The Prediction of Damage to Masonry Houses Caused by Foundation Movements

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Abstract: 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 of practice 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 footing 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 (static) 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 the results with those obtained from the existing experiments.

Key words: masonry; footing movement; numerical modelling; distinct element method; cracking.

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 '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, where expansive soils in these areas are extensive.

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). 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.

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

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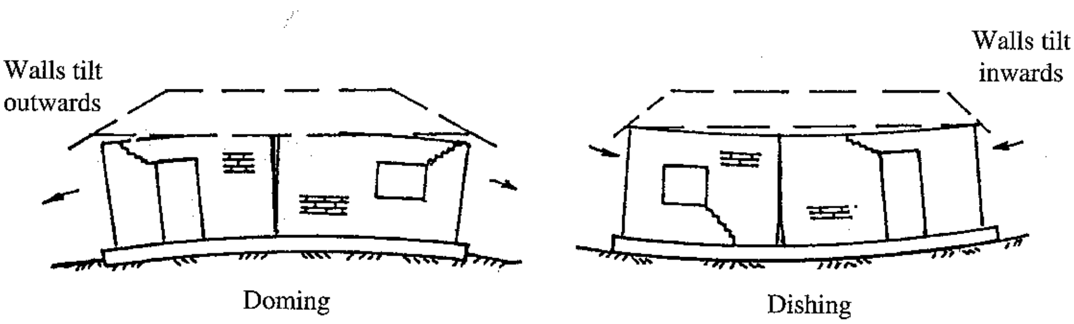


Figure 1. Typical cracking from reactive soils (Page 1993)

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 footing 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 footing 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.

The problem was also studied recently by Masia et al. (2002). They considered 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 paper will discuss the research work carried out at stage one of the project, where 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.

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. A two-phase material model (micro modelling of brick and mortar), has been used by several researchers in recent years to model masonry, where line interface elements were applied to model the joints. However, such models undoubtedly made analysis more complex and may not be suitable for a discontinuous material such as masonry or when the structure is under a high intensity dynamic loading condition.

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 and Hunt 2003; 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 footing movement, where a progressively increasing displacement boundary is applied at the bottom of the wall in the vertical direction. In the following sections first an introduction is given to the Distinct Element Method and its application to unreinforced masonry walls under footing movement, together with an outline of the basic procedures involved. Following this, the material models for bricks and joints are then discussed as well as the selection of material properties. Finally the analysis is performed and the results between the Distinct element model and experiments are compared and discussed.

2. 2D DISTINCT ELEMENT MODELLING OF UNREINFORCED MASONRY UNDER FOOTING MOVEMENTS

The Distinct Element Method has been progressively developed over the past two decades. Cundall (1971) first introduced the Distinct Element Method to simulate progressive movements in blocky rock systems and the model has been implemented into a computer program UDEC since then. The DEM was primarily intended for analysis in rock engineering projects, ranging from studies of the progressive failure of rock slopes to evaluations of the influence of rock joints, faults, bedding planes, etc. (Itasca 2000). 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 deformable blocks are connected by spring like joints with normal and shear stiffness k_n and k_s, respectively (Figure 2), that represent the force-displacement relationship of the joints. Similar to the Finite Element Method (FEM), the unknowns in the DEM are also the nodal displacements and rotations of the blocks. However, unlike FEM, which is based on a continuum mechanics formulation, DEM provides the capacity to represent the motion of multiple, intersecting discontinuities explicitly. DEM uses an explicit time-marching scheme to solve the equations of motion directly. The calculation alternates between application of a force-displacement law at all joints and Newton's second law at all blocks. The constitutive law of joints is used to find contact forces/stresses from known displacements. Newton's second law then gives the motion of the blocks resulting from the known forces/stresses acting on them. This procedure for unreinforced masonry is presented in details in the next two sections.

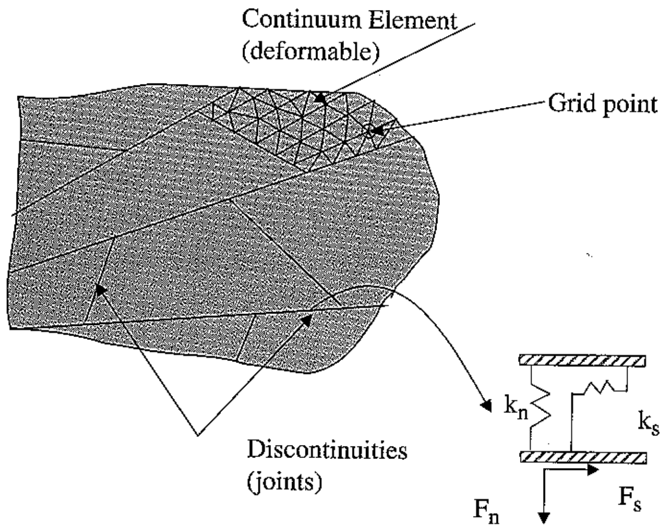


Figure 2. Continuum and discontinuum elements in DEM

2.1. Constitutive Laws and Failure Criterion of Joints

For unreinforced masonry under footing movements, 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:

$$\Delta\sigma_n = k_n \Delta u_n \quad (1)$$

$$\Delta\tau_s = k_s \Delta u_s \quad (2)$$

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, there is a limiting tensile strength f_t for the joint. If the tensile strength is exceeded, then $\sigma_n = 0$. For shear, 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.

