The sustainability and assessment of drystone retaining walls

Le développement durable et l'évaluation des murs de soutènement en pierres sèches

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ABSTRACT: The art of drystone walling is a highly sustainable traditional practise which uses local materials and craftsmen. As no mortar is used they have low embodied carbon, and much repair work or rebuilding can be carried out using very little if any new materials. However local practices developed to suit local materials, leading to a range of construction styles, making them difficult to assess. This paper examines a range of construction styles of drystone retaining walls in use across the United Kingdom. Understanding of the substantial variations of construction style is essential to enable proper assessment of these structures. Different frictional and weathering characteristics, and the naturally occurring shapes of stone found in an area, all affect the ways in which the stones have traditionally been assembled into walls. Ease of construction also plays a part, as the craftsman will naturally wish to achieve a robust construction in a way that is economical of time and effort. Aesthetics may be very important, for both client and craftsman. It is also shown that construction style is influenced by the location and function of the structures, with harbour walls particularly likely to have unique characteristics, and the reasons for this are explored.

RÉSUMÉ : L'art de la pierre sèche est une pratique hautement durable traditionnelle qui utilise des matériaux et des artisans locaux. En l'absence de mortier, elles ont une faible carbone incorporé, et les travaux de réparation ou de reconstruction bien peut exiger très peu ou pas de nouveaux matériaux. Cependant les pratiques locales développées pour répondre à des matériaux locaux, conduisant à une gamme de styles de construction, ce qui les rend difficiles à évaluer. Cet article examine une gamme de styles de construction de murs de soutènement en pierres sèches utilisées dans l'ensemble du Royaume-Uni. Compréhension des variations importantes du style de construction est essentielle pour permettre une évaluation adéquate de ces structures. Différentes caractéristiques de frottement et aux intempéries, et les formes naturelles de pierre trouvés, affectent la façon dont les pierres ont traditionnellement été assemblés. Facilité de construction joue également un rôle. L'esthétique peut être très important, à la fois pour le client et l'artisan. Il est également démontré que le style de construction est influencée par l'emplacement et la fonction des structures, avec des murs du port particulièrement susceptibles d'avoir des caractéristiques uniques, et les raisons de cette situation sont explorées..

KEYWORDS: Drystone, Construction styles, Assessment

1 INTRODUCTION.

Throughout the UK there are many different styles and types of walling to be found. Most styles can be categorised as horizontal construction, vertical construction or random construction (Figure 1). Each has its own unique features and is often associated with certain areas of the country and corresponding rock types. Horizontal construction is often found with more blocky types of stone such as limestones, which can be stacked in a more conventional fashion; the stones are also sometimes worked to give a better fit. Horizontal construction is probably the most common type of construction within the UK. Vertical construction is mainly associated with slate type stones that can be tightly packed and may be less successful in a horizontal configuration. Random construction is mainly associated with more granitic type rocks which are hard to work and are often irregular in shape. These styles are sometimes found in combination in a single wall with a single type of stone, and there are variations such as the herringbone construction, found in parts of Cornwall.

It could be argued that every drystone retaining wall works in essentially the same way, as every wall is essentially a gravity retaining wall that relies on the frictional forces between the stone for stability. However, each style is likely to use the mechanical properties of the stones in different ways to achieve the required coherence. The failure and movement of horizontally constructed walls is comparatively well documented and understood (Mundell, 2009) when compared to the other construction styles. The mechanical differences between the styles are explored below.

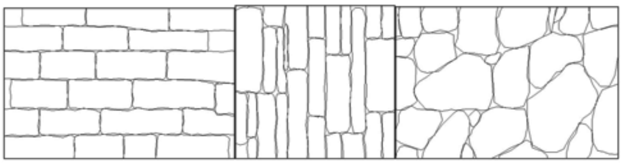

Figure 1. Different wall styles found in the United Kingdom: horizontal construction, vertical construction, random construction.

1.1 *Horizontal Construction*

Experimental testing and numerical modelling (McCombie et al. 2012, Mundell et al. 2009, Colas et al. 2010, Villemus et al. 2007) have shown that the overturning moment due to the horizontal component of earth pressure is resisted in part by the vertical component acting in downwards shear on the back of the wall, with very small deformations for well-constructed walls in a normal condition. As walls become overloaded the deformations can become considerable, often showing the classic bulged profile as the walls adapt their shape to the higher applied load (Figure 2). Ultimately, the walls will typically overturn, though if a smooth stone is used the wall or a part of it may slide forwards first. If the wall is constructed in a well-bonded manner, with stones overlapping, then a tensile strength can develop along the length of the wall which greatly assists in the redistribution of load, and helps give the wall substantial ductility. This behaviour is dependent upon a horizontal construction. A less beneficial consequence of horizontal construction is the reliance on through stones to connect coursed layers of stone at the front and back of the wall across an infill of rubble. These stones are necessarily larger than those used for the rest of the construction, and there may not be sufficient to ensure that the wall behaves monolithically, giving a greater chance of movement and hence failure.

