A study on occurrence characteristics of cavity and relaxation zone according to damage scale of sewage pipe in underground

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ABSTRACT: In this study, finite element analysis was carried out to analyze the occurrence mechanisms of underground cavity and relaxation zones caused by soil outflow during the damage to the upper part of the sewage pipe. The occurrence characteristics of the cavity and relaxation zone according to the damage scale of sewage pipe were analyzed. The results showed that the cavity and relaxation zone can be quantitatively estimated by using the void ratio and shear stress reduction ratio based on finite element analysis. The occurrence amount variation based on height and width of cavity and relaxation zone was evaluated. The results showed that the occurrence amount variation of cavity and relaxation zone by damage width of sewage pipe was larger in application of the void ratio distribution than the application of the shear stress reduction ratio distribution.

Keywords: Cavity, Relaxation zone, Shear stress, Reduction ratio, Finite element analysis

1 INTRODUCTION

Recently, the ground subsidence in the urban area has become a social issue in Korea. The major causes of the ground subsidence were indicated as soil outflow due to damage of the sewage pipe, ground excavation, and insufficient construction management of excavation (Park & Park, 2014; Choi et al., 2016). Especially, the ground subsidence with sewage pipe damage accounts for about 85% of the total accident in Seoul (Korea), because many old sewage pipes and underground facilities are distributed. It has been analyzed that the damage of sewage pipe in underground is closely related with the ground subsidence (Choi et al., 2016). Therefore, it is necessary to establish the prevent measures of cavity occurrence, which cause of ground subsidence, in order to prevent accidents in the urban area. It is also necessary to research the investigation of cause and mechanism for cavity occurrence.

Various research has been carried out to clarify the cavity occurrence mechanism and the effect of cavity on the ground behavior. Brady & Brown (1985) has analyzed the mechanisms that ground cavity cause ground failure after ground subsidence. The research has been carried out to investigate the relationship between subsurface subsidence and ground subsidence caused by cavity using factors such as geological conditions, cavity type, and anomaly zone (Suchowerska et al., 2012). Kim & Umm (2013) has studied the expansion case of underground cavity due to the outflow of underground soil disturbed by groundwater flow. In order to utilize the effective results of numerical analysis in analysis of the ground subsidence mechanism, Song & Yoon (2015) suggested that the application of the discrete element method, which can effectively simulate failure pattern of cavity (include surrounding areas) and the behavior characteristics of discontinuum model, is appropriate. Lee et al. (2016) have studied that cavity caused by sewer pipe damage is extended with the relaxation zone, which causes an increase in surface settlement. However, the previous research has only analyzed the relationship between the failure (or deformation) of the cavity and the ground. That is, there are few case studies that have precisely analyzed the mechanism of the process from cavity occurrence to the ground failure.

In this study, finite element analysis was carried out to analyze the occurrence mechanisms of underground cavity and relaxation zones caused by soil outflow during the damage to the upper part of the sewage pipe. The finite element method is applied to the forced displacement method to simulate the cavity and relaxation zone of underground. The simulation of cavity and relaxation zone using the forced displacement method are based on the results of previous study (You et al., 2017). The analysis results are compared with the previous experimental results (Kuwano et al.,2010), in order to verify the finite element analysis model. Based on the verified analysis model, the occurrence characteristics of the cavity and relaxation zone according to the damage scale of sewage pipe were analyzed by the shear stress reduction ratio of analysis results.

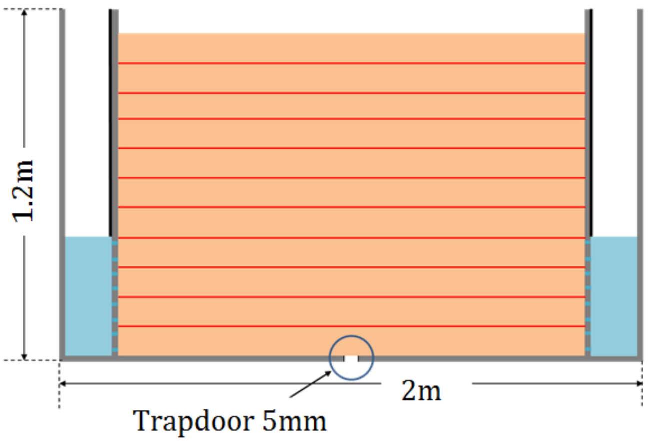
2 NUMERICAL ANALYSIS

This study described that numerical analysis based on the elasto-plasticity theory was performed to consider the cavity occurrence affected by groundwater conditions in order to analyze the ground behavior by cavity. That is, the finite element method with elasto-plasticity model was conducted to clarify the cavity occurrence and its surrounding ground behavior. The application of the elasto-plasticity model is based on the results of previous experimental study (Kuwano et al.,2010) conducted under groundwater condition.

