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Analysis of Historic Rammed Earth Construction

Paul A. Jaquin

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Volume II

Chapter 4 Typologies of rammed earth construction
Chapter 5 Failures in rammed earth structures
Chapter 6 Rammed earth repair
Chapter 4

Typologies of rammed earth construction
4.1 Introduction

A brief description of rammed earth construction is given in Section 1.2 and Figure 1.1, but the technique has developed internationally (Appendix A) and a rich variety of different rammed earth styles exist. This chapter investigates different types of historic rammed earth construction, looking at techniques and material used in construction and the resulting rammed earth walls. A comprehension of both the methods of construction and the composition of historic walls is vital for the understanding of failure and repair of rammed earth. However, until recently typological rammed earth descriptions have 'raised little interest when compared to ornamental and spatial studies' (Graciani García and Tabales Rodríguez 2003). This chapter looks at descriptions of rammed earth in Seville, Spain proposed by Graciani García and Tabales Rodríguez (2003) and aims to extend and improve their framework based on the field visits discussed in Appendices B, C and D.

Graciani García and Tabales Rodríguez (2003) identified the following aspects to distinguish between various rammed earth types in the Seville area of southern Spain.

- **Compositive** - looking at the construction techniques used to make the wall and the resulting wall. This comprises simple rammed earth; chained – which contains horizontal layers of brick between each lift; and mixed fabric rammed earth which contains both brick layers and brick columns within the rammed earth.

- **Dominant aggregate** - distinguishing between predominantly gravel mixtures used to make the rammed earth, and those which contain ceramic fragments.

- **Height of the formwork** - distinguishing between short (0.80m), and high (0.85m and 0.95m).

This chapter extends the characterisation, and the following aspects are investigated:

- **Formwork**
- **Mix design**

These aspects are considered important when identifying historic rammed earth. This chapter shows that a development of the rammed earth technique over time can be traced, and a framework is provided into which other historic rammed earth may be placed.
As will be discussed in Chapters 5 an understanding of the method of construction and composition of a historic structure allows an engineer to more precisely assess the structural performance of, or damage to, a building. Chapter 6 describes repair to rammed earth, and only with an accurate understanding of the methods of construction can high quality repairs be enacted. Therefore in addition to those above, the following aspects are also discussed, as it is felt that an understanding of them is vital when considering both the failure and repair of historic rammed earth:

- Compaction process
- External face
- Foundations
- Tension members
- Wall tops
4.2 Formwork

It is the formwork which distinguishes rammed earth from other variants of earthen construction such as cob or adobe brick. Various types have been suggested over time and in different parts of the world, with the formwork evolving to become more efficient, or being forgotten and rediscovered some years later. A number of different formwork designs have been suggested, some of which are shown in Figure 4.5, Figure 4.6, Figure 4.7 and Figure 4.9.

4.2.1 Formwork sides

The formwork is usually made from planks of timber, fixed together using nails and placed to form a box within which the earth is rammed. The length of the formwork cannot usually be established with any certainty from an inspection of the walls, but Font and Hidalgo (1991) suggest that the formwork should be 2200mm long, while Cointeraux (1791) suggests the formwork be 3000mm long. At the vast majority of sites it is not possible to tell the length of the formwork from observation, because there is no visible line on the surface of the wall, although there are some exceptions. At Villena (Vi1, Appendix C) the length of the formwork is around 1750mm, which can be established by observing whiter sections of the wall (Figure 4.1). At Seville (Se2) vertical joints delineate the formwork box which here is 1900mm.

The height of the formwork, and thus of each lift, is usually between 0.75 and 0.95 m, which corresponds to two codos or one vara both traditional Hispanic-Muslim measures. Garcia and Rodriguez (2003) notes that the height of the formwork increases over time in Seville, but the height of formwork is determined by regional carpentry traditions, and it is therefore not possible to draw global conclusions about change in formwork size over time.
Typologies of rammed earth construction

4.2.2 Wall thickness

The rammed earth technique dictates that the width of the ends of a formwork box define the thickness of the wall, and in most cases the walls are constructed one block thick. Where a greater thickness is required, there are examples (Ja1 and Se2) where two blocks are used with a soil or rubble fill between. As the majority of surviving constructions observed were defensive in nature, where the walls were constructed for thickness, rather than efficient design. However many rammed earth towers are constructed with thicker walls at the base than at higher stories – Villena (Vil), for example, has walls 3.6m thick at the base reducing to 2m at the third floor. In contrast, the walls at Baños de la Encina (Ba1, Appendix C) constructed in 967AD are a constant 0.6m thick, to a height of 14m.

4.2.3 Construction method

The method for construction of a building may be as follows – a number of teams, each with a formwork box and supply of earth mixture, begin construction of walls at different points around the perimeter of the new building. These teams move their formwork horizontally, until they meet with another team. Upon competition of a horizontal layer the formwork is moved vertically and the next horizontal lift begun.
There are two techniques for the provision of opening, to insert a blank into the formwork, and ram around it (favoured by some modern rammed earth builders), or to cut the opening once the whole building has been constructed. Observation of beams at sites Ba1 and Ta1 suggest that substantial scaffolding was employed, and the formwork placed onto this scaffolding in order to ram a beam section. Floor and ceiling sections usually appear to be rammed in situ, with beams 'cast' into the walls. Where these beams have been removed, it is possible to see the holes within the rammed earth (Da3 and Ta1). Crawling or externally supported formwork can be used.

4.2.4 Crawling formwork

This is by far the most common type of formwork observed, and is still used in traditional rammed earth construction in Morocco (Keable 2005) and the Himalayas (Jest, Chayet et al. 1990). Here horizontal timbers are placed through the full thickness of the wall and the formwork rested on them, tightened at the top and bottom with a variety of different techniques.

4.2.4.1 Horizontal timbers

The horizontal timbers support the formwork during construction of the wall and are generally removed or snapped off on completion of the wall. These timbers have holes in each end through which the vertical timbers are placed. A number of sites have bricks or flat stones which are placed above the timbers to ease the removal of the timbers and presumably to allow for the spreading of the load around the hole. On removal of the timber a hole is left in the wall known in English as a putlog hole and Spanish as mechinal, these holes are often seen as a characteristic feature of rammed earth, and in some cases become an architectural feature of the facade. The shape of the timbers used can be inferred from the holes they produce.

Small rectangular holes were found at many sites in southern Spain (Appendix C), here the timbers are around 75mm long and 15-20mm high, at a spacing of 500mm to 1000mm (e.g. Figure 4.1). These timbers are either removed or trimmed flush to the face of the wall. The original shape of these timbers has been suggested by Font and Hidalgo (1991) based on observations of traditional techniques in Els Port, Catalonia, Spain (Figure 4.5). Later constructions, for example Daroca, constructed in 1837
Typologies of rammed earth construction

(Da2) have definite circular holes, but these are probably produced using steel rods to pull the formwork together. Large holes were found at two sites (Ja1 and Ta1) in southern Spain (Figure 4.2). These larger holes suggest that more substantial timbers were used to support heavier formwork. The size of these holes is 100mm by 100mm with spacing similar to that of the small holes (750mm).

Where small rectangular horizontal timbers are used, the timbers are usually left in the hole and cut off on completion of the construction. Thus a rough edge is present, generally flush with the wall (for example at sites Am1, Am2, Ba1 and Bi1). Where the timbers have been removed, they appear to have been pulled out. However, broken and removed timbers are often found together at the same site. In early Muslim Spain rammed earth was used for the ease and speed of construction (Graciani Garcia and Tabales Rodriguez 2003) and thus it is assumed that if it was possible to easily remove a horizontal timber, it was removed, but otherwise it was left in place.
Often bricks or stones are found above the timbers (Figure 4.3 and Figure 4.4). These have been placed within the formwork both to aid compaction of the earth and to allow removal of the timbers. At some sites the bricks or stones are visible at the surface of the wall, whereas at others the surface remains smooth as the stones are placed only in the central section of the wall.

Figure 4.3 Bricks above the putlog holes, exposed though failure. Carmona, Ca
4.2.4.2 Vertical timbers

Vertical timbers are used to hold the formwork against the wall. These are placed through holes in the horizontal timber, fixed with wedges as shown in Figure 4.5, Figure 4.6 and Figure 4.7 and tightened at the top as explained below. In the Himalayas a different technique is used where thick wedges are forced between the vertical timbers and the formwork (Jest, Chayet et al. 1990).

Font and Hidalgo (1991) and Acedo (2006) suggests that solid timbers are used across the tops of the vertical timbers, fixed using wedges as shown in Figure 4.5. Modern ‘traditional’ rammed earth construction, as found in Morocco (Figure 4.8) joins the vertical timbers with a rope, twisted with a stick to tighten it (Cody 1990; Easton 1996, Walker, Keable et al. 2005).
Figure 4.5 Traditional formwork from the Els Ports, Catalonia, Spain. Font and Hidalgo (1991)
Typologies of rammed earth construction

Horizontal timbers
Wedges
Putlog holes

Figure 4.6 Traditional American formwork, 1806-1870. Cody (1990)

Figure 4.7 Formwork suggested for use in France. Cointeraux (1791)
Rope tying formwork together

Horizontal steel

Vertical timbers

Figure 4.8 Traditional rammed earth construction in Morocco. Keable (2005)
4.2.5 Externally supported formwork

Chazelles (1993) notes that pre-Muslim rammed earth sites in Spain lack putlog holes, and that the walls are constructed as a solid mass. A number of later Spanish medieval location; sites in China and in India (Appendix A); and modern rammed earth construction have no putlog holes. This indicates that the formwork was supported externally using scaffolding. This means that putlog holes do not appear in the wall, but implies that scaffolding must be used to support the formwork (Figure 4.10). This technique is most similar to modern formwork systems, although most modern formwork covers the whole of the wall.
4.2.6 Horizontal movement of the formwork

Once the formwork box is full of rammed earth it is deconstructed, moved horizontally along the wall and reconstructed so that it can again be filled with earth. To produce a 'seamless' wall, the formwork is 'shunted' along, with compaction always taking place within the formwork but the formwork being supported on a number of horizontal timbers. When compaction at the back of the formwork box is complete, the formwork is moved forwards by one horizontal timber and compaction continued (Figure 4.8). If the box is completely filled then moved, a visible vertical join may be seen, an example of which is moved the city walls of Seville (Se2, Figure C.83). If the box is filled to an angle then moved, an angled joint is seen (Figure 4.11) This technique is seen at Daroca, Spain (Da1) and Leh (Le2, Figure D.18) and Shey (Sh1, Figure 4.11, Figure D.24) in India. The use of an definite angled joint was made popular in France following the publications of Cointeraux (1791), where a steep angle within the formwork is coated with lime (Figure 4.7). Buildings produced following the publication of this text show characteristic diagonals in the walls delineating the edges of the formwork (Appendix A).
A Spanish technique of placing mortared stones in the corners of the formwork box, may have been used to increase the strength of the vertical join between formwork boxes (Font and Hidalgo 1991; Houben and Guillaud 1994). This technique (Figure 4.12) produces white lime crescents at the base of each formwork box known as *lunetos* in Spanish (moons).

The increased use of brick in the Iberian peninsula in the 15th century led to an increased use of individual rammed earth blocks, acting as fill between vertical brick columns and horizontal brick *males*. Examples of individual rammed earth blocks can be seen in Spain at Salobrena (Sal) and at Palma del Rio (Pa2). Vertical and horizontal lines of lime between blocks, in a manner akin to masonry construction were observed at one site in northern Spain (Figure 4.14).
4.2.7 Vertical movement of the formwork

When one horizontal layer (lift) of rammed earth was complete, the formwork is dismantled, moved vertically, and another horizontal layer begun. Because work progressed horizontally, there may have been a substantial time delay in the construction of one lift to another and therefore the bond between each lift may be weaker than the bond between each compaction layer within the formwork box.

Layers of material placed between the lifts to improve the strength of the bond are known in Spanish as males (Graciani García and Tabales Rodríguez 2003). Rammed earth constructed with males is termed chained by Graciani García and Tabales Rodríguez (2003). Langenbach (2004) has argued that males are related to seismic resistance, and notes that horizontal introductions into the walls of buildings are not unique to rammed earth, or even earthen architecture. The horizontal members are designed to act as weak layers, forcing diagonal shear cracks to propagate horizontally, thus not collapsing the building (see...
The use of a lime *male* was seen at Cordoba (Co1, Figure 4.13) and Daroca (Figure 4.14). Brick *males* were introduced into Spain in the second half of the 12th century (Figure 4.15) (Graciani García and Tabales Rodríguez 2003). The brick is only present at the surface of the wall, which suggests that they are used as an architectural feature rather than to provide bonding between the lifts. The *male* can be between one and three bricks thick, and this varies at individual sites as well as between sites. The putlog hole is usually below the level of the *male*, indicating that the male was the first, rather than the last layer of a lift.

![Figure 4.13 Lime layers. Cordoba, Co1](image)

*Figure 4.13 Lime layers. Cordoba, Co1*
Typologies of rammed earth construction

Figure 4.14 Thin lime layers between blocks. Daroca, Spain

Figure 4.15 Brick males. Alaca de Guadaira, A12
4.3 Mix design

This section looks at different techniques which were used for the filling and ramming of formwork. Many of the historic sites in southern Spain used lime as an stabilising additive to improve the performance of the rammed earth. The amount of stabiliser, and how it is used is discussed in this section. Three technique are shown:

- Plain - using a mixture of soil, with perhaps some stabilising agents;
- Calicastrado where a stabilised mixture is present at the face of the wall;
- Royal rammed earth, most similar to modern concrete, where an extremely lime rich mixture is used

Erosion of structures makes diagnosis of the techniques difficult and the distinction between each is sometimes subtle, with the methods coming together at increased lime content.

As outlined in Section 1.8.2, the particle size distribution of a rammed earth mixture is particularly important in determining the structural and erosional properties of the completed wall. It is assumed that the historic builders were aware of the advantages of an optimum particle size distribution and thus chose quarry sites with care. Observations in Granada by Graciani García and Tabales Rodríguez (2003) suggest rammed earth mixtures are taken from quarries as close as possible to the site, but are selected on the basis of silt and clay content. Unfortunately no analysis of the particle size distribution or chemical composition of the mix used at historic sites has been undertaken. It is difficult to obtain a representative wall sample without careful procedures and specialist equipment, and in many cases illegal to do so without permission.

Rammed earth with no extra material added to the mixture is known as unstabilised rammed earth, but its inherent low tensile strength has led to additives being placed in the mixture. Lime is the most common additive to rammed earth, and was found as nodules within the wall at some of the sites (Figure 4.17). Investigations into lime additions were carried out on samples from Granada (Valverde Espinosa, López
Osorio et al. 1993). Following identification of the quarry sites from which the rammed earth mixture was taken, comparisons were made between the soil used for the wall and that taken from the ground. It was found that gypsum and carbonates were added to the mixture. 2% gypsum (SO₄Ca₂H₂O) was added to the whole mixture, and 5% carbonates were added to the material used in the centre of the wall and 10% carbonates to the render (careado) mixture. It was also observed that there was a higher carbonate content in samples taken from the city walls than from samples of vernacular architecture.

4.3.1 Plain rammed earth

Plain rammed earth uses the same rammed earth mixture through the whole body of the wall, and if no stabiliser is added then the technique is closest to modern unstabilised rammed earth (Figure 4.16). However it is possible that amounts of lime, hair, straw, pottery or other stabilising agents would be added to the mixture (Figure 4.17). Depending on the degree of compaction this type of wall exhibits horizontal banding visible at the face of the wall, which may be due to either compaction of the soil in layers because of the planks of wood used to make the formwork. On completion the wall may or may not be rendered.
Typologies of rammed earth construction

Figure 4.16 Plain rammed earth, showing density banding and lines of putlog holes. Lorca, Lo1

Figure 4.17 Lime nodules and pottery fragments. Carmona, Ca1
4.3.2 *Calicastrado* rammed earth

This method uses a lime and earth mixture (*careado*) which is spread by a shovel again the formwork. The interior is then filled with a mixture of tamped down sand and gravel which may not be stabilised. The formwork is removed and thus the exterior surface of the wall appears as covered with lime render. The render fuses with the fill behind it which initially provides a very resilient surface (Bazzana 1993; Gallego Roca and Valverde Espinosa 1993). The wall then has two distinct materials, a core of rammed earth which acts to give the wall structural strength and mass, and an outer face which protects the wall from erosion (Valverde Espinosa, Lopez Osorio et al. 1993; Arango Gonzalez 1999). When formwork is removed following completion of the lift a lime rich but pitted face is presented. This face is then rendered again, and re rendering continues periodically. This render may be perfectly smooth (Figure 4.19) but does allow patterns to be inscribed into the face of the wall, (Figure 4.18).

![Figure 4.18 Inscribed calicastrado. Baños de la Encina, Ba1](image)
Figure 4.19 Plain *calicstrado*. Cox, Cx1.
4.3.3 ‘Royal’ rammed earth (*Tapial Real*)

Also known as Arab-concrete, Royal rammed earth consists of a lime and earth mixture compacted in layers, with the lime : sand ratio being approximately 1:3. 8th century walls constructed using this technique are found in Granada (Arango Gonzalez 1999). These structures are not rendered due to their higher initial lime content (Figure 4.20). It is assumed that due to its higher lime content, this rammed earth is both stronger and more expensive, and the name royal justified because of its rare use. Royal rammed earth is difficult to distinguish from plain rammed earth, except in colour and through testing of samples.

![Figure 4.20 Royal rammed earth blocks. Palma del Rio, Pa2](image-url)
4.4 Compaction process

Study of modern 'traditional' rammed earth constructions may allow an understanding of historic construction practices. Jest, Chayet et al. (1990) suggest that the mixture is first wetted and worked by foot, then placed in the formwork and compacted in time to traditional songs. The material is compacted within the formwork until a tapping sound is heard (Hoz, Maldonado et al. 2003; McChlery 2004) indicating that the maximum density has been reached. After two or three hours the formwork is removed and the process repeated and Michon (1990) suggests that around six formwork blocks can be completed in one working day. In the Himalayas the work is done by women (Jest, Chayet et al. 1990), whereas in Morocco the work is carried out by a master mason and assistant (Michon 1990).

It is possible that techniques used by historic builders may also now be used by modern unstabilised rammed earth builders. One such example observed by the author is the placing of soil within the formwork using a spade. If the mix material is thrown against interior of the formwork, then a slope will form with the lower end at the centre of the formwork, and the upper end against the formwork face. This slope causes the larger particles to fall to the centre of the wall, thus giving the smoothest possible wall face.
4.5 **External face**

The external face of rammed earth is very important in preventing erosion. Problems related to erosion of rammed earth are outlined in Chapter 5. The external face usually depends on the mix design (Section 4.5) and a rammed earth wall may be left plain or be periodically rendered, a *calicastrado* wall will have a lime rich face and weaker core, and may also be rendered, while a royal rammed earth wall is sufficiently lime rich to not require rendering.

