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# FAULT RUPTURE MODIFICATION BY BLOCKY INCLUSIONS

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## ABSTRACT

Subterranean fault rupture has been responsible for many recorded instances of building damage during past earthquakes. Differential displacement in the ground can cause shearing in overlying structures and can leave buildings in an unsupported condition. As the demand for land use increases, it may be necessary to adopt strategies to protect certain key structures from fault-related damage. This paper presents the results of an investigation of one potential mitigation scheme, that of providing rigid inclusions in the soil beneath the structure. Theoretically, the blocks should split the fault so that the fault expression at the surface is not a single surface scarp but a more gradual profile, with the effect of reducing the risk of the building being damaged either by rupture emergence along the length of the foundation or by excessive rotation. Modelling of a simple footing above a uniform sand is performed using both discrete element modelling and centrifuge model testing. While the numerical model demonstrates that blocks may be beneficial, the centrifuge tests were unable to demonstrate any splitting of the main rupture plane. However, the block mass was sufficient to increase local stresses and guide the fault. Based on this, it is concluded that while blocks may be capable of deflecting faults the method is too unreliable to be recommended without further supporting research.

Keywords: fault rupture, centrifuge, DEM, ground improvement.

## INTRODUCTION

The rupture of fault planes is the most fundamental aspect of an earthquake, although from an engineering point of view the effects of strong shaking, being more wide-reaching, are given greater attention. This should not be taken to imply, however, that large ground displacements are not a problem, nor that that problem is unsolvable. Relatively recent reconnaissance missions, such as those following the earthquakes in Turkey (Youd et al., 2000) and Taiwan (Uzarski and Arnold, 2001) in 1999, provide ample evidence of the potential problems that buildings near to fault ruptures can experience (Figure 1).

The aim of this work was to investigate a possible method of protecting buildings over tectonic faults. This paper considers dip-slip faults rupturing in a normal direction: that is, the moving ground (the hanging wall) displaces downwards relative to the stationary rock (the foot wall) giving an extensional zone as shown in Figure 2a. In general, there will be a soil layer between the moving fault and the ground surface through which the displacement propagates. Therefore the surface expression of the fault will occur some distance from the source. The direction of such fault ruptures under different dip angles has been examined by Cole and Lade (1984) and Lade et al. (1984) who used 1-g models to conclude that rupture direction depended on soil thickness, soil dilation angle and fault dip angle. More recently, this problem has been investigated by Bray and his co-workers (e.g. Bray, 1990; Bray

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et al., 1994). Roth et al. (1981) performed centrifuge tests (and then numerical analysis; Roth et al., 1982) on reverse faults only using both sand and sandy silt, which had also shown the influence of soil dilation angle on results. This is represented more accurately in the centrifuge (where effective stresses are identical to a large-scale prototype) as dilation angle depends on effective stress (e.g. Bolton, 1986). The EU-funded QUAKER project (http://www.dundee.ac.uk/civileng/quaker/) was instigated in part to examine such failures using field work (e.g. Anastosopoulos & Gazetas, 2007a, b), centrifuge modelling (El Nahas et al., 2006) and numerical modelling (e.g. Anastasopoulos et al., 2007).

Should this surface expression occur beneath a structure then it is likely that the structure will be damaged by a large differential displacement (e.g. Figure 1b). Alternatively, El Nahas et al. (2006) demonstrated that heavy buildings may cause fault ruptures to deviate and miss the structure, at the expense of large rotations (e.g. Figure 1a) and this has been confirmed by study of case histories (e.g. Bray, 2001; Anastosopoulos & Gazetas, 2007a). This could be due to the kinematic restraint of the ground by such buildings or due to the bearing pressure applied to the soil surface (e.g. Berill, 1993).


**Figure 1. Dip-slip fault rupture near/through structures. a) Gölcük, Turkey, photograph by EERI; b) Wu-Feng, Taiwan, photograph by K.I. Kelson, EERI.**

