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Centrifuge modelling of the collapse of shaft linings

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ABSTRACT: The collapse of abandoned and often hidden mine shafts is a serious problem in the UK and many parts of Europe. The collapse of these shafts is often related to the failure of the shaft lining. Understanding the mechanisms of ground movements around deforming/collapsing mine shafts is therefore important in the assessment of mine shaft location as well as lining condition. This paper presents an experimental study of the mechanisms of soil failure around a deforming shaft lining. Geotechnical centrifuge modelling of reduced-scale buried mine shafts were tested to determine the magnitude and pattern of ground deformations that occurred during loss of internal support pressure. An axis-symmetric centrifuge container was used along with half-cylindrical model shafts. These allowed for the acquisition of digital images of the sub-surface soil and mine shafts which enabled the measurement of soil and shaft deformation using image analysis techniques. The results from two model shaft tests are presented; the first test involved the loss of internal support along the entire shaft length whereas the second test studied the effect of a discrete weakened zone within the lining.

INTRODUCTION

Stable shafts are essential to any mining operation. Shaft linings are designed to maintain stability and prevent displacements in and around the shafts. Historically in the UK and Europe, many shafts have been abandoned and/or buried, with little information left as to their whereabouts or the type and state of the lining. These shaftspose a serious health and safety issue to the general public. Various research projects have been undertaken relating to the behaviour of mine shafts, including Burke and James (1990), Erasmus et al. (2001), Güler (2013), Jia et al. (2013), Jia (2010), Jiang and Liu (2010), Lade et al. (1981), Ortlepp et al. (2008) and Ortlepp (1974). The stiffness and strength of shaft linings inevitably decreases with time due to various reasons, including weathering effects, often in harsh acidic mine water. The degradation of shaft lining integrity may result in a significant ground collapse. Therefore, it is important to understand the soil behaviour during the period that the shaft lining is degrading, and ultimately after the collapse of the shaft lining.This paper presents a study of the behaviour of superficial soils (extending from bedrock to the surface) around deforming and ultimately collapsing shaft linings. Two scenarios are considered; one in which the support of the entire shaft lining is reduced uniformly along its length, and the other in which a discrete weakened zones created at the rock-soil interface. Geotechnical centrifuge modelling of small-scale axis-symmetric shaft models was employed in this study to ensure soil behaviour was accurately replicated and to enable for the acquisition of sub-surface soil displacement data using image analysis techniques.

This study was undertaken as part of the 'Mine Shafts: Improving Security and New Tools for the Evaluation of Risks' (MISSTER) project, funded by the European Commission Research Fund for Coal and Steel (RFCS).

TEST DESIGN

The aims of the study were to examine the behaviour of superficial soils during shaft deformation and collapse and to determine the effect of a discrete weakened zone within the shaft lining on the resulting subsidence. Physical modelling was undertaken using the University of Nottingham Centre for Geomechanics (NCG) geotechnical centrifuge, which allowed for the study of failure mechanisms of shaft linings near the ground surface. The centrifuge allows for the replication of full scale soil stresses in a reduced scale centrifuge model. The principle of centrifuge modelling is that by reducing the dimensions of a prototype by a scale factor N, whilst at the same time increasing the body force applied to the model by centrifuge acceleration at the same scale factor, the stresses and behaviour of the model soil remain the same as those in the corresponding full-scale prototype. The scaling factors for centrifuge tests are summarised in Table 1. The scale factor for all the centrifuge tests was 80 in this study.

Table 1. Centrifuge scale factors.

Parameters	Units	Scaling factor (prototype / model)
Gravity	m/s^2	$1/N$
Linear dimension	m	N
Volume	m^3	N^3
Stress	N/m^2	1
Strain	Dimensionless	1
Force	N	N^2
Bending moment	Nm	N^3
Bending stiffness, EI	Nm^2	N^4
Axial stiffness, EA	N	N^2
Acceleration	m/s^2	$1/N$

Container and Test material

To perform the study, a centrifuge model container with a diameter of 490 mm and a depth of 500 mm was been designed and constructed. The model container (Fig. 1c) was built for axis-symmetric simulation of shafts, using a transparent Perspex wall as the plane of symmetry. This means that only half the shaft is modelled and that digital images can be taken of the model shaft and soil throughout tests in order to measure soil and shaft displacements and failure patterns. Dry Leighton Buzzard

