

Underground cavity remediation using membrane grouting method

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Abstract. Ground collapse may occur around the tunnel when the cavity caused by groundwater runoff cannot resist the surcharge load. Any cavities or subsidence must be managed to avoid dangerous situations by stabilizing the ground through appropriate remedial measures. Trench and trenchless grouting methods can generally be used for the cavity restoration. The trench method is difficult to properly control the injection range and may cause environmental problems due to grout leakage and damages to the adjacent structures due to grouting pressure. In this study, Membrane-grouting method (MGM) is proposed, which, can be an appropriate trenchless grouting method that fills the void tightly and effectively controls the injection range. This method can be an alternative to eliminating the influence of adjacent structures and environmental pollution by inserting a membrane into the cavity and filling the membrane with grout. The membrane blocks the outflow of grout. In addition, it is easy to control the injection pressure to avoid heaving failure. This paper investigates the principle and application of the MGM using a theoretical method, model test and numerical analysis.

Keywords: environmental; heaving; membrane grouting method; remediation

1. Introduction

Developing underground spaces including tunnels, frequently causes ground subsidence and cavities due to soil loss and groundwater leakage during excavation. Ground loss and environment problem in urban areas may result in damages to adjacent structures and loss of life and property (Rogers 1986, Nam and Lee 2022, Liu *et al.* 2022).

Most of the cavities in urban areas are caused by groundwater discharge with soil particles into the construction site, or existing tunnels and pipes through cracks. Significant loss of soil particles in the ground may generate surface subsidence, subsequently developing into cavities (Guarino *et al.* 2012, Martinotti *et al.* 2017, Kong *et al.* 2018).

Many researchers have studied the mechanism of ground collapse due to cavities using model tests to investigate the cause of cavities. Kim (2018) proposed a conceptual progressive mechanism of a cavity from subsidence to collapses around tunnels. Mukunoki *et al.* (2009) simulated cracks of a conduit in the soil tank and repeated inflow and outflow water of through the cracks. They reported that the effective stress decreases due to increase in pore water pressure with an increase in repeated numbers, which causes more discharge of soil particles.

Kuwano *et al.* (2010) found that runoff of groundwater through pipe cracks enlarges the cavity size due to sediment runoff as the groundwater level rises. Mukunoki *et al.*

(2012) also reported that the smaller the relative density, the more significant the influence on the size of cavity occurs. Guo *et al.* (2013) has shown that the cavity volume is related to the groundwater level, particle size, and crack width.

The common measure for restoring cavities is the trench method, in which the upper ground is removed, then the excavated space including the cavity is filled with ground materials or grouts, and finally the excavated upper ground is recovered. However, this cut & cover method disturbs the surface traffic considerably during excavation and remedial works and is also costly and time-consuming.

So far, various studies related to ground subsidence and cavities have been conducted to examine the causes and mechanisms. However, studies on their recovery and remediation have been hardly found. Although the possibility that the grout material will leak out is significantly high during grout injection, no remedial methods which can limit the influencing range of injection.

Therefore, there is still a need for developing a specific grouting method in which the grout material does not leak into the surrounding facilities through ground. This study proposed a specific membrane-grouting method (MGM) that can be classified as trenchless grouting method which can limit the influence range of grouting by controlling grouting pressure.

2. Membrane-grouting method

2.1 Principle and method

In restoring cavities, many restrictions can be faced to protect adjacent structures such as deep foundations and

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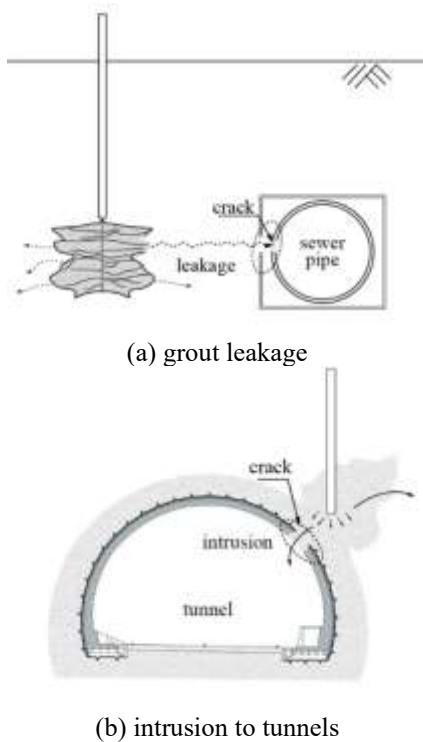


Fig. 1 Problems caused by grouting pressure

tunnels. For instance, now days in urban area the cut & cover method is rarely allowed because it causes inconvenience to surface traffic. Therefore, a technique for remediation of the cavity without affecting the surface traffic and damaging adjacent structures is preferred. In this case, a grout injection method without open excavation is mainly considered to avoid surface inconvenience and disturbance. However, even in the trenchless method grouting may often cause environmental problems, and damages to the surrounding structures. Sometimes, grout penetrates adjacent structures or run off to the far distance. The MGM was devised to restore cavities without the leak of grout to the outside of the cavities. The method can also be used for filling locally collapsed spaces or limestone caves during tunnel construction (Fig. 1).

