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BEHAVIOUR OF MASONRY WALLS UNDER FOOTING MOVEMENTS – THE EFFECT OF WINDOW OPENING

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Abstract

Cracking and damage in masonry structures founded on expansive soils has been widely reported throughout Australia and other regions around the world. Buildings constructed on expansive soils are frequently subjected to severe movement with consequent cracking and damage due to distortion. The cost associated with such damage is significant. In the past years, a new analytical model has been developed to simulate the response of unreinforced masonry walls under foundation movements which is based on Distinct Element Method (DEM). In this paper, a parametric study is performed to examine the effect of window opening. The results are compared with those obtained from the existing experiments.

Key Words

Masonry; footing movement; numerical modelling; distinct element method.

1 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 land area is covered by expansive soils.

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. 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 particular common for lightweight unreinforced masonry structures.

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Unfortunately, the current codes of practice, AS 2870 (Residential slabs and footings, 1996) and AS 3700 (SAA Masonry Code, 2001) only provide 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 of previous 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.

The problem was further studied by Masia et al. (2002) to consider the interaction of soil and structure and a probabilistic model was developed to predict the cracking in masonry walls. However, in order to simply 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. At the stage one of the project, DEM has been successfully applied to model unreinforced masonry walls under prescribed footing movements, where experimental results are available for comparison (Zhuge and Hunt 2003b).

Masonry is not a simple material, 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).

In order to model the discontinuous types of material, such as masonry, the investigators of this paper have carried out research for several years and found out that a distinct element method (DEM) could be used. Although DEM was primarily intended for analysis in rock engineering projects, 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 2002; Zhuge & Hunt 2003a). 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 with the experiments of masonry shear walls. Two sets of results agreed very well and the comparison proved the abilities of the distinct element model developed by the investigators.

The model was then further developed to study the structural behaviour of the masonry walls under foundation movement, where a progressively increased displacement boundary is applied at the bottom of the wall in the vertical direction (Zhuge and Hunt 2003b). The results obtained were validated by comparing with those obtained from the existing experiments.

In this paper, a parametric study is performed to study the effect of window opening for both doming and dishing curvatures.

2 Outline of Distinct Element Method

Distinct Element Method has been progressively developed over the past two decades. Cundall (1971) first introduced the DEM to simulate progressive movements in blocky rock systems and the model has been implemented into a computer program UDEC since then. DEM simulates the response of discontinuous media subjected to either static or dynamic loading.

In the DEM method, a solid is represented as an assembly of discrete blocks. Joints are modelled as interface between distinct bodies. The contact forces and displacements at the interfaces of a stressed assembly of blocks are found through a series of calculations which trace the movements of the blocks (Itasca, 2000). At all the contacts, either rigid or de-formable blocks are connected by spring like joints with normal and shear stiffness k_n and k_s respectively (Fig. 1). Similar to Finite Element Method (FEM), the unknowns in DEM are also the nodal displacements and rotations of the blocks. However, unlike FEM, DEM is a dynamic process and the unknowns are solved by equations of motion. The speed of propagation depends on the physical properties of the discrete system. The solution scheme used by DEM is the explicit time marching and finite contact stiffness.

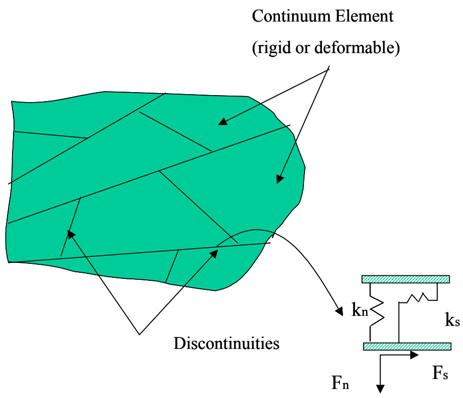


Figure 1 Continuum and discontinuum elements in DEM

It should be noted that time has no real physical meaning if a static analysis was performed. Damping is utilised in the above equations. However, different methods were used for static and dynamic analysis. A detailed DEM formulation can be found in the literature (Zhuge 2002; Zhuge & Hunt 2003a)

3 Numerical simulation of masonry walls under footing 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 2000).

As it is introduced previously, DEM is fully 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 is proved from the current research that a local damping in which the damping force on a node is proportional to the magnitude of the unbalanced force, is more suitable for the type of problem where the progressive failure of the structure was the major interest of the research.

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. A typical discrete element mesh of the wall is shown in Figure 2 with more 50,000 elements.

