment of which it is comprised.

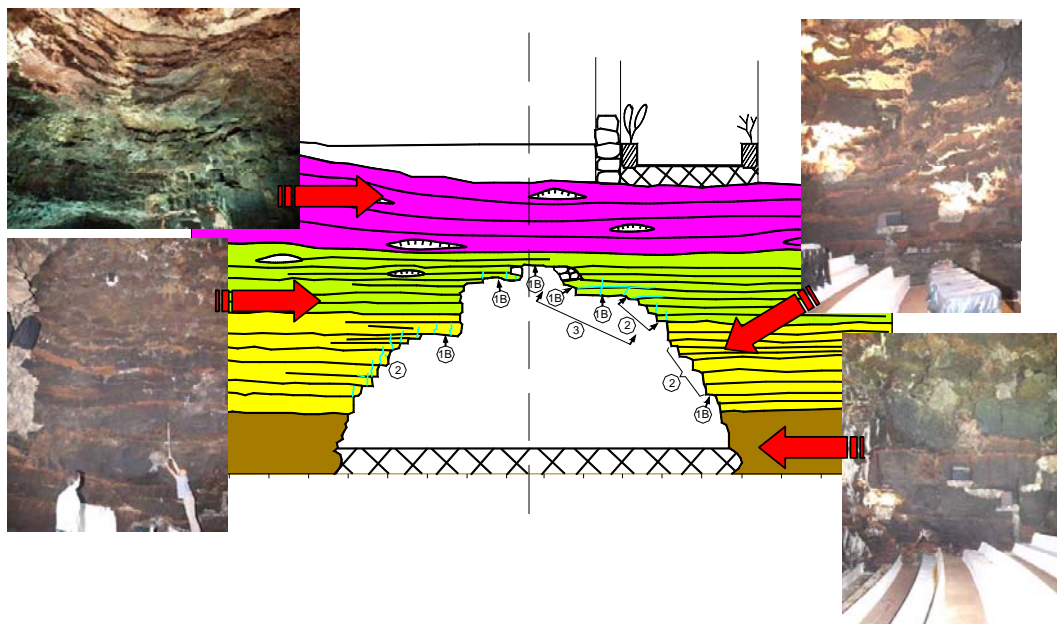
2 GEOLOGICAL FRAME

In a previous paper the most important geological local features are described in detail. (Signorelli et al. 2007).

Geologically, the “Jameos del Agua” cave is formed by two different basaltic lava units:

- the Malpaís Lava Unit (MLU), and
- the Lava Tube Unit (LTU).

The MLU is present in the entire section of the cave and is formed by a succession of different sub-horizontal (N10° E strike/1–5° ESE dip) lava members: Lower, Intermediate, Upper and Top lava sub-units.



From the lower to the top lava members visually there is an increase in vesicularity and a decrease in the thickness of lavas, grading from aa lavas at the base to pahoehoe lavas at the top. The Lower malpaís member consists of massive grey lava flows surrounded by a thick and irregular layer of blocky and scoriaceous reddish lava rubble. The thickness of each massive lava flow is 3m whereas the scoria zones range in size from 0.2 to 2m thick. The intermediate, upper and top members are formed by a succession of pahoehoe lava flows. The lava flow has less vesicular nuclei at the base (Intermediate mal-

país member) which grade into highly vesicular upper and top members.

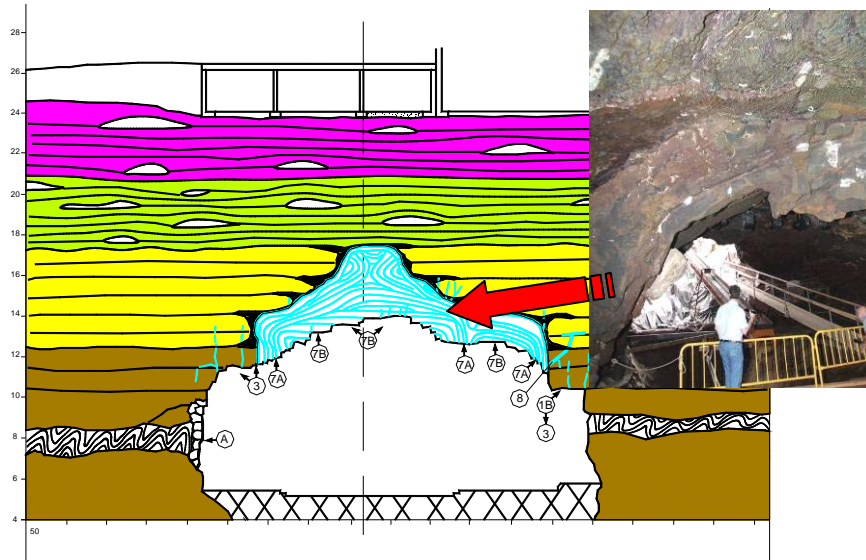
The thickness of the single lava flows decreases from the intermediate (1–1.5 m thick) to the upper and top lava members (up to 0.5m thick). In the intermediate and upper lava members some interbedded scoriaceous layers are present. The upper and top lava members are characterized by several cavities made of a thin crust. When an artificial filling, covering the external roof of the cave was removed, a volcanic landscape made of highly vesicular, cavernous-type lava flows appeared, referred to as

shelly pahoehoe lavas. Shelly produces cavernous flows with fragile crusts. Other surface features (hornitos, pressure ridges, tumuli and others) that usually occur on pahoehoe lavas are not present here and may have been destroyed during the construction of the Tourist Centre.