Fig. 2 presents the schematic diagram and illustrates application principles of the MGM. The membrane material can be made of highly flexible materials such as polyethylene or rubber. Basically, as in the ASTM standard, the characteristic tests of geomembrane must be satisfied, and it has sufficient tensile strength to withstand the injection pressure and impermeability to prevent leakage from the cavity. Folded membrane (membrane pocket) is attached at the end of the injection rod. A hole is drilled from the ground into the cavity, and the rod with a folded membrane pocket is inserted into the cavity. An air vent pipe(horse) is also installed at the membrane in advance to release trapped air or measure the cavity volume. Grout is then injected into the pocket until full filling of the cavity. If the cavity is close to the ground, the ground surface may heave due to the injection pressure, thus a plate of a suitable size and surcharge on it may be needed to prevent ground heaving.

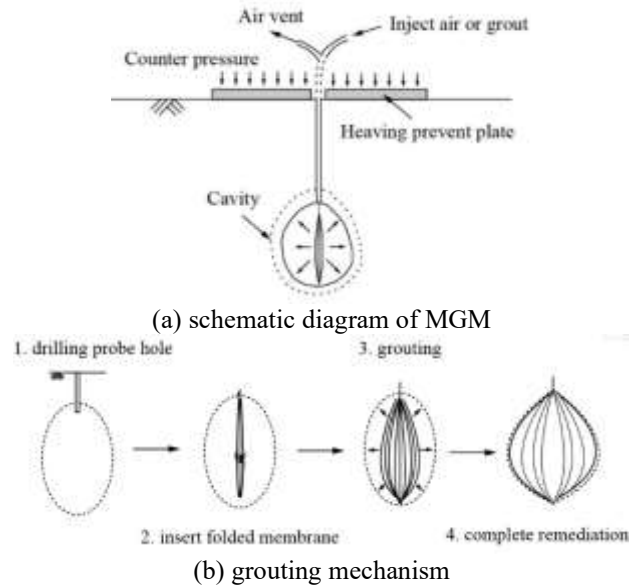


Fig. 2 The process of membrane grouting

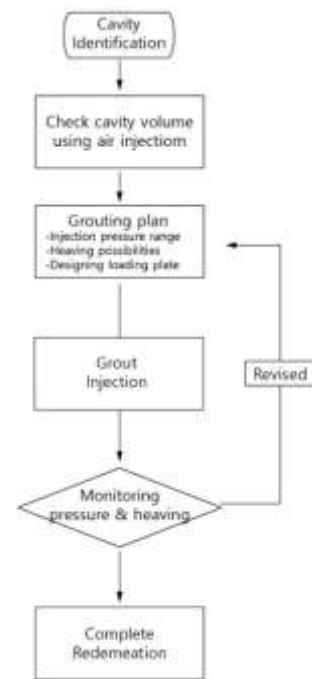


Fig. 3 Flow diagram of the MGM

Fig. 3 demonstrates the flow diagram of the MGM cavity remediation process. The upper ground is first drilled. The volume of cavity can be measured by injecting air. During this process, the loosened inner surface of the cavity can be compacted, and the amount of grout to be place can be determined.

Grout volume should be slightly oversized than the measured cavity volume. The degree of filling is checked by monitoring the injection amount and pressure.

The design of the MGM includes determination of the injection pressure and prediction of surface influences such as heaving. To control heaving it is required to determine the allowable pressure compacting the loose areas inside the

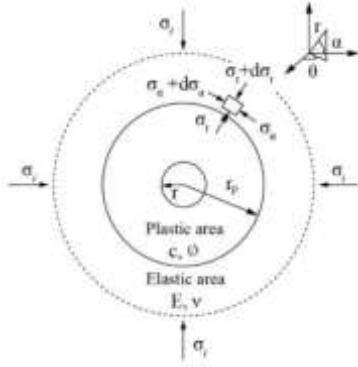


Fig. 4 Three-dimensional cavity expansion

cavity without failure of ground. If heaving possibly occurs during injection, it can be controlled by putting loading plate and surcharge on it.

It can be concluded that the injection pressure