Fraction C silica sand, provided by David Ball Group Plc, was used in all the tests. This sand has a typical average grain size, D_{50}, of 0.5 mm, with minimum and maximum grain sizes, d_{min} and d_{max}, of 0.3 mm and 0.6 mm, and minimum and maximum void ratios of $e_{min} = 0.552$ and $e_{max} = 0.802$, respectively. The unit weight of the soil was approximately 1610 kg/m^3 in the tests. This corresponds to a relative density of 63%.

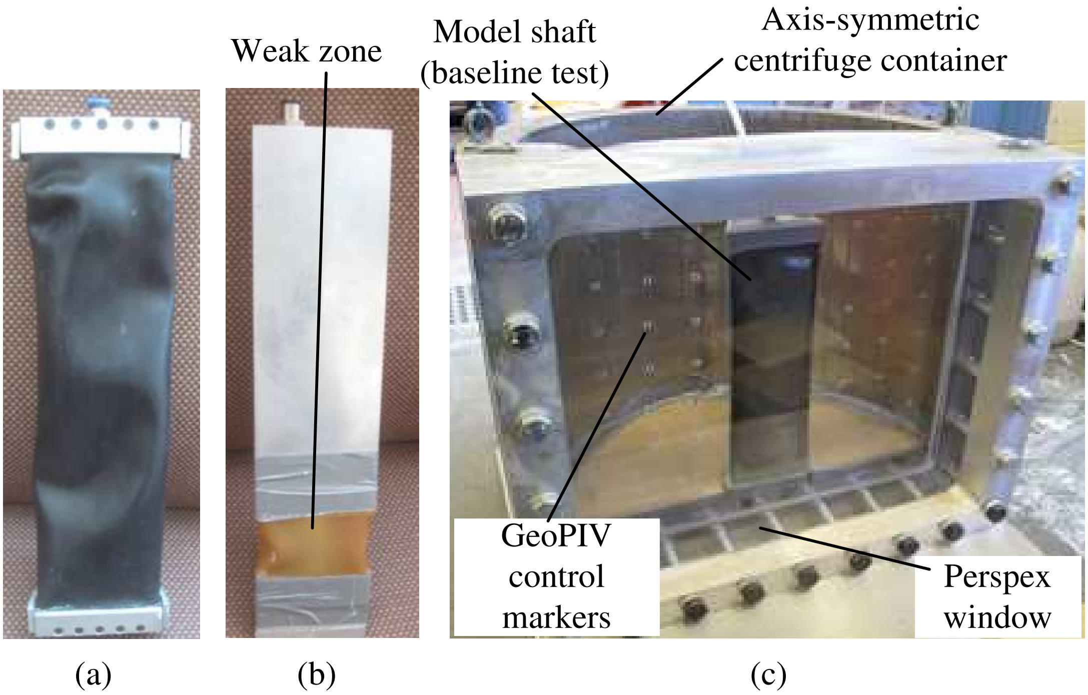


FIG. 1. (a) baseline test shaft, (b) weak zone shaft, (c) view of axis-symmetric container with baseline test shaft.

Experiment models

Two centrifuge tests were conducted. The first was used to study the scenario in which the internal support was reduced along the full length of the shaft within the superficial soil (baseline test) and the second examined the case of adiscrete weak zone formed just above the rock-soil interface (weak zone test).

For the baseline test, a semi-cylindrical rubber membrane was used to model the shaft lining, as shown Fig. 1(a).The model shaft was pressurised with air to provide internal support against soil loads. The diameter and depth from the top of the shaft to rigid rock of the model shaft were 90 mm and 300 mm, respectively. The corresponding prototype scale shaft is 7.2 m in diameter and 24 m in depth to the rigid rock base (the scale factor for the centrifuge test was 80). MDF wooden sheets were used as a rigid base to model the rock in the experiment. The top of the model shaft was buried to a depth of 20mm (1.6 m prototype scale).An aluminium cap was used for the shaft as shown in Fig.1(a).During the baseline test, the reduction in stiffness and strength of the lining was replicated by decreasing the air pressure within the model shaft, thereby gradually inducing the collapse of the whole shat lining.

