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Analysis of Historic Rammed Earth construction

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ABSTRACT: Rammed earth is a widely used historic building material, found in Mediterranean regions, along the Silk Road, and in parts of the Himalayas. While guidelines exist for the construction of new rammed earth structures, there is very little guidance for the structural analysis of historic structures.

A novel approach to the modelling of rammed earth using finite elements is presented. Each rammed earth lift is modelled as two layers, one representing the actual rammed earth and one representing the interface between each rammed earth lift. These layers are both modelled using the Mohr-Coulomb failure criteria, but different strength properties are assigned to each. A rammed earth wall is then built up using a number of these layers. These simulations have been compared with rammed earth test walls constructed in the laboratory and the above technique has been used to model these walls, with a good degree of success.

1 INTRODUCTION

To make a rammed earth wall, soil is taken from the ground, poured into formwork and compacted in layers, usually around 100mm deep. The formwork is then removed leaving a solid wall. Historically this compaction was done manually, but modern rammed earth construction takes advantage of pneumatic rammers to achieve the same result. Rammed earth has also seen a revival as a modern construction technique, due to its low carbon content and inherent recycleability. There is a need for the development of modelling methods for rammed earth structures, both historic and new-build. In this paper we describe features of historic rammed earth, particularly layering. We then detail a constitutive model for rammed earth and use it in finite element analyses of walls built and tested in the laboratory. The finite element models are tuned to replicate effects seen in the laboratory and the strength parameters required are compared to textbook and sample test results.

2 HISTORIC RAMMED EARTH

Many World Heritage sites contain structures constructed from rammed earth. Examples include Muslim fortresses dating from the 8th century throughout Spain and North Africa, Buddhist monasteries, some over 1000 years old in India, and parts of the Great Wall of China and the Potala Palace in Lhasa.

At present there is little guidance available on the analysis of historic rammed earth structures. Due to being constructed in soil, the structures are particularly vulnerable to decay caused by environmental factors such as rain, wind and water flow. Deterioration of these structures is well documented in some regions for example Sikka (2002), Cooke (2005) and Jaquin (2004) but less so in other regions due to the perceived unimportance of earth structures (Turkelova, 2004).

Relatively few design guidelines are available for the construction of new rammed earth structures (Walker 2005; McHenry, 1989; and Easton, 1996) but new build design guidelines cannot be applied to historic structures (Yeomans 2006). This is the motivation for the current programme of research into the analysis of historic rammed earth structures at Durham University.

3 HISTORIC RAMMED EARTH COMPARED WITH MODERN RAMMED EARTH

Figure 1 Villena, Spain (1172)

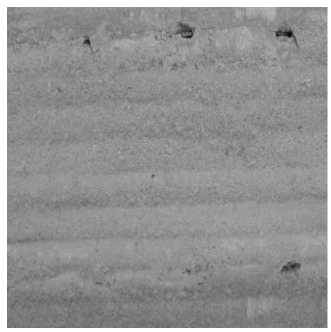


Figure 2 Cordoba, Spain (1085)

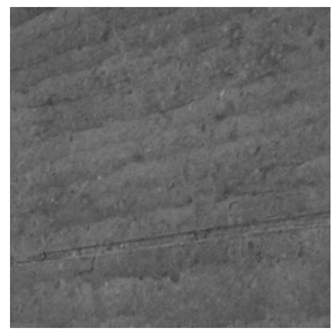


Figure 3 Laboratory wallet, Durham, UK (2005)

A number of small walls (wallets) were constructed in the laboratory in order to study the effects of loading on rammed earth walls. (The results from these tests are used later in this paper to calibrate the numerical models). A rammed earth mixture was manufactured and mixed with water in a vertical axis cement mixer to a moisture content of 12%. The mixture was then placed in formwork in layers of approximately 150mm and compacted using a vibrating electric hammer providing 27 Joules per blow. This reduced the layer depth to around 100mm. When maximum compaction had taken place (the hammer did not make any further indentation) the process was repeated, thus increasing the height of the wall. Once the wall reached the required height the formwork was struck and the wall left to dry out for 14 days prior to testing.

