Geotechnical Aspects of Underground Construction in Soft Ground, Kusakabe, Fujita & Miyazaki (eds)
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Centrifuge investigation on deformations around tunnels in nailed clay

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ABSTRACT: A series of centrifuge model tests was carried out to observe deformations around tunnels in clay reinforced by soil nails and to investigate the effects of nailing on the overall stability of the clay model grounds with different pre-consolidation stresses. The settlements were larger in the ground with the lower pre-consolidation stress. Effects of the rate of tunnel support pressure reduction were discussed. The nail reinforcement worked more effectively in the stiff ground than in the soft ground.

1 INTRODUCTION

Recent pressure on land use within urban areas has led to an increase in the number of tunnelling projects for services and mass transit purposes. Tunnel excavations inevitably cause ground deformations and may affect existing structures near the tunnel. Current practice for the prediction of tunnelling-induced near surface settlement profiles is usually based on an empirical approach. Many studies on deformation and stability of ground with tunnelling have been made (Taylor 1995) and methods of predicting near-surface settlement profiles induced by tunnelling have been proposed (Peck 1969, O'Reilly & New 1982, Mair at al., 1993). Most of these studies were made for uniform ground conditions, and a study on surface and subsurface ground movements caused by tunnelling in layered ground has been made recently (Grant & Taylor 1996). In addition to predicting ground deformations due to tunnelling, a key issue is to increase stability and so decrease the overall deformation of the ground around a tunnel. For this, soil nailing method is a possible solution. Most of the current design methods for the construction of a nailed tunnel are empirical and do not consider ground deformations (Leca & Clough 1992). Studies on the soil nailing method published so far are mainly case studies (Lunardi 1992) or numerical studies (Dasari 1996). Kuwano et al. (1998) carried out centrifuge model tests on stability around tunnels in stiff clay reinforced by soil nails and showed that when the nails were installed in the region of large tensile strain, around 45° from the horizontal, reinforcements worked most effectively. However, the effects of clay model ground's stiffness have not been studied yet. The objectives of this study were to observe deformations around tunnels in clay reinforced by soil nails and to investigate the effects of nailing on the overall stability of the clay model grounds with different pre-consolidation stresses.

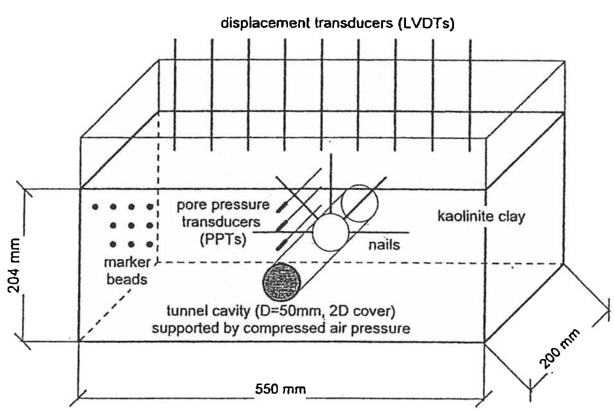

Figure 1. Schematic diagram of centrifuge model.

2 CENTRIFUGE MODEL TESTS

A series of plane strain centrifuge model tests was carried out. Figure1 is a schematic illustration of the model. The model was designed to represent a 5m diameter tunnel constructed in overconsolidated clay. The main scaling law applicable to this study is that of length. If the gravity scaling factor for the model is N, the scale factor for linear dimensions in the model is 1/N. The scaling law for the nailing is more complicated. The scale factor for this might be $1/N^2$, since it is found that the shear resistance of sand

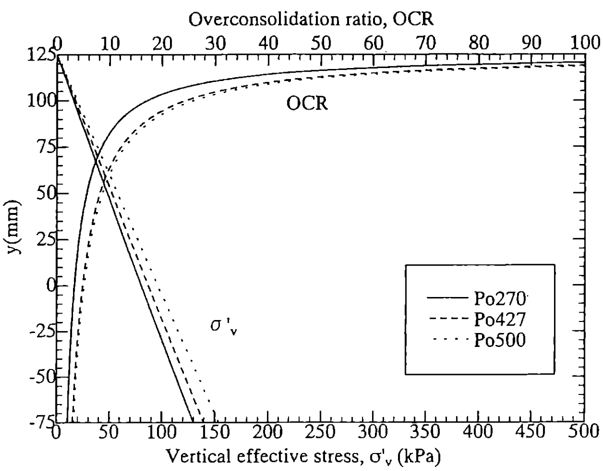

Figure 2. Stress distributions in the model.

