The paper was published in the proceedings of the 9th Australia New Zealand Conference on Geomechanics and was edited by Geoffrey Farquhar, Philip Kelsey, John Marsh and Debbie Fellows. The conference was held in Auckland, New Zealand, 8 – 11 February 2004.

The Prediction of Damage to Masonry Houses Caused by Combined Foundation Movements and Seismic Disturbance

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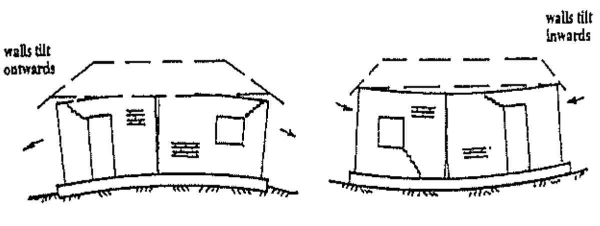
Summary: Cracking failure in masonry houses founded on expansive soils has been widely reported throughout Australia and other countries. The cost associated with such damage is significant. The current codes ofpractice only provide broad guidance on the design principles of masonry under ground movement, due to a lack of research in the area. In this paper a numerical model has been developed to study the behaviour of masonry walls under foundation movements as a result of expansive soils. The model is based on Distinct Element Method (DEM) which has been applied successfully by the authors to model the masonry walls under simulated in-plane earthquake forces. The model is capable of predicting the crack initiation, propagation and failure modes of masonry walls under various footing movements (doming or dishing curvatures). The numerical solutions obtained from the distinct element analysis are validated, by comparing them with results obtained from existing experiments. The results clearly show that increased damage is evident for the dishing case where the damage zone extends higher within the structure than for the domed case. The distinct element method is shown to have great potential for modelling multiple modes of ground displacement applicable to masonry structures.

INTRODUCTION

Cracking and damage in masonry structures founded on expansive soils has been widely reported throughout Australia and other countries. Buildings constructed on expansive soils are frequently subjected to severe movement arising from non-uniform soil moisture changes, with consequent cracking and damage due to distortion. The cost associated with such damage is significant. In Australia, approximately 30% of the total 'built-up' land area is covered by expansive soils. This figure has increased, in the last few years, as the outer suburbs of Sydney and Melbourne have been developed, as expansive soils in these areas are extensive.

Earthquake resistant design of structures is still quite new in Australia and the concept of earthquake risk was far behind until the Newcastle earthquake occurred in December 1989. Masonry structures seem to have experienced the worst damage/failure during this earthquake. Therefore, there is potential need for extensive evaluation of the dynamic behaviour of the masonry during earthquake excitations

The movement caused by expansive soil can be quite large. The extent of the movement depends mainly on the extent of soil moisture or suction change under the footing. These moisture changes are often induced by seasonal changes in rainfall and evaporation, watering of gardens, leakage from waterpipes, or extraction of water by trees and shrubs. If the soil is reactive, large relative movements could be expected in the soil producing either a "dishing" or "doming" of the soil profile under the building (Figure 1, Page 1993). The above effects can create angular distortions and therefore stresses in walls and can lead to problems such as jamming of doors and windows. This type of failure is particularly common for lightweight unreinforced masonry structures.



Doming Dishing

Figure 1. Typical cracking from reactive soils (Page 1993)

Unfortunately. the current codes of practice. AS 2870 (Residential slabs and footing;, 1996) and AS 3700 (SAA Masonry Code, 2001) onlyprovide broad guidance on the design principles for masonry wall/footing systems due to a lack of research in the area. Therefore, there is a significant need for research aimed at developing a rational design procedure for footings and masonry structures on expansive soils.

In the literature, reference to masonry deformation due to foundation movements is very limited. A review ofprevious studies has revealed that only unreinforced masonry walls have been investigated at University of Newcastle for several years. Bryant (1993) performed a series of two-dimensional tests to study the response of masonry structures due to foundation movements. The major objective of the tests was to investigate the relationships between external deformation and structural cracking. An analytical model was developed based on their testing results using a linear finite element program (Strand 6). However, the stress redistribution effects and non-linear material behaviour could not be modelled, as isotropic elastic behaviour was assumed for both the masonry and concrete footing. The interaction of the foundation beam and soil was not considered in the model.