During a recent field visit to Spain, a large number of rammed earth structures were investigated. Remarkable similarities were found between the historic rammed and modern rammed earth construction undertaken in the laboratory, as can be seen in figures 1 to 3. A density change is clearly visible; distinguishing each layer of soil compacted within the formwork. It is these layers which have been shown to delaminate in the laboratory.

A major difference between modern and historic rammed earth is the placing of timbers in the wall. These timbers usually penetrate through the wall and are used to support the formwork as the height of the wall increases. In modern construction, concrete formwork is used, and this formwork is continuous for the full height of the wall, thus not needing support through the wall. Where supports are required (in historic rammed earth) these are found in horizontal layers around 80cm apart, around the height of the formwork used. The voids left after removal of the timbers further weakens the interface between layers, however the walls are considered similar enough to allow testing on the modern rammed earth constructed in the laboratory to be applicable to historic structures.

4 CONSTITUTIVE MODEL FOR RAMMED EARTH

A three pronged approach is being adopted at Durham, involving field investigation of a number of historic sites, laboratory construction and testing of rammed earth specimens, and numerical analysis of rammed earth, using soil mechanics principles. Numerical modelling of rammed earth has been rarely reported in the literature. A rare example is given in Maniatidis (2005) using triaxial test data for the analysis of rammed earth columns. Before embarking on finite element modelling of a rammed earth structure, one has to choose an appropriate constitutive model for the material itself.

An elastic- perfectly plastic continuum approach is taken, using a common failure criterion often applied to frictional soils, Mohr-Coulomb. This criterion states that if at any point on any plane within the soil the shear stress becomes equal to the shear strength of the soil then failure will occur at that point (Craig, 2004). The shear strength (τ) of a soil can be expressed as a linear function of the normal stress (σ) at the same point

$$\tau = \sigma \tan \phi + c \qquad (1)$$

where ϕ and c are material properties or shear strength parameters, ϕ is the *angle of shearing resistance* and c the *apparent cohesion.*

If a number of stress states are known, each of which produce shear failure in the soil, these can be plotted as a series of Mohr's circles, with a common tangent represented by Eqn 1. This tangent represents the failure envelope of the soil in normal-shear stress space. The Mohr-Coulomb failure criterion does not take into account strains, and assumes that the intermediate principal stress has no influence on the shear strength of the soil.

The angle of shearing resistance can by thought of as the amount of particle interlock within the soil body, and the frictional resistance between particles. The apparent cohesion is a summation of the chemical, electrochemical and suction forces within the soil.

5 FINITE ELEMENT MODEL DESCRIPTION

The model uses elastic-perfectly plastic material properties (as described above) and assumes plane stress conditions, which limits movement to the in-plane direction. From observations of laboratory walls, it was thought most important that the model captured in-plane failure through cracking, and layer delamination. In laboratory testing of wallets (i.e. small sections of wall) at Durham University it has been found that in some cases failure occurs through delamination or shear failure of the compaction layer, due to decreased normal stress across the compaction plane. To simulate this feature, a finite element model of a rammed earth wall has been developed which uses two layers of different elements to represent each rammed earth layer, one layer of elements to represent the rammed earth as a soil mass, whose properties are assigned via laboratory testing of the rammed earth in shear boxes and in triaxial cells. The other layer models the interface between the compacted layers of rammed earth, using reduced Mohr-Coulomb parameters.

The analyses were carried out using the Strand7 finite element analysis program. Non-linear load stepping analyses were carried out, increasing the load until the model showed failure. Since conventional continuum finite elements were used it was not possible to model cracking failure as actually observed. Therefore we assumed failure was approaching when there was loss of convergence to a solution (i.e. the point where the stiffness matrix goes singular due to formation of a mechanism) as recommended in various texts (Potts and Zdravkovic, 2001).