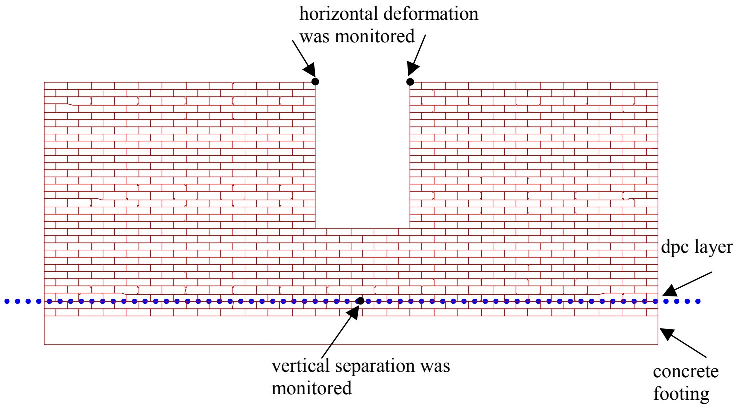


Figure 2 Wall meshes modelled using UDEC

3.1 Constitutive laws and failure criterion of joints

Micro modelling of masonry has to consider all basic types of failure mode including both mortar joints and the unit. The mortar joint cracks and the separation along the damp proof course (dpc) are the major failure modes being observed during the testing, therefore the major objective of the model is to simulate the crack initiation and propagation. In the model, the mortar joints are represented numerically as a contact surface formed between two block edges. The constitutive laws applied to the contacts are:

$$\Delta\sigma_n = k_n \Delta u_n \tag{1}$$

$$\Delta\tau_s = k_s \Delta u_s \tag{2}$$

where k_n and k_s are the normal and shear stiffness of the contact, $\Delta\sigma_n$ and $\Delta\tau_s$ are the effective normal and shear stress increments, and Δu_n and Δu_s are the normal and shear displacement increments.

Stresses calculated at grid points located along contacts are submitted to the selected failure criterion. For the proposed model, the Coulomb friction is formulated:

$$|\tau_s| \le C + \sigma_n \tan\phi = \tau_{\max} \tag{3}$$

where C is the cohesion and ϕ is the friction angle.

There is also a limiting tensile strength ft for the joint. If the tensile strength is exceeded, then $\sigma_n = 0$.

3.2 Constitutive laws and failure criterion of blocks

The selected constitutive law for the blocks is used to determine stresses at each grid point. For the present study, the relation of stress to strain in incremental form is expressed by Hooke's law in plane stress as:

$$\begin{aligned} \Delta\sigma_{11} &= \beta_1 \Delta e_{11} + \beta_2 \Delta e_{22} \\ \Delta\sigma_{22} &= \beta_2 \Delta e_{11} + \beta_1 \Delta e_{22} \end{aligned} \tag{4}$$

where $\beta_1 = E/(1-\upsilon^2)$ and $\beta_2 = \upsilon E/(1-\upsilon^2)$

$$\Delta e_{ij} = \frac{1}{2}\left[\frac{\partial \dot{u}_i}{\partial x_j} + \frac{\partial \dot{u}_j}{\partial x_i}\right]\Delta t \tag{5}$$

where Δe_{ij} is the incremental strain tensor, $\dot{u}_i$ is the displacement rate and Δt is time step.
As the tensile splitting or crushing of the brick is not a common type of failure for masonry walls under serviceability performance, in order to simply the problem, the brick unit material is modelled with Mohr-Coulomb failure criterion with tension cut-off (Zhuge & Hunt 2003a).

3.3 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 not provided from the Bryant's (1993) experiments, where only the material properties of masonry and concrete footing were available. From the constitutive relationship curves of brick, mortar and masonry shown in Figure 3 (Dhanasekar 1985), it can be seen that the masonry and brick curves are very similar and close to each other. Therefore the properties of brick are taken to have similar values as masonry. The material properties of the blocks are shown in Table 1 (Bryant 1993).