Discontinuities among and inside the different basaltic units are a common feature. As the different basaltic flows cool, shrinkage occurs and cracks form in the rock. Sometimes these discontinuities

are responsible for unstable blocks of rock up to 1m across on the sides and the roof of the cave. Domed sections of the roof testify that collapses occurred in the past at the joint intersection of fractured rock. In any case it appears that the sides and roof of the cave have evolved in order to achieve more stable rock profiles.

The LTU is spatially limited to the backstage/upstage, the stage and the first 8 rows of seating.



Only in the zone of the backstage does the lava tube structure appear to be in its original state showing thin layers of lava with a concentric shell structure (like an onion) and levees (terraces marking different stages of filling flows). The shell was formed where the lava chilled against the colder rock. Most of the roof appears to be a circular stable arch. The tube profile here is in the shape of an “eight” (two superimposed circles). This profile is the result of the cooling of lava flow surfacing to produce a crust, beginning at the levees and growing inward and downstream.

An active lava flow is actually a river of lava, a central stream of molten rock with levees of solid lava along its sides. As the lava continues to flow, the two sides start to form a roof across the flowing lava. When the two sides have completely covered the flowing lava, a lava tube is formed. Sometimes the flow sides form levees as the sides harden, and the top remain liquid. At the stage and in particular in the auditorium (first 8 rows of seating) the LTU is spatially limited to the central part of the roof. Here the LTU presents features like adaptation folds, a fissure where the levees came together and glaze structures.

Most of the roof associated with the simultaneous presence of LTU and MLU appears to be a broad and stable arch.

3 PROBLEMS DETECTED IN THE AUDITORIUM

3.1 Approach Adopted

The problems detected in the area of study had a variety of pathologies of very different levels of magnitude which had to coexist:

- from the possible structural instability of complete packets of rock,
- to the possible “chineo”, (detaching of particles the size of sand or less), in areas which have deteriorated.

The criterion followed to decide on the treatments to be used was to group both problems and solutions depending on their order of magnitude or the size of the phenomenon to be studied.

Although the classification of the pathologies was carried out according to their magnitude, the extent of the need to treat them was the same when the ob-

jective was to guarantee the general stability of the Jameo Auditorium in such a way as to ensure that it could accommodate the public over relatively long periods.

Naturally, a severe structural fault would have catastrophic consequences, however identifying such a fault is relatively easy and the probability of its occurrence very low. Nevertheless, other faults which have an affect to a lesser degree are more difficult to detect and would have a higher probability of occurrence and their consequences would be far more serious.

In some ways the risk which defines the need and scope of the treatment of a specific type of problem would has to be reassessed in accordance with the probability of occurrence and the resulting damage. In this case the use of the complex as an auditorium, i.e. its use as a venue open to the public, requires the capacity for a large number of people, in a motionless situation, over long periods.

As such, it is absolutely essential to assess the risk of any type of incident occurring based on simi-

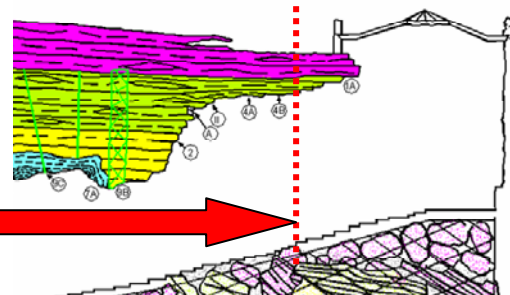
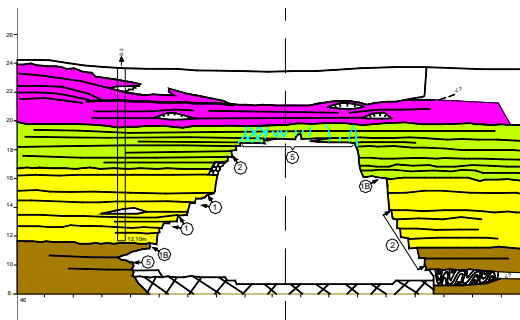
lar values and of lesser magnitude than those accepted for other types of constructions intended for human use.

3.2 First-level Problems: Structural Instability

General Features

This is the most important type of problem. It is related to the possible collapse of all or part of the arch in the event of exceeding the structure's resistant capacity formed by the actual layers of rock in their natural state. This situation is particularly obvious in the entrance area to the auditorium where there is the additional problem of the rock thickness in the area closest to the entrance Jameo.

This is a laminar-type structure with horizontally structured layers of rock, superimposed which at the same time are not very well bound. Their resistant capacity depends to a large extent not only on the thickness and quality of the rock, depending on the span or the opening of the cavity, but on the degree and type of the existing fractures.



The stability conditions can turn into situations which are dangerous as the result of various causes amongst which it is worth highlighting the following:

- The increase in external loads which can be easily avoided by preventing access to the surface.
- Changes in the interior geometry of the arch which modify the stress when increasing the opening or the support conditions. This situation

is, to a large extent, related to minor detachments or loss of blocks along the free edges of the layers.

- The loss of resistance in the matrix rock of the mass or in the material in the discontinuities due to the fracturing or the progressive alteration of the material.

Throughout this process it must be taken into account, apart from the overall structural stability of the group, the problem presented by the existence of the open joints in the rock mass where resistance is fundamentally mobilised in the contacts between the irregularities of both sides. These circumstances give rise to the possibility that two bending (traction) areas exist in some parts of the layers and very high compression stress in the contacts of the rugosities. Another factor is alteration due to the attack capacity presented by the existence of the network of cracks and by the large specific surface area of the mobilised ledges.