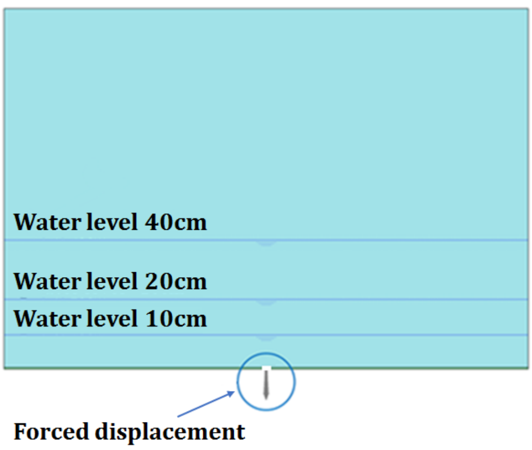
Kuwano et al. (2010) have conducted a laboratory model test for cavity occurrence in order to evaluate the cavity and grund behavior caused by the soil outflow as the groundwater level change, and then it analyzed the shape and scale of cavity according to the groundwater level change. The ground model was made of Toyoura sand with a width of 1.6m and a height of 1.1m as shown in Fig. 1(a). A trap door with a width of 5mm was formed at the center of the bottom of the soil box to induce an occurrence of artificial cavity due to the damage of the sewage pipe. The cavity was formed by sequentially increase the groundwater levels of 0.1m, 0.2m and 0.4m.

As mentioned above, the finite element analysis model was constructed with the same boundary condition based on the study of Kuwano et al. (2010). Then occurrence and expansion of cavity were simulated using forced displacement method at each groundwater level(0m → 0.1m → 0.2m → 0.4m), and then the analysis model was verified(see Fig. 1(b)). In analysis, Hardening soil model was applied for the modeling of elasto-plasticity behaviors. Hardening soil model can more clearly express the behavior of the surrounding ground due to cavity occurrence, because it is possible to consider the characteristics of soil dilatancy. The engineering properties of the soil applied to the finite element analysis are shown in Table 1.

Based on this numerical analysis, the analytical method applied in this study can be verified, and the analysis using the verified model was performed according to the damage width of the sewage pipe. In addition, the analysis was carried out according to the soil depth at the damage width of sewage pipe was 5mm, in order to evaluate the effect of soil depth on cavity occurrence. The width of the ground model was 3.0m for consideration of soil depth and sewage pipe damages. The forced displacement in each groundwater condition was also applied to the previous study (You et al., 2017). Then the distribution characteristics of the shear stress and the shear stress reduction ratio of the cavity and relaxation zone were analyzed by analysis results. The analysis conditions are shown in Table 2.



(a) Diagram of static water level's model test



(b) Analysis model

Figure 1. Numerical analysis model

Table 1. Engineering parameters for finite element analysis

E_{50}^{ref} (Mpa)	E_{oed}^{ref} (Mpa)	E_{ur}^{ref} (Mpa)	C (kPa)	ϕ' (°)	ψ (°)	γ (kN/m^3)
56	56	168	0	26.5	11.0	23.2

Table 2. Analysis condition according to damage scale of sewage pipe in underground