To perform the weak zone test, another model shaft with the same dimensions as that from the baseline test was made. The shaft was made of aluminium with a section of rubber membrane used to replicate a weak zone, as shown in Fig. 1b. The rubber section was pressurised by air and had a depth of 50 mm (4 m in prototype scale). The weak zone was located just above the rock-soil interface. The location of the weak zone is based on the hypothesis that shaft lining materials may become weakest at the rock-soil interface where water infiltration into the shaft is likely to be greatest. Similar to the model for the baseline test, a layer of soil (20mm depth) was placed on top of the model shaft. During the test, the air pressure within the weak zone was reduced in order to model the reduction in strength and stiffness of this portion of the shaft lining. The aluminium portion of the shaft remained fixed in its original position. Therefore, only the collapse of the weak zone is modelled in the experiment.

To perform the test successfully required accurate measurement and control of the pressure within the model shafts during the tests. A pore pressure transducer (PPT) was used to measure the pressure in the model shafts and the PPT reading was monitored and recorded by a DAQ card. Based on the real time reading from the PPT, the air pressure was controlled by using an air regulator.

The deformation of soil was measured using a digital camera and image analysis. GeoPIV (White et al., 2003), which runs within MatLab. GeoPIV uses particle image velocimetry (PIV) to track the movement of discrete patches of soil and close range photogrammetry to convert pixel space coordinates to object space (which requires control markers on the inside face of the Perspex wall, as shown in Fig. 1a). During tests, while the air pressure within the model shafts was reduced, digital images were taken which were later analysed to determine the displacement field of the soil.

Test Procedure

For both tests, the pressure in the model shafts was increased to pre-determined values during centrifuge spin-up in order to stabilize the shaft. After the centrifuge reached 80 g, the air pressure within the model shafts was reduced at fixed intervals, such as 90%, 80% and 70% of the original pressure, until all the pressure was fully released. The air pressure was measured by the PPT and accurately controlled by the air regulator in both tests. By reducing the air pressure, the decrease of the stiffness and strength of the shaft lining was simulated. At each increment of pressure reduction, an image of the model was taken and the displacement field of soil was calculated using the GeoPIV system.

RESULTS AND DISCUSSION

The displacement field calculated from the image analysis for the baseline and weak zone tests at a number of shaft air pressure increments is shown in Fig 2. The percentages indicated in Fig. 2 indicate the shaft pressure normalized by the initial shaft pressure at the start of the test. At high shaft pressures in both tests (normalized pressures larger than 60%), the soil displacement were relatively small, suggesting that the shaft lining was still stable. For the baseline test, a pattern of displacements is observable at a normalized pressure of 50%, whereas displacements are still very small in the weak zone test at this stage. The pattern of soil displacements in the baseline test is quire clear at a normalized pressure of 30% and 20%. In the weak zone test, the pattern of displacements only begins to become clear at a normalized pressure of 20%.In the two tests, very large soil displacements occurred when the shaft pressure was reduced below 20%, making it difficult to measure displacements using image analysis, and hence this data has not been included.

There are some noteworthy differences between the data from the baseline and weak zone tests. Using the shaft pressure as a reference to compare the data-sets from the two tests, it is noted that the magnitude of soil displacement in the baseline test is considerably larger than the weak zone test. For the baseline test, soil displacements were clear at a normalized pressure of 50%. For the weak zone tests, clear soil displacements were not observed until a normalized pressure of 20%.

The pattern of displacements is also quite different for the two tests. For the baseline test, the main displacements occur at a location just above the mid-level of the shaft. The influence zone (subsidence bowl) is quite large, and horizontal displacements are similar in magnitude to vertical, especially around the lower sections of the shaft. In the weak zone test, the main displacements occur near the weak zone (as one would expect), the influence zone appears smaller than in the baseline test, and displacements are predominately vertical around most of the shaft length.