This situation, which can be assumed to be general for the entire subterranean complex, is particularly critical in the entrance areas of the Jameo, where on a joint basis there are four unfavourable characteristics which act complementarily and are the following:

- The larger dimension of the cross sections of the cavern. This means a greater “equivalent” span between supports than in the rest of the cavern.
- Reduced thickness of the solid rock mass in the keystone of the corresponding section.
- An almost flat arrangement of the section roof due to the loss of the “shoulders” area. It is indeed this shape which is the clearest symptom of how critical the current situation is. It must be remembered that it has developed until becoming a situation in strict equilibrium.
- A greater ease of alteration due to the proximity of the free surface area.

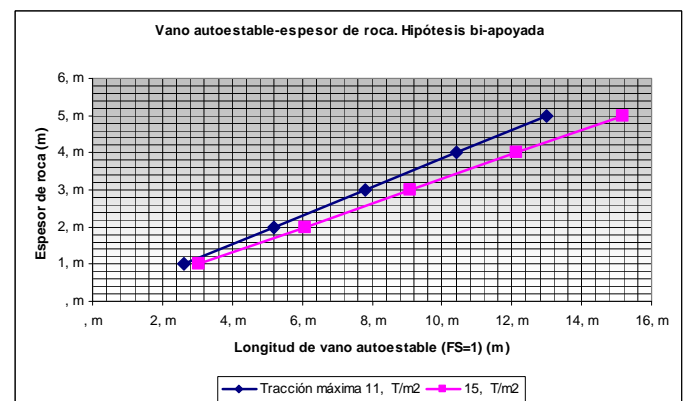
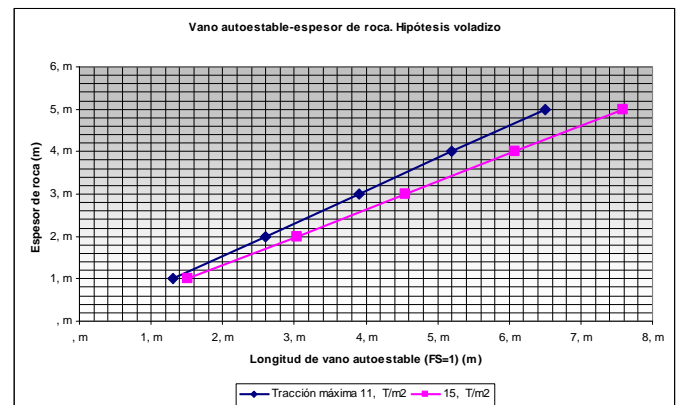
Simplified calculations carried out to assess the condition of the Jameo

The first attempt to be made was that corresponding to a minimum cantilevering and opening which would be self-supporting and for which a simplification was used treating them as a built-in-free and bi-supported beam (maximum tractions in the centre of the opening) subjected to its own weight. These hypotheses do not take into account the three-dimensional nature of the problem, nor the fact that the numerous subvertical fractures can make blocks become detached. Whilst aware of the degree of conservatism and simplification of the problem that has been assumed the objective was however essentially to have a reference framework of how the group functions.

For the purposes of the geomechanical characterisation of the upper unit and roof it can be considered as being the one only, allocating a resistance to simple compression to these materials ranging between 11 and 15 MPa. This hypothesis is conservative if

taking into account the results of all the tests, however this conservatism has to be used when there is a relatively limited amount of available information. With regard to the specific weight a value of 21.7 kN/m^3 is proposed, an average value for all the tests.

There is no information on resistance to simple traction. It is necessary to assess this based on normally accepted reasonable criteria and which usually allow assessing it as a tenth part of the resistance to compression i.e. between 1.1 and 1.5 MPa.



The cantilevers and openings observed were, in general, close to those calculated. This would imply a strict equilibrium of the structure of the solid mass which would require a reinforcement to allow separating the reinforced situation from the current one with regard to the safety factor. This reinforcement can be focused from the point of view of modifying the working hypotheses of the solid mass using anchoring modifying the thickness of competent rock, thus increasing, if possible, its average resistance to traction (a possible approach would be to incorporate an artificial stratum over the surface) or a combination of both.

3.3 Second-level Problems Isolated Instability by Average-sized Blocks

These correspond to instability produced due to faults of lesser importance than previously mentioned. However, notwithstanding the physical risk that these pose for people, they present the danger that they could make the general structural weakness

of the rocky medium previously studied spread or deteriorate over time by creating larger openings.

This represents a second level of problems. It was detected throughout practically the entire auditorium and would affect blocks with a size of approximately 50-60 cm.



In some cases the blocks have clearly open joints which could indicate the strict equilibrium of these. Stability would be produced by possible bridges or rock joint contacts with other adjacent blocks.

There is also the existence of another type of blocks in which the joints are totally or partially closed, however in which it is not possible to predict the real condition in interior areas where air bubbles or fractured or weakened areas could appear due essentially to the chaotic nature of the formation of these kinds of volcanic masses.

Finally, there are blocks formed by the strata of the different flows which are practically detached from the solid mass by way of “platforms”. This lack of unity could be the result of material loss in the joints which surround them or of the presence of smaller caverns thus producing an empty area. Within this group there would also be platforms the formation of which could originate from the lava tube unit (LTU) which has produced a cover similar to “onion skin” the thickness and quality of which cannot be determined in depth.

In all of these cases, the hypothesis must be that of fastening it using systems which allow securing the blocks under consideration with regard to their own weight. Although there is always a certain degree of friction between the planes, due to being unable to determine the extent of this, as well as the

condition, it is recommendable to exert caution and not consider its effect as beneficial.