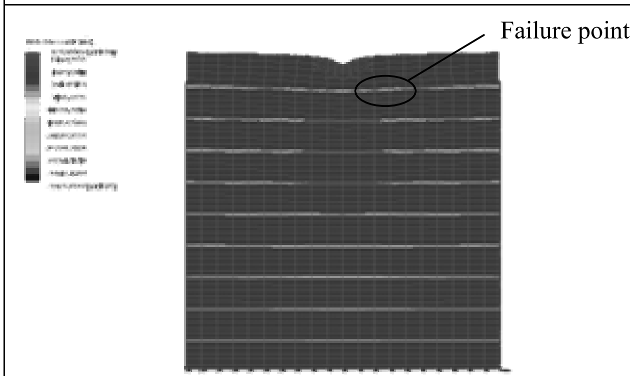
6 COMPARISON BETWEEN THE FINITE ELEMENT MODEL RESULTS AND THE WALLET TESTING

The walls were loaded vertically over their full width using a hydraulic ram, with a digital load cell placed between the ram and the loading plate on the wall. A number of walls were tested; this article deals only with those which showed in-plane failure.

The walls were constructed as described in (3) and tested to failure using a displacement controlled hydraulic loading ram with a load cell placed between the ram and the loaded surface of the wall. The loading rate was kept at a around 3.6kN/min. The walls were loaded over their full thickness (300mm) using a timber beam of width 60mm (except Figure 5, which was loaded over a width of 300m). Following loading the moisture content was determined at a number of positions within the wall to ensure that full drying of the wallet had occurred. Typically the moisture content of the failed wallets was 2-3%.

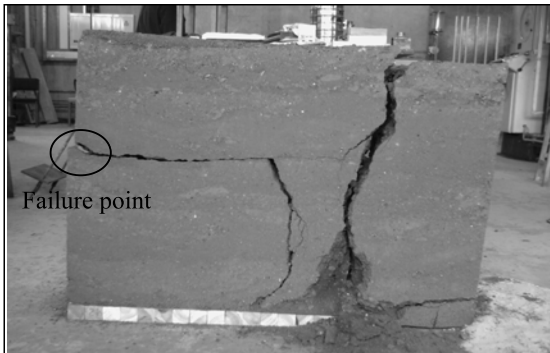
Figures 4-7 show the failed wallets, together with the stress recorded at failure. Figures 4 and 5 show walls where failure occurred through delamination of the compaction layer. This is due to insufficient normal (vertical) stress acting across the compaction plane, in Figure 4 the topmost layer fails through delamination because there is little self weight acting at the plane. Figure 5 shows a wall which is supported at the right hand end, forming an overhang of 300mm at the right hand base. The wall was loaded directly above this overhang, over a width of 300mm. The wall showed slight signs of pivoting about the end of the support, which led to uplift at the base on the left side. This caused a direct tensile stress across the compaction plane which initiated delamination of the layer at that point. Subsequent cracking occurred on impact of the wall with the ground.

Laboratory wall	
$\sigma_{Failure}$	0.61MPa
Height	990mm
Length	1015mm
Width	300mm

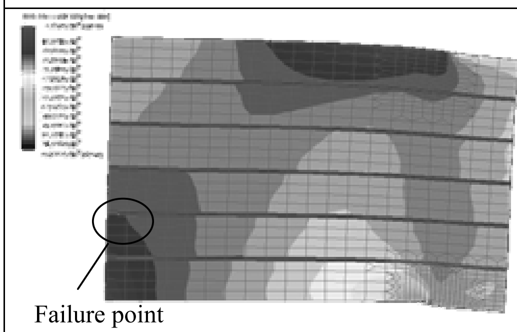


Finite Element model	
$\sigma_{Failure}$	0.62MPa
Mohr-Coulomb Properties used	
ϕ Rammed earth	45°
c Rammed earth	150kPa
ϕ Layer	37°
c Layer	37.5kPa

Figure 4 Point loaded wall, failure through delamination



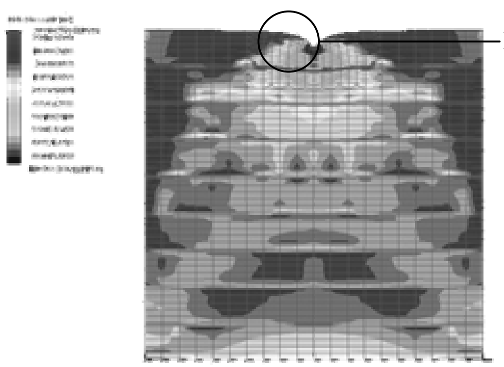
Laboratory wall	
$\sigma_{Failure}$	0.042MPa
Height	770mm
Length	960mm
Width	300mm
Overhang	300mm