The surface settlement due to mine shaft collapse is of particular interest to engineers. The surface displacement (in both vertical and horizontal direction) at normalized pressures of 90% to 20% (in 10% increments) are shown in Fig. 3 (baseline test) and Fig. 4 (weak zone test).According to Fig.3a, the surface has an almost uniform settlement in the vertical direction down to a normalized pressure of60%. With further reduction of the shaft pressure, larger displacement occurred closer to the shaft and a subsidence bowl was formed. A significant increase of the vertical displacement is noted as normalized pressure drops from 50% to 20%. Very small horizontal displacements are observed at the surface in Fig. 3b when the normalized shaft pressure is larger than 30%. Horizontal displacements only increased substantially when the normalized pressure was reduced below 30%.

Fig.4 shows the surface displacement for the weak zone test. The displacements are much smaller than in the baseline test. A clear increase of the vertical displacement was observed only after reaching a normalized pressure of 20%. Horizontal displacements at the free surface were very small. The surface horizontal displacement is almost insensitive to the change of shaft pressure in the weak zone. This is due to the fact that the weak zone is small and far away from the surface.

These results suggest that unless a significant reduction of the stiffness and strength of the shaft lining occurs, it will be difficult to observe surface displacement, especially if the collapse of the mine shaft occurs at a localized area far from the ground surface. However, once displacements are observed at the surface, any further reduction of lining stiffness and strength may result in large surface displacements. In reality, a catastrophic collapse may occur with little warning. The results suggest that the observation of substantial displacements at the ground surface indicates a significant reduction of lining integrity and therefore measures should be put in place immediately to safeguard against collapse and loss of life.