As such, the hypothesis would be that of a block with a volume of approximately 0.5 to 1 m^3 , to own weight which would require a resistant force of approximately 20 to 40 tonnes. A safety factor of 1.6 was applied and a specific weight of 25 kN/m^3 was assumed, maximum value obtained in all the cases tested in the MTU intermediate units and the roof.

One of the premises, which will be discussed in more detail further on for this treatment, given its extent throughout the cave, is to avoid as far as possible, that these are visible once the action has been finished.

3.4 *Third-level Problems Isolated Instability by Small-sized Blocks*

This type of problem, which could produce small detachments, could arise practically anywhere in the auditorium.

These blocks would be smaller in size, approximately 20 cm, i.e. 1 to 1.6 kN in weight employing an increase of 1.6 as a pessimistic hypothesis. Given the reduced size it would be difficult to apply isolated stabilisation solutions using borings since the area is too small to make a boring without causing the block to become detached.



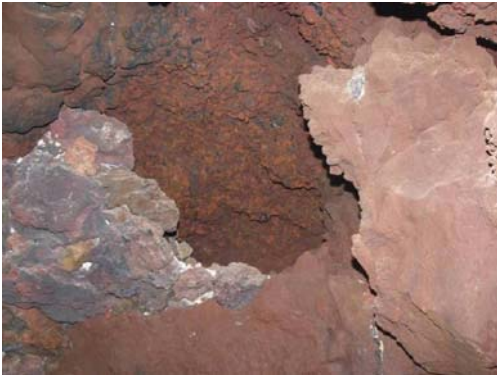
Based on these premises, the system studied and ultimately used was directed at improving the joint between various blocks thus improving each of these individually. This could give the case of a specific area suffering from a second-level problem once all the smaller blocks have been joined.

3.5 *Fourth-level Problems Superficial Instability*

These problems present the possibility that there are erratic and random detachments, isolated elements, individual, with a variable size amongst which there are types such as sand, grit, gravel, coarse gravel or similar (which is generally referred to in civil works as “chineo”).

As a general rule it can be affirmed that these types of detachments bear no relation to the structur-

al stress of the cavern. They can occur at any point of its surface as the result of the individualisation of a fragment of rock or due to the loss of cohesion or the reduced resistance of some of the discontinuities or in the actual matrix of which it is comprised as a result of the alteration.



In this sense superficial-type treatments studied focused on consolidating the first centimetres of the material by increasing its cohesion and reducing the susceptibility of the material to erosion.

At the same time the treatment enabled the rock to continue being permeable, it “transpires” thus, more importantly and as a compulsory measure, its visual effect must be as invisible as possible or, in the event of being detected, be more concealed, blending into the area to which it is applied.

3.6 *Anthropic Actions*

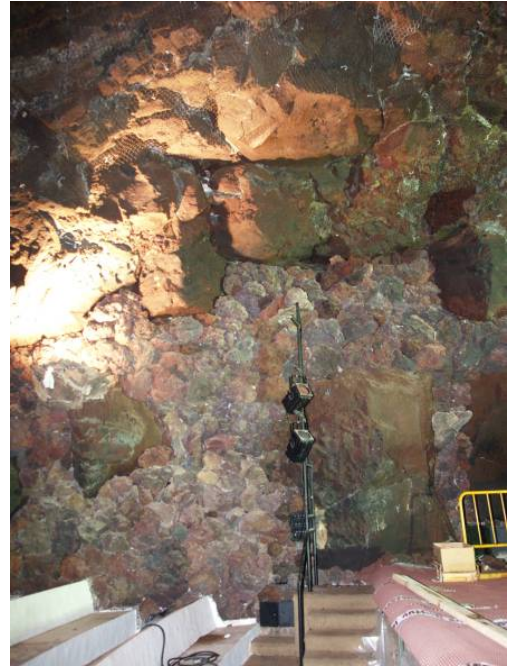
During the period that the auditorium was in open to the public various anthropic actions were undertaken directed at minimising minor instability, or to cover small gaps which had been appearing throughout the entire area of the complex.

These actions essentially consisted in fitting strips of stone, at times using materials from the area, (dark in colour) and at other times using light-coloured stone which affected the aesthetics of the surroundings. These last actions were more visually obvious given that they were emphasised due to their comparison with the rest of the walls as a result of the different colouring.

At times behind some of these strips mortar had been used for filling the gaps behind them. Neither the composition of these mortar fillings nor the depth they had reached could be accurately assessed.

It must be emphasised at times that these strips did not correspond as much with the attempt to fill and conceal gaps, but rather with the attempt to underpin areas with insufficient support and with the objective of concealing existing installations. Examples of this are cases of numerous cables and re-

cesses for lights in the auditorium as well as for sound equipment.



Within this context it is worth highlighting the existence of a triple torsion protective mesh which was located in the area closest to the stage. This mesh extended from the keystone up to the sidewalls and the fixtures were clearly visible due to their galvanising.



4 ANALYSIS OF SOLUTIONS

4.1 *General Approach*

Once the various types of problems had been studied, the solutions to be adopted were analysed for the renovation of the auditorium. In order to do this it was very useful to classify the problems described in the previous sections of this paper, even although there were actions which aimed to solve various types of risk at the same time.