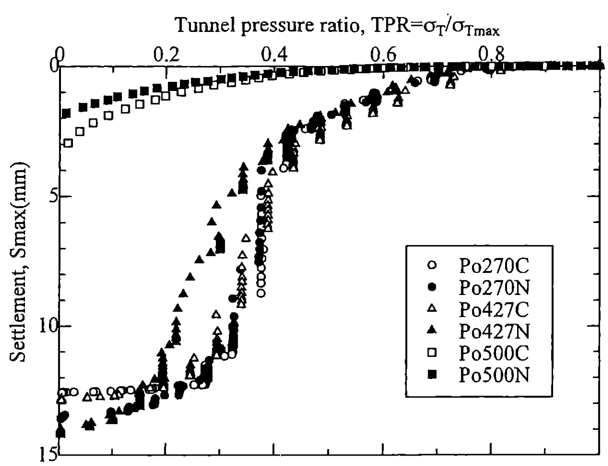

Figure 3. Settlements with the reduction in the tunnel support pressure.

samples reinforced by different types of fibres with the same surface area is almost the same irrespective of thread characteristics, e.g. tensile modulus, (Kuwano et al. 1995). However, the scale factor of 1/N was simply assumed for nails, as there were many other factors which could affect the mechanism of reinforcement.

Kaolin clay slurry with an initial moisture content of 120% was consolidated in the model container to the maximum vertical effective stress of 270, 427 or 500 kPa. The vertical stress was then removed and the tunnel with a diameter, D, of 50 mm was excavated. For each test the clay cover above the tunnel crown was equal to 2D. Model nails made of steel wire, 80 mm or 40 mm in length and 0.58mm in diameter, were inserted into the clay from the tunnel cavity in the direction normal to the tunnel wall in arrays at intervals of 20mm along the length of the tunnel. The nail had an end-plate of about 3 mm in size. The nails were arranged in the direction of 30° and 60° from the horizontal. It was decided from the results of simple shear tests on sand reinforced fibres (Kuwano et al. 1994), which showed that the highest shear resistance was obtained when the reinforcing materials were arranged in the direction of the largest tensile strain, ε_3. Grant et al. (1997) showed that the strains were large in the region of 30° to 60° from the horizontal. According to the pre-consolidation stress and nail reinforcement, the tests are named Po270C (clay only without nail), Po270N (nails@30°, 60°) and so on.

Test series of Po270 and Po427 were performed at Tokyo Institute of Technology. Approximately 360 targets were painted on thin rubber membrane placed between the front vertical face of the clay and the Perspex window with silicon oil for lubrication. Pins were glued on the membrane behind the targets to ensure the targets moving together with the model ground. Po500 tests were carried out at the London Geotechnical Centrifuge Centre at City University. About 500 marker beads were pressed into the front vertical face of the clay. The model was then subjected to a centrifuge acceleration of 100g and left for half a day to allow excess pore pressures to dissipate. With the increase in the centrifuge acceleration up to 100g, compressed air pressure was supplied to the tunnel to balance the weight of overburden above. Upon reaching equilibrium the tunnel air pressure was reduced to simulate the excavation process at a rate of about 20 kPa/min for Po270 and Po427 and about 100 kPa/min for Po500. Surface settlements were monitored by LVDTs. Patterns of displacements and strains in the model were determined from the photographs of targets in the front face of the model for Po270 and Po427 test series. Images from the CCD camera were digitized and recorded every second by PC in Po500 Tests. Coordinates of the targets were determined later by the image processing (Taylor et al. 1998).

3 RESULTS AND DISCUSSIONS

Vertical effective stresses in centrifugal acceleration field of 100g and overconsolidation ratios, OCRs, are shown in Figure 2 for three test series. As seen in the figure, OCR was about 3.5 in Po270 and about 5 in Po500 at the tunnel axis and was very large near the ground surface.