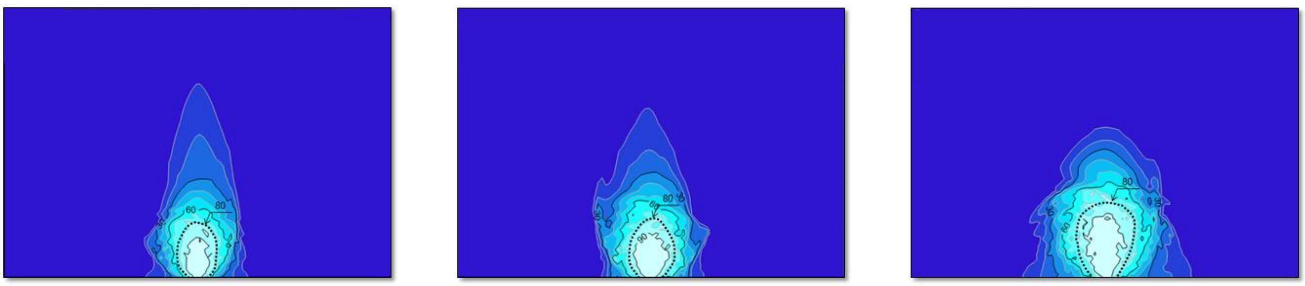
<table>
<tr><th>Analysis cases</th><th>Damage width of sewage pipe (mm)</th><th>Soil depth (m)</th><th>Groundwater level (m)</th></tr>
<tr><td>Case Ⅰ -1</td><td rowspan="5">5</td><td>0.9</td><td rowspan="8">0.4</td></tr>
<tr><td>Case Ⅰ –2</td><td>1.0</td></tr>
<tr><td>Case Ⅰ –3</td><td>1.5</td></tr>
<tr><td>Case Ⅰ -4</td><td>2.0</td></tr>
<tr><td>Case Ⅰ -5</td><td>3.0</td></tr>
<tr><td>Case Ⅱ</td><td>10</td><td>0.9</td></tr>
<tr><td>Case Ⅲ</td><td>20</td><td>0.9</td></tr>
<tr><td>Case Ⅳ</td><td>40</td><td>0.9</td></tr>
</table>

3 ANALYSIS AND RESULTS

3.1 *Evaluation of cavity and relaxation zone*

The scale of cavity and relaxation zone around the damaged area of the sewage pipe was evaluated by the shear stress reduction ratio based on the finite element analysis results under the groundwater conditions. The shear stress reduction ratio is defined as the ratio of initial shear stress and the decreased shear stress due to the increased void ratio.

The evaluation results found that the cavity area (dotted line) by void ratio distribution of the previous study (You et al., 2017) almost coincided with the boundary of the shear stress reduction ratio of 80% (see Fig. 2). This means that the area of shear stress reduction over 80% of the initial shear stress can be evaluated as a cavity. In addition, the shear stress reduction ratio was gradually decreased and expanded at shear stress reduction ratio was out of bounds of 80%. This area was determined as a relaxation zone.



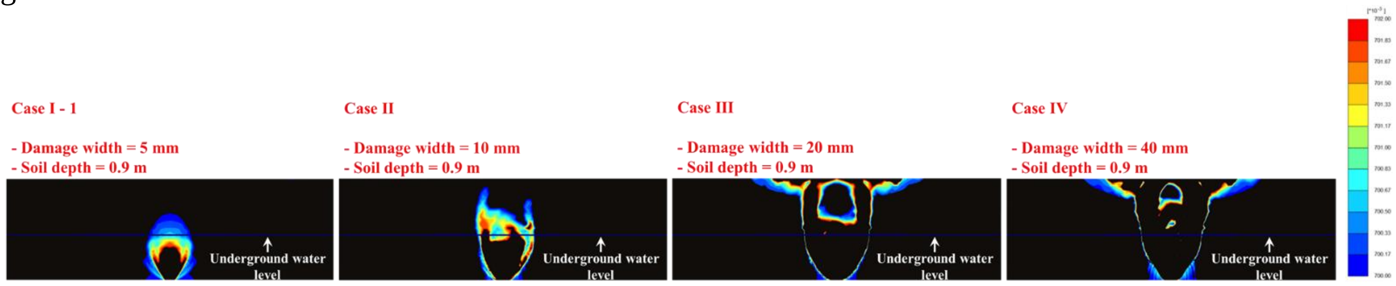
(a) Groundwater level = 0.1m (b) Groundwater level = 0.2m (c) Groundwater level = 0.4m

Figure 2. Distribution of shear stress reduction ratio with groundwater level (You et al., 2017)

