Highlights

- Wireless sensor network to assess dolmen structural performance for the first time
- Barely-seen structural stability analyses performed for the self-supporting dolmen
- Scarcely-investigated visitation effect on dolmen interior microclimate analysed
- Mechanisms of dolmen painting deterioration caused by visitations addressed
- Advice on enhancing structural robustness and environmental resilience proposed

Real-time condition assessment of a painted megalithic cave using Wireless Sensor Network

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ABSTRACT: The deterioration of underground heritage caves caused by visitations has attracted extensive attention over the recent decades. Most previous research focused on investigating the impact of visitors on the microclimatic conditions of the interior of large show caves, but much less relevant effort was made for small confined caves, for example, megalithic burial dolmen caves. In addition to environmental condition issues, the structural performance of underground heritage caves also deteriorates in the long-term subject to both natural hazards (e.g. creep in geo-materials and extreme weather) and manmade ones (e.g. construction activities).To this end, a real-time Wireless Sensor Network (WSN) system is deployed inside an underground megalithic dolmen to monitor its structural performance with time as to assess its long-term structural stability. Meanwhile, the WSN system together with other field sensors and inspection monitors the interior environmental change caused by human visitation effect, aiming to reveal the mechanism behind visitor-caused rock painting deterioration in the small confined dolmen chamber. Results show that structurally, the dolmen can be regarded as generally stable despite a progressive development of structural performance during the first 1.5 months and accidental instability of the near-opening pillar A. In terms of environmental condition, the presence of visitors leads to significant changes of interior microclimatic conditions frequently inside the confined cave against consistent rock painting conservation. Particularly, the cave paintings may deteriorate critically with time as visitation induces a ‘hotbed’ environment for interactions between microorganisms and microstructures of the rock paintings due to the variations of interior microclimate. To ensure long-term structural stability and restore acceptable level of interior microclimate, tinted hydraulic lime and steel rod/brace were recommended for enhancing structural robustness and a mechanical ventilation system for improving environmental resilience of the dolmen.

KEYWORDS: Wireless sensor network; long-term structural performance; environmental conditions; human visitation impact; rock painting deterioration

1 Introduction

Underground heritage caves have a wide existence in Europe, Asia and around the globe. Many of them bear exceptional archaeological, cultural and historic significance due to the widespread presence of symbolic but mostly-abstract prehistoric paintings and/or engravings, rendering them unique in understanding the evolution of humanity and civilisation (Krzeminska et al., 2018). These caves with prehistoric remains, in particular buried megalithic dolmens, were mostly believed to appear between the fifth and the third millennium BC (Giesen et al., 2014; Ramírez and Valcarce, 2003). After first discovery, some small caves were left unattended due to various reasons, whilst progressive deterioration of the cave panels continuously develops at the risk of some of the most prominent prehistoric rock art inside (Bagde et al., 2010; Saiz-Jimenez et al., 2011). On the other hand, some other large and renowned caves were heavily visited because of tourism development, and growing evidence showed that visitations accelerated the deterioration of rock art inside these tourist caves, exemplified by the UNESCO World Heritage caves of Lascaux (Dordogne, France) (Bourges et al., 2014) and Altamira (Cantabria, Spain) (Parga Dans and Alonso González, 2018) which had been closed to the public for multiple times over concerns on further destroying the precious heritages subject to continuous visitation (Saiz-Jimenez et al., 2011).

Extensive research has been done to study the performance/condition of such underground heritages, especially show caves. Among the factors influencing cave conditions, the microclimatic and microbiological conditions inside such touristic caves around the world have been the main focus of many previous investigations (Bourges et al., 2020; Dragovich and Grose, 1990; Giesen et al., 2014; Martin-Sanchez et al., 2014; Mulec, 2014; Novas et al., 2017; Sánchez-Moral et al., 1999). As an early study, the CO_2 level in Jenolan Caves, Australia was found to increase following tourist visitation but the rate of increase and dispersal of CO_2 was dependent on various factors (Dragovich and Grose, 1990). In addition to CO_2 monitoring, Mulec (2014) added bacterial count monitoring inside two Slovenian show caves (Škocjan Caves and Postojna Cave) and concluded that the alteration of bacterial count was more indicative than the changes of CO_2 level in detecting tourist visits. Similarly, Martin-Sanchez et al. (2014) conducted aerobiological and microclimate studies in the Lascaux Cave, France in two separate seasons, and summarised that the concentration and dispersion of airborne microorganisms was noticeably correlated to the interior microclimate. On top of CO_2, three other environmental parameters including temperature, relative humidity and $^{222}R_n$ were monitored for one year in the Altamira Cave, Spain by Sánchez-Moral et al. (1999) to analyse how they contributed to the wall corrosion process. In this study, visitations were found to significantly enhance cave wall corrosion, up to 78 times when compared to natural scenarios. Likewise, another five-year monitoring of microclimatic conditions inside the Chauvet-Pont d'Arc cave, France draw a similar conclusion that an increasing level of CO_2 concentration may cause drastic wall painting deterioration (Bourges et al., 2020).

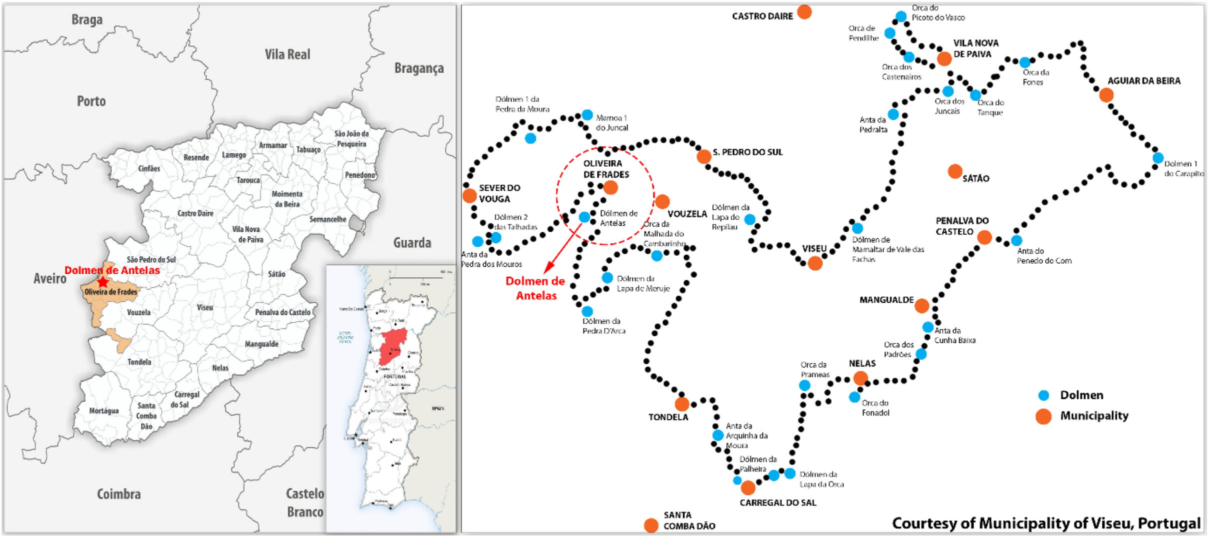
In comparison to the heatedly-investigated environmental and microbiological studies of large-scale tourist caves, few studies focusing on the structural performance of another type of heritage caves, megalithic dolmens, were reported. To understand the possible instability issues during restoration works, a mobilisation analysis of the Dolmen de Dombate, Spain was presented by Navarro et al. (2008) and was verified using a self-developed numerical solver. Similarly, Martínez-Torres (2014) examined the force system of a Neolithic dolmen (Alto de La Huesera) in Spain with imbricated architectural style so as to assess its structural stability. Out of concern on destabilising the self-supporting dolmen structure during excavation and restoration, Reinosa and Romera (2015) conducted a stability analysis on a megalithic monument against overturning and concluded that the proposed approach in the study could provide a specialised and convenient implement for archaeologists to evaluate the stability of such monuments.

Even though all those previous research has enriched the understanding of heritage performance, some gaps still remain, especially for those small-sized, confined megalithic dolmens, which number tens of thousands and widely distribute in Portugal, Ireland, Europe and the world. Scarce investigations on the environmental conditions of such types of underground heritage caves have been reported, let alone studies on their structural performance. Moreover, efforts on examining the effect of visitation on the interior microclimatic conditions and how this effect may deteriorate cave paintings of such monuments have also been barely seen in literature. In this regard, a joint research under the framework of European Cooperation in Science and Technology (COST) Action Underground for Value (U4V) is carried out to assess both the structural and environmental conditions of a megalithic heritage cave based on field monitoring, aiming to enhance the understanding of megalithic monuments' performance. In this study, a real-time Wireless Sensor Network (WSN) monitoring system is deployed inside a Portuguese heritage cave, the Dólmen de Antelas (the Dolmen), to monitor its long-term structural behaviour with time, thus to assess the long-term stability of this megalithic structure. In addition, a monitoring of visitors' impact on this underground cave's environmental conditions is conducted and the possible mechanism behind visitation-caused rock painting deterioration in such confined dolmen chamber is analysed.

