Article

Earth to Earth: Patterns of Environmental Decay Affecting Modern *Pisé* Walls

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Abstract: Rammed earth/*pisé* is an earth building technique with a deep history in several countries across the globe. In the past twenty years, *pisé* buildings have seen a resurgence in popularity, primarily because of their environmentally friendly, passive energy characteristics, but also due to the aesthetic appeal of the fabric. As with all other earth architecture, *pisé* is susceptible to decay by moisture ingress. This paper presents longitudinal observations on the decay of capped and uncapped *pisé* walls of an early twenty-first-century complex of four buildings in Albury (NSW, Australia). It can be shown that while surface treatment with water-repellent sealants prevents the ingress of penetrating damp, it also traps moisture (falling damp) in the fabric by restricting evaporation. This leads to internal cleavage between the consolidated and the unconsolidated fabric and accelerates the decay of uncapped walls. The future design of both stabilized and unstabilized external rammed earth walls must ensure effective protection from rainfall through well-proportioned overhanging eaves. While the capping of feature walls may be aesthetically pleasing, and thus architecturally desirable, it does not adequately protect the walling against long-term decay.

Keywords: building conservation; earth construction; environmental decay; modern architecture

1. Introduction

Historically, earth-walled buildings were common throughout the world [1,2], with many building techniques (wattle and daub, adobe, and *pisé*) still being practiced in many modern-day communities [3,4]. Vernacular earthen architecture was common, for example, in colonial settler communities in the Americas [5–7], as well as in Australia, where a number of techniques were practiced, such as pug-and-pine, cob, mudbrick, and *pisé* [8–11]. With increasing standards of living in the late nineteenth and early twentieth centuries and the associated public perceptions as to what constituted 'proper' architecture, however, earth-walled buildings became uncommon in the developed world.

While mudbrick homes have a long post-World War II history, particularly among people aspiring to alternative life styles [12], the international debate on climate change during the mid-1990s brought about a new emphasis on sustainable, energy efficient architecture. Consequently, the period saw a revival and adaptation of traditional vernacular earth building techniques in many countries [13–16], among them Australia [17–20].

One of the frequently expressed concerns in relation to earthen architecture is the longevity of such structures, particularly their resistance to various agents of environmental decay. Such considerations gain in importance in an era of global climate change where environmental extremes (droughts, floods, and fires) are becoming more frequent and more intense.

Several longitudinal studies have examined how historic earth-walled buildings decay, be they of pug-and-pine [8,10] adobe [21–23], or *pisé* construction [9]. This is of relevance to both the owners of the properties and to cultural heritage professionals tasked with the conservation of the structures. Setting aside research into seismic performance [24–26], there is, at present, no literature that examines the environmental decay processes that affect modern-day rammed earth construction.

A common method to prevent or restrict moisture ingress into concrete masonry, as well as rammed earth and other earthen constructions, is to treat the external surfaces with a deep-penetrating, substrate-bonding sealer. This treatment is commonly applied post-construction [27,28], but can also be applied retrospectively as a conservation treatment [29]. While laboratory tests confirm the suitability of the treatment to prevent penetrating moisture (driving rain and condensation), the long-term effects have not been examined in real-life situations.

Following a review of the general decay processes and the ways that they impact earthen construction, this paper will discuss the longitudinal effects of environmental decay acting on *pisé* structures

It will do so through a series of macroscopic examinations and diachronic observations of unprotected walls at a late twentieth-century complex of rammed earth buildings located in New South Wales, Australia, and by contrasting the findings with the decay affecting protected walls in the same complex.

2. Methodology

2.1. Study Site

Between 1997 and 1999, Charles Sturt University (CSU) erected the Environmental Sciences complex of buildings at Thurgoona (NSW)($-36.038013, 146.990988$), using cement-strengthened rammed earth. While the majority of the walls are capped to prevent moisture ingress, eight shield/privacy walls remained uncapped. The six free-standing walls assessed for this study are all located on the northern side of buildings 761 and 762. For ease of reference, they have been numbered from W1 to W6, starting in the east. Each wall has two faces, an eastern (E) and a western (W). Two uncapped, but roofed, walls on the southern side of buildings 761 and 762 serve as controls (C1 and C2).

2.2. Assessment and Documentation

The assessment of the decay occurred in situ, examining the visual and tactile appearance of the walls, as well as their integrity when subjected to gentle physical-impact testing (with the blunt end of a broad marker pen). The documentation of the decay is based on two methodologies of macroscopic observation: measurements and stratigraphic recording.

The recording of the first wall surface (wall 1, eastern face) used a laser beam (Bosch PLL 1P) mounted on a robust tripod (Gitzo GT5561SGT with a G2270M three-way head), which was set up so that the beam was aligned parallel to the wall surface. Relative to that arbitrary line, measurements with 1 mm accuracy were taken, set in a 20 × 20 cm grid. A level of accuracy greater than 1 mm was deemed spurious given the irregularity of the wall surface.

The contour analysis of these detailed measurements led to the simplification of the recording method for the remaining five walls. The documentation was thereafter limited to the recording of the visible decay with a method akin to a standard archaeological/pedological stratigraphy, with measurements taken in a 40 × 20 cm grid.

Unless specified otherwise, all photos were taken by the author.

2.3. Environmental Settings

Albury has a warm, temperate climate, characterized by very warm to hot summers and cool to mild winters, with temperatures rarely dipping below 0 °C [30]. While a freeze–thaw action, one of the major destructive forces in colder climates, is very rare and thus not a concern in Albury, the walls do experience a large temperature variation during the summer. During the middle of summer, diurnal temperatures range from 15 °C at night to a maximum in the mid-40s during the day [30]. Temperatures in the direct sun, however, can be up to 25 °C higher (pers. obs.).

3. General Patterns of Decay of Unreinforced Rammed Earth and Adobe Walls

In the literature, the pattern and mechanics of the decay of earthen structures are well described [31–35]. In principle, the decay processes affecting *pisé* buildings are physical, chemical, and biological.