At some sites the rammed earth is fronted with rubble masonry. This masonry was probably placed to defend the wall against artillery attack and occurs only on those fortifications which were still in use when artillery came into use (around 1340 in Spain, Williams 2000). At most of the sites observed (Ja2, Ta1, Ti1) the masonry has been added some time after the construction of the wall, apparent because the wall appears slightly eroded at the masonry/rammed earth interface. At Carmona (Ca1) masonry was incorporated in the rammed earth during construction, which is made visible due to the later removal of the masonry, leaving distinctive holes in the wall (Figure 4.21).

In northern Spain, rammed earth fronted with brick is observed (Am1). Here half bricks are placed within the formwork on the outside face of the building (Figure 4.22). This technique combines expensive brick with lower cost rammed earth fill to present a building which appears to be wholly constructed in brick. Investigations detailed in Gerrard (2003) indicate that the bricks used are only half bricks, split parallel to their long axis, thus reducing the material cost at with no loss of visual effect.

Such walls can only be identified when the covering face is removed and there may be a large number of rammed earth walls still hidden beneath masonry or rendered faces.
Figure 4.21 Holes resulting from removed masonry. Carmona, Ca1

Figure 4.22 Brick faced rammed earth. Ambel, Am1
4.6 Foundations

Foundations are an important part of a historic structure, their failure can be disastrous and their repair difficult and expensive. Many of the rammed earth sites studied were defensive, and as a result built on high ground. This necessitated mortared rubble foundations onto rock, as shown in Figure 4.23 and Figure 4.24, to make a level bearing course before the rammed earth could be placed. Easton (1993) notes that a historic low rise rammed earth structure was built directly onto the ground. Most modern earth building guidelines (e.g. Walker, Keable et al. 2005) recommend foundations which extend above ground level, meaning the base of the wall does not contact the ground, to prevent water infiltration. At a large number of sites, a change in the external ground surface meant that the base of the rammed earth was in contact with the ground, meaning investigation of the foundation was impossible (Figure 4.25). Investigation of the foundations of existing structures is difficult without invasive techniques. Failure of the foundations is discussed in Section 5.3 and their repair in Section 6.4.

Figure 4.23 Mortared rubble foundations. Carmona, Cal
Typologies of rammed earth construction

Figure 4.24 Mortared rubble foundations. Leh, Le1

Figure 4.25 'Invisible' foundations due to ground level change. Jaen, Ja1

Analysis of historic rammed earth construction
4.7 Internal tension members

Rammed earth is known to have a low tensile strength, and timber beams were found inside walls section at two sites in southern Spain (Ra1 and Ta1). These timbers embedded with the body of the rammed earth may be added to increase the strength of the section of wall. The beams appear to be laid within the formwork, with the earth rammed around them. At Tabernas (Ta1) two timbers were found in a tower which were 200mm diameter within a 900mm thick wall (Figure 5.49). The hole was lined with lime filled with straw which surrounded the timber. Ring beams are difficult to detect, as they are embedded within the body of a wall, and are thus only exposed when erosion has taken place to the wall. Problems caused by the decay of such members is outlined in Sections 3.7.2 and 5.9.3
4.8 Wall tops

In Chapter 3 it was argued that protection of the tops of the walls is the most important factor in determining the survivability of a rammed earth wall. It is therefore important to quantify the techniques used for protection of the wall tops. The majority of sites surveyed in southern Spain were castle, city wall or tower constructions with intentionally exposed flat roofs to allow access to the top level of the building (Figure 4.26). In northern Spain the buildings surveyed were all originally roofed with large eaves (Figure 4.27). While a roof structure acts to prevent water from entering the head of the wall, large eaves are used to prevent water running off the roof and blowing against the face of the wall causing erosion. Such large eaves are not limited to rammed earth buildings and are common in almost all historic structures in northern Spain.
Typologies of rammed earth construction

Figure 4.26 Rammed earth wall top. Baños de la Encina, Ba1

Figure 4.27 Projecting eaves. Malvenda, Spain

Analysis of historic rammed earth construction
4.9 Characterisation

The acknowledged lack of understanding of rammed earth construction typologies is outlined in Section 4.1. Such a characterisation would be invaluable in the cataloguing of historic rammed earth structures, and would allow engineers a better understanding of how and why historic buildings fail, such that they can be better repaired.

The descriptions presented above show that structures studied can be broadly grouped according to their common characteristics. Accepting that the examples studied represent only a sample of the total number of surviving rammed earth building taken from two areas of Spain, and while other types will probably be discovered in the future, what is set out below represents the building blocks of a first classification. This classification allows the development of rammed earth in Spain to be traced and identification of the chronology of a structure which may otherwise be unknown. It is possible that further research using these methods can be applied to the rammed earth found in India (Appendix D) whose origins are uncertain. This framework also allows an understanding of what lies beneath the face of a wall, without recourse to destructive testing based on other similar examples.

Four aspects were identified, within which different methods or techniques would produce a variation in the type of rammed earth produced. The aspects are outlined below and Table 4.1 shows the wide range of rammed earth which can be portrayed using such descriptions. Each type is presented with a schematic, a photograph and examples of sites where the type has been identified. Table 4.2 defines each type based on the aspects (for example Mix : calicastrado) shows that such a characterisation can be used to describe the development of the rammed earth technique in Spain over time. The four aspects are:

1. Mix (plain, calicastrado or royal)

The selection of plain, calicastrado or royal rammed earth for a building's construction defines both the mix design and the construction technique. The selection was usually made based on the geology of the site, with constituents perhaps sieved
and varied if the correct mix was not available. If lime was freely available in the area, then it is probable that a more lime rich plain rammed earth, or a calicastrado mix was used, and if lime was plentiful then a royal rammed earth mix, more similar to modern concrete was employed.

2. Lift bond (none, lime, brick or stone)

As shows, the earliest rammed earth had no layers between each lift. In the early 13th century layers known as males of both brick and lime appear between lifts, and over time these become more elaborate, becoming architectural features between individual rammed earth blocks by the 16th century. The reasons for the males are either to act as crack stoppers, as suggested by Langenbach (2004) or to provide an improved bond between each lift.

3. Formwork (supported externally or crawling)

It is the formwork which distinguishes rammed earth from other variants of earthen construction such as cob or adobe. Many formwork types have been suggested over time and in different parts of the world, with the formwork evolving to become more efficient, or being forgotten and rediscovered some years later. Two distinct types of formwork may be used – where the formwork box supported using an external scaffolding or where the box rests on horizontal timbers placed in the wall, which when removed leave characteristic putlog holes. The size of the horizontal timbers, and consequently the hole has been noted to vary, with either small (70mm x 25mm) or large (up to 100mm square) timbers used.

4. Design (lunetos, brick quoins, brick facing)

Aspects of the design of rammed earth may cover a broad range of facets. Here it is used to distinguish between the use of brick, using lunetos, or the facing with masonry.
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Table 4.2 shows the clear development of the rammed earth technique in Iberia from the 10th to the 19th century. Within this development however, there is room for spatial and economic variation, with the mix design and formwork size changing to suit local geology and traditions. For example the choice between calicastrado, royal or plain rammed earth would be based on geological and economic considerations.

The visual appearance of a structure becomes increasingly important in monumental buildings over time, and the use of brick slowly increases, for ornamental and prestige purposes. Where a rammed earth structure is purely defensive, it is clad in masonry from the 15th century onwards, but the use of rammed earth in vernacular structures such as barns continues into the 19th century.

Buildings constructed during the Muslim expansion and civil war periods (8th to 11th century, Section B.2) were built in rammed earth for their speed of construction and structural integrity. Internally supported formwork, leaving small putlog holes was used and were lime available a calicastrado mixture (Type 1, Table 4.1) or plain rendered rammed earth (Type 2, Table 4.1) was used. Where lime was not available, a plain rammed earth mixture was used (Type 3, Table 4.1). For city walls, too thick for internally supported formwork, external scaffolding was used, and no putlog holes are left in the wall (Type 4, Table 4.1). Both brick (Type 5, Type 9, Table 4.1) and lime (Type 8, Table 4.1) males are introduced into rammed earth walls at the beginning of the 13th century, and where males are not used both stone (Type 6, Table 4.1) and
brick (Type 7, Table 4.1) are used above the horizontal timbers. Brick was used in conjunction with rammed earth in various forms, such as facing of rammed earth walls to appear as brick (Type 10, Table 4.1), and as brick quoins with a rammed earth infill (Type 11, Type 12, Table 4.1). Following the reconquest of Iberia by Christians, Muslim builders were employed by the Christians, and these Muslims continued to use rammed earth as a construction technique. The advent of artillery in the 15th century led to the cladding of rammed earth structures in masonry, and there may be many rammed earth walls currently ‘hidden’ beneath masonry walls. Rammed earth continued as a vernacular building technique throughout Spain, Portugal and France until its ‘rediscovery’ by Francois Cointeraux in 1793. Rammed earth continued to be used in conjunction with brick as a ornamental feature (Type 13, Table 4.1) or using as a quick cheap construction material using lunetos (Type 14, Table 4.1).

<table>
<thead>
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<th>Typology</th>
<th>Form work</th>
<th>Mix</th>
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<th>Design</th>
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<td>Lunetos</td>
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Table 4.2 Types of rammed earth in Spain
4.10 Concluding remarks

This chapter has described the rich typologies of historic rammed earth construction. Drawing on modern 'traditional' rammed earth construction, a historic documentation, and field observation, different formwork designs have been highlighted. The type of formwork used influences the type of wall which is constructed and that it is possible to infer the formwork used through observation of a historic wall. The introduction of material between each lift, known in Spanish as a male was explained, and it was shown that both lime and brick males were introduced in the early 13th century in Spain.

The mix used has been shown to affect both the construction method and the type of wall. It was argued that the choice of plain, calicastrado or royal rammed earth depends on the geology of the surrounding area. If the mix was considered insufficient, then where possible lime was added to improve the performance. The compaction process was then discussed, and it is assumed that modern traditional compaction would be similar to historic compaction techniques.

The external face of a rammed earth wall is discussed, it is argued that while some rammed earth buildings are rendered, others are not, and that both rubble masonry and fired brick have been used to face rammed earth walls. This would mean that many rammed earth walls may be hidden behind covering faces.

The foundations and wall tops of the rammed earth structures studied are discussed, Chapter 5 argues that it is these which play the biggest part in the survival of a historic rammed earth building. Internal tension members, such as timbers embedded within a wall are described, and it is shown in Section 5.9.3 that a decay of these members can lead to major damage to a structure.

A characterisation framework is presented based on four aspects of historic rammed earth construction. By looking at mix, lift bond, formwork and design, it was shown that many facets can be described, and distinct rammed earth styles portrayed. This framework allowed the development of rammed earth in Spain to be traced, and it is
hoped that such a framework may be extended to include the rammed earth in India (discussed in Appendix D) and eventually many more historic rammed earth architectural styles (described in Appendix A).
Chapter 5

Failures in rammed earth structures
5.1 Introduction

Rammed earth, being constructed from soil, is perceived by many to be a very delicate material, requiring a sympathetic climate and frequent maintenance to preserve its appearance and structural integrity. This chapter aims to determine the ways in which rammed earth structures fail. This will improve the ability of engineers to assess whether rammed earth is able to remain in a viable state over a long period of time, and if there are any limiting factors to the survival of a rammed earth structure.

There have been many specific case studies regarding the repair of historic earthen architecture, often looking at the failure mechanisms before proposing and implementing repair strategies. A number of authors have presented general failure mechanisms for earthen architecture, but few take account of the geotechnical nature of earth building, and none take account of its unsaturated nature outlined in Chapter 3.

This chapter combines those failure mechanisms reported by previous authors with those identified during field visits by the author described in Appendixes B, C and D. These failure mechanisms are explained, and in a number of cases the previously ignored unsaturated nature of the material is explored. A number of case study structures are then discussed, charting combinations of the different failure mechanisms which combine to precipitate major problems in the structure. Finally, conclusions are drawn as to the most common and most problematic failure mechanisms, drawing out pertinent advice on the determination of problems in rammed earth structures.
5.2 Methods

The failures of rammed earth structures outlined below were collated from a number of sources. An assessment of the problems associated with rammed earth buildings was undertaken by reviewing of previous literature published on the problems associated with general earthen architecture. From these sources an initial list of problems was drawn up, which was refined during the field visits described in Appendices B to D.

Many case studies regarding the failure and repair of earthen structures have been carried out (e.g. Jest, Chayet et al. 1990; Michon 1990; Easton 1993) but only a few authors have presented a broad view of the failures of earth buildings. Of these some are general to earth buildings, whilst others concentrate on a specific type (for example cob or adobe), and none are specific to rammed earth. Eight of these are summarised below.

Hughes (1983) produced one of the first examinations of soil walls, looking at structural and material behaviour, and decay mechanisms. The interrelated range of problems associated with earth walls is acknowledged and classified into decay caused by poor, inadequate or changing material properties; poor building technique; structural performance and inadequate repair; and a change in external climatic conditions.

A decade later Warren (1993) argued that failures of earthen architecture relate to the introduction of water, biological organisms, stress or temperature change. It is sensibly argued that analysis of the problem will lead to identification of a cause, and only when this is satisfactorily determined can the remedial action be decided upon. The judgement of the conservator is considered to be of great importance in earthen architecture conservation, due to a perceived lack of engineering expertise available in the subject area.

Houben and Guillaud (1994) concentrate mainly on design guidelines for new earthen buildings but in doing so devote a small section to possible failure modes, providing
advice on how to mitigate these. Typical structural defects such as structural cracking, shrinkage and bulging are discussed, and the presence of water as dampness in a structure is highlighted as dangerous.

Nother (2000) produced a small document, aimed mainly at cob conservation, but applicable to other types of earthen structures, which describes some types of failure observed in cob buildings in Devon, UK. Problems in structures are argued to be due to lack of maintenance or inappropriate repairs and alterations. Simple guidelines propose that the roof should be fully maintained with a generous overhang, and the base of the earth walls should be well above ground level. The wall surface coating should be well maintained and free from cement, allowing the structure to breathe. Damp proof courses should be avoided as they are unlikely to be of benefit and may possibly be harmful.

A meeting following the Terra 2000 conference (Houben and Avrami 2000) looked at outstanding research requirements for earthen architecture, and the mechanisms of failure were highlighted as requiring specific attention. The exact nature of the binding and unbinding mechanisms were considered to be important avenues to explore at a fundamental level. The non-structural decay of earthen buildings was identified as an issue involving two substances, water and salts, and it was argued that further research was needed into the role water plays in the cohesive mechanisms of earthen structures. In looking at the structural decay of earthen buildings, the phenomenon of creep in ancient earthen structures was noted, and it was proposed that more research was required into the relationship between water content and the load bearing capacity of earthen structures. An important observation was that cracks in earthen buildings may be regarded as normal and part of the functioning system of the structure, and should not necessarily be regarded as problematic. It was recommended that structural engineers intervening on earthen structures become familiar with cracking patterns of earthen structures, and thus be able to discern ‘threatening’ behaviour.

Keefe, Watson et al. (2001) proposed a diagnostic survey procedure for cob buildings, based on observations of Devon cob structures, having undertaken a study of 22 failed cob structures. Unsound structures were uncovered by means of a six point checklist,
Failures in rammed earth structures

namely site analysis; building description; maintenance and repair history; building condition; wall moisture content and cob composition. Features which should be present for a healthy cob building are listed as a watertight roof with projecting eaves, exposed or lime washed walls, and an absence of structural movement.

Walker, Keable et al. (2005) concentrate on modern rammed earth construction, but offer advice on the deterioration of rammed earth structures. They highlight wind driven rainfall, direct water flow and abrasion damage, rising damp in buildings and cracking as issues which must be addressed when considering a new rammed earth structure.

Most recently Trotman (2007) produced simple guidelines on the inspection and repair of earth walls. This document was based on Pearson (1997) and simple, well understood rules for cob structures which have been followed with great success in the southwest of England.

All of the above documents (with the exception of Hughes 1983) ignore the geotechnical nature of earthen architecture, and treat earth only as a soluble, brittle construction material. Taken together, the documents present a confused picture. Many of the books (e.g. Warren 1993; Houben and Guillaud 1994; Pearson 1997) and some journal articles (Hughes 1983; Hughes 2001) are the distillation of many years of experience and therefore very useful, but undoubtedly not as valuable as the presence of the author on site. Conversely, handy short documents (e.g. Trotman 2007) are a further distillation of the larger texts, and as such suffer the disadvantage of losing a great deal of information, which may be of use in the field. Without exception, the texts ignore the unsaturated nature of the construction material, and as a result it is difficult to link many of the issues discussed in anything other than a broad qualitative manner. The above documents are also specific, usually to either cob or adobe, and no such document exists for historic rammed earth.

The interconnectedness of many of the problems in earth buildings (for example a structural crack being widened by water) makes it difficult to distinguish where one problem finishes and another begins. The following categories are an attempt to distinguish between different types of problem, but certain overlap may occur. In this

Analysis of historic rammed earth construction
chapter failures in rammed earth structures have thus been divided into; ground movement, structural element problems, render problems, water, organic matter and abrasion. Each category is further subdivided, such that individual issues can be addressed.

The issues discussed are taken from the above authors and experience of failed historic rammed earth structures gained through the field visits described in Appendices B to D. Qualitative explanations are given for the situations observed, such that the findings may be applied to other similar situations. Finally, five example structures are shown, which were studied in greater detail. These buildings contain a number of interconnected failures as a result of their being constructed from rammed earth.
5.3 Ground movement

A major cause of damage to buildings is ground movement. Movement of the ground is transferred through the foundations to movement or distortion of the structure. This may cause distortion or cracking of the structure. At one extreme cracking may be visually disturbing, and at the other extreme may cause collapse of the building. Issues involving building movement usually necessitate large sums of money to be spent in the diagnosis, analysis and remediation of such structures, and many guidelines exist to assist in this process. However, such guidelines generally relate to concrete or masonry buildings, and little specific advice exists on structural movement in earthen structures. As structural movement is widely discussed, this thesis will concentrate on issues specific to historic rammed earth structures.

Any non-uniform movement of the ground on which a building is constructed will be transferred through the foundations and cause distortion of the structure. If three points beneath a building are considered (generally each end and a point between them) then if the central point moves below the ends the movement is known as sagging, and if the centre is raised in relation to the ends then the building is said to be hogging. The magnitude of the distortion of the building depends on the differential movement of different points beneath a structure, known as the differential settlement (Figure 5.3). Charles and Skinner (2004) describe six different types of foundation settlement based on the differential movement of these three points, allowing rigid body tilt or a settlement of one end of a structure to be defined.