An existing numerical model has been developed at the University of South Australia for slab deflections on expansive soils (Li and Cameron, 1995). The analysis was carried out using a finite element code. However, the upper structure (masonry wall) was not considered. Until Masia et al. (2002), they did consider the interaction of the soil and overlying surface structure. From this work a probabilistic model to predict cracking in the masonry walls was produced. However, in order to simplify the problem, all cracks in the masonry walls were pre-specified in their model. Automatic crack initiation and propagation were not included.

In order to study the behaviour of masonry structures and footings (concrete slabs) resting on expansive soils, a numerical model which is based on Distinct Element Method (DEM) is being developed to model the system as a whole, that is, wall and footing systems and it is expected that an improved design can then be engineered for an integrated system for structures on expansive soils, this achieved, to further model instability caused by seismic dynamic excitation. This paper will demonstrate that DEM has been successfully applied to model unreinforced masonry walls under prescribed footing movements (for both doming and dishing curvatures) where experimental results are available for comparison, and can further model later damage caused by seismic stresses.

Masonry is not a simple material, it is composed of two materials in a geometric array - an assemblage of bricks set in a mortar matrix. The influence of mortar joints and bond as a plane of weakness is a significant feature which is not present in concrete and this makes the numerical modelling of masonry very difficult especially when the loading condition is complicated. Therefore, a simplified linear elastic one-phase (mortar joints were not modelled separately) model has been employed by many researchers to investigate the effect of foundation movements on masonry walls (Bryant 1993; Muniruzzaman 1997; Masia et al 2002).

The finite element method is a very powerful numerical method for the analysis of structures. Two-phase material models (micro modelling of brick and mortar), have been used by several researchers in recent years, to model masonry. Applying line interface elements to model the joints. However, such models undoubtedly made analysis more complex and may not be suitable when the structure is under a complicated loading condition (Zhuge 2002). According to the author's knowledge, previous micro modelling of unreinforced masonry has been limited to static analysis only.

Magenes and Calvi (1997) attempted to develop a procedure to assess the seismic response of brick masonry walls. A substitute structure model, where the true nonlinear response was simulated with a linear model with equivalent stiffness and viscous damping, was developed. The model was applicable only to one-degree-of-freedom systems, which was not hlly applicable to real masonry structures. Various failure modes of URM were well defined in their model, however, the real dynamic response was simulated using a linear model characterised by an appropriate period of vibration and equivalent damping. More recently, earthquake response of unreinforced masonry column has been studied by Psycharis et al. (2000). They applied DEM to investigate the stability of freestanding classical columns under earthquake excitation. A simplified 2D model was adopted and the deformability of the blocks was neglected. Their studies proved that the DEM is very efficient in simulating the progressive collapse of blocky type structures.

In order to model discontinuous material types, such as masonry, the current investigators found that a distinct element method (DEM) could be used. With the DEM, a solid is represented as an assembly of discrete blocks. Joints are modelled as interfaces between distinct bodies. The contact forces and displacements at the interfaces of a stressed assembly of blocks are found through a series of movements, which trace the movements of the blocks. DEM was primarily intended for analysis in rock engineering projects, however, it has been demonstrated by the investigators with their pioneering research that the non-linear behaviour of masonry walls may be simulated using DEM (Zhuge & Hunt, 2002; Zhuge, 2002). In their papers, the DEM has been applied to simulate the in-plane shear behaviour of unreinforced masonry walls where the testing results were available for comparison. The model was validated by comparing the results with the experiments of masonry shear walls, which were conducted at micro-scales. Two sets of results agreed very well and this comparison proved the capabilities of the distinct element model developed by the investigators.

In this paper, the model has been further advanced to study the structural behaviour of the masonry walls under foundation movement, where a progressively increasing displacement boundary is applied at the bottom of the wall in the vertical direction, followed by a synthetic sesimic wave applied in-plane to the pre-deformed wall. The material models for bricks and joints are then discussed as well as the selection of material properties. The analysis is performed and the results between the Distinct element model and experiments are compared and discussed.

