Conditions of the cavity formation and sinkholes in the practical ground

Mari SATO(i), Yoshinori UNO(ii) and Ryota ITO(iii)

i) Assistant Professor, Academic Assembly, SHIMANE University, 1060, Nishikawatsu, Matsue 690-8504, Japan.
ii) Executive Officer, OYO Co., Ltd., 2-61-5, Toro-cho, Kita-ku, Saitama city 331-8688, Japan.
iii) Geotechnical Engineer, OYO Co., Ltd., 2-61-5, Toro-cho, Kita-ku, Saitama city 331-8688, Japan.

ABSTRACT

Sinkhole accidents bring various damages to the society and the infrastructures. Some of the accidents are induced by internal erosion or seepage. Concretely, soil is drained to cracks and breakages of sewer pipes in urban areas with rainfalls. The underground cavities are expanded by soil drainages and finally it causes sinkholes. Recent studies simulated these phenomena but there are some differences between experimental conditions and actual ones. For examples, practical ground containing fines is not uniform, having lower permeability than of the model ground. This study aims to make connection of the knowledge indicated by the previous researches using simulations by the model ground, and actual phenomena happening in the ground. Firstly, we performed the model tests using a backfill soil. Obvious collapse and cavity expansion hardly occurred because of the very low permeability. It is suggested that two specific conditions are required to promote the cavity expansion; one is the strong seepage close to the cavity, and which directly flow into there. Another is repetitions of drying–wetting in the ground. After the end of infiltration, cone penetration test was performed to evaluate the stiffness vicinity of the cavities. We proposed the new evaluation method based on the fines contents.

Keywords: sinkhole, backfill soil, internal erosion, cavity, model test

1 INTRODUCTION

Sinkhole accidents induced by collapse of underground cavities are often reported whole around the world. Factors of underground cavities are generally classified into geological ones, artificial cavities and cavity generation due to soil drainage by seepage, a kind of internal erosion. The surface collapses suddenly occur and therefore have risks both of human damages and economical ones. The limestone layer is well-known as the geological factor of sinkhole accidents (e.g., V.D. Eechhaut et al. (2007)1), which is dissolved with underground water. One example of artificial cavities is an old mine that has various underground caves.

Our research studied about sinkholes generated by soil drainage with seepages, especially about drainage from sewer pipes in urban area. Large numbers of sewer pipes will finish the lifetime in advance in Japan5. Therefore, some of them are already repaired but of others contains cracks and breakages. Soil is drained from those and finally underground cavities are generated. Pipes are mainly constructed under roads and streets in urban cities where vehicles equipped with ground penetrating radar2 is commonly applied to detect underground cavities before collapsing as shown in Figure 1. However, treatment methods of detected cavities have not yet fully systemized. For example, MLIT in Japan evaluated the risks of detected cavities due to the size and the depth4.

We aimed to reveal the significant factors to develop cavities with soil drainage by a model test. Previous researches also performed the model test simulating soil drainage from cracks of sewer pipes and have done the numerical analysis (e.g., Kuwano et al. (2010b)5 and Maeda et al. (2014)6). Many of them use and simulate uniform sand mainly because of the rapidity and simplicity, but there are various differences between practical applied soil that is called as backfill soil, and experimental sand as shown in Table 1. Hydraulic conductivity of backfill soil is obviously smaller than that of experimental soil, although backfill
soil is different in each site. Therefore we applied typical backfill soil to the model test and proposed some factors causing expansion of cavities in practical sites. Concretely, repetition of seepages and drying process is imposed on the model ground considering that of rainfalls under actual conditions. Pavement is often impermeable and the ground has low water content. The initial cavity is created because evaluation of detected cavity due to penetrating radar is significant for improving treatment methods.

2 TEST APPARATUS AND PROCEDURE

The size of the model chamber made of acrylic plates is 30.0 cm × 10.0 cm × 40.0 cm as shown in Figure 2. The deformation of the ground can be observed through transparent acrylic plates. The center of left and right walls has a hole of 8mm diameter. The inlet tubes are connected to the holes, through which water is infiltrated from funnels placed at 40.0cm height. The front panel of the soil chamber can be opened. An aperture of size 5.0mm × 100mm is set at the center part of the bottom plate. The water and soil are drained from there with seepages.

