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Modelling of Soil Extraction Technique for Restoration of Building Tilt from Geotechnical Centrifuge Tests

원심모형실험을 통한 기울어진 건물의 기울기 교정에 이용되는 Soil Extraction 공법의 모델링

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요 지

건축구조물이나 탑 등의 구조물이 부등침하의 영향으로 기울어지게 되는 것은 그리 드문 현상이 아니다. 그동안 구조물의 기울기를 감소시키기 위한 다양한 공학적인 해결방안이 시도되어 왔는데, 그 가운데는 soil extraction 공법도 포함되어 있다. 본 논문에서는 최신의 로보트 굴착장비를 이용한 2개의 원심모형실험을 실시하여 soil extraction 공법을 이용하여 기울어진 건물의 경사를 감소시키는 데 있어서의 주된요소에 대한 연구를 실시하였다. 원심모형실험에서는 모형토조가 고속으로 회전하는 가운데 로보트를 이용하여 기울어진 건물의 주변에 구멍을 천공하였다. 지반에 구멍을 천공함으로 지중응력의 감소를 유도하여 건물의 기울기를 성공적으로 감소시킬 수 있었다. 원심모형실험을 통해서 분석된 천공의 순서, 지반의 밀도 및 배열 등이 건물의 기울기를 감소시키는 정도에 대하여 심도 있는 연구를 실시하였다.

Abstract

It is not uncommon to observe tilt of buildings and towers as a result of unexpected differential foundation settlements. Over the years, a number of engineering methods including the soil extraction technique have been attempted to reduce inclination of buildings and towers. In this research, a series of novel geotechnical centrifuge model tests by using a state-of-the-art in-flight robotic manipulator have been conducted to study key factors which govern the restoration of building tilts. In the centrifuge model tests, the robotic manipulator was used to drill and extract soil in-flight near an initially tilted model building. The soil extraction was to induce stress release, thereby mitigating the inclination of the model building. Insights into the effects of different configurations, soil density and sequences of drilling observed during the centrifuge model tests on the restoration of the model building are to be investigated.

Keywords : Geotechnical centrifuge tests, In-flight robotic manipulator, Soil extraction technique, Tilt

1. Introduction

Buildings and towers may suffer from unwanted tilts due to differential foundation settlements, resulting from non-uniform subsoil and/or loading conditions. Frequently building tilts increase with time due to stress

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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 sometimes eventual collapses and complicated social and legal problems (Tamez et. al 1997; Jamiolkowski 2001). Over the last few decades, a number of different engineering methods have been attempted to restore tilted buildings and structures. These methods may 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 (called soil extraction technique) (Liu 1990). The world famous leaning tower of Pisa of about 60m in height is a good example of tilted structure corrected by the so-called stress release method, as illustrated in Fig. 1. Underground inclined holes were drilled from the high side to extract soil and to release the part of in-situ soil stresses, thereby reducing inclination of the tower by about half a degree (Jamiolkowski 2001). Similarly, soil extraction technique by drilling vertical holes near an inclined building is widely used in China to reduce and/or stabilise many inclined buildings and towers founded on soft soils (Liu 1990). However, most of these restoration techniques are essentially empirically-based. In addition, parametric experiments to investigate governing factors on the restoration

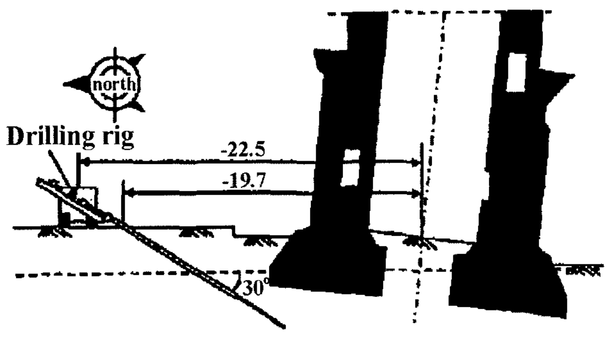

Fig. 1. Soil extraction process at the leaning tower of Pisa (unit: m)

of building tilt 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, if not impossible.

This paper reports an investigation of the effectiveness of the soil extraction technique for restoration of an initially tiled building, by using a state-of-the-art 4-axis in-flight robotic manipulator in novel geotechnical centrifuge model tests. Details of model preparation and testing procedures and results from the two centrifuge model tests (tests 1 and 2) are described. It is expected that the measured data may be useful for the understanding of the mechanism of soil extraction technique.