Dickinson and Thornton (2004) describe the processes which may cause ground movement as; settlement or subsidence of the building foundations, undermining of the foundations and consolidation or chemical alteration of any fill material (Figure 5.1). While these issues apply to any building construction material, some may be considered specific to earthen materials. The majority of historic rammed earth structures studied (Chapter 4) appear to have either a lime mortared rubble foundation, to be constructed directly onto bedrock, or else built onto a rammed earth foundation. Figure 5.1 shows ground movement problems which may be particular issues in rammed earth construction.
Failures in rammed earth structures

Join opening

Wall lean

Differential settlement

Undermining of foundations

Settlement or subsidence of foundations

Consolidation of fill material

Change in ground water conditions

Figure 5.1 Ground movement problems

5.3.1 Settlement / subsidence of foundations / fill material

A change in the volume of the ground beneath a structure, or of the foundations of the structure will lead to a change in the profile of the base of the building, and therefore to distortion of the building. A change in volume may be brought about by a change in groundwater conditions, for example the raising or lowering of the water table, or diversion of a stream, or through a change in loading of the ground. Subsidence of the ground surface may occur if a structure is constructed on a site without prior compaction of the soil. The subsequent settlement is known as consolidation. However due the historic nature of all of the buildings studied, it was difficult to ascertain if there has been any settlement or subsidence of the foundations. Repeated rebuilding at Ambel (Am1) coupled with diversion of an adjacent watercourse suggests that there may well have been structural problems with a number of previous buildings, necessitating their removal or reconstruction. The case of Ambel is
discussed in detail in Section 5.9.2. However the majority of sites visited were
defensive structures built on high ground, and as a consequence, were built with a
rubble mortar foundation above solid rock.

5.3.2 Undermining of foundations

Undermining of the foundations was observed at a number of sites where random
rubble foundations were exposed, and some material had been removed (Figure 5.2).
One of the characteristics of historic rammed earth structures is the thickness of the
walls. In many cases the depth of erosion was only superficial and there appeared to
be no danger of overturning of the walls.

Figure 5.2 Undermining of the foundations. Lorca, Lo1

5.3.3 Cracking

Because it is a dry, brittle material rammed earth will be subject to cracking for a
given tensile strain. A number of methods for determining strains in buildings have
been proposed (Skempton and MacDonald 1956; Burland and Wroth 1975; Boscardin
and Cording 1989) which are based on treating the building as a deep beam subject to
load which would induce a displacement equal to the differential settlement. These methods allow estimation of tensile strains within the building, and analysis of a number of case histories has allowed development of critical tensile strains for specific materials before cracking occurs. The most recent method for estimation of tensile strains within buildings without recourse to detailed numerical analysis is by Boone (2001) who introduces the strain superposition method. This technique separates the different components of shear, bending and direct extension, which may be expected when a deep beam is deformed, then recombines them to produce a principal strain magnitude and direction. An index of critical tensile strains for different materials is provided in Burland and Wroth (1975) but does not include earth buildings.

Burland and Wroth (1975) included a summary of building damage severity based on observed crack width. A severity factor from 1 to 5 is defined based on observed crack widths ranging from less than 0.1mm to greater than 25mm, and this classification is now widely used (e.g. Driscoll 1995). However, there is no link between this damage classification and the critical tensile strain, as the number of cracks affects the width of each individual crack.

Houben and Avrami (2000) maintain that cracking in earthen architecture may be less problematic than similar structures of different building materials. However, it should be possible to determine, through visual inspection of crack patterns, the nature of movement of a structure, and therefore if the cracking is affecting the stability of the structure. Simple descriptions of shear, bending and extension cracking patterns (Figure 5.5) are given by a number of authors (e.g. Boone 2001; Kastner, Kjekstad et al. 2003), and allow basic identification of most structural movement. Shear cracking is distinguished by diagonal cracks, best thought of as a result of lengthening the diagonal when transforming a square to a parallelogram (Figure 5.4) and are shown in Figure 5.5. Bending crack patterns are shown in Figure 5.3 and Figure 5.5 and may be distinguished by being open at the top or bottom surface and closed at the centre of the wall, and of greatest length over the point of inflexion. Direct extension of the façade leads to the cracking pattern shown in Figure 5.5, with equal width cracks perpendicular to the direction of extension. Bending is more likely when there is no
Failures in rammed earth structures

tie to a perpendicular wall, and shear cracks are more likely with a rigid connection to a perpendicular wall, preventing rotation of the ends of the wall.

Rammed earth offers an additional complication to the identification of cracks because of the flow of water, which is likely to increase the width of a crack, or increase the length vertically downwards. It is therefore important to differentiate between structural and water based cracks, and to further differentiate between structural cracks which have been further opened by water.

As described in Chapter 3, rammed earth moves from being a ductile material at high water contents, to a brittle material at lower water contents. In uniaxial unconfined compression tests (Figure 3.36) the vertical sample strain at failure increases with increasing water content, and it is therefore expected that a similar relationship may be applied to rammed earth structures, with failure taking place at increased strain (but generally reduced stress) for increased water content. It is therefore possible to explain the phenomenon of façade ‘flow’ described by Houben and Avrami (2000). Unfortunately this phenomenon was not observed in any of the structures visited by the author, due to the quality of their foundations as described above. However it may be possible to find evidence of façade flow in rammed earth by observing if the lines of putlog holes (Section 4.4.4) are dipping to follow the current ground surface.

![Figure 5.3 Cracking due to sagging in repaired rammed earth wall. Novelda, Nol](image-url)
Failures in rammed earth structures

Figure 5.4 Shear crack patterns

Example structure

Sagging

Hogging

Differential settlement

Cracking pattern

Shear

Bending

Extension

Figure 5.5 Building scale crack patterns expected for different types of differential settlement

Analysis of historic rammed earth construction
5.4 Structural element problems

Problems occur when the structural elements of a building do not act as intended. This type of problem includes (but is not limited to); roof elements, beam and wall connections, perpendicular wall connections, openings and wall to foundation connections. Figure 5.6 provides an indication of these types of problems.

5.4.1 Wall to foundation connections

Modern rammed earth construction places great emphasis on the foundation to wall base connection (McHenry 1984; Easton 2007). This connection is usually provided by placing reinforcing steel vertically in a concrete foundation, and casting the rammed earth around it. However, no such tie exists in many historic structures where the rammed earth appears to be placed directly onto the random rubble foundations.

5.4.2 Roof elements

An ineffective roof may place excessive horizontal thrust onto the top of the wall. This usually occurs where the joint between the diagonal and horizontal member of the roof truss is not rigid, or if a horizontal member is ineffective or missing. This causes the diagonal members to exert a horizontal thrust on the top of the wall. Where this occurs the wall acts as a cantilever, and may deform horizontally at roof level. This deformation may then cause subsequent problems, as the roof load is then placed on a smaller section of wall. This problem was observed at Villafeliche church (Vi2) and is discussed in detail in Section 5.9.5.

5.4.3 Perpendicular walls

The connection between perpendicular walls appears to be lacking in some rammed earth structures. This is particularly the case where a different material is used at the corner (for example brick) and no tie exists between the rammed earth block and the corner material. This lack of tie means that any structural movement (caused for example by ineffective roof elements or ground movement) is not restrained by the perpendicular walls and allows opening of the joint between the two materials (Figure 5.7 and Figure 5.8), two examples (Vi1 and Am1) are discussed in Sections 5.9.2 and 5.9.5.
Failures in rammed earth structures

Flexible joint
Failure of horizontal member
Horizontal thrust from roof
Beam loading without wall plate
Beam bowing
Surface spalling
Lintel
Opening/movement of joint
Cracking
Ground movement leading to wall lean
Tie between foundations and wall
Lift joint
Vertical joint
Tie at perpendicular walls

Figure 5.6 Failure of structural elements
Figure 5.7 Opening of joint between dissimilar material. Ambel, Am1
Failures in rammed earth structures

Figure 5.8 Opening of joint between dissimilar materials. Villafeliche chapel, Vi2
5.4.4 Join between adjacent rammed earth blocks

The join between rammed earth blocks was discussed in Chapter 4, and it was shown that the join may be either vertical or angled. If any structural movement occurs, then separation of the material may occur, and this separation (cracking in a homogeneous material) will take place at the weakest point. As butted vertical joint between two rammed earth blocks cannot carry any tensile stress, the join between the blocks will open (Figure 5.9).

![Figure 5.9 Separation of two rammed earth blocks. Villafeliche chapel, Vil](image)

5.4.5 Lift joint

Rammed earth is formed by compacting earth in layers called *lifts*. A number of problems can occur due to insufficient compaction, both in the compaction of each lift leading to density banding, and between each lift introducing a horizontal plane of weakness.

Density banding (Figure 5.10) appears at the face of the wall as a concentration of highly compacted soil at the surface of a compaction layer with a gradient of decreasing density through to the base of the compaction layer. When another layer is placed and compacted above the original layer, density bands arise. The cause of the
Failures in rammed earth structures

banding is thought to be due to the passage of the impact wave through the body of the soil which spreads out as it passes through down through the soil. As the wave spreads out, the compactive load is spread over a larger area, and thus the energy imparted per unit area decreases. Thus greater compaction occurs at the surface compared to the lower layers.

No problems with the density bands were observed in the historic structures visited, but testing in the laboratory (Wall 2.1, Chapter 2) and observations of modern rammed earth builders (Lilley and Robinson 1995; Hodsdon 2006b) suggest that this is a possible source of failure.

The bond between each vertical lift of formwork was also considered to be an area of weakness, although this was only observed at one site (Bg1). The horizontal nature of construction of rammed earth means that a significant period of time may pass between compaction of one layer and of the one above. It is therefore possible that one layer may for instance become dry, and provide an insufficient key to the lift above. However, only one example of failure between the lifts was observed, and it is thought that this is due to a shearing action between the lifts (Figure 5.11).
Failures in rammed earth structures

Figure 5.10 Density banding. Villena, Vil

Figure 5.11 Failure along the compaction plane between lifts. Basgo, Bgl

Analysis of historic rammed earth construction
5.4.6 Openings

A lintel is usually provided above an opening in a structure. The lintel acts in bending to distribute the load from above the opening to the structure on each side of the opening. If this lintel is insufficient or absent, then the rammed earth is forced to act as a beam element (or arch), and tension is induced in the bottom face. The historic builders of rammed earth knew that lintels were required in some aspects of rammed earth construction, as shown in Figure 5.12. The removal of valuable material from abandoned historic structures can be problematic, as shown by the removal of a timber lintel at Daroca (Figure 5.13). It is possible for rammed earth to span openings without a lintel being present or effective, as shown in Figure 5.14. Here it is assumed that a degree of arching action is taking place.

TBIA (1999) states arching action will occur providing the abutments are sufficiently strong and rigid to resist the horizontal thrust due to the arching action, that a 45 degree isosceles triangle of material exists above the beam, and that there are no openings which would hinder the load path of the arching action. When these conditions are met, the beam will only carry the weight of the isosceles triangle of material directly above the opening, and thus a lower tensile strength is required.

![Figure 5.12 Beam above rammed earth. Villafeliche, Vil](image-url)
Failures in rammed earth structures

Figure 5.13 Lintel removed. Daroca, Da4

Figure 5.14 Rammed earth with no lintel. Alcalá de Guadaira, Al1

Analysis of historic rammed earth construction
5.4.7 Lack of or ineffective wall plate

Wall plates found in heritage structures are timbers placed in the wall below a perpendicular beam, and allow a spreading of the load on the beam to a wide section of wall. Wall plates are recommended in earth structures due to their intolerance of point loading, and have been observed in many historic structures (Figure 5.16). Where repairs have taken place, and no wall plate has been added, cracking beneath the loading point can occur (Figure 5.15). Out of plane failure can also occur where a beam joining a wall is insufficiently stiff and bows under loading. This causes an increased load at the face of the wall, and can lead to spalling of the material at the face (Figure 5.17).
Failures in rammed earth structures

Figure 5.15 Joist loading with lack of wall plate causing in plane cracking. Ambel, AmI
Failures in rammed earth structures

Figure 5.16 Wall plate hole. Tabernas, Ta1

Figure 5.17 Bowing of ceiling beams leading of spalling of the face. Ambel, Am1
5.5 Render

The purpose of a render on a wall is to protect it against water damage - to provide a liquid impermeable barrier to water movement into the wall, while remaining vapour permeable to allow evaporation and condensation. If these conditions are not met, then the water content of the wall may increase, leading to the changes in behaviour as described in Chapter 3. Issues which cause problems with render are outlined in Figure 5.18.

Traditionally lime (Section 3.6.6) was used as a render, with two different methods of application found in medieval Spain, as described in Chapter 4. Calicastrado construction lines the inside of the formwork box with lime, producing a lime rich outer surface with an uncemented core to the wall. Plain, unstabilised rammed earth does not contain any lime on initial construction, but the faces of the walls are subsequently rendered once the formwork has been struck, and this rendering is repeated at intervals during the lifetime of the building. This re-rendering may also be found on Calicastrado walls, where the rendering has degraded over time. A third type of construction was identified in Spain, that of Royal rammed earth, where an extremely lime rich mixture was used in construction. This mixture did not require rendering.

Cement has become increasingly used to repair or re-render rammed earth, but this has been highlighted as a poor repair solution (Keefe, Watson et al. 2001). As the cement is significantly less vapour permeable than lime based renders, water build up may occur in the body of the wall through reduced evaporation.

The splitting of render from the face of a wall is known as spalling, and a number of explanations have been given for this phenomenon. Hammond (1973) and Hughes (1983) cite the different expansion coefficients of the wall and the render material, and argue that heating and cooling of the wall leads to stresses building up causing the render to crack. Hall and Djerbib (2006a) argue that the spalling of render from a face is caused by an increase of pore water pressure behind the render caused by the
infiltration of water. This increased water content may lead to a volume change of the wall, manifested as a bowing at the free surface.

Hughes (1983), Warren (1993) and Walls (2003) argue that the precipitation of salts on the surface of a wall causes a breakdown of the surface of the wall. Mineral salts are dissolved in the pore water, and movement of the pore water to the surface, followed by evaporation deposits the salts at the surface of the wall. If these salts are deposited in pores, then as they precipitate they grow and increase the stresses locally on the face of the wall causing fracture. This mechanism seems similar to the ‘popping’ of unslaked lime highlighted by Pearson (1997) who describes the disadvantages of producing slaked lime on site when rendering UK cob buildings. Slaking quicklime (Chapter 3) on site is liable to leave small particles of unslaked lime which are then incorporated into the render. When this unslaked lime reacts with moisture it is liable to ‘pop’ causing blisters in the render; a process which is liable to continue for a number of years.

Given the horizontal construction of rammed earth, most commonly using crawling formwork (described in Section 4.4.4) a single batch of less well-mixed lime may be used for a series of formwork boxes, and the resulting poor render mix only becomes apparent years after construction. It is possible to cover this substandard section, but once the building falls into disuse, routine rendering ceases and the original mistakes quickly become apparent. Popping is probably the cause of the apparently randomly pitted surfaces at Baños de la Encina (Ba1) which was built using Calicastrado rammed earth, probably using lime slaked on site. Here single discrete lifts appear to be missing render, while the lifts around are in good health (Figure 5.21).

Structural problems outlined in Sections 5.3 and 5.4, such as failure of lintels, lead to cracks in both the render and the body of the rammed earth and allow water into the body of the wall. Once the render is split there is a path for water to enter the body of the wall, which leads to further problems because of the increased water content and allows further erosion to the face of the wall behind the render. If decay of the render is sufficiently advanced then the remaining render may not be able to support sections of split render, and thus larger sections fall away from the wall (Figure 5.19).
Unslaked lime particles 'popping'

Evaporation leads to deposition of salts which break apart the render

Insufficient evaporation leading to increased water content and possible build up of pore water pressure.
Increase in volume of section leads to bowing of surface

Calicaraedo rammed earth | Rendered Plain rammed earth

Figure 5.18 Issues which cause problems with render

Figure 5.19 Cracked cement rendering. Ambel village, Spain

Analysis of historic rammed earth construction
Failures in rammed earth structures

Figure 5.20 Splitting of render from the wall. Ambel Preceptory central tower (Appendix B)

Figure 5.21 Decay of render due to quicklime popping. Baños de la Encina, Bæl
5.6 Water

The poor resistance of rammed earth to water penetration is highlighted by comments made by a French officer defending rammed earth castles in Morocco in 1956 - “It’s not their guns I’m frightened of, but God help us if they use water pistols” (Maxwell 2000).

An increase in water content of rammed earth has been shown to reduce the strength of the material, to reduce the stiffness, but to increase the ductility. In Chapter 3 it was argued that the strength of unstabilised rammed earth was due to the phenomenon of suction, and that the unsaturated nature of rammed earth caused an increase in strength above that provided through pure interlock.

It was further argued that the suction in the rammed earth was controlled by evaporation and condensation, and that infiltration of water into a body of rammed earth could be determined by considering capillary flow. If the rate of flow of water into rammed earth is greater than the rate of evaporation, then the moisture content of the body of rammed earth will increase, and this will cause a reduction in strength and stiffness as shown by the experimentation detailed in Chapter 3. However, this increased water content and consequent reduction in stiffness may be one reason that earth buildings have been considered as able to ‘flow’ (Houben and Avrami 2000), and therefore if the strength is not exceeded, it is possible that at increased water contents the rammed earth may deform plastically, leading to slumped structures.

Figure 5.22 shows water based problems in rammed earth structures. These problems are generally related to either a lack of upkeep of the building (for example lack of render coat or removal of roof) which allow rainfall to impact the surface of the wall, or through a change in environment in the vicinity of the building (for example the wall is used to retain soil, or a change in the groundwater conditions), which allows water to rise from the ground into the body of the wall. All these mechanisms lead to an increase in the water content of the wall if the evaporation rate is not raised to match it.
5.6.1 Rainfall onto the surface of a wall

Historic structures in northern Spain, and most modern rammed earth construction employ broad eaves to prevent rainwater from impacting the wall. Although Houben and Guillaud (1994) argue that water which strikes a wall surface is not particularly serious if it subsequently evaporates, current guidelines (Walker, Keable et al. 2005) recommend 400mm eaves, of similar proportions to those observed in historic buildings in Spain. However, where these eaves are not present, rainwater is able to impact the wall, and it is thought that this impacting can cause erosion. Warren (1993) argues that water is absorbed into the outer skin of the wall which causes it to swell. This closes the pores which reduces the rate of absorption but slow penetration of water takes place through capillary action. Once the layer is saturated the outer particles will be carried away, but in most cases the wetted but not dissolved outer skin becomes a barrier which prevents the passage of moisture. Hall and Djerbib (2006b) present a similar argument describing a waterlogged overcoat region at the face of a wall, which increases with depth through capillary flow. Both of the above postulates require absorption of water through capillary suction, which does not cause saturation, and therefore collapse, of the surface face.