2 Site description

2.1 Site background

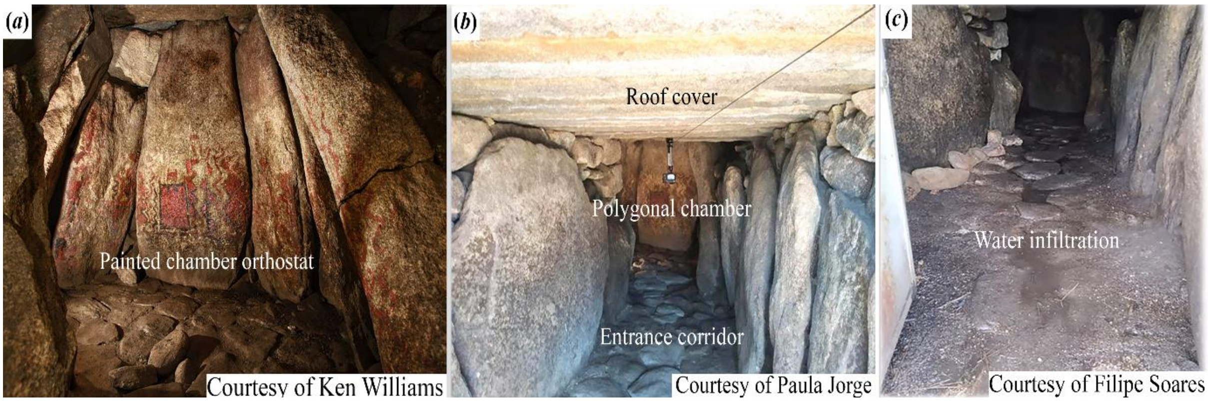
Located in the Municipality of Oliveira de Frades (the Municipality), Viseu district, Portugal, as shown in Figure 1(*a*), the Dólmen de Antelas was uncovered in 1956 following the first documented archaeological excavation, enabling the restoration of this megalithic structure (Albuquerque e Castro et al., 1957). However, these researchers, who were aware of their own incapability to assure its safekeeping, backfilled the burial chamber as an approach to preserve this valuable asset, particularly the delicate two-colour paintings. Classified as a National Monument in 1990, the Dolmen was later integrated into a Megalithic Route that houses 24 such monuments in central Portugal, Figure 1(*b*), due to its archaeological and cultural significance (Sanches, 2009). In 1993, the second excavation by a team from University of Coimbra, Portugal extended the archaeological works from dolmen interior to the forecourt which included architectural consolidation and restoration such as excessive earth removal and protective mound reconstruction (Ramírez and Valcarce, 2003). Afterwards, it was found by C14 dating that the primary dolmen construction and the utilization of pictorial decoration possibly occurred at some time between 3980 and 3700 BC (Steelman et al., 2005).



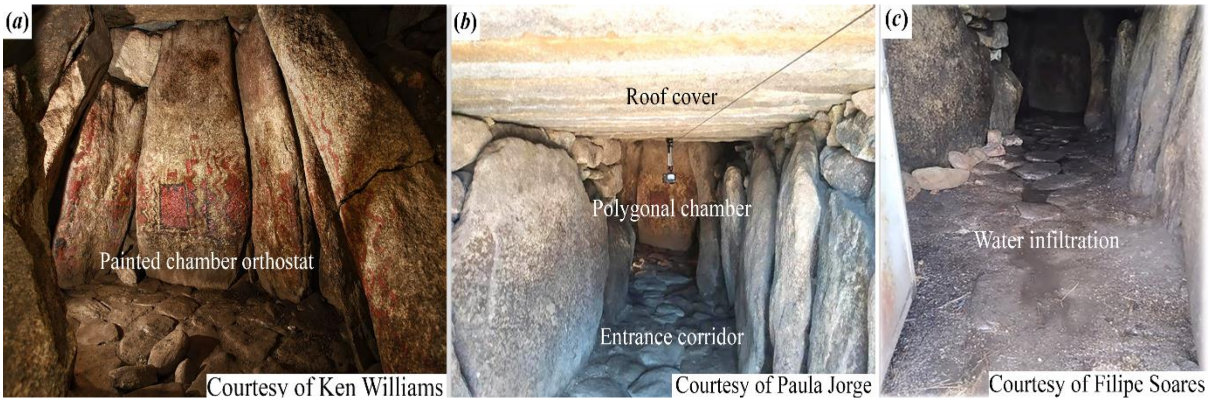
(*a*) Dolmen location (*b*) Megalithic Route in Viseu, Portugal

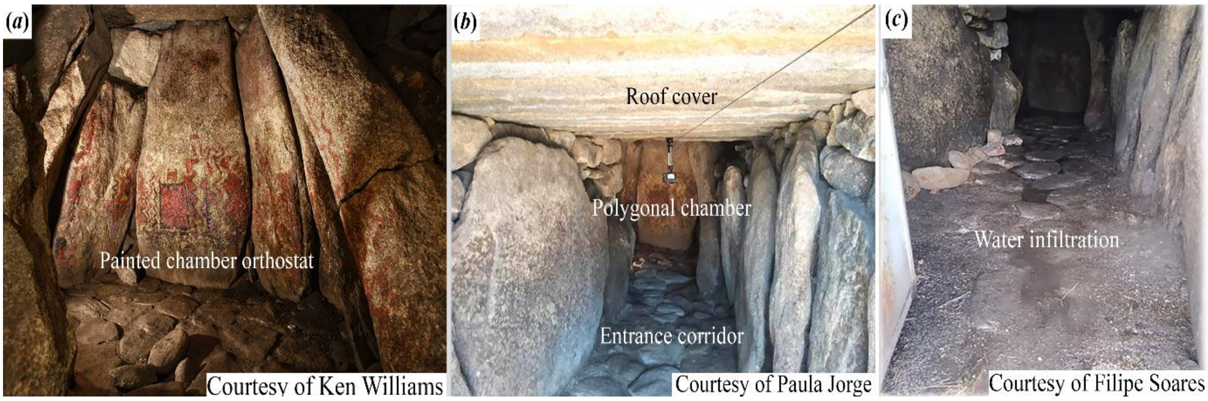
Figure 1. Geographical location of the dolmen

Unlike most non-painted dolmens in central Portugal, the Dólmen de Antelas features an extensive collection of well-preserved black-red paintings, as well as some small engravings, on each dolmen pillars, as shown in **Figure** 2(*a*) and Figure 7(*a*), which renders it a representative of this megalithic cultural phenomenon that spanned across Europe between the 5th and the 3rd millennium BC (Costa, 2020). The



Dolmen consists of an irregular polygonal funeral chamber with eight imbricated pillars measuring a maximum height of 2.0m, and a 9-pillar entrance gallery with an approximate size of 1.3m (height) × 4.0m (length) × 1.0m (width) (Sanches, 2009). Following the construction of the artificial mound, the back of this monument was sealed by earth and stone fragments, with roof slabs covering the whole dolmen structure (**Figure** 2(*b*)). With time, deteriorations of the Dolmen were observed. The infiltration of water (**Figure** 2(*c*)), the lack of circulation in a confined space (Figure 4(*a*)), and the decades-long canvas perforation by vegetation roots (Figure 4(*a*)) are all likely contributors threatening painting deterioration and structure stability. If left unmanaged, the Dolmen will deteriorate even faster, further jeopardising its archaeological, cultural, historic values.





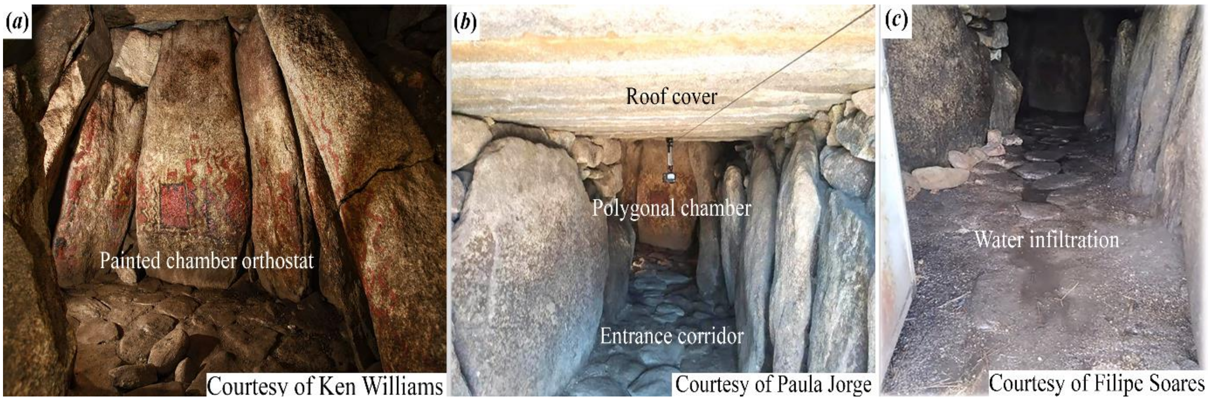


Figure 2. Painted chamber of Dólmen de Antelas

Twenty-plus years on, the previous restoration efforts turned out not as effective as expected in the long run. Having been aware of this, the Municipality has developed a series of rescue actions aiming at preserving the paintings and protecting the dolmen. In 2019, a comprehensive characterisation and diagnosis of the monument, including the identification of rock, biological colonisation, and painting pigments (see Section 2.3), was firstly conducted, contributing to the definition of future clear-cut conservation measures for this megalithic art piece (Antonio et al., 2019; Costa, 2020). Following the diagnosis, another recent conservation project aiming at creating better environmental conditions for preserving the prehistoric remains was implemented in 2020. The main tasks included the replacement of the perforated waterproofing screen and the placement of a drain around the perimeter of the artificial mound to stabilise the interior environment of the monument as well as to restore acceptable levels of humidity and temperature inside the chamber and eliminate condensation problem. Figure 3 and Figure 4 present the detailed tasks carried out in this recent intervention project and the dolmen view before and after the intervention, respectively. In the last quarter of 2020, a joint research under the COST U4V framework was carried out to investigate the long-term structural and environmental performance of this monument, aiming to understand the data-based structural stability and environmental conditions before planning the next-stage conservation and officially opening it to the public.