EXPERIMENTAL PROCEDURES FOR THE WALL TESTS

A series of full-scale tests on masonry walls supported on a foundation beam were carried out at the University of Newcastle, Australia (Bryant 1993). The tests have been limited to structural elements relevant to housing. In all cases the walls were supported by a foundation beam, the beam was subjected to either upward or downward curvature. The testing set-up is shown in Figure 2, the wall panel has a dimension of 6m x 2.4m and was supported on a standard 300mm x 300mm reinforced concrete strip footing. Vertical curvatures in the form of prescribed displacements at three points along the bottom of the foundation beam can be applied in either the upward or downward direction. A uniform vertical compressive load of 6 kN was applied via a simulated roof system consisting of timber joists at 600mm centres resting on a timber top plate located along the top of the wall. A membrane type damp-proof course was located in the mortar joint at or near the base of the wall and acted as an isolation joint. During the testing, a series of successively increasing upward and downward curvatures was applied to the wall.

The deflection of the central loading point was used to control each test. Throughout each test load, all of the three load points beneath the foundation beam were kept equal. Hence the curvature of the footing was governed by its bending with three equal loads applied across its span which simulates a foundation beam on a relatively flexible soil. The deflections at the quarter points and the supports were monitored throughout each test.

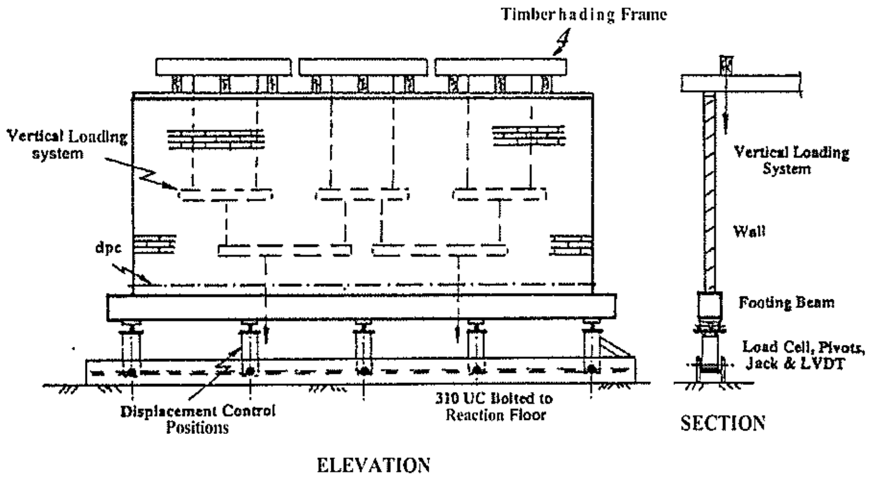


Figure 2. General Arrangement of the testing rig (Bryant, 1993)

NUMERICAL MODELLING OF MASONRY WALLS UNDER FOUNDATION MOVEMENTS

Numerical modelling of each unreinforced masonry wall resting on a concrete footing beam which was subjected to typical upward (doming) or downward (dishing) curvatures was carried out using the distinct element code UDEC (Universal Distinct Element Code, Itasca) (Cundall, 1971).

As it is introduced previously, DEM is hlly dynamic and it deals with pseudo-static problems by allowing the dynamic behaviour to reach equilibrium with notional time. In general, a velocity-proportional damping (the magnitude of the damping forces is proportional to the velocity of the blocks) could be used for pseudo-static problems. However, it was found from the research described herein, that a local damping, in which the damping force on a node is proportional to the magnitude of the unbalanced force, was more suitable for the type of problem where the progressive failure of the structure was the major interest of the research. The damping method applied to seismic motion is discussed later.

The dimensions of the wall are based on the experimental testing of Bryant (1993), where a total of 832 blocks were used. In order to calculate the internal deformation and stress distribution of blocks, the deformable blocks have to be discretised into finite difference triangular elements first. The discrete element mesh of the wall has approximately 50,000 elements. Constitutive laws and failure criterion of bricks has been discussed previously (Zhuge, Jin and Hunt, 2002).