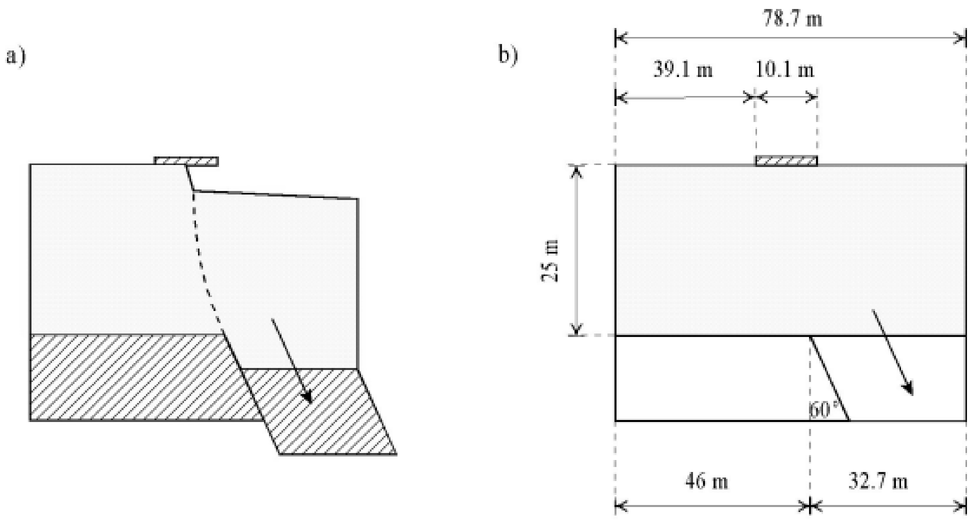


**Figure 2. a) Schematic of normal fault rupture; b) Dimensions of the benchmark centrifuge model (prototype scale).**

Little work has been done experimentally to determine solutions for such problems. An attitude of avoiding potentially problematic areas, or considering such damage highly unlikely, has been taken. However, with increasing demands on land use avoidance is becoming more difficult and, should key structures be required in the vicinity of potentially active earthquake faults, it would be prudent to have a reliable strategy available for their protection. In addition, if a suitable strategy was found for protecting surface structures then there may be a simple extension to improve the soil around critical underground structures such as pipelines that cannot avoid fault areas. A number of possible solutions have been proposed by Tani (2003), Bray et al. (1993) and Bray (2001). These mostly operate by absorbing the fault movement such that large differential displacements at the surface are reduced to more gentle gradients or many smaller differential displacements. One of the methods suggested by Tani (2003) was to use large blocks in the soil to break up the fault into many smaller faults as shown in Figure 3.

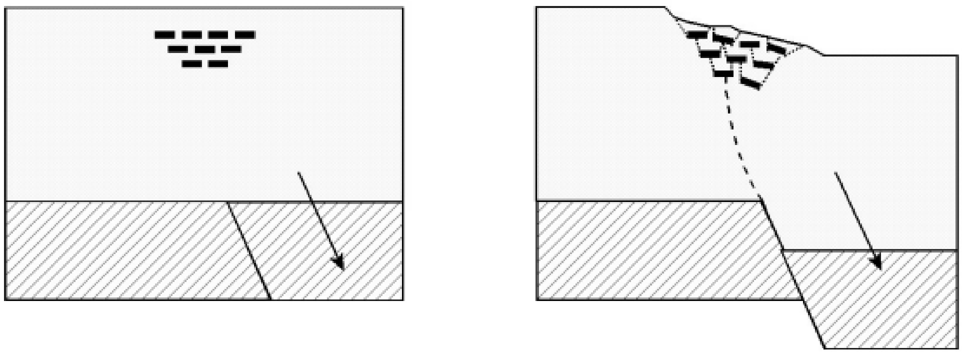

**Figure 3. Intended block protection mechanism.**

The aim of this paper, therefore, is to investigate the suitability of such blocks in a single soil stratum as a ground improvement strategy preventing shallow foundation failure due to normal faulting and also to quantify their effect. Both numerical and physical modelling has been performed, and ground deformation (displacement and rotation) evaluated in order to determine if the method is suitable for reducing the size of the surface expression (scarp) formed due to the rupture. To establish the extent of the influence of the blocks, soil deformation is also monitored in both modelling approaches. Finally, the foundation rotation (an indication of foundation distress) has been monitored as a function of fault "throw", the vertical component of bedrock displacement.

## MODELLING TECHNIQUES

### Centrifuge Modelling

As faults will commonly be under soil of significant depth and hence high effective stress, the physical modelling was performed using the 6 m diameter beam centrifuge at the University of Dundee. The centrifuge applies an increased gravity to enable reduced-scale models to be tested under the same self-weight stress conditions as full-scale prototypes (e.g. Schofield, 1980). Laboratory (1-g) models under low effective stress might experience excessive dilation, the importance of which was emphasised by Cole and Lade (1984). For the work reported here, tests were carried out on a soil model of $1/115^{th}$ scale, spun to give a centrifuge acceleration of 115 times Earth's gravity to represent the prototype geometry shown in Figure 2b. A 25 m soil depth was investigated in all tests and all modelling in this paper is performed as plane strain, and all values are given in prototype scale. Some further details of the test apparatus and procedure was given by El Nahas et al. (2006).

Models were prepared by dry pluviation of Fontainebleau sand (critical state friction angle $\phi' = 31^0$, peak friction angle $\phi'_{pk} \approx 35^o$, dilation angle $\psi' \approx 5^o$ at mid-depth in the soil layer) to a relative density of around 60%. This sand was also used, dyed blue, as marker sand at the container's Perspex sides (see Figure 5 below). Blocks are modelled by aluminium alloy bar or rod, whose density is similar to that of rocks or grout (~ 2700 $kg/m^3$). A small thickness of sponge foam was added to each end of these to thrust against the window and hence ensure that the blocks maintained their visibility during testing without imposing any additional friction. The model footing was also constructed of aluminium (i.e. rigid compared to the soil) and imposed a bearing pressure of 37 kPa representing a 3-4 storey building with a mat foundation. The four cases tested on the centrifuge are shown in Figure 4.

Fault actuation was achieved using a hydraulic piston beneath the moving floor. For a normal fault test, the hydraulic piston was first 'locked' to balance the static soil weight before faulting and then oil was removed from the piston to cause the container boundary to drop along the dip angle and simulate the fault. This is necessarily a slow process, although the rate effects observed in sandy silt by Roth et al. (1981) should not be an issue in the clean, dry sands tested here.