Pisé is a building technique whereby lumps of clayey soil with a high plasticity are placed between the formwork and then compacted using a stamper. This results in layers of clay/soil that alternate between low (bottom of layer) and high compaction (top) (Figure 1). The strength of the bonding between the layers depends on the amount of time the surface of the compacted layers is allowed to dry out and also the smoothness of the compacted surface before the next layer is applied (Figure 2).
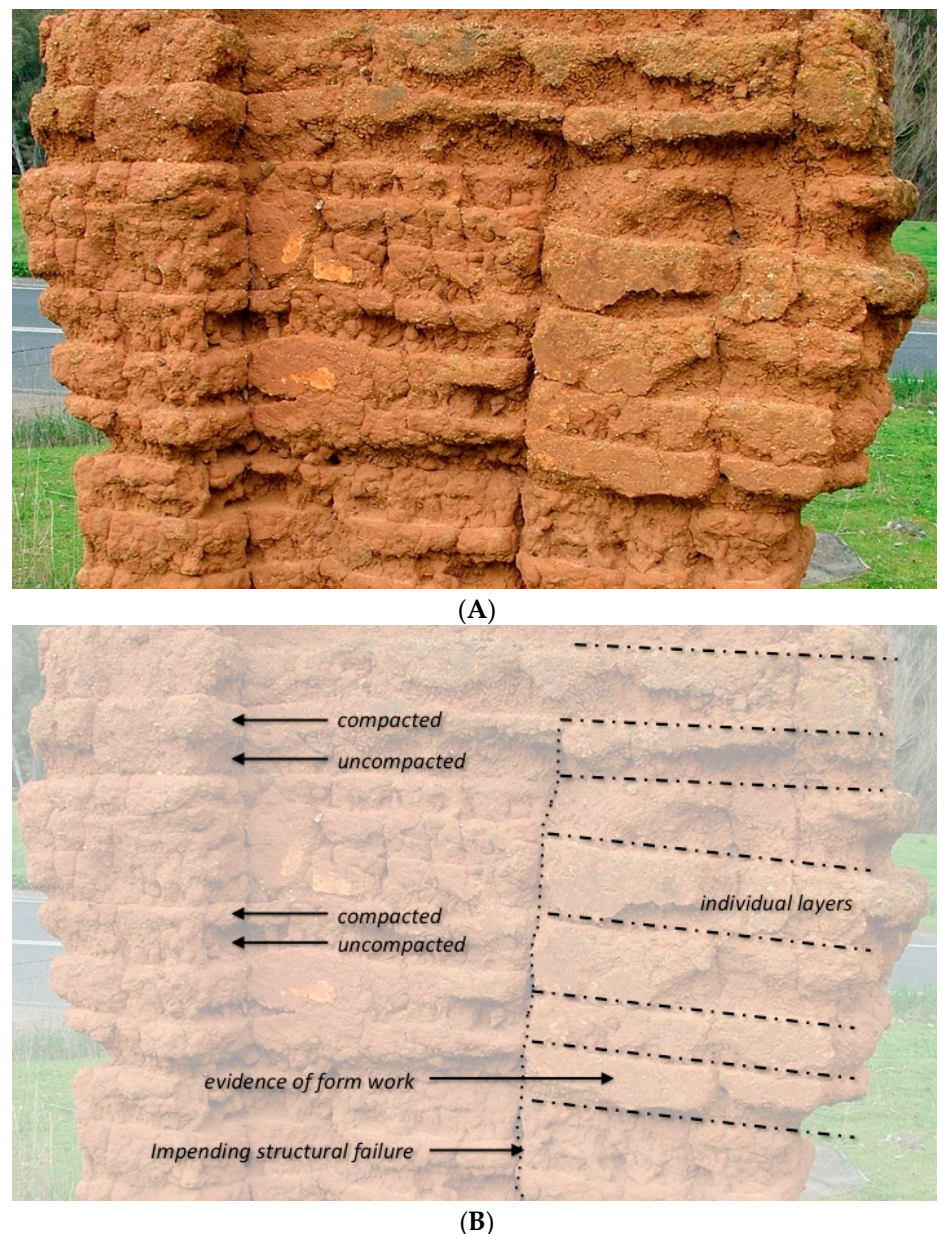

(**A**)

(**B**)

Figure 1. Influences of construction technique and quality of work on the preservation of *pisé* walls of a nineteenth-century ruin at Jugiong (NSW). (**A**) Photograph of a section of the northern face of the now collapsed southeastern wall block, as seen on 30 September 2005. The layers of fill and compaction are well evident. (**B**) Annotated interpretation of the image. Reprinted from Ref. [9].

Figure 2. The collapsed southeastern block as seen from the southeast on 30 September 2015. Note the clean breaks and lack of bonding between the compaction layers. Reprinted from Ref. [9].

Traditionally, the walls were then rendered with a fine clay/sand mixture and whitewashed. During the second half of the nineteenth century, Australian rural newspapers regularly carried columns that explained the technique to the colonial settler community [36–44].

Pisé work has some resistance against deterioration, and as long as the earthwork is not exposed to rain or surface moisture, long-lasting houses can be erected by this technique. The agents of decay are predominantly physical, with the bulk of the damage caused by rainfall and its derivatives. A *pisé* structure becomes susceptible to decay due to the ingress of water once it has lost its surface finish. *Pisé* buildings, which essentially consist of unfired loams or clays with a high hygroscopic index, will shrink and swell depending on the moisture content of the ambient air. Because of the high hygroscopic index, they are also very vulnerable to rising damp (Figure 3f) [45]. Subject to the duration of the immersion event, a flooding of the bottom part of the walling, be it riverine flooding or rainfall-induced sheet flooding significantly threatens the stability and integrity of a *pisé* structure. Walls may bulge under the weight of the roof once the clay becomes so wet that it reaches its plasticity limit.

Given the unconsolidated, compressed nature of *pisé* walls, damage to or loss of a roof allows rainfall to enter the unprotected top ends ('falling damp', Figure 3b). Prolonged wetness will accelerate the severity of the decay, depending on the intensity of the rainfall, as well as the pre-existing moisture content of the walling at the time of precipitation.

Vortexes created by winds (Figure 3a) can exacerbate the decay of the exposed wall tops (Figure 4). The high hygroscopic index of *pisé* walls also facilitates the ingress of penetrating damp caused by wind-driven rain as well as dew (Figure 3c). During heavy downpours, the lower parts of the walls are not only susceptible to general wetting but also to raindrops or hail pellets splashing off the ground through micro-impact (depending on raindrop velocity), which can, over time, dissolve the render and thus provide further avenues for moisture ingress (Figure 3d,e). This process is accelerated if the base of the walling has already been weakened by rising damp (Figure 3f). If left unchecked, this basal erosion eventually undermines the walling to such an extent that entire walls may topple or collapse (Figure 2).
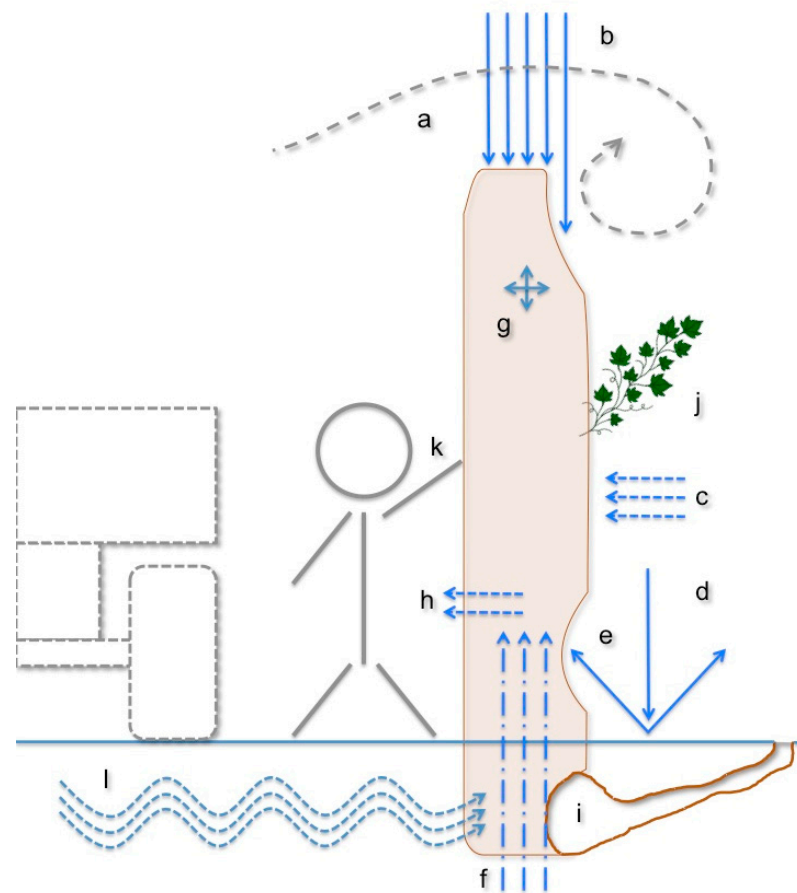
Figure 3. Schematic representation of the decay processes observed in *pisé* buildings after the roof has been removed/collapsed (see text for explanation). Reprinted from Ref. [9].
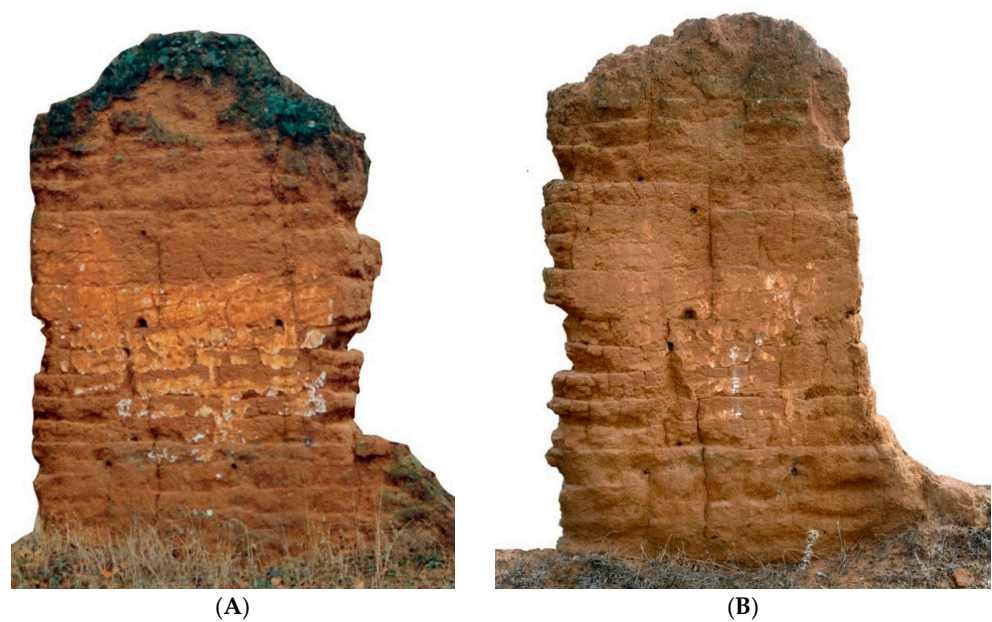