All the solutions considered shared the common denominator of the strict maintenance of the natural

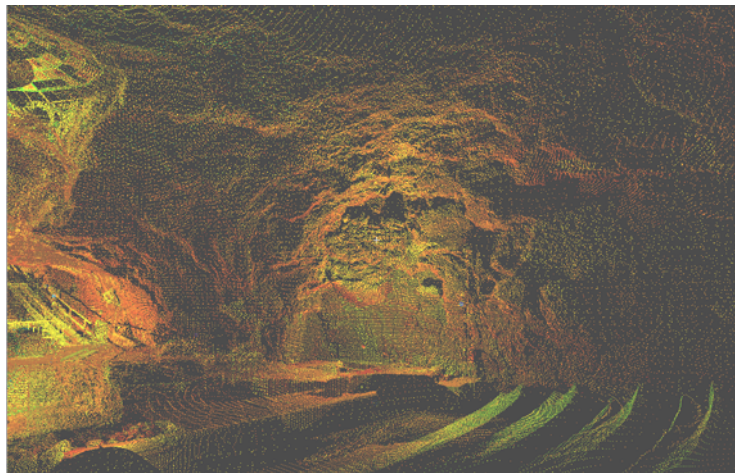
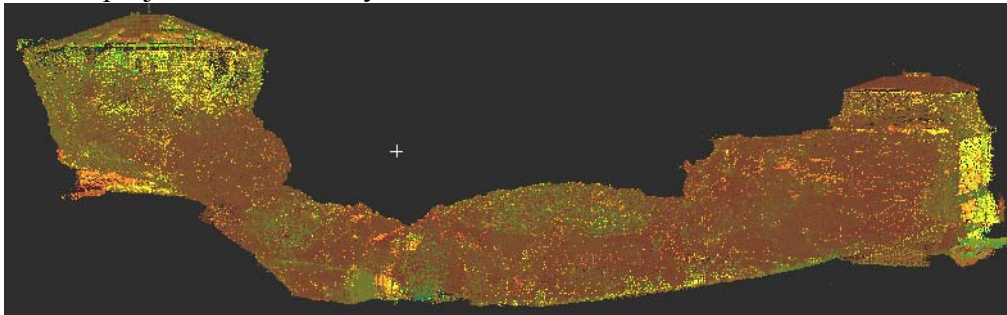
aesthetics of the volcanic materials affected, whilst changing their state as little as possible. In this sense tests had to be performed on site of all the treatments being considered for any level with the objective of verifying their suitability from an aesthetic point of view.

As already commented, the starting point for the focus of solving the problem was treating the complex as a patrimonial asset which had to be preserved, whilst constantly respecting the aesthetics of its natural surroundings.

This approach had to be observed without compromising the engineering actions which had to be undertaken to provide a solution to the various geotechnical problems detected in the complex and which have been described in the previous sections of this paper. The harmonisation of both tasks had been considered in the project in such a way that the

complex could be preserved and, if possible, would even see its aesthetics improved. Safety had to be guaranteed to the extent that it would be feasible to open it to the public whilst making the task of maintenance indispensable given the presence of a natural process the ultimate result of which is destabilisation.

At the same time, the work undertaken was undertaken without the presence of similar previous experience based on which approaches could be compared and solutions clarified. It was also ascertained that the different orders of magnitude of the problem needed to be graphically depicted in greater detail than those used up to that point. This was the reason for an additional detailed topographical survey using a laser-scanner which would enable obtaining a highly accurate topographical three-dimensional model of the entire Jameo.



4.2 Objectives of the Intervention

With this group of determining factors an action and implementation protocol was developed with the following complementary and concurrent objectives:

- Restoration: This refers to the process of recovering the formal and aesthetic appearance whilst respecting the original structures and materials.
- Renovation: The objective of this is to recover the functionality of the complex without the respect for its originality being a premise.

- Conservation: This is understood as an intervention on the auditorium with a dual purpose of active conservation with the emphasis on its surroundings, or passive conservation with the objective of preventing the natural environment deteriorating any further.

This triple concept of the intervention process must be considered as a theoretical framework of illustrative reference and in keeping with the solutions to be adopted.

4.3 Catalogue of Alterations and Defects

Apart from the structural geotechnical problems of greater or lesser magnitude evident throughout the complex, which are not included within the scope of this section and which represent a classical mechanical problem inherent in geotechnical engineering, the catalogue of the most serious alterations which usually arise in the rock materials at the heart of the renovation, and the treatment of which must subsequently be considered, are the following:

- Jointing.
- Fracturing.
- Fragmentation.
- Displacements.
- Powdering.
- Alveolar erosion.
- Scaling:
- Formation of crusts or concretions on the surface.

All of the above were addressed taking into account the importance, scope and typology of each of them in the solutions adopted.

5 SOLUTIONS CONSIDERED IN LOS JAMEOS

The following sections discuss the solutions adopted for each problem in view of the approaches described above.

5.1 Structural Solutions: Solutions Type 1

These correspond to phenomena related to the horizontal arrangement of the numerous volcanic flows.

It is typical in this type of structural arrangement of volcanic flows to see the formation of stepped profiles in the areas of shoulders which results in the terrible situation of the work in cantilevering in the layers. In reality, apart from the influence of the alteration processes, the stepped areas comprise the part which is most sensitive to the geometrical modification of the profile due to the detaching of the layer edges which increases the effective opening subsequently increasing the risk of collapse of the roof.

These situations are always difficult to assess in terms of safety since, to a large extent, they depend on the quality of the rock and especially on the location and condition of the discontinuities many of which are not visible.

As such, in natural processes it is fundamental to accept that the situation produced at a specific time

can be that of strict equilibrium at least in a certain area of the cavity which requires two types of actions.

- Adoption of actions which prevent further deterioration in the rock matrix and in the edges of the joints.
- Adoption of structural reinforcements which improve the safety margins until reaching acceptable levels suitable for the use for which the complex is intended.