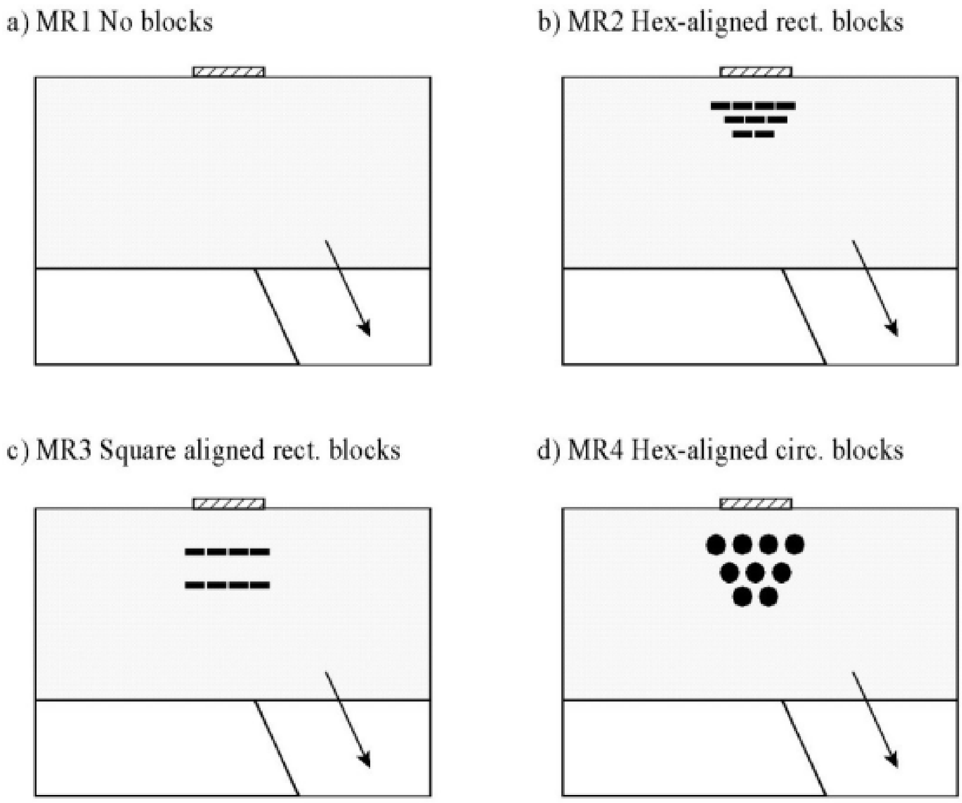


**Figure 4. a) MR1 benchmark case; b) MR2 hexagonally arranged rectangular blocks; c) MR3 regularly arranged rectangular blocks; d) MR4 hexagonally arranged circular blocks. N.B. Foundation and soil geometry shown in Figure 2b.**

**Discrete Element Modelling**

The large relative displacement problem with a localisation is a difficult one for a conventional continuum analysis, and even though this is not impossible (e.g. Roth et al., 1982; Bray et al., 1994, Anastasopoulos et al., 2007) the discrete element method (DEM) is intuitively closer to the problem in question. The 2D DEM method considers the soil to be constructed of self-supported standing frictional disks. Therefore a simple displacement of the boundary of a DEM model should mimic the fault-rupture phenomenon. For this study, the LMGC90 2D code was used (Dubois and Jean, 2004) to obtain some preliminary information (Roby, 2006). The disks were of 0.5 m diameter for the initial (untreated) case (test MR1) and 0.25 m for the later, treated cases (tests MR2 only presented). Blocks are modelled as rigid, with interface friction angle the same as the soil.

There were drawbacks with the method, both practical (duration of a single calculation) and theoretical (particle packing density/arrangement). The second problem is of course more important. Particles in the analysis were arranged in a regular hexagonal-close-packed configuration, giving a high relative density and dilation angle. It also meant that the particle centres were arranged at $60^0$ to the horizontal, the same angle as the dip of the fault, which may induce some bias towards shearing in this direction.

Therefore, the role of the DEM in this research is simply to observe the *differences* obtained between soil with and without blocks, and to identify the cases that will be of the most interest for further testing on the centrifuge. It is appreciated that in order to obtain more quantitative information then further work should be done using a random particle distribution, but this was not possible within the constraints of the project.

## UNTREATED CASE

Test MR1 was reported by El Nahas et al. (2006). Figure 5 shows digital images captured at two particular time instances of this test: (a) before fault movement (throw = 0 m), and (b) after a fault throw of 3.1 m. After a throw of 3.1 m (Fig. 5b), two shear bands have clearly formed in the sand layer. One, labelled (1) in Figure 5b began to travel towards the centre of the foundation but did not reach the soil surface and became inactive after the second shear localisation formed. The second, labelled (2) as it appeared later in the test (and at a fault throw of around 1.3 m, El Nahas et al., 2006), diverts around the left hand edge of the foundation forming a surface scarp. The fault throw causes rotation of the foundation which ceases after the second shear plane is fully mobilised. This is similar behaviour to that seen in the field, e.g. Figure 1a.