2. Equipment and Model Preparation

2.1 Geotechnical Centrifuge Test

Two novel 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 in the Hong Kong University of Science and Technology (HKUST). The 8.5 m diameter beam centrifuge has a design capacity of 400 g-tons with a maximum design centrifugal acceleration of 150g (Ng et al. 2001), where g is the Earth's acceleration (9.8 m/s). A state-of-the-art 4-axis computer controlled robotic manipulator (Ng et al. 2002, Ng et al. 2005), which has the ability to simulate various construction activities in-flight, was used to create cavity in the ground by drilling nine vertical boreholes to correct building tilt. Figs. 2 (a) and 2 (b) show the HKUST geotechnical centrifuge and a schematic diagram of the robot, respectively. 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° in-flight. Changes of operation tools such as an excavation tool and a penetration testing device to simulate construction and site characterisation activities are possible during a centrifuge test.

Fig. 3 illustrates a sectional view of the entire model

Fig. 2 (a) The 400 g-ton geotechnical centrifuge at HKUST

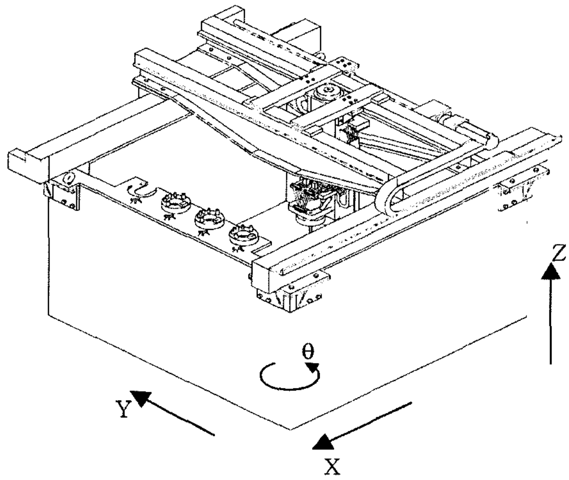

Fig. 2 (b) A schematic diagram of the 4-axis robotic manipulator

package. A large (1.5 m by 1.5 m by 1 m 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 563 mm (length) × 563 mm (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 95 Newton at 1 g. During the centrifuge tests at 52 g, the size of the simulated prototype building foundation was 9.36 m by 9.36 m on plan and the building generated an average bearing pressure of about 150 kPa underneath the foundation. Assuming building pressure 10 kPa/floor, this pressure may be equivalent to a 15 story high residential building.

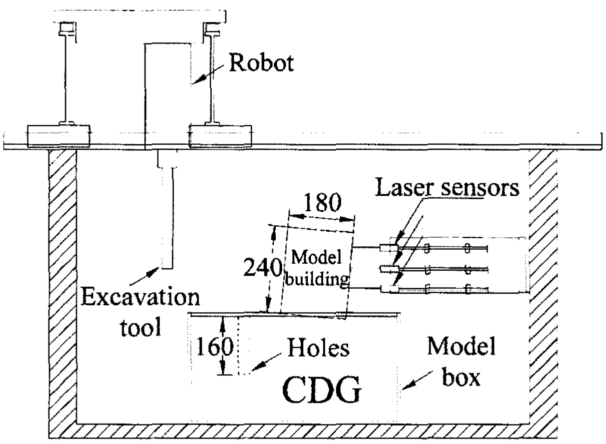

Fig. 3. A sectional view of model package (unit: mm in model scale)

2.2 Test Programme and Procedure

Two different sequences of drilling vertical holes were adopted to investigate their effectiveness on correction of building tilts (see Fig. 4) in the two centrifuge model tests (i.e., tests 1 and 2). The building model had an initial tilt of 3.8 and 3.9 % for tests 1 and 2, respectively. The model building was found on completely decomposed granite (CDG), a typical weathered soil in Hong Kong, 300 mm in thickness in the model scale (15.6 m in prototype). Totally nine vertical boreholes were drilled in-flight into the model ground near the higher side of the model building using the robotic manipulator in a sequence of hole #1 to #9. Each drill hole was 30 mm (1.56 m in prototype) in diameter and 160 mm (8.32 m in prototype) deep. The distance of each hole from the model building is shown in Fig. 4. A thin hollow steel tube of 30 mm in outer diameter was used to create the holes and to extract soil from the ground. The steel tube (excavation tool) 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 centrifugal acceleration level reached 52 g. 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 eliminate suction and hence to remove the excavated

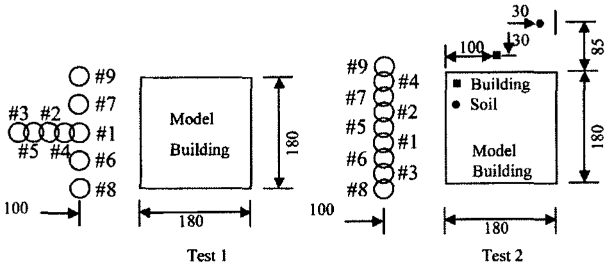

Fig. 4. A plan view of boreholes (unit: mm in model scale)