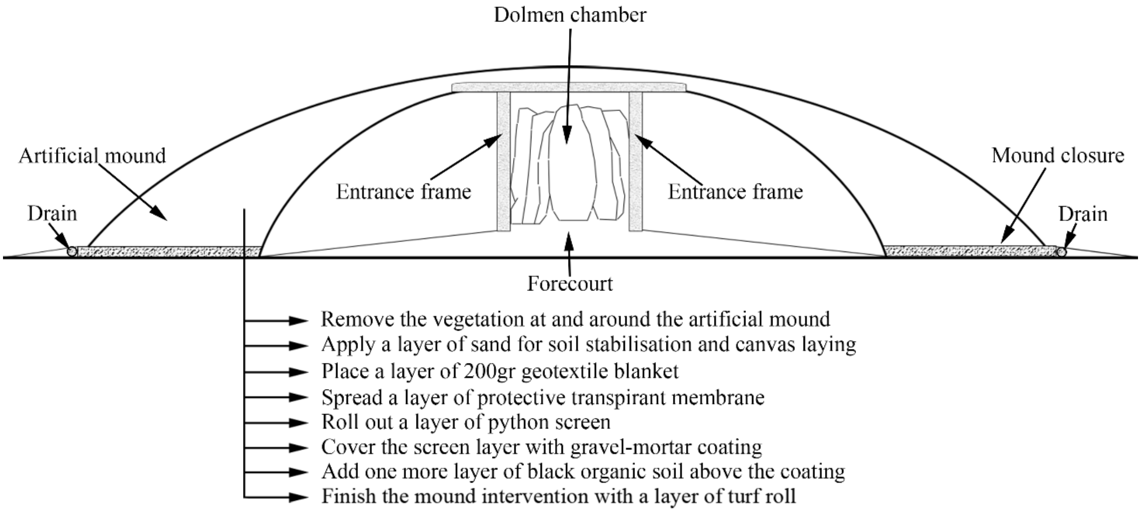


Figure 3. Sequence of intervention

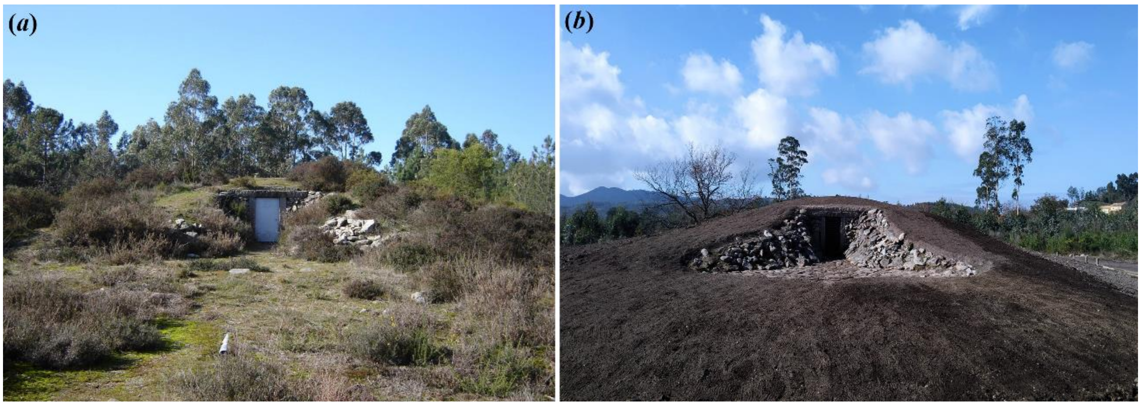


Figure 4. Dolmen view. (a) Before intervention (b) After intervention

2.2 Dolmen characterisation

To better understand this painted heritage cave, a group of specialists conducted a series of detailed analyses on the characterisation of dolmen pillars, paintings, and biological colonisation. The rock pillars were identified as weathered granite rich in three minerals: quartz, potassium feldspar and muscovite, upon analysing the petrographic and X-ray diffraction results (Antonio et al., 2019). Based on microscopic analyses, it was concluded that there is a wide pink existence of a fungi in its growth and colonisation phases on all granite pillars (Figure 5(*a*)) and all other coloured samples collected were found to have no obvious live microorganisms (Figure 5(*b*-*c*)) (Antonio et al., 2019). Moreover, the composition of painting materials was determined by X-ray diffraction and SEM: (1) the deep-red painting layer (Figure 5(*d*)) is dominantly-rich in hematite (Fe_2O_3), with a cracked base layer suggesting some deterioration possibly associated with wet-dry cycles; (2) the black pictorial layer (Figure 5(*e*)) is identified to be plant-nature, *C*-rich and *Al*-rich charcoal sitting on a base layer of kaolinite.

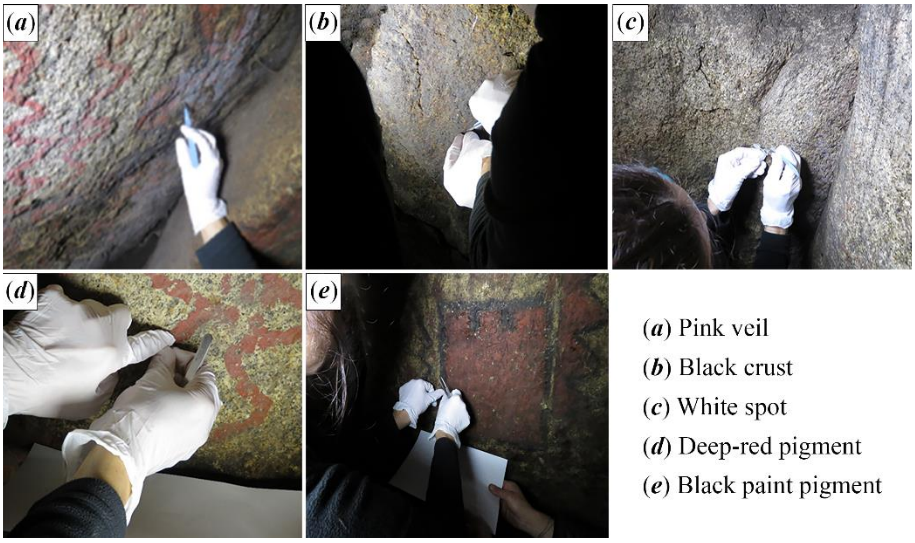


Figure 5. Dolmen painting characterisation (Antonio et al., 2019)

3 Sensor deployment inside the cave

3.1 Structural health monitoring

In the context of extensive observations of heritage cave deterioration, such as rock painting decay and cave microclimate alteration, many studies were carried out to offer more insights into the conservation and preservation of these heritages (Benavente et al., 2014; Freire-Lista et al., 2014; Jalandoni, 2019; Krupińska et al., 2013; Novas et al., 2017). However, much attention was paid to the indoor environment of such caves with scarce reports on their most-fundamental structural performance. Besides, most of these studies were conducted in large touristic caves while almost no investigations on small-scale megalithic dolmens were found, let alone their structural behaviour. In this study, a real-time WSN structural monitoring system is deployed in the Dólmen de Antelas with an aim to assess its structural stability.

3.1.1 Wireless sensor network

Different from conventional AC/DC-powered and wired monitoring system, the Internet of Things-based WSN features real-time acquisition and wireless transmission of data within a battery-powered system (Rodenas-Herráiz et al., 2016). Figure 6 illustrates the working principle and components of a WSN system. Sensor nodes detect the changes of their surroundings, and then process and transmit the collected data either directly to the gateway or to their neighbouring nodes (self-organisation) via radio frequency-based wireless links (under a customised WSN data transmission protocol), before the data are sent to the user end for visualisation in real time through mobile network (Bennett et al., 2010). In reverse, if any change, for example, sampling frequency and data transmission cycle, is needed, such commands are delivered from the user end to the system in real time as well. All data can be accessed by logging onto a web portal which allows different levels of users to consult the evolution of parameters of interest in real time. This kind of battery-powered, self-organised and wireless monitoring system allows a fast, low-cost, highly-scalable and efficient deployment in both normal and harsh engineering conditions (Bennett et al., 2010), including small-sized burial structures (e.g. Dólmen de Antelas) in this study.

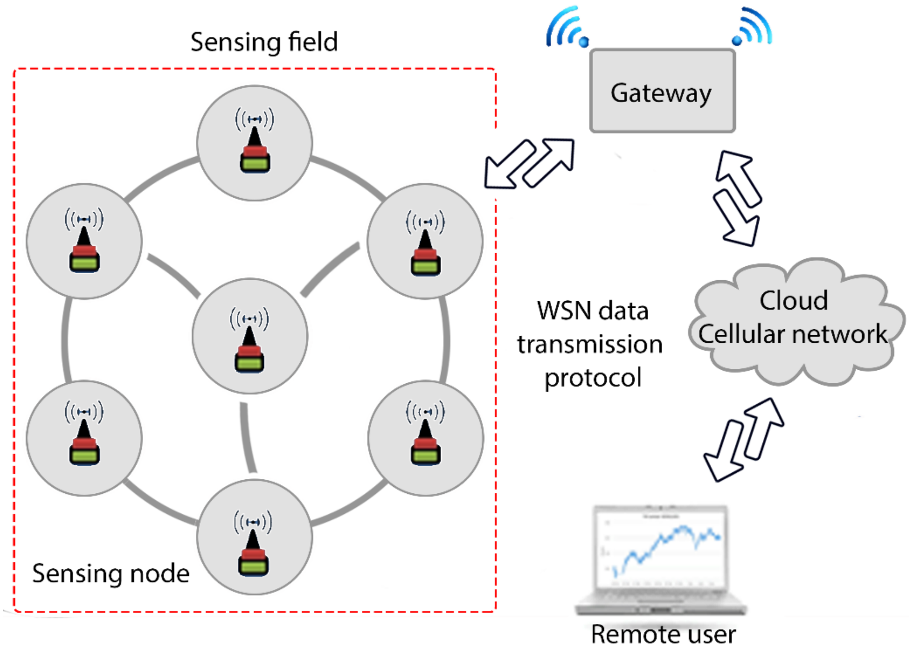
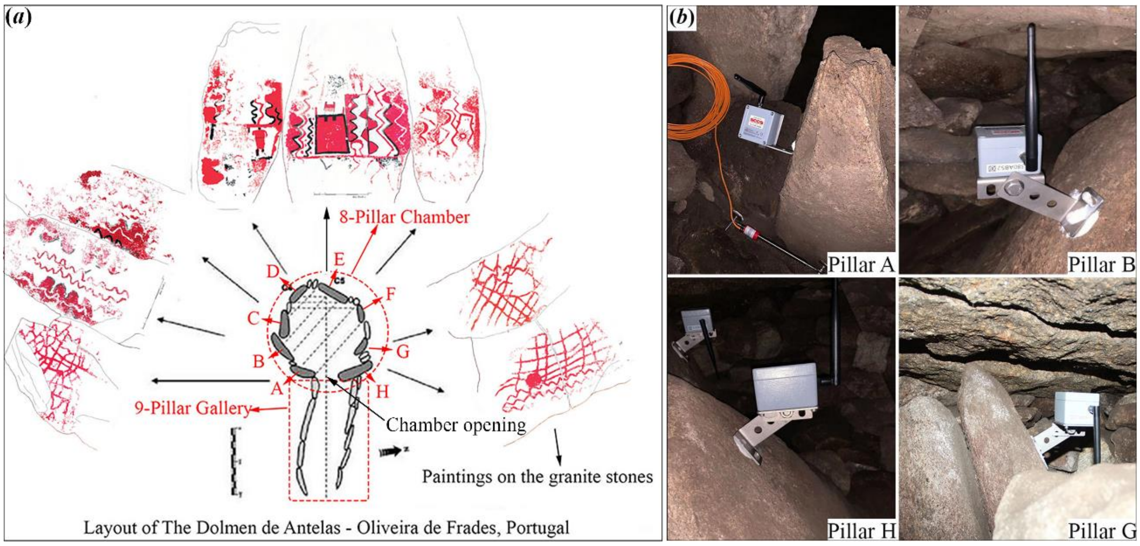


Figure 6. WSN system

3.1.2 Onsite deployment

Based on the configuration and onsite conditions of the Dolmen, a package of WSN sensors was deployed on some critical chamber pillars to investigate the long-term structural behaviour of this self-supporting structure. Figure 7(*a*) presents the layout of this painted dolmen (Sanches, 2009).