From the perspective of this type of problem various areas were distinguished within the longitudinal development of the Jameo Auditorium:

- The entrance area.
- Areas with reduced thickness of rock of up to 2-3 metres.
- Areas which there is a sudden increase in the rock thickness up to 8 metres, however without the cover which constitutes the tube unit (MLU).
- Areas where the formation of the tube (MLU) appears covering the intermediate unit (LTU) like "onion skin".

It was decided to adopt reinforcement solutions which do not modify the natural appearance of the complex, whilst avoiding other visible structural solutions which would require great attention to be paid to adaptation to the environment, always subjectively.

Solutions Type 1-A: Resin Injections and Bolts of 16 mm

A fundamental characteristic of this solution is that it originates from aesthetic reasons. This means that the treatment must be practically invisible with no possibility of using distributions panels. The surface of the rock must remain unchanged which is why the injection process must be undertaken with great care.

The aim of using this treatment is to achieve the compaction of the first metre of material thus creating a crown of treated material which represents a distribution surface, or ring, of the deepest braces (something similar to the results of sprayed concrete in a conventional tunnel). This also avoids the possibility of many of the medium-sized blocks falling and there is considerable improvement in the alteration action by sealing a large part of the joints found in the solid mass.

This treatment also enables treating, at least partially, second-level instability even although it is not considered as a complete guarantee of treatment for

all the second-level blocks, especially those closest to the surface due to the limits of the effective access of the resin to the surface of the cavity.

The solution consisted in injecting high-viscosity resin manually using rotational drilling in a mesh ranging between 0.7 to 1 metre. These drills were selected with the smallest possible diameter to enable positioning the plug and cleaning the areas in which the injected resin was released to the outside whether via the joints of the actual rock or via the adjacent borings.

Once the injection is finished, a fibreglass rod with a diameter of 16 mm and a length of 1 metre is positioned inside each hole by way of top-up injection. As a last detailed action, the mouth of the drill is concealed using mortar made using the same injected resin mixed with stone from the Jameo which is ground beforehand.

The type of bolt planned is made from fibreglass because of its increased durability over time. This bolt is fully injected with epoxy-like resins thus guaranteeing attaching it to the rock.

Solution Type 1-B: Resin Injections and Bolts of 25 mm

The treatment using long bolts measuring 4 m was also planned to be implemented systematically reaching as far as the sidewalls of the cavern, generally occupied by the lower unit of the massive basalts with a scoriaceous-type band.

In order to perform the injections, during the work phase it was recommended to position the plugs fully into the mouth of each hole without distribution panels being required which would be more difficult to conceal.

Given these characteristics, the diameter of the solid bar of 25 mm provides a working load of 170 kN and a weight which enables easily handling the bolt.

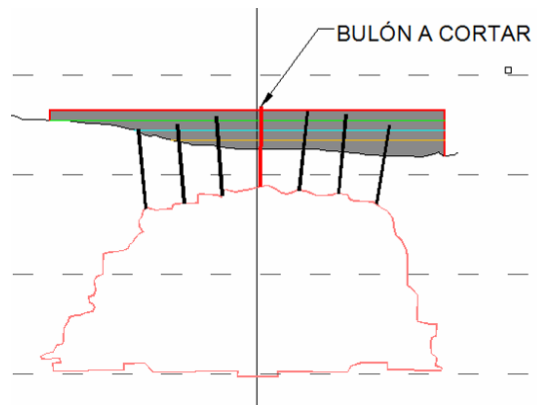
With regard to the geometry of the bolting it was recommended to have a maximum length of 4 metres in the areas where the rock was thick enough. In this sense, the areas with weaker rock require a special treatment directed at providing the bolting with an artificial stratum to enable subsequent anchoring to it.

The mesh planned will be 2x2 metres which means approximately between 8 and 10 bolts located in every 2 metres of Jameo.

With the two treatments considered in previous sections of this paper, complete treatment is given to the first-level problems and partially to second-level and third-level problems.

Improved stratum for anchoring the bolts in the entrance area

The aim of this solution is to create an artificial stratum of improved soil in the areas in which the rock thickness in the keystone was considerably reduced. It was considered that this treatment is required up to a profile where the thickness of the rock is practically 8 metres. The reinforcement is intended to prevent, in the long term, the combination of various vertical and horizontal groups of fracturing which could cause a large block to fall. In the event of a block with such characteristics becoming detached, the bolts would ensure that it remained attached.



The objective of this treatment is to create an artificial stratum to anchor the bolts and not, strictly speaking, to create a flagstone-like structural element. Nevertheless, to improve its behaviour with regard to possible tractions or fissures which could arise, a reinforced grating was included with three levels of bars measuring 25 mm in diameter.

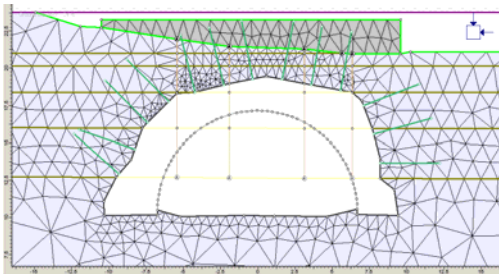
A fundamental aspect analysed in this artificial stratum is its weight since it is located over an area which is particularly sensitive to possible overloads. With the objective of not applying overloads any greater than those which already existed, it was rec-

ommended to use concrete made of light aggregate which enables achieving very low densities and concrete with resistance of up to 25 MPa.