3.1 *Ground surface settlements*

Figure 3 shows S_{max}, the ground surface settlements above the centreline of the tunnel, induced with the reduction in the tunnel pressure ratio, TPR, which is a ratio of the support pressure to the maximum pressure. TPR decreases from 1 to 0 with the decrease in the support pressure used to simulate the excavation process. As seen in Figure 3, S_{max} was negligibly small for all the cases when TPR was

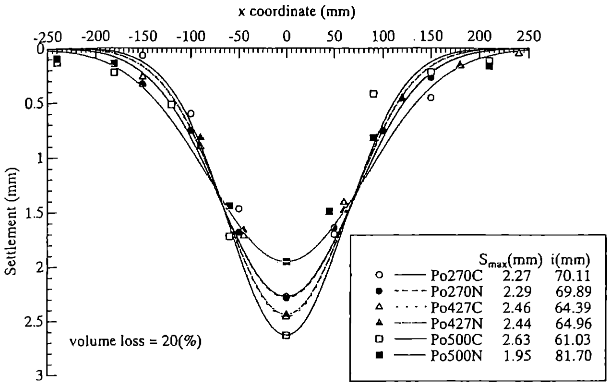

Figure 4. Settlement troughs at the ground surface.

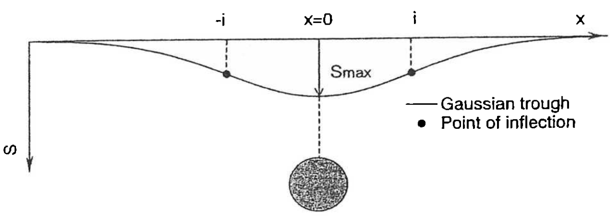

Figure 5. Approximation of settlement trough by Gaussian distribution.

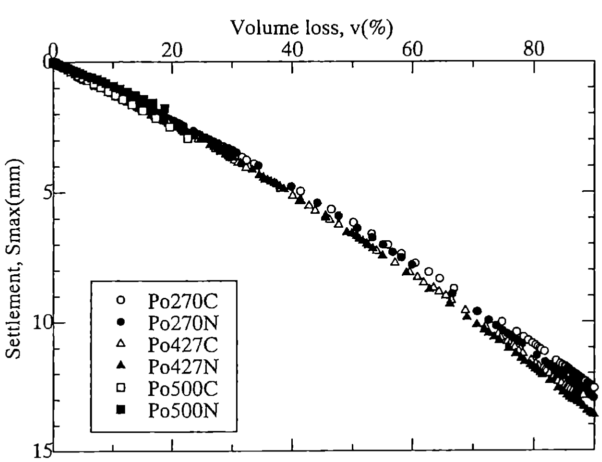

Figure 6. S_{max} versus v relationships.

bigger than 0.7. S_{max} started to increase when TPR was less than 0.7 for Po270 and Po427, while 0.5 for Po500. At about TPR=0.4, S_{max} showed sudden increase in the cases of Po270 and Po427. The tunnels were thought to reach collapse. When TPR was less than about 0.3, there was no more obvious increase in S_{max}, probably because the tunnel cavity was already almost closed. Although Po427N model ground, which was reinforced by nails, showed the less increase in the settlement than Po427C, S_{max} of Po270N increased almost in the same manner as that of Po270C. The settlement was very small in Po500 even at TPR=0 as compared with Po270 and Po427, especially if the ground was reinforced by soil nails. It was, of course, partly because of the difference in the pre-consolidation stress. However, the large S_{max} of Po270 and Po427 seemed to be attributed also to the slower rate of tunnel pressure reduction than in Po500. If the tunnel pressure is reduced slowly, the clay model ground may suck water from the boundary and become softer.

Figure 4 shows the distributions of the settlements at the ground surface induced by the reduction in the tunnel support pressure. The curves shown in the figure are Gaussian distributions to approximate the settlement curves. It is discussed later. These data shown in the figure are those obtained at the volume loss, v, of 20%. As seen in Figure 4, there is not much difference in shapes of troughs of Po270 and Po427. They were still at an early stage of the reduction in TPR before collapse of the tunnel. The width of the trough, which is represented by i shown in the figure, is smaller for the stiffer ground, maybe because settlements seemed to occur only locally near the centreline in the case of Po500C for example. On the other hand, if the nails worked effectively as in Po500N, the trough became wider.