Theoretically, the two pillars A and H are more structurally unstable than the remaining pillars as no support exists for their flanks close to the chamber opening. To mitigate the risk of potential instability, pillar A is now supported (partially penetrated) by a steel rod on its upper part (Figure 7(*c*)). Moreover, only limited space is accessible at the back of pillars A, B, G and H as these pillars are mostly surrounded by earth and stone fragments, whereas the other four pillars are nearly inaccessible. Therefore, in the light of structural stability, four two-axial wireless tilt-meters with an accuracy of 0.01° were mounted to the back of these four accessible pillars using non-intrusive industrial adhesive to monitor their radial and tangential inclination with time, respectively (Figure 7(*b*)). The inclinometer on pillar A was installed at a height of around 0.8m above the ground surface, with the one on pillar H around 1.6m and the other two on pillars B and G around 1.8m respectively. In addition, two crack-meters (with an accuracy of ±0.025mm) were installed on pillar A and pillar H to detect the relative movement between pillars A and B and to monitor the movement of pillar H's two broken halves, respectively (Figure 7(*c*)). To determine the movement of the main chamber generating pillar E (keystone), one laser convergence sensor with an accuracy of 0.5mm was deployed at the entrance headstone (Figure 7(*d*)).



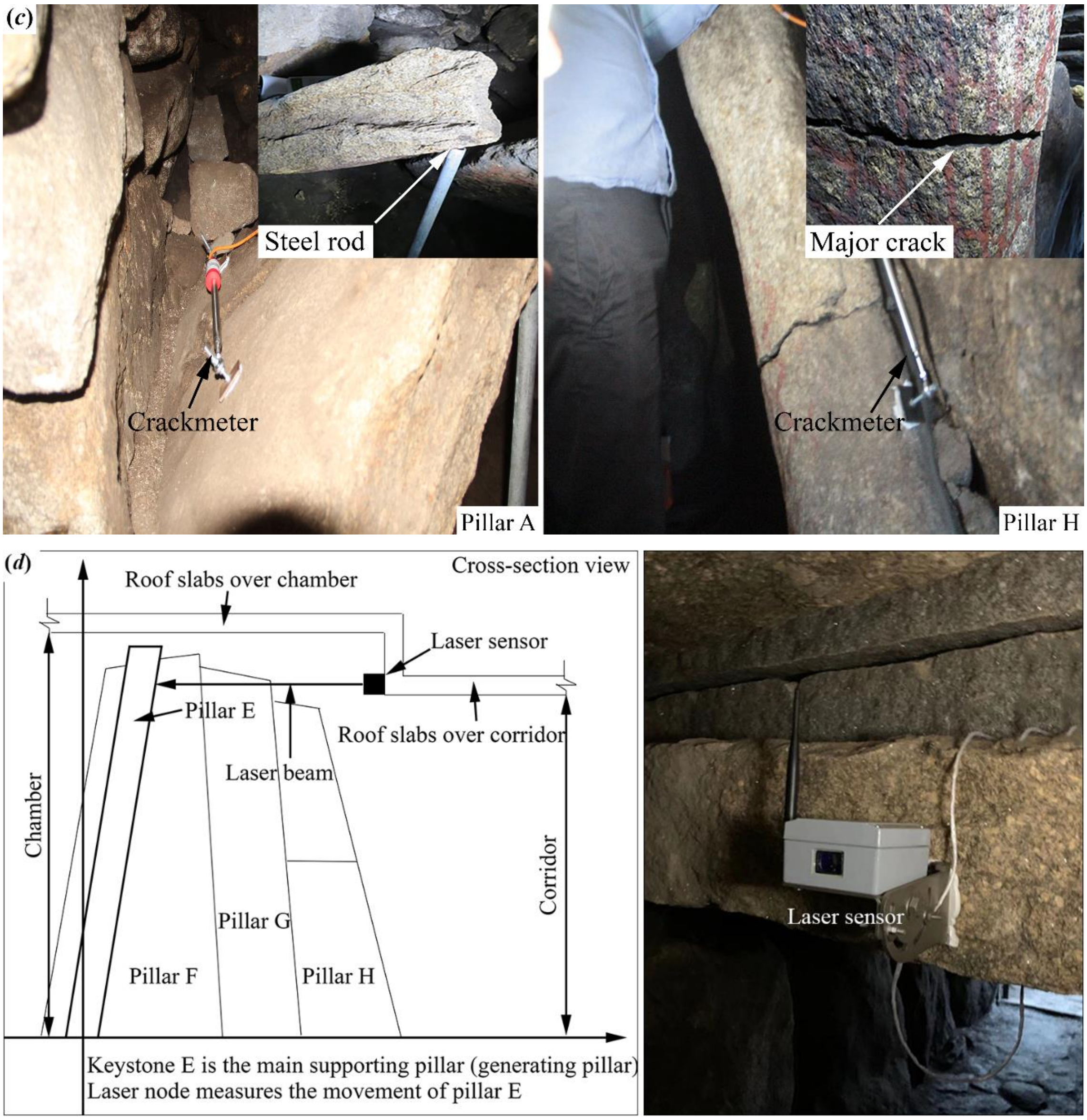


Figure 7. Onsite deployment of WSN

3.2 Environmental condition monitoring

As concluded in many previous studies, the stability of interior environment of heritage caves plays a significant role in their conservation and preservation in the long term (Bourges et al., 2014; Bourges et al., 2020; Mulec, 2014; Novas et al., 2017). To examine the environmental conditions inside the Dolmen, a programmable environmental sensor incorporating the monitoring of carbon dioxide (CO_2), temperature (T) and relative humidity (RH) was deployed inside the dolmen chamber. Afterwards, the Dolmen was closed for two days to restore the pre-visit natural environmental conditions, followed by an onsite experiment to investigate the effect of visitors' presence on the dolmen interior microclimate.

The experiment was implemented by inviting visitors to stand and talk inside the dolmen chamber for a certain period of time (e.g. 10 minutes) so as to mimic different future visitation scenarios. The experimental details are listed in Table 1. On account of the confined chamber space, a maximum of three people were invited. After the experiment, the cave was closed for long-term monitoring, with occasional visits by local authorities, researchers, preservers and conservationists recorded and registered by the Municipality during the monitoring period in order to complement the analysis of the visitation effect (Table 2).

Table 1. Experimental details

Experiment	Scenario 1	Scenario 2	Scenario 3
Number of visitors	1	2	3
Duration of presence	10min	10min	15min
Parameters monitored	CO_2, RH, T	CO_2, RH, T	CO_2, RH, T

Table 2. Visit registry

Order	Date	Duration	Headcount	Order	Date	Duration	Headcount
1	18/11/2020	15mins	2	13	16/03/2021	5mins	2
2	20/11/2020	35mins	3	14	17/03/2021	20mins	3
3	10/12/2020	20mins	2	15	18/03/2021	5mins	2
4	11/01/2021	30mins	2	16	20/03/2021	25mins	3
5	12/01/2021	20mins	1	17	21/03/2021	30mins	3
6	27/01/2021	10mins	1	18	22/03/2021	60mins	5
7	28/01/2021	40mins	3	19	25/03/2021	10mins	3
8	29/01/2021	5mins	1	20	07/04/2021	5mins	1
9	05/02/2021	5mins	1	21	12/04/2021	5mins	1
10	11/02/2021	60mins	3	22	15/04/2021	5mins	1
11	26/02/2021	40mins	2	23	17/04/2021	4hrs	20
12	11/03/2021	15mins	5	24	18/04/2021	10mins	4

Note: the duration shown for visits after the 10th visitation is the total time spent on site instead of the time spent in the chamber.

4 Structural and environment assessment of the cave

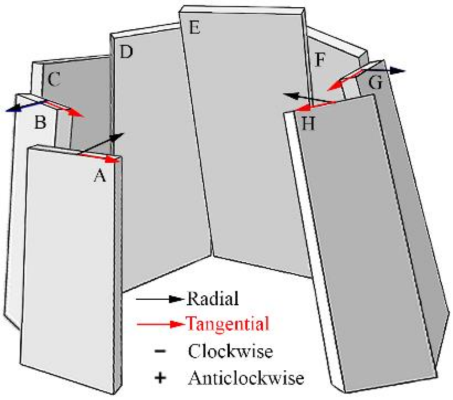
4.1 Structural performance

The structural performance of such a small-sized painted dolmen plays a significant role in its preservation and conservation. Ensuring the stability of the dolmen structure, therefore, serves as the most fundamental task. In this section, the results obtained from the real-time WSN structural monitoring on the selected dolmen pillars are presented and the stability of the Dolmen is subsequently assessed.

