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Thermal imaging assessment of drystone retaining walls

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ABSTRACT Drystone retaining walls form an essential part of the infrastructure in hilly and mountainous regions around the world, by providing platforms for roads, buildings, and for agricultural terraces. Research carried out in England and in France has led to a good understanding of their behaviour, but it is difficult to determine the details of the construction of individual walls without dismantling them - so it can be hard to tell if apparent defects and deformations are a threat to stability. Replacing every apparently defective or deformed wall would be a waste of resources, yet dismantling a wall would obviously be completely disruptive to its function. Invasive investigation, such as drilling, could easily cause damage to the wall structure and destabilise the wall. There is therefore a pressing need for non-intrusive methods of investigation that can reveal critical aspects of a wall's construction. Thermal imaging can reveal important information about aspects of a wall’s construction that are critical to its stability. This paper presents case studies and numerical modelling that have contributed to the development of this technique, and demonstrate its potential.

1 INTRODUCTION

Drystone construction has been used for the construction of retaining walls since ancient times. The stones usually come from close to the construction site, and are of a size that can be moved by hand - although some cultures, most notably in South America, have used very large stones (e.g. Inca construction in Machu Picchu, Peru). Because drystone walls use local materials and no form of mortar, they are a very low-energy and sustainable form of construction, and blend well in their landscapes. Indeed, in many hilly and mountainous areas, the drystone walls are an important part of the landscape. Through discussion with experienced members of well-regarded walling associations in both the UK and France, it has been found that the stability of drystone walls is dependent on the quality of the stone used and on the skill and knowledge of the builder, with the best wallers discarding stones that are weak or fissured. The quality of stone and good construction practices determines the wall’s ability to transmit the wall loading forces between individual stones, and through to the foundation. The average stress carried by a stone is likely to be insignificant in comparison to those which consolidated the stone in its original geological setting. However within the wall construction the loads are transmitted through small points of contact due to the rough nature of the surfaces (Walker & Dickens, 1995), which may result in localised high stresses. The stones may also be subject to some bending stresses if they are not adequately supported.

It can be difficult to assess the durability of the stones forming a drystone wall. Stones exposed on the face of a wall may not weather and deteriorate at the same rate as stones hidden behind the wall face; for example Cotswold wallers regularly reported to the authors that on the dismantling of the limestone walls found in this area they would expect up to 40% of the walling material to have to be replaced. Wind and rain will mechanically weather stones at the wall face at a greater rate than hidden stones and will tend to remove any weakened material within the wall. However, this process may not be obvious during wall stability assessment. Wetting, drying, and biological weathering can lead to the progressive deterioration of the strength of some stone types that might be used for drystone retaining walls, and this deterioration may be happening out of sight within the body of the wall, as well as at the face where the weathering products will be removed rather than accumulating.

(a) (b)

Figure 1. (a) Front and (b) back faces of an experimental wall constructed in Le Pont-de-Montvert in the Cevennes, France, reflecting normal good practice for construction in granite.

The quality of the stone used in wall construction is relatively easy to ascertain from visual inspection but the quality of the wall construction can be concealed behind the wall face. One waller reported being asked to replace a wall that on completion had appeared to be of high quality, but had soon collapsed; it was found that instead of well packed stone fill, shingle had been used which was unable to transfer loading between the faces (personal report). A carefully made stack of blocks will resist earth pressures, but the great strength of drystone walls is their ability to tolerate uneven and variable loading and support. This is achieved by redistributing load within their construction via good overlaps between carefully laid stones (McCombie et al, 2013 & 2015). Because of the retaining function, the vertical load near the front of the wall is greater than that at the back, and this combined with the fact that the front face is what is seen by the client leads to the construction of the face often differing significantly from that at the back. This can be seen in the experimental granite wall shown in Figure 1. The wall shown was extremely strong and stable, despite the difference in appearance between the two faces. The builders of this wall rank among the best in the world, and the quality of the construction was very high (Colas 2009).

Further experimental walls constructed on the same site showed that when the builders were asked to construct with less regard to the appearance of the face (*paysan* style), the overall density of the construction was identical to that of an equivalent 'engineer style' wall which had excellent visual appearance but took twice as long to build. In this case, the construction style adopted for an engineering client was no more sound than what would be built for any client - it just looked ‘tidier’, and cost more to construct.