Finite Element model	
$\sigma_{Failure}$	0.042MPa
Mohr-Coulomb Properties used	
$\phi_{\text{Rammed earth}}$	40°
$c_{\text{Rammed earth}}$	36kPa
ϕ_{Layer}	20°
c_{Layer}	15kPa

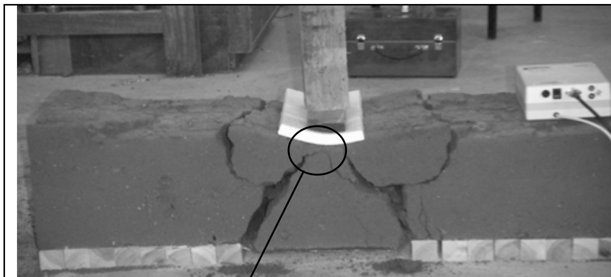
Figure 5 Cantilever section, failure through delamination

Laboratory wall	
$\sigma_{Failure}$	0.71MPa
Height	840mm
Length	1015mm
Width	300mm

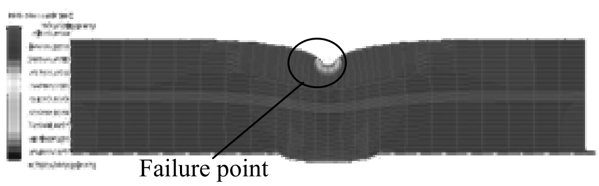


Finite Element model	
$\sigma_{Failure}$	0.71MPa
Mohr-Coulomb Properties used	
$\phi_{\text{Rammed earth}}$	45°
$c_{\text{Rammed earth}}$	150kPa
ϕ_{Layer}	20°
c_{Layer}	60kPa

Figure 6 Point loaded wall, failure in shear



Laboratory wall	
$\sigma_{Failure}$	0.61MPa
Height	220mm
Length	1015mm
Width	300mm
Central section	280mm



Finite Element model	
$\sigma_{Failure}$	0.61MPa
Mohr-Coulomb Properties used	
$\phi_{\text{Rammed earth}}$	45°
$c_{\text{Rammed earth}}$	131kPa
ϕ_{Layer}	30°
c_{Layer}	50kPa

Figure 7 Point loaded beam, failure in shear

Figures 6 and 7 show in plane cracking of the wallets, and failure of the body of rammed earth through shear. In both cases failure initiated at the loaded surface. Figure 6 a wall loaded at its midpoint, in a similar manner to that shown in figure 4. There is some initial out of plane failure, but it can clearly be seen that the main failure occurs through in-plane shear cracking. Figure 7 shows a beam, unsupported over its central section (280mm) loaded at the centre. An initial tensile crack was observed in the centre of the wall at the base, but failure occurred through the formation of shear cracks, initiated at the loaded surface.

The purpose of this study was to assess the feasibility of using finite element modelling to model rammed earth walls. Figures 4 to 7 also show the results from finite element modelling below the photographs of the equivalent laboratory test. The different layers of elements, modelling compacted rammed earth and interfaces between layers are clearly visible.

Of the four walls tested in the laboratory, two failed in shear, and two failed through delamination of the layers. The finite element models were given strength parameters such that the failure load and mode matched the results found in the laboratory (These strength parameters are shown in Tables 1 and 2). An elastic modulus of 60kPa was used throughout the numerical modelling, based on previous triaxial tests.