Table 1 Summary of blocks material properties

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

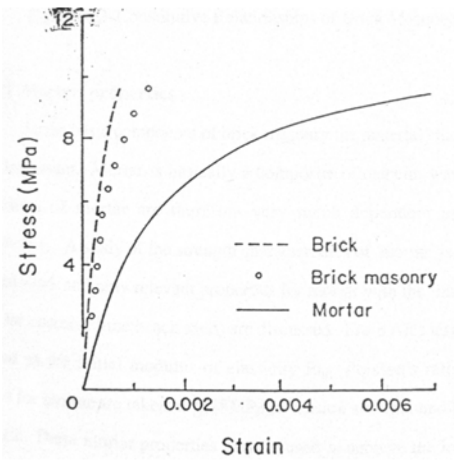


Figure 3 Average stress-strain curves for bricks, masonry and mortar (Dhanasekar 1985)

k_n and 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 are 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 2003a). 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 2 Summary of joint material properties

Tension f_t N/mm^2	$\tan\phi$	Shear $\tan\psi$	C MPa	Normal stiffness k_n N/mm^3	Shear stiffness k_s N/mm^3
0.453	0.75	0.0	0.375	82	36

3.4 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 dpc's 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 **ft** for the dpc layer could be assumed in the model. In order to model the shear sliding type failure along the dpc layer, a suitable value for the coefficient of friction along the dpc is required. 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.

4 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). In all cases the walls were supported by a foundation beam, the beam was subjected to either upward or downward curvature. Three load/displacement points were evenly spaced between the reactions, at which hydraulic jacks were used to apply the displacements to the footing. A detailed description of the testing set up can be found in the literature (Bryant 1993; Zhuge and Hunt 2003b).

For the wall model discussed in this paper, the panel has the same dimension as solid walls (Zhuge and Hunt 2003b), but a window opening of 900 mm wide and 1500 mm deep was sawn from the top of the wall at mid length (Fig 4). Only the walls tested with no load to the top of the wall (non-loadbearing walls) were modelled and discussed here. The experimental behaviour of the walls is shown in Figure 4.

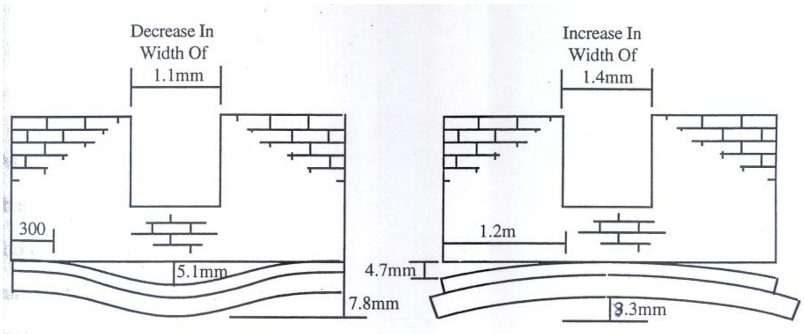


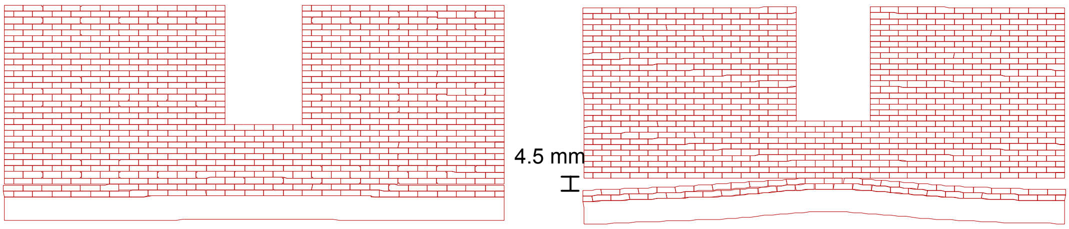
Figure 4 Experimental behaviour of masonry walls under foundation movements (Bryant 1993)

5 Effect of window opening

In general, the behaviour of the walls with a window opening was similar to those walls without an opening, for both doming and dishing cases.

5.1 Doming curvatures

The testing results indicated that for doming case, the separation also occurred at the ends of the wall along the dpc at small deflections and increased in width as the deflections increased (Bryant, 1993). It was also found from the testing that the width of the window opening increased as the footing curvature increased. Figure 5 shows the computed cracking initiation and separation at the maximum curvature. The results compared well with those obtained from the experiments. The computed horizontal stress distribution (σ_{xx}) for the doming curvature at a central deflection of 7 mm is shown in Figure 6. The figure shows that the horizontal stresses around the window opening are in tension, which indicates the width of the window opening would be increased. Also, as these stresses were less than the tensile strength of the material (0.453 MPa), the wall was not cracked in this region. However, the diagram indicated that the region underneath the window sill may be already cracked.



