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# Hydro-mechanical behaviour of earthen construction material repairs

## Le comportement hydromécanique des réparations du matérieu terre

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**ABSTRACT:** Earthen construction materials are of increasing interest to geotechnical engineers, where it is now recognised that these materials can be viewed as manufactured unsaturated soils. Many heritage rammed earth structures require repairs that involve replacing damaged old material with new. However, very little work has been done to understand the hydro-mechanical interactions once the new material has been added. Future experimental work is planned to investigate the dynamics of water retention across interface surfaces and how salts can be transported via these mechanisms, the influence of environmental factors, and the durability of these interfaces. In this paper previous work exploring water transport and its interaction with soluble salts is discussed, which could provide a basis for research in this area.

**RÉSUMÉ:** Les ingénieurs en géotechnique s'intéressent de plus en plus aux matériaux en terre, car il est maintenant reconnu que ces matériaux peuvent être considérés comme des sols non saturés fabriqués. De nombreuses structures en pisé du patrimoine nécessitent des réparations qui impliquent le remplacement de vieux matériaux endommagés par du nouveau. Cependant, très peu de travail a été fait pour comprendre les interactions hydro-mécaniques une fois que le nouveau matériau a été ajouté. De futurs travaux expérimentaux sont prévus pour étudier la dynamique de la rétention d'eau à travers les surfaces d'interface et la façon dont les sels peuvent être transportés via ces mécanismes, l'influence des facteurs environnementaux et la durabilité de ces interfaces. Dans cet article, nous discuterons des travaux précédents sur le transport de l’eau et son interaction avec les sels solubles, ce qui pourrait servir de base à de futures recherches dans ce domaine.

**Keywords:** Rammed earth, unsaturated flow, salts, capillary rise, unsaturated soils

## 1 INTRODUCTION

Earth has been used across the world as a building material for thousands of years. Rammed earth (RE) is one such technique, and is made by compacting damp subsoil inside formwork to form a mass wall, then removing the formwork and allowing the soil to dry. Soil mixes typically include clay, silt, sand and gravel while heritage structures can feature pebbles or occasionally larger stones. Modern use of rammed earth, for example in New Zealand and Australia, often adds cement to the mix to improve its durability and strength, and the use of a variety of stabilisers has been seen in heritage earthen buildings. However, unstabilised RE is often encountered in the heritage context.

Although many historic RE buildings have survived for centuries, the material is vulnerable to erosion from water and wind, particularly when regular maintenance stops. Water ingress can lead to material loss and often collapse due to reduced material integrity, which can be exacerbated by salt crystallisation and efflorescence. Conservation interventions therefore often involve replacing lost material or applying new renders. Previous repairs with inappropriate concrete or cement have led to further damage, highlighting the importance of understanding the material for effective conservation (Jaquin and Augarde, 2012).

Using unsaturated soil mechanics, progress has been made in understanding the basis of how moisture affects the strength and durability of RE (Gallipoli et al, 2017), but less has been done to investigate how water and salts are transported through the material. As RE is a manufactured unsaturated soil, research on this problem from the unsaturated soils community is anticipated to be applicable. Furthermore, there is debate on whether salts are damaging purely due to their hygroscopic properties increasing water content, or whether separate mechanisms of damage occur due to the presence of salts alone. In addition, if the assumption is made that soluble salts are carried by water, a model of water transport is needed to form the basis of any model of salt transport. This paper will provide examples of damage as seen by the authors, review previous work on water transport and the effect of soluble salts on RE, and identify ways unsaturated soil mechanics could be used to improve models of these processes.

## 2 RAMMED EARTH AND MOISTURE

### *2.1 Vulnerability to moisture*

A three-day field trip was undertaken in 2018 to the Aragon region of Spain to find examples of water degradation processes in different contexts. Historic rammed earth from urban and rural contexts were found in varying conditions depending on the level and quality of maintenance being provided. Examples from this field trip will be used to illustrate common decay processes in heritage RE in this section.

In the cities visited (Borja and Tarazona) it was common to find RE walls with cement renders at the base and extensive heights of wetted material above. These cement renders were also prone to delaminate and reveal the RE surface beneath.

*Figure 1: Rising damp and delamination of cement render exposing the RE beneath, Tarazona city.*

In both urban and rural settings RE walls were found with stone bases 1-2m high; the RE in these walls was generally in better condition as the height of rising damp did not exceed the stone base height. However, water ingress was often visible within the stone part of the wall, particularly for sandstones.