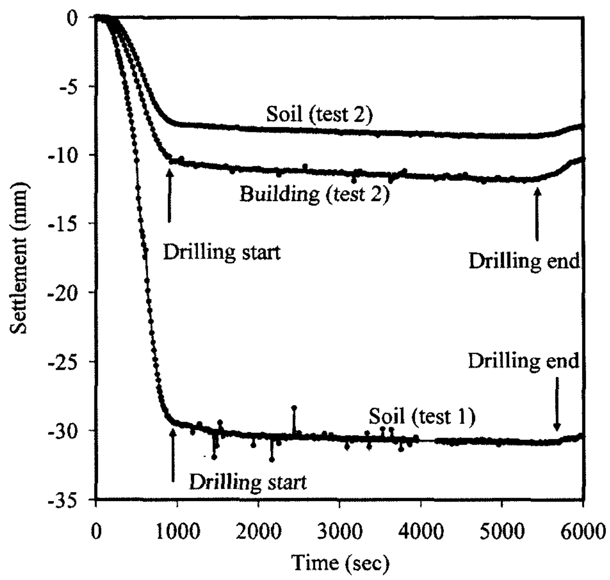

Fig. 5. Variations of soil surface and building settlement during tests (model scale)

soil. Drilling of each borehole was carried out by two steps; the upper part of each hole from 0 to 3.62 m in depth and the lower part from 3.62 m to 8.32 m in depth (prototype).

The mean particle size of CDG used was about 1mm with the maximum particle size of 5 mm. 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 tensiometers ranged from about 7 kPa to 10 kPa, depending on the locations in each test. Hence, CDG probably had high effective cohesion due to the soil suction, thereby preventing collapse of the vertical boreholes after drilling.

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

3. Results of Centrifuge Tests

3.1 Settlement of Soil Surface and Building During Tests

Fig. 5 shows measured soil surface and building settlements (model scale) during each swing-up (from 1 g to 52 g) and soil extraction. Movements of the building and ground surface were attributed to the increase in centrifugal acceleration from 1g to the nominal centrifugal gravity of 52 g and drilling of the boreholes. As expected, soil settled as the centrifugal acceleration increased, resulting in an increase in vertical soil stresses. Due to the looser state of CDG in test 1 as compared with that in test 2, a substantially larger settlement was observed in this test than the measured settlements in test 2. As a result of the self-weight of the model building, settlement of it was larger than the soil surrounding it in test 2. These measured settlements during the centrifuge swing-up may be useful for deducing soil stiffness in each test for numerical analyses. Hence Young's modulus of the model ground in test 2 may be more than three times larger than that in test 1. During drilling of boreholes, the soil and the model building continued to settle as a result of formation of cavity. However, the increase in the settlement is much smaller compared to the measured one during swing-up. Details are described and discussed later.

3.2 Reduction in Building Tilt

During the increase in centrifugal acceleration from 1 g to the nominal 52 g, tilt of the model building in each test increased (i.e., test 1: 3.8% (initial) + 3.0% (increase); test 2: 3.9% (initial) + 0.5% (increase)). Hence, the building tilt immediately prior to the drilling was 6.8%

and 4.4% at test1 and test 2, respectively. The increase in tilt might be caused by non-uniform stress increases in the soil underneath the building foundation. The smaller increase in building tilt in test 2 than that in test 1 was attributed to denser soil state (i.e., dry unit weight; test 1: 13.60 kN/m^3; test 2: 16.30 kN/m^3).

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 cavity. Fig. 6 shows a reduction in building tilt with the execution of the two drilling sequences. For the first three drilled holes (#1-3), 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 might be because of the closer distance of the three drilled holes (#1-3) to the building as compared with drilled holes #2-3 in test 1. This test result clearly illustrates the importance of drilling configurations.

As the drilling operation continued from drilled holes #4 to 9 in-flight, the amount of building tilt was reduced in both tests. At the end of drilling, the inclination of building was reduced by 0.80% and 0.48% in tests 1 and test 2, respectively. Although a direct comparison between the two tests is somewhat difficult, one may still deduce