The assessment of existing drystone retaining walls is therefore far from simple because the construction hidden behind the face of the wall is critical to their overall stability. The thickness of the fill placed behind the wall and the width of the wall near its crest could be ascertained with a small excavation, if possible. However, to obtain further information about the wall construction would require the wall to be dismantled, which would defeat the object of making an assessment.

2 INVESTIGATION REQUIREMENTS

Key features to identify in drystone wall stability assessment include:

- the wall porosity - the gaps between the stones must be clear for the wall to maintain its free-draining nature, and so preclude the development of positive pore water pressures;
- the dimensions of the wall and the individual stone dimensions;
- the condition of the stone within the wall;
- the degree of bonding between stones and the use of through-stones.

The wall porosity can be investigated comparatively easily, assuming safe access to the wall face is possible, because gaps between stones are usually sufficient to allow visual inspection and probing with wires. The use of an endoscope might also assist, but the authors have not investigated this. Sometimes a careful visual inspection has revealed that the builders used mortar within the wall, whilst presenting the outward appearance of drystone wall construction (O'Reilly & Perry 2009).. This has been found at a number of locations in the Cotswolds, where the visual appearance of the walls has an important impact, and the authors have been able to discuss the practice with builders; the mortar is usually used only in patches, and has not obstructed the permeability of the walls, and the motivation for doing so is to increase the speed of construction whilst reducing the level of skill required.

Determining the dimensions of a wall can be difficult, as normally neither the founding level nor the back of the structure can be accessed without risking damage to the structure itself, and perhaps to the inspector. If the visual inspection described above is possible, it can allow measurements of the minimum thickness of the wall, but this can be difficult if rubble from the wall construction has been used as backfill immediately behind the wall. The condition of the stone at the wall surface might be assessed during the visual inspection, but it can be difficult to identify any deterioration of stones within the wall.

The final requirement will be the concern of the remainder of this paper. A common form of wall construction in the United Kingdom, where drystone is used predominantly for field walls, is to have well-defined front and back faces to the wall, with rubble filling the space in between (DSWA, 1999). For a wall to resist earth pressures, it is crucial that the front and back faces are tied together, so that the wall cannot be overturned without the wall behaving essentially as a monolith (Figure 2). If the front and back faces can act independently, with the rubble between just rearranging itself a little, then the resistance is very much reduced. In this form of construction, through-stones are used, spanning the full thickness of the structure to tie the two faces together. It is also important that the rubble fill is made of, tightly packed pieces of strong stone which can be locked together by the through-stones. Therefore where this fill has been constructed properly and no deterioration has occurred, it will be almost impossible to see through to the back face of the wall.

In the mountainous regions of southern France, drystone construction has been used principally to form earth-retaining structures and revetments. In this region, through-stones do not have quite the same importance as in the UK because good construction practice ensures that there is good bonding between the stones stones (CAPEB et al., 2008). That is, stones overlap with those above and below and to either side, throughout the thickness of the construction, with deliberate intent to fulfil the role played by through-stones, which will also be used if suitably large stones are available. Each stone rests on two or more stones beneath, so making it difficult for them to be moved apart. This in effect produces a directional tensile strength within the structure (McCombie et al, 2012) which extends from front to back, as well as along the length of the wall. In the two-faced construction style (e.g. in the UK), tensile connection between front and back of the wall only exists where there are through-stones.

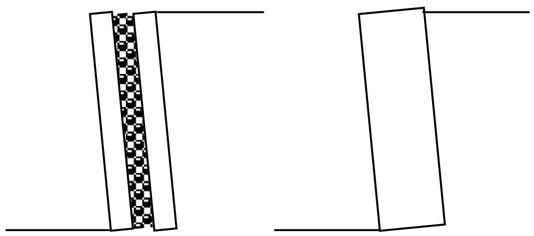


Figure 2. Poor bonding between the front and back face of the wall allows them to act independently, reducing the wall stability (left). Good bonding allows a wall to behave monolithically and better resist overturning forces (right).