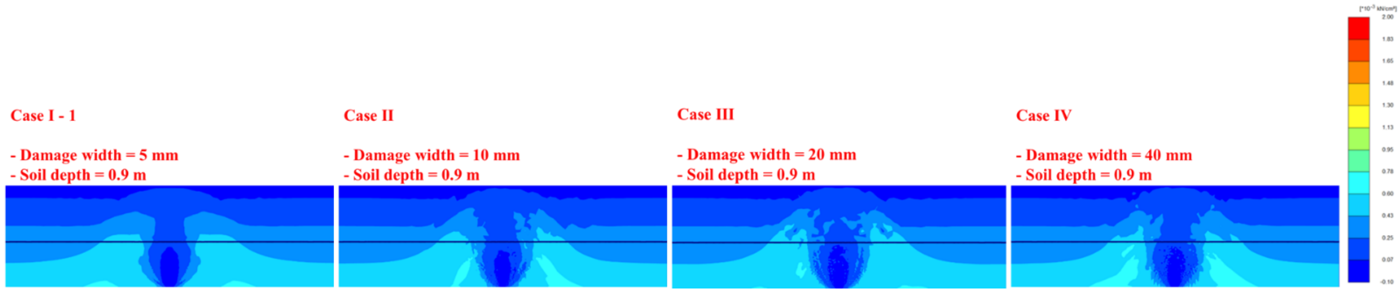
3.2 *Occurrence characteristics of cavity and relaxation zone*

Finite element analysis was carried out considering the damage scale and soil depth of the sewage pipe, when the ground width and groundwater level were 3.0m and 0.4m, respectively. The engineering properties of soil for the analysis were applied in the same conditions at the analysis for model verification.

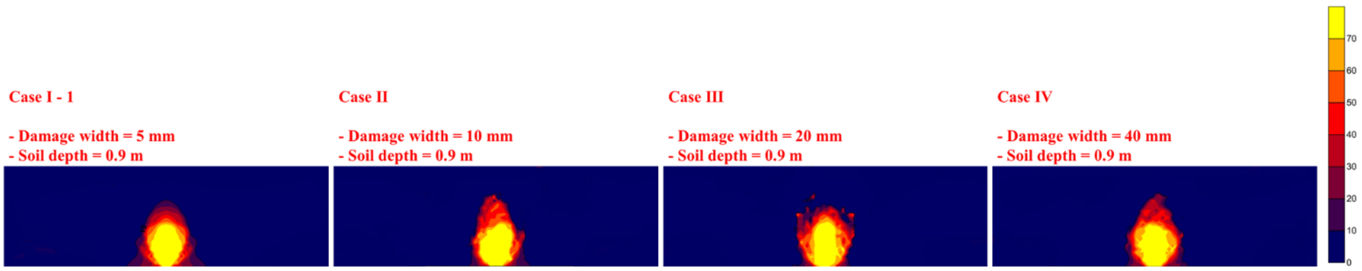
Fig. 3 shows the distribution of void ratio, shear stress, and shear stress reduction ratio using the analysis results according to damage width increase of the sewage pipe, when the soil depth and groundwater level had 3.0m and 0.4m, respectively. The distribution range of the increased void ratio and the decreased shear stress due to increase of damage width were extended from the upper area of cavity to the ground surface as shown in Fig. 3(a) & Fig. 3(b). The distribution of shear stress reduction ratio was analyzed to estimate the stability of its surrounding ground, since the cavity occurred (see Fig. 3(c)). It found that the distribution of shear stress reduction ratio with increase of damage width extended slightly toward the ground surface.