Section 3.12 outlines the process of infiltration into a wall. Provided that the surface of a wall is not fully saturated, and that water is able to flow down the wall, it is apparent that infiltration through capillarity will be relatively low. It was argued that the saturated region described by Warren (1993) and Hall and Djerbib (2006b), should instead be described as a region of increased relative humidity. This increased relative humidity at the surface penetrates into the wall, but in doing so moves water away from the surface, ensuring that the surface does not become saturated. A saturated, and therefore eroding region will only occur when the relative humidity of the pores at the surface reaches 100%. A particle may then be carried away by the water at the surface as described in Section 5.6.3. Figure 5.23 shows rammed earth during a severe rainstorm, the wetted regions of wall appearing darker than the dry sections. There appears to be little infiltration into the walls due to rainfall impact, and the dark sections are caused by water ponding on the top of the wall before it flows down, exactly the process described in Section 5.6.2.
5.6.2 Water ponding at the top of a wall and flowing down the face

Where the roof of a structure is insufficient or absent, or the wall is retaining soil behind it, then water may pond above the wall and run down the face. This ponding and subsequent running causes incised vertical runnels in the vertical surface of the wall. If these runnels are allowed to grow and join, then the whole face of the wall is in danger and may erode completely. This was observed to be a very common problem in many of the structures studied in Spain, though notably where the top surface of the wall was sufficiently durable to resist erosion and the formation of ponds, no vertical runnels were formed. It was also observed that water was able to pond in putlog holes, then flow out of the hole down the face of the wall, again causing vertical incised runnels. Vertical runnels were not observed where water was not able to pond at the top of the wall, such as at Baños de la Encina (Ba1) where the topmost lift of rammed earth appeared more lime rich than the remainder of the wall. If an effective roof structure is present then ponding does not occur at all. If sufficient time passes with erosion acting on the face of the wall, then the vertical face will eventually erode to a slope. This was observed at a number of sites (for example Tal and Da2) and illustrated in Figure 5.27.

5.6.3 Water flow down a wall

If the rate of water flow down a wall is low, then cast type structures (Figure 5.31) may be found. These casts were observed at a number of sites (for example Am1, Tal and Da4) and should be interpreted as a material which has first flowed into a slurry, then dried to leave mounds of fine material on the wall face. The presence of these structures indicates the downward movement of material and is thus indicative of past water flow. The likely cause of the formation of the structures is the slow downward movement of water down the face of a wall, for example a drip which is able to pick up material and transport it in solution down the wall, until such a point as the drip evaporates and the material is returned to the wall. Inspection of these structures indicates that they contain only very small particles, as it is only these which may be picked up by the water.

The rate of infiltration of water into a wall is governed by capillary size. If the rate of infiltration is sufficiently high then it is possible that the face of the wall will not become saturated during a rainfall event, rather that the moisture content of the whole
Failures in rammed earth structures

wall increases slightly. This may explain Figure 5.23, although it is possible that this wall contains a certain proportion of cementing agents, which are able to act regardless of the water content.

5.6.4 Water flow at the base of a wall

Where the roof eaves are insufficient or when channels have formed, water is able to flow at the base of a wall. This flow erodes any foundations (Figure 5.2), and if no foundations are present, then the rammed earth itself is eroded and undermined (Figure 5.32). Walker, Keable et al. (2005) recommend eaves of at least 400mm overhang and a concrete upstand at the base of the wall of 225mm to prevent water splash and water flow. The removal of material from the base of a wall may cause it to overturn (Figure 5.33), or lead to unconfined compressive failure of the remaining material.

5.6.5 Water flow through a wall

Earth structures which act as retaining walls must be considered differently to masonry or concrete structures due to the possible flow of moisture through the wall and the changed behaviour of the wall due to this moisture flow. A number of examples were found where a historic wall was acting as a retaining wall, which usually occurred after the building fell out of use or when parts of an earth structure had been knocked down. For example if the tops of towers are removed, the material may fall inside the tower, elevating the internal ground level (observed at site Tal) or outside the tower (Lo1), creating a slope at the base of the tower. At site Bal, the inside of the castle walls were used as a graveyard, artificially increasing the internal height, and leading to water flow through the walls (see case study of Baños de la Encina castle, Section 5.9.1)

5.6.6 Capillary rise

A seasonal or permanent rise of groundwater level can cause water to rise by capillary action into the walls. This process is described in Chapter 3. If the rate of evaporation is lower than the rate of water uptake, then an increase in moisture content of the wall will result. This increase in water content will reduce compressive strength and increase the ductility of the wall, as shown in cylinder tests described in Chapter 3. This may in turn lead to a slump of the wall, but collapse of this kind was not
observed at any of the sites visited. Because many of the sites observed were
defensive hilltop sites and being built onto solid rock, were not significantly
susceptible to ground water level changes. The diversion or containment of a stream
or river may also change the ground water profile, and it is thought that this has
occurred at Ambel as is described in Section 5.9.2.

5.6.7 Wind causing increase in suction

Hall and Djerbib (2006b) postulate that moisture penetrating a wall will migrate
towards the face of lowest pressure. Incident wind on a wall would cause the air
pressure at the wall surface to increase, which, it was assumed would drive moisture
towards the leeward side of the wall. This would cause differential drying on the
leeward side, which could lead to this side being stiffer and stronger than the
windward side, causing a lean of the wall.

Chapter 3 outlines an alternative situation to that envisaged by Hall and Djerbib
(2006b). It was argued that increased air pressure at the face of a rammed earth wall
would lead to increased suction. This increased suction reduces the air entry pore
radius which would cause evaporation from the wall, leading to the collapse of some
liquid bridges at the face of the wall. The removal of these stabilising liquid bridges
does the removal of the particles at the surface of the wall leading to erosion. The
magnitude of such effects has not yet been studied, but the mechanism described may
account for erosion of walls directly through wind, as opposed to through the impact
of wind borne particles (described in Section 5.8).
Failures in rammed earth structures

Water flow through retaining wall

Figure 5.22 Problems caused by water

Capillary rise

Rainfall onto surface

Water flow down face

Water ponding causing incised vertical runnels

Wind causing an increase in suction

Figure 5.23 Rammed earth wall during a severe rainstorm. Alcala de Guadaira, Al4

Analysis of historic rammed earth construction
Failures in rammed earth structures

Figure 5.24 Small incised runnel. Cordoba city wall, Co4

Analysis of historic rammed earth construction
Figure 5.25 Large incised runnel. Cordoba city wall, Co5
Failures in rammed earth structures

Figure 5.26 Incised vertical runnels. Basgo, Bg1

Figure 5.27 Heavily eroded face. Daroca, Da3

Analysis of historic rammed earth construction
Failures in rammed earth structures

Figure 5.28 Rammed earth retaining wall during a severe storm. Alcalá de Guadaira, Al3

Figure 5.29 Rammed earth retaining wall during a severe storm. Alcalá de Guadaira, Al3

Analysis of historic rammed earth construction
Failures in rammed earth structures

Figure 5.30 Water sheet failing to erode a rammed earth wall. Alcalá de Guadaira, A13

Figure 5.31 Cast structures. Ambel, Am1
Failures in rammed earth structures

Figure 5.32 Eroded rammed earth. Daroca, Da4
Failures in rammed earth structures

Figure 5.33 Base of collapsed wall. Daroca, Da4
5.7 Organic matter

Living organic matter is considered to be problematic in earthen architecture. Organic matter in the vicinity of a rammed earth wall, on the surface or within the body of the wall is usually recommended for immediate removal. By contrast the inclusion of dead organic matter in all earthen architecture is commonplace. In rammed earth chopped straw is sometimes included in the mix, and putlog timbers have been found embedded in the walls (Chapter 4).

5.7.1 Growth

Vegetation growing adjacent to a rammed earth wall allows the development of a local microclimate, and possible increase in relative humidity and reduced temperature compared to the ambient. As outlined in Chapter 3, an increase in relative humidity may lead to a reduction in strength of the wall. Lichen was observed on north facing walls at two sites (Bi and Ra) and grass was observed to be growing on the eroded wall tops at Carmona (Ca) (Figure 5.34), but this vegetation did not appear to have any detrimental effect on the wall. Hughes (1983) and Warren (1993) argue that the growth of roots will cause the formation of internal cavities in the structure, but this was not observed at any of the sites visited.

While it is thought that while plant growth is probably problematic for reasons of changing the microclimate as described above, they may also serve a protective purpose. For example in Ambel (Am1) it has been observed that large leafed climbing plants such as ivy may be deliberately planted on top of rammed earth walls around gardens. The leaves serve to direct rainwater away from the top of the wall. Therefore, when deciding if a plant is likely to cause damage, the methods of attachment (suckers or leaves) should first be determined. It was interesting to note that a large number of historic and abandoned sites, displayed no sign of any vegetation growth (for example sites Ba1, Bi1 and Ra1) and this is thought to be due to the high lime content and thus alkalinity of the wall.

5.7.2 Decay

Organic matter within the wall, if exposed to the atmosphere, may decay and cause voids to form within a wall. These voids cause increases in stress in the adjacent...
material, which could lead to failure of the wall. Timber is found in two main forms within rammed earth, as ring beams running horizontally thought the wall at a number of different levels, and as putlog timbers, used to support the formwork during construction, and not removed afterwards. Timber may also be used as a lintel over opening, and as either a wall plates for joists supporting a ceiling or floor.

Where the moisture content of the timber is allowed to increase above that of the wall, and the rate of evaporation is insufficient to quickly reduce the moisture content, then it is possible that the wetted timber will transfer moisture to the body of the wall. If there is insufficient evaporation from the wall, then the moisture content of the wall will increase, leading to the problems outlined in Section 5.6. The rate of moisture flow through timber is thought to be greater than through rammed earth, and so it is possible that timbers act as reservoirs of water, able to distribute water around the wall.

The wetting of putlog holes did not appear to be an issue at the sites visited. This is likely to be due to the presence of stones above the holes as detailed in Chapter 4. The stones above the holes act to bridge the load over the void, and thus any increase in size of the void does not affect the integrity of the structure. In addition the small face area of the timber means that comparatively little water is absorbed into the timber, and thus is able to evaporate once a rainfall event has ceased. The decay mechanism may also be self regulating, as exposed timber decays and is removed, the remaining timber is then more sheltered from rain than before, and so it is possible that there is a depth of decay which is never passed (Figure 5.35)

Unfortunately it is only possible to observe ring beams where the fabric of the wall is destroyed, therefore many ring beams probably exist which are not visible. However, where ring beams have become exposed to the atmosphere, they appear to be relatively decayed, and therefore reduce the integrity of the structure. The reason for the decay is thought to be either due to animal infestation (such as rats - Figure 5.36), or through degradation by virtue of the increased water content. A ring beam acting as a conduit for water was found at Tabernas and is discussed further in Section 5.9.3.
Figure 5.34 Grass growth on rammed earth wall. Carmona, Cal
Failures in rammed earth structures

Figure 5.35 Putlog timber still present in wall. La Rambla Tower, Ra1

Figure 5.36 Decayed ring beam hole. La Rambla wall, Ra2

Analysis of historic rammed earth construction
5.8 Abrasion

Abrasion is the mechanical movement of one surface against another, resulting in the removal of material from one or both of the surfaces. Abrasion is not normally considered to be a major durability issue in masonry or timber structures, but has been identified as problematic in rammed earth structures (for example Pearson 1997 and Walker, Keable et al. 2005). The removal of material by abrasion causes an erosion of the surface, and the rate of erosion depends on the hardness of the interacting surfaces, the velocity and the mass of the objects abrading.

Abrasion is most studied in the field of rock mechanics and geology, both when looking to understand natural geological formations (for example glaciers cutting valleys) or man-made structures (for example aggregates used in road surfacing). Unstabilised earthen structures are thought to abrade more easily than rock or concrete because of the lack of any cementing compounds between the particles. Abrasion tests for rock samples are relatively simple and well developed, and consist of placing a sample in a horizontal axis rotating drum above a body of water. The sample contacts the water once every rotation and abrasion is measured as a volume of sample lost per rotation. Such a test is unsuitable for uncemented rammed earth and so dry tests for earth building have been developed by Minke (2000) and Walker, Keable et al. (2005) which measuring the depth of erosion produced by a wire brush rubbing the surface under constant load for a given period of time. While these simple tests are indicative of the potential for erosion of a given dry earth mix, the erosion found in the field is likely to be influenced significantly by other environmental factors. Three different types of abrasion were defined – that caused by human, animal and wind.

5.8.1 Human

Damage to structures by abrasion was most noticeable in urban areas, where the rammed earth city walls were part of a city thoroughfare and thus subject to abrasion on a daily basis. Abrasion is found at foot, hand and shoulder level, and can leave a slope of weathered material at the base of the wall (Figure 5.37). Examples can be found at these levels at walls in Seville (Se2), Palma del Rio (Pa3) and Cordoba (Co5). However city, walls are generally around 2-3m wide and thus even erosion to a
depth of 10cm (as observed in Seville) is not significant due to the thickness of the wall. This type of damage is not usually found at independent castle sites.

5.8.2 Animal

Infestation of animals or birds has been reported as a major cause of damage to some rammed earth structures (for example Walker, Keable et al. 2005), and the damage may be considered as removal of material therefore erosion through abrasion. In the UK masonry bees have been reported to burrow into the face of earth walls. Hughes (1983), Keefe (1993) and Pearson (1997) describe problematic rodent damage in cob barns where animal feed is stored. Langenbach (2004) argues that termite runs through adobe bricks may have led to reduced strength and increased vulnerability of buildings during the Bam earthquake in Iran. However, rammed earth in Western Australia is sold as an alternative to timber construction due to its increased termite resistance when compared to timber. In extreme circumstances, tunnelling at the base of a structure by burrowing creatures, and excavation of material by nesting birds by reduce the plan area in parts of a wall. This will increase the vertical stress in the remaining parts of the wall, and if the stress is sufficiently increased it is possible that the strength of the wall might be exceeded causing collapse.

Rat infestation was found at one site (Ra2), with rats running through existing tunnels which originally contained timber ring beams. It is possible that the rats are gradually increasing the volume of the tunnels and therefore reducing the structural integrity of the wall. Pigeon infestation was found at a number of abandoned rammed earth sites, and they appeared to nest in and enlarge existing holes such as at Baños de la Encina (Ba1), La Rambla (La2), Carmona (Ca1) and Palma del Rio (Pa3) (Figure 5.38). However, the infestation by birds is in itself unlikely to lead to collapse of the building.

5.8.3 Wind

Hughes (1983) argues that erosion of the windward side of a building can be caused by the impact of sand particles against the exposed face. This is likely to occur where the wind is able to pick up loose sand particles and cause them to impact a wall. Such erosion of earthen structures may therefore occur in desert environments such as observed at Merv in Turkmenistan by Cooke (2005). However, abrasion of rammed
earth walls through impacting sand particles was not observed at the sites visited by the author. This is due to the sites either being in urban areas, where the wind has less opportunity to pick up and retain sand sized particles, or were defensive and therefore usually hilltop sites, exposed to the wind, but not to wind borne sand particles.

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Figure 5.37 Human caused erosion at city wall section, now childrens play area. Cordoba, Co5

Figure 5.38 Pigeons nesting in rammed earth wall, Palma del Rio town walls, Pa2
5.9 Case studies

A small number of case study structures have been examined in more detail. These structures contain a combination of the failures mentioned above, and serve to illustrate the sometimes complex and interconnected nature of rammed earth construction.

5.9.1 Baños de la Encina – rammed earth retaining wall

The castle at Baños de la Encina is described fully in Appendix C, and is briefly described here. The castle was constructed in 967AD using a lime rich rammed earth mix (Figure 5.39 and Figure 5.40). It was used as a Muslim fortification until surrendered to the Christians in 1225 (Ramos Vazquez 2003), and continued to be used for a further four hundred years. The structure lay abandoned and was used as the village graveyard from the mid 19th century until 1928. As a result the internal ground level is over 5m higher than the external (Figure 5.40). The walls are founded on bedrock and all the material inside the walls has been transported there from the surrounding area. The building appears structurally sound and whilst large cracks are evident there are no reports of structural movement. The placement of 5m of material to the inside of the walls appears to have caused damage of the external surface of the walls (Figure 5.39). Cement has recently been placed against the damaged face, and it now appears that the damage process has moved up the wall. Figure 5.41 shows a section of the wall.

Any rainfall which falls within the walls is likely to flow out through the more permeable walls rather than the less permeable bedrock. This flow of water has obviously caused damage to the external surface, as shown in Figure 5.39, where it can be seen that the base of the wall is significantly more pitted than the section above. It is also interesting to note in the towers that the ground level is original, and significantly lower than the ground level in the centre of the castle (Figure 5.40). Figure 5.39 shows that the damage at the base of the wall occurs only in the joining wall sections, and not at the towers - the reason for the damage to the base of the left hand tower is thought to be ‘popping’ of unslaked lime, explained in Section 5.5.
Hughes (1983) and Walls (2003) argue that the cause of this damage is the precipitation of minerals on evaporation from the wall. This is very possibly the case in this instance, but the high lime content of the wall and damage in unrelated sections also suggest that the mineral may be unslaked lime. The flow of the water through the wall transports the lime to the face of the wall, where it precipitates, and reacts with atmospheric carbon dioxide, causing the popping observed in other sections of the wall. The flow of water through the wall merely increases the speed of this process. Figure 5.39 shows three distinct bands on the rammed earth - a lower band where damage to the surface is distinctly evident, a central section where the rammed earth appears more brown, and a grey top section which is presumably the original colour of the rammed earth. A small concrete repair has been effected at the base of wall, and similar repairs exist in most of the wall sections around the castle. The purpose of this layer is to stabilise the face of the wall, but is considered not to be best practice (see Chapter 6 for more details).
Failures in rammed earth structures

Figure 5.40 Raised ground surface inside castle, note ramp down to door (left). Baños de la Encina, Ba1

Figure 5.41 Wall section. Baños de la Encina, Ba1

Analysis of historic rammed earth construction
5.9.2 Ambel – Floor collapse leading to gable end lean

The chronology of the north east tower at Ambel is complex and difficult to determine accurately. Detailed plans, photographs and a suggested chronology are given in Appendix B. Monitoring of cracks, undertaken since 1997, shows an increased lean in the upper part of the gable wall (Figure 5.43). This alarmed the guardians of the building, who installed ties at the top three stories, attempting to join the gable end to the rest of the structure. These ties are discussed further in Chapter 6, but to date appear ineffective.

Detailed analysis of the structure, observation of the crack patterns, and routine monitoring of crack movement mean it is possible to determine the reason for the cracking, and to suggest possible remedies. Figure 5.44 and Figure 5.45 show the external and internal elevations of the structure. Cracking is shown in green, crack monitoring points on the east wall in yellow, and crack monitoring points on the west wall in blue. In Figure 5.45 brick is shown in red, stone in grey and rammed earth remains white. The exterior of the wall was originally rendered, but most is now missing leaving an eroded rammed earth face. A ruined lean to barn abuts the structure to the east side (visible in Figure 5.43), and the wall below its roof line is plastered. Plans of each level of the structure are shown in Figure 5.46, with cracking visible on the floor marked in green.