It is essential to determine the quality of the connection between the front face and back face of the wall during drystone retaining wall assessment. The presence of large voids or loose material between the two faces will cause the earth pressure behind the wall to be resisted by the back wall face only, without support from the front face of the wall. This effect has been seen in some partial wall failures in the Cotswolds, where patches of the front face fall away, leaving the rest of the wall standing (but often not for very long).

3 THERMAL INVESTIGATIONS

The frequency and firmness of connections between the back of the wall and the front face of the wall help to determine its capacity to conduct heat in response to temperature changes at the wall surface. The earth retained by the wall changes temperature much more slowly than the surface of the soil or the stone at the face of the wall, and will probably not show a detectable change over a 24 hour period. On the other hand, the stone at the wall face is exposed to the weather - wind, rain, and heat from the sun. The degree of this exposure is in turn dependent upon the wall's location and orientation. Even with none of these weather effects, the stone at the face will lose heat to the air, or gain heat from the air, through conduction.

The temperature of the stone at the face of the wall reflects atmospheric processes on the wall, but is also affected by the flow of heat within and between the stones, driven by internal wall temperature gradients. Hence stones that have better thermal contact with the rear of the wall, such as through stones, would be expected to show a difference in temperature to those surrounding them. These temperature differences may not be obvious to the touch, but by using a thermal imaging camera which has a high sensitivity they can be detected, so revealing aspects of the hidden construction of the wall. In this way the temperature effects of other features such as water build up or voiding behind the wall may also been seen. Thermal imaging has one particular advantage over other methods of investigation - it can be undertaken at a distance, without requiring any physical contact with the wall. This can be important, for example if the stability of the wall is in question, or if there is a road or other hazard immediately in front of it.

Thermal imaging cameras do not measure temperature directly – this would require the wavelength of the infrared light to be determined. Rather, they rely on an assumption of high emissivity in the object being examined, and then infer temperature from the amount of infrared radiation being emitted. Therefore the intensity or colour in the image does not necessarily indicate temperature, even though it is shown against a temperature scale (FLIR 2011). This can produce misleading results in a wall made up of different types of stone – for example, the emissivity coefficient (ε) of granite is relatively low, half that of limestone, while the value for sandstone lies in between. This means that attention must be given to variations in stone type. Typical values for some relevant materials are given in Table 1; a value of around 0.9 is very commonly found, and is usually assumed in thermal imaging systems.

Table 1 Thermal emissivity of typical wall construction materials (ASHRAE, 2009)

Material type	Total Hemispherical Emissivity
Brick	0.9
Concrete, rough	0.91
Granite	0.44
Limestone	0.92
Sandstone, red	0.59

3.1 First trial of thermal imaging

In order to explore this approach thermal imaging was used to investigate a number of walls in the UK and in France. This work was carried out at varying times of the day and on a number of walling types in order to assess the range of construction types for which the technique might work, and to determine if there are optimum conditions for its use.

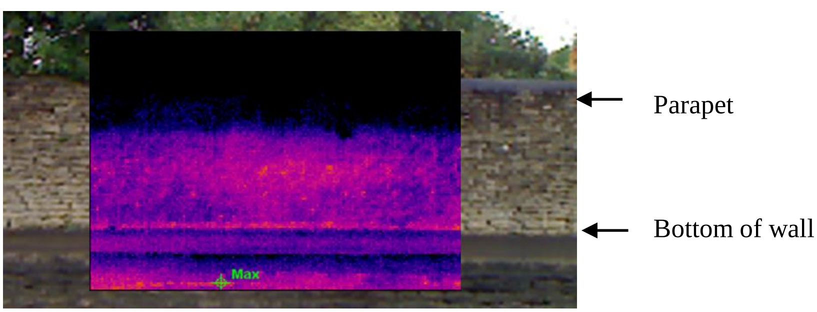


Figure 3. Thermal image of a limestone wall in Wiltshire, UK, overlaid on the visible light image.