(a) Void ratio distribution



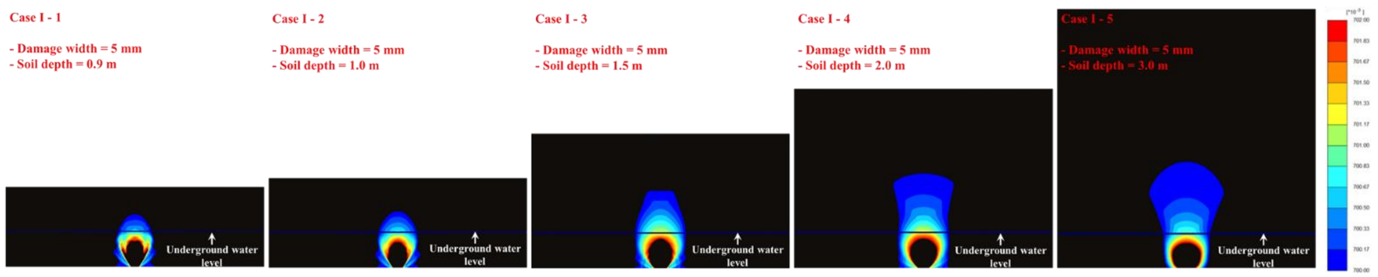
(b) Shear stress distribution



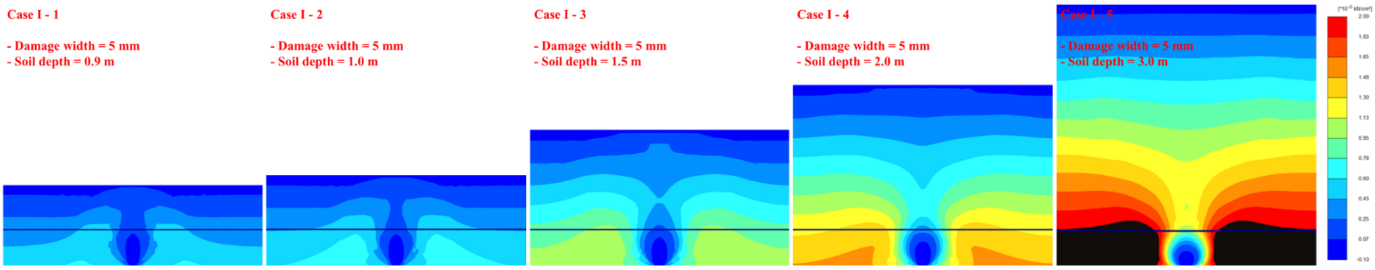
(c) Shear stress reduction ratio

Figure 3. Occurrence characteristics of cavity and relaxation zone according to damage width of sewage pipe

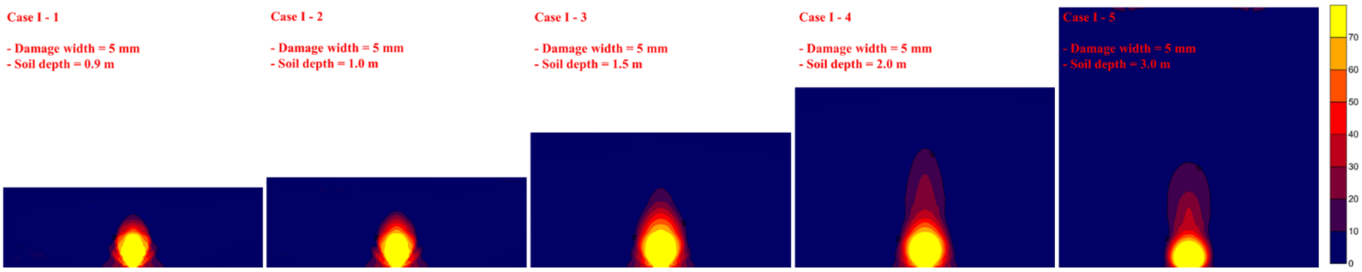
Fig. 4 shows the distribution of void ratio, shear stress, and shear stress reduction ratio using the analysis results according to variation of soil depth, when the damage width of sewage pipe and the groundwater level had 5mm and 0.4m, respectively. The results confirmed that the increasing trend of void ratio was expanded slightly, and the shear stress distribution decreased at the upper area of the cavity regardless of the soil depth. In addition, the shear stress reduction ratio was gradually expanded to the soil depth of 2m, however, it was slightly reduced at the soil depth of 3m.