There are multiple mechanisms of water ingress. For example, insufficient protection from rainfall and subsequent runoff can lead to water eroding the wall height and the surfaces. Alternatively, water can enter any existing cracks and thus penetrate into the core of the wall (Jaquin and Augarde, 2012). The subsequent reduction in material strength often leads to further cracking which will increase water ingress. However, this paper will focus on an alternative method of water ingress via the base of the wall, often known as rising damp or capillary rise. This source of moisture can penetrate into the core of the wall and cause surface material loss, leading to “coving” or “undercutting” of the wall. If not addressed, a significant percentage of the wall cross section can be lost, eventually leading to wall collapse (Franzoni, 2018; Jaquin and Augarde, 2012).

*Figure 2: Severe coving of wall at abandoned monastery ruin, Mulzalcorag, near Agon village.*

A complication of water ingress can be if water-soluble salts are transported into walls, where changes in water content can induce crystallisation that leads to a reduction in material strength. This can also occur if the soil mix used in construction has a high concentration of salts. This is a particular issue for heritage structures, where there is usually no damp proofing at the base of walls.

*Figure 3: RE house displaying mild coving due to rising damp despite stone base, Ambel.*

The presence of salts is usually noticed due to surface efflorescence, although it is common to test heritage samples for salt concentrations when gathering evidence to prepare a conservation plan (Cooke, 2010). This accumulation of salts near the surface can also lead to surface delamination, often seen in combination with rising damp, and thus accelerating wall coving. Although salt damage in RE has been observed by many (Cooke, 2010; Fodde et al., 2007, Miccoli et al., 2017; Röhlen and Ziegert, 2011), the exact mechanisms by which salts enter and move through RE have not been researched.

*Figure 4: Surface delamination due to rising damp with salts efflorescence, Borja.*

One technique used by conservators to remove salt from earthen materials is to apply a sacrificial mortar to the material, which draws salt from the core to the surface. This mortar can then be removed and re-applied until no more salt is being drawn out (Fodde, 2008). This technique is currently designed by trial and error on particular sites and is an area where further research could aid conservation techniques.

## *2.2 Rammed earth as an unsaturated soil*

Rammed earth is essentially a highly compacted unsaturated soil, and therefore unsaturated soil mechanics could provide insight into the decay mechanisms described previously. For example, the soil mix water content at compaction can be optimised to produce the maximum material dry density by analysing a Proctor curve for the chosen mix (Jaquin and Augarde, 2012).

Unsaturated soil mechanics can also explain the sensitivity of RE to water content. The soil water retention curve (SWRC) relates water content and suction. For measured curves, depending on the range of suction, either the total suction or matric suction can be recorded, where total suction is defined as

$$\psi = \psi_m + \psi_o \tag{1}$$

where $\psi_m$ is the matric suction and $\psi_o$ is the osmotic suction. As unstabilised rammed earth does not have a cementing material component, the high suctions developed in RE are a significant contribution to the overall material strength. This key result has been demonstrated by multiple researchers (Gelard et al., 2007; Beckett et al., 2018). In Jaquin et al. (2009) unconfined compression tests on cylindrical unstabilised rammed earth samples were carried out, using tensiometers to measure suction at the top of the samples. They showed that lower water contents resulted in higher strengths and increased suction was also associated with higher strength. Bui et al. (2014) similarly found that higher suctions and higher strength was correlated, this time measuring suctions via the filter paper method which uses the change in water content of a filter paper to determine the corresponding change in suction by use of a calibration curve. In addition, increasing relative humidity (RH) has been shown to reduce these materials' strength via a similar mechanism (Beckett and Augarde, 2012; Gallipoli, 2017), and the presence of salts in solution will increase the osmotic suction within the material.

## 3 MODELLING WATER TRANSPORT

### *3.1 Modelling rising damp*

An understanding of the large scale process of rising damp in a wall is needed in order to apply any work on water flow done using RE samples. A first-order sharp front approximation produces a model of rising damp within walls which only requires the material sorptivity to predict the water behaviour (Hall and Hoff, 2007). By equating the rates of water absorption and evaporation, the equilibrium height of the wetting front can be found as

$$h_{ss} = S\left(\frac{b}{2e\theta_w}\right)^{0.5} \tag{2}$$

where $h_{ss}$ is the steady state height of wetting, $b$ is the width of the wall, $\theta_w$ is the average water content over the height of the wetted wall region, $e$ is the evaporation rate and $S$ is the sorptivity.

Sorptivity, $S$ can be defined as

$$S = \frac{i}{t^{0.5}} \tag{4}$$

where $i$ is the cumulative volume of absorbed water per unit area and $t$ is the absorption time. It can be found experimentally by measuring the water absorbed via capillary rise for a material.

The initial wetting process before equilibrium can be described by

$$h^2 = \frac{S^2 b}{2\theta_w e}\left(1 - e^{-\frac{2e}{\theta_w b}t}\right) \tag{3}$$

where $h$ is the transient height of the wetting boundary at time $t$, and $t$ is the time since the start of water ingress. This model makes a variety of simplifications: gravity effects are ignored, the water content is assumed to be uniform within the wetted region of wall, the rate of evaporation is assumed to be constant for given environmental conditions, and the material is assumed to have a constant sorptivity value.