A flow chart for testing procedure is shown as Figure 3. The model ground is compacted to total 40cm thickness, under vicinity of optimum water content. Then the front plate is opened for digging initial cavity. The shape of the initial is based on the tendencies of site investigations; aspect ratio being 1:5 is most common. After closing the front plate and the preparation of the model ground is completed, water infiltrations from walls of the chamber are initiated. Cavity deformation is recorded by a video camera placed in front of the soil chamber. This infiltration process is repeated every 2-3 days of drainage, which is called as ‘repetition of drainage, RD’ in this paper. Drying process is set on some test cases instead of drainage process, which is called as ‘repetition of drying and wetting, RDW’. Please note that RDW also allow drainage from the aperture. The water content after drying can’t be directly measured in these test series, but it is estimated around 1-2% from the unpublished and the latest experimental data. We call a ‘cycle’ from onset of wetting to the next wetting.

| Test code | Material  | W_{wi} (%) | Cavity size / location** | Average infiltrated water in one cycle (ml) | RD/RDW | cycle (times) |
|-----------|-----------|------------|--------------------------|-------------------------------------------|--------|---------------|
| BLB       | Backfill  | 14.4       | L/B                      | 1530                                      | RD     | 17            |
| BLC       | Backfill  | 14.4       | L/C, sand pipe           | 3600                                      | RD     | 2             |
| BSB       | Backfill  | 14.4       | S/B                      | 1720                                      | RD     | 7             |
| BLB_DW    | Backfill  | 14.4       | L/B                      | 3600                                      | RDW    | 3             |
| SLB       | Silica No.6 | 10        | L/B                      | 3600                                      | RD     | 1             |

*L: large, S: small  **B: bottom, C: center

Table 1 Differences between experimental sand and backfill soil

| Concrete example | Experimental sand | Backfill soil |
|------------------|-------------------|---------------|
| Grain size distribution | Uniform, Uc=1.7-1.8 | Wide, Uc=60 |
| Hydraulic conductivity | $10^{-4}~10^{-5}$ (m/s) | $10^{-6}~10^{-7}$ (m/s) |

![Fig. 2](a) Schematically figure of the model test, (b) Measured spots of the cone penetration test and (c) Front plate of the chamber.
3 TEST MATERIALS AND CONDITIONS

Two kinds of testing material are applied: Silica sand No.6 \((G_s = 2.627 g/cm^3)\) and typical backfill soil \((G_s = 2.683 g/cm^3, w_{opt} = 14.4\%\) mainly consists of decomposed granite, Masa in Japanese. Particle size distributions are shown in Figure 4. The average particle size is both around 0.35mm, but backfill soil contains much more fines and gravels, \(U_c = 66.4\%\).

Test conditions are shown in Table 2. The aspect ratio of the cavity is similar in all cases, and the depth of the cavity is 10cm as same as that of soil chamber. Therefore it is estimated that deformation in deep direction is uniform. Initial shape and location of each case is shown in Figure 5, separated into large/small by size, and into bottom/center by location. The compacted condition is similar in all testing cases with \(Dc = 90\%\) and \(w_{min} = w_{opt} = 14.4\%\), except for SLB. SLB is controlled by relative density \(D_r = 95\%\) and \(w_{min} = 12\%\) because measurement of compaction degree is difficult for uniform sand. Approximately 400 ml of water pouring from left and right flatters is repeated because of the observation of gradual deformation in one penetration cycle in the intervals of drying or drainage. The water is poured not only from the right/left side but also from the surface ground on testing cases: BLC, BLB_DW and SLB. Total approximate mass of poured water in one cycle of RW/RDW is shown in the table. This is not constant because permeability is very low and then duration of pouring is restricted to 6 hours. BLB_DW is followed by BLC because case didn’t cause expansion of cavity. BLC has a 5mm thickness and 15 cm height sand pipe to the cavity for air escaping. This pipe is consists of Silica sand No.3, \(D_{50} = 1.7mm\).

4 TEST RESULTS

4.1 Cavity formation

Expansion of the cavity is observed in the following cases: BLC and BLB_DW as shown in Figure 6 and Figure 7. Other cases didn't induce expansion on backfill soils. Therefore, factors of cavity expansion are separated into two groups in the backfill soil. One is concentrated flow to the cavity and another is drying-wetting process. Concentrated flow occurs when seepage is nearby cavity as with BLC. Firstly, upper part of cavity is deformed to downward direction after 2 hours of onset of 1st cycle seepage. Water is pooled at the bottom of the cavity. During the drainage, the

regardless of whether RD or RDW. The front plate is opened after the end of water infiltration, and subsequently the ground is dried by a hot air blower. Details of conditions of water infiltrations and that of the cavities size are shown in the following chapter. Additional indices are also measured in several cases; the speed of infiltrated water and total mass of drained soil in dry conditions.
The deformed area is collapsed and the cavity rises up to the surface. This collapsed portion is slightly spread with the onset of 2nd cycle seepage, which makes higher water level than of 1st cycle. During the drainage, cavity formation doesn’t change. By the way, the trial test case without a sand pipe doesn’t cause collapses. It leads

Fig. 6 Cavity deformation in BCL

Fig. 7 Cavity deformation in BLB and BLB_DW

Fig. 8 Cavity deformation in SLB
that soil chamber has high air-tightness and air is supposed to be trapped at the cavity, which prevents collapse. This rarely occurs in the practical ground but air escaping is suggested to be necessary.