The first trial image is shown in Figure 3, superimposed on the visible light image. This image was taken at around 8 a.m. on a winter morning, following a cold night. A number of features can be seen. The wall retains about 1m of fill, and is at the back of a footpath which is itself supported on a small wall of five courses alongside the road. The wall carries a parapet, which shows dark on the thermal image because it is the same temperature as the air. On the other hand, the retaining wall beneath it shows lighter because it is warmer, even after the cold night. Part of this wall has been repaired following a failure; the repaired area shows warmer than the adjacent wall, presumably because the fill within the wall has been packed carefully and so has conducted heat from the backfill more effectively. The darker areas below the repair probably indicate parts of the wall which were loose but were not involved in the failure. At the right hand edge of the thermal image is another brighter area which was presumably built well enough to begin with so that it has remained sound. Within the repaired area are a small number of regularly spaced hot spots, which almost certainly correspond to through-stones. Some of these interpretations can be confirmed to an extent by listening to the sound on hitting the wall with a hammer, but this is to be done only with appropriate caution, and is not an approach which this paper addresses.

3.2 24 hour study of wall temperature imaging

A 24 hour study was subsequently carried out in June 2013 of a limestone wall near Northleach in the Cotswolds, UK. Images were taken at regular intervals, to identify the optimum time to take thermal images and identify wall features.

The wall is over 200m long and has many sections of varying construction, some in poor condition. One length was rebuilt in 2011, with unusually large through-stones and soil-reinforcement in the backfill connected to the wall using galvanised steel bars. The authors visited the wall in 2011 during the reconstruction process the design and construction is also well documented by the parties involved, making it a good test for this method, The wall is south facing and is exposed to the sun throughout the day. Four other sections of the wall were also imaged in conjunction with this section.

Some specific points were identified regarding the use of thermal imaging for this type of investigation; these are explained below, and illustrated using Figures 4-6. Within the new wall section the through-stones were easy to see using the thermal imaging camera, as shown in Figure 4. This image was taken in the late evening (10pm) when the air had cooled down after a warm day. The through-stones in this section were visible using the thermal imaging throughout the 24 hours, but became less prominent when direct sunlight first came onto the wall in the morning (8am readings); the through-stones appeared cooler than the rest of the wall in most of the images taken. The changes in temperature over the 24 hours of observations are also shown (figure 4c); the most significant differences are seen early in the morning when the wall face has cooled overnight, and then late morning when the smaller stones have heated up, but the through stones have not. Both these differences must be influenced by the size of the stone as well as its connection with the retained soil, but connection is more likely to be important at the end of the night when temperatures are changing slowly.

