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Novel centrifuge simulations of restoration of building tilt

Nouvelle simulation de centrifugese pour la restauration de la inclination de bâtiment

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ABSTRACT

It is not unusual to observe inclination of buildings and towers as a result of unwanted differential foundation settlements. Over the years, a number of different engineering solutions including the method of soil extraction have been attempted to reduce unexpected inclination of buildings and towers. By using a state-of-the-art robotic manipulator, a series of novel centrifuge model tests conducted to investigate key factors which govern the restoration of building tilts are described and reported. In the centrifuge simulation tests, the robotic manipulator was used to core and extract soil in-flight near an initially tilted model building. This soil extraction was to induce stress release, thereby mitigating the inclination of the building. Effects of different configurations and sequences of drilling on results of restoration were investigated in the centrifuge.

RÉSUMÉ

Ce n'est pas rare d'observer la inclination des bâtiments et des tours en raison des tassements différentiels non désirés de fondation. Au cours des années, un certain nombre de différentes solutions de technologie comprenant la méthode d'extraction de sol ont essayé de réduire la inclination non désirée des bâtiments et tours. En utilisant un robot manipulateur de l'état de l'art, une série de nouveaux essais de centrifugeuse effectués pour étudier les facteurs principaux qui contrôlent la restauration des inclinaisons de bâtiment sont décrits et rapportés. Dans les essais de centrifugeuse, le robot manipulateur a été utilisé pour creuser et extraire le sol en vol près d'un bâtiment modèle au commencement incliné. Cette extraction de sol devait induire le dégagement de constrainte, atténuant de ce fait la inclination du bâtiment. Des effets de différents configurations et ordres du forage sur des résultats de restauration ont été étudiés dans la centrifugeuse.

1 INTRODUCTION

Buildings and towers may be suffered from unexpected tilts due to differential foundation settlements, resulting from non-uniform subsoil and loading conditions. Very often building tilts increase with time due to stress concentration beneath the tilted buildings and change of ground water conditions (Ranzani 2001). Tilting of buildings and structures often lead to distortions and formations of cracks, an increase in seismic vulnerability, and sometime eventual collapses and complicated social and legal problems (Tamez et. al 1997; Jamiolkowski 2001). Over the last few decades, a number of different engineering solutions have been attempted to restore tilted buildings and structures. Theses methods include underpinning, strengthening superstructure, jack-up inclined structure, extracting soil through inclined drilling holes underneath a tilted building (Amirsoleymani 1991; Tamez et al. 1997; Jamiolkowski 2001) and drilling of vertical boreholes near the high side of a titled building (Lui 1990). Most of these restoration techniques are essentially empirically-based. Parametric experiments to investigate governing restoration factors are generally not permitted by owners and statutory bodies to be carried out on sites. Therefore, a systematic experimental study of the effectiveness and mechanisms of a restoration technique is extremely difficult. Without reliable experimental data, it is very difficult, if not impossible, to calibrate any numerical model and modelling procedures for analysing various restoration techniques.

By using a state-of-the-art 4-axis robotic manipulator in a centrifuge (Ng et al. 2002), an investigation of the effectiveness of the soil extraction technique for restoration of an initially tiled building is reported in this paper. Details of model preparation and testing procedures and results from two novel geotechnical centrifuge model tests (tests 1 and 2) are described and discussed. The measured data may be useful for calibrating numerical models and modelling procedures.

2 EQUIPMENT AND MODEL PREPARATION

2.1 *Geotechnical centrifuge test*

Two geotechnical centrifuge model tests were carried out to investigate restoration of an initially tilted model building founded on a shallow foundation at the Geotechnical Centrifuge Facility (GCF) in Hong Kong University of Science and Technology (HKUST). The 8.5m diameter beam centrifuge has a design capacity of 400 g-tons with a maximum design centripetal acceleration of 150g (Ng et al. 2001), where g is the Earth's acceleration (9.8 m/s^2). A state-of-the-art 4-axis computer controlled robotic manipulator (Ng et al. 2002), which has the ability to simulate various construction activities in-flight, was used to create cavity in the ground by drilling holes to correct building tile. Figs. 1 and 2 show a schematic diagram and a photograph of the robot. The 4-axis robot can be controlled either by a computer or manually to move in the X and Y directions in the horizontal plan, in the vertical direction (Z-axis) and to rotate 270^o in-flight. Changes of operation tools such as an excavation tool and a penetration testing device to simulate construction and site characterization activities are possible during a centrifuge test.

