Surface Subsidence Caused by Trench Excavation under Construction Machinery Load

Ming Fang¹, Shaopei Chen¹* and Yi Zhang²

¹ School of public administration, Guangdong Univ. of Finance & Economics, Guangzhou, Guangdong, 510320, P. R.
² Institute of Survey and Design, Architectural Design and Research Institute of Guangdong Province, Guangzhou, Guangdong, 510010, P. R.
*Corresponding author’s e-mail: shaopei.chen@gdufe.edu.cn

Abstract: There are many labor accidents in which workers or operators are buried under collapsed ground and/or construction machinery such as a drag-shovel that falls or topples over the edge of the trench during excavation. A series of centrifuge model tests was conducted in order to examine the stability of the edge of excavation under the load of construction machinery by the following procedure: 1) Failure behavior and depth of excavation were studied by conducting centrifuge model tests using an in-flight excavator. 2) The stochastic medium model of surface subsidence caused by trench excavation under the construction machinery load was established. The surface subsidence results from calculation model agree with the surface subsidence results in the centrifuge tests.

1. Introduction
There are many labor accidents in which workers are killed and buried under collapsed ground when construction machinery such as a drag shovel overturns or topples over the edge of the trench during excavation.

Preventing these types of labor accidents requires understanding of how the stability of excavated slope changes under relative conditions such as the magnitudes and locations of loaded construction machinery weight, geometry of ground excavation (e.g. excavation depth), and characteristics of ground strength[1-2].

Centrifuge modeling tests have been used for resolving geotechnical issues in which effects of the own weight of soil, such as bearing capacity of the ground, slope stability and earth pressure exerted on retaining walls, cannot be ignored. An excavated trench changes in depth and form in the course of the excavation process. Therefore, the stability of excavated ground under the loaded weight of construction machines cannot be accurately studied unless the changes in load conditions are taken into consideration along with the geometric conditions of the excavated trench.

Centrifuge modeling is an effective method for verifying the collapse mechanism where various relative conditions influence each other. Although the issue of stability of excavated ground has been studied in the centrifugal field[3-7], only a few such studies address the cases when loads are working on the slope edge, and even fewer studies faithfully reproduce the excavation process. In view of this situation, this study investigates the collapse phenomena caused by excavation under the loaded weight of construction machines, through centrifuge modeling tests.
A series of centrifuge model tests was conducted on ground model under conditions of different location of the machinery load in order to examine the stability and failure mechanism of trench excavation under the construction machinery load.

A stochastic medium theory method for the calculation of surface subsidence caused by trench excavation under the construction machinery load was put forward. The calculation model of surface subsidence caused by trench excavation under the construction machinery load was established, and the selection method of calculation parameters was discussed. Finally, the reliability of the method was confirmed through comparison with the results of the centrifuge tests.

2. Centrifuge modelling

A series of centrifuge tests under the center load of construction machinery was performed using the Mark-II centrifuge, respectively, at the Centrifuge Test Laboratory of the National Institute of Industrial Safety (NIIS). The NIIS Mark-II centrifuge and the in-flight excavator, which is capable of excavating the ground model during high centrifuge acceleration, are described in detail by [8]. Figure 1 shows a diagrammatic sketch of the drag shovel commonly used in trench excavation. The geometry of the drag shovel such as the full width of the vehicle or crawler (B), wheel width (b) and side clearance from the slope crest (ab) are also presented in this figure.

![Figure 1. Diagrammatic sketch of drag shovel.](image)

The ground model was prepared in a rigid model box (internal dimensions of 100 mm in width, 450 mm in length and 272 mm in height). The ground model is Kanto loam (volcanic cohesive soil in Japan; Table 1). In addition, the ultimate bearing capacity is 91 kPa. The ultimate bearing capacity of the ground equals to the machinery load (91.7 kPa).

| Water content | Density (kg/m³) | Dry density (kg/m³) | Void ratio | Saturation degree, Sr (%) | Degree of compaction, Dc (%) |
|---------------|----------------|--------------------|------------|--------------------------|-----------------------------|
| 106.7         | 928            | 449                | 4.92       | 57.6                     | 66.0                        |

A series of centrifuge tests was conducted on the ground model under conditions of different location of the construction machinery load[9]. The test conditions are summarized in Table 2.

| Ground Model | Construction machinery load |
|--------------|-----------------------------|
|              | Weight(kg) | B(mm) | Contact pressure q(kPa) | ab(mm) |
| 1            | 1.246      | 20    | 91.7                    | 10     | 15    | 25    | 35 |

Figure 2(a) shows a cross section of Model 1 after ground failure in the case of no machinery load. A maximum excavation depth of about 220 mm was observed after the failure. Figure 2(b) and (c) are an example of the failure pattern of Model 1 under the center machinery load. Figure 2 also shows schematic illustrations of the failure mechanism observed in Model 1. The failure mechanism was initiated by the collapse of ground beneath the machinery load due to the insufficient ground bearing capacity, and then the surrounding ground was pushed towards the excavation face. It is considered that the failure mechanism is similar to the bearing capacity failure of a foundation.
Furthermore, it should be noted that at a side clearance of 10, 15, 25, and 35 mm, the maximum excavation depth is 38, 70, 72, and 98 mm, respectively, although at a side clearance of 35 mm, the maximum excavation depth is less than 50% of that observed in the case of no machinery load (maximum excavation depth of 220 mm) of Model 1.