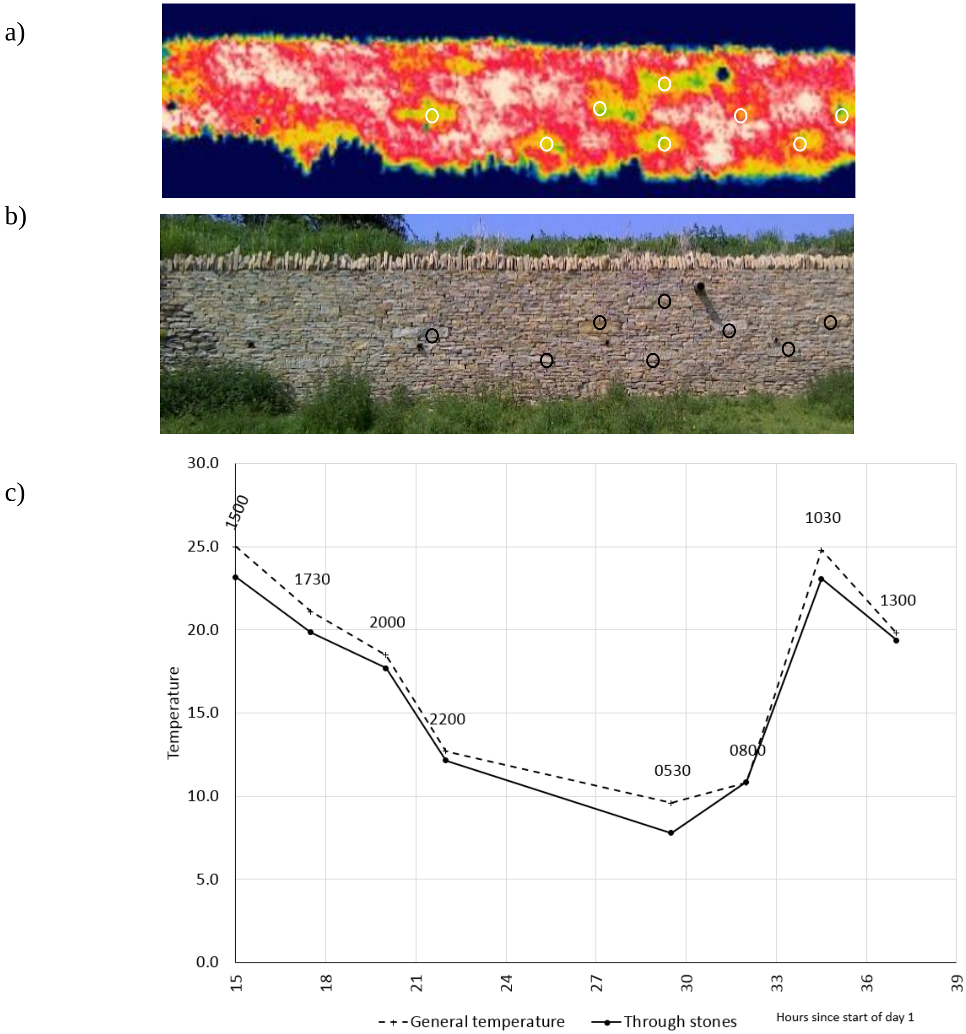


Figure 4: Thermal image of new wall section at Northleach, UK. a) Thermal image: some of the most conspicuous through-stones have been marked with circles; b) visible light image; c) temperature variations over 24 hours.

Other potential features appeared in the thermal images of the older sections of wall; for example, an area of wall which may be affected by water appears cooler in Figure 5. This area was not obvious at the face of the wall but the presence of vegetation is indicative of the presence of moisture. This feature was only visible in the late evening and early morning when the wall was cooler.

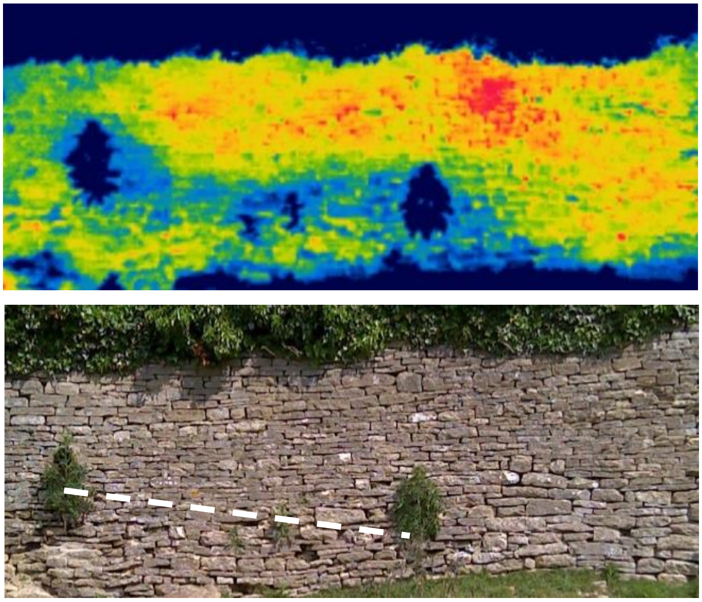


Figure 5: Thermal image of older wall section at Northleach, UK, showing a potential area of water (along the dashed line)

The influence of shading can affect the thermal images, as shown in Figure 6. Part of the wall is shaded by a large tree, and where this shading occurred very little thermal information could be gathered in comparison to the unshaded adjacent areas. This effect was still present once direct sunlight was no longer present on the wall.

Figure 6: Thermal image showing the effect of shading.

3.3 French Study

Following the work at Northleach a 3 day field study was carried out in the Cévennes area of France. This presented the opportunity to use thermal imaging on walls constructed using larger stones than are typically found within the UK. The varied construction style of drystone walls across the Cévennes area of France reflects the varied geology and available stone in each local area. Therefore the thermal imaging technique was trialled for a variety of different construction styles. This investigation was aided considerably by the guidance of those who had built some of the walls being investigated, as they could give great detail on the construction principles, and provide comments on the thermal images.