Second, wetting and drying is affected to expansion of cavity. It is revealed by the differences between BLB and BLB_DW. BLB doesn’t cause cavity expansion except first slight collapse that is initially weakened area as shown in Figure 7. On the other hand, cavity is gradually expanded with repetitions of RDW cycles for BLB_DW. The differences of two cases are only drainage/drying process. Therefore, it is suggested that drying process caused progression of cavity formation to upward direction. The mechanisms are discussed in chapter 6.

These factors are revealed when backfill materials are used. The tendency of cavity expansion is different from Silica sand No.6, case SLB (see Figure 8). The cavity expanded to upward direction so rapidly in the case. While the initial longitude cavity formation is kept in all cases using backfill material, this is deformed to vertical direction. Area of cavity is also rapidly increased, which is because the weight of drained soil is larger as explained in following section.

Effect of initial cavity size isn’t recognized to cavity expansion. BSB has smaller size but didn’t induce collapse of the cavity as pictured in Figure 9. Initial cavity sizes of other cases are fixed to the maximum ones not to be influenced by walls of chamber. The larger chamber is required to evaluate the width of cracks. The difference of average infiltrated water is also considered; BLB and BSB have smaller amount comparing to others. However, these cases have large number of cycles, which means total volume of infiltrated water is adequate to increase water contents in the ground. Drainage process doesn’t cause complete drainage of infiltrated water in wetting process. Therefore, water is gradually accumulated due to repetition of cycles.

4.2 Infiltrated speed and weight of drained soil

Average infiltrated speed in one cycle is listed in Table 3, calculated by the average of the ratio: total infiltrated volume of water/elapsed time of each cycle. It can be seen that RW has slower speed of infiltration except for BLC; initial cavity located nearby the input holes of cavity. Therefore, water is infiltrated easier because of the connection from the inlet to the cavity. It can be also suggested from that BLB and BSB have similar speed nevertheless the different size of cavity. Silica sand no.6 has around 10 times larger speed and this might be relative to hydraulic conductivity of each material.

Weight of drained soil was measured with dry condition, namely being total weight through each testing case. Weight of drained soil is very subtle on backfill soil cases. Case has largest drained soil, 12.8g equivalent to 0.06% of entire compacted soil. That is possible to slightly underestimate because some portion of soil is lost from collective tray during the experiments, although is not too large to change the tendency of itself. Backfill material is cohesive and soils were trapped at the aperture. In addition, flow speed is very low due to low hydraulic conductivity, which is not enough to induce collapse by seepages. SLB: Silica No.6 doesn’t contain fines and non-cohesive sand, which made massive drainage, 5066.9g. Such degree of drainage never occurs in the narrow crack conditions on backfill material. The wider crack is necessary to induce both large amount of drainage and expansion of the cavity on backfill materials having cohesion.
5 PENETRATION RESISTANCE

Cone penetration resistance is measured by Soil strength probe that can be referred to as Dokenbou in Japanese. Small diameter both of rod (16mm) and of cone (28.6mm) are connected to the spring gage as shown in Fig 10. It is commonly applied to the investigation site as the figure but is applicable to the model ground. The bottom part is not for friction from chamber walls. Three penetrated spots were shown in Figure 1, through the center line of the wide direction. The test was performed on three cases: BLC, BSB and BLB_DW. As shown in Figure 11, BLC has lower resistance area surrounded to the cavity from 10cm to 20cm depth of the ground. On the other hand, BSB and BLB_DW can’t be measured the resistance lower than 10cm and 15cm at depths, respectively, since initial cavity located at the bottom and middle part of the ground is difficult to penetrate for the high friction of the acrylic walls. It is possible to contain the disturbed area vicinity of the cavity but not capable of measuring.