If $|\tau_s| \ge \tau_{max}$ then,

$$\tau_s = sign(\Delta u_s)\tau_{max} \tag{4}$$

2.2. Constitutive Laws and Failure Criterion of Blocks

The normal and shear stresses calculated in Eqns 1 and 2 are then used as the boundary stresses to either rigid or deformable blocks. If the blocks are deformable, they will be internally discretised into finite difference triangular elements first. The use of triangular elements eliminates the problem of hourglass deformation that may occur with constant-strain finite difference quadrilaterals. The vertices of the triangular elements are grid points (Figure 2). Newton's second law is applied at each grid point as follows:

$$\frac{\partial \dot{u}_i^{(t)}}{\partial t} = \frac{\int \sigma_{ij} n_j ds + F_i^{(t)}}{m} + g_i \tag{5}$$

where s is the surface enclosing the mass m lumped at the grid point, n_j is the unit normal to s, $F_i^{(t)}$ is the resultant of all external forces applied to the grid point and g_i is the gravitational acceleration.

A net nodal force vector, $\Sigma F_i^{(t)}$ is calculated at each grid point. This vector includes contributions from applied loads and from body forces due to gravity. Gravity forces, $F_i^{(g)}$ are computed from:

$$F_i^{(g)} = g_i m_g \tag{6}$$

where m_g is the lumped gravitational mass at the grid point, defined as the sum of one-third of the masses of triangles connected to the grid point.

If the body is at equilibrium, $\Sigma F_i^{(t)}$ on the node will be zero; otherwise, the node will be accelerated according to the finite difference form of Newton's second law of motion and following the central difference integration scheme:

$$\dot{u}^{(t+\Delta t/2)} = \dot{u}^{(t-\Delta t/2)} + \frac{F^{(t)}}{m}\Delta t \tag{7}$$

where $\dot{u}$ is the velocity, m is the mass, and t is the time.

During each time step, strains and rotations are related to nodal displacements in the usual form:

$$\begin{aligned} \dot{\varepsilon}_{ij} &= \frac{1}{2}(\dot{u}_{i,j} + \dot{u}_{j,i}) \\ \dot{\theta}_{ij} &= \frac{1}{2}(\dot{u}_{i,j} - \dot{u}_{j,i}) \end{aligned} \tag{8}$$

Then the selected constitutive law for the blocks is used in an incremental form to determine stresses at each grid point. A nonlinear model can be easily incorporated as the solution scheme used by DEM is the explicit time marching scheme. For the present study, 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 Mohr-Coulomb failure criterion with tension cut-off is adopted in the model. A more detailed description of the model is available in the literature (Zhuge and Hunt 2003; Itasca 2000).

The new position of the block induces new conditions at block boundaries and thus new contact forces. Resultant forces and moments are used to calculate linear and angular accelerations of each block. The calculation scheme summarised above is repeated until a satisfactory state of equilibrium or continuing failure is reached for each block. 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.

3. EXPERIMENTAL PROCEDURES FOR THE WALL TESTS

A series of full-scale tests on masonry walls supported on a footing 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 footing beam, the beam was subjected to either upward or downward curvature. The testing set-up is shown in Figure 3, the wall panel has a dimension of 6 m × 2.4 m and was supported on a standard 300 mm × 300 mm reinforced concrete strip footing. A 310UC137 beam was used as a base held down at each of the reaction points in the floor. On this base two reaction points for the footing beam were mounted 6 m apart, with one being fixed against horizontal movement and both against vertical movements, resulting in the footing being simply supported. Three load/displacement points were evenly spaced between these reactions, at which hydraulic jacks were used to apply the displacements to the footing. Vertical curvatures in the form of prescribed displacements at these points 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 600 mm 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,