| (A) | (B) |

Figure 4. The southern face of the southeastern wall block at Jugiong (NSW). (**A**) Appearance on 15 February 1993; (**B**) appearance on 2 April 2015. Reprinted from Ref. [9].

Earth buildings can also be subject to a saline threat [46,47]. Depending on the level of ground moisture and the concentrations of water-soluble salts therein, this may lead to salt crystallization in the pore spaces and subsequent efflorescence. Repeated dehydration

and hydration events increase the problem, which will bring about a decay of the fabric through micro-erosion, which may, eventually, lead to structural failure (Figure 3h) [48].

It is important to note that the clay, as a binding agent of the walls, relies on the presence of moisture. Thus, *pisé* buildings should not be allowed to completely dry out, even if external moisture acts a major decay agent. In consequence, the introduction of a damp-proof course into traditionally erected *pisé* buildings could prove to be counter-productive as it might affect the stability of the structure. A total drying out of the walls would result in the separation of the sand and fine gravel that acts as an aggregate due to the shrinkage of the clay particles, resulting in a gradual granular erosion of the exposed surfaces. Structural cracking of the walling decreases its load-bearing capacity and stiffness (Figure 4). If structural unconformities exist, such as where poor quality of the initial construction work results in the walls lacking overlapping layers (Figure 1), the result may be large-scale cleaving of the wall segments.

On a more micro-scale level, the effects of the differential thermal expansion, such as the freeze–thaw action, of the components of the *pisé* may also need to be considered. This applies in particular to hot climates, where daytime surface temperatures on unshaded walls can exceed 65 °C, while nighttime temperatures drop to 20 °C or less; repeated differential thermal expansion between the core and the exposed surfaces of the walling may cause separation of the clay matrix and the aggregate. As the *pisé* earth mix is unfired, the bonds between the clay particles and the sand and fine gravel aggregate are weak. Differential bonding occurs in areas that exhibit variable compaction during the construction process, with the less compacted layers clearly more susceptible to granular erosion (Figure 1). This can be exacerbated if the surface of the aggregate particles is rounded and smooth rather than rough and textured. Moreover, the nature of the clay inclusions, such as gypsum, influences its bonding characteristics.

Finally, changes in the weight distribution of a roof may have severe or even catas-trophic implications on the structural integrity of a building during seismic events, largely due to the low tensile strength of adobe and *pisé* walls. These are well described in the literature [49–51]. Given that the study area is not known for its seismic risk [52–55], we need not be overly concerned with these effects. It should be noted, however, that that destructive earthquakes affected the area in the nineteenth century [56,57].

Additional causes of decay that do not impact on the structures under discussion, but that may compromise other *pisè* structures, are the effects of vehicular traffic in close proximity, both chemical (CO_2 and SO_2 vehicle emissions) and mechanical (low-frequency ground vibrations) (Figure 3l); burrowing animals that can weaken the foundations and lower wall sections (Figure 3i); and vascular plants growing in cracks with expanding roots exerting lateral pressures in the fissures (Figure 3j) [9].

4. Modern Decay at Thurgoona (NSW)

In 1993, Charles Sturt University (CSU) acquired land at Thurgoona, 8.2 km northeast of the Albury CBD and commenced the green fields development of a campus. The initial suite of buildings was erected in an arc along the northern slope of a small knoll (Figure 5). The design concept aimed at making the development as environmentally neutral as possible. This entailed passive energy in the buildings, facilitated by the use of rammed earth construction, natural ventilation, and solar heating; the exclusive use of sustainably grown or recycled timber and other building materials (incl. fire-retardant wool carpets); the use of composting toilets with artificial wetlands for the purification of the effluent; the collection of surface runoff in large farm dams to prevent creek erosion; and the reuse of this water for landscape irrigation (using a windmill to pump it to a higher elevation) [19,58–64]. In total, fourteen rammed earth buildings were erected between 1997 and 2004 (Table 1).

Figure 5. The eastern wing of the Environmental Sciences building (Bldg 760) as seen from northwest.

Table 1. Chronology of rammed earth structures erected at Charles Sturt University Campus, Thurgoona, NSW, Australia.

Date	Event	Building (n°)
1993	Charles Sturt University acquires the site	
1995–1996 (May)	Student Pavilion Building	672
1997–1999 (Feb)	School of Environmental (and Information) Sciences Offices	760
1997–1999 (Feb)	Specialist teaching building (and computer lab)	761
1997–1999 (Feb)	Office building, a regional herbarium	762
1998	Network facility completed (telephone and computer switch)	754 (part)
1998–2000	Four eight-room student cottages and laundry block	680–684
1998 (Oct)–2001	Two-story teaching complex, including a 200-seat lecture theatre.	751
2001–2002 (Feb)	Two additional eight-room student cottages	685–686
2002–2003 (Jul)	Student Recreation Facility	752
2004 (Feb)–2005 (Jun)	School of Early Childhood Education Offices	763

The campus design received a number of awards and has been showcased as an example of sustainable architecture in a sustainable tertiary teaching environment [59,64]. The site development and architectural design influenced other buildings in the region, ref. [65] including a church and the associated priest's residence. In view of its architectural and social significance, the Environmental Sciences Building, a two-storey building housing 100 staff (Figure 5), was identified as culturally significant in a 2003 heritage study [66], and subsequently included as a protected heritage item in Albury City's Local Environmental Plan 2010 (schedule 5, item 330) [67].