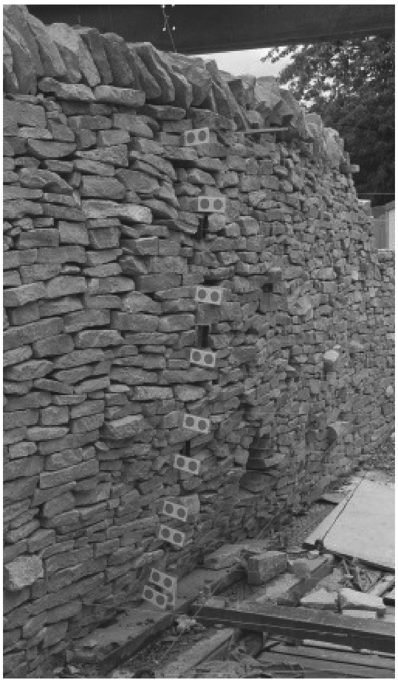

Figure 2. 2.4m high test wall at the University of Bath showing a classic bulged profile in a limestone wall of horizontal construction.

1.2 *Vertical Construction*

There has been no notable published research into vertical or random forms of construction, but some indications of how they preform may be inferred from observations, in relation to the behaviour of horizontal constructions.

Figure 3. Model test showing concrete blocks partially rotated and wedged in against the sides of the test box.

Discussions with wallers who use the vertical form of construction, and detailed observations carried out in Somerset and Cornwall, suggest that vertical construction is reliant on compressional pre-stressing forces. In the majority of vertically constructed walls all stones either penetrate the full width of the wall, or are tightly packed throughout the wall depth creating an effectively continuous cross section. During construction pre-stressing is induced through the wedging of stones at regular intervals which when combined with the overall confinement from the rest of the wall produces a compressional force. As the walls are backfilled, material will fill any remaining gaps at the back of the wall further strengthening the wedging. Evidence of this is shown in work carried out by Bailey (2008) in conjunction with Mundell (2009) (Figure 3). In Bailey's work during initial experiments using smaller individual blocks it was found that the backfill became wedged between the blocks making them virtually impossible to remove from the testing box. This was a nuisance for these tests, but gives useful information about the mechanical wedging of other wall types.

1.3 *Random Construction*

Random construction is likely to have features common to both the horizontal and vertical construction methods, however the variable morphology of the stones in random construction make it difficult to make generalised assumptions regarding any further mechanisms involved. However, it can be seen that an absence of bonding prevents the development of tensile strength along the wall face, whilst the lack of alignment of vertical stones prevents useful pre-stressing. Randomly constructed walls must rely much more on the size and weight of individual stones.

Table 1. Locations, principal stone types, and principal construction styles in this study.

Location	**Geology**	**Wall Construction**
Boscastle, Cornwall, UK	Slate	Vertical Herringbone
Mousehole, Cornwall, UK	Granite	Random
Dartmoor, Devon, UK	Igneous Intrusion	Random
Brompton Regis, Somerset, UK	Morte Slate	Vertical
Northleach, Gloustershire, UK	Limestone Formations	Horizontal
Bath, Somerset, UK	Interbedded Limestone	Horizontal

The use of these different styles is often found to relate to the types of stone available in a given area. Horizontal construction is often found where stones are more block like in their nature, either naturally or by easy working to desired shapes. The stones used in horizontal construction are often stone types with more frictional surfaces, such as limestones, which help the stones to transfer loading more than any other mechanisms which might occur within the wall. Vertical construction seems more likely to be used with more slatey type materials. Due to its laminated nature slate is often found with a comparatively thin cross section that lends itself more to this style. This form of construction is likely to be beneficial for stones such as slate which have comparatively low surface friction because shear load from earth pressure is transmitted through contact between the rough edges of the stones rather than the smooth surfaces. Random construction is often found where stone is difficult to work e.g. granitic areas or where there is a variety of local stone types, which may all be used in conjunction within a wall. The geology of an area therefore has considerable influence on the locally dominant forms of construction, but it is still possible to see different styles within the same wall (Table 1).

2 SPECIFIC CONSTRUCTION STYLES – HARBOUR WALLS

Although wall construction style is often a reflection of locally available stone, sometimes the construction style reflects the purpose of the wall. Probably the best examples of this are the harbour walls found around the United Kingdom. Many of these walls are of significant age - parts of the quay in Mousehole are reported to date back to 1390 (Cornwall-online.co.uk) suggesting that they are well suited to their usage. Mousehole is also unusual when looking at harbour walls as much of it is uncut random rubble.