In figure 2 (c), the surface subsidence values surrounding the trench wall caused by excavation were also recorded.

3. Stochastic medium model of surface subsidence caused by trench excavation under the construction machinery load
Litwiniszyn introduced the theory of stochastic medium into the calculation of surface deformation [10], and this theory is perfected by Liu B.C. and other scholars [11~16]. This theory is an effective method to accurately predict the ground movement caused by underground excavation. The basic parameters of the stochastic medium theory model are comprehensive parameters, which represent the synthesis effect of practical engineering. This method also makes up for the deficiency of the existing calculation methods. In addition, this method has higher computational efficiency than the three-dimensional finite element method, which makes it to be a practical method of predicting the strata movement.

According to the stochastic medium theory, underground excavation can be divided into many infinitely small unit excavations. The result of total underground excavation should be equal to the
3.1. Surface subsidence calculated by stochastic medium model

3.1.1. Establishment of stochastic medium model. Simplify the trench excavation to a plane deformation problem, as shown in figure 3. The expression of unit subsidence caused by excavation (see formula (1)) was deduced in [11].

\[ W_e = h(z) \exp \left[ -\frac{h^2(z_0)(x-x_0)^2}{\sqrt{\pi}} \right] \]  

(1)

In figure 3, \( H \) is the depth of excavation, the upper plane is \( z = 0 \), the bottom plane is \( z = -H \), \( \alpha \) is the slope angle. In this study, because the trench was excavated vertically, so the slope angle \( \alpha = 90^\circ \). There is a unit excavation \( d_0dz_0 \) at the set point \( p(x_0, z_0) \). Then the micro-layering of \( dz_0 \) obtained by formula (1) can be expressed as formula (2).

\[ \Delta W(z_0) = \int_0^H h(z_0) \exp \left[ -\frac{h^2(z_0)(x-x_0)^2}{\sqrt{\pi}} \right] dx_0 \]  

(2)

After all micro-laying was excavated, the surface subsidence can be expressed as formula (3).

\[ W(x) = \int_0^H \int_0^H h(z_0) \exp \left[ -\frac{h^2(z_0)(x-x_0)^2}{\sqrt{\pi}} \right] dx_0 dz_0 \]  

(3)

In formula (3), \( r(z_0) = -z_0 \tan^{-1} \beta \), \( h(z_0) = -\sqrt{\pi}z_0^{-1} \tan \beta \).

\( \beta \) is defined as the main influence angle of rock and soil, and its value depends on the stratum condition of excavation. \( \beta \) is a comprehensive parameter.

After integration, the expression for surface subsidence (see figure 4) can be expressed as formula (4).

\[ W(x) = \int_0^H \int_0^H \tan \beta \frac{1}{z_0} \exp \left[ -\frac{\pi \tan^2 \beta}{z_0^2} (x-x_0)^2 \right] dx_0 dz_0 \]  

(4)

In formula (4), \( a = -z_0 \cot \alpha_1 \), \( b = H \cot \alpha_1 + L + (z_0 + H) \tan^{-1} \alpha_2 \).

Figure 3. Trench excavation profile diagram.  
Figure 4. Trench excavation cross-section diagram.

Because of \( \alpha_1 = \alpha_2 = 90^\circ \), so \( a = 0 \), \( b = L \). Formula (4) can be changed into formula (5).

\[ W(x) = \int_0^H \int_0^H \tan \beta \frac{1}{z_0} \exp \left[ -\frac{\pi \tan^2 \beta}{z_0^2} (x-x_0)^2 \right] dx_0 dz_0 \]  

(5)
The parameters needed to be inputted in the calculation model are trench excavation depth $H$, trench excavation width $L$, and tangent of the main influence angle of rock and soil $\tan \beta$. By inputting the values of $x_0$ and $z_0$ according to the specific location of trench excavation, the subsidence curve of the surrounding surface caused by trench excavation can be obtained.

### 3.1.2. Selection of basic calculation parameters.
For a specific trench excavation works, it is necessary to determine the basic calculation parameter $\tan \beta$. It is determined by the stratum conditions where the excavation is located, and it is a comprehensive parameter. The parameter can be determined by the back analysis of the trench measurement data, which represents the comprehensive effect of the actual engineering. According to the calculation formula of surface subsidence, the corresponding program was compiled by MATLAB language.