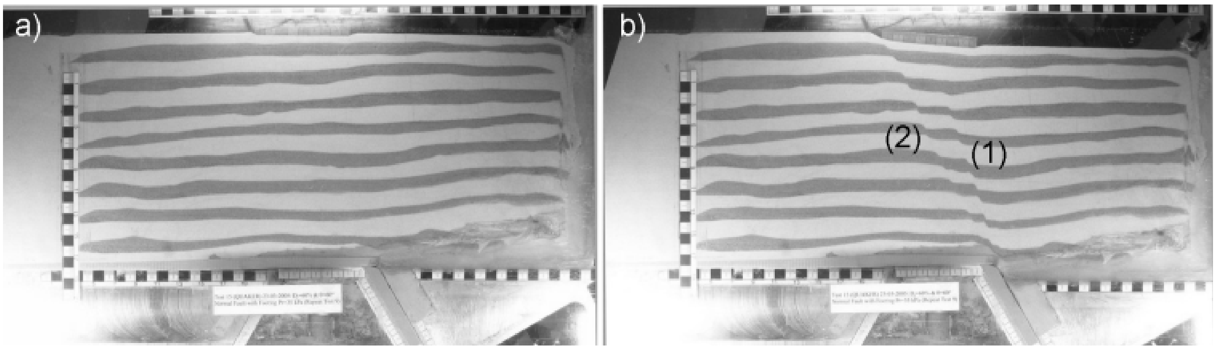


**Figure 5. MR1 no blocks a) before faulting; b) fault throw = 3.1 m**

When this situation was modelled with the DEM, a different result was achieved. Figure 6 shows the wider view as well as a close-up of the foundation. Clear shear banding is seen along the fault at a dip angle of 60$^{o}$ (to the horizontal), with an additional shear band at 120$^{0}$ to the horizontal (i.e. towards the right). This is probably due to the artificially high packing density referred to above causing very brittle behaviour of the soil and the large dilation necessary to accommodate shearing Focussing on the behaviour under scrutiny, that of the foundation, it can be seen that the fault did not divert. Although some kinematic particle movement is evident (and the associated footing rotation, Figure 6b), a scarp clearly forms beneath the foundation. It is such surface discontinuity formation that the blocks are specifically intended to target, so this data is retained to compare with later models using blocks.

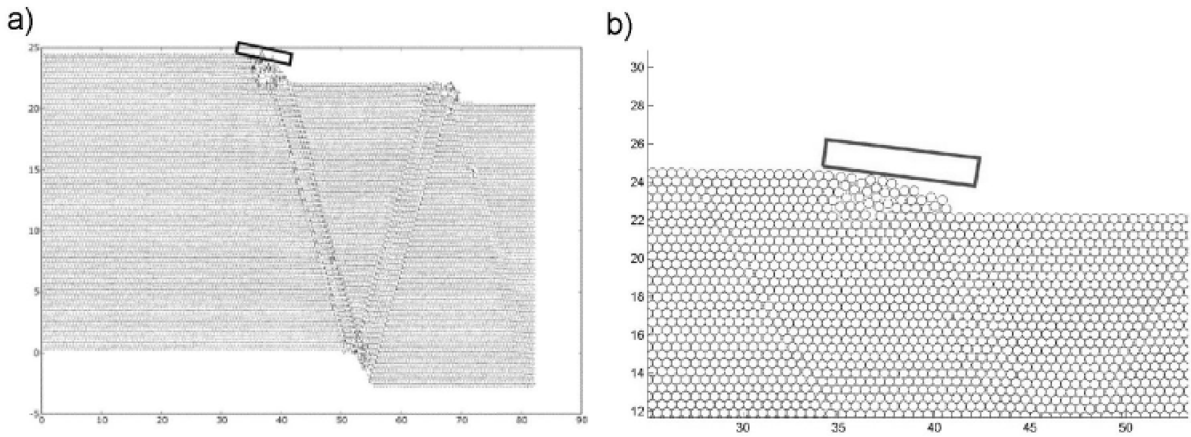

**Figure 6. DEM result, untreated foundation a) complete box; b) close up. Fault throw = 3.0 m.**

## TREATED CASES

### Rectangular Hexagonally-Aligned Blocks

The DEM was used in order to choose cases to model on the centrifuge. Shown in Figure 7 is the model based around MR2 (see Figure 4). Blocks are taken as rectangular inclusions arranged on a hexagonal grid, and their dimensions are 2.2 m wide by 0.7 m thick. Block separation is 1 m horizontally and 2 m vertically.

The deformation pattern in Figure 7 is somewhat different to that in Figure 6 above (the untreated case). Each rigid block has propagated its own pair of shear bands, leading to the dispersed shear band pattern envisaged in Figure 3. The surface scarp obtained in the untreated case has gone and had been replaced by a slope, which will cause rotation of the foundation but not differential displacements beneath it. Based on this preliminary result, a centrifuge test was carried out on an identical model in order to establish how close this matched reality.

Photographs from the first and last stage of centrifuge test MR2 are shown in Figure 8. A different result is now obtained in the medium dense sand of the physical model. Although the blocks appear to have blocked initial shear band (1), the second fault rupture (corresponding to band (2) in Figure 5b) has simply negotiated its way between the blocks leaving them relatively undisturbed compared to the DEM result in Figure 7. Rather than creating many shear bands, the blocks here have actually reduced their number from two to one, but made no difference to the final mechanism. A scarp is still evident next to the footing. This has an effect on the foundation rotation, as examined quantitatively later.