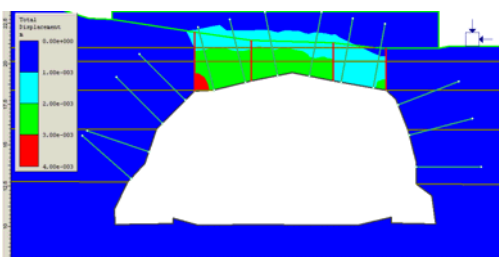
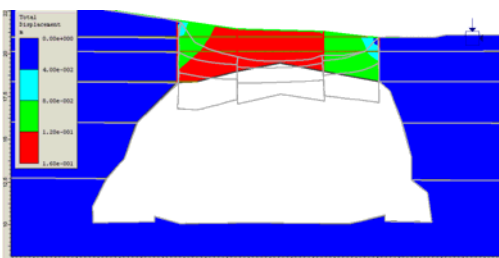
It was required that the stratum be constructed in one go to avoid any type of discontinuities which is why it was intended for the three levels of reinforcing to be positioned in one go.

As a precautionary measure the area located within the cave under the vertical of the improved stratum had to be dismantled while work was being performed on the surface and while waiting for the concrete to achieve its resistance over 28 days.

Likewise, to make a more simplified analysis of the effect of this stratum, two finite element models were made which included joining elements to reproduce the generation of one joint throughout the rock solid mass.



In the first calculation model the formation of the auditorium up to its present condition is reproduced in successive phases. In the final phase of the calculation a long-term hypothetical situation is simulated in which the resistant and deformational characteristics of the vertical joints is reduced until achieving the instability of the calculation model. The second model is exactly the same as the first. The only difference is that in the last phase the improved concrete stratum is added and the bolts to verify that this reinforcement manages to stabilise the arch of the auditorium.



5.2 Isolated Solutions: Solutions Type 2

These are solutions which aim to secure blocks from 10 centimetres up to 1 m³ which could become detached from the rock solid mass being in a strict equilibrium situation. This strict equilibrium can be clearly seen in blocks which can be seen to have become detached from the solid mass. Nevertheless, those which show signs of unfavourable fractures and which have welding in their planes on the surface or not must also be considered as sensitive.

Solutions Type 2-A: Micro-seaming of blocks

For the largest blocks of approximately 1 cubic metre a weight was estimated of approximately 40 kN. They had to be considered as entirely supported by the treatment to be used given that initially the behaviour and orientation of the fracture planes is uncertain, especially at depth with there could even be the possibility of gaps appearing (bubbles).

The treatment of these blocks was carried out partially with the injection treatment discussed in the previous solutions. This treatment, however, is complemented by using the micro-seaming of blocks and also by using fibreglass rods injected using epoxy resins.

For diameters which are commercially available, the working load of the rods was calculated by using a safety coefficient of 1.6 (maximum value which is usually applied to conventional anchoring).

With the range of loads considered, the treatment was planned with a diameter of 8 mm, with the objective of making the hole as small as possible (approx. 2 mm in addition to the rod diameter). In the case of the largest blocks it would therefore be necessary to use two or three rods positioned in such a way as to take full advantage of the capacity of the rod (i.e. as parallel as possible to the direction of movement of the unstable block which in general will be considerably vertical).

The maximum length commercially available for these types of rods is 2 metres which covers the range of lengths planned for use for this treatment.

Solution Type 2-B: Chemical welding of smaller blocks

These are the cases where it was not possible to make holes in the blocks due to their small size (third-level problem), i.e. blocks of approx. 20 · 20 cm maximum. This would be equivalent to weights between 1 and 1.6 kN, with an increase factor of 1.6. It was considered joining the blocks by using so-

called “chemical welding”, which is basically the creation of bridges between different blocks using low viscosity epoxy resin weld beads applied manually.



This creates one larger block with which it could, at least theoretically, be possible to treat using micro-seaming. As occurred with treatment 2-A there is already a first previous action level since the generalised injections type 1a have already been performed. This action is therefore complementary in those cases in which there is no safety in the finish of the first action level.

5.3 Superficial Solutions: Solutions Type 3

This is the treatment which solves more minor problems i.e. this includes gravel-type sizes (between 2 and 50 mm). Logically it was considered that this could affect any point of the Jameo Auditorium due to the very small dimensions of the particles to be supported.

To find a solution to this problem it was planned to apply a compaction treatment to the surface of the rock where this phenomenon was expected to appear. A rock behaviour model was studied which assumed a material formed by a sandy and silty matrix containing inclusions of larger edges embedded in it (scoria). As from the gradual deterioration of this matrix “micro-cutting” could be produced to the edges embedded in the ground mass thus causing it to fall when finally a sufficient volume of the matrix has disappeared.

A rocky material exposed to the atmosphere deteriorates more on the surface than on the inside. This deterioration could be accompanied by the formation of hard surface crusts with low porosity.

Basically a compaction treatment must improve the mechanical resistance of the material, especially to traction, whilst improving its structure making water ingress more difficult and the circulation of saline or acidic solutions.

These products adhere to the walls thus reducing the empty space and creating connection points between these walls. In short, their objective is to act as a mineral cement, non-existent originally or lost due to alteration. The improvement in the mechanical properties of the rock depends, in this case, on the abundance of links or anchoring points which are established between the precipitated compound and the components of the stone material.

As a consequence of the compaction treatment there should be an increase in the resistance to alteration processes which conduct volume changes in the porous network of the material and which imply mechanical stress which affects the structure of the material (crystallisation of salts, etc.).

The compaction treatment considered had, as such, the objective of acting on the rock surface by increasing the cohesion of its matrix and increasing its resistance to weathering.