(a) Crack initiation (b) At the max curvature

Figure 5 Simulated behaviour of the wall with opening - Doming

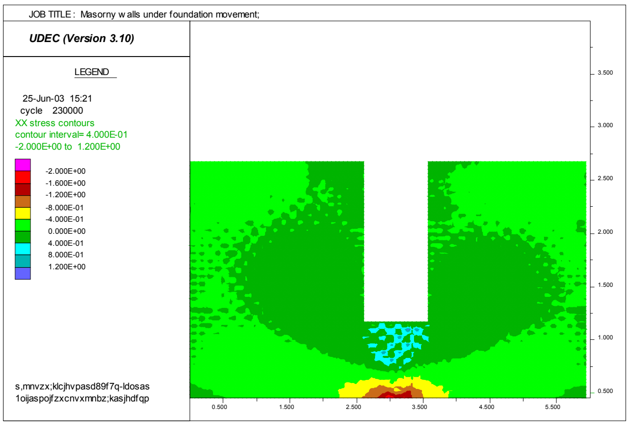


Figure 6 Horizontal stress distribution for the wall under doming curvature with window opening

5.2 Dishing curvatures

Under a dishing curvature, vertical separation along the dpc at mid length in the wall also occurred at small deflections and increased in width with increases in the footing deflection. At the maximum central deflection, the experimental results indicated the top of the window opening had closed by 1.1 mm from its starting position (Bryant 1993).

The changes in width of the window opening were monitored in the proposed numerical model (Fig 2); the results are shown in Figure 7 together with the computed changes of vertical separation of dpc above the centre of the footing. It can be seen from the figure that the change (decrease) in width of the window opening is approximately

proportional to the increase in vertical separation of dpc or footing curvature. An exaggerated view of the wall deformation under dishing cases is shown in Figure 8, which clearly indicates the change in width of the window opening.

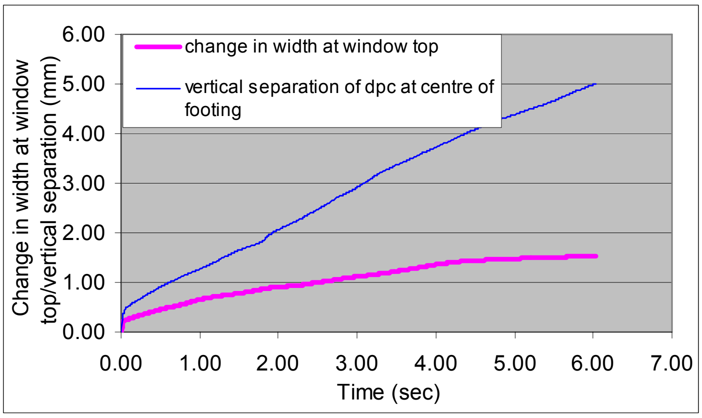


Figure 7 Change in width of the window for the wall under dishing curvature

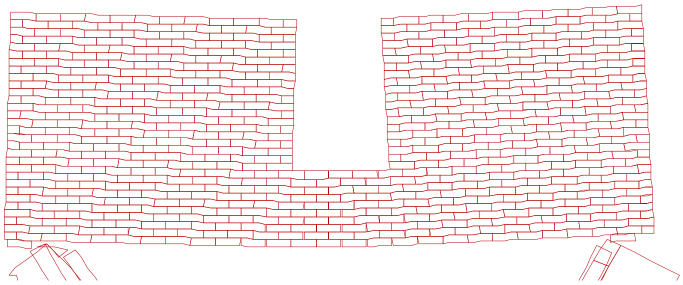


Figure 8 Simulated behaviour of the wall with window opening - dishing curvature

The predicted wall behaviour with window opening again proved the capability of the model in representing the progressive failure of masonry walls under footing movements. However, it should be noted that for the dishing curvature, the testing results indicated the horizontal sliding occurred at the wall ends along the dpc. Although a friction coefficient of 0.5 was applied, the model could not simulate this behaviour well and further research is required.

6 Conclusions

Cracking and damage in masonry structures founded on expansive soils has been a major concern for Australian structural engineers. A numerical model which is based on distinct element method has been developed to simulate cracking and failure in masonry walls due to foundation movements and in this paper, the model is further applied to study the effect of window opening. 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.

It should be noted that due to the effect of dpc, the predicted crack initiation and propagation were along the joints containing the dpc. The full potential of the model for predicting the “through-wall” cracks was demonstrated in the modelling of shear wall panels (Zhuge and Hunt 2003a).

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