Sorptivity can be related to soil permeability and suction by

$$S = (2fK\psi)^{0.5} \tag{5}$$

where $f$ is the effective soil porosity, $K$ is the effective permeability and $\psi$ is the capillary suction (Hall and Allinson, 2009).

These soil parameters all vary with void size distribution (VSD) of the soil, so Equation 5 could be used to predict how changes in permeability or suction for different soil mixes or levels of compaction would affect sorptivity.

### *3.2 Experimental work on RE water transport*

The majority of work looking at RE water ingress has concentrated on absorption rather than movement through the material (McGregor et al., 2016). Work by M. Hall and Djerbib measured the sorptivity of a variety of rammed earth soil mixes by adapting the IRS (Initial rate of suction) BS 3921:1985 test for use on unstabilised RE (British Standards Institute, 1985; Hall and Djerbib, 2004a). This test measures capillary absorption but the original procedure results in disintegration of unstabilised RE. Therefore, the IRS `wick' test was developed to compare the sorption of conventional fired masonry, stabilised and unstabilised rammed earth, measuring the IRS defined as the absorbed mass of water per area per minute.

They found rammed earth had a lower IRS than fired masonry, cement stabilisation increased the RE IRS, and that the RE PSD affected the IRS. Hall and Djerbib confirmed that capillary absorption in unstabilised RE was proportional to the square root of time, i.e. had a constant sorptivity. This means that the Hall and Hoff capillary rise equations can be applied (Hall and Djerbib, 2004a, 2006). Clay contents over 10% by mass significantly reduced the sample sorptivity, and the ratio of the aggregate specific surface area (SSA) and the clay fraction mass (SSA/CC ratio) was linked to the IRS observed. In a later paper, sorptivity, suction and material permeability were related using the wetting sharp front model of Hall and Hoff (Hall and Allinson, 2009). They note that RE follows root-t behaviour unlike concrete, an example of how RE is a distinct material from concrete. The IRS `wick' test was used again to measure the retreat of the `wet front' in drying stabilised RE and a sharp wet front model for evaporative drying was applied (Hall and Allinson, 2010; Hall et al., 1984). This proposed that drying could be split into two stages; Stage 1 where pores are filled in the wetted region and suction is below the air entry value (AEV), and Stage 2 where pores begin to cavitate as suction increases beyond the AEV. However, they note that if the rate of capillary transport is greater than the evaporation rate then Stage 1 will continue until the evaporation rate becomes dominant.

Another study investigated water ingress for RE mortar repairs via a capillary absorption test on repaired samples (Gomes et al., 2017). The performance of various earthen mortars on filling small scale holes and re-rendering of delaminated surfaces were compared, with a focus on comparing the effects of lime, cement and fibre additives on unstabilised mortar mixes. However, the results for this were not measured beyond visual inspection of the wetting front. They also performed absorption tests on mortar specimens where they found an initial non-linear relationship between water content and root-time for the unstabilised mortars, in contrast to Hall and Djerbib’s finding for RE.

# 4 SALTS TRANSPORT

## *4.1 Effect of salts on RE*

Minimal experimental work has been carried out on the effect of salts in earthen materials. Fodde describes a lab study of the effect of salt concentration in earthen material (Fodde, 2008), which found increasing the salt concentration also increased the water content for a given humidity, but the very small size of the study with only one replicate and eight samples tested in each experiment limits its validity.

Miccoli et al. (2017) detailed a collaboration between structural engineers and archaeologists on a site in Aragon, Spain to develop a conservation strategy for a historic RE site. They performed laboratory testing which included measuring salts and water contents at different wall heights as well as finding PSDs of historic material. They measured a decreasing salt concentration with height within a basement wall, and observed 2-10 cm of material loss from that wall base.

Shen et al. (2017) performed humidity cycling on RE samples with different concentrations of sodium sulphate ($Na_2SO_4$) and sodium chloride (NaCl) and measured shear strength, compressive strength and resistance to wind erosion. They found that increasing the salt concentration reduced compressive strength and resistance to erosion but the shear strength exhibited a peak at c. 0.5-1% salt content. They tested samples containing either $Na_2SO_4$, NaCl or a mixture of the two and found that $Na_2SO_4$ had a greater deteriorating effect than NaCl when alone, but that the mixed salt had the greatest effect. They hypothesise this is due to the relative solubility change with water content at greater depths from the material surface.

None of these studies examine the transport mechanisms of salts in RE but demonstrate that salts affect the water content and the strength capacity of the material. However, as RE is a compacted unsaturated soil, models of salt transport in soil should be applicable.