(a) Void ratio distribution



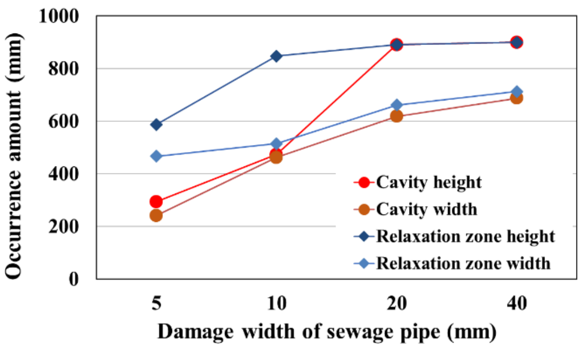
(b) Shear stress distribution



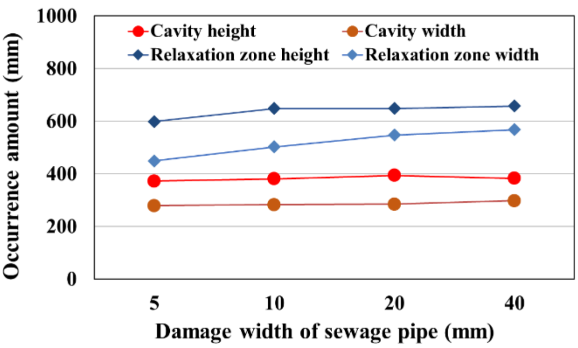
(c) Shear stress reduction ratio

Figure 4. Occurrence characteristics of cavity and relaxation zone according to soil depth

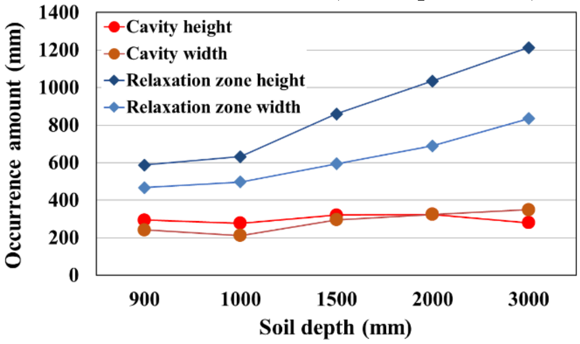
The size of cavity and relaxation zone were evaluated by the occurrence amount of cavity and relaxation zone according to the damage width of sewage pipe and soil depth, and the results are shown in Fig. 5.
In case of the occurrence amount of cavity and relaxation zone due to damage width of the sewage pipe, the height variation of cavity and relaxation zone using the void ratio distribution was larger than its width. However, the width and height variation of cavity was not large according to the damage width increase of the sewage pipe, when the shear stress reduction ratio is used. The width and height variation of relaxation zone also has slightly increased.
In case of the occurrence amount of cavity and relaxation zone due to soil depth, the width and height variation of cavity using the void ratio distribution was not large, whereas that of relaxation zone has changed greatly. The same result was obtained when the shear stress reduction ratio was used.



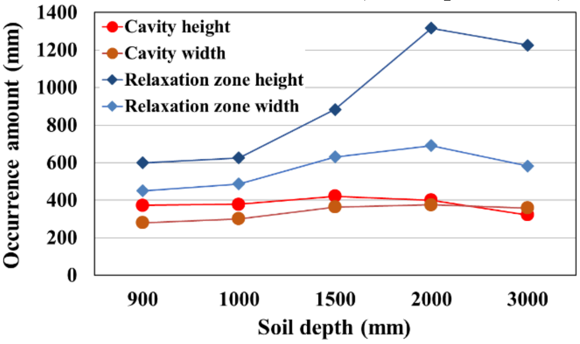
(a) Occurrence amount by damage width
- void ratio distribution (soil depth=0.9m)



(b) Occurrence amount by damage width
- shear stress reduction ratio (soil depth=0.9m)



(c) Occurrence amount by soil depth
- void ratio distribution (damage width=5mm)



(d) Occurrence amount by soil depth
- shear stress reduction ratio (damage width=5mm)

Figure 5. Occurrence amount analysis

4 CONCLUSION

This study described a numerical analysis results to analyze the occurrence mechanism of cavity and relaxation zone due to soil outflow at damage of sewage pipe. Therefore, the distribution and occurrence characteristics of the cavity and relaxation zone according to the scale of sewage pipe damage were analyzed by the finite element method results.
The results are summarized as followed;
(1) It confirmed that the cavity and relaxation zone can be estimated by using the distribution of void ratio and shear stress reduction ratio in underground according to cavity occurrence, and the its boundary can be quantitatively evaluated.
(2) In case of this study, the cavity area by void ratio distribution was almost identical to the boundary of shear stress reduction ratio of 80%, and the shear stress around the cavity different relatively according to damage width of sewage pipe and soil depth.
(3) Each occurrence amount based on height and width of cavity and relaxation zone was evaluated. The results showed that the occurrence amount variation of cavity and relaxation zone by damage width of sewage pipe was larger in application of the void ratio distribution than the application of the shear stress reduction ratio distribution.

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