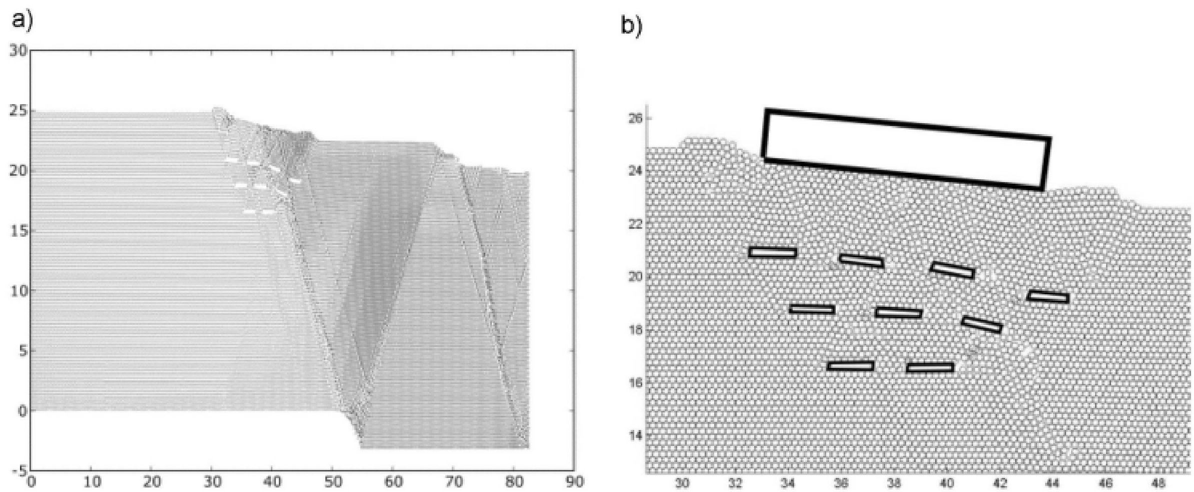


**Figure 7. DEM result for the untreated foundation a) complete box; b) foundation close up. Fault throw = 3.5 m.**

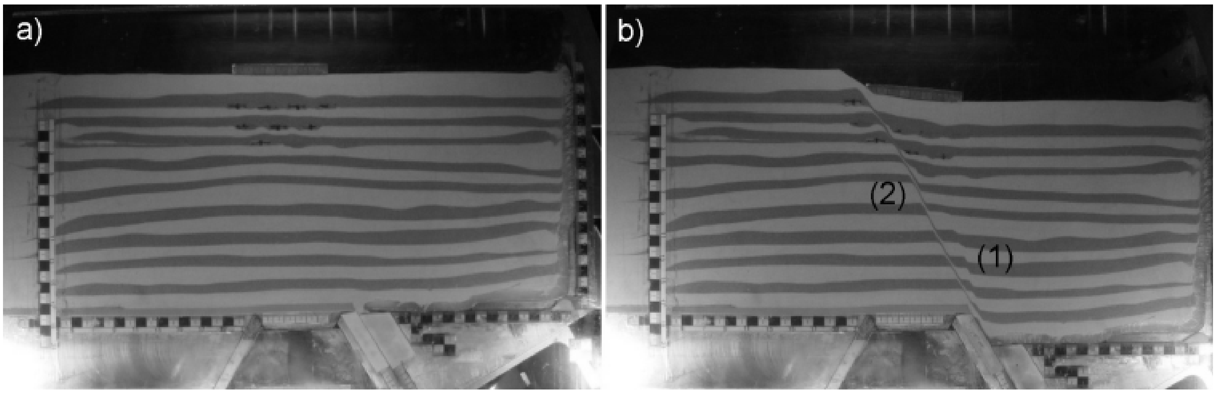


**Figure 8. MR2 hexagonally arranged rectangular blocks a) before faulting; b) fault throw = 3.4 m.**

### Rectangular Square-Aligned Blocks

Following the disappointing performance of the hexagonally spaced blocks, a second arrangement of the same blocks was proposed as shown schematically in Figure 4c and photographically in Figure 9a. The rationale was that if the fault had negotiated the blocks on a $60^0$ grid then this arrangement should catch the shear band and disperse it as intended. In addition, the horizontal separation of the blocks was reduced from 1 m to 0.35 m and vertical separation increased from 2 m to 5.3 m.

This experiment was hindered by focussing problems with the camera lens under the high g level of the centrifuge. Nevertheless, some qualitative conclusions may be drawn.

Figure 9 shows the initial and final image captured in the centrifuge for a fault throw of 3.5 m. Again, there is a single clearly defined shear band travelling between the blocks and emerging to the left of the footing. It appears as if the fault has chosen to travel in this direction: this fault direction differs slightly from that in the previous experiments and the blocks are circumnavigated. Furthermore, the final discontinuity has been brought *closer to the structure* than in the untreated case (compare Figures 5b and 9b) because of the position of the inclusions.