Fig. 3 illustrates a sectional view of the entire model package. A large (1.5m by 1.5m by 1m height) three-dimensional outer model container was used to carry the 4-axis robot. Inside this large container, a smaller inner container with sizes of 563mm (length) × 563mm (width) × 300 mm (height) was used to accommodate model soil and a model building. The building had a square cross section (on plan) with dimensions of 180 mm (X-direction) by 180 mm (Y-direction) and 240 mm in height (Z-direction). The weight of the model building was 94.7 N at 1g. During the centrifuge tests at 52g, the size of the simulated prototype building foundation was 9.36m by 9.36m on plan and the building generated an average bearing pressure of about

150kPa underneath the foundation. Assuming 5kPa/floor, this pressure is equivalent to a 30 story high residential building.

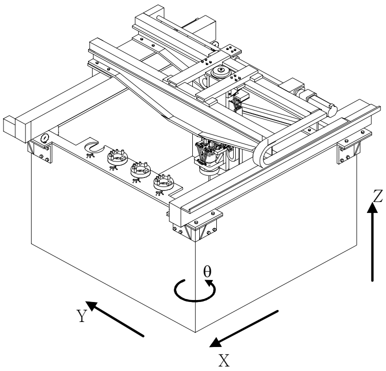

Fig. 1. A schematic diagram of the 4-axis robotic manipulator

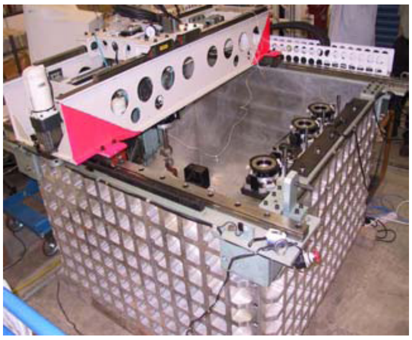

Fig. 2. The 4-axis robotic manipulator

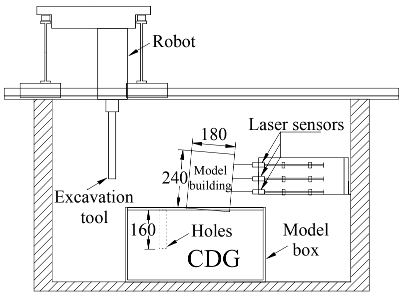

Fig. 3. A sectional view of model package (unit: mm in model scale)

2.2 *Test programme and procedure*

Two different sequences of drilling vertical holes were adopted to investigate their effectiveness on correction of initial building tilts (see Fig. 4) in two centrifuge model tests (i.e., tests 1 and 2). The building model had an initial tilt of 3.8 and 3.9 % for test 1 and 2, respectively. Totally nine vertical boreholes were drilled in-flight near the higher side of the model building using the robotic manipulator in a sequence of hole #1 to #9. Each drill hole was 30mm (or 1.56m in prototype) in diameter and 160mm (or 8.32m in prototype) deep. The distance of each hole from the model building is shown in Fig. 4. A thin hollow steel tube of 30mm in outer diameter was used to create holes and to extract soil from the ground. The steel tube was connected to the robotic manipulator which was controlled by a computer in the centrifuge control room. A robotic excavation sequence was commenced after the nominal gravitational level reached 52g. A soil bin was located at a corner of the large outer container for the removal of excavated soil inside the tube. After each drilling, the steel tube was moved to the soil bin and submerged in water by the robot to destroy suction and hence to remove the excavated soil. Drilling of each borehole was carried out by two bites: the upper part of each hole from 0 to 3.62m in depth and the lower part from 3.62m to 8.32m in depth (prototype).

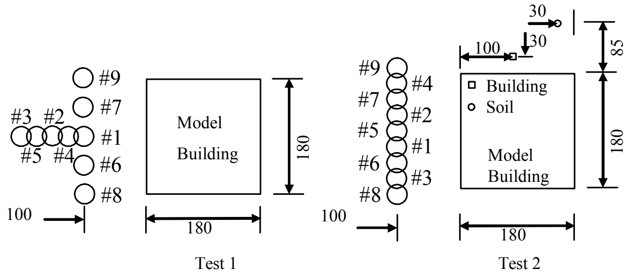

Fig. 4. A plan view of boreholes and LVDTs (unit: mm in model scale)

In this study, completely decomposed granite (CDG), a typical weathered soil in Hong Kong, was used. The mean particle size of CDG used was about 1mm with the maximum particle size of 5mm. The soil model made of CDG was prepared in three layers by compaction to a dry unit weight of 13.60 kN/m^3 and 16.29 kN/m^3 with water content of 16.6% and 13.5% in tests 1 and 2, respectively. The degree of saturation in CDG was about 48 and 60% in tests 1 and 2, respectively. Before the tests, soil suction measured by a tensiometer ranged from about 7 kPa to 10 kPa, depending on the locations in each test.

Lateral displacements of the building were measured by laser sensors as shown in Fig. 3. Any change of the inclination of building was then calculated by using the measured lateral displacements between two measuring points. In addition, settlements of soil surface and model building were monitored by LVDTs shown in Fig. 4.