Material properties

The numerical model developed here will be compared with the existing experimental work (Bryant 1993) in the next section. However, the material properties of bricks and mortars were obtained from Dhanasekar (1985).

The normal stiffness k_n and shear stiffness k_s of the interfaces between the wall blocks are potentially important parameters in the numerical analyses of masonry walls using UDEC. Unfortunately, there are very few testing data on stiffness properties for mortar joints available. The only testing results the authors could find were the experiments conducted at the University of Delft, the Netherlands (Lourenco 1996). These testing results were used to validate the numerical model developed by the authors of masonry shear wall panels under in-plane lateral load (Zhuge & Hunt 2002). The values of k_n and k_s have been adopted again for the current model (Table 2). In Table 2, the tensile strength of the bond was taken from Bryant's (1993) experiments.

Table 1. Summary of blocks material properties

Material	Elastic Modulus	Poisson's ratio	Density
	E (MPa)	ν	γ (kg/m^3)
Concrete footing	7000	0.2	2130
Clay brick masonry	9000	0.19	2000

Table 2. Summary of joint material properties

Tension	Shear			Normal stiffness	Shear stiffness
f_t (N/mm^2)	tanϕ	Tanψ	C (MPa)	k_n (N/mm^3)	k_s (N/mm^3)
0.453	0.75	0.0	0.375	82	36

Modelling of the damp-proof course (dpc)

The provision of dpc in domestic construction in Australia primarily is to provide a barrier to the upward movement of moisture from the ground. The experimental results of Bryant (1993) indicated that the dpcs have a secondary purpose as well that is acting as a horizontal plane of weakness in the wall panels, with vertical separation occurring along this plane under both dishing and doming curvatures. During the testing, the dpc membrane was laid directly onto the brick course below, therefore a zero f_t for the dpc layer could be assumed in the model. Based on the experimental results carried out at the University of Newcastle (Page 1992), a constant value of 0.5 was suggested and this value has been adopted in this paper.

COMPARISON WITH EXPERIMENTAL INVESTIGATIONS

The shear and tensile characteristics of the damp proof course are obviously significant parameters in the behaviour. In all cases the two courses of brick work below the damp proof course followed the profile of the foundation beam with all slip and separation occurring on the one weak plane.

Dishing curvatures

For the dishing case, the beam was deflected downwards until the load in the three jacking points approached zero, simulating the effects of soil expansion near the end of the beam. In this case separation occurred along the dpc, in the central section of the wall, with some sliding along the dpc. The brickwork was then spanning with some frictional restraint between the two ends of the beam (Bryant 1993). The numerical and experimental results are compared in Figure 3a and 4. In the test at very small deflections vertical separation along the dpc was noticeable along the centre of the wall. At the maximum central deflection of 8mm the separation along the dpc extended to within 350mm of the ends of the wall (Figure 3a). Figure 4 shows the computed crack initiation, progressive development and the wall movements for the dishing case modelled with DEM. The crack initiated at the centre of the joint containing the dpc (Figure 4a). Vertical separation then took place and extended as the downward displacement increased (Figure 4b). Finally, when a central dishing deflection reached 8mm, the separation along the dpc extended towards the ends of the wall with only a small connecting length on each side of the wall and also no crack was detected in the masonry wall above the dpc (Figure 4c). It can be seen from the figure, the behaviour of the wall is well captured by the proposed model.