It is clear from these two tests (MR2 and MR3) that the block patterns chosen do cause the fault to deviate a little, but not disperse the fault.

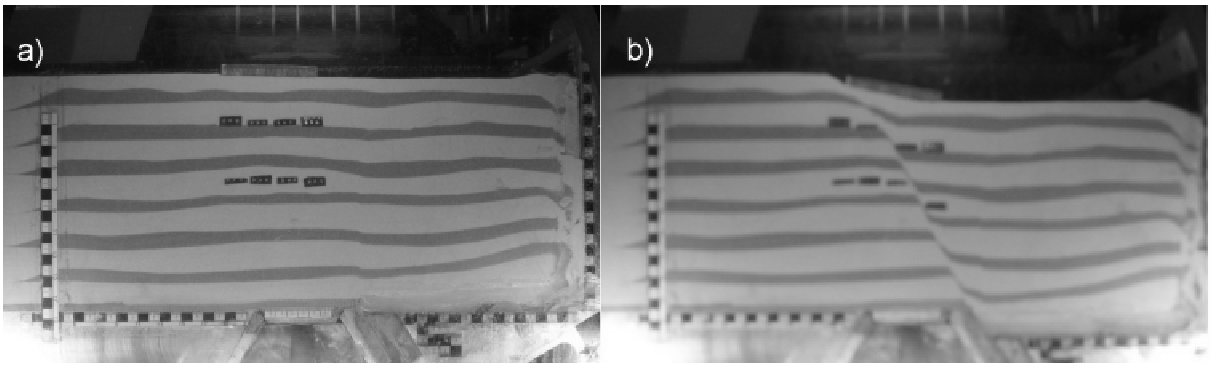


**Figure 9. MR3 square-arranged rectangular blocks a) before faulting; b) fault throw = 3.5 m.**

### Circular Hexagonally-Aligned Blocks

To investigate if block shape has any effect, a final test was performed using inclusions of 2.2 m diameter. There is 1.4 m clear gap between blocks horizontally and 1.4 m clear gap between horizontal layers. Images captured before fault displacement and after a fault throw of 3.4 m are shown in Figure 10.

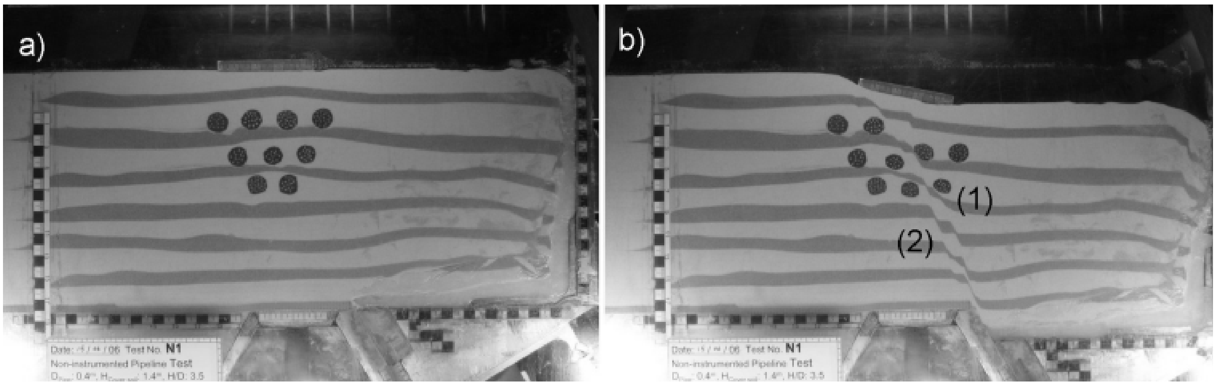


**Figure 10. MR4 hexagonally arranged circular blocks a) before faulting; b) fault throw = 3.4 m.**

The first mechanism to develop is that marked (1) in Figure 10b. This heads for the middle-right block before diverting through the group towards the centre of the foundation creating a small scarp on the soil surface (note also the gap formation beneath the foundation visible in Fig. 10b). This shear plane ('1' in Fig. 10b) is unable to develop further due to the weight of, and the kinematic constraint imposed by, the foundation and so a secondary mechanism (2) begins. This goes between the same blocks as (1) but diverts sharply near the surface to emerge to the left of the foundation. The shear zone is now not a single band but a zone between the two bands (1) and (2) directly beneath the footing, into which all the deformation is concentrated. Significant foundation rotation is now required to obey compatibility, as described below. This is similar to the above case MR3 in that the deformation is brought closer to the structure.

Again, the presence of blocks deviates the main shear band from its untreated path (c.f. Figure 5b. This does not appear to be due to splitting as hypothesised by Tani (2003) and observed in the DEM analysis but consists of a deviation through the soil either due to stress changes or block kinematics.

## DISCUSSION

As a means to quantify the comparison above, the rotation of the footing is presented as a function of the vertical distance moved by the fault in Figure 11. This was calculated using digital image analysis of sequential images captured during the test using the GeoPIV program of White et al. (2003). Cases MR1 (no blocks), MR2 (rectangular blocks) and MR4 (circular blocks) are presented. Test MR3 suffered focussing problems preventing digital image analysis and could not be included.