In order to minimize the environmental impact, the original group of Environmental Sciences buildings is not sewered, but is serviced by a series of Clovis Multrum composting toilets. Public toilets are attached to buildings 761 and 762, and there is an additional, dedicated, staff toilet in building 762 (Figure 6). The design of the maintenance access to these toilets differs from that of the toilets of building 760. While the latter access is flush with the building, the toilets of buildings 761 and 762 have two protruding wing walls each, which provide visual screening and also prevent wind from accessing the system. These walls are fully exposed; they lack capping and also lack shading (Figures 6 and 7).
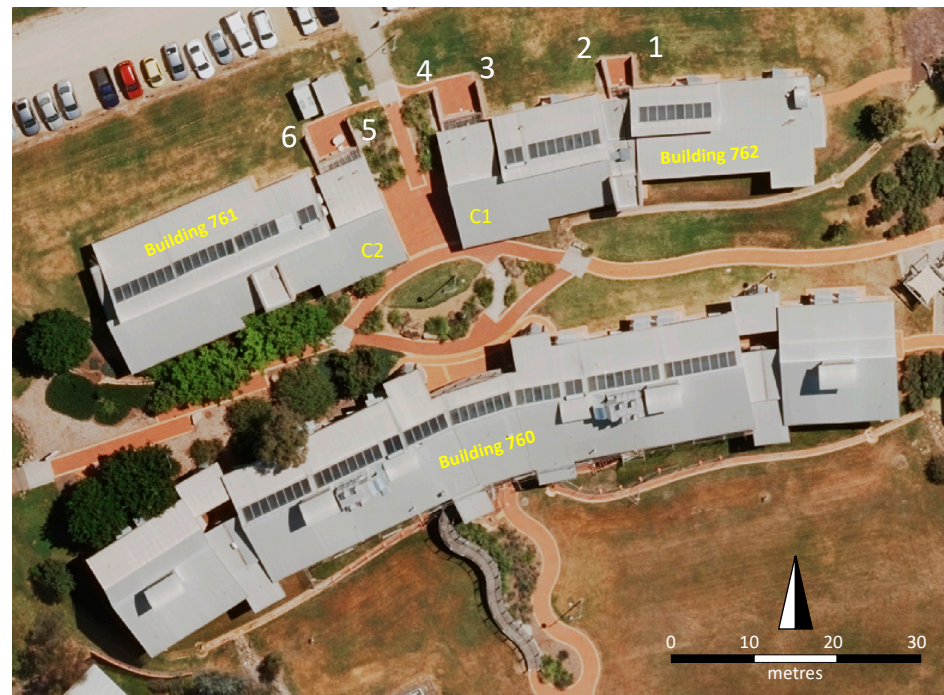

Figure 6. The School of Environmental Sciences building complex, Charles Sturt University, Thurgoona, showing the location of the buildings and the eight walls under discussion (1–6, C1, C2). Base image: Google Earth.

Figure 7. Uncapped *pisé* wing walls (walls 3 to 6), as seen from the northeast. Building 761 (right) and building 762 (left).

The buildings are erected on a slight slope, which provides the required depth for the toilet cavity that is dug into the slope (Figure 7). As a consequence, the free-standing wing walls exhibit a base of concrete blocks (400 × 200 × 200 mm) that follows the line of the slope, topped by a rammed earth wall (Figures 8–10). Each of the rammed earth walls was created in two sections: a short single-layered section adjacent to the building and a longer section projecting away from the structure, which exhibits three layers. These layers correlate with the original form boards. The top two layers are 600 mm high, while the bottom layer makes up the remainder of the wall height.

Figure 8. Wall 1 seen from the west. Note the accumulation of eroded debris at the base of the wall.

Figure 9. Wall 1 seen from the east.

Figure 10. Wing wall 3 seen from the east. Note the linear decay at left, indicating different layers of compaction.

4.1. The Construction of Buildings 760, 761, and 762 at Thurgoona

The buildings were constructed by Terry Wright Riverina Rammed Earth Constructions (Table Top, NSW, Australia), based on the designs by architects Marci Webster-Mannison and Chris McInerny [68]. While traditionally the soil for a *pisé* building would be obtained on site or close by, the soil used for the CSU buildings was sourced from a clay pit in Jindera (11 km northwest of the site). The testing of the supplied soil, as well as the resulting mixes, was carried out to the relevant standards, as prescribed at the time [69–76].

The specifications, as issued for the rammed earth buildings, are set out in Table 2. Similar specifications were issued for the subsequent buildings [77], including the projected School of Business, which was eventually erected for the School of Early Childhood Education (Bldg. 763) [78].

Table 2. Specifications for the buildings.

Constituent Materials	
Soil particle sizes	
Organic content	<2%
Clay and silt content	<20%
Sand content	≥50%
Coarse aggregate content	>30%
Water	Clean, fresh, free from impurities
Stabilizing agent	Cement (AS 3972) GP grade
Stabilized earth mix at placement	
Cement content (range)	max. 5% by weight
Adj. compressive strength (min.)	2.5 MPa
Moisture content (range)	8–16%
Dry density (t/m^3)	2.13
Liquid limit (max.)	35%
Plastic limit (max.)	20%
Plasticity index (max.)	12%
Linear shrinkage (max.)	5%
Plasticity index: linear shrinkage	2.5:1

The construction technique followed established principles [79] and entailed the erection of moveable sections of formwork, with the earth fill added with vibration and subsequent compaction and curing. The load-bearing external and internal walls of the buildings, irrespective of whether it was a double-storey (760) or a single storey office building (761, 762), are 300–310 mm thick. The internal partition walls have a thickness of 200 mm. By comparison, the screening walls (C1, C2) for the toilets of buildings 761 and 762 are also 300 mm thick (beveled to 210 mm). The final walls exhibited a very smooth, almost shiny, surface finish, caused by the clay particles being pressed against the smooth form boards. As the bolts fastening the form boards onto the support frame were recessed, the final wall surfaces show these recesses as small and low circular protrusions (Figure 11).

(A) **(B)**

Figure 11. Uncapped, protected wall C1, screening the entrance to the external toilets of building 762: (**A**) frontal view seen from the south; (**B**) sideways view seen from the west.

To prevent the ingress of penetrating damp, silicone-based sealants were applied that made the inherently hydrophilic rammed earth construction more hydrophobic [27]. For buildings 752, 760, 761, and 762, Tech-dry® Plasticure was added to the rammed earth mix [68]. The product remains permanently bonded to the substrate, cannot be washed out, and reduces water absorption and efflorescence by over 80% [80]. For Building 763, the surfaces of the finished walls were treated with a water-repellent coating, a silane/siloxane sealer with a deep-penetrating, substrate-bonding clear impregnating finish that, theoretically, would prevent moisture ingress while allowing vapor transmission [68,78]. The interior walls that are not exposed to the elements have a smooth and shiny finish.

4.2. General Observations of Decay

Unlike traditional rammed earth, the structures constructed for CSU have a small admixture of Portland cement (Table 2), primarily to increase the structural strength required to hold the heavy concrete ceilings that were required for the innovative cooling and heating systems. Even though the walls are stronger, this does not imply that they are immune from decay.

The decay documented here has occurred in an incremental fashion but seems to have accelerated in the past few years (pers. obs). The decay of some of the walls is very obvious, with the loss of surface finish on most of the wall areas, the loss of fabric in some sections of the wall, and the concomitant accumulation of the gravelly component of the mix at the base of the wall (Figure 8).

4.3. Results of Decay Measurements and Observations

The standard or control sample, against which all decay could be assessed was provided by two free-standing walls, which were both privacy walls shielding the entrances to the male and female public toilets of buildings 761 and 762 (Figure 12).

Figure 12. Section of an external wall covered by a large overhanging roof. Note the details of the recessed bolts holding the form boards as well as the sections of form boards (Bldg 762).