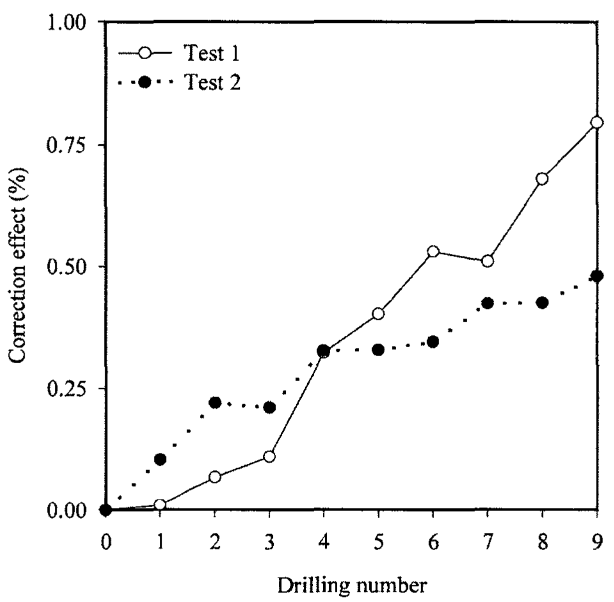

Fig. 6. Reduction of building tilt

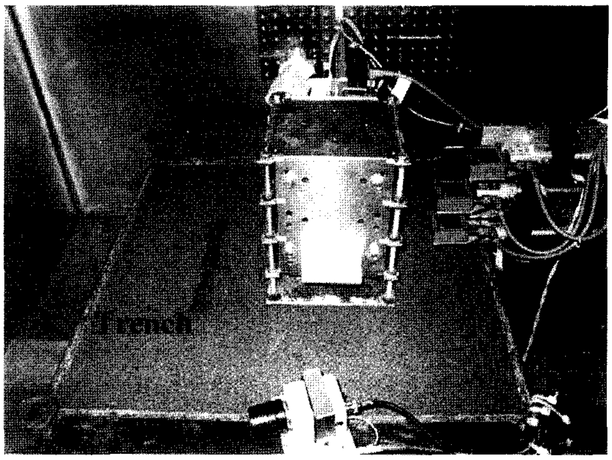

Fig. 7. Model package after test 2

that the higher the soil density, the smaller the restoration effect for some given numbers of drill holes (i.e., a giving amount of cavity induced stress relief in the ground). Fig. 7 shows the excavated trench of approximately 1.6 m wide, 10.4 m long and 8.3 m deep (prototype) after the test. Visual inspection after the model test shows development of several tensile cracks near the model building. This indicates lateral ground movements toward the trench relating to the reduction in the building tilt.

3.3 Settlements of Soil Surface and Building During drilling

Fig. 8 shows the 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 in both tests. The measured maximum soil settlement was about 1.4 mm (or 73 mm in prototype) in test 1 whereas the measured maximum soil and building settlement was about 0.6 mm (or 31 mm in prototype) and 1.0 mm (or 52 mm in prototype), respectively. Due to the body weight of the building, the measured building settlement was larger than soil surface settlement. Since LVDT measured building settlement was located at the high side of the building (see Fig. 4), an increase in the measured settlement implied a reduction in building tilt. Comparing the two tests at the end of drilling, it was not surprising to observe a larger soil settlement in test 1 than that in test 2. Changes of the measured soil settlements are consistent with the measured reduction in building tilt

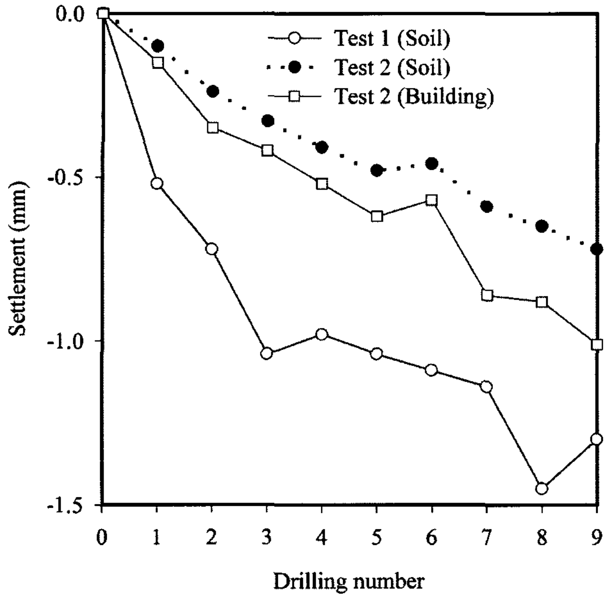

Fig. 8. Variations of soil surface and building settlements during drilling (model scale)

shown in Fig. 6. All these results seem to suggest that the effects of soil density dominated the restoration of building tilt at the end of drilling for the given configurations of the drilled holes in these tests.

4. Conclusions

In-flight restoration of an initially tilted building supported on a shallow foundation was investigated by drilling vertical boreholes in-flight using a state-of-the-art 4-axis robotic manipulator in the centrifuge. In the two novel centrifuge model tests conducted in the current study, the inclination of the tilted model building was reduced by about 0.5-0.8% from 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 drilled holes and soil density. It has been demonstrated that with the use of the robotic manipulator in-flight centrifuge modelling technique is very effective and powerful for conducting a series of parametric experiments studying the restoration of building tilts.

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