Wall No (Figure)	**Failure stress**	**Failure mode**	ϕ	c	ϕ_{Layer}	c_{Layer}
	MPa		**°**	**kPa**	**°**	**kPa**
Wall 1 (4)	0.610	Delamination	45	150	37	37.5
Wall 3 (5)	0.042	Delamination	40	36	20	15
Wall 2 (6)	0.710	Shear	45	150	20	60
Wall 4 (7)	0.610	Shear	35	131	30	50

Table 1 Properties of Rammed earth derived from the numerical model

Table 2 shows textbook properties for clay and sand samples and properties obtained using shear box and quick, undrained triaxial cell apparatus. It can be seen that that cohesion values obtained from triaxial tests are much greater than the textbook values given for clay, and were much higher than those found from shear box testing. A comparison of Tables 1 and 2 indicates that the rammed earth properties required for the finite element model are comparable with the cohesion of a stiff clay, and the shear angle of a dense uniform sand. These in turn are comparable to the properties found using triaxial testing.

	ϕ	c
	°	kPa
Stiff Clay (Craig 1996)	25-35	100-150
Dense Uniform Sand (Craig 1996)	45	0
Laboratory Shear box	40	36
Laboratory Triaxial cell	30-40	75-230

Figure 2 Shear angle and cohesion properties found from sample tests

Where failure through shear of the rammed earth is investigated, for a reasonable shear angle, a significantly higher value of cohesion is required to prevent localised shear failure close to the point of load application (punching shear failure). However once this value is set, failure occurs through shear as demonstrated in the test wall. The nature of triaxial and shear box loading does not allow punching shear to take place because loading is applied over the whole face of the sample. This may account for the high values needed to prevent failure in the walls.

When delamination of the compaction layer is considered, the properties required to initiate failure in the layer material are similar to those properties for the rammed earth in shear box-tests. Further large scale shear box testing is required to give more accurate values to the properties of this compaction layer.

It appears that rammed earth can be modelled using the Mohr-Coulomb failure criterion. However prediction of failure through delamination is difficult as it requires careful choice of the parameters for the compacted layer, which may not actually accurately represent the properties of the layer. Any model of rammed earth should take into account punching of the loading into the rammed earth, in addition to global shear failure. The main conclusion from the study is that one cannot just take strength parameters from laboratory tests and apply them to a numerical model. One needs to take account of the layered nature of rammed earth when building the model.

7 FURTHER WORK

7.1 Numerical models

This paper has shown that the modelling of rammed earth can be geotechnical in nature, as opposed to simply structural. The Mohr-Coulomb criterion is used widely in industry, but is not considered to be the cutting edge of geotechnics. The reason for this is that the criterion does not take into account parameters such as dilatancy or the effects of strain. Both the apparent cohesion and the angle of friction are known to vary with the applied stress state and soil density (Bolton, 1986), and further modelling of rammed earth should take this into account. Further geotechnical models such as Critical State can be used to both model the rammed earth material and the process of ramming. More advanced “bubble” models, including the change in stiffness due to strain as developed by Rouainia and Muir Wood (1999) for instance, might also provide better predictions of movements but at greater computational cost.

Another option is to model the interface between layers using interface finite elements (e.g. Day and Potts, 1994), although determination of strength and stiffness parameters for these elements remains a challenge. As an alternative to finite elements, a discrete element approach (Cundall and Strack, 1979) could also be used to model the interface between the compacted layers of rammed earth. This would allow contact parameters to be assigned to the compaction layers thus allowing failure as observed in the laboratory.

7.2 Historic structures

The determination of material properties for geotechnical materials is usually undertaken by destructive sampling in the field. This is not practical for most historic structures, especially those which are being investigated due to doubts about their stability. Thus there will always be a degree of uncertainty in any material properties used in the analysis of these structures. Thus non-destructive testing should be developed and employed, and some reliance must be placed on empirical relationships developed for soil.

7.3 Laboratory work

The determination of parameters required to fit a numerical model can be assisted by undertaking experimentation in the laboratory. The properties of historic rammed earth can be inferred through experimentation on similar soils, if parameters such as the particle size distribution, chemistry and water content are well matched.

8 APPLICATIONS OF THIS WORK

Laboratory work has highlighted the weakness of the compacted planes within the rammed earth, and the numerical model has provided an analysis technique which will allow analysis of rammed earth facades and investigation of intervention procedures on historic structures, such as placement of wall ties or assessment of settlement. It has also been shown that historic rammed earth is similar to new build rammed earth, meaning this technique can be used for the design and analysis of modern rammed earth construction.

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