### 3.2 Results of surface subsidence and discussion

Figure 5 shows the results comparison between the stochastic medium model and test results. When $ab = 35\text{mm}$, the trench excavation depth $H = 98\text{mm}$, the trench excavation width $L = 260\text{mm}$. Based on the measured data of centrifugal model test, the calculation was carried out by using MATLAB programming language. According to the calculation, $\tan \beta = 0.125$. The maximum surface subsidence test value is -9.5mm, and the calculation value is -10.0mm, respectively (see figure 5). The relative error rate is 5.3%. In this study, the calculated results of the stochastic medium model agreed well with the test results. It is shown that the calculation model established in this study is reliable.

![Figure 5. Comparison of results of the stochastic medium model with test results ($ab = 35 \text{ mm}$).](image)

### 4. Conclusions

A series of in-flight excavation tests were performed in which a construction machine was modeled, and the construction machine load was assumed to be closest to the excavated trench in a 30G centrifuge field. Also, for comparison with the test results, the stochastic medium model of surface subsidence caused by trench excavation was established. The main conclusions are as follows:

1. When the contact pressure is approximately equal to the bearing capacity of the ground, the failure mechanism is similar to the bearing capacity failure of foundations (the ground collapses after being pushed out forward (toward the excavation side)). The distance (between machinery load and trench wall) has a significant effect on the maximum excavation depth.
(2) Based on the stochastic medium theory, the calculation model of surface subsidence caused by trench excavation was established. The surface subsidence results from calculation model were compared with the surface subsidence results in the centrifuge tests, and a good agreement was found. For this research, tests and analyses were performed assuming two-dimensional and static loads of trench excavation. In actual situations, however, collapse caused by three-dimensional loads or dynamic loads should also be considered. Further studies in this regard are awaited.

Acknowledgement
This study was supported by the Guangzhou Science and Technology Project (No. 201607010264) and Guangdong Provincial Department of Education Research Project (No. 2017KTSCX075).

References
[1] Gayarre F. L., González-Nicieza C., Alvarez-Fernández M. I., et al. (2010) Forensic analysis of a pile foundation failure. Engineering Failure Analysis, 17: 486-497.
[2] Kusakabe, O. (1975) Studies on the stability analysis of slopes under strip loads on the top surface, M.D. thesis, Tokyo Institute of Technology.
[3] Zhao K., Ning F.J., Zhang J.P., et. al. (2018) Analysis of mechanical properties of a new type of foundation pit supporting structures. Journal of Chongqing University, 41: 49-56.
[4] Ng C.W., Shi J.W., Hong Y. (2013) Three-dimensional centrifuge modelling of basement excavation effects on an existing tunnel in dry sand. Canadian Geotechnical Journal, 50: 874-888.
[5] Huang X., Huang H.W., Zhang D.M. (2014) Centrifuge modelling of deep excavation over existing tunnels. Geotechnical Engineering, 167: 3-18.
[6] Huang X., SCHWEIGER H.F., Huang H.W. (2011) Influence of deep excavations on nearby existing tunnels. International Journal of Geomechanics, 13: 170-180.
[7] Zheng G., Wei S.W. (2008) Numerical analyses of influence of overlying pit excavation on existing tunnels. Journal of Central South University of Technology, 15: 69-75.
[8] Toyosawa, Y., Yang J.J., Miura, S. and Suemasa, N. (2004). Bearing capacity of reinforced ground using centrifuge tests. Journal of Geotechnical Engineering, JSCE, No.757/III 66: 247-257.
[9] Fang, M., Yang, J.J. (2017) Centrifugal model test on stability of excavation by construction machinery. Journal of railway science and engineering,14: 167-172.
[10] Litwiniszyn J. (1985) The theories and model research of ground. Colliery Eng, 10: 327-335.
[11] Liu, B.C. (1992) Stochastic medium theory and its application to surface subsidence caused by excavation. Chinese Journal of Nonferrous Metals, 3:8-14.
[12] Yang, J.S., Liu B. C. (2002) Ground Movement and deformation caused by Urban Tunnel Construction. China Railway Publishing House, Beijing
[13] Shi, C.H., Peng L.M., Liu B.C. (2004) Influence of shallow tunnel excavation on ground surface buildings. Chinese Journal of Rock Mechanics and Engineering, 19: 3310-3316.
[14] Shi C.H. (2008) Research on time-space united calculation theory of stratum deformation for urban tunnel excavation and its application. Chinese Journal of Rock Mechanics and Engineering, 5:1082.
[15] Shi, C.H., Peng, L.M. (2004) Application of stochastic medium theory to predicting settlement in longitudinal surface due to tunnel construction by shield. Rock and Soil Mechanic, 2:320-323.
[16] Jin,Y.P., Li X.G., Chen, M., Zhang T.H. (2017) Deep foundation pit excavation analysis of influence on the adjacent buildings. Journal of Railway Science and Engineering,14:1217-1224.