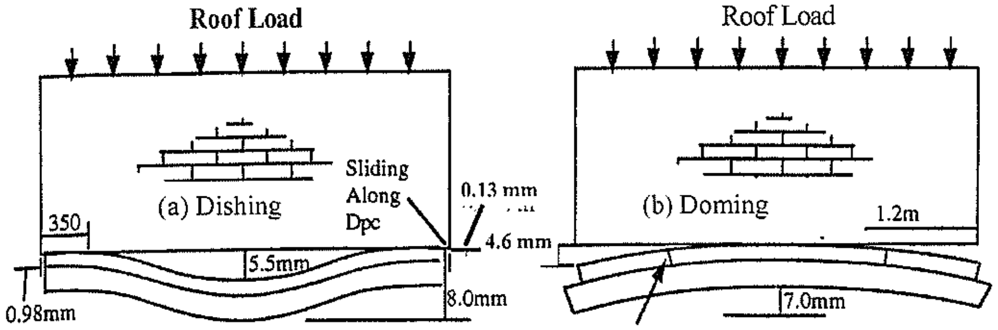
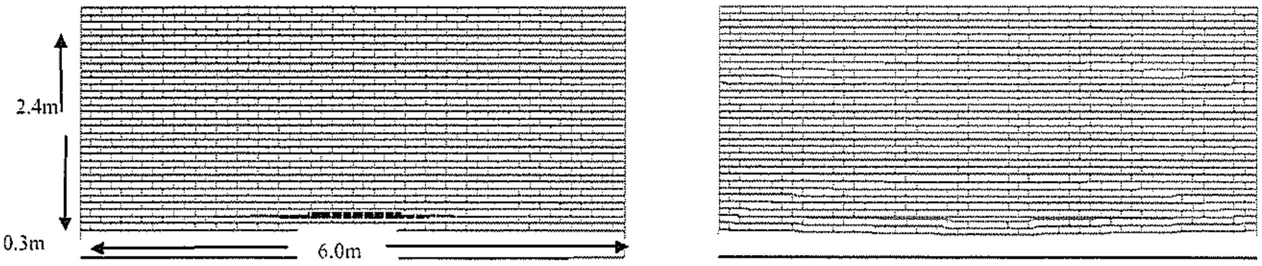
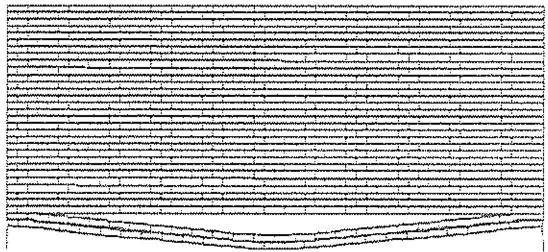


Figure 3. Experimental behaviour of masonry walls under foundation movements (Bryant 1993)



a) crack initiation

b) crack development



c) wall behaviour at max curvature

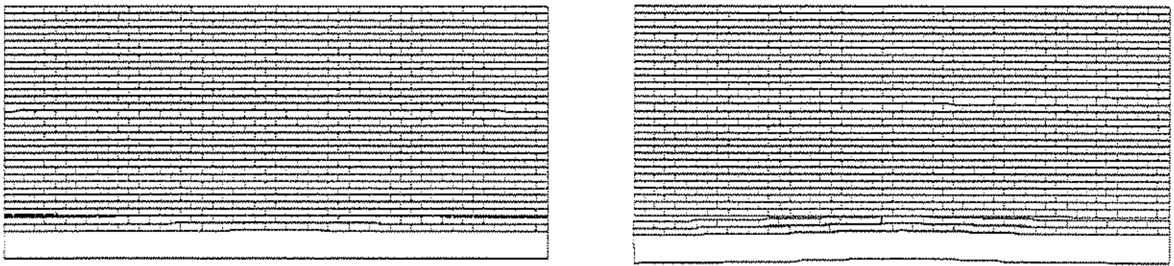
Figure 4. Simulated behaviour of the wall under dishing curvature

The contours of horizontal stress distribution at a central displacement of 1mm and 6mm were calculated. Increments of central displacement will only increase the stresses in the foundation beam, with little effect on the masonry wall above the dpc. This again proves that the dpc acts as a horizontal plane of weakness for masonry walls under foundation movements.

Doming curvatures

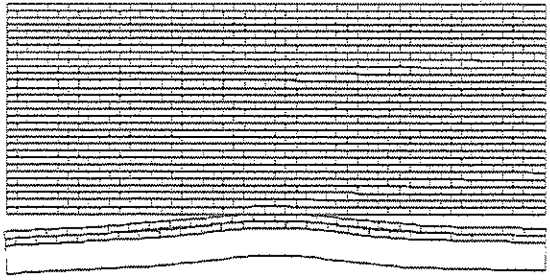
For the doming case, the experimental beam was deflected upwards until the load at the two support points approached zero, simulating the effects of soil shrinkage near the ends of the beam. Again separation occurred at the dpc level, but at the ends of the wall. At a central doming deflection of 7mm the separation on both ends was about equal at 4.2mm and 4.9mm on either end of the wall (Figure 4b). Again no distress occurred in the masonry wall above the dpc.