### *4.2 Modelling salt transport*

Given the previous work decribed above one approach to modelling salt transport in RE would be to find the effect of salts on sorptivity or the parameters contibuting to it as described in Equation 5, and use that to predict effects of salt ingress on water content distribution in RE. This could then be linked to suction via the SWRC.

Dongli et al (2015) performed water ingress tests under three levels of suction for a silty sand with varying concentrations of sodium chloride (NaCl) using a tension infiltrometer . The soil had a particle size distribution close to a 1:5:4 ratio of clay: silt: sand which is similar to common RE mixes (Hall and Djerbib, 2004b). They noted that previously a decrease in capillary rise has been seen with increasing sodium ion concentration in soil. They found that the sorptivity and intrinsic permeability both decreased with increasing salt content. Clay swelling behaviour was also observed, and was hypothesised to be a cause of the reduced water ingress, along with clay dispersion within the water causing blocking of larger pore sizes and therefore decreasing the available free space for water flow.

An alternative approach is to work from first principle models of solute flow within unsaturated materials. Medved & Cerny (2014) derived expressions for moisture diffusivity $\kappa$ and salt diffusivity D from the Bear and Bachmat diffusion-advection model. They used this to predict the effect of salt concentration on chloride ion diffusivity in lime plaster, comparing their results to a numerical curve which showed a quasi-quadratic relationship with an initial high chloride diffusion coefficient decreasing to a minimum at around 0.75 $kgm^{-2}$ chloride concentration before rising again. Their model produced a good replication of the shape of the experimental data at concentrations above 0.25 $kgm^{-2}$, but significantly overestimated D at lower salt concentrations.

## 5 DISCUSSION

### *5.1 Implications of water transport theory*

The Hall & Hoff model of rising damp in Section 3.1 makes several assumptions which may not be valid for RE. The first is the assumption of constant sorptivity, i.e. a linear cumulative water absorption with respect to root-time. As described in Section 3.2, Hall and Djerbib showed constant sorptivity could be assumed for unstabilised RE (Figure 10 in Hall and Djerbib, 2004a), but if the data are inspected more closely there appears to be a non-linearity particularly at the beginning of the absoprtion process. Now, as sorptivity is related to permeability as shown in Equation 5, and permeability in unsaturated soils increases with increasing water content, this could be driving the possible changes in sorptivity. Sorptivity is also related to porosity, which can change within clay-rich soils on wetting, which may explain why Gomes et al. (2016) found their earthen mortars did not follow the root-t law, i.e. sorptivity was not constant during wetting. In fact they identify clay swelling as a possible cause of this initial non-linearity (Gomes et al, 2016).

When thinking about very low water contents such as the 1-2% achieved in dry RE, the water phase will be discontinuous, meaning that capillary flow is unlikely to occur and instead vapour transport processes will contribute more (Lu and Likos, 2004). As sorptivity is derived via the Buckingham-Richards model of unsaturated flow, therefore a calculated sorptivity from Equation 5 may not be valid for this highly unsaturated case (Hall and Hoff, 2007; Lu and Likos, 2004).

Secondly, the Hall and Hoff model assumes a constant evaporation rate. They justify this by assuming the wetted region is within the range of saturation where evaporation is independent of water content, giving the example of brick where this holds for water contents greater than 30% of the saturated water content (Hall et al, 1984). This would need to be confirmed to hold true for RE. Finally, the sharp front approximation itself may be an oversimplification, for example if the distribution of water with height in a non-sharp front model results in water contents above the predicted sharp front height that are high enough to cause significant decreases in material strength and durability.

### *5.2 Open questions in salts transport*

The papers detailed in Section 4.2 indicate that increasing salt concentration reduces the ability for water to flow in unsaturated soil which could indicate that as salt accumulates within RE the rate of subsequent water and salt ingress would decrease. However, the ability of salts to hygroscopically attract water is well established and so the relative magnitudes of these effects would need to be compared to determine the overall effect on the water and salt distribution.

Although the effect of salts on water transport is being investigated, there appears to be less work investigating how salts ingress into building materials, and so taking examples from other areas of geotechnics seems to be the best strategy for future work.

## 6 CONCLUSIONS

- Water and salts ingress are a common source of decay in heritage rammed earth, as demonstrated by buildings observed in Aragon, Spain.
- Suitable models exist in the literature to describe water ingress; these can be used to develop theories for cases where RE is not homogeneous such as application of earthen mortars and coving repairs.
- An equivalent model of water ingress incorporating the effect of salts has not yet been developed for RE; similarly a model of salt transport requires development to better understand how RE becomes salinated. Models for other building materials and conventional soils should be used as a base for further development.
- Little experimental work exists investigating salt transport in RE so it is proposed to carry this out in future in order to apply to repair strategies for heritage buildings.

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