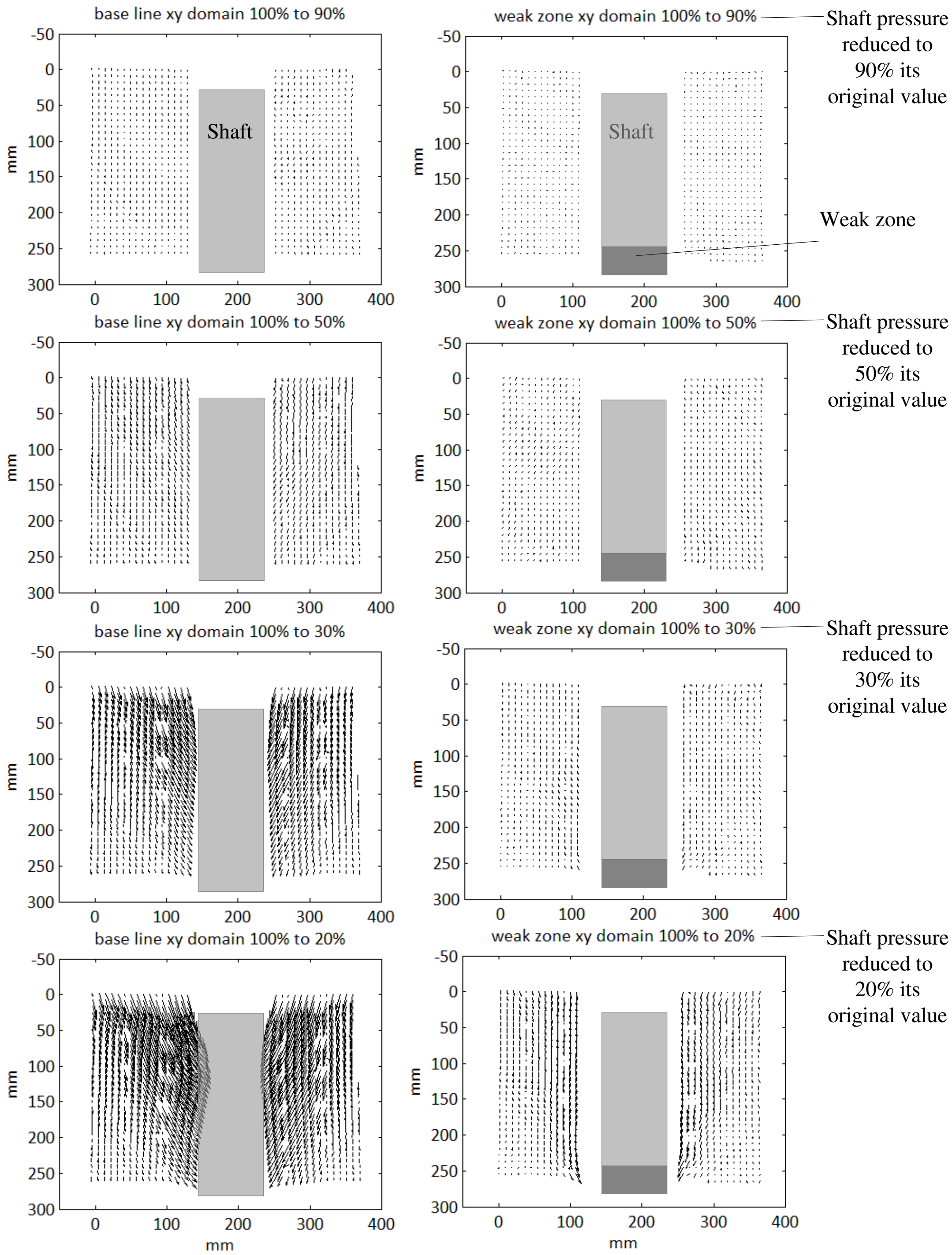
CONCLUSIONS

Results of a centrifuge study on failure mechanisms of soil around deforming shaft linings were presented. Two experiments were performed using the NCG geotechnical centrifuge at the University of Nottingham. The first test was used to study the failure mechanism of the full collapse of a shaft (baseline test) and the second test examined the weak zone effect on the failure mechanism (weak zone test). According to the results obtained from the experiments, the following conclusions can be drawn.

For both tests, the vertical displacement of the soil is larger than the horizontal displacement. For the baseline test, after reaching a normalized shaft pressure of 50%, a pattern of soil displacement initiated in the ground and the magnitude of displacements increased significantly with further reduction of shaft pressure. For the weak zone test, a clear pattern of displacements was observed only when the shaft pressure was reduced to 20% of the original air pressure.

Different failure mechanisms were observed from the two tests. For the baseline test, the main displacements were in an area just above the mid-level of the shaft, a large subsidence bowl formed, and horizontal displacements were significant. For the weak zone test, most displacements occurred very locally around the weak zone, a small subsidence bowl formed, and horizontal displacements were insignificant.

The soil displacements at the ground surface for both tests showed that the vertical surface displacement of soil is clearly larger than the horizontal displacement. This suggests that the vertical surface displacement is more sensitive to the movements of the shaft lining compared to the surface horizontal displacement.



base line xy domain 100% to 90%

base line xy domain 100% to 50%

base line xy domain 100% to 30%

base line xy domain 100% to 20%

weak zone xy domain 100% to 90%

weak zone xy domain 100% to 50%

weak zone xy domain 100% to 30%

weak zone xy domain 100% to 20%

Shaft pressure reduced to 90% its original value

Weak zone

Shaft pressure reduced to 50% its original value

Shaft pressure reduced to 30% its original value

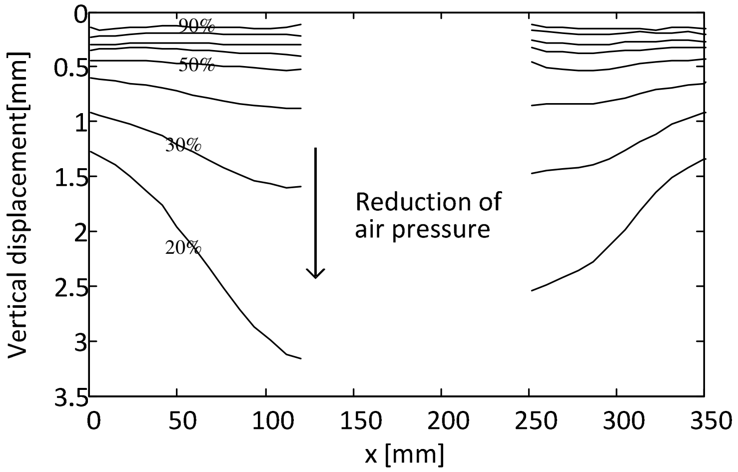
Shaft pressure reduced to 20% its original value