At the time of construction, the wing walls were 200 mm thick, 1.65 m tall at their highest point, and measured between 3.6 m (walls 1 and 2) and 4.9 m in length (walls 3–6). The base of the walls is made up of one row of 200 mm-tall concrete blocks. The top of these wing walls is not only uncapped, but its surface is also rough and unfinished—and as such, a prime candidate for moisture ingress. As the main roof of the building extends over the walls and adjoining area, none of the wall surfaces is exposed to rainfall-derived moisture. Consequently, these walls have retained a very smooth, almost glossy surface (caused by the compression of clay particles against the form boards) and also show all the small circular protrusions that originate from the recessed bolt sections of the form boards. None of the six exposed wing walls examined for this study shows this level of preservation.

The eastern face of wall 1 (Figure 13A) is the one that has been studied in the most detail. It comprises a small section under the eaves, with a clear boundary of the form section and a larger section ending at 3.60 m from the wall of the building. While the small section was executed as one piece, the larger section shows three horizontal lines indicating the form board levels (Figure 12). The top half of the second wall segment exhibits extensive and largely uniform surface decay, exposing the coarse aggregate. The wall section closest to the northern wall of building 762 exhibits a small patch of original surface finish, located under and protected by the eave. All the measurements obtained relative to the laser beam (see methodology) were recalculated relative to the base value provided by this original surface.
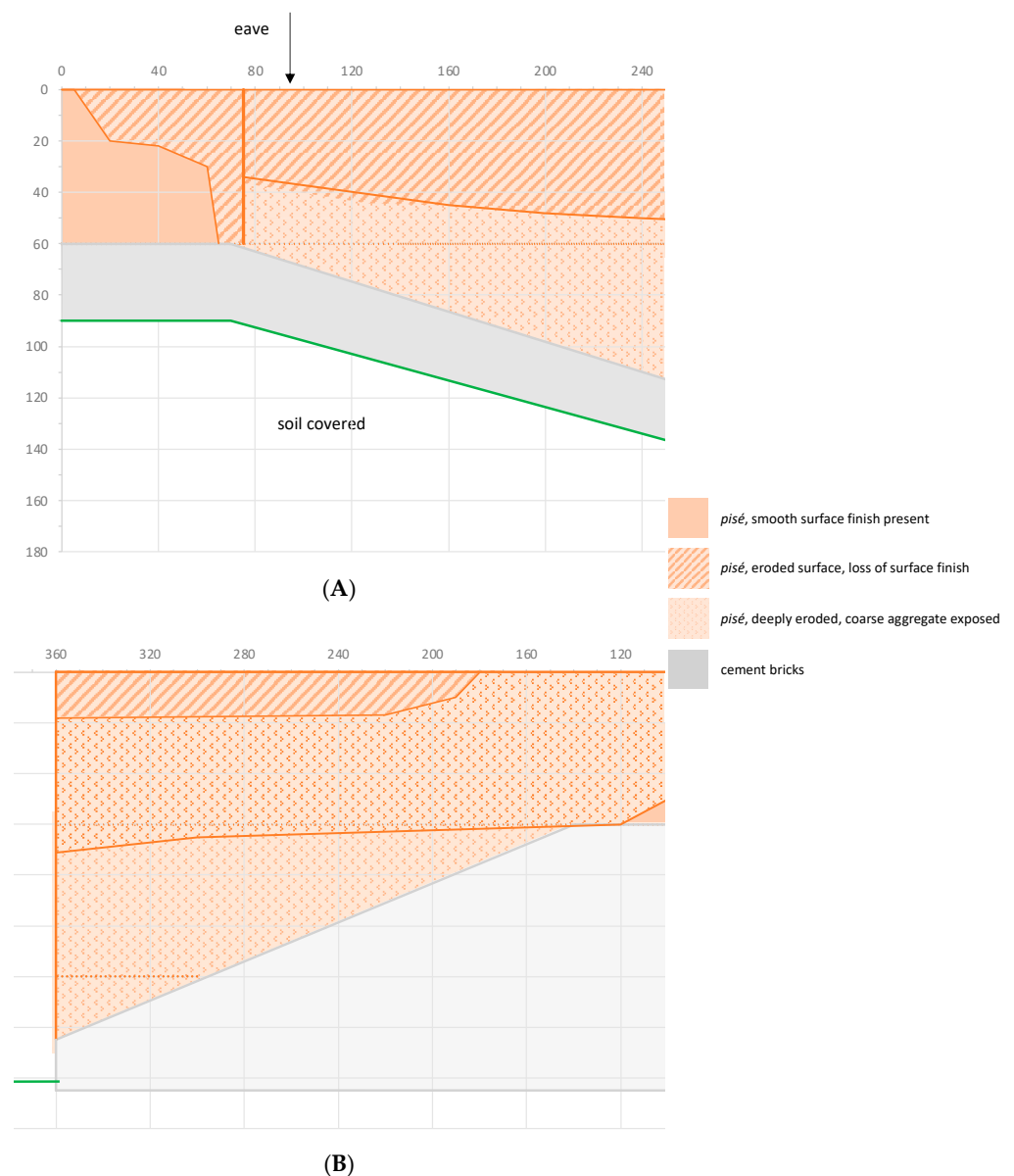
Figure 13. Schematic representation of the observed decay of wall 1: (**A**) eastern face; (**B**) western face.

Based on general observations, as well as experience gathered at the Jugiong site (Figures 2 and 4), it was expected that the wall would exhibit a general overall surface loss, resulting in a reduction in wall thickness, with the upper sections showing a greater loss than the lower sections. As the contour map shows, however, the reality is more complex (Figure 14). A small section, shielded by the eave, appears to have retained its original level. Compared to the control walls that are fully roofed (Figure 11), however, the surface of that section has experienced a loss of smoothness as well as the loss of form board details, indicating some degree of broadscale erosion. As expected, the very top of the walling exhibits the greatest loss of fabric, especially in the area just below the (guttered) drip-line of the eave. The upper section of the wall generally also shows major loss of fabric. A considerable quantity of erosion product, mainly fine- and coarse-grained aggregate, has accumulated at the base of the walls, with the finer clay particles washed out by rainfall. A general loss of surface was also observed in the lower section of that half of the wall closest to the dripline, while the lines between the form board levels are filled with coarser material and thus are prominently visible in the finished walls. In the exposed walls this infill has eroded out and allows for moisture to reside there.
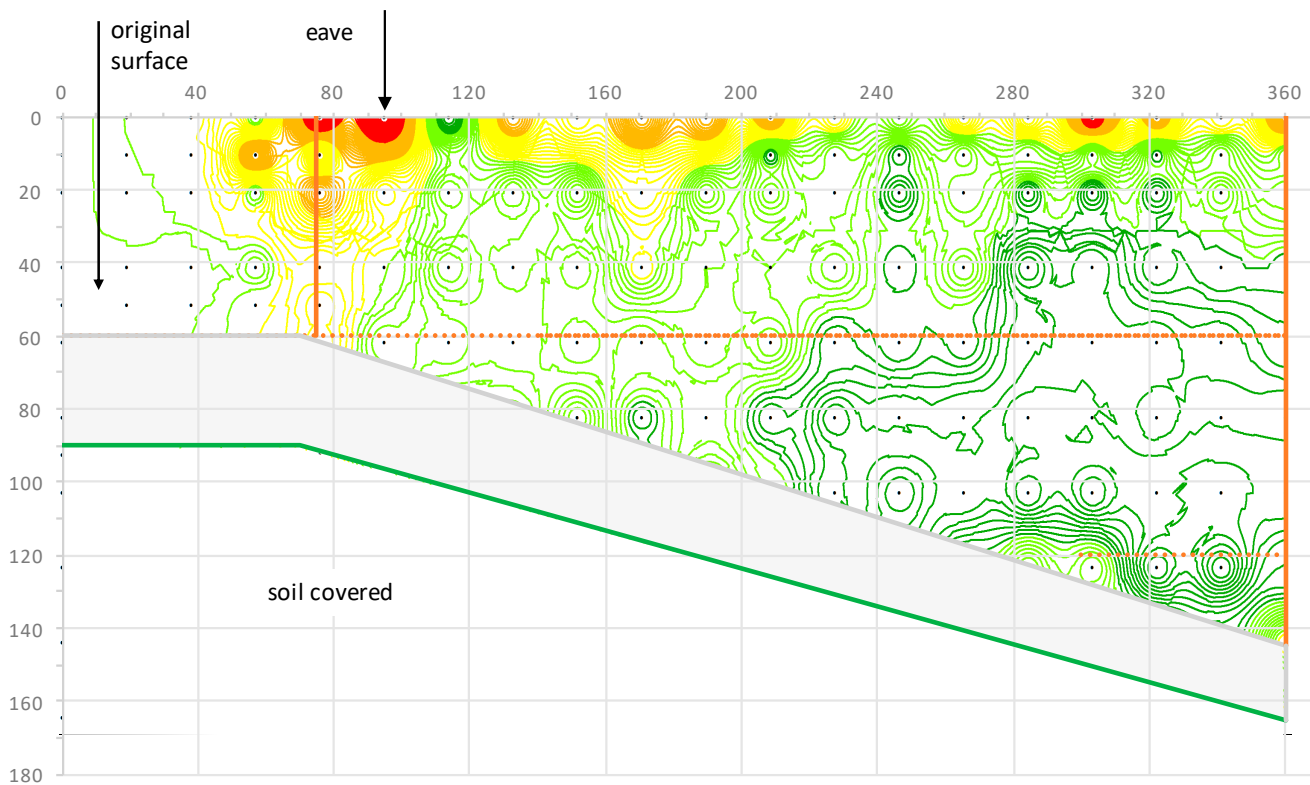
Figure 14. Observed decay on the eastern face of wall 1. Contour intervals 2 mm. Contours (relative to the patch of original surface): dark green 11–22; green 0–10; yellow −13−−1; orange −29−−14; red −50−−30.