Cracks running NW-SE on the floor at first and ground levels (Figure 5.46) suggest that the north east corner of the structure is settling with respect to the rest. These cracks may be viewed as opening when the structure is in the process of hogging as described in Figure 5.5. Repeated rebuilding, evidenced by the possibility of three earlier structures on the site (Appendix B) also suggests that there may have been previous settlement of the ground, causing the various phases of building to collapse or require major reconstruction.

The crack pattern in the centre of the structure (Figure 5.47) suggests direct extension, combined with a possible downward movement, of the north end of the structure. These cracks have now been patched and appear stable, but it is clear from the imperfect patching that the crack growth did not stop on filling of the cracks. The
extension may be caused by an ineffective retaining wall to the north of the site, as shown in Figure 5.47 and in Appendix B. This may have caused a movement of the ground beneath the structure leading to opening of both the central cracks, and on patching of these cracks, the opening of the gap between brick and rammed earth at the northern gable end. The outward lean of the gable end suggests a rotation action, which would lead to the opening of bending cracks at the top of the structure. It appears that the bottom (leaning) section of the gable wall was buttressed at one time (holes are visible in the lower brickwork on the gable end (Figure 5.42 and Appendix B), in order to arrest further movement. Current crack monitoring suggests the greatest movement at the top of the gable end (0.6mm in 9 years), indicating that the leaning section below is continuing to move (opening of crack 9) which is causing movement of the vertical section above this (cracks 1 and 2). The west wall of the north east tower (monitoring points shown in blue, Figure 5.46) appears also to be moving slightly northward at the top level, which would indicate a movement of the gable end, pulling the west wall apart. Although monitoring has taken place over only a relatively short period of time, the full extent of the damage may be better determined from observation of the floor to wall connection at each level. 18th century rebuilding replaced and repaired the ceiling beams at every level at the gable end, suggesting that there had previously been movement (see internal elevation, Figure 2.7 Appendix B). Assuming these beams were flush with the wall in 1797 documentary evidence suggests that the repair took place (Gerrard 2003), the gap between the floor and the wall is now 35mm at ground floor, 44mm at first floor level, and 45mm at roof level (approximately 0.22mm per year). This suggests continuing northward movement of the vertical section of the wall (roof and first floor level) and increased lean of the lower section (basement and ground floor level).

The historic crack patterns, combined with crack monitoring data, all point to a settlement of the north east corner of the tower. Given current crack monitoring, this settlement does not appear to have abated. Repair strategies for this structure are discussed in Chapter 6.
Failures in rammed earth structures

Figure 5.42 Ambel north east tower, Am1

Figure 5.43 Ambel north east tower, Am1

Analysis of historic rammed earth construction
Failures in rammed earth structures

Figure 5.44 External elevation, showing cracking and numbered monitoring points. Ambel north east tower east wall, Am1

Figure 5.45 Internal elevation of the west face of the east wall, here inverted to match the external elevation. Cracking, numbered monitoring points and construction materials shown. Ambel north east tower east wall, Am1

Analysis of historic rammed earth construction
Figure 5.46 Floor plans at each level. Floor cracks shown in green, monitoring points on east wall in yellow, and west wall in blue. Ambel north east tower, Am1
Failures in rammed earth structures

Figure 5.47 Cracking patterns 1. Ambel north east tower east wall, Am1

Figure 5.48 Cracking patterns 2. Ambel north east tower east wall, Am1

Analysis of historic rammed earth construction
5.9.3 Tabernas tower - decayed timber allowing internal water transport

The site at Tabernas (Ta1) is extensive, with a number of now isolated towers once linked by an encircling castle wall (described in detail in Appendix B). The date of the construction of the castle is uncertain, because of the highly decayed nature of the site. However the castle is the symbol of the town, and of a famous Olive Oil factory in the town. Therefore the majority of the castle visible from the town has been rebuilt in concrete. A number of sections of wall have also been faced in masonry, but one intact tower remains.

The tower (Figure 5.50) is partially destroyed, with the top sections removed and pushed into the centre of the tower, increasing the internal floor level of the tower. A section of wall has been removed and the ground is sloped, allowing access to the inside of the castle. The break reveals two timber beams embedded in the centre of the wall (Figure 5.49, Figure 5.50, Figure 5.51 - A), and further investigation revealed more timber embedded in a perpendicular wall at the same height (Figure 5.49, Figure 5.50, Figure 5.51 - B). Another hole was discovered in the opposite wall (Figure 5.51, Figure 5.50 - D) where it is thought another timber is present.

In Chapter 3 it was argued that the purpose of these timbers is to act as tension members within the rammed earth; as a simple reinforcement, or ring beam. The method of joining timbers at the corner of the structure could not be determined, but if the timbers are indeed fixed together then this offers an excellent insight into the additional reinforcement provided by the medieval Muslim engineers who built these structures.

The decay of the structure has led the timbers to act as reservoirs and conduits for water within the structure, and has allowed water to flow easily to areas which would otherwise have remained dry (as described in Section 5.6.5). In particular the top of the structure has eroded through the ponding of water (as shown in Figure 5.52), leading to a crack in the external face (Figure 5.50). This crack is however mirrored by a perfectly vertical crack on the inside of the structure (Figure 5.52). 0.5m above the internal floor of the structure, there is a large hole in the wall (B) which provides access to a timber running through the centre of the wall. Figure 5.50 shows the likely
route of water within the wall, showing that flow is likely to have occurred downwards from an initial point of access at the top of the structure (1), through the topmost ring beam hole, and out of point D (2 and 3), or continued downwards to point B (4), where it flowed out of the wall into the interior of the structure.

This example highlights the danger of previously sealed and dry timbers, which become exposed to the elements. Hughes (1983) argues that once wetted these timbers may remain at a higher moisture content than the rest of the structure. This may cause the surrounding sections of wall to become waterlogged and may reduce their strength and stiffness. However, this reduced strength does not seem to have occurred, and instead erosion of material through increased solubility appears to have happened at points B and D (Figure 5.50) where water has flowed out of the wall.

Figure 5.49 Ring beam embedded within wall. Tabernas, Ta2
 Failures in rammed earth structures

Water flow

Ceiling beam hole and wall plate (internal) → Crack (external)

Possible ring beam positions

Hole caused by water (external)

Hole caused by water (internal)

Ground surface

Figure 5.50 Diagram and photographs of water movement. Tabernas, Ta2

Analysis of historic rammed earth construction
Failures in rammed earth structures

Figure 5.51 Detail tower plan. Tabernas, Ta2

Figure 5.52 Tower internal, looking west. Tabernas, Ta2
5.9.4 Villafeliche barn – ineffective roof leading to gable end lean

A barn observed at the village of Villafeliche, in northern Spain provides an excellent example of combined water and structural problems. The building is fully described in Appendix B and a brief outline is given here. The method of construction is similar to that found in southern France, but known in Spanish as *tapial con lunetos*, a reference to the half moon shaped lime sections in the corners of each rammed earth block (described in Chapter 4). The barn is situated on the main thoroughfare into the village and appears to still be in use. The present historic structure abuts a concrete barn but does not appear structurally connected to it. The rear wall of the structure may be acting as a retaining wall, but this was impossible to establish. Unfortunately access internally was not possible.

The gable end of the structure is leaning outwards, and a crack extends from roof level through the rammed earth almost to the rubble foundations of the building. It is difficult to establish if the movement of the gable end has caused the roof to collapse, or if the roof collapse has led to the water penetration and enlargement of the crack. The former is more likely, for the following reasons:

- The initiation of the crack at roof level is between two rammed earth blocks.
- The crack does not flow vertically downward, but instead seeks out the ‘weakest’ point in each lift (Figure 5.53).
- The construction of the roof – U-shaped tiles laid in layers – even when partially destroyed, would not channel water towards the crack, but would instead always direct water to the face of the wall.
- The crack is widest at the top of the structure and tapers towards the bottom.

With these observations in mind, it is possible to assume that the crack is structural and not caused by water. Although the cause of the lean of the wall is uncertain, and difficult to establish without further detailed investigation, the structural nature of the crack requires that the cause of the lean be mitigated and any remediation work carried out should offer structural support in addition to filling and waterproofing of the crack.

This relatively simple example shows that diagnosis methods, such as those described in Section 5.3.3, may in this case be applied to rammed earth. Here water flow has not
Failures in rammed earth structures

disguised the cracking pattern and it is possible to show that the rammed earth blocks here act as large unmortared masonry, with the crack pattern attempting to weave between the rammed earth blocks. Only when it is not possible for the crack to travel between blocks does it actually split the rammed earth block through the centre. The problem of debris in the crack, as discussed by Hughes (1983) is clearly visible here and may be observed, if this debris were to be removed then the crack could close.

Figure 5.53 Elevation. Villafeliche barn, Vil

Crack pattern
- At vertical joint
- Following lime arc
- At vertical joint
- Following lime arc
Figure 5.54 Cracked face. Villafeliche barn, Vil
Failures in rammed earth structures

Figure 5.55 Gable end. Villafeliche barn, Vil

Analysis of historic rammed earth construction
5.9.5 Villafeliche chapel – Roof collapse

The chapel in Villafeliche was probably built in the 19th century, and lies on the outskirts of the village. The distinctive patterns of brickwork beams and columns with rammed earth infill is similar to that found at Ambel (Am1) and Buretta (Bu1). However, the placing of red tiles in the centre of the rammed earth section appears unique to this particular village, being found at a number of buildings and on garden walls in the surrounding area. The chapel consists of a core square of sixteen columns, with semicircular extensions to the north, south and east. The nave and entrance is to the west of the structure and appears to have been added later - there is no structural connection between the walls of the church and the nave. A plan of the chapel is shown in Figure 5.58 and a full description given in Appendix B.

The construction of the chapel is shown in Figure 5.59, with vertical brick columns intersecting horizontal brick beams, running the full thickness of the wall, and three bricks deep. Single rammed earth blocks then form the infill between the bricks, each block having been rammed individually after construction of the brick beam. This is evident from the differing number of brick layers on the north and south sides of the chapel, and can be appreciated in Figure 5.56 and Figure 5.57. Close inspection of Figure 5.56 shows that the horizontal brick layers are not actually tied to the brick columns at every level, and the tying generally occurs at alternate levels.

The structure has suffered from a collapsed roof. Although currently the east elevation remains fully intact (Figure 5.56), the north and south walls both lean outwards. The north and the south walls are partially destroyed and the south apse contained a full height window which has been destroyed to its base level. At the west of the chapel, the nave remains intact, and the doorway is of full height, but little remains of the west wall above 3m height. The north and south walls taper from full height at the east side to 3m high at the south side. Internally the eight columns to the west remain intact, supporting arches in varying degrees of decay. The two central east columns have collapsed outward, knocking the external east columns through the walls and onto the ground outside to the north and south east of the chapel. The roof of the structure is mostly absent, apart from an intact dome in the north east corner. It is clear that the exterior corners of the chapel were roofed with small domes and that the
central cross consisted of either perpendicular pitched roofs or pitched roofs at the ends and a large dome over the centre of the chapel. A series of photographs of the chapel may be seen in Appendix B.

The cause of the collapse at the Villafeliche chapel is likely to be overloading of the roof leading to excessive horizontal thrust being placed onto the tops of the walls. One possible cause of roof overloading could be snow loading. The greatest erosion is to the north west face, suggesting a north west prevailing wind direction. A prevailing wind from this direction would deposit snow on the roof as shown in Figure 5.60. This loading would lead to increased horizontal thrust at the top of the columns, leading to collapse. On failing, the central columns fell outward, hitting the external corner columns at the west of the building. The remains of these four columns now lie outside the body of the structure to the west of the site. This collapse led to the eight eastern most columns supporting the remaining roof. The lack of restraint at the centre of the structure placed increased loading onto the east and west wall, causing their outward movement but not collapse (Figure 5.56 and Figure 5.57). This outward movement has led to cracking through the brickwork at the topmost three rammed earth lifts, and has caused a lean of the wall which is clearly visible to the naked eye. Currently the structure appears to be in perilous danger of total collapse.

The situation of the structure highlights the dangers of building using the technique of rammed earth infill between brickwork beams and columns (described in more detail in Chapter 4). In particular this structure has highlighted the need for full tying of the brick beams to the columns at each level. Observation of the ruined structure leads to the conclusion that the rammed earth is not tied to the brick in any way, but merely sits on the surface. However the considerable mass of the rammed earth blocks appears to be sufficient to prevent sliding of the blocks when the wall is leaning. Although this failure is not directly related to rammed earth as a construction material, it is related to the construction technique, and as such is considered to merit inclusion in this section.
Failures in rammed earth structures

Figure 5.56 East elevation photograph. Villafeliche chapel, Vi2

- Crack through rammed earth
- Crack due to separation of leaning face from gable end
- Crack in column
- Vertical timber incision
- Brick plinth
- External faces of internal columns
- No plinth at internal corner
- Rammed earth to top of windows, adobe above
- Brickwork not tied to column

Figure 5.57 East elevation. Villafeliche chapel, Vi2

- Wedge section to correct for initial lean of walls
- Leaning wall caused by roof collapse
- Highly eroded section above roofline
- Red tiles on white plaster for strong visual impression
- Highly eroded panels
- Tiles lying on road, not smashed by vehicles, indicating recent removal

Analysis of historic rammed earth construction
Failures inrammed earth structures

Arch
Missing arch
Arch about to collapse
Destroyed brick column
Destroyed rammed earth
Brick column
Rammed earth

Figure 5.58 Plan. Villafeliche chapel, Vi2

Column collapse direction

Figure 5.59 Wall detail. Villafeliche chapel, Vi2

Analysis of historic rammed earth construction
Failures in rammed earth structures

Analysis of historic rammed earth construction
5.10 Concluding remarks

This chapter has described a number of different failures which may occur in historic rammed earth structures. These have been grouped into categories, and each category further subdivided into specific issues. Examples of the issues have been shown, gathered from visits to a total of 59 individual rammed earth buildings. Five case study structures were presented which show combinations of the failures described.

The work of previous authors into failure in earthen architecture has been consolidated, and specific engineering issues have been highlighted. It has shown that while there is a great deal of interlinking, it is possible to isolate many of the failures types to provide a more detailed understanding of the situation of the structure. Many of the questions posed at the Terra 2000 conference (Houben and Avrami 2000) and discussed in Section 1.9 have been qualitatively answered, in the main by considering rammed earth as a highly unsaturated soil.

Settlement of the foundations or fill material were discussed, and were found to be little problem at many of the historic sites visited – because the sites were defensive, thus built on high ground, sometimes directly onto bedrock. It was assumed that the ground beneath historic structures would have consolidated during the early part of the building’s life, and any further ground movement would likely be due to a recent change in existing conditions, such as a change in ground water conditions (Am1), or increased erosion beneath the foundations (Bg1). Cracking patterns in historic rammed earth structures were discussed, and simple diagrams presented to assist in the diagnosis of cracking patterns.

Issues with structural elements of a rammed earth building were described, and particular attention drawn to the join at rammed earth block interfaces. It was shown that failure of rammed earth structures may not be due to the construction material, but that damage to structural elements such as lintels or roofs can lead to damage of the whole structure. The purpose and failure of render was described, and it was observed that consideration must be taken of the type of construction (Plain, Calicastrado or Royal) in determining problems with rendered rammed earth. The
phenomenon of *popping* of unslaked lime was described, previously observed in cob structures, but not yet discussed in relation to rammed earth construction.

The treatment of rammed earth as an unsaturated soil was found helpful in qualitatively explaining a number of the failure mechanisms. The acknowledged phenomenon of creep in historic earthen architecture has been shown to be an artefact of the increased ductility at increased water content, and a qualitative understanding into the relationship between water content and load bearing capacity has been explained. The microscale binding forces in rammed earth have been shown to be due to liquid bridges between soil particles, and that a loss of apparent cohesion with increased water content is due to the reduced number of these liquid bridges (Chapter 3). The greatest problem observed was considered to be the ponding of water on horizontal surfaces of rammed earth walls, which then causes the formation of vertical runnels that can lead to great erosion of the structure. It was found that plain, unrendered rammed earth walls were able to survive, with initial rainfall causing the face to become damaged, but subsequent rainfall having only a small effect on the integrity of the rammed earth face. It was argued that covering the top of the wall to prevent ponding and vertical runnels is sufficient to ensure the durability of the structure, and that eaves be placed to prevent water being blown against the wall face. Where rammed earth acts as a retaining wall, the exterior face has can become damaged due to transfer of water and dissolved salts through the body of the wall. The precipitation and reaction of these salts can damage the exterior surface of the wall. Wind against the face of a wall is shown to increase the suction, which would lead to evaporation from the wall and causing erosion of the face.

Problems with organic matter within rammed earth construction are highlighted and it has been argued that the growth of plants is not necessarily problematic. A large number of structures were found with little plant growth was considered to be due to the high alkalinity of the walls. The decay of organic matter within rammed earth was discussed and it was shown that this material may act as reservoirs and conduits for water flow around a structure. Finally abrasion of rammed earth was described, and the problems of human and animal contact highlighted.
This chapter has argued that specific failures must be recognised and Figure 5.1, Figure 5.5 and 5.6; and Figure 5.22, may be useful in determining such issues. In this way it is possible to determine, for example, if a crack in a building is due to water or to structural movement; or if wall lean is due to foundation failure or an ineffective roof. It was argued that the difference between a crack in homogeneous rammed earth and a gap between rammed earth blocks or rammed earth and other materials should be appreciated which will aid in the understanding of structural analysis. In particular it is considered important that structural problems be discerned from problems caused by water, usually by considering the cracking pattern. Many of the problems relating to rammed earth buildings which were outlined by Houben and Avrami (2000) and Hughes (2001) and discussed in Section 1.9 may be explained by viewing rammed earth in the framework of unsaturated soil mechanics which was described in Chapter 3. The relationship between strength and stiffness; and water content discussed in Chapter 3 was shown to be useful in explaining some of the failures observed in historic rammed earth buildings. In particular the ability for unstabilised rammed earth to withstand rainfall impact was discussed and it was argued that water flow down a wall as a result of its ponding on the horizontal surfaces. Most importantly the cause of a problem should accurately be determined before any intervention or repair work is carried out.
Chapter 6

Rammed earth repair
6.1 Introduction

Chapter 5 introduced failures which may beset historic rammed earth buildings. This chapter looks at repair methods which could be adopted following such failures. It is important that the cause of any damage be determined before repair is carried out. In many instances, if the structural integrity of the building is not at risk, then stopping the cause of the damage may be all that is required to ensure the safety of the building. Warren (1993) notes that property owners may rush to repair damage for aesthetic reasons when it may not be necessary.