Transverse settlement troughs such as those shown in Figure 4 are often approximated by the following Gaussian distribution (O'Reilly & New 1982) shown in Figure 5.

$$S = S_{\max} \exp\left(\frac{-x^2}{2i^2}\right) \tag{1}$$

where S = settlement; x = distance from the centreline in transverse direction; S_{max} = settlement at x=0; i = distance from the centreline line to the point of inflection ("i" is the standard deviation of a Gaussian distribution). The parameter i for equation (1) is determined by the following equation (2) from the regression analysis.

$$i^2 = -\frac{\sum x^2}{2\sum x^2 \ln(S/S_{\max})} \tag{2}$$

If i is determined through this, S at larger x, which is generally very small, has greater weight than S near the centreline, which is usually more important.

Volume loss, V, which is the area of the settlement trough, together with S_{max} is a good index to describe the geometry of the trough. For consideration of short term displacements due to tunnelling in clays, undrained conditions are assumed and V is considered to be equal to the volume reduction of the tunnel. The volume loss is often expressed as v (%), a percentage of the tunnel volume.

For the Gaussian distribution, the following linear relationship between V and S_{max} is obtained from equation (1):

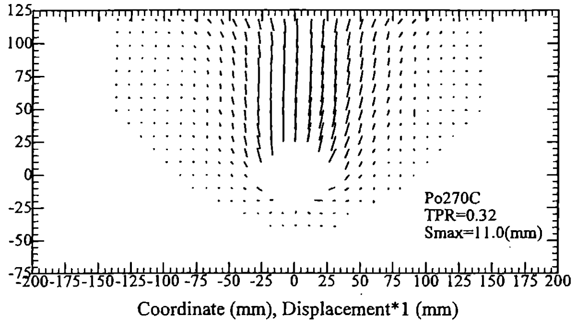

Figure 7. Deformations in the model of Po270C.

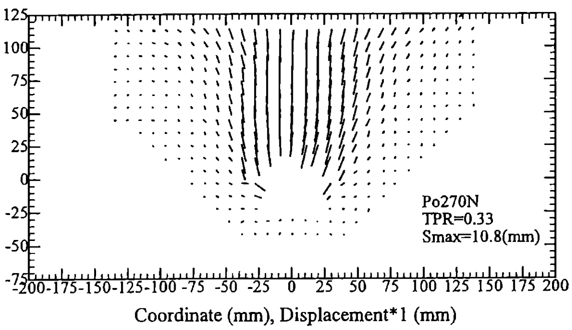

Figure 8. Deformations in the model of Po270N.

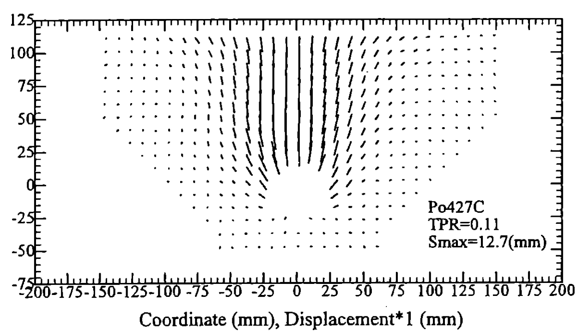

Figure 9. Deformations in the model of Po427C.

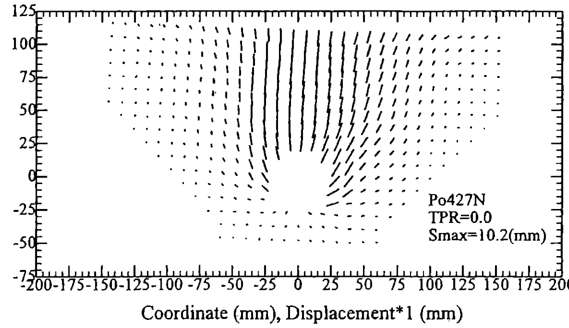

Figure 10. Deformations in the model of Po427N.

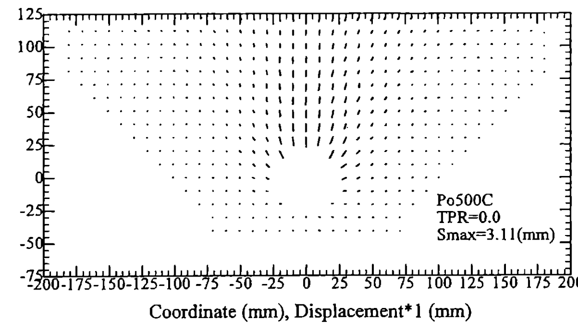

Figure 11. Deformations in the model of Po500C.