Wholly unexpected, however, was the fact that the majority of the lower sections of the unprotected wall seemed to be protruding from the baseline (as defined by the section under the eave). In particular, the lower section of the wall towards the northern end appeared to be much thicker than the rest. The contours clearly show a bulging wall surface (Figure 14). Gentle impact testing (with the blunt end of a broad marker pen) showed that the surface was 'drummy,' indicating a large-scale separation of the surface layer from the wall substrate. This indicates eventual structural failure and cleaving of the wall surface. The extent of the bulging suggests that the fissure between the core of the wall and the surface layer is considerable.

Macroscopic observations of the surface on the eastern face of wall 1 show five states (Figure 13A), which, at different heights and to different degrees, are manifested on the surfaces of all the other walls (Figures 13 and 15–19):

(i).   An original surface with a rougher texture and some loss of detail compared to the surfaces of the control walls that are roofed and protected from the environment.

(ii).   Surfaces that show pitting and general loss of finish, resulting in a coarse-textured surface revealing the nature of the aggregate. The top of the wall is eroding and loses definition, exposing the aggregate.

(iii). Below-surface separation of the external skin from the core, resulting in bulging of the exterior and noticeable 'drumminess'.

(iv). Surfaces where the original skin has spalled off, resulting in a very uneven and very coarse textured fabric, exposing the aggregate. The top of the wall has become rounded.
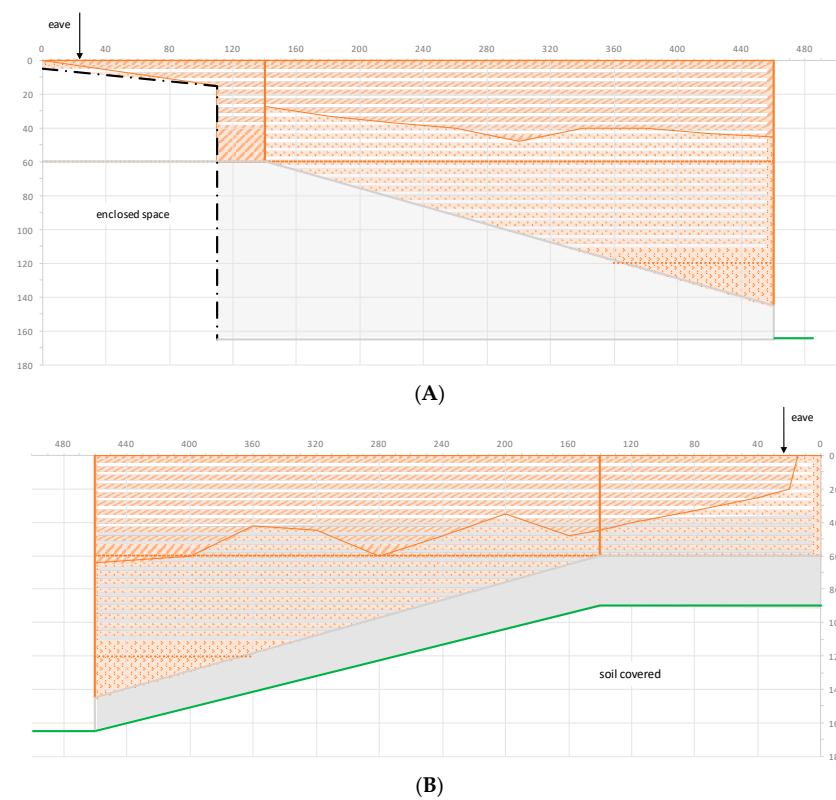
(v).   Continued deep erosion.

Figure 15. Schematic representation of the observed decay of wall 2: (**A**) eastern face; (**B**) western face. For the legend, see Figure 13.
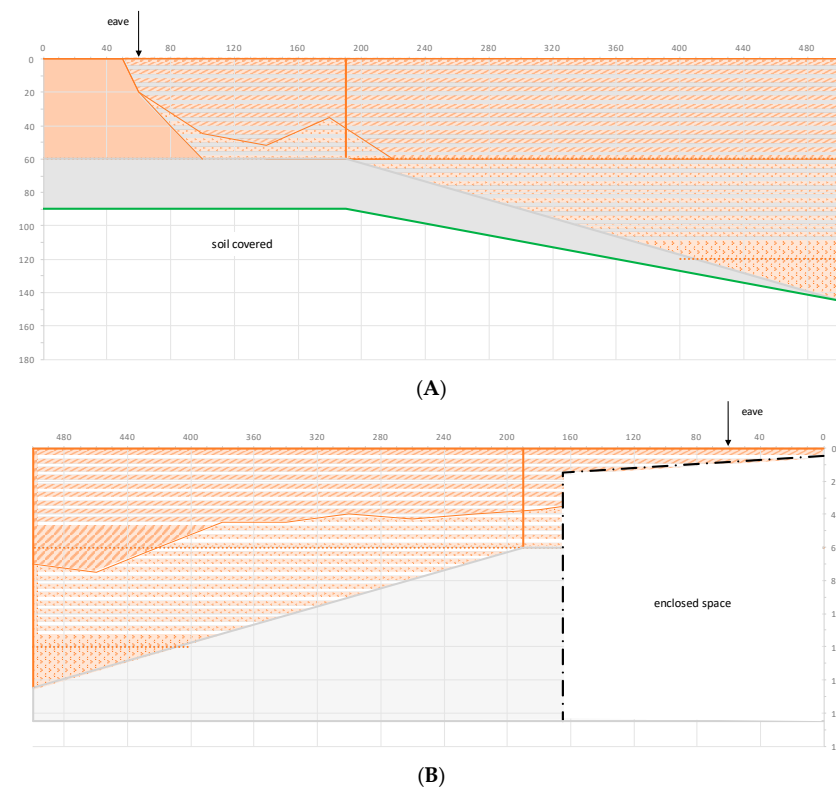

Figure 16. Schematic representation of the observed decay of wall 3: (**A**) eastern face; (**B**) western face. For the legend, see Figure 13.