The principles of repair are discussed and it is argued that western ideals of historic building conservation may be at odds with other repair philosophies. Although no specific document relating to the repair of historic rammed earth buildings exists, a small number of authors have discussed repair strategies for earth buildings and their applicability to historic rammed earth buildings is discussed.

This chapter presents methods for dealing with ground movement, highlighting those which have been suggested for historic earth buildings. As many solutions are independent of building type, this section is intentionally brief. Issues with structural elements were highlighted in Section 5.4, and while many of these impact on rammed earth structures, the elements themselves are not rammed earth, and their repair requires further specialist knowledge (for example for the repair of timber roof members). Where the structural member issues were integral to rammed earth (for example the joint between rammed earth blocks) it was considered that this issue would be brought about by a further problem, (for example ground movement) and strategies for the alleviation of these problems are presented. Both soft crack stitching and hard wall tying techniques are given. In Chapter 5 it was argued that excess water in a rammed earth wall is undesirable, so ways to reduce the amount of water entering a structure and methods for increasing evaporation are presented here. Where erosion has occurred a range of techniques to replace missing material are given. Finally the techniques presented are evaluated and those considered most effective are recommended.
6.2 Repair principles

The need to repair and conserve structures is very different in different cultures. This is most readily observed when considering the conservation of historic sites in the United States, Australia and New Zealand, where buildings constructed by the first European settlers are now national monuments (e.g. Cody 1990; Bowman 2000; Pogue 2007), where buildings of the same age in other parts of the world barely receive a second glance. European and other ‘western’ views of the conservation of historic sites are perhaps the most stringent, aiming at rehabilitation to conserve cultural integrity rather than the restoration of a structure, returning it to its original condition and function. In this philosophy it is considered better to turn a historic site into a museum than return it to a functioning property. By contrast, the Buddhist philosophy of renewal, most importantly reincarnation, means that monastery buildings constructed in the previous year or decade are of equal importance to those constructed in previous centuries (observed in India, Appendix D). Here a philosophy of replacing old with new is considered perfectly acceptable. In order to appear (but not be) historically accurate repair with modern materials is practiced. This philosophy observed found in Spain (Appendices B and C) and was a policy in China during the previous century. The most famous example of this philosophy is the repair of the Ming Great Wall to the north of Beijing in 1972 for the visit of American President Carter. Here the heavily decayed wall was reconstructed in masonry just prior to the visit (Appendix A). Pearson (1997) argues that the majority of earthen architecture was not ‘built to last’ and that once too much damage occurred, the structure was demolished and rebuilt.

International agreements, such as the Venice (ICOMOS 1964) and Burra (ICOMOS 1999) charters set standards of practice and strategies to be followed in the conservation of historic monuments. Such charters, while very broad, do offer principles which should be adhered to in the conservation of historic buildings, and may be applied to earth buildings. The charters advocate a cautious approach to repair, and a practice of minimum intervention - ‘to do as much as is necessary but as little as possible’, to care for and maintain a site, such that the cultural significance is retained. A high value is attributed to the cultural significance of the structure, the
construction materials and the fixtures of a building. The conservation process is viewed as one of change, and change which reduces the cultural significance of a site, and is considered undesirable and should be reversible. When conserving a site the charters call for a detailed assessment of the reasons for deterioration followed by a well defined conservation policy. The process of conservation should be clearly documented and to ensure that further deterioration of the site does not occur a maintenance and monitoring regime should be implemented.

Rojas and Crocker (2000) discuss the emerging distinct conservation profession and highlight the conflict between the preservation strategies defined by the Venice Charter and the inherently vernacular construction of most earthen architecture, which falls under the remit of the charter. It is argued that 95% of international cultural heritage is treated the same as 5% of monumental architecture such as the Taj Mahal and Eiffel Tower for which the Venice Charters were intended, which leads to vernacular earthen architecture being excluded from accepted charters and standards.
6.3 Suggested earth building repair methods

There are only a small number of documents relating to the repair of earthen architecture, most produced by practitioners for use in their specific field of architecture (adobe, cob etc). Although a small section in Walker, Keable et al. (2005) presents some techniques for rammed earth repair and many case study repairs to historic rammed earth buildings have been documented (Jeannet, Pignal et al. 1993; Correia and Merten 2000; Mesbah, Morel et al. 2000; Easton 2007), there is currently no general document relating specifically to the repair of historic rammed earth. Because many earth building repair techniques are similar, they may easily be transferred from one construction type to another. In the UK, the repair of earth buildings is mainly limited to cob and it is felt that repair techniques suggested for at cob building (Ashurst and Ashurst 1988; Keefe 1993; Bouwens 1997; Pearson 1997; Nother 2000; Keefe 2005; Trotman 2007) may in some cases be applied to rammed earth.

Taylor (2000) presented a critique of research into repair and maintenance methods for earthen architecture, arguing that while many interest groups existed, and many international conferences had taken place, only a small amount of progress had taken place in the years 1970 to 2000. While much research was done on the possibility and viability of chemical consolidants, it was concluded that chemical consolidants are often neither compatible with earthen architecture nor cost effective to use. Natural additives, combined with good craftsmanship are now the preferred methods for restoration.

A research meeting following the Terra 2000 conference proposed a number of themes for research relating to the repair of earthen architecture (Houben and Avrami 2000). It was agreed that earthen structures be allowed to function in a soft mode, and acknowledged that the stiffening of a structure could lead to further damage. It was accepted that guidelines for the clear identification of structural and seismic cracks were necessary and recognised that improved methods for the repair of such cracks were required.
The aim of this chapter is to combine the knowledge provided by the above authors with methods observed in the field to assess which repair techniques may be applicable to rammed earth. This chapter describes both techniques described by the above authors and methods observed on field visits in Spain and India (Appendices B, C and D). The applicability and effectiveness of the methods is assessed in light of the previously ignored unsaturated nature of rammed earth and recommendations are made about preferred repair strategies.
6.4 Foundation issues

There are two distinct issues which may cause a building to deform because of problems with the foundations caused by either

- failure of the foundations, remedied by foundation improvement; or
- changes in soil behaviour, necessitating ground improvement

Failure of the foundations, for example through erosion will lead to their becoming ineffective in supporting the structure and they should then be repaired or replaced. A change in behaviour of the soil, for example a loss of stiffness or strength, will lead to a change in the ground profile, causing the deformation of a structure. There are then two alternatives – either to improve the behaviour of the soil, or to increase to effectiveness of the foundations, by distributing the load of the structure over a greater area, or by increasing the depth of foundations to reach a suitable bearing strata. Unless the movement of the ground beneath a structure is uniform, differential settlement will occur and cause the tilt or deformation of a building. Once it has been ascertained that ground movement is the cause of damage to a structure, steps should be taken to mitigate the ground movement. If these steps are not taken then any further repairs to the structure (such as crack filling) are likely to be ineffective.

6.4.1 Ground improvement

There are a myriad of reasons for ground movement and some are given in Figure 5.2. These reasons include undermining, settlement or subsidence of the foundations; and consolidation of the fill material, perhaps brought about by a change in groundwater conditions. While many ground improvement methods are available, only a few are likely to be acceptable in the vicinity of a historic structure. One solution which may be possible is injection grouting, which may be used to return the ground to its original profile. An expansive gel such as that manufactured by Uretek is injected into the ground beneath a structure. This then expands in the soil, increasing the volume and raising the profile of the surface. With care it is possible to raise the settled surface and reduce the deformation of a building.
Ground movement may be caused by changes in the groundwater distribution in the vicinity of a structure. For example an unsaturated soil will increase in water content if the water table is raised. This will cause a reduction in strength and stiffness of the soil and may cause a change in the profile of the ground surface. This movement can be rectified by changing the ground water profile, through the installation of drains or containment of a watercourse such as has occurred at Ambel (Am1, Appendix B).

6.4.2 Foundation improvement

If it is impossible to return the level of the ground surface to that prior to settlement, or if heave of the ground has led to one section of a building being unsupported, then underpinning of the structure may be necessary. Underpinning may serve two purposes, to replace ineffective foundations or to allow effective foundations to transfer building forces to a suitable foundation strata. Many experts (for example Richardson 1997) argue that underpinning can be a traumatic procedure for the building. There are a great deal of underpinning methods available on the market today, and a whole industry involved in the design and construction of such methods. As such methods are independent of the building type, they will not be discussed in great detail.

Pearson (1997) suggests the use of mini piles, specifically Pali Radice (Italian for root piles), which may be inserted in low headroom, with minimum vibration and noise. Crocker (2003) describes the underpinning of a historic adobe building using helical piers. These act in a similar way to piles, but are hollow tubes (50mm – 200mm diameter) with large individual screw threads along the length. The piers are twisted and driven into the soil, transferring the load of the building to the soil via the screw threads.

Examples of foundation repair of historic rammed earth structures are rare. The Chew Kee Store in California (Appendix A) was extensively repaired by David Easton in 1986. After the base of leaning walls were excavated, it was found that there were no foundations and that the rammed earth walls were simply seated on the ground. A foundation of cement stabilised rammed earth was formed at the base of the walls. This replaced eroded material at the base of the wall and was extended beyond the original rammed earth wall to increased the footing size and prevent overturning.
6.5 Cracks

Section 5.3.3 identifies the main reasons for the development of cracks, differentiating between those resulting from ground movement, failure of structural elements, and those which are related to water. Prior to any remediation work the cause of the cracking should be determined, and this arrested before the cracking is dealt with. If the cause of cracking has been dealt with completely and no further structural movement will occur, then a crack can confidently be filled. If there is a risk of slight structural movement, or it is possible that a small amount of stress may act across the crack, the ‘soft’ repair techniques such as stitching may be attempted. Such repairs aim to replace the fabric of the structure, allowing structural continuity to be maintained.

If there is the risk of movement, or a requirement for stress transfer (for example through wind loading or the lean of a perpendicular wall) then hard methods, such as those recommended for wall lean (Section 6.6) should be used.

6.5.1 Filling

When crack monitoring suggests that no further structural movement is taking place, filling of cracks is suggested. This prevents further water ingress, and is likely to improve the appearance of the building. While the filling of cracks with similar material to that of the wall is recommended, rammed earth presents a particular problem with this method. The nature of compaction of rammed earth means that verticalramming cannot usually be applied to material in cracks, and the compaction of any material must take place from the face of the wall. Therefore Pearson (1997) recommends the column method, involving cutting back of a crack, such that a new column of material may be compacted in place of the crack. This column is not tied to the adjoining walls, but merely acts to present an aesthetic continuous face to the wall. Such columns are obviously subject to the problem of shrinkage, and should therefore not be tied to the adjoining walls for fear of inducing further stresses and cracking on shrinkage.

For small cracks the application of a mortar mix has been used effectively (Figure 6.2), although Ashurst and Ashurst (1988) warn that cement based mortars may
inhibit evaporation, and act as dams within the wall, preventing moisture movement. Larger cracks may require the placement of bricks to fill them, although Ashurst and Ashurst (1988) again warn of ‘perimeter problems’ due to the accumulation of moisture and of differing thermal properties.

If the cause of the crack is purely water based, then filling using either of the above methods is likely to be acceptable, provided sufficient space for thermal expansion is provided. The source of the water should be dealt with prior to filling of the crack. In this instance structural continuity is not restored when cracks are filled. If further wall movement occurs, the fill material is likely to become dislodged (Figure 6.1). It is considered that such inert crack filling (not attempting to join each side of the crack together) is preferable in this instance. This allows monitoring of movement of the structure, and would prevent the opening of further cracks. If the aim is to stop movement of the structure, then stronger stitching (Section 6.5.2) or tying (Section 6.6.1) methods should be employed.
6.5.2 Stitching

When the decision is made to stitch a crack, it should be ensured that the structural movement which has led to the cracking is stopped completely, otherwise excess stress will be placed on the stitch, causing it to fail, or cracking will move to some other part of the structure. Assuming that ground movement is stopped, soft stitching of a crack should be seen as an additional safety measure.

The physical stitching of a crack, by forming a staple across each side of the crack, has been presented by a number of authors (Ashurst and Ashurst 1988; Pearson 1997; Hurd 2006b). The concept of a ‘soft’ stitch is employed, creating a staple using a similar material to that of the wall. This method attempts to match the material properties (stiffness, thermal expansion) of the stitch and the wall, allowing the stitch
to become an integral part of the wall, restoring some structural continuity across the crack. While one would expect rammed earth to be used to fill a crack in a rammed earth wall, methods using bricks constructed of a similar material are first described.

The method described by Hurd (2006a) involves the cutting of a horizontal *chase* into the face of the wall, across the crack. A deeper section is cut at each end of the chase to provide a hook into the wall. The interior of the chase is then sprinkled with water then covered in a wet Hessian cloth. Next a layer of wet soil is laid as mortar at the bottom of the chase, onto which the first layer of bricks is laid. Further layers of interlaced bricks are added, with layers of Hessian in the mortar layer. When the top of the chase is reached, a final layer of dry mortar is packed into the gap, and rammed to insert as much mortar as possible. The face is then cleaned and the stitch complete.

Ashurst and Ashurst (1988) and Pearson (1997) suggest the insertion of a vertical metal mesh reinforcement in the chase, as shown in Figure 6.3. If using this mesh it is likely that any subsequent stress induced across the crack will be carried by the mesh. If the mesh is not present, then any additional stress must be carried in shear by the mortar layer. If further movement does occur then additional time and warning may be provided prior to collapse through the development of cracking in a different part of the structure.

This technique was used at Basgo fort (Bg1, Appendix D) where two crack systems were evident in the wall (Figure 6.4, Figure 6.5). The deformation and cracking of the structure was thought to be due to erosion of the foundations. This erosion has now been stopped and a masonry retaining wall built at the base of the wall (visible in Figure D.21). Two stitches were placed in 2000 by Mr John Hurd and are shown in Figure D.22. This structure was visited in November 2006, and the stitch did not appear cracked, although the development of the secondary crack system could not be determined (its presence is not discernable from photographs taken in 2000).
Figure 6.3 Crack repair technique, Ashurst and Ashurst (1988), Pearson (1997), Hurd (2006a)
Figure 6.4 Crack tying. Basgo, Bgl
Figure 6.5 Crack stitching of rammed earth wall. Basgo, Bg1
6.6 Wall lean

Section 5.3 described mechanisms by which walls may begin to lean. It was shown that insufficient structural continuity between different materials may lead to the opening of gaps between leaning and perpendicular walls at the corners of structures. There are two types of wall lean, rigid tilt of the wall - which may be caused by foundation failure; and bending of the wall, which is indicated by spalling on the compression face and horizontal tension cracks on the opposite face. Gaps between the floor and the wall at upper levels, and the cracking of transverse ceiling arches indicate wall lean.

Pearson (1997) describes a method for assessing the stability of leaning walls (Figure 6.6). A scale drawing of the wall should be produced, by measuring the thickness of the wall, and assessing the lean through use of a plumb line. The base of the wall should be divided into five equal segments and if a vertical line drawn from the centre of gravity bisects the outer two segments, then the stability of the wall should be called into question and fully assessed prior to remediation work being undertaken. This method is more conservative than similar tests for masonry (where the base is divided into three segments, known as the middle third rule).

Methods for the mitigation of wall lean are shown in Figure 6.7. These include building length ties, where tension members are fixed between opposite walls; battens placed into perpendicular walls; anchors grouted into the walls and the placing of buttressing against leaning walls. Such techniques however should be considered as part of a solution and the reasons for wall lean should be understood and alleviated prior to the installation of these systems.
Figure 6.6 Assessing leaning wall stability (After Pearson 1997)
6.6.1 Internal tying

Leaning walls may be stabilised by the insertion of tie members through a structure. Spreader plates are fixed to the ends of tie bars which run through the length of a building. Where leaning of walls and opening of cracks has occurred, through either ground movement or failure of structural elements, tie bars are a simple method of increasing the lifetime of a building without recourse to major structural alteration.

Pearson (1997) argues that tie rods are of dubious value to earth buildings and does not recommend their use. It is argued that increased stress is placed on the anchor point and it is possible that the spreader plate may shear through the earth wall. Ashurst and Ashurst (1988) argue that tie bars may be placed through a structure, providing a sufficiently large spreader pad is placed on the wall. It is recommended that the 1m square pad is placed behind each spreader plate to prevent the plate punching through the wall. This pad should consist of a mesh reinforcement placed into a cut in the wall, which is then faced with a similar earth mix to that which has been removed. Tie bars are usually inserted at ceiling/floor level, holes are drilled
through the face of the wall, tie bars inserted, then spreader plates fixed to the outside of the walls. If the aim of the tie bars is to close cracks and to reduce the lean of walls, then the bars are tightened to reduce the distortion of the structure, using either a screw thread, or through the cooling of preheated bars.

A similar method to internal tie bars is the placement of external beams and wires, which may give a lower visual impact than spreader plates. Here a steel channel section may be loosely fixed to a wall, with wires running from the ends of the section the full length of the building. These wires are then tightened and leaning walls may be pulled back towards vertical (Figure 6.7).

Figure 6.10 shows the placement of tie bars at the north east tower at Ambel (Am1, Appendix B). The situation at Ambel is outlined in Appendix B and failures at the building are described in Section 5.9.2. The north wall (Figure 6.10) appears to be leaning away from vertical, opening cracks at the joint between the east and north walls (Figure 6.8 and Figure 6.14). The guardians of the building placed tie bars in the structure, below the ceilings at the roof, first and ground floor levels (Figure 6.9). The tie bars (Figure 6.11 and Figure 6.12) are I beam sections approximately 150mm x 80mm. These are fixed to H shaped stretcher plates on the exterior face (Figure 6.9 and Figure 6.10) by a bolted connection through the wall (shown in Figure 6.13). The tie bars are then bolted at intervals to the rammed earth and to the ceiling beams (e.g. Figure 6.11), but do not extend through the full width of the building (Figure 6.8). Crack monitoring (Figure B.16) shows that the rate of crack growth has not changed since installation of this scheme, suggesting either that the scheme is ineffective or that it has yet to 'engage'. When the system does engage, the overturning action of the wall will be countered by the bolts fixing the internal tie bars to the rammed earth walls and roof timbers. This is contrary to how tying schemes are designed to work, and the system would be more effective if additional spreader plates were fixed to the south wall of the structure and the tie beams extended to reach these plates. The system should then be tightened in an attempt to pull the north wall towards the vertical.

However, as Pearson (1997) points out, the use of spreader plates in earthen buildings is potentially dangerous due to the low shear strength of earth, which is likely to lead
to the punching of a plate through the wall. The dimensions of the H plates fixed to the north wall of Ambel (Figure 6.10) suggests insufficient out of plane stiffness, which could lead to a folding of the plates upon application of tensile load in the tie bars. It is therefore recommended that the spreader plates at the north wall are increased in stiffness through the addition of flanges. The brick facing of the north wall would suggest that spreader pads are not necessary, but the rough south wall would require cleaning and the introduction of spreader pads to ensure good contact and load transfer to the tie beams.