With the objective of complying with all the requirements a treatment is considered based on ethyl silicate as the active ingredient diluted in solvent in varying concentrations depending on the penetration desired.

With these kinds of products the thickness is between 5 and 10 centimetres which means that the ethyl silicate must be applied in variable concentrations in successive phases using a smaller or greater concentration. This enables restoring the material matrix by making it more resistant and less prone to weathering.

The selection of the product application method was carried out on site in such a way as to obtain as much penetration as possible in the material. This is a fundamental characteristic which conditions the effectiveness of the product. This penetration capacity is influenced, not only by the characteristics of the compaction agent, but by the product application mode, the type of solvent, the contact time, relative humidity and the pressure and temperature at which it is carried out.

A limit in the use of this type of treatment is the existence of salts on the rock surface which occurs in the case of the auditorium in some parts close to the stage. In these cases the project planned surface and isolated treatments based on paper pulp poultices. As such, it was recommended to plan a treatment that would cut the origin of the salts reaching the Jameo, although this treatment was not by any means the purpose of the project.

Another limit of the treatment refers to the edges which are already beginning to detach with open micro-fissures greater than 50-100 µm which cannot be treated with ethyl silicate due to very low viscosity hindering its penetration. For these edges the recommendable treatment is their elimination prior to treatment by thoroughly cleaning using compressed air. Afterwards, and as an additional measure to guarantee the effectiveness of the treatment, a second cleaning is proposed once the compaction treatment has been carried out.

As a complementary treatment directed at creating a film which could stabilise some edges superficially the spraying of a liquid polyurethane membrane was planned. In some ways this treatment would aim to perform a function similar to a very fine mesh since the largest sizes of stone will be stable due to the serious of actions at different levels already considered. This membrane has a resistance to traction of approx. 3.5 MPa which allows fixing edges which have already started to detach or those areas in which it is necessary to create “bridges” for micro-fissures of greater importance of 50-100 µm.

Some of these last surface treatments were modified on site for aesthetic reasons in some cases (shine in the polyurethane membrane) or due to the use of replacement techniques such as hydrodemolition.

6 RECOMMENDED CONTROL AND SUPERVISION OF THE WORK IN THE PROJECT

The auscultation and supervision programme of the work was proposed as part of a series of test sections of each treatment along with the systematic supervision of the work. The following areas were proposed for the test sections:

Treatment name		Description	Type of check to be performed
Type 1	1-A	Resin injections from the inside	Test area of 2 m ²
	1-B	Fibreglass bolting	3 bolts including their injection and load test
Type 2	2-A	Micro-seaming of blocks	5 bolts spaced differently at various depths of 1 to 1.5
	2-B	Chemical welding of smaller blocks	Test area of 1 m ²
Type 3		Superficial solutions using binders and polyurethane membranes	Test area of 2 m ²
Type 4		Solutions for existing anthropic actions	In two existing actions

Supervision and control actions were also recommended which had to be documented and systemised. The supervision team (geotechnical engineer and restorer) will be responsible for confirming on site the treatment to be applied in each case and for checking the final outcome of each one.

The working methodology planned was as follows:

- Division of the auditorium into “treatment rings” of 2 metres of treatment with a geotechnical survey and a photographic report of each one using cards or a dossier. This survey was to be detailed enough so as to enable a comparison to be made of the current condition and the final one.
- On site decision regarding the treatments to be used in each ring. In those considered systematic there will be an indication of the ideal areas for carrying out each one (holes, anchoring, etc).
- Supervision of the execution of each ring by carrying out a survey upon completion of work in order to verify the effect of the treatment applied, as well as the starting point for systematic maintenance during the operational phase.
- Check of the final treatment of each ring by stating whether new actions are required.

As a conclusion to this process it was planned to create a final report on the condition of the action in order to apply it to subsequent phases and to each of the sections.

As auscultation measures during the work a detailed topographical control was planned using key-tone levelling and recording convergences in key-tone and shoulders using prisms in each treatment ring. Likewise, in the area of the upper slab-stratum a network of levelling reference marks was planned with a measurement frequency every 12 hours after removing the provisional propping of the arch.

All of the instruments, suitably concealed, were intended for continued use to enable supervision during the operational phase.

During the operation of the auditorium, once the actions described in the previous sections were completed and given its status as a “Cultural Asset”, routines were devised for the control and supervision of the work carried out as well as maintenance programmes to guarantee its perfect conservation by using periodic controls aimed at checking effectiveness and ageing.

The maintenance routines will continue for the time deemed necessary in accordance with the conservation of the Asset.

The “Letter of 1987” defines maintenance as “*the set of actions programmed on a recurring basis, aimed at keeping the objects of cultural interest in optimum conditions and functionality, especially after they have undergone exceptional interventions for conservation or restoration purposes. The schedule and implementation of regular maintenance and control cycles to ascertain the conservation condition of an architectural monument is the only guarantee to ensure that prevention is opportune and suited to the site with regard to the nature of the interventions and their frequency.*”

In short, during the operational phase there must be continuous supervision of the auditorium similar to that performed prior to this intervention, as a complement to the systematic care of it by specialised teams from the Town Council of Lanzarote which is considered as absolutely essential.

7 REFERENCE

Signorelli, S.; Jover F.L., Pacheco, M.L, Zafrilla, S. and Cárdenas, A.. 2007. “The Jameos del Agua cave (Lanzarote, Canary Islands): Some morphological and geological features of a spectacular lava tube adapted to auditorium”. *Volcanic Rocks – Malheiro & Nunes (Eds) Taylor & Francis Group, London, ISBN 978-0-415-45140-6*