Figure 17. Schematic representation of the observed decay of wall 4: (**A**) eastern face; (**B**) western face. For the legend, see Figure 13.

Figure 18. Schematic representation of the observed decay of wall 5: (**A**) eastern face; (**B**) western face. For the legend, see Figure 13.

Figure 19. Schematic representation of the observed decay of wall 6: (**A**) eastern face; (**B**) western face. For the legend, see Figure 13.
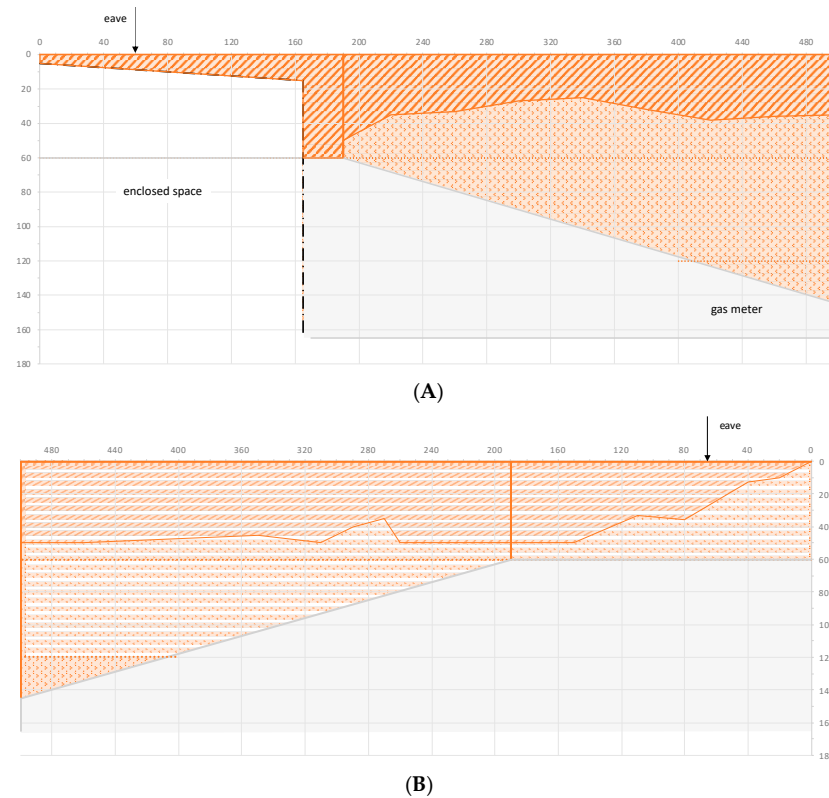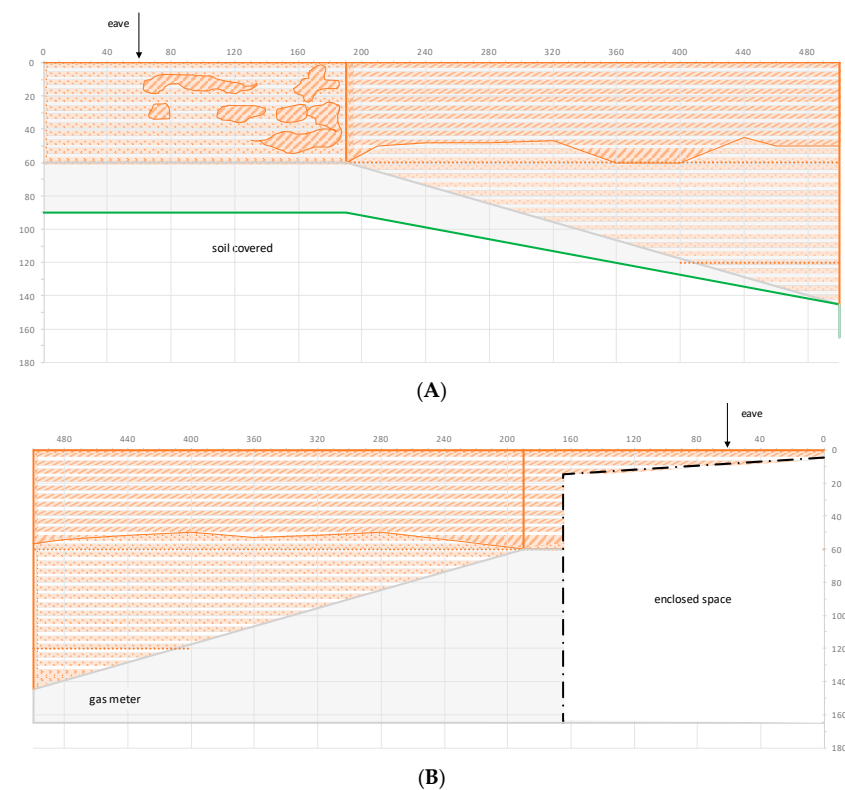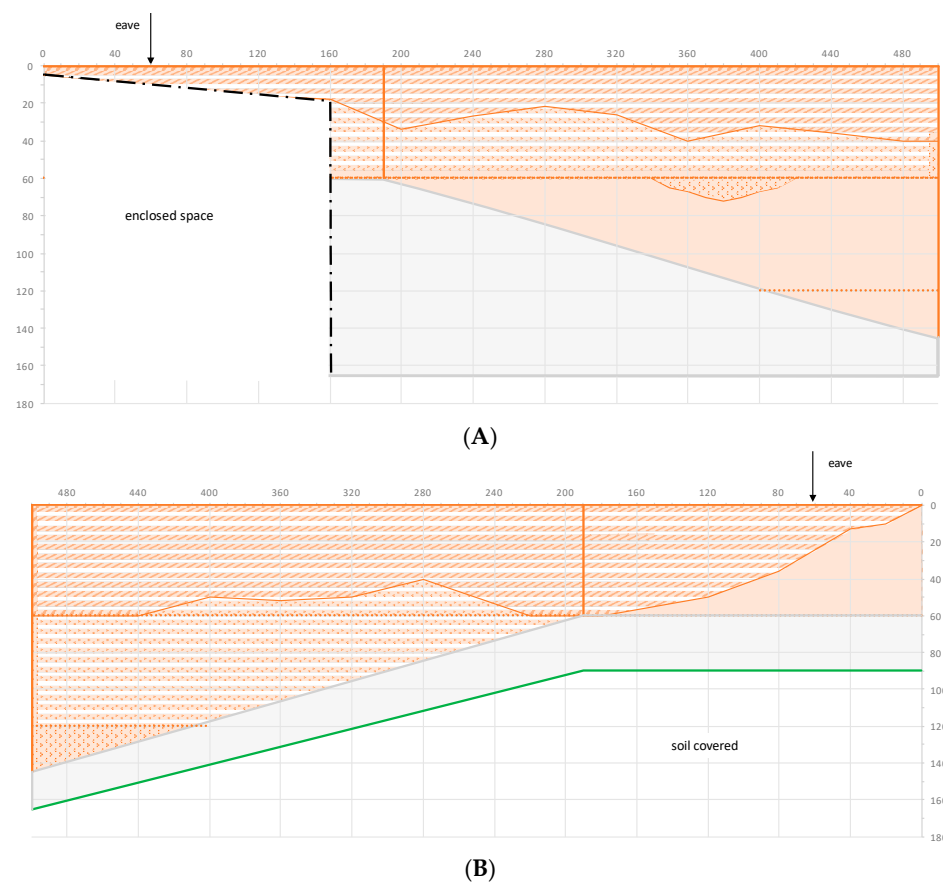
A variation occurs when the external skin does not spall off as a large chunk, but in horizontal stripes that seem to reflect different levels of compaction during construction.