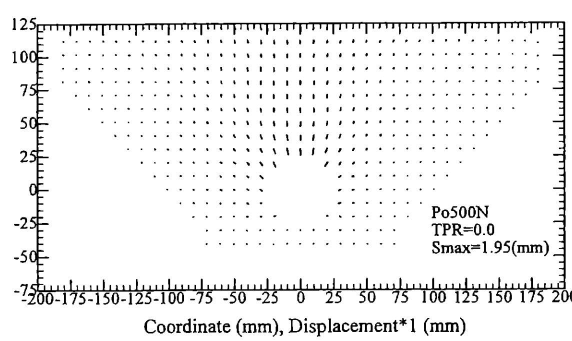

Figure 12. Deformations in the model of Po500N.

$$V = \sqrt{2\pi} \cdot i \cdot S_{\max} \quad (3)$$

Both S_{max} and V are obtained from the surface settlement measurements. Relationships between S_{max} and v are shown in Figure 6. It is seen that they can be approximated by straight lines as determined by equation (3). From the slopes of the lines, the values of i can be also determined and are shown in Figure 4. It is also found in Figure 6 that i decreases slightly as TPR approaches zero indicating that the trough becomes narrower.

3.2 *Deformations in the model ground*

Displacements of the targets obtained by the readings from the photographs or image processing are shown in Figures 7-12. They are the displacements in the final stage of the tests. The area of large displacements in the ground was situated above the tunnel as seen in the figures and wider in Po270 and Po427 than in Po500. Although the displacements were mostly above the tunnel, some displacements to the bottom of the tunnel were observed. In the cases of large displacements, horizontal displacements into the centre of the trough as well as settlements were induced near the ground surface.

Strain components in the model can be calculated from the displacements. Minor principal strains in the ground are shown in Figure 13-18. It is seen in Figures 17 and 18 that ε_3 is almost radial from the tunnel in the stiff ground of Po500. The minor principal strains are large in the region of 30° to 60° from the horizontal and almost radial as shown in Figures 13 - 16. However, strains above the tunnel are

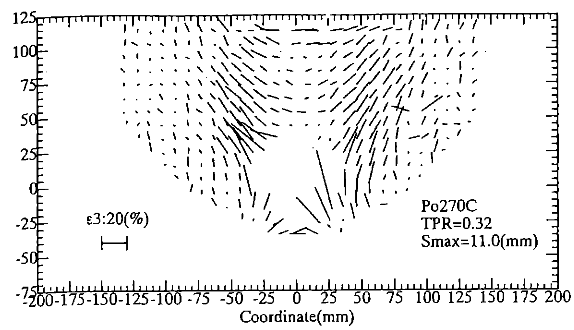

Figure 13. e_3 vectors in the model of Po270C.

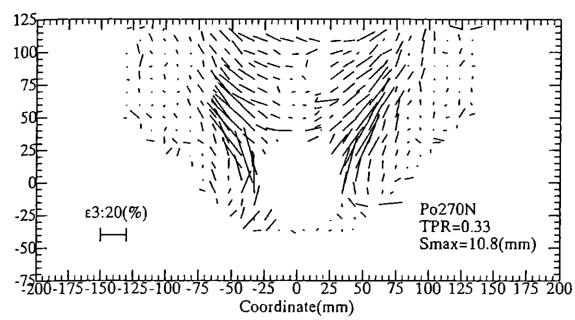

Figure 14. e_3 vectors in the model of Po270N.

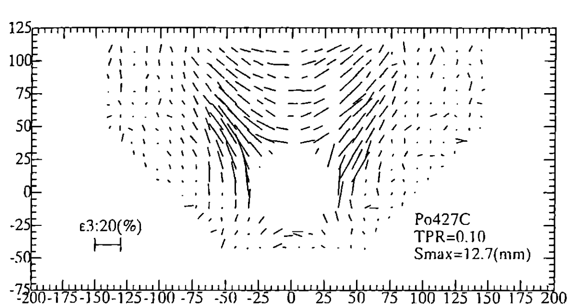

Figure 15. e_3 vectors in the model of Po427C.