Initially (i.e. at small fault displacements) the rectangular blocks appear to be inhibiting rotation, by apparently blocking mechanism (1) that is operating in both MR1 and MR4 and is presumably responsible for the similar rates of rotation of these models (compare Figure 8b with Figures 5b and 10b). However, once the fault breaks the surface in MR1 (untreated case) there is almost no further foundation rotation which settles at around $5^0 – 6^0$. The principal difference of the blocks is that this does not happen even for the large displacements examined, and rotation keeps on increasing. This is particularly evident in MR4 (circular blocks) where the creation of two faults to the surface caused a wide deformation zone immediately beneath the footing with a final rotational mechanism. The magnitude of the surface discontinuity beside the footing was reduced at the expense of this large and increasing rotation.

Rotation in test MR2 is comparatively smaller. Here, the blocks have blocked mechanism (1) and all deformation is concentrated onto the single fault labelled (2). With all deformation concentrated onto a single slip plane, little deformation is required in the soil beneath the foundation and so rotation is reduced and a single larger cliff formed.

It is therefore implied that by reducing the number of slip planes, rotation (i.e. surface gradient) is also reduced (if the fault does not emerge directly beneath the foundation) as deformation concentrates itself over a smaller area. This was expected, and was not the intended function of the blocks which are were designed to increase the number of slip planes and reduce the scarp size. This happened in neither case – MR2 reduced the number of slip planes and created a larger cliff, while MR4 managed to guide a slip plane to the centre of the footing, the exact situation it had been intended to prevent. Therefore, despite the apparent improvement of rotation characteristics in MR2 it is suggested that the blocks failed in all cases, and cannot yet be considered a reliable method of remediation.

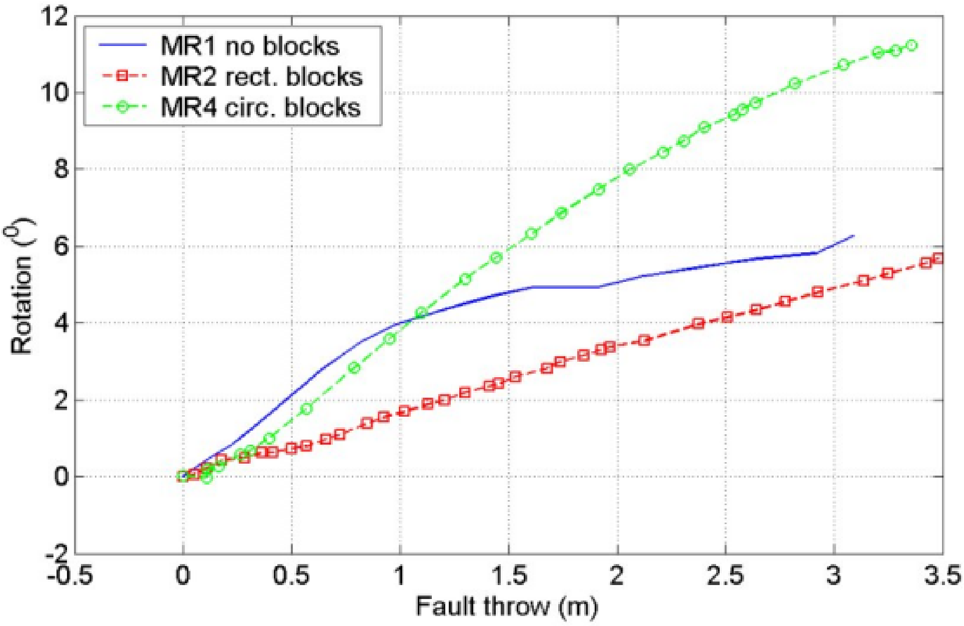


**Figure 11. Footing rotation as a function of fault throw for MR1, MR2 and MR4.**

With blocks being demonstrated to be so unreliable, more research is needed before there can be any attempt to use them in the field. In particular, their success in the preliminary DEM suggests that in extremely dense soil with the potential for huge dilation they may be able to achieve their aim, although it might be somewhat limiting if this is the only appropriate situation.

One possible way forward for the blocks may in fact be through their mass. As reported earlier, researchers in the QUAKER project had reported heavy buildings causing faults to deviate away from their foundation (e.g. El Nahas et al., 2006; Nagaoka, 2007) due to their bearing pressure which both increased the stresses in the soil beneath them and required additional work for movement. Examination of the behaviour patterns in Figures 8b and 9b suggest that the blocks may behave as submerged footings and causing similar deviation. It may be that the deviation here may be due not to their kinematic presence, but to their mass.

Blocks tested in this study have been at a density similar to rock or grout, but if blocks had been much denser, for example, steel or brass, then the increased stresses in the soil might have had the same effect as these heavy footings and caused a large scale deviation of the main fault. Thus, the operation of the blocks would cease to be the dissipation of the main fault and become a simple matter of stressing the soil in order to deter it. Further study would be needed to demonstrate if this is indeed the case.

If it can be proved that ruptures can be repelled or attracted by small areas of increased or reduced stress respectively, this could form the basis for further strategies (using blocks, cavities, or grout e.g.) for mitigating the fault-rupture problem.