3 RESULTS OF CENTRIFUGE TESTS

3.1 *Settlement of soil surface and building*

Movements of the building and ground surface are expected due to an increase in centripetal acceleration from 1g to the nominal centrifugal gravity of 52g and drilling of the boreholes. Fig. 5 shows measured soil and building settlements (model scale) during each swing-up and soil extraction. As expected, soil settled as the centripetal acceleration increased, resulting in an increase in vertical soil stresses. Due to the looser state of the CDG in test 1 as compared with that in test 2 as discussed previously, a substantially larger settlement was observed in this test than that measured in test 2. Because of the self-weight, settlement of the model building was larger than the soil surrounding it. These measured settlements during the centrifuge swing-up are useful for deducing soil stiffness in each test for future numerical analyses. During drilling of boreholes, the soil and the model building continued to settle as a result of formation of cavities, leading to stress relief. Details are described and discussed later.

3.2 *Reduction in building tilt*

During the increase in centripetal acceleration from 1g to the nominal 52g, tilt of the model building in each test was increased (i.e., test 1: 3.8% (initial) + 3.0% (increase); test 2: 3.9% (initial) + 0.5% (increase)). The total building tilt immediately prior to drilling was 6.8% and 4.4% at test1 and test 2, respectively. The measured increase in tilt was likely caused by non-uniform increases in the soil stresses underneath each building foundation. The smaller increase in building tilt in test

2 than that in test 1 was attributed to different compacted soil densities in these two tests (i.e., test 1: 13.60 kN/m^3; test 2: 16.30 kN/m^3).

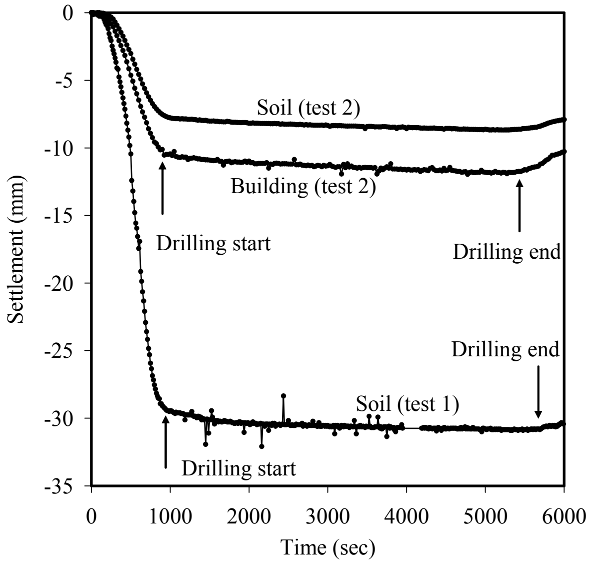

Fig. 5. Variations of settlement with time

As the drilling of boreholes started in-flight, the tilt of each model building was reduced as a result of stress relief due to the formation of cavities. Fig. 6 shows a reduction in building tilt with the execution of the drilling sequence in each test. For the first three drill holes (#1, 2 and 3), effects of drilling (or stress relief) on building restoration (i.e., reduction in building tilt) were more significant in test 2 than test 1, despite the fact that the density of CDG in test 1 was substantially looser than that in test 2 as discussed previously. The larger building restoration in test 2 was likely because of the closer distance of the three drill holes (#1, 2 and 3) to the building as compared with the distance of drill holes #2 and #3 in test 1. These test results clearly illustrate the importance of drilling configurations.

As the drilling operation continued from drill holes #4 to 9 in-flight, the amount of building tilt was reduced further in both tests. At the end of drilling, the inclination of building was reduced by 0.80% and 0.48 % in test 1 and test 2, respectively. Although a direct comparison between the two tests is somewhat difficult, one may be still able to deduce that the higher the soil density, the smaller the restoration effect for some given numbers of drill holes (i.e., a giving amount of cavities induced stress relief in the ground).

3.3 *Reduction in building tilt*

Fig. 7 shows measured settlements of soil surface and building during drilling in model scale. It can be seen that the soil surface and the building settled continuously with the drilling operations in both tests. The measured maximum soil settlement was about 1.4mm (or 73mm in prototype) in test 1 whereas the measured maximum soil and building settlement was about 0.6mm (or 31mm in prototype) and 1.0mm (or 52mm in prototype) in test 2, respectively. Due to the body weight of the building, the measured building settlement was larger than soil surface settlement. Since the LVDT measured the building settlement was located at the high side of the building (see Fig. 4), an increase in measured settlement implied a reduction in building tilt. By comparing between the two tests at the end of drilling, it was not surprising to observe a larger induced soil settlement in test 1 than that in test 2. The measured soil settlements are consistent with the measured reduction in building tilt shown in Fig. 6. All these results seem to suggest that effects of soil density dominated the restoration of building tilt at the end of drilling for the given configurations of the drill holes in these tests.