6 DISCUSSION

We proposed the provisional evaluation method of cavity expansion on backfill soil as shown in Figure 12, although this study is ongoing project and the experimental data is not sufficient for determining of these factors of evaluation. It is mainly governed by fines content, F_c of the applied material, because F_c can be easily measured at the practical sites. Firstly, test results show that infiltration speed straightly influenced the expansion of cavities. In tests, where the the average speed is over 10ml/min induce cavity expansion. Infiltration speed is fundamentally relative to the hydraulic gradient of a material. Therefore, low-density and non-cohesive sand may cause severe damages of sinkhole accidents. This is the one factor of progression of cavity. The direction from seepage to a cavity also affects to the infiltrated speed, as revealed by SLB. Estimation of the direction is difficult at the practical investigation, so that we don’t adopt those as a estimating index. Secondary, cohesive soil affected by drying–wetting repetition because of shrinkages inferred by Estabragh et al. (2015). The large collapse occurs at the first reaching of the wetting front to the cavity. If the soil is under drying–wetting process, cohesive soil took severe damage and seepage concentration might be extended. So the risks of sinkhole accident don’t decrease just by increasing of cohesion. Thirdly, crack of the width is supposed to straightly influence on the expansion of the cavity. Cohesive-sand has small hydraulic gradient and speed of expansion of the cavity is supposed to be low. The sand is trapped to the narrow crack and drainage is subtle, so that wider cracks are required for soil drainage. On the other hand, cohesion-less sand is easily drained even if the crack is narrow. These differences have not yet adequately evaluated, but it can be done by additional experiments. In conclusion, three items are set for risk factors; 1) cohesion-less sand, having small percentages of fine particles under 0.075mm: r_f 2) wetting and drying affecting cohesive sand: r_d 3) Width of cracks affecting total soil loss: r_c. These are chosen by the measurable indices at the sites.

The equation to evaluate the risks of three factors is shown as equation (2)-(4). Total risk R_2 is given by equation (1)

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Fig. 11 Penetration resistance of BLC, BSB and BLB_DW

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\[ R_2 = (r_f + r_d) r_c \]  \hspace{1cm} (1)
\[ r_f = k_f (F_{b1} - F_c) , \text{ if } F_c \leq F_{b1} \]  \hspace{1cm} (2)
\[ r_d = d_d S_d k_f (F_c - F_{b2}) , \text{ if } F_c \geq F_{b2} \]  \hspace{1cm} (3)
\[ r_c = f(x_c, F_c) , \quad x_c: \text{width of the crack} \]  \hspace{1cm} (4)

Where \( k_f, d_d, h_d, h_c \) are coefficients greater than zero. \( F_c \) is fines content (%) and \( F_{b1}, F_{b2} \) are the boundary of fines contents; each risk increase below/over this boundary in each factors; \( r_f \) is for cohesion-less sand and \( r_d \) is for cohesive sand. The details of coefficients are shown as below.

- \( k_f \): Coefficient of fines contents
- \( d_d \): Coefficient of duration of drying
- \( S_d \): Secondary coefficient for \( r_d \), degree of influence comparing to \( r_f \)
- \( f(x_c, F_c) \): Function of the effect of crack width determined by the crack size and fines contents

\( d_d \). Drying duration is difficult to evaluate simply and concrete method has not yet decided. Our proposed indices are determined by Fines Contents except for \( d_d \). It reflects the conditions of each practical sites where the cavities are detected. The current expectation is that we can estimate this item by the pavement conditions, rainfalls, and temperature. For example, permeable pavement doesn’t necessary to consider the drying process in Japan having temporary rainfalls. \( f(x_c, F_c) \) has not yet clarified, but expected, advisory function; \( F_c \) is smaller, \( f \) is not changed dynamically. It reflects that cohesion-less sand drained easily even if the crack is narrow. On the other hand, if \( F_c \) is larger: cohesive soil, \( f \) is affected by \( x_c \). Then, this risk factor of crack width: \( r_c \) is multiplied by other risk factors: \( r_f \) and \( r_d \). This evaluation can be combined with existing evaluations such as mentioned in Introduction. The example is equation (5).

\[ \alpha R_1 + \beta R_2 = R_{sinkhole} \]  \hspace{1cm} (5)

\( R_{sinkhole} \) means total risks of sinkhole accidents, having a higher value when sinkhole accidents can be easily occur. \( R_1 \) is previous evaluations, for example, decided by the depth and size of the detected cavities\(^3\)). \( R_2 \) is our proposals determined by three contents as equation (1)-(4). \( \alpha \) and \( \beta \) are coefficient of the weights of each evaluations. The value has not yet determined but when \( R_1 \) is large, being equivalent to a detected large cavity at the shallow ground, contribution of \( R_1 \) should be large. Therefore, \( \alpha \) has large value comparing to \( \beta \). It means when the large cavity is detected at the shallow ground, we should repair those immediately regardless of the other ground conditions.

7 CONCLUSIONS

We conducted small model test by the use of backfill soil. Backfill soil has low permeability and cohesion, so that risks of sinkhole accidents are supposed to be low. However, there is another trigger; repetitions of wetting and drying cause cavity expansion. Wetting-drying is known to induce shrinkage and deterioration of the ground. The concentrated seepage is possible to occur due to this shrinkage. The details are not yet shown in this study,
but the provisional evaluation using fines contents is proposed. We should determine concrete values of coefficients and validate our equations by conducting experiments and by studying previous researches.

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