Figure 5 shows the computed crack initiation, progressive development and the wall movements for the doming case modelled with DEM. The crack initiated at the ends of the joint containing the dpc (Figure 5a). Separation then took place and extended as the upward displacement increased to around 3mm (Figure 5b). Finally, when a central doming deflection reached 7mm, the wall was then, only supported by the central section of the beam, with each end of the wall acting as a cantilever (Figure 5c). Again the behaviour of the wall is well captured by the proposed model.



a) crack initiation

b) crack development



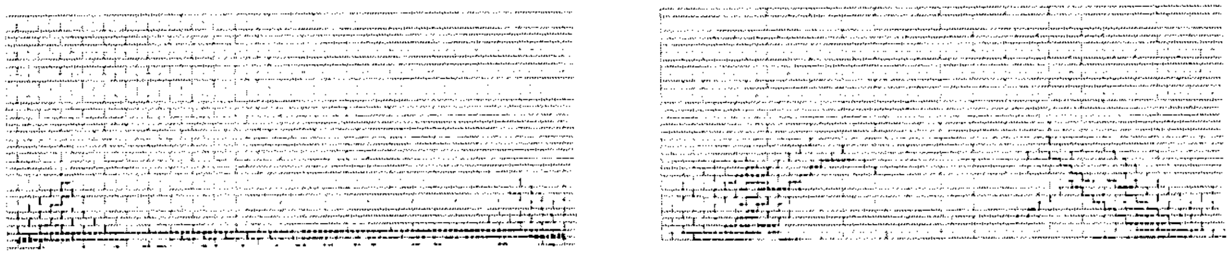
c) wall behaviour at max curvature

Figure 5. Simulated behaviour of the wall under doming curvature

WALLS WITH A SEISMIC STRESS APPLIED IN-PLANE

Using the explicit finite difference scheme, UDEC allows a 2D full dynamic analysis for in plane-stress. The dynamic input can be applied in a number of ways. In this work the dynamic input is applied as a stress history in-plane (x-direction) to the base of the model. A simplistic cosine synthetic waveform is applied. In creating a UDEC model for a dynamic analysis, three aspects are considered. These are 1) dynamic loading and boundary conditions 2) mechanical damping 3) wave transmission through the model. For the dynamic loading and boundary conditions a stress wave was applied in the x-direction at the model base as a cosine wave of 100 cycles/sec applied over a problem time period of 0.02 seconds, with an amplitude of 7.5Pa. Quiet boundaries were obtained using the viscous boundary approach (UDEC option) developed by Lysmer and Kuhlemeyer (1969). All four boundaries were made viscous allowing necessary energy radiation and creating non-reflecting boundaries. In masonry natural damping is mainly hysteretic but it is difficult to reproduce this type of damping numerically (Cundall et al, 1979). In time domain programs Rayleigh damping approximates to the hysteresis effect. Mass proportional damping was applied in this part of the study. One tenth of critical damping over the central frequency was applied. With respect to wave transmission through the model, the finite difference mesh size was selected to produce a realistic representation of the stress wave transmission through the model using the procedure described in the UDEC manual, a maximum edge length of 0.1 and a minium edge length of 0.02 was applied, as previously shown in Zhuge, Jin and Hunt, (2003).