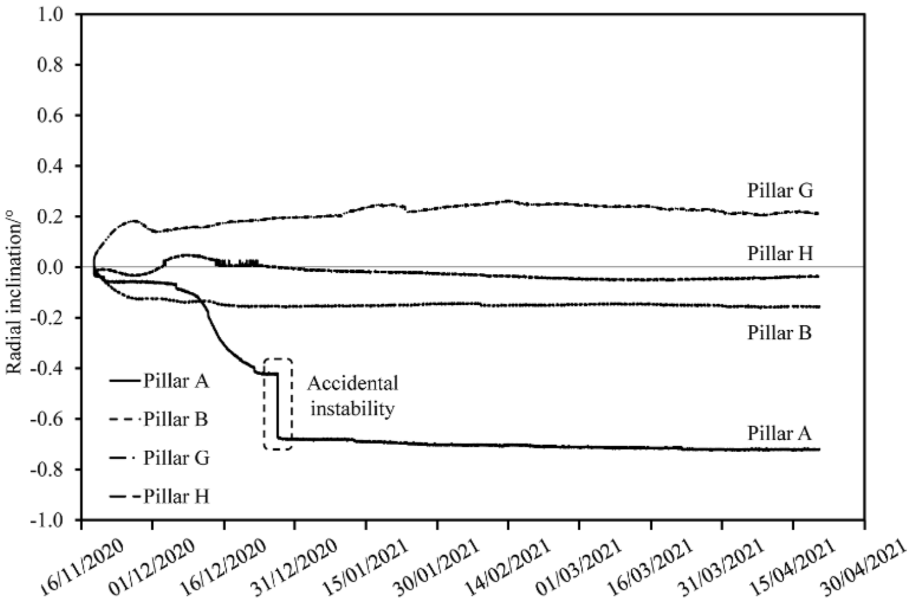
4.1.1 Structural inclination and stability

Figure 8 gives the inclination development of four critical pillars of the dolmen structure with time. The four two-axial inclinometers monitor both the radial (moving inwards/outwards the chamber) and tangential (moving away from/close to adjacent pillars) inclination development of pillars A, B, G and H, as illustrated in Figure 8(*a*). Readings are negative when the two directions move clockwise and vice versa. According to Figure 8(*b*), all four pillars were observed with slight inward movement, in general. For the two near-opening pillars, a maximum inward inclination of around 0.7° during the first 1.5 months was recorded for pillar A, while a negligible inclination variation of less than 0.1° for pillar H. This indicates a much faster rate of inclination development for A than that for H, but their development stabilised after around 1.5 months for both pillars. In particular, an accidental increase in inclination was observed on 27/12/2020 for the most structurally unstable pillar A of the whole dolmen structure. To the authors' best knowledge, there were no known onsite manmade interventions during the accidental inclination change on that day, which may be attributed to a sudden natural instability caused by possible contact interface sliding of pillar A away from pillar B. For their supporting pillars B and G, a first fast increase in inward inclination for both was obtained during a period of approximate 20 days into the monitoring, followed by a stabilisation for the rest of the monitoring period. The maximum inclinations developed during the monitoring period for pillar B and G are 0.15° and 0.26° respectively.

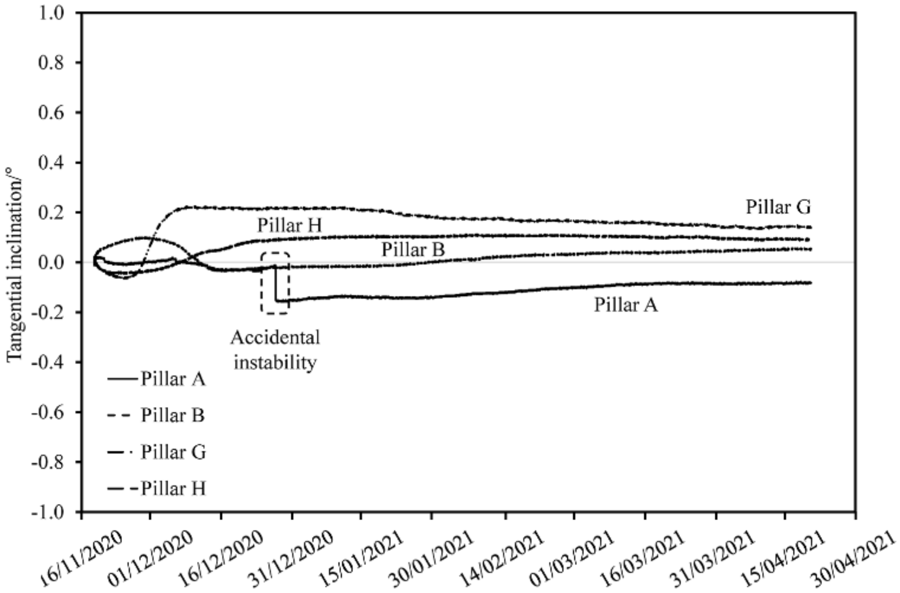
The inclination movement of these four pillars in the tangential direction is presented in Figure 8(*c*). All four pillars are slightly moving away from their supporting pillar gradually. For example, pillar H was moving away from pillar G towards the opening during the first 1.5 months into the period and stabilised at around 0.1° thereafter. However, pillar G's inclination development towards pillar H nearly levelled off at a maximum of 0.2° after around one month. For the other two pillars, near-zero development for pillar A was observed before the same accidental instability in tangential inclination occurred, followed by a stabilisation at around 0.2° for the rest of the monitoring period. Upon comparison, the slightest tangential inclination development of around 0.03° during the same period was recorded for pillar B.



(*a*) Inclinometer axis direction



(*b*) Radial inclination development



(*c*) Tangential inclination development

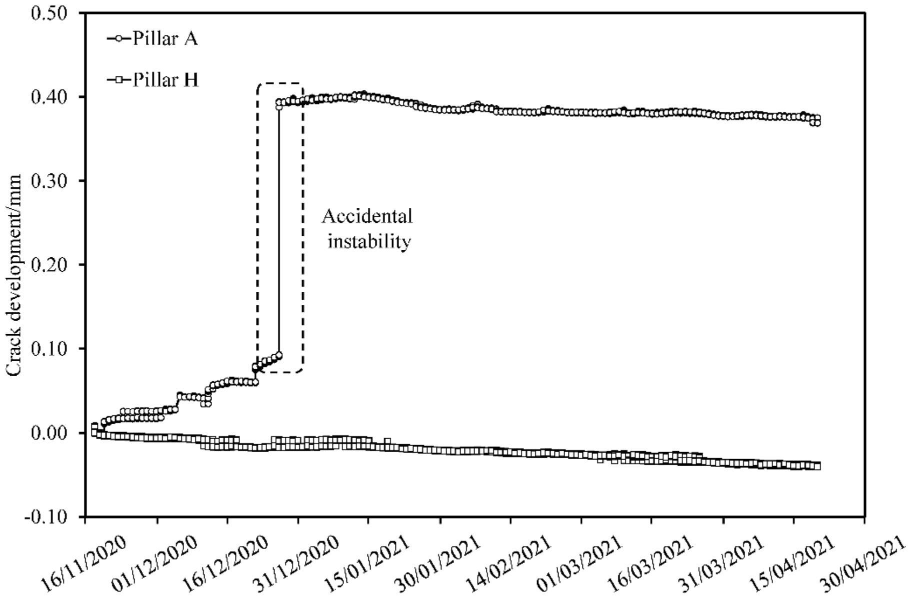
Figure 8. Pillar inclination development

Therefore, it can be summarised that during the short five-month period, the four pillars were moving inwards the chamber while moving towards the opening at a very slow rate within the first six weeks and the obtained maximum inclination was even less than an ignorable 1.0° on the most unstable pillar A, indicating a generally structurally-stable state for the dolmen structure. However, it is worthwhile to note that the rate of inclination development for pillar A and the accidental instability caused by possible contact interface sliding between pillar A and B should be given prioritised attention as such factors may destabilise the dolmen in the long run if left disregarded.

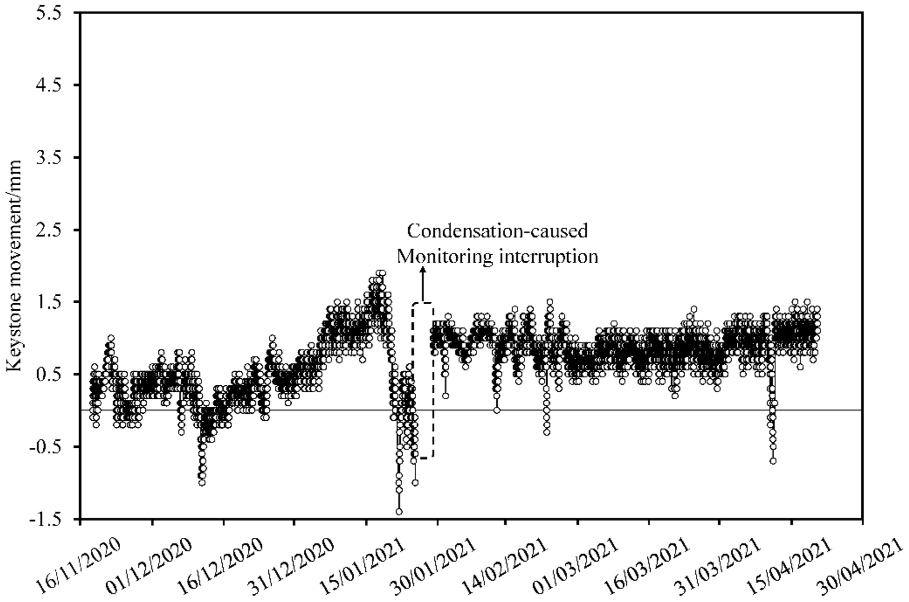
4.1.2 Crack development and keystone movement

Figure 9 shows the development of crack on pillars A and H and movement of the keystone E with time. The crack-meter mounted on pillar A monitors its relative movement away/close to its supporting pillar B while the crack-meter on pillar H records the crack propagation between its two broken halves, as shown in Figure 7(*c*). Figure 9(*a*) shows that during the five-month period, a receding movement of a negligible maximum 0.4mm between pillar A and B was recorded whereas a minute contraction of less than 0.05mm between the two broken halves of pillar H was detected, indicating an acceptable structural stability for the two near-opening pillars. However, the increasing rate of relative movement between pillar A and B during the first 1.5 months and the subsequent accidental propagation possibly caused by the same contact interface sliding effect may threaten the long-term global stability of the dolmen if these two factors are ignored.