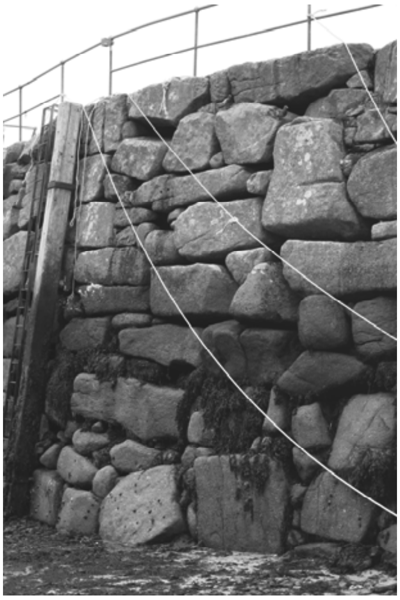

Figure 4. Wall at Mousehole, Cornwall, containing of large blocks.

It is typical when looking at harbour walls to find vertical construction as you would find with slate type materials, but they can be on a far larger scale to that found in a typical wall. Stones may also be shaped to suit vertical construction even if they are not usually built in the fashion, or are constructed from slate sheets far larger than you may expect to find in a typical vertically constructed wall. This is likely to be linked to the convenience of transport material by water, allowing larger stones to be transported. The vertical construction and larger stone sizes are both advantages in harbour construction. The verticality of the stone helps to prevent uplift by presenting a small bottom face for waves to act on, and provides better drainage for sea water, both during the changing tides and under wave penetration. Being drystone and hence free draining is better suited to harbour construction than most other wall types, in which any water which penetrated the wall under wave pressure may not flow out quickly under gravity alone, inducing extra pressures on the rear of the wall. Having a more massive construction provides better protection from wave action as a greater force is needed to move individual stones within the wall. The voided nature of drystone is also likely to help with wave energy dissipation as waves will break up into the wall on impact, as opposed to being reflected or running up and over an impermeable concrete wall.

Research has been carried out into the construction and tradition of drystone harbours by Richard Tufnell (2012) which he presented at the 13th International Dry Stone Walling Congress in September 2012

3 UNDERSTANDING CONSTRUCTION AND ASSESSMENT

Many of the current drystone retaining structures were constructed around 100 years ago with no records of how or exactly when they were constructed. Even many of the modern walls are constructed based on rules of thumb, with little or no input from engineers. Many of these walls have remained stable for a number of years and still continue to do so, retaining a significant proportion of various transport infrastructures throughout the United Kingdom, as well as being used in other applications such as harbour walls and domestic use.

Since the majority of these structures have been built, the loadings that they are subjected to have increased, particularly on the road networks. This combined with the increasing age of the walls and the need to be able to replace or repair walls before collapse means that improved assessment drystone retaining wall stability is increased. The assessment of these structures by engineers is often tricky due to the lack of formal engineering input during their design, as well as a lack of knowledge of failure mechanisms, unlike with more modern retaining structures. Assessing these structures in the same way as modern structures is inappropriate due to their un-mortared nature and inherent flexibility, which means that obvious deformation within the wall does not automatically mean that the wall is unsafe. Guidance on assessment can be found in work by O'Reilly and Perry (2009) and through the various publications by the dry stone walling association. However much of the guidance given is qualitative and relies on the judgement of the engineer assessing the wall as to whether it is safe or not. Where an engineer is familiar with drystone walls in general and the walls he is looking at in particular, then a reasonable assessment is likely to be made. However if an engineer has little to no experience of drystone walls they may take the walls' natural deformations and oddities to be signs of failure, and hence make an inaccurate or insecure judgement. This in turn may lead to walls unnecessarily being taken down and replaced with less sustainable modern alternatives which are out of keeping with their surroundings. It could also lead to a failure which should have been prevented

In order to improve assessment of these structures further engineering knowledge of them is required, both in terms of overall structural behaviour and the effects of properties of individual elements. This should include consideration of how these factors might change with time, such as the weathering of the stone. By understanding generic wall behaviour and how different factors affect this new assessment techniques can be developed that can enable the engineering judgement to be better informed.

It is also important to note the modifications that are often made to drystone retaining walls, often in good faith, which can be detrimental to the wall's health. For example, it is common practise for dry stone walls to be grouted or pointed either in an effort to prevent further movement, or to protect the base of a wall from salt spray, particularly in limestone areas. However in doing so the drainage paths through the wall are often blocked, thus taking away one of the main advantages of drystone retaining walls, which is that due to their un-mortared nature they are free draining. This can cause a build-up of water pressures behind the wall which did not exist before, and ultimately lead to collapse. The grouting of a wall will probably reduce its flexibility, which can be detrimental in two ways. If the wall is less ductile then it is unable to redistribute load concentrations, or distribute load away from weak areas, which could result in a local failure leading to a general collapse. On the other hand, a local crack which might allow a safe redistribution of load might give serious concern.