The thermal images were used to visualise the connectivity of stones within the French walls of differing construction style and wall stone material. In the English Cotswold walls, the through-stones were sometimes obvious due to their larger size. In the French construction more emphasis is placed on good bonding throughout the wall, including from front to back, and through-stones are not always used. It became clear that one cannot assume that large stones are through-stones. In the granite wall shown in Figure 7, for example, there are a number of stones that at the wall face appear to be very similar, and so might be expected to show a similar temperature. However this is not the case, implying that they extend to different depths within the wall face itself, or that some of these stones taper whereas others are blockier in shape, so making different contributions to the stability of the wall. There is a possibility that the indicated temperatures are affected by differing emissivities between the stones in each pair; however, the stones to the left of the photograph have a quite varied appearance, but do not show corresponding differences in temperature. Whilst variations in emissivity could potentially confuse results, it might be expected that in any wall face using a mixture of stone types there will be enough areas of generally uniform temperature to indicate whether or not this is a problem. The converse of this was also seen, both in this wall and in other walls, with the thermal imaging indicating that some stones which appeared small at the wall face must extend much deeper into the wall than expected.

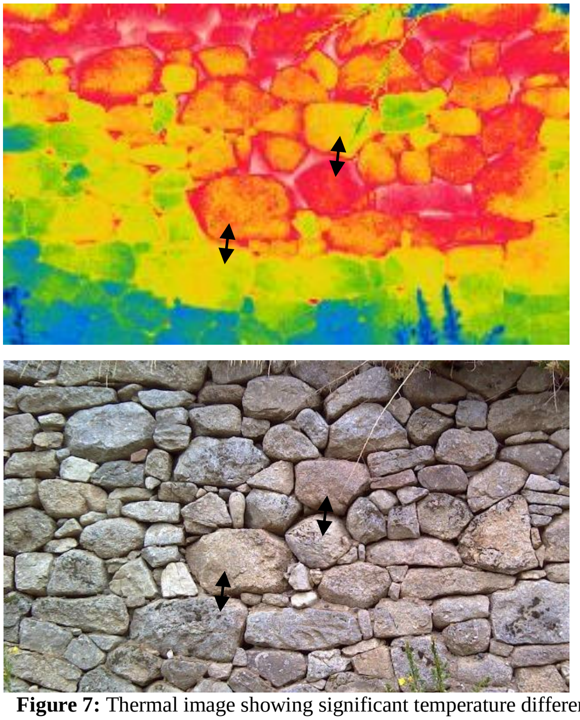


Figure 7: Thermal image showing significant temperature differences between stones that initially appear to be of similar size - indicated by arrows (Lotissement Plaisance, Le Pont-de-Montvert, France.

4 THERMAL MODELLING

The cases presented have shown that thermal imaging can identify important characteristics affecting drystone retaining wall stability. Thermal modelling was used to obtain insights into the underlying thermal behaviour of drystone walls. One-dimensional simulations were performed using the thermal simulation program WUFI (Künzel, 1995). WUFI was used to model heat transport by thermal conduction, short-wave solar radiation, and night-time long-wave radiation cooling. WUFI imposes a constantly changing boundary condition on the face of the wall, accounting for heating from the sun, heating or cooling by conduction into air moving at the correct speed, heat loss through evaporation, cooling (or warming) by rain, and cooling through radiation.