Figure 9(*b*) presents the movement of the keystone E recorded by the laser sensor node. Frequent fluctuations were observed during the monitoring period but a generally slight rising tendency was manifest during the first two months, with a maximum of around 2.0mm which is still insignificant from the structural stability point of view. The absence of data from 25/01/2021 to 29/01/2021 was caused by the condensation accumulation on the laser protection glass interrupting the transmission of laser beam (relative humidity during this period remained near saturation 99.3%). This monitoring interruption indicates the challenges of laser sensing for long-term distance monitoring in a constantly highly-humid indoor environment but in turn demonstrates the ability of WSN system to visualise the encountered problems in real time. Subsequently, a generally stabilising development of keystone movement within 0.5~1.5mm was observed for the rest of the monitoring period.



(*a*) Crack development



(*b*) Keystone movement

Figure 9. Crack development and keystone movement

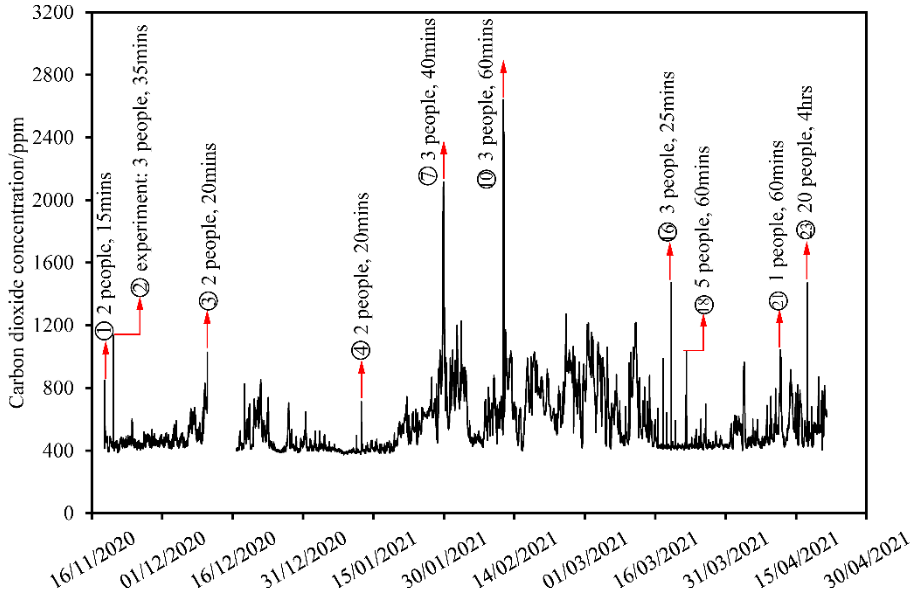
4.2 Cave environment

The visitation-caused alteration of microclimatic conditions, such as CO_2, temperature (T), relative humidity (RH), has been identified as a significant factor contributing to the deterioration of most large-scale heritage show caves (Bourges et al., 2020; Freire-Lista et al., 2014). However, no reported studies focused on investigating how visitation alters the interior environment of painted megalithic dolmens and how the alteration may deteriorate their prehistoric paintings. The following section presents the monitoring results of three typical environmental parameters under natural and visitation scenarios.

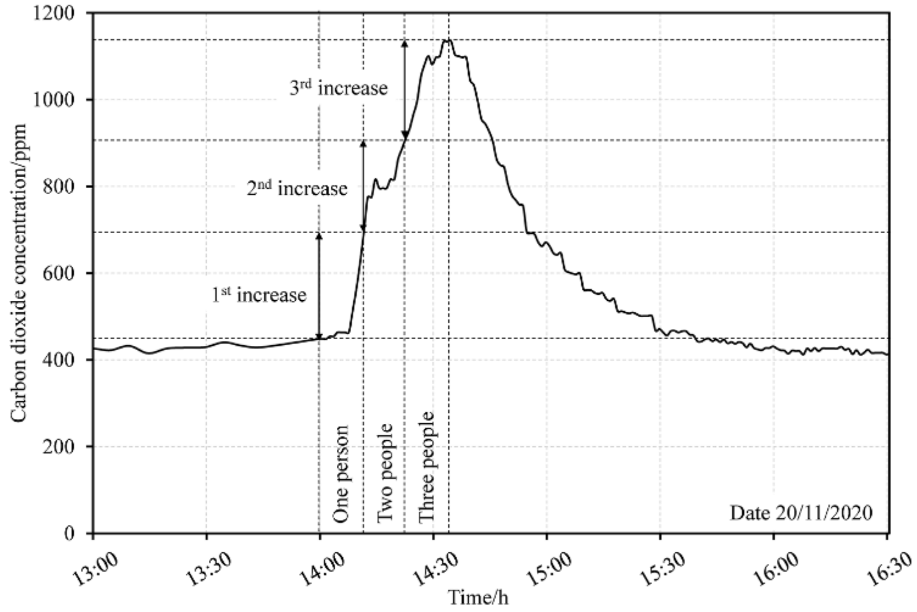
4.2.1 Carbon dioxide

Figure 10 gives the fluctuations of CO_2 concentration (CDC) inside the dolmen chamber during the five months. Several significant spikes associated with visitations were observed (see Table 2 and Figure 10(*a*)). The second CDC surge arises from the onsite experiment aiming to mimic the visitation effect. During the no-visitation period, the interior CDC level fluctuated mostly between 400ppm and 800ppm depending on the local climate, in consistency with but slightly higher than open-air CO_2 concentration of around 400ppm (Batog and Badura, 2013), whereas, during human interventions, the concentration level was observed with obvious increases, followed by gradual restoration to normal levels, in line with previous findings (Bourges et al., 2014; Dragovich and Grose, 1990; Saiz-Jimenez et al., 2011).

To take the second spike as an example, three phases of CDC increases were recorded during the three-stage experiment. The first visitor raised the interior CDC level from 440ppm to around 640ppm in the first 10 minutes, followed by another increase of 240ppm to 880ppm after the second visitor joined for another 10 minutes, and finally, a third person's presence for further 15 minutes prompted the CDC to a maximum of around 1,140ppm, as shown in Figure 10(*b*). Likewise, a spiralling surge of CDC level from around 500ppm to a maximum of around 2,600ppm was observed during the 10th visit for a duration of 60mins with the same number of people. For a maximum of three visitors, an increase of CDC to 1,140ppm during 35mins is less than the threshold considered damaging for heritage caves (2,400ppm) or visitor comfort (5,000ppm) (Dragovich and Grose, 1990) but a maximum of 2,600ppm within 60mins has exceeded the heritage conservation threshold (2,400ppm). This means that for one thing, a 160% increase of CDC level during the 2nd experiment indicates more visitors lead to higher level of CO_2 concentration; for another, a 420% increase in 60mins might deteriorate the wall paintings. The 700ppm increase of CDC level caused by the 2nd visit with three people in a short period of time poses a stark contrast to a similar increase of CDC for the gigantic "El Soplao" cave in Spain but caused by 1,654 visits in August 2014 (a daily average of 55 visits) alone (Novas et al., 2017), meaning that the management and conservation measures for big heritage show caves may not be directly applicable to this type of megalithic dolmen as the extremely confined interior space lack of ventilation makes it easier for CO_2 concentration. Additionally, according to spikes 2, 7 and 10, it suggests that longer duration of visitation may lead to more significant increase of CDC with the same number of visitors. However, it should be noted that this duration effect may not be accurate as it relies on various factors, such as how visitors behave in the chamber, where the sensor is deployed, etc. Also, the presence of visitors may not be the sole cause of CDC increase but is widely believed to be the major source based upon previous findings (Ming et al., 2008; Novas et al., 2017).



(*a*) CDC change with time



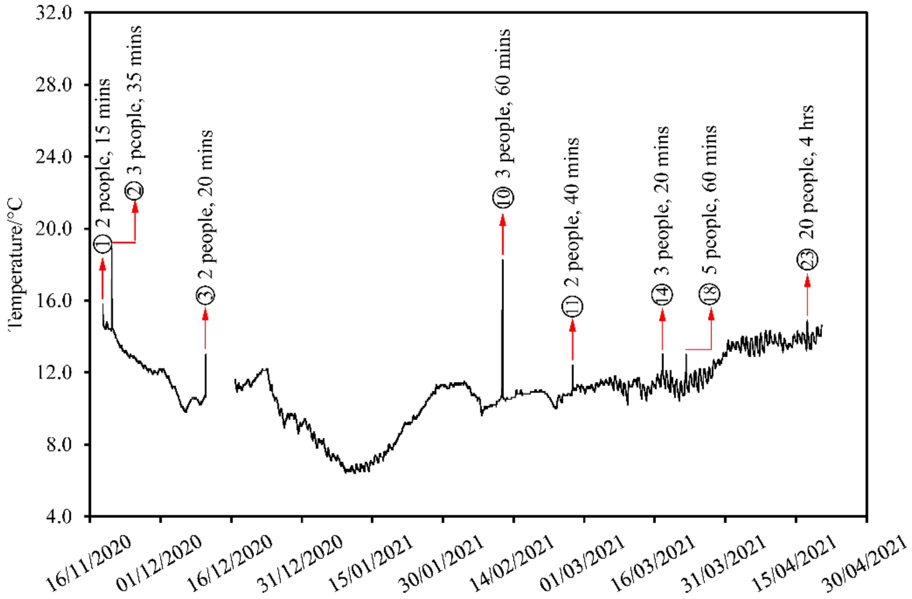
(*b*) CDC change during experiment

Figure 10. CO_2 concentration changes inside the dolmen (Note: the duration shown for visits after the 10th visitation is the total time spent on site instead of the time spent in the chamber.)