Figure 6.8 Tie bar repair at Ambel, Am1. 20th century ties bars shown in red. Active cracks shown in blue.
Figure 6.9 Spreader plates at Ambel, Am1 added in 2000
Figure 6.10 Spreader plates at Ambel, Am1 added in 2000
Rammed earth repair

Figure 6.11 Internal ties bolted to walls and roof beams. Ambel, Am1

Figure 6.12 Wall plate at 1st floor level, to internal tie. Ambel, Am1
6.6.2 Battens

An alternative to ties is the placing of battens directly into perpendicular walls. Pearson (1997) advocates the use of external battens, fixed to the wall using bolts inserted in pre drilled holes through the full thickness of the wall. Here steel or iron bent through 90° may be fixed to adjacent walls. This external solution appears unsightly, but is offered by Pearson (1997) as a simple solution which may prolong the life of a building.

In the late 18th century a number of measures were enacted at Ambel (Am1, Appendix B) to prevent collapse of the leaning north wall of the north east tower. Analysis of the architectural fabric suggests that buttressing was placed against the external wall, and repairs carried out to the ceiling arches at each floor (Figure 6.14). In addition battens were embedded at the north end of the east and west walls, spanning to the leaning north wall. The repairs were simple, and have not been hidden in any way. Their effectiveness is questionable, as cracks are present at the south end of the timbers (Figure 6.15). This indicates that the timber may have succeeded in stiffening the north end of the structure, but because ground movement has not been halted, further deformation and cracking has occurred.
Figure 6.14 Repairs carried out in 1796. Ambel, Am1

Figure 6.15 Late 18th century timber beam embedded in rammed earth (left) and perpendicular brick (right) walls. Note cracks to south (left) of horizontal timber.
6.6.3 Grouted anchors

Pearson (1997) suggests the use of grouted anchors. These have been used to repair historic masonry structures, the most common is one installed by the company Cintec. The anchor system comprises a drilled hole, into which a polyester based sock is inserted. Steel reinforcement bars are then inserted into the sock, and the sock filled with a cementing grout. This system has a wide range of applications but in this instance may be used across cracks to tie together perpendicular walls. However, the strength of the anchor depends on both the length of embedding, and the bond between the sock and the wall material. Pearson (1997) argues that their use in earth walls is limited because of the low shear strength of earth, and they should not be relied upon to stitch major structural cracks.

6.6.4 Buttressing

Buttressing of leaning walls to prevent structural collapse is a simple method of providing support without major alteration to the structure. However buttresses do change the external appearance and the character of a building. If leaning walls are a result of structural member failure (for example an ineffective roof causing increase thrust onto the tops of walls), then buttressing may be a solution. However if wall lean or cracking is caused by ground movement, then it is possible that the addition of a buttress will exacerbate the problem. A buttress will increase load on the ground outside a structure, which may lead to further consolidation and increase differential settlement. This will cause the whole body of the buttress to lean, therefore not resolving the wall lean problem.
6.7 Water

The role of water in rammed earth walls was explained in Chapter 3 and it was argued that the highly unsaturated nature of rammed earth should be considered. It was shown that water will continue to evaporate from a rammed earth wall until the relative humidity of the pores is equal to that of the surrounding air. During a rainfall event water will be absorbed into the pore structure of the wall, at a rate determined by the pore size. This absorbed water will increase the water content of the wall and reduce the suction, leading to reduced strength and stiffness. If the water is prevented from evaporating then there is a permanent increase in water content. This section presents strategies for reducing the problem of water at a site.

Figure 6.16 Methods for preventing water from entering the structure
6.7.1 At the head of the wall

In ponding of water at the head of wall was identified as a major problem for rammed earth structures, with overflow from this ponding causing water flow down the face leading to channels being cut (Section 5.6.2). If this ponding can be prevented, then erosion to the face is greatly reduced. Methods for the preventing water entering a structure are given in Figure 6.16. The most effective way to prevent water ponding on the top surface of a wall is to provide a roof above the wall, and the first measure in repair of a rammed earth structure would be to ensure that the roof structure is effective.

In some cases it is not viable to erect a roof to the existing rammed earth structure, either because a roof was never present or because the current structure is too eroded to support a roof without significant alteration. In these cases, extreme measures such as erecting a superstructure over the whole site may be viable if the site is of significant cultural value (Figure 6.18), but this must be weighed against the impact such a structure may have. Smaller scale alternatives, to prevent the impact of rain drops on the wall surface, include a tower at Tarazona (Appendix C) which has been wrapped in a layer of chicken wire (Figure 6.17).

Restoration of two sites in southern Spain included the placement of a concrete ring beam at the top of the structure which serves to prevent water from ponding and entering the body of the wall.

Guillaud and Avrami (2003) argue that capping of a wall is the most common method of protecting historic earth ruins, and define three types of capping – prefabricated blocks, renders and roof structures. In a 15 year study at the adobe Fort Selden, Oliver (2000) evaluated a number of different capping strategies, looking at asphalt stabilised adobe bricks, cement based render and brick coping. The study concluded that while all of the caps protected the head of the wall, they may have accelerated erosion of the wall directly beneath the capping. It was recommended that further research be carried out into separating and quantifying the effect of natural erosion compared to the accelerated erosion caused by the caps. The current management plan at Fort Selden (NPS 2004) is to cap the wall tops with natural adobes, replacing these when they
erode, and to accept that a degree of erosion is inevitable. A technique observed in Spain was the capping of the tops of the walls with a concrete beam (Biar, Bi1, Figure 6.19 and La Rambla, Ra1 Figure 6.20). This prevents water from ponding at the top of the wall, and drains prevent its flow down the surface of a wall.
Figure 6.18 1932 structure constructed over the Casa Grande adobe ruins. Dodds (2004)

Figure 6.19 Concrete repair to the top of a wall, and drainage duct. Biar tower, Bil

Analysis of historic rammed earth construction
6.7.2 Repairs at the base of walls

Water damage to the base of the wall is caused by

- Water impact from above,
- Water flow against the surface,
- Excess water in the wall present though capillary rise or other flow which is then trapped through reduced evaporation.

Ways to prevent water damage are shown in Figure 6.21. To prevent water impact from above, the size or effectiveness of the eaves should be increased. At many sites in northern Spain the eaves are decorated, becoming an integral part of the architecture of the building. If water flow against the wall, is causing damage, then the water should be diverted, and the face rebuilt as described in Section 6.7.2.
Any barrier to evaporation at the base of the slope should be immediately removed (McHenry 1984; Ashurst and Ashurst 1988; Pearson 1997). The barrier will cause an increase in water content and reduce the strength and stiffness of the wall. Evaporation is reduced by the build up of a talus slope at the base of a wall. Such slopes are a consequence of erosion of the wall with damage to a structure (for example the removal of the top of a tower) increasing the size of this slope.

'Repairs' to the base of a wall, such as for example the placing of concrete (e.g. at Baños de la Encina, Figure D.18 and Palma del Rio, Figure D.80) reduce the evaporation, leading to increased water content behind the repair and further capillary rise above the repair. Such repairs should be removed.

McHenry (1984) argues that most historic buildings were likely to be built on sites with good natural drainage, as historic builders knew of the dangers to rammed earth structures which water could bring. However, over time the drainage of a site may be significantly altered, causing a change in the natural soil water content. Ashurst and Ashurst (1988) therefore recommend the installation of drainage around a site to change the profile of ground water to reduce water entering the base of the wall.
Increase size of eaves

Reduce internal ground surface

Remove talus slopes

Remove cement render

Splash base

Diversion of watercourse

Drain installation

Figure 6.21 Methods for preventing water at the base of a rammed earth wall

Analysis of historic rammed earth construction
6.8 Face repair

The nature of rammed earth wall construction is that some damage will occur to the face if it is not sufficiently protected. It has been argued that the main cause of damage to a face is the ponding of water at the top surface and that ambient rainfall is seldom a cause of major damage and collapse (McHenry 1984). However, repair of the faces of rammed earth buildings is common, to such an extent that many rammed earth walls many be hidden behind many years of face repair.

Repair of the face of a wall falls into two categories, that to reinstate or establish a protective surface, and that to replace areas where erosion and physical loss has occurred. A protective surface may be established through the application of render or a chemical consolidants to the face. Fallen or similar material should be used to replace areas where erosion has taken place, and two methods to achieve this are described. Masonry and concrete can be used to both replace the fallen material and provide a protective face.

6.8.1 Render

The re-rendering of many historic rammed earth structures continued throughout the lifetime of the building. A sacrificial layer of lime based render was applied to a rammed earth face and renewed every few years where necessary. Render was not applied to all rammed earth walls. In India (Appendix D) the rammed earth appeared not to be rendered, and in southern Spain (Appendix B) Royal rammed earth (described in Chapter 4) was sufficiently lime rich to not require rendering. Calicastrado rammed earth, with a lime rich surface, was also repeatedly re-rendered, as shown by contrasting patterns on different layers at Baños de la Encina (Ba1, Appendix B). When a building falls into disuse, the re-rendering ceases, and the sacrificial render layer eventually disappears. Once this layer disappears, it is considered that the rate of erosion to the face increases, which will lead to eventual disappearance of the building. However, in many historic structures, the non-rendered face has become part of the historic fabric of the structure, and repair of this face by re-rendering would significantly alter the cultural significance of the site (for example NPS 2004). Therefore, at these sites, the re-rendering of a face is not an option.
Ashurst and Ashurst (1988) describe the process of limewashing of historic cob structures, and Correia and Merten (2000) describe the limewashing of repaired rammed earth in Portugal. Ashurst and Ashurst (1988) suggest a 1:3 lime:sand render should be applied to a dampened wall surface in three layers. The first coat is expected to combine with the wall to form a slurry which cracks as it dries out. Two more coats of this limewash should then be applied to hide the shrinkage cracks and to provide a solid colour.

The cement rendering of many buildings is highlighted as a poor repair method (e.g. Pecoraro 1993), with problems resulting from the reduced permeability of the cement compared to a lime based render (see Section 6.7.2). Because cement does not adhere well to decayed earth wall, mechanical keys such as nails and mesh are placed into the decayed wall. Pearson (1997) argues that these act as reservoirs for water, causing further damage to the rammed earth. In many cases cement render falls off earth walls, never to be replaced. Any repair strategy should include the removal of cement based render, but if this is not possible Pearson (1997) suggests that damage caused by a cement based render may be mitigated by removing the bottom 200mm of render. This allows evaporation at the base of the wall, therefore not allowing water build up within the wall.

6.8.2 Chemical consolidants

The idea of chemical consolidation of earth buildings began in the 1980s, with conservators looking for stabilisation methods which did no alter the physical appearance of a site, but which repelled water thus reducing erosion potential.

Warren (1993) describes twelve criteria against which the performance of a chemical consolidants can be judged, but argues that no material has yet fulfilled all of these criteria. The criteria include the following: reversibility; invisibility; to be unaffected by and allow movement of water; to increase the mechanical strength but not introduce brittleness, and to not decay.

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1 Consolidation in this context meaning the making good, rather than the geotechnical meaning of the gradual reduction of volume of a saturated soil

Analysis of historic rammed earth construction
A 15 year project at Fort Selden in New Mexico (detailed in Oliver 2000) looked at the suitability of a wide range of surface coatings to treat historic adobe ruins. Amongst the consolidants tested were cement additives, soil additives designed to prevent erosion, plant oils and a range of PVA based products. The consolidants fell into three groups, those attempting to encapsulate the substrate in a new material, those aiming to present a water repellent surface, and those attempting to increase the mechanical strength by acting as a flexible adhesive. The consolidants were applied to new adobe walls in 1985, and evaluated in 2000. The most effective consolidant was found to be *El Rey Superior 200*, a cement mortar modifying agent which has been consistently used for the preservation of adobe since the 1970s.

Ashurst and Ashurst (1988) and Warren (1993) discuss the use of sprayed ethyl silicate (silicon ester). This is a surface modifying agent, providing a Silicon Dioxide layer around the soil particles. This provides the earth wall with increased water resistance, and a similar silicon based treatment is used in modern rammed earth construction in Australia. Ashurst and Ashurst (1998) point out that these chemicals do not perform a gluing action and should only be seen as a method to improve the water resistance.

Chemical consolidation methods appear to have recently fallen out of favour in historic earthen monument preservation, and are not recommended on current preservation projects. At Fort Selden for example chemical consolidation is now not recommended (NPS 2004).

### 6.8.3 Repair with fallen or similar material

Repair of rammed earth with fallen material is cited as the best way to repair rammed earth structures (e.g. Pearson 1997). In using fallen material the mineralogy and particle size distribution will be similar to that of the wall. However, where a chemical reaction has taken place (for example the development of a cementing matrix) then particles produced by this reaction if reused will act as inert particles. In this case a reapplied mix made from fallen material will be a different particle size distribution and offer fewer cementing agents. The use of fallen or similar material negates the problems of different properties of the materials of a wall. Hughes (1983) warns that there may be issues with differential expansion coefficients, and that a...
more durable material may direct water towards a less durable material, accelerating decay.

The material used for a rammed earth building is usually taken from an adjacent site. In some cases field names are indicative of the source of the soil, but generally material taken from close to the building have similar characteristics to that used in the historic structure. Two methods for the repair of rammed earth faces are presented. Both involve the cutting back of an eroded section to form a good interface to new material, the first method replaces the eroded material by ramming excess material between formwork, and the second method introduces pre shrunk bricks into the cavity.

Pearson (1997) suggests the repair method shown in Figure 6.22. The eroded section is first cut to produce a cavity with a uniform surface against which to ram. Temporary formwork is setup parallel to the wall and filled in thin horizontal layers with a mix similar to that of the wall. This work is done slowly to allow time for each layer to dry and shrink. The formwork is thus filled with rammed earth to above the level of the erosion and thoroughly compacted. The formwork is then removed and when the whole section is dry, the extra rammed earth is carefully removed to present a surface flush with the rest of the wall. The whole wall should then be rendered if required.
Ashurst and Ashurst (1988) describe a technique for the repair of deteriorated cob faces (Figure 6.23). The eroded area should be cut back to produce a cavity with a clean back. If the area is greater than 500mm square then it is recommended that 'shelves' of clay tiles or wire mesh be placed in slots cut in the back of the cavity, onto which the repair can be placed and compacted. Pearson (1997) suggests a similar technique, placing hazel spars at intervals to provide a mechanical key. To perform the repair, the cavity should first be wetted, and earth built up in layers of around 100mm. If possible, formwork could be placed to facilitate compaction. Each layer should be rammed vertically, with the exception of the final layer, which must be compacted from the face.
Rammed earth repair

Both of these methods are subject to shrinkage and the issues of bonding between the repair and the original wall. To avoid the problems of shrinkage, Warren (1993) and Pearson (1997) both suggest using bricks, shrunk prior to their installation in the wall (Figure 6.24). Holmes (2000) notes that this is a traditional rammed earth repair technique in China. It is suggested that the cavity is cut back and measured. Bricks are constructed using fallen material to fill the cut cavity. The bricks should be made using custom formwork, and ideally compacted to a similar density to that of the wall. The bricks are then left to dry out completely and shrink. To place the bricks in the wall, the surface of the brick and that of the chase should be wetted, and the bricks placed. Pearson (1997) recommends the use of a clay mortar around the edges of the chase, and thin mortar joints between each brick. If possible, a mortar of the same material to the wall should be used. Once all of the bricks have been placed, the top of the chase is filled from the face. Any shrinkage which does occur should be filled.
Rammed earth repair

1. Cut to create a clean backed cavity
2. Measure cavity
3. Construct bricks to fill using similar material to wall
4. Wet cavity and bricks
5. Insert pre shrunk sized bricks
6. Fill final layer from face

Figure 6.24 Preshrunk brick repair. After Warren (1993)

6.8.4 Facing with masonry

Figure 6.25 shows the facing of rammed earth with masonry which was found at a number of sites in southern Spain (for example Jaen, Jn, Tabernas, Tb1 and Talamantes, Tn1). The city wall of Xian in China is rammed earth and was faced with masonry in 1555 (Yunxiang 2003). In Section 4.5 it was argued that the facing in masonry of historic rammed earth structures may be a response to the threat of artillery. At the majority of the sites the masonry appears to have been placed some time after the construction of the rammed earth wall, against a rammed earth face, although at Carmona (Ca, Appendix C) the masonry and the rammed earth appear to have been constructed at the same time, with the masonry acting as formwork to the rammed earth.

The use of brick in the facing of decaying rammed earth walls was observed at Magallon farm (Figure 6.26, Appendix C) where an eroded section of wall had clearly been fronted with a brick wall to prevent further decay to the face. There may be many similar sites across Spain where such a technique was practiced, and rammed earth walls are hidden behind a brick façade.

Brick and stone repairs were found at two sites in southern Spain (Malaga, Ma1 and Granada, Gr4, Appendix C). In Malaga repairs carried out in the 1930s (Malaga castle
tourist office 2006), fulfil the letter of the Venice Charter (Section 6.2) that work should be clear and identifiable, while showing what has been repaired. The gaps left in the repaired sections show that a rammed earth wall lies beneath (Figure 6.27 and Figure 6.28). This technique (lines of brick interlacing with lines of stones, set in a cement mortar) was seen across Spain, and may indicate hidden rammed earth walls which were repaired during this period.

Figure 6.25 Ashlar masonry placed to front of rammed earth wall. Jaen, Ja
Figure 6.26 Facing eroded rammed earth with brick. Magallon farm, Appendix B
Analysis of historic rammed earth construction
6.8.5 Facing with concrete

Repairs to rammed earth using concrete were observed at many sites in southern Spain (Appendix B). While the use of concrete render on earth buildings has been widely condemned by many authors (e.g. Pearson 1997; Walker, Keable et al. 2005), the practice appears well developed and currently used in Spain. In the UK the use of cement is usually limited to the rendering of earth structures to provide an impermeable barrier, while in Spain it appears that a much thicker coat is applied to the wall, which may act independently of the rammed earth wall. Two distinct techniques were observed in Spain, to partially protect sections of the wall or to completely encapsulate the decaying rammed earth in concrete.