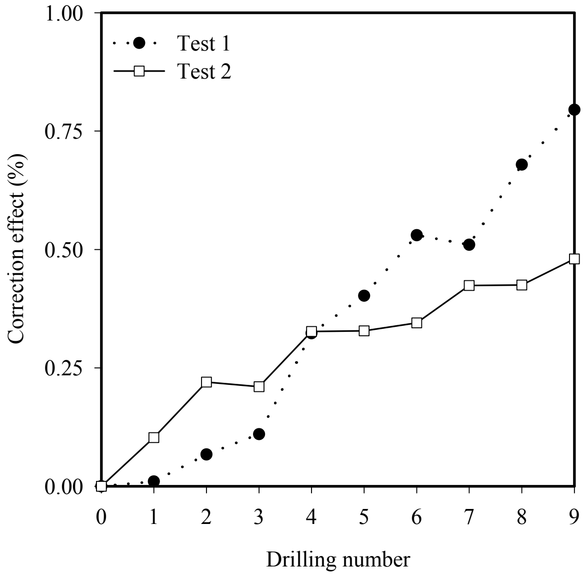

Fig. 6 – Reduction of building tilt

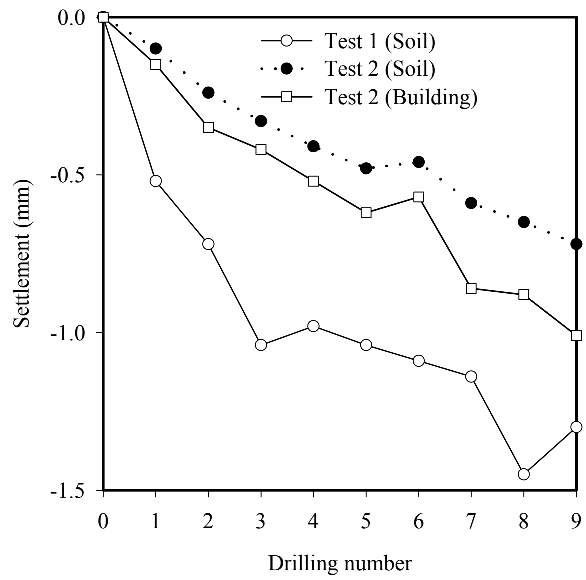

Fig. 7. Variations of ground and building settlements during drilling

4 CONCLUSIONS

In-flight restoration of an initially tilted building supported on a shallow foundation was investigated by using a state-of-the-art 4-axis robotic manipulator in the centrifuge at the Hong Kong University of Science and Technology. In the two centrifuge model tests conducted, the inclination of the tilted model building was effectively reduced by soil extraction in nine drilled holes. Stress relief resulting from the formation of cavities in the ground was found to be an effective means to restore tiled buildings and towers. The magnitude of restoration was governed by the configuration of drill holes and soil density. With the use of the robotic manipulator in-flight, it has been demonstrated that centrifuge modelling technique is a very effective and powerful for conducting parametric experiments to study of restoration of building tilts in various ground conditions.

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REFERENCES

Amirsoleymani, T. 1991. Removing soil layers under foundations to rotate buildings, *Proc. 9th Asian Regional Conf. on. Soil Mechanics and Foundation Engineering*, 2, 201-204.

Jamiolkowski, M. B. 2001. The leaning Tower of Pisa—Present situation, *A look back for future geotechnics*. (Editors, Wu, Zhang & Woods), Rotterdam : A. A. Balkema, 93-129.

Liu, Z. D. 1990. A new technique of remediation of leaning building — Relieving subgrade stress, *Chinese Journal of Soil Engineering and Foundation* 4, No.1, 1-6. (in Chinese)

Ng, C.W.W., Van Laak, P. Tang, W.H., Li, X.S. & Zhang, L.M. 2001. The Hong Kong Geotechnical Centrifuge. *Proc. 3rd Int. Conf. Soft Soil Engineering,* Dec., Hong Kong. 225-230.

Ng, C. W. W., Van Laak, P.A., Zhang, L. M., Tang, W. H., Zong, G. H., Wang, Z. L., Xu, G. M. & Liu, S. H. 2002. Development of a four-axis robotic manipulator for centrifuge modeling at HKUST. *Proc. Int. Conf. on Physical Modelling in Geotechnics*, St. John's Newfoundland, Canada. 71-76.

Ranzani, S. M. T. 2001. Stabilisation of leaning structures: the Tower of Pisa case, *Geotechnique* 51, No. 7, 647-648.

Tamez, E., Ovando, E. & Santoyo, E. 1997. Underexcavation of Mexico City's Metropolitan Cathedral and Sagrario Church. *Proc. XIV ICSMFE*, Hamburg. 2105-2126.