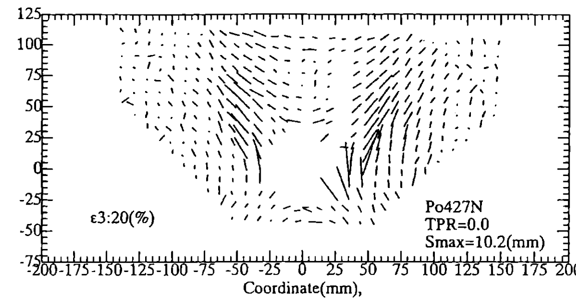

Figure 16. e_3 vectors in the model of Po427N.

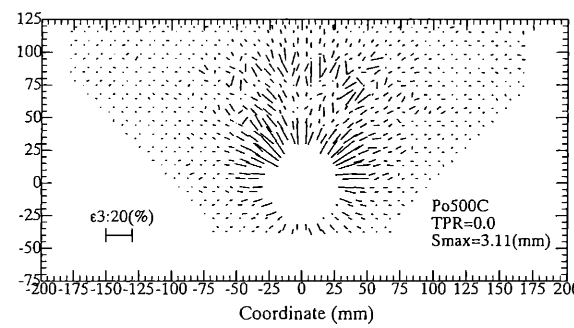

Figure 17. e_3 vectors in the model of Po500C.

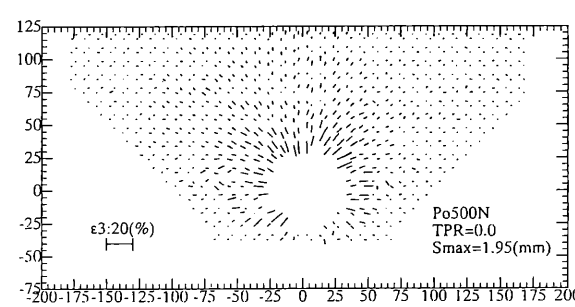

Figure 18. e_3 vectors in the model of Po500N.

relatively small. It is probably because the soil above the tunnel moved to the tunnel cavity as a block and the region of large strain behaved like a shear zone. When the soil nails were installed to confine the soil in those regions, the minor principal strains, ε_3, in the region of 30° to 60° were much less in Po500N than in Po500C. Such reduction in the strain is also reported by Nishida & Nishigata (1996). As the wider area in the model ground deformed in a body due to the confinement by nails, the surface settlement trough of Po500N was wider and gentler than that of Po500C. However, if the nails did not work effectively in the soft ground as in Po270 and Po427, reduction in ε_3 around soil nail was not so obvious and ε_3 was slightly concentrated between two nails.

4 CONCLUSIONS

A series of centrifuge model tests was carried out to observe deformations around tunnels in clay reinforced by soil nails and to investigate the effects of nailing on the overall stability of the clay model grounds with different pre-consolidation stresses.

The settlements, represented by the value at the centreline, S_{max}, increased with the decrease in the tunnel pressure ratio, TPR. At about TPR=0.4, S_{max} showed sudden increase in the cases of Po270 and Po427. The tunnels were thought to reach collapse. On the other hand, the settlement was very small in Po500 even at TPR=0. The larger settlements in Po270 and Po427 as compared with S_{max} in Po500 was caused not only by the lower pre-consolidation stress but probably also by the slower rate of TPR reduction in the former two test series. The clay may have sucked water and become softer during the TPR reduction.

Displacements in the ground were measured at the certain stages of the tests and strains were calculated. In the cases of large displacements as in Po270 and Po427, the horizontal displacements into the centreline of the trough as well as the settlements were induced near the ground surface. The minor principal strains, ε_3, associated with the ground deformations were large in the region of 30° to 60° from the horizontal and almost radial. When the nails were installed in the region of large ε_3 to confine the soil around them, strains were reduced obviously in the stiff clay ground of Po500. However, the nails did not work very effectively in the soft clay.

ACKNOWLEDGEMENTS

The authors are grateful to Prof. R.N. Taylor and Dr. R.J. Grant for their great help to test series of Po500 performed at City University. Financial support of the Kajima Foundation enabled the first author to made research in London.

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