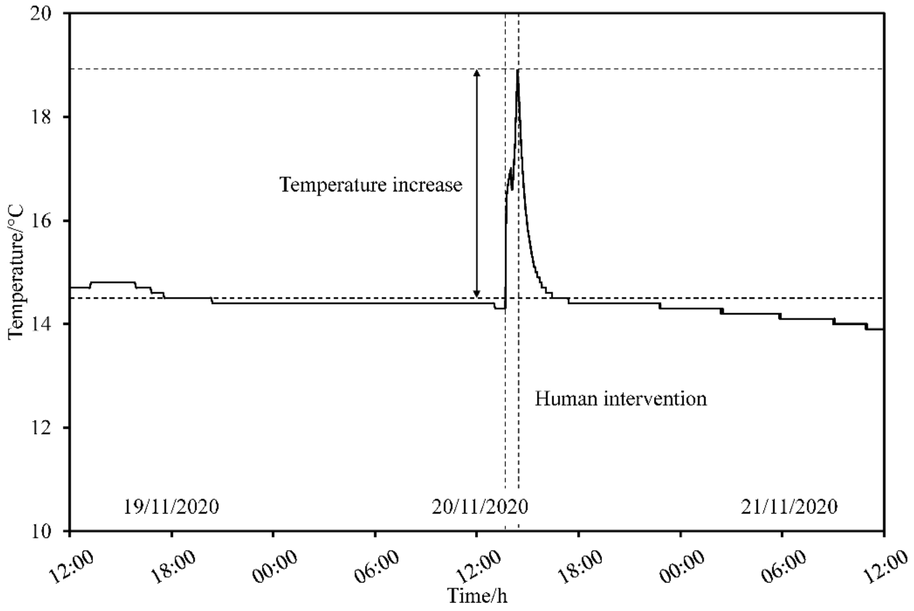
4.2.2 Temperature

Figure 11 presents the temperature changes during the monitoring period where several visitation-related major increases were also recorded. The temperature increases observed in **Figure** 11(*a*) exhibit an obvious effect of visitation on dolmen chamber temperature. The second temperature rise associated with visitation experiment reached a maximum of 18.9°C after the third person joined, increasing by 4.4°C up from a natural temperature of 14.5°C with no human presence, as presented in Figure 11(*b*).

The temperature spike caused by the 10th group visitation of three people for data retrieval witnessed an increase from around 11.2°C to 18.5°C by 7.3°C in a continuous period of 60 minutes. The 4.4°C and 7.3°C increase of temperature for the 2nd and 10th spike respectively strikes a remarkable contrast to a maximum variation of ±0.5°C in the 17-mile-long "El Soplao" cave during a six-year monitoring period (Novas et al., 2017). Unlike significant temperature increases caused by the 2nd and 10th visitation, relatively mild temperature increases were captured for other spikes caused by the 14th, 18th and 23rd visitation shown in Figure 11(*a*). This is because the latter three visitations (the 14th, 18th and 23rd visitation) were conducted in the form of individual visitation within a short period of time, such as 5 minutes, and the duration shown is the total time spent onsite instead of the time spent in the chamber.



(*a*) Temperature change with time



(*b*) Temperature change during experiment

Figure 11. Temperature changes inside the dolmen (Note: the duration shown for visits after the 10th visitation is the total time spent on site instead of the time spent in the chamber.)

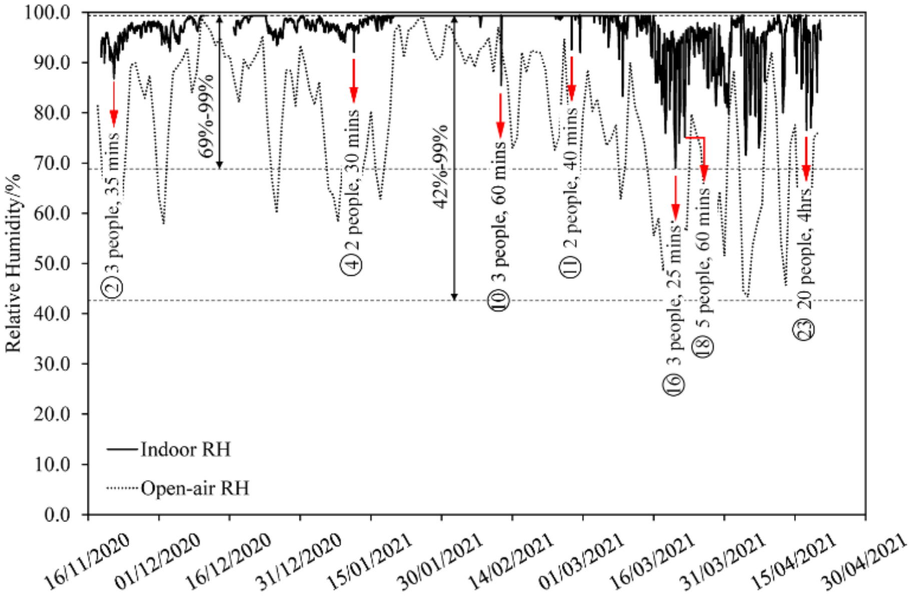
Therefore, it can be concluded that the presence of visitors may lead to a certain degree of temperature increase in this type of confined, small-sized dolmen, and the 2nd and 10th spikes manifest the correlation between the temperature fluctuation and the duration of visitation. Further work may be necessary to determine the optimum duration of visitors' stay so as to provide insights on managerial and conservational policy-making for such type of caves.

4.2.3 Relative humidity

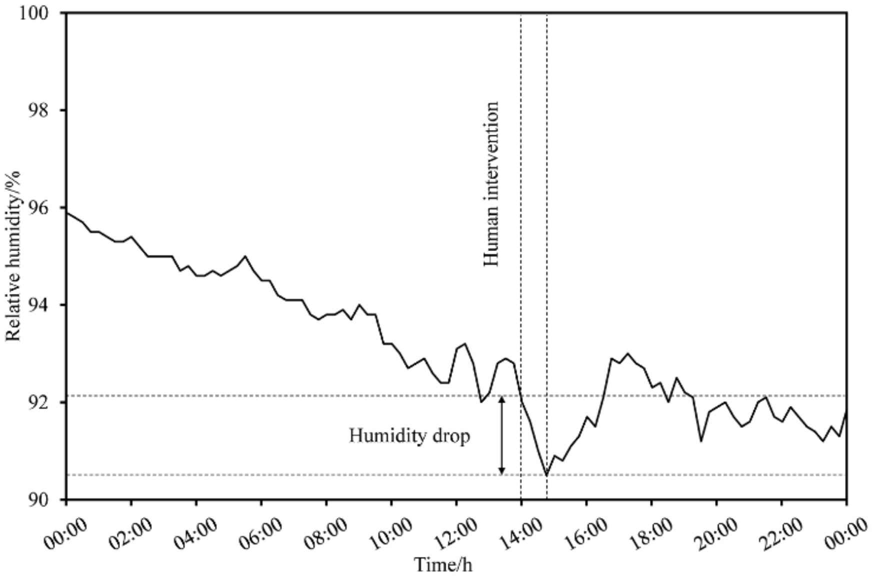
Figure 12 shows the RH variations with time. Due to the lack of ventilation in the cave chamber, the interior humidity mostly maintained within 90%~100%, with significant fluctuations in the last 1.5 months of the monitoring period from around 69% to 99%. This is because in the first 3.5 months, the local rainy season in winter contributed to the high relative humidity whereas in the last 1.5 months, an increasingly warmer and dryer weather led to significant reduction of RH during the day. Upon comparison, the open-air RH lies within 42%~99% based on the data from the nearest meteorological station, indicating a comparatively lower level of RH outside the dolmen, as shown in Figure 12(*a*).

To explore the visitation effect on relative humidity, the RH variation during the second experimental visit and the 10th visit for data retrieval was specifically analysed. Unlike an increase in T and CDC, a slight 2% reduction and a significant 14% reduction in RH, were recorded during the 2nd and 10th intervention, respectively, as shown in Figure 12(*b*). The RH drop possibly arises from the dominating natural ventilation effect, which features the airflow exchange between the highly-humid interior and the moderately-humid outside due to the state of an open dolmen gate during visitation (Rosbach et al., 2013; Teleszewski and Gładyszewska-Fiedoruk, 2020). The difference in magnitude of drop is likely to be caused by the duration of the ventilation effect, which means longer duration of ventilation may lead to longer duration of airflow exchange, thus bigger reduction in RH, in such type of confined underground caves. Similarly, the reduction of RH during the 16th, 18th and 23rd visitations could possibly be attributed to this cause as well.

The extremely humid interior, together with the cyclic RH variation in warmer seasons (low RH during the day but high RH during the night), may accelerate/contribute to painting deterioration due to the possible RH-caused microstructural changes of painting materials, the growth of microorganisms on painting colorants (Issa et al., 2020) and the potential coupled geochemical/biochemical effect (Iriarte et al., 2009; Unković et al., 2017).



(*a*) RH change with time



(*b*) RH change during experiment

Figure 12. Relative humidity changes during the period (Note: the duration shown for visits after the 10th visitation is the total time spent on site instead of the time spent in the chamber.)

4.3 Discussion and recommendations

4.3.1 Discussion

A real-time WSN monitoring system was deployed inside the Dólmen de Antelas to assess both its structural and environmental performance with time, which has been barely reported in such confined megalithic monument.

Structurally, the WSN monitoring suggests that the dolmen structure generally remained stable during the five-month period as no significant interventions occurred onsite. However, the relatively high rate of inclination and crack development for pillar A, together with its accidental instability possibly caused by the pillar contact interface sliding, should be given prioritised attention, as these two factors may exert detrimental impact to the dolmen structural stability if not appropriately addressed. The accidental disturbance on pillar A and the condensation-caused interruption to pillar E monitoring showcased an advantage of a real-time WSN monitoring scheme enabling synchronous visualisation of encountered problems but also a limitation in deploying laser sensor in highly-humid environment, which offers a potential solution to some restoration/conservation-related stability issues for other unearthed megalithic dolmens. Based on the 5-month monitoring, it is recommended to proceed with the current structural monitoring into a longer period so that the dolmen's long-term stability can be assessed and understood before the monument will be officially open to the public.