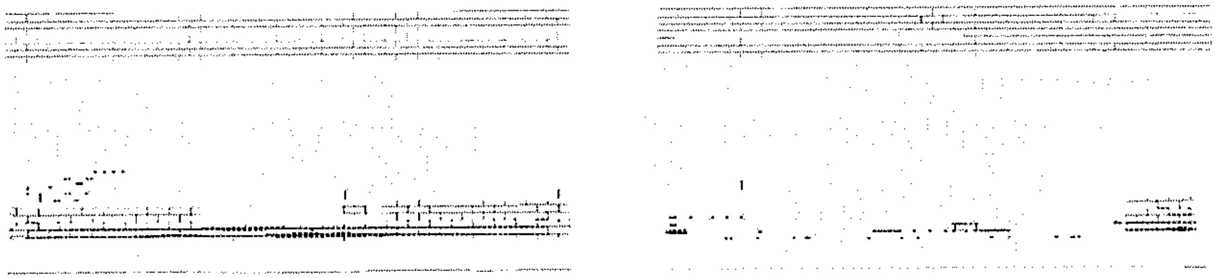
Applying the conditions described above a series of models were run. In order to validate the model, an initial run was performed with the wall fixed at the base. The results of this study are shown in Figure 6, for a model containing the damp-proof course (Figure 6a) and one without (Figure 6b). The mortar joints at either shear limit or open (ie zero normal stress) are shown as dark lines. The fracture pattern has propagated to approximately 2m in Figure 6b. The damp proof course is acting as a barrier to wave damage propagation.



a) wall fixed at base with damp-proof course

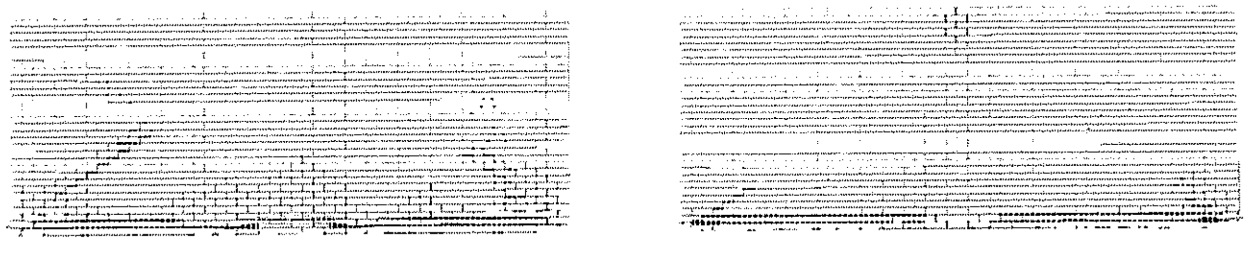
b) wall fixed at base with no damp-proof course

Figure 6. Mortar joints at either shear limit or open under in-plane seismic stress.



a) seismic loading post crack initiation under dishing curvature

c) seismic loading post crack initiation under doming curvature



b) seismic loading post crack development under dishing curvature

d) seismic loading post crack development under doming curvature

Figure 7. Mortar joints at either shear limit or open. Wall under effect of in-plane seismic stress.

Figure 7 shows the results for walls that have undergone dishing and doming deformation (the models include the dpc). The seismic stress wave is applied post crack initiation Figure 7a and c (following the deformation shown in Figure 4a and 5a) and post crack development Figure 7b and c (following the deformation shown in Figure 4b and 5b), therefore damage has already been initiated at the base of the wall. The seismic damage is significant in both cases. Again the mortar joints at either shear limit or open (ie zero normal stress) are shown as dark lines. The results clearly show that increased damage is evident for the dishing case where the damage zone extends higher within the structure. Although at the top central location in the domed model (Figure 7d) failure is evident to approximately 0.5m below the top of the wall. As predicted for an increase in doming amplitude, as shown in Figure 1. The seismic wave appears to enhance the effect of dishing and doming as well as causing damage propagation to regions above the dpc.

CONCLUSIONS

Cracking and damage in masonry structures founded on expansive soils has been a major concern for Australian structural engineers. A numerical model for predicting cracking and failure in masonry walls due to foundation movements has been described in this paper, which is based on the Distinct Element Method. Masonry is not a simple material, the influence of mortar joints as a plane of weakness is a significant feature and this makes the numerical modelling of masonry very complex. This paper has discussed an alternative and simple way of modelling masonry, which is using the Distinct Element Method. The crack initiation, propagation as the footing curvature changes for both doming and dishing cases were successfully simulated in the model and the results compared well with those obtained from experiments. The next step of the research will be aimed at including the soil moisture movements in the model and therefore to consider the soil/structure interaction. The results obtained in the current research have also shown the great potential of the method, especially for dynamic analysis.

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