In the case of the eastern face of wall 1, these four states only partially correlate with the observed contours (Figure 14). The major bulging occurs in the area that shows pitting and general loss of finish, but no spalling. Some of the area returned a hollow sound when knocked, indicating a separation of the external surface from the core. Tapping the surface at the upper margins of that zone led to spalling.

4.4. Ancillary Observations

The bases of all the wing walls are erected on at least one row of 200 mm-high concrete brick, which effectively protects the lower sections of the *pisé* walls from splash impacts. The composting storage area between each set of walls is enclosed by a 0.9 m-high *pisé* wall towards the north and covered with a skillion roof covered with corrugated iron, which prevents falling damp. The eaves of these small structures are generally very narrow (100 mm) and unguttered. Consequently, the surface of the wall shows only very limited loss, mainly in the form of broadscale erosion. As the floor space between the walls is paved (Figure 20), however, rainwater dripping off the unguttered short skillion roof will bounce off the hardened surface and cause splash-effect damage to the lower section of the wall. The effects are variable, with a height of 75–220 mm above the level of the pavers between wing walls 1 and 2, 145–175 mm between wing walls 3 and 4, and 145–220 mm between wing walls 5 and 6.

Figure 20. Paved space between wing walls 3 (left) and 4 (right) of Building 762. Note the decay at the base of the wall of the composting chamber.

The effects of merely capping the walls instead of roofing with an eave can be studied at the entrances to buildings 761 and 762. These show raised parapets as architectural features (Figure 21A). These walls are capped with concrete pavers but have no eaves and only 20 mm-wide protective overhangs. Consequently, the rainfall runs off the flat capping onto the wall and then straight down the front façade (and presumably also the back), causing slight but broadscale erosion of the surface of the *pisé* wall (Figure 21B). The fact that the tops of the walls are flat contributes to the problem, as a similarly capped, but sloping, feature wall of the network facility (Bldg 754) does not show this level of decay. The walls of the single-storey buildings, 760–762, that are protected by overhanging eaves do not exhibit any obvious decay and only exhibit a broadscale micro-erosion. This manifests itself in a loss of the shine on the otherwise smooth surface.

Figure 21. Parapet over the entrance to building 761, seen from southeast: (**A**) the portico; (**B**) decay below the capping, southern façade; (**C**) decay below the capping, eastern façade.

An examination of the walls of building 760 at the ground-floor level showed that eaves even protect the rammed earth walling of two-storey structures. Very limited micro-

erosion occurred, and the walls have retained both the very smooth surface and the small circular protrusions that originate from the recessed bolt sections of the form boards. Any observable micro-erosion that exceeds the loss of the surface shine is limited to a small section at the very bottom that would have been exposed to the splash effects of very heavy rain.

5. Discussion

The buildings at CSU's Thurgoona Campus, erected between 1996 and 2004 (Table 1), were an early adoption of the emerging technology of stabilized rammed earth architecture. The nature of the buildings, which have been exposed to the same environmental conditions, provides examples of the propensity for decay of four different wall types: roofed walls, with and without eaves, capped walls, and uncapped walls. It is very obvious that those walls that are uncapped and otherwise unprotected from the elements, suffer decay much more than the other walls.

From the observations gleaned at all the wall types, the following decay sequence can be inferred:

Phase 1. Moisture ingress into the walling occurs primarily through the top as falling damp. Where the walls are roofed, the falling damp is prevented altogether, whereas the capped walls show a reduced exposure to falling damp. The hygroscopic characteristics of the clay particles lead to a retention of moisture, as well as a swelling of the clay matrix at the top of the wall. This will recede during each drying phase. The cyclic expansion and contraction of the clay particles during the successive wetting and drying phases leads to reduced adhesion to the aggregate. In parallel, extreme diurnal temperature fluctuations, particularly during the summer months, cause a differential expansion and contraction of the binding matrix and the embedded aggregate. This is particularly true for the aggregate components closest to the wall's surface. The resulting micro-fissures set up a capillary action which progressively allows moisture ingress to ever deeper sections of the wall. This leads to an increasing swelling of the clay matrix, which explains why the surface contour map (Figure 14) shows a thickening of the wall. The admixture of the Portland cement (Table 2) seems to have had little effect.

Due to the very smooth nature of the form boards, and the compression used, fresh rammed earth seems to have a higher-density outer skin, akin to, but not as strong as, the fire skin of brick. As long as that skin remains intact, penetrating damp seems to be restricted.

Phase 2. Adhesion failure will progress to such a degree that the surface skin separates from the wall's core, leading to spalling. This large-area cleaving can only be explained by the differential adhesive qualities and stability of the clay matrix between the external skin and the core of the wall. While the compression caused by the form boards plays a major role in establishing a dense skin, it can be posited that the application of deep-penetrating sealants added to this. Even though the sealant, which is designed to repel penetrating damp, is supposed to allow for moisture evaporation, the hygroscopic potential and the sorption of the compressed and impregnated skin are fundamentally different from the less compacted core. Thus, any moisture trapped in the core will expand during increases in daily temperatures and thus set up pressures that will exploit differences in the adhesive potential. This results in structural bonding failure between the matrix and the aggregate and between the core and the skin, opening up ever-expanding and widening fissures that will eventually result in small- to large-scale spalling.

Phase 3. Once this skin has eroded, or spalled off, the surface area increases and the less compacted material with a higher hygroscopic index is exposed. Moisture ingress from both falling and penetrating damp impacts on the clay particles, causing adhesion failure to the gravelly component of the aggregate, which results in a gradual degranulation of the wall. In the case of the walls under discussion, a considerable amount of erosion material had accumulated at the base of the walls.

6. Conclusions

In the past twenty years, rammed earth/*pisé* buildings have seen a resurgence in popularity, primarily in terms of their environmentally friendly, passive energy characteristics, but also because of the aesthetic appeal of the fabric. As with all other earth architecture, *pisé* is susceptible to decay by moisture ingress.

To counteract the ingress of environmental moisture, primarily penetrating damp, both the stabilized and the unstabilized rammed earth walls have been treated with a water-repellent coating, commonly a silane/siloxane sealer with a deep-penetrating, substrate-bonding clear impregnating finish. The effectiveness of these sealants has never been formally assessed in the actual, built environment, let alone as a longitudinal study.

The exposure and decay data available for the Thurgoona buildings span a period of 18–26 years (1996–2004, depending on the building), which is equivalent to between one third and one half of the average life span of an office building (50 years).

The observed patterns of decay show that the stabilized rammed earth at Thurgoona that has been permanently roofed with wide eaves is less likely to show evidence of falling or penetrating damp. The sloping walls that are capped show no falling damp either, while the horizontal walls with capping exhibit falling damp effects in the upper sections below the capping. The capped walls also exhibit broadscale slight surface erosion.

Uncapped walls exhibit both broadscale surface erosion as well as structural failures between the part of the wall that was saturated with the deep-penetrating, substrate-bonding sealer and that part that remained untreated. The sealed skin effectively cleaves off. Based on the available data, the decay of the tops of the capped walls will continue to progress, extending down the walling with deepening erosion at the top.

7. Implications

The future design of both stabilized and unstabilized external rammed earth walls must ensure effective protection from rainfall through well-proportioned overhanging eaves. While the capping of the feature walls may be aesthetically pleasing, and thus architecturally desirable, it does not adequately protect the walling from long-term decay.

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