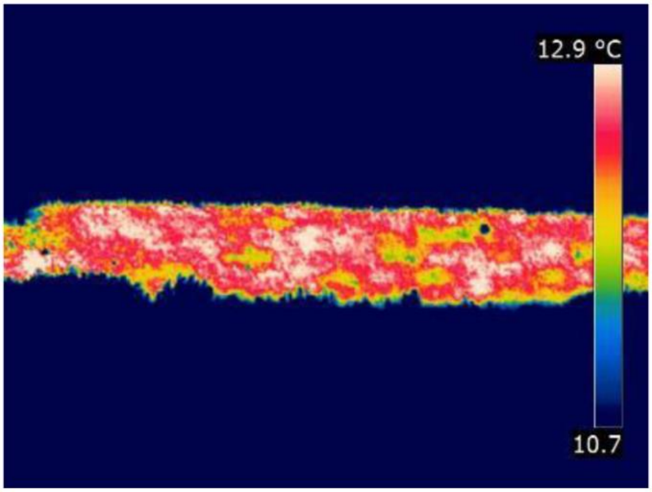
Simulations were carried out for different stone arrangements across the width of walls corresponding to those found in the investigations in the U.K. and in France. The wall face temperature was predicted at regular time intervals for a variety of weather conditions, allowing the effects of different arrangements to be examined so that consequent temperature differences could be predicted. Ten different wall construction cases were examined, summarised in Table 2, with two sub-cases in many, making fifteen cases altogether. The wall construction was in all cases 1.2m thick. All cases used limestone thermal material properties available within WUFI. The fill boundary condition at the rear of the wall was set at a constant temperature of 10^{o}C. The weather file used for the simulation was taken from actual recordings for Brize Norton airfield in the Cotswolds in the UK, for 2013 (http://weather.whiteboxtechnologies.com). Each simulation was run for three years using this file for each year; 75 separate days were examined from the final year of each run, to be during and after periods of high temperatures, low temperatures, large and small variations between day and night time temperatures, and when air temperatures were close to the 10^{o}C of the backfill.

Table 2 Wall construction cases for the thermal modelling simulations

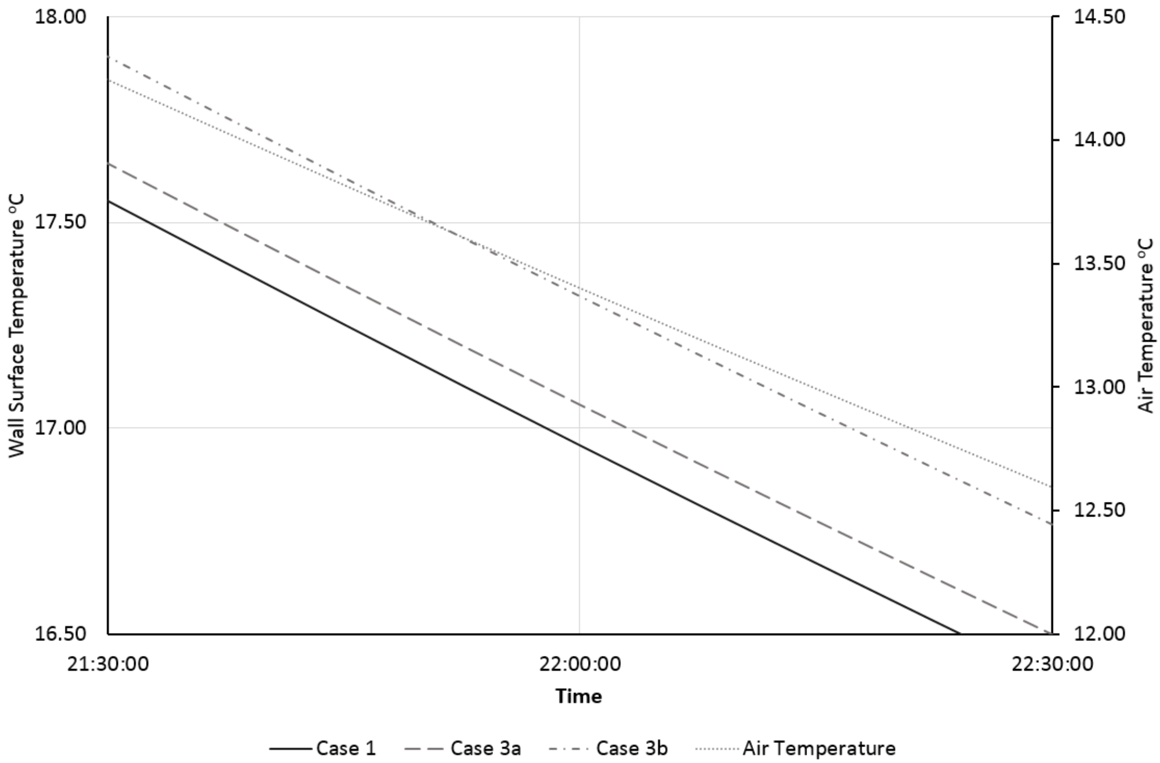
Case	*Description*
1	U.K. style construction, through stone
2	U.K. style construction, front and back faces with fill in between, no gaps
3	U.K. style construction, front and back faces with fill in between, a) 5mm gaps b) 20 mm gaps
4	French style, sequence of large stones from front to back, no gaps
5	French style, sequence of large stones from front to back, a) 5mm gaps b) 20 mm gaps
6	French style, sequence of large stones from front to back no gaps
7	French style, sequence of large stones from front to back, a) 5mm gaps b) 20 mm gaps
8	French style, two lapped stones acting as a tie between front and back, no gaps
9	French style, two lapped stones acting as a tie between front and back, a) 5mm gaps b) 20 mm gaps
10	Through stone, gap between stone and back fill, a)0.2m b)0.4m