Construction of a concrete cement face was observed at two sites, Palma del Rio (Pa3) and Elche (El3). Figure 6.29, Figure 6.30 and Figure 6.31 shows the Spanish method for repairing rammed earth with concrete. Formwork is placed close to the wall, supported by scaffolding. Timber formwork is used, of similar size to the formwork boards found at historic sites, such that the pattern on the finished wall matches that found at the site. A fine aggregate is used, and appears to be poured into the formwork in layers of similar height to historic lifts. Timber inserts are inserted into the cement at each lift line, and removed following construction of the wall. These inserts give the impressions of characteristic putlog holes in the wall (Figure 6.32), a distinguishing feature of historic rammed earth in Spain.
Figure 6.29 Concrete repair. Palma del Rio, Pa3

Figure 6.30 Concrete repair. Palma del Rio, Pa3

Analysis of historic rammed earth construction
Figure 6.31 Concrete repair. Palma del Rio, Pa3

Analysis of historic rammed earth construction
Where concrete was used to partially protect a structure, it is placed only at the base of a wall leaving other parts exposed to retain an impression of the ruined state. This method serves to show the ruined nature of the site, while still aiming to preserve parts. If possible, the concrete is made flush with the wall, but otherwise a horizontal lip is formed. (e.g. Figure 6.33). This type of repair was observed at Elche (El3), Cordoba (Co1), Palma del Rio (Pa5) and Seville (Se2). Figure 6.35 and Figure 6.36 show the consequences of such repairs. The concrete creates an impermeable barrier at the base of the wall, as described in Section 6.7.2. This causes further capillary rise and increased water content of the wall above the repair (Figure 6.34) which may lead to reduced strength and stiffness. If water is able to gather on the horizontal surface then erosion of the rammed earth may occur, necessitating further mortar repairs (Figure 6.35). If the water instead runs down the face of the wall, then erosion of the concrete occurs (Figure 6.36).
Figure 6.33 Partial protection of a structure using concrete. Elche, EL3
Figure 6.34 Capillary rise due to cement rendering of base, note colour change. Palma del Rio, Pa5
Figure 6.35 Concrete repair Calle Muñoz, Seville, Se2

Figure 6.36 Concrete repair Calle Muñoz, Seville, Se2

Analysis of historic rammed earth construction
A second approach is to reconstruct the whole building, as it is likely to originally have stood, in concrete. This may entail facing of the whole decayed structure in concrete, and the formation of artificial features such as crenellations (such as at Tabernas, Ta4, Figure 6.37). While this goes against the spirit of the Venice charter, such action could be justified when considering that the earth structure may eventually decay to nothing, while a concrete structure may take longer to decay.

Problems with this type of repair occur where the concrete is not sufficiently fixed to the original rammed earth. Investigation at Novelda (No3, Appendix B) revealed 10mm reinforcement bars at the base of the repaired wall, suggesting that the repair concrete was either reinforced in the direction of the wall, or that reinforcement bars were embedded within the wall, around which the concrete was cast. Figure 6.38 shows shear cracking resulting from the settlement of the centre of the repaired wall section. The date of repair is unknown, but is assumed to be relatively recent, given the lack of decay to the timbers remaining embedded in the wall. The base of the repaired section is unsupported, meaning that the weight of the concrete is taken by the rammed earth it is protecting. This may lead to the whole concrete section becoming detached from the rammed earth.
Analysis of historic rammed earth construction
While the addition of a thin layer of cement to the face of a wall as a protective render is currently discouraged, the technique of covering a decayed rammed earth wall in a thick layer of fine aggregate concrete appears extremely popular in Spain. Two techniques were identified, and each has different associated issues. Where sections of rammed earth are repaired in concrete, a lip is often formed at the interface between the repair and the original wall. If water is able to collect on this lip, then erosion of both the rammed earth and the concrete can occur, as highlighted in Figure 6.35 and Figure 6.36. The problem of reduced permeability of the concrete repair is highlighted in Figure 6.34, where clear capillary rise can be seen. In Chapter 3 it was shown that this increased water content reduces the strength and stiffness of the wall. It is therefore possible that concrete repairs may actually directly cause collapse of a structure.

Encapsulating the whole structure in concrete reduces some of these problems. Water is not able to contact the rammed earth, and therefore no further erosion occurs. No evaporation takes place, and problems with capillary rise will be limited by a constant relative humidity within the concrete. The structure is therefore likely to survive as long as the concrete is present. Such drastic repairs are against the spirit of the international charters (Section 6.2), being irreversible and not a minimum intervention strategy. However it could be argued that the cultural significance of a site is retained through the presence of the structures, which would otherwise eventually decay.
6.9 Concluding remarks

As outlined in Section 6.2, many earth buildings were constructed as vernacular, yet are now considered to be of great cultural value. The repair of such structures is subject to much debate and consideration before any work begins. It must first be decided if the structure is to become a working building or a cultural monument, as such decisions determine the nature of any repair strategy proposed. In many cases, the decision not to intervene may be the most prudent. The nature of historic rammed earth is such that providing external dangers are removed (for example flowing water), a structure can exist for a long period of time. If erosion is minimised and evaporation allowed, then a historic rammed earth structure can last for centuries.

Houben and Avrami (2000) acknowledge that in the case of earthen buildings, ill-informed repair to a structure may be worse than no repair at all. In all cases, the problem causing the failure should be mitigated prior to any repair being carried out. The idea of hard (using steel and concrete) versus soft (using fallen or similar material) repairs was raised. Soft repairs are intended to act with the structure, having the same mechanical characteristics, and essentially replacing structural fabric which has been lost. Hard repairs are those which support the structure, for example pulling leaning walls to vertical using steel ties. If the cause of the failure has been fully mitigated, then only soft repairs are necessary, whereas hard repairs must be considered if failure is likely to continue. The different cultural attitudes to repair were discussed, and it was argued that the Venice and Burra Charter principles, while offering noble ideals, may not be suitable for all historic rammed earth repair projects. While few guidelines specific to rammed earth are available, expertise in the repair of cob buildings may be applicable for the repair of historic rammed earth.

Movement of the ground is a significant issue for historic buildings, and without remediation may cause complete collapse of the structure. Methods for improving the ground in the vicinity of a structure were only briefly discussed because they are independent of the construction material. Foundation improvements such as underpinning using helical piers and mini piles were also discussed, and a simple foundation repair to a historic rammed earth building was examined. It is imperative
that if the cause of building failure is ground movement or foundation failure, this must be corrected prior to any further repair work. If ground movement continues after repair has taken place then further deformation of the building may take place and the repair will not be permanent.

Methods for crack repair for cob structures were presented, and it is considered that these repairs are equally applicable for rammed earth. If all structural movement has ceased, and there is no requirement for stress transfer, then the soft repair of inert crack filling should be used. If a degree of stress transfer is required then a stitch type repair should be attempted. These soft repairs however do not aim to increase the stiffness of the structure, and are unlikely to prevent further collapse.

A simple method for the assessment of wall lean was presented. If the reason for wall lean is the failure of a structural member (for example ineffective roof tying), then replacement or repair of that member should be considered prior to intervention to the building. A range of different tying schemes were shown, the majority of which aimed to introduce a tension member into the structure. It is considered that the most effective of these is probably the placement of steel C sections on opposite walls, with wires running between them. These sections allow the load produced by the wall lean to be spread over a large area, and if combined with spreader plates recommended by Ashurst and Ashurst (1988) may provide an effective solution to reduction of wall lean in historic rammed earth structures.

The dangers of water in a structure were highlighted in Chapter 5, and it was argued that the most pressing issue was water at the head of the wall. Where water is allowed to collect and flow down the face, then significant erosion will occur. If this water can be prevented from collecting, then the lifespan of a historic rammed earth structure can be significantly increased. If possible a roof should be placed at the head of the wall, with sufficient eaves to prevent water from being blown against the face. Where this is not possible an external structure may be placed over the whole site, but this is generally not a feasible option. Possibilities for the covering of individual walls were experimented with at Fort Selden (Oliver 2000) and the method of placing sacrificial adobes on the walls is considered to be currently the best option. Where it may not be possible to periodically replace the roof structure, then a concrete beam
with built in drains is a possibility. While the use of modern materials (especially concrete) is discouraged in the conservation, the example of La Rambla (Figure 6.20) shows that this may be considered.

Where water is present at the base of a rammed earth wall through capillary rise, it was shown that an impermeable barrier served only to increase the height of this rise by saturating the lower part of the wall. Therefore it is recommended that any impermeable barrier at the base of a wall be removed. Any other repairs (for example crack stitching) should also allow movement of water vapour from one section of wall to another, to prevent build up of moisture in any part of the structure.

Repair strategies for eroded rammed earth faces were given in Section 6.8. While re-rendering using a lime based (vapour permeable) render is recommended, this may not be possible if it were to drastically change the appearance of the site. However the use of chemical consolidants is not recommended, and it is considered that the small amount of erosion from direct rainfall impact and great thickness of rammed earth walls means that protection of the face may be unnecessary if the head of the wall is sufficiently protected. Where physical removal of material has taken place similar material should be used for repair. Care should be taken in using fallen material which may previously have been cemented, because any parts of the cementing matrix will now act as inert particles. The problems of ramming new material and of shrinkage were highlighted, and it is considered that the best repairs may be those using custom bricks constructed from similar material. These should be left to shrink then placed into the wall as a soft repair. Repairs in concrete are not recommended because of its reduced permeability. If further decay of the structure is to be avoided then any concrete repairs should protect the top of the structure.
6.10 Thesis conclusions

Section 1.9 presented research needs in earthen architecture, as identified by Houben and Avrami (2000) and Hughes (2001). It was argued that while Project Terra has been established, little progress has been made in the fundamental aspects of earthen architecture. While a large group at CRATerre acting under the auspices of Project Terra has recently made some progress (Gelard, Fontaine et al. 2007) in identifying fundamental cohesive forces, this thesis presents a substantially enhanced view.

Two interlinked strands of research were carried out. Because of the small initial understanding of rammed earth at Durham, a series of walls were constructed and crudely tested. This highlighted the layered nature of rammed earth and improved our appreciation of the construction material. These walls were crudely modelled, first by using a simple Mohr-Coulomb layered approach, then by looking at the compacted nature of rammed earth using a hardening soil model. It was shown that it is possible to model rammed earth using techniques available to practising engineers as proposed by Hughes (2001), but it became clear that the unsaturated nature of rammed earth must be taken into account.

In investigating the unsaturated nature of rammed earth, it was found that this shed light on many previously poorly understood aspects of earth construction. While water was acknowledged to play a critical role in earthen architecture (Section 1.9.1.2), an understanding of the relationship between strength and water content was previously elusive (Houben and Avrami 2000). The relationship between suction and relative humidity was highlighted, and this was linked to the air entry value of reducing pore sizes. It was shown that a liquid bridge will only exist in a pore of a certain size for a given relative humidity. This allowed explanation of the small but non zero moisture content of rammed earth walls, when it was realised that evaporation will continue from a wall until the relative humidity of the pore air is equal to that of the surrounding air. Evaporation from unsaturated surfaces was investigated and a basis for the relationship found by Wilson, Barbour et al. (1995) was proposed. It was shown that the greatest evaporation takes place at low suctions reducing exponentially as the relative humidity of the sample approaching that of the
surroundings. This helps to explain why rammed earth building have been held up as excellent in maintaining their internal relative humidity, and shows that through evaporation and condensation rammed earth walls may act as relative humidity 'flywheels'.

Liquid bridges between particles were suggested to be the source of additional strength in rammed earth, and that the added sample strength depends on the number and strength of these bridges. The concept of pore size distribution was introduced together with the idea of saturated and unsaturated pores, based on the pore radius for a given relative humidity. It was argued that samples may be considered as saturated above their air entry value, but must be considered as a bonded soil once liquid bridges form. The double structure theory was used to explain the behaviour of the samples on loading, and it was proposed that the saturated and unsaturated parts of the sample be considered separately. On loading the air filled pores would be compressed in preference to those which are water filled, and thus air filled pores would eventually become water filled because of their reduced pore radius. This means the sample would eventually become saturated and would then behave as a critical state material. The void ratio used in saturated soil mechanics was shown to be a blunt instrument when dealing with unsaturated soil, and better measures such as maximum pore size, or pore volume distribution should be introduced.

It was illustrated that the previously held notion that cohesion of rammed earth and other types of earthen architecture is due to clay chemistry may be false. An understanding of the binding mechanisms in earthen materials, described as 'fundamental to advancing knowledge' by Houben and Avrami (2000) is now a little closer. By linking relative humidity to pore size, it was shown that there is a minimum pore size across which a meniscus will always exist, and that pores below a certain radius may always be considered as saturated. It was argued that within these DLVO theory may be applied, but that liquid bridges rather than Van der Waal’s attraction are responsible for the additional strength of dry rammed earth. This is most effectively illustrated when considering that a saturated clay brick is significantly weaker than an air dry clay brick.
The Fuller formula has been proposed as a method to determine the optimum particle size distribution to achieve maximum density for rammed earth mixes. By considering the notion of pore size distribution, it can be seen that a particle size distribution approximating to that given by the Fuller formula will result in both minimum pore volume and minimum pore radius. This will result in the maximum number of liquid bridges in a sample, and thus increased strength.

These finding have some relevance to modern rammed earth construction. Many guidelines (for example Walker, Keable et al. 2005) suggest that rammed earth samples be compacted at optimum moisture content, determined by a standard geotechnical method, then tested after being dried for a specified time period. Compacting at the optimum moisture content produces the most dense sample, for a given compactive effort, and it is assumed that maximum density equates to maximum strength (which may be the case, although no tests have yet been carried out). The practice of testing of optimum moisture content using the Proctor, Heavy Proctor or any other laboratory test should be abandoned. It is widely understood in geotechnical engineering that the density of a specific sample is affected by both the water content and the energy applied. Some practitioners compact very wet of optimum and it was found that the recommended ‘drop test’ overestimates the optimum moisture content of a sample. In geotechnical terms, the optimum moisture content should be used for compaction, as this will result in the maximum density. Any tests looking to obtain the moisture content for compaction should use the field compaction method to determine the optimum moisture content and therefore maximum density.

The cement stabilisation of rammed earth is currently a widely debated topic within the earth building community. At present there is a very confused picture regarding the addition of cement. It is acknowledged that there is an optimum cement content, above which the strength of a sample does not increase, but the reason for this peak is unknown. Many tests have been carried out which attempt to determine the optimum moisture content for compaction of cement stabilised rammed earth, but have provided mixed results (e.g. Kumar and Reddy 2007). The picture becomes clearer when the unsaturated nature of rammed earth is taken into account. The strength of cement stabilised rammed earth is a combination of particle interlock, liquid bridges
and an incomplete cementing matrix. Because the formation of the cementing matrix relies on the presence of water it is unable to form completely because of evaporation of water from the rammed earth. The peak cement content may be seen as that which can form a matrix with the water present in the sample before it evaporates. Further cement powder added to the samples does react to form part of the cementing matrix and does not therefore increase the sample strength. Unfortunately a series of experiments comparing both the water content at compaction and the cement content to sample strength, which could test this hypothesis have not yet been carried out.

The highly unsaturated nature as shown for rammed earth is likely to hold for all types of earthen architecture, and as such cob and adobe may be understood using the same principles. However, much further work is required before a full understanding of earthen architecture can be achieved. This thesis has detailed only very simple tests carried out on rammed earth, but with the understanding gained through these tests more complex experimentation may be attempted. At the macroscale, masonry type tests on rammed earth wallets may reveal more about the bond between each compaction layer, and lead to a better understanding of the behaviour of the wall in shear. The behaviour of rammed earth when subject to erosion by water may be better understood by placing tensiometers within a wall to measure the change in suction, or by measuring the relative humidity of the pore air. Better geotechnical information may be gained by testing cylindrical samples triaxially, and by better measurement of both the load and deformation of a sample. At the microscale it should be possible to explain the cracking of highly unsaturated rammed earth, if it is viewed as an interlocked sample weakly bonded by liquid bridges. An Environmental Scanning Electron Microscope (ESEM) has already been used to view liquid bridges (Lourenço 2008) but their behaviour and strength at high suctions should be investigated. Modern soil chemistry deals with suction above the air entry value of the soil but the precipitation characteristics of dissolved minerals at high suctions are currently unknown. It is possible that solid precipitate bridges will form between particles at high suctions and chemical analysis and investigation using ESEM techniques may shed light on this possibility.

While much work was done about the engineering behaviour of rammed earth as observed in the laboratory, the focus of the thesis is historic rammed earth.
Investigation of many historic rammed earth sites informed work in the laboratory, and the treatment of rammed earth as an unsaturated soil improved understanding of the behaviour observed in the field. The presence of rammed earth in Spain was known through previous work (Jaquin 2004), but the international distribution of rammed earth beside the frequently quoted examples of the Great Wall of China and the Alhambra was unknown. Appendix A (published as Jaquin, Augarde et al. 2008) was compiled during the PhD and serves as a broad spatial study of rammed earth distribution. It is hoped that this information will allow a greater understanding of the spread of rammed earth, and may help those outside the field of engineering. Study of many of the sites was initially hindered by the lack of description of different types of rammed earth. Chapter 4 presents a unified set of descriptions which can be used to illustrate different types of rammed earth. With these descriptions it is possible to speculate how a historic wall may be constructed without destructive intervention.

The lack of case histories of earthen architecture where engineering is the key concern is highlighted by Hughes (2001) as important in the lack of appreciation of the unique structural behaviour of earthen architecture. A wide range of failures of rammed earth structures were identified based on the work of previous authors and observations during fieldwork. It was argued that the specific nature of each failure should be accurately determined, and a number of diagrams were provided to facilitate the analysis of historic rammed earth buildings. It was stressed that structural problems be discerned from those caused by water, and shown that many of the issues discussed in Section 1.9 could be better understood by viewing rammed earth as a highly unsaturated soil.

Hughes (2001) called for assessment and documentation of repair techniques. A range of repair strategies were shown, based on observations in the field and recommendations by conservation experts. The cause of the damage should first be determined and mitigated, then a repair strategy implemented. It was argued that soft repair strategies such as those which replace the fabric of a structure, be used when the cause of damage has been removed, and hard repairs, those using foreign materials, when a structure is still under threat. The problems of facing a wall in concrete were highlighted, and this practice is discouraged in favour of repair using similar materials. Pre shrunk custom bricks made using the same material as the wall
were considered to be the best option for rammed earth repair. Because the greatest threat to a rammed earth wall is considered to be the ponding of water at the head of the wall, methods for covering the top of the wall were shown, and these are considered to be of greater use than any consolidation and repair techniques to the face. While the best option is always likely to be the roofing of a structure, a variety of different techniques for covering eroded wall sections were shown.

The low volume of research material and absence of prior work at Durham made it difficult to continue with previous work. This research has evolved, with experimentation and observation guiding further work. Many blind alleys were explored before the highly unsaturated nature of rammed earth was acknowledged. This allowed the explanation of many issues which have been plaguing the earth building establishment for a long time. Many of the ‘research issues in earthen architecture’ described in Section 1.9 may be answered by considering the unsaturated nature of rammed earth, but much further research is required. Treatment of the building material as a highly unsaturated soil represents a step change in understanding for earthen architecture and it is hoped a much greater understanding will be gained from it.

This study will allow earthen architecture professionals to better recognise historic rammed earth structures, to describe them and to place them in a historical context. Because individual failures have been identified, it is possible to distinguish and target them. Recommendations for repair have been given, and because the unsaturated nature of rammed earth is now acknowledged it is hoped that repair strategies will now be much improved.