Environmentally, the dolmen interior microclimate remained stable with no visitations while remarkable variations of typical environmental parameters were detected during visitors' presence. This visitation effect is of significant concern to preservers and conservationists as the alteration of the three representative parameters (CO_2, RH, T) has been identified as a major cause to the deterioration of most large painted tourist caves (Zucconi et al., 2012), with the Spanish Altamira Cave (Jurado et al., 2009) and the French Lascaux Cave (Dupont et al., 2007) being two prominent examples. For this particular confined painted dolmen, the possible mechanism of visitation-induced painting deterioration could be elucidated from the following two aspects:

- For one thing, the near-saturation humid dolmen interior, together with other visitor-contributed environmental variations including light exposure, CDC alteration, temperature increase and organic/inorganic substance dispersion, provides a favourable environment for the continuous growth and colonisation expansion of a live pink fungi group. Such live pink fungi group has an extensive existence on all dolmen pillars of this confined dolmen (Figure 5(*a*)), which in the long term may mask, discolour and/or degrade the surface paintings as a consequence of their metabolic activities (Sánchez-Moral et al., 1999; Zucconi et al., 2012).
- For the other, the wetting-drying cyclic process on pillar surface and painting layers, that is, the high humidity-related condensation in cold season and temperature increase-linked vaporisation in warm season, may be an important contributor to the further initiation and propagation of the cracked pictorial base layer. This may lead to possible structural change of the base and thus destabilise the painting pigment layer (Antonio et al., 2019), even though the mineralogical properties of both the red ochre hematite pictorial layer (Figure 5(*d*)) and black charcoal pictorial layer (Figure 5(*e*)) normally remain relatively stable in changing environmental conditions (Coccato et al., 2017; Wang and Hellman, 2018).

To gain an in-depth understanding of the microclimatic conditions alteration effect on these rock-art paintings deterioration, more quantitative research from a micro perspective should be carried out.

4.3.2 Recommendations

To preserve and conserve the megalithic heritage dolmen, some recommendations based on the findings from this and previous studies are provided as follows for the reference of local heritage conservation & preservation authorities and beyond:

Structural robustness

The field measurements indicate a possible tendency of the four selected pillars moving away from their supporting pillars and inwards the chamber, together with the relatively fast development of inclination and movement of the near-opening pillar A, which causes concern over long-term structural stability. Therefore, some structural reinforcement measures may be taken to enhance the structural robustness of this self-supporting cave. For example:

(1) As this dolmen was constructed in an imbricated style, the stability between two adjoining pillars mainly relies on the balance of contact forces. Therefore, tinted hydraulic lime may be adopted to enhance the surface resistance between two adjacent pillars, enabling effective contact forces transfer at lower risk of compression failure (see Figure 13(*a*)) (Martínez-Torres, 2014).

(2) Pillar A still remains the most unstable element of the whole structure. It would be beneficial to reinforce this critical pillar by either strengthening the existing steel rod or adding steel braces/rods between the pillars to prevent shear movement-caused instability, as illustrated in Figure 13(*a*). These structural reinforcement measures will enhance the dolmen structural robustness and mitigate the risk of cascading failure in the event of both manmade and natural hazards.

Environmental resilience

Unlike a large show cave where the visitation-caused microclimatic condition alteration remains mild, the CDC level, temperature and humidity inside this confined dolmen chamber can experience significant variations in a short period of time with a small number of visitors, as concluded from the experiment. To restore a permissible level of CDC for the sake of mural and coloured sculpture preservation, a mechanical ventilation system was deployed in a small cave (with an area of around 35m^2) of UNESCO World Heritage Mogao Grottoes. It was proved that this mechanical system increased the air exchange rate effectively without causing noticeable air disturbance and shortened the restoration time of such environmental parameter significantly, when compared to natural ventilation

(Wang et al., 2016).

Therefore, such a mechanical ventilation system may also be adopted for the preservation of the rock paintings in this confined dolmen. The deployment of this system will provoke fast dispersion of CO_2 concentration caused by visitors, bring down the high humidity and maintain a steady temperature inside the cave chamber, even during frequent visitations. Figure 13(*b*) shows a possible solution to maintain acceptable level of microclimatic conditions (the mechanical system can only be deployed at the back of accessible pillars A and H), which aims to enhance the environmental/microclimatic resilience for the sustainable valorisation and development of this underground heritage.

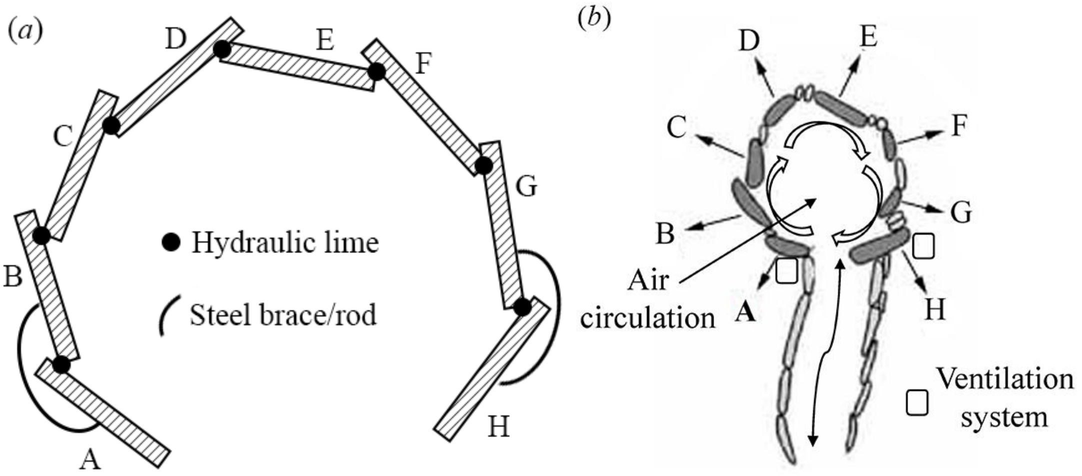


Figure 13. Dolmen conservation (a) structural reinforcement (b) mechanical ventilation

5 Conclusions

Different from extensive previous efforts on investigating the microclimatic performance of those large and renowned touristic caves, this paper investigated the less commonly examined structural behaviour and visitation-related microclimate performance of a confined prehistoric dolmen with megalithic significance using a real-time Wireless Sensor Network monitoring system. The main conclusions of this study are drawn as follows:

(1) The real-time inclination monitoring shows that pillars were tilting inward radially and moving outward tangentially at a slow rate during the first 1-1.5 months, followed by subsequent stabilisation, suggesting a general structural stability of the dolmen structure within a short 5-month period and probably beyond.

However, a higher rate of inclination development and an accidental instability occurred at the steel rod-supported pillar A probably caused by pillar contact interface sliding. Such local instability occurred accidentally with little pre-warning signs even from the real-time WSN data. In the event of a worse scenario, local instability may trigger cascading failures and undermine the global stability of the dolmen in the long run. In practice, such risk can be mitigated by structural reinforcement such as 1) the tinted hydraulic lime to enhance contact surface resistance between pillars and 2) the steel brace/rod to prevent shear movement between pillars.

(2) Among all the dolmen structural members, the two near-opening pillars were considered to be the most structurally critical. According to the real-time WSN field data, pillar H near the opening was observed with slight crack contraction due to the self-weight of its upper half, whereas pillar A experienced progressive movement away from its supporting pillar, with an accidental instability before reaching stabilisation, the same as that recorded by inclinometers.

Additionally, the real-time WSN monitoring scheme also enables synchronous data visualisation, clearly indicating some fluctuation and an interruption in the laser sensor reading. Such data noise / error is likely due to condensation inside the cave, suggesting the limited capability of laser sensors for distance measurement inside highly humid confined environment.

(3) The chamber internal environmental conditions varied remarkably during visitations while remained largely stable with no presence of visitants. In particular, CO_2 concentration (CDC) was found with spiralling growth due to increasing number of visitors and duration of visitation. Such combined headcount and duration effect may contribute to the deterioration of paintings in this confined dolmen if the CDC level rises up beyond a commonly-believed threshold of heritage conservation (e.g. 2,400ppm). Moreover, the significant increase of CDC by 1~3 people in this small dolmen within a short period strikes a huge difference to the CO_2 alteration in large show caves reported by previous studies, highlighting the challenges of CDC control in managerial and conservational practices of such caves to confined megalithic dolmens.

(4) Similar combined headcount and duration effect was also observed in the temperature and relative humidity monitoring inside the dolmen chamber, with longer duration of more visitors' stay leading to bigger increase in temperature but reduction in relative humidity. The humidity decrease was

caused by the ventilation effect of airflow exchange between the high-humidity interior and medium-humidity outside. The near-saturation humidity level (mostly between 90%-100%), together with the frequent alteration of other visitor-contributed environmental parameters (e.g. CDC, light exposure, etc.), may deteriorate the prehistoric remain possibly by 1) either masking/decolouring the paintings with the continuous growth and colonisation expansion of the widely-existing pink fungi; or 2) destabilising the microstructure of the cracked pictorial base layer under the cyclic wetting/cold-drying/warm process.

To this end, a mechanical ventilation system can be adopted to restore the environmental conditions inside this cave at an allowable level quickly during frequent visitations. The steady cave environmental condition (e.g. CDC, humidity and temperature) maintained by the ventilation system will reduce the risk of continuous deterioration of rock paintings, thus enhancing the environmental/microclimatic resilience for the sustainable valorisation and development of this underground heritage.

Ideally, the WSN dolmen monitoring is expected to last over a number of years for greater insights into long-term cave condition assessment subject to seasonal change, global warming and etc. In practice, however, this WSN system had to be dismounted in April 2021 due to subsequent project management and financial limitations.

CRediT authorship contribution statement

Chao Wang: Conceptualisation, Methodology, Formal analysis, Investigation, Writing – Original Draft. **Alice Tavares**: Supervision, Project administration, Writing – Review & Editing. **Jorge Fonseca**: Investigation. **Filipe Soares**: Resources, Project administration. **Zili Li**: Supervision, Project administration, Funding acquisition, Writing – Review & Editing,

Declaration of Competing Interest

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

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