(a) Baseline test

(b) Weak zone test

FIG.2. Soil displacements with reduction of shaft pressure: (a) Baseline test, (b) Weak zone test

(a) Base line vertical displacement at the surface



(b) Base line horizontal displacement at the surface

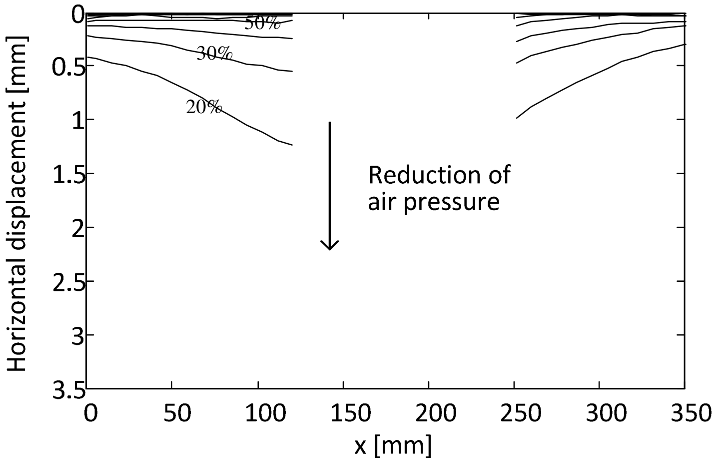
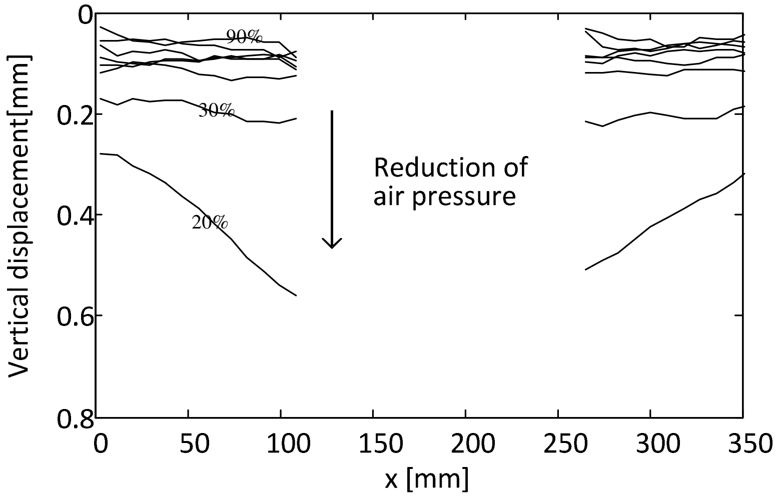


FIG.3. Surface displacement for baseline test at each air pressure; (a) vertical and (b) horizontal direction

(a) Weak zone vertical displacement at the surface



(b) Weak zone horizontal displacement at the surface

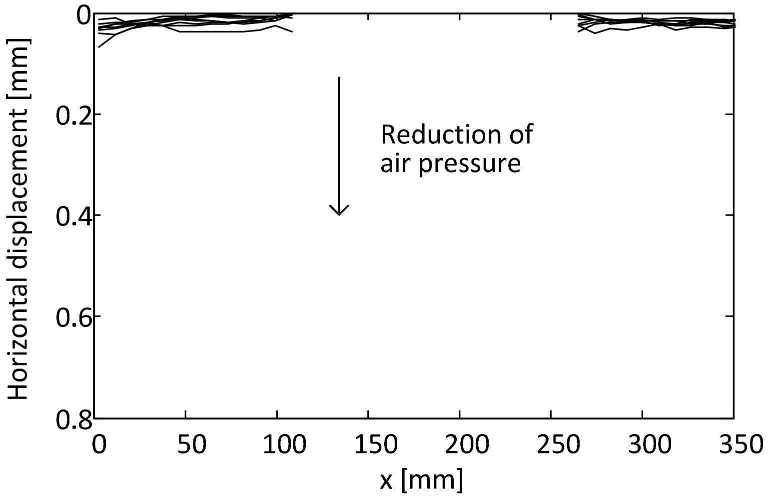


FIG.4.Surface displacement for weak zone testat each air pressure; (a) vertical and (b) horizontal direction.

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