Unfortunately as with most retaining type walls a number of harbour walls are also being grouted. This is potentially understandable in harbour walls as over time wave action is likely to have caused some visible damage to the wall, and it may be deemed necessary to protect the wall. However due to their voided nature these walls often need more grout than initially estimated and there is no guarantee that the grouting has been done sufficiently to fill all the voids in a wall. It is also difficult to know where the injected grout ends up. Grouting not only stops the draining of water that enters the wall through wave and sea action, but also most harbour walls retain land behind them so that the grouting will also prevent the drainage of groundwater, which as before exerts extra pressures on the wall and potentially causes failure.

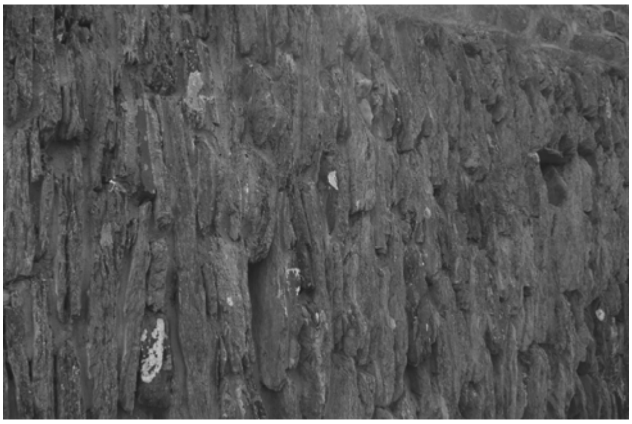

Figure 5. Grouted wall of vertical construction at Port Gavern, Cornwal

A general difficulty of assessing walls which have failed is that due to their un-mortared nature, all that is usually left of a failed section of wall is a pile of rubble that is almost impossible to analyse, and it cannot be assumed that adjacent standing sections give a true indication of the form of a failed section. Some judgement may be able to be made about the foundations or conditions of the backfill but little can be said about the wall. Increasing the understanding of how these walls work as well as improving assessment it may make it easier for engineers to use drystone walling in new build projects or to replace existing damaged walls, rather than their more modern and less sustainable counterparts.

3.1 *Appearance Vs. Wall Quality*

When assessing a drystone wall much weight might be given to the appearance of the wall at its face. This can be deceiving, especially as the way in which walls are finished is likely to have changed over the years. It is likely that the majority of walls built a hundred years or more ago had greater emphasis on function, whereas aesthetics are likely to be an important factor in choice of drystone walling today. This means that quality of the aesthetics is easily taken as a proxy for quality of construction, but just because the wall face looks even and is cleanly finished does not mean that the wall behind will be to the same standard - and vice versa. For example, wallers cite cases where freestanding walls have appeared to be well constructed and have a good finish but have failed within months of being built, because instead of being constructed with properly packed filling they have been filled with pea shingle with no through stones, preventing the wall from performing as a monolith. In another case a waller was asked by a client to build a small retaining wall which was to have a hedge planted in front of it, so ultimately was not worried about the finished appearance of the wall. He also did not want any wastage of the stone, whereas normally a certain amount of stone is left at the end where stones have been shaped or just not used in the wall. However this wall was built to no less a standard than other walls he had built for the same client which had a very high quality of finish to them.

4 THE SUSTAINABILITY OF DRYSTONE WALLS

As with most constructions the sustainability of drystone walls must also be considered. When considering drystone structures this will also include the ecology impacts of the walls providing habitat and shelter for both animals and plants.

Drystone walls are naturally very sustainable structures and with the current imperative of low carbon structures are an almost ideal solution. Their main advantage is a lack of mortar, this not only means that the walls lack the embodied carbon associated with the mortar, but that when repair or rebuild is required very little if any new material is required. This does however depend on the stone type; or example a limestone wall is more likely to need some new material as limestone is prone to decay from water and frost. Traditionally walls have been built with materials local to where the wall was built, as with most vernacular structures, and this has continued through the generations of wall builders so that even today new materials are usually obtained from local quarries or sources well known to the waller. This means that there is minimal transport of materials, thus reducing the embodied carbon within a drystone wall. Drystone walls also provide an excellent habitat for a variety of animals and plants and various research has been carried out where drystone walls have been highlighted. (Hynes and Fairley 1978, Cody and Cody 1972,)

5 CONCLUSIONS

Drystone retaining walls of horizontal construction have dominated scientific work to date, but regional construction styles which have developed in response to the type of stone available or particular requirements may behave in significantly different ways. It is important that these differences are understood if the stability of walls is to be asssessed correctly.

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