## CONCLUSION

Ground improvement strategies using rigid inclusions were investigated to find out whether they can improve the performance of shallow foundations in close proximity to normal earthquake faults. This was achieved using a combination of discrete element testing and centrifuge model tests.

Fault-rupture mitigation appears to be a trade off between the size of the surface discontinuity and the amount of rotation experienced by the foundation. This is because the shift in bedrock level (fault throw) must be accommodated by the soil deformation. Increasing the size of the surface discontinuity reduces rotation if the fault discontinuity avoids the foundation.

Blocky inclusions beneath footings appear theoretically and in a rudimentary DEM simulation to be a potentially useful method of reducing the cliff-type surface discontinuities associated with fault ruptures. Physical modelling has shown that blocks are unreliable at this, and without significant further work must be considered unsuitable. However, the blocks are probably capable of guiding ruptures due to their local stressing of the surrounding soil. It is anticipated that this feature may be exploited in future possible remediation schemes.

## ACKNOWLEDGEMENTS

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## REFERENCES

Anastasopoulos I, Gazetas G, Bransby MF, Davies MCR and El Nahas A. "Fault rupture propagation through sand: finite element analysis and validation through centrifuge experiments, " submitted to the Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 2007

Anastasopoulos I and Gazetas G. "Foundation-Structure Systems over a Rupturing Normal Fault : I. Observations after the Kocaeli 1999 Earthquake, " Bulletin of Earthquake Engineering, 2007. In press.

Anastasopoulos I and Gazetas G. "Behaviour of Structure-Foundation Systems over a Rupturing Normal Fault : II. Analyses, Experiments, and the Kocaeli Case Histories," Bulletin of Earthquake Engineering, 2007. In press

Berill JB. "Two-dimensional analysis of the effect of fault rupture on buildings with shallow foundations," Soil Dynamics and Earthquake Engineering, 2(3), 156-160. 1983

Bolton MD. "The strength and dilatancy of sands," Géotechnique, 36(1), 65-78, 1986

Bray JD. "The effects of tectonic movements on stresses and deformations in earth embankments," Ph.D. Dissertation, University of California, Berkeley, 1990

Bray JD "Developing mitigation measures for the hazards associated with earthquake surface fault rupture,", in A Workshop on Seismic Fault-Induced Failures– Possible Remedies for Damage to Urban Facilities, Japan Society for the Promotion of Science, University of Tokyo, Japan, January 11-12, pp. 55–79, 2001

Bray JD, Ashmawy A, Mukhopadhyay G, and Gath EM. "Use of Geosynthetics to Mitigate Earthquake Fault Rupture Propagation Through Compacted Fill," Proceedings of the Geosynthetics ’93 Conference, Vol. 1, pp. 379-392, 1993

Bray JD, Seed RB, Cluff LS and Seed HB. "Earthquake Fault Rupture Propagation through Soil", Journal of Geotechnical Engineering, ASCE, 120(3), 543-561. 1994

Cole DA and Lade PV. "Influence zones in alluvium over dip-slip faults," Journal of Geotechnical Engineering, ASCE, 110, 599-615, 1984

Dubois F and Jean M. "LMGC90 end user guide," http://www.lmgc.univ-montp2.fr/~dubois/LMGC90/, 2004

El Nahas A, Bransby MF and Davies MCR "Centrifuge modelling of the interaction between normal fault rupture and rigid, strong raft foundations," Proc. Int. Conf. on Physical Modelling in Geotechnics, Hong Kong, 337-342, 2006

Lade PV, Cole DA and Cummings D. "Multiple failure surfaces over dip-slip faults, " Journal of Geotechnical Engineering, ASCE, 110, 616-627, 1984

Nagaoka S. "The interaction of earthquake faults with foundations and pipelines," PhD thesis, University of Dundee, UK, 2007

Roby M. "Exploring ways to reduce the impact of earthquake faults on buildings, " Project report, Ecole Polytechnique, France, 2006

Roth WH, Scott RF and Austin I. "Centrifuge modeling of fault propagation through alluvial soils," Geophysical Research Letters, 8, Issue 6, 561-564, 1981

Roth WH, Sweet J and Goodman RE, "Numerical and physical modelling of flexural slip phenomena and potential for fault movement," Rock Mechanics, Suppl. 12, 27–46. 1982

Schofield AN. "Cambridge geotechnical centrifuge operations," Géotechnique, 30(3), 227-268, 1980

Tani K. "Proposal of ground improvement method to prevent fault rupture modification, " Proc. 11th Int. Conf. on Soil Dynamics and Earthquake Engineering/3rd Int. Conf. on Earthquake Geotechnical Engineering, U.C. Berkeley, USA, 590-597, 2003

Uzarski J and Arnold C (eds.) "Chi-Chi, Taiwan earthquake of September 21 1999 reconnaissance report," Earthquake Engineering Research Institute publication 2001-02, 2001

White DJ, Take WA and Bolton MD. "Soil deformation measurement using particle image velocimetry (PIV) and photogrammetry," Géotechnique, 53(7), 619-631. 2003

Youd TL, Bardet J-P and Bray JD (eds.) "Kocaeli, Turkey earthquake of August 17, 1999 reconnaissance report," Earthquake Engineering Research Institute publication 2000-03, 2000