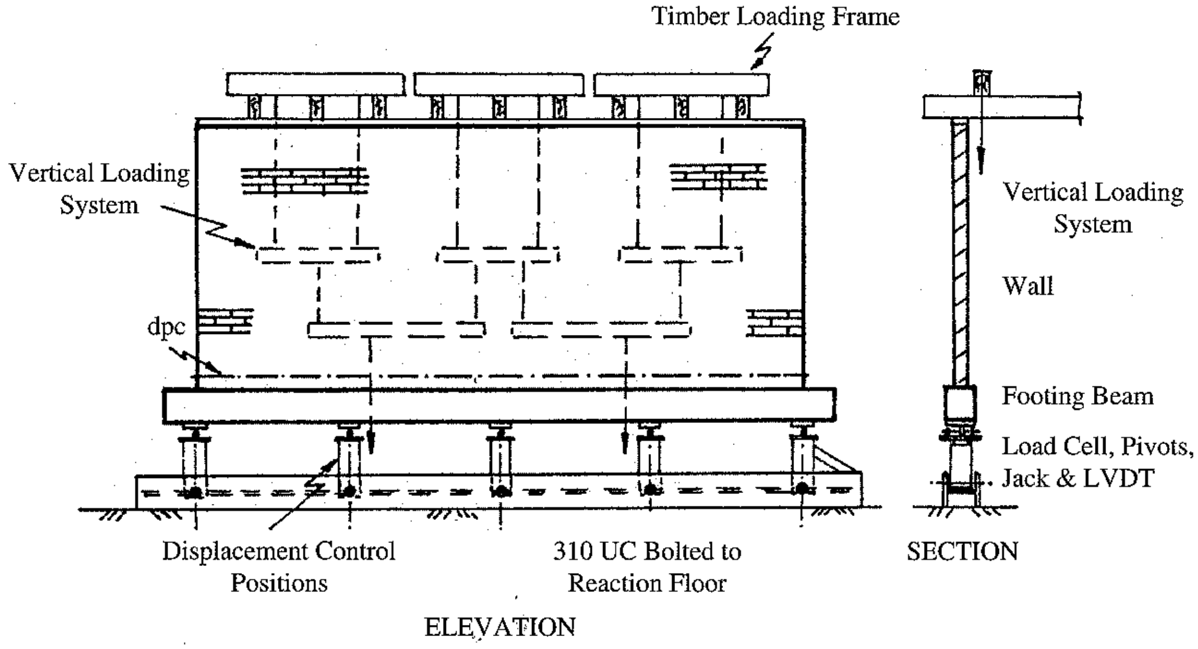


Figure 3. General arrangement of the testing rig (Bryant 1993)

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 at all of the three load points beneath the footing beam were kept equal to each other. Hence the curvature of the footing was governed by its bending with three equal loads applied across its span which assuming a footing beam on a relatively flexible soil. The deflections at the quarter points and the supports were monitored throughout each test.

4. NUMERICAL IMPLEMENTATION 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).

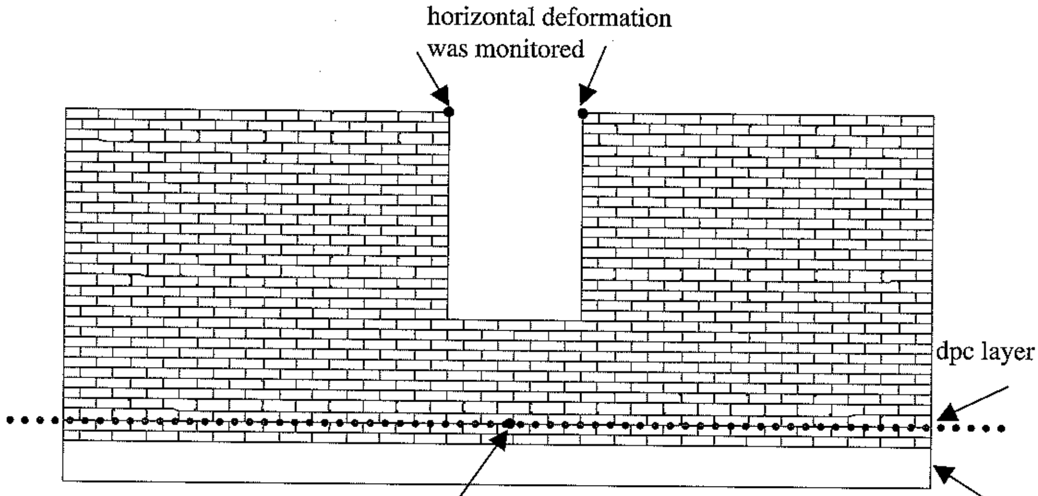
As it is introduced previously, DEM is fully dynamic and it deals with pseudo-static problems by allowing the dynamic behaviour to reach equilibrium with notional time. In general, a velocity-proportional damping (the magnitude of the damping forces is proportional to the velocity of the blocks) could be used for pseudo-static problems. However, it 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, 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 and to simulate the failure of blocks, the deformable blocks have to be discretised into finite difference triangular elements first. The DEM model built up is shown in Figure 4(a) and a typical discrete element mesh of the wall and footing is shown in Figure 4(b) with more 50,000 elements.

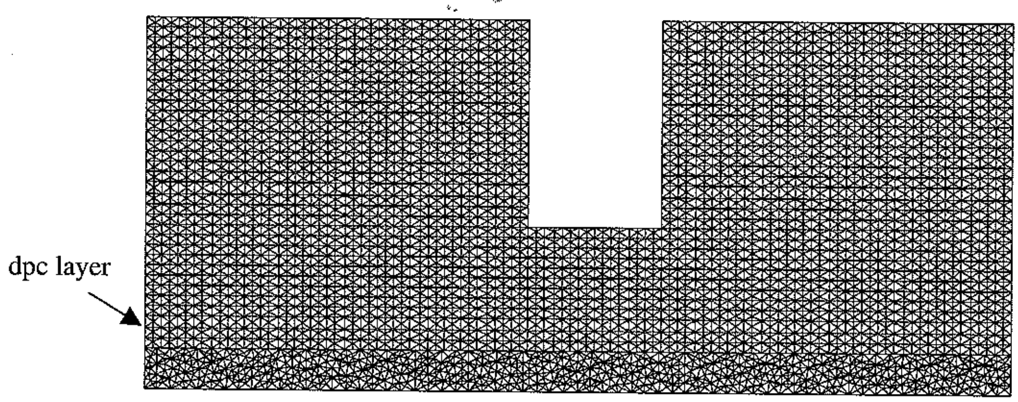
4.1. Material Properties

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 5 (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 bricks are shown in Table 1 (Bryant 1993).

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



(a) Wall and foundation model



(b) Wall and foundation model after zoning

Figure 4. Wall and foundation meshes modelled using UDEC

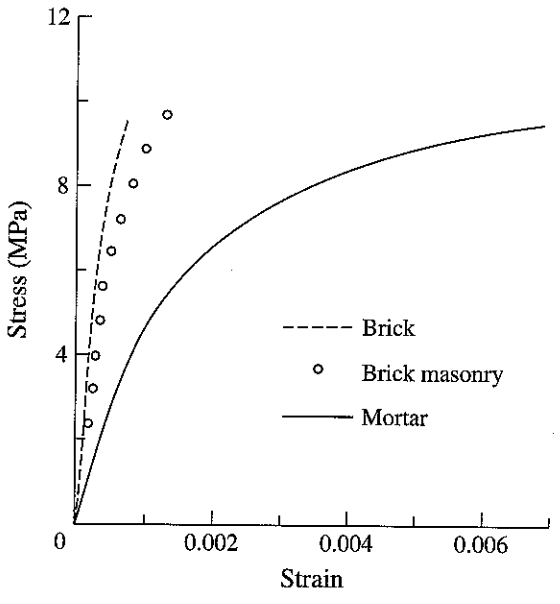


Figure 5. Average stress-strain curves for bricks, masonry and mortar (Dhanasekar 1985)

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 and Hunt 2003). These 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.

4.2. 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.

Table 1. Summary of blocks material properties

Material	Elastic Modulus E (Mpa)	Poisson's ratio ν	Density γ (kg/m³)
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/mm²)	$\tan\phi$	$\tan\psi$	C (MPa)	k_n (N/mm³)	k_s (N/mm³)
0.453	0.75	0.0	0.375	82	36

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. 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.

5. COMPARISON WITH EXPERIMENTAL INVESTIGATIONS

During the testing, the wall suffered no distress when subjected to dishing or doming except for the separation and sometimes sliding that occurred at the damp proof course (Bryant 1993). 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 footing beam with all slip and separation occurring on the one weak plane.

5.1. 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 damp-proof course (dpc), in the central section of the wall, with some sliding along the damp-proof course. 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 Figures 6(a) and 7. In the Bryant's test at very small deflections vertical separation along the dpc was noticeable along the centre of the wall. At the maximum central deflection of 8 mm the separation along the

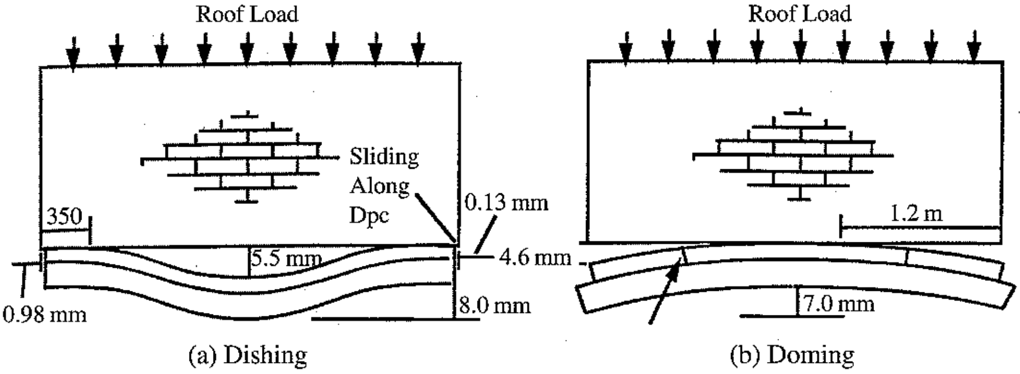
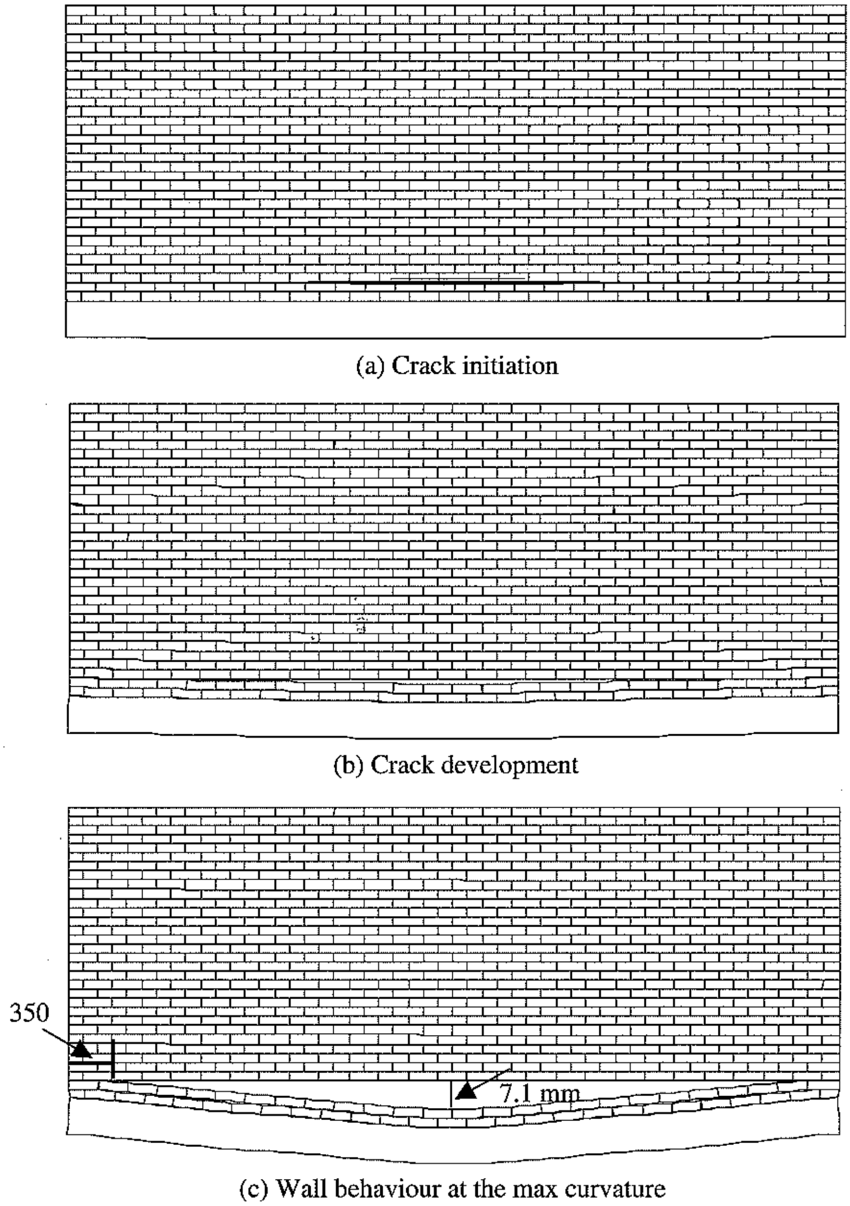


Figure 6. Experimental behaviour of masonry walls under foundation movements (Bryant 1993)

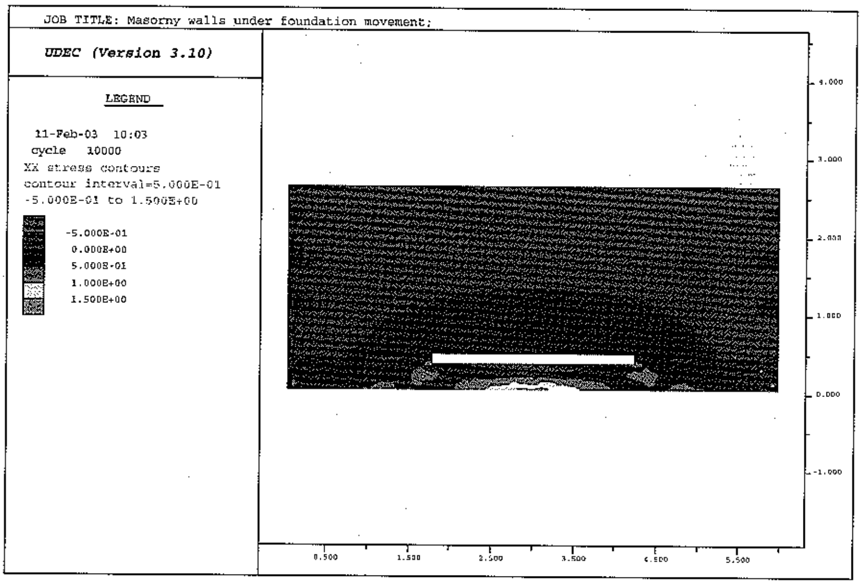


(c) Wall behaviour at the max curvature

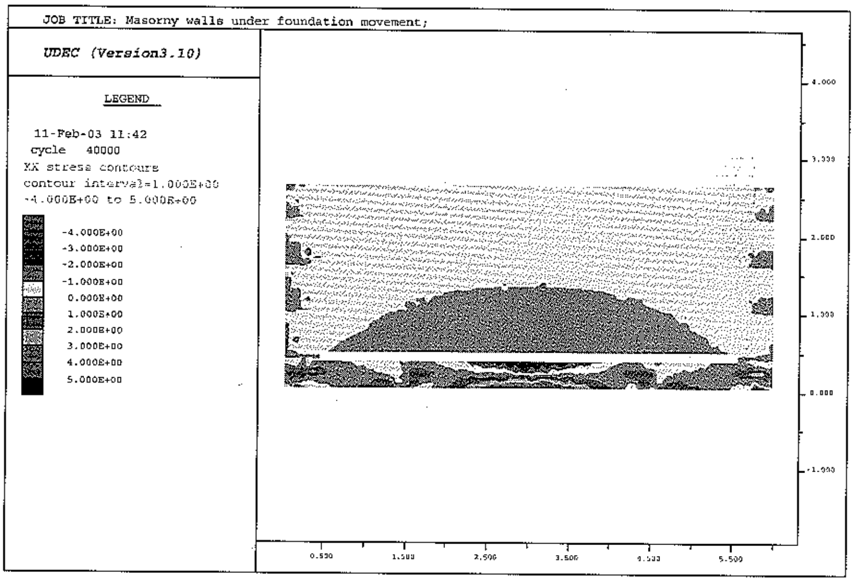
Figure 7. Simulated behaviour of the wall under dishing curvature

dpc extended to within 350 mm of the ends of the wall (Figure 6(a)). Figure 7 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 damp-proof course (dpc) (Figure 7(a)). Vertical separation then taking place and extended as the downward displacement increased (Figure 7(b)). Finally, when a central dishing deflection reached 8 mm, the separation along the dpc extended towards the ends of the wall with only a small connecting length on each side of the wall (350 mm) and also no crack was detected in the masonry wall above the dpc (Figure 7(c)). It can be seen from the above figure, the behaviour of the wall is well captured by the proposed model. However, it should be noted that the vertical separation of the dpc (crack width) could not be modelled accurately in the current model partially because the concrete footing was modelled as a linear elastic material and in Bryant's experimental testing, the concrete footing was heavily cracked.

The contours of horizontal stress (σ_{xx}) distribution at a central displacement of 1 mm and 6 mm are shown in Figures 8(a) and 8(b) respectively. It can be seen from the figure, the increment of central displacement will



(a) At central deflection of 1 mm (Stress magnitude in x-direction, -ve = compressive)



(b) At central deflection of 6 mm (Stress magnitude in x-direction, -ve = compressive)

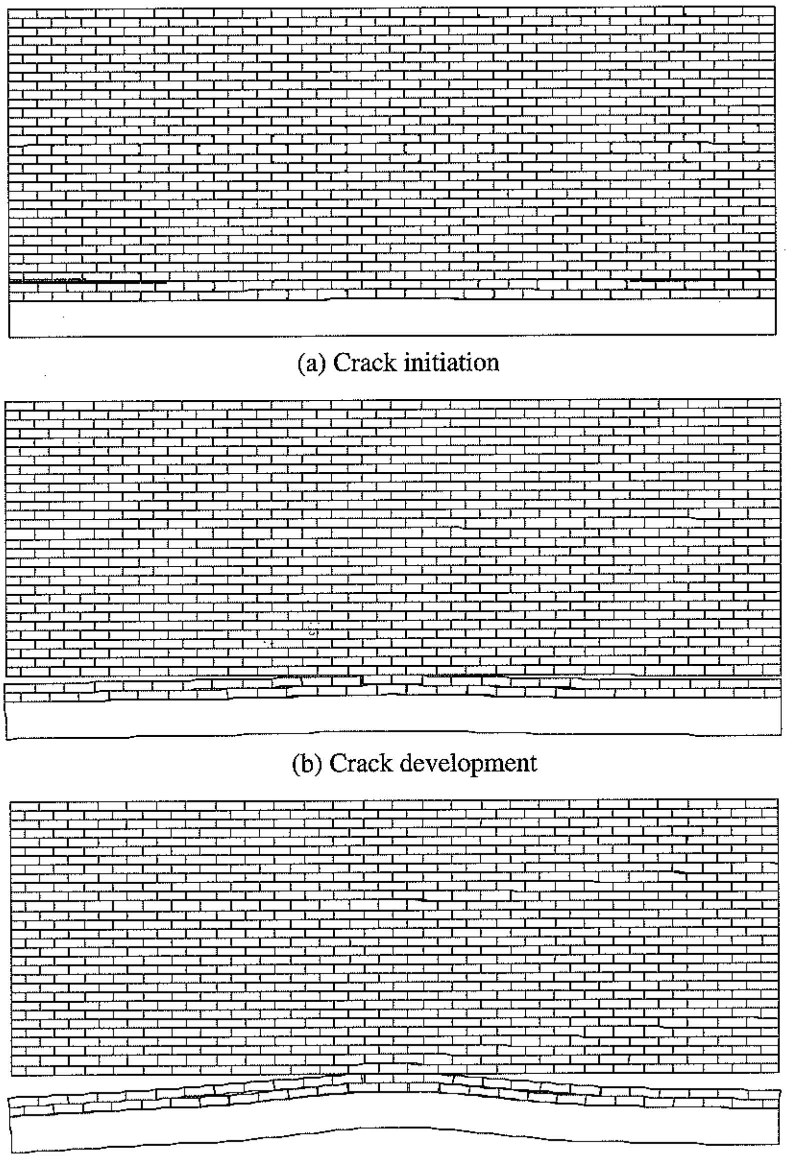
Figure 8. Horizontal stress distribution – dishing

only increase the stresses in the footing beam, but with little effect on the masonry wall above the dpc. This again proving that the dpc acts as a horizontal plane of weakness for masonry walls under footing movements.

5.2. Doming Curvatures

For the doming case, the 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 7 mm the separation on both ends was about equal at 4.2 mm and 4.9 mm on either end of the wall (Figure 6(b)). Again no distress occurred in the masonry wall above the dpc (Bryant 1993).

Figure 9 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 damp-proof course (dpc) (Figure 9(a)). Separation then taking place and extended as the upward displacement increased to around 3 mm (Figure 9(b)). Finally, when a central doming deflection reached 7 mm, the wall



(a) Crack initiation

(b) Crack development

(c) Wall behaviour at the max curvature

Figure 9. Simulated behaviour of the wall under doming curvature

supported only by the central section of the beam, with each end of the wall acting as a cantilever (Figure 9(c)). Again the behaviour of the wall is well captured by the proposed model.

5.3. Walls with a Central Window Opening

Here the wall panels have the same dimensions as previously discussed, but a window opening of 900 mm wide and 1500 mm deep was sawn from the top of the wall at mid length. Only the walls tested with no load to the top of the wall (non-loadbearing walls) were modelled and discussed here.

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. 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. The computed horizontal stress distribution (σ_{xx}) for the doming curvature at a central deflection of 7 mm is shown in Figure 10. 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

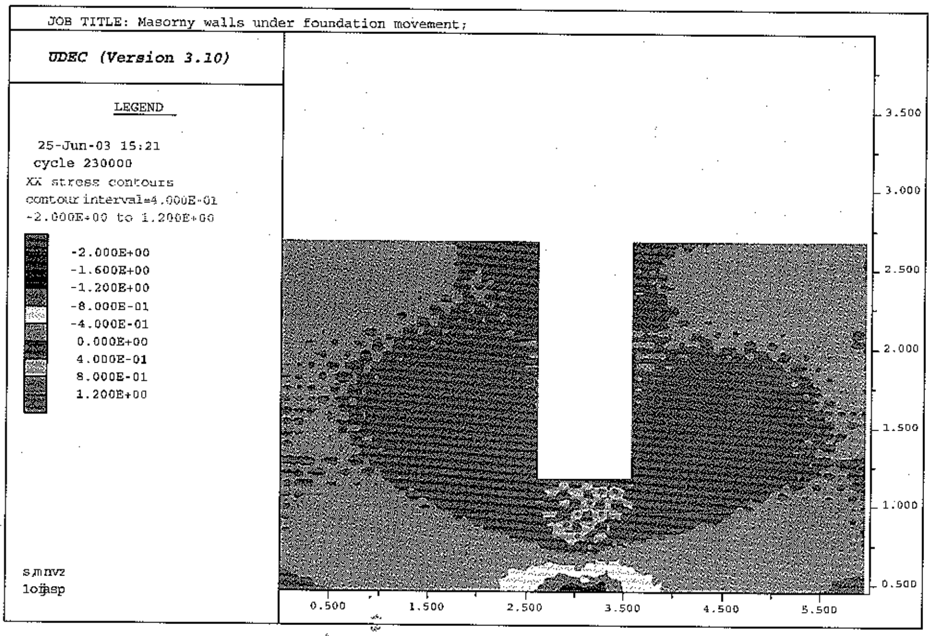


Figure 10. Horizontal stress distribution for the wall under doming curvature with window opening

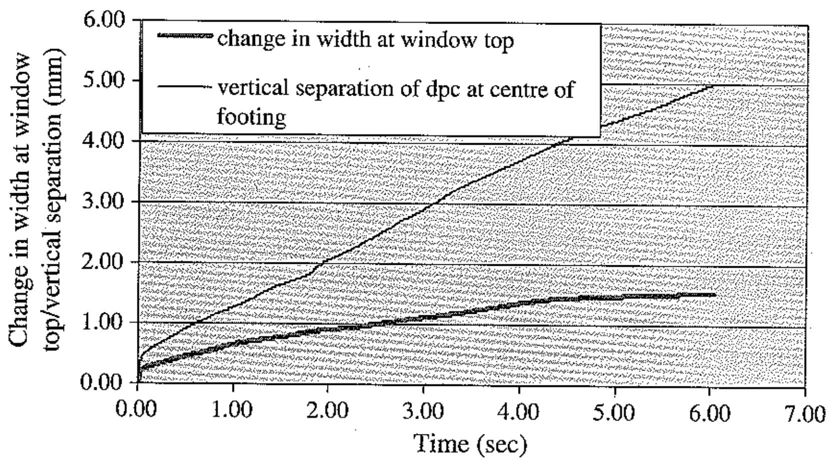
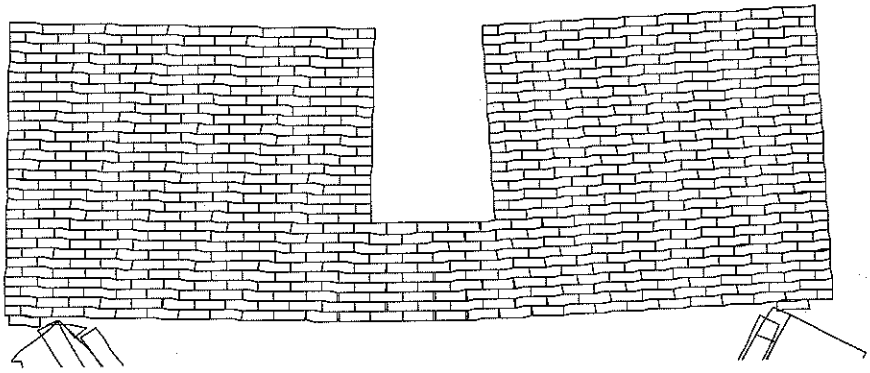


Figure 11. Change in width of the window for the wall under dishing curvature

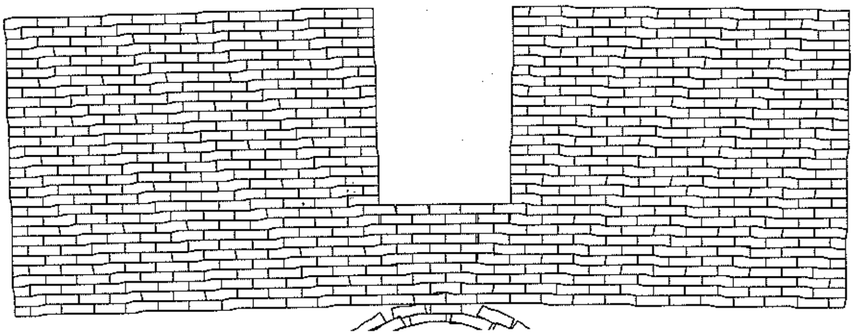
(0.453 MPa), the wall was not cracked in this region. However, the diagram indicated that the region underneath the window sill may be already cracked.

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 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 (Figure 4(a)); the results are shown in Figure 11 together with the computed changes of vertical separation of dpc above the centre of the footing (Figure 4(a)). 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 both doming and dishing cases is shown in Figure 12, which clearly indicates the change in width of the window opening. 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.



(a) Dishing curvature



(b) Doming curvature

Figure 12. Simulated behaviour of the masonry wall with window opening

6. 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 footing 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. 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 2003).

However, the noticeable difference between numerical and experimental results on the crack width under the maximum curvature was found in the current research. The following factors may have contributed to these differences:

1. The concrete footing was modelled as a linear elastic material and in Bryant's experimental testing, the concrete footing was heavily cracked.
2. Damping parameters were not appropriate.
3. The rate of vertical displacements applied to the numerical model at the bottom of concrete footing was faster than experimental testing.

The next step of the research will be aimed at improving the performance of the model and to include the soil moisture movements 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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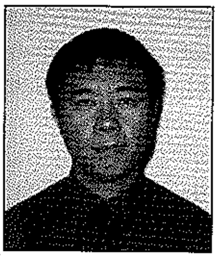

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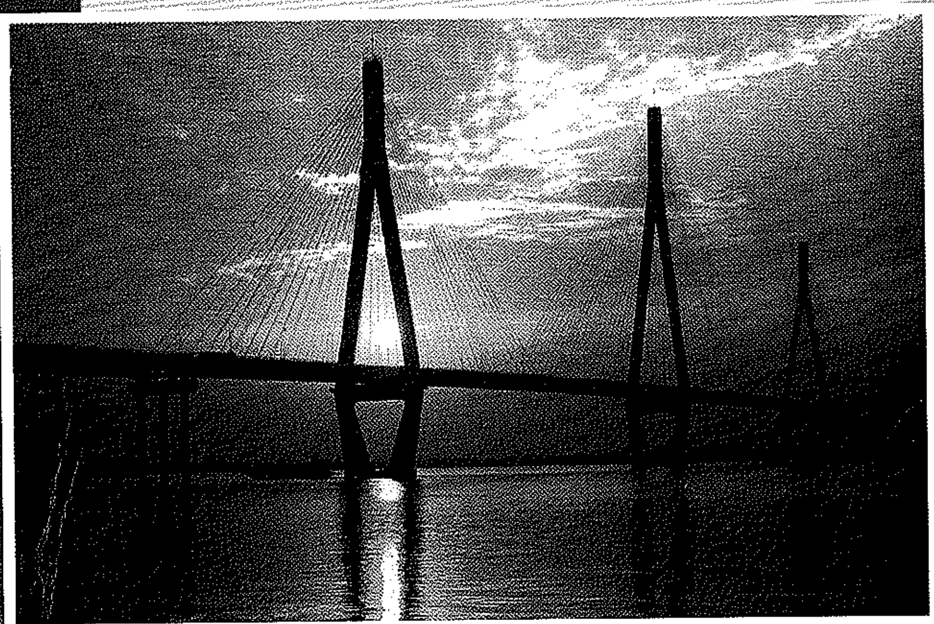

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