The daily variation of face temperature was plotted for 75 separate days, for each of North, South, East and West facing walls. However, it was found that cases 2,4, 6 and 8 produced very similar results to case 1, the through stone, due to conductive thermal contact between the stones, so these cases were not included in the concluding analysis.

It was found that though North facing walls showed the most uniformity throughout a day, there were particular times of day that showed the clearest distinctions between the different wall construction cases, regardless of orientation. These were during the early morning, before any direct sunlight was on the wall; around solar noon, when direct sunlight has been on the wall for a number of hours; and late evening, once direct sunlight is no longer on the wall. From the very large volume of data generated, one example is presented in Figure 8 to demonstrate the results. A thermal image of the main section of wall at Northleach is shown in Figure 8a, while the model results for typical UK construction styles for the same time are shown in Figure 8b. The model shows the through stones (case 1) to be the coolest, at about 0.5° cooler than the other stones. It may be noted that the observed temperatures are indicated to be rather closer to the air temperature than those given by the simulation – this is likely to be due to differences in reflectivity and emissivity between the thermal properties assumed in the model and the thermal properties of the real stone. The model shows clearly that detectable temperature differences can be expected between different parts of the face of the wall due to differences in the construction.



a)



b)

Figure 8: a) Thermal image of the Northleach wall at 22:00 on 6 July 2013; b) modelling results for the same date and time.

5 DISCUSSION

The field study investigations and simulations have shown that thermal imaging can identify important features within a drystone retaining wall. The clearest observable feature is the distribution of through-stones, as seen in the Northleach study, which are critical to the stability of the two-faced form of construction most common in the UK. In France, where there is a greater emphasis on good bonding than on through-stones, the thermal images where shown to indicate how far stones might penetrate into the wall, revealing the effectiveness of the bonding. Through the use of thermal simulations it has been shown that thermal imaging has the potential to detect these features throughout the year. The images can also indicate the overall density of the construction, as this affects the transmission of heat from the backfill to the face of the wall, and can thus reveal areas of a wall which may not have been constructed sufficiently well, or reconstructed at a later date. Thermal imaging at Northleach also suggested that thermal imaging can also indicate the presence of water within a wall, which may influence wall stability, as well as causing deterioration of the walling stones themselves.

The timing of the thermal imagery is very important. Both the experimental and the simulation results, showed that early in the morning following a cold night gave the clearest temperature difference between the stones. Prolonged periods of direct sunlight onto the wall could result in good observations, whilst times to be avoided appear to be during transition periods of the day when heating and cooling occur, such as mid-morning or early evening, when the temperatures of the surrounding walls match that of the features, as shown in Figure 4.

6 CONCLUSIONS

It has been shown that thermal imaging can be used to identify wall features that are not visible using conventional, non-destructive wall assessment techniques. The thermal response of individual wall stones at the face to atmospheric temperature variations reflects differences in the thermal mass and connectivity of the wall stones, and their thermal connectivity with the backfill. This can be used to help identify features such as the depth of retained fill, historic wall repairs, areas of high moisture and the presence of through-stones. By identifying such features within a wall (or a lack thereof), a better understanding of the wall can be obtained, and hence a better judgement can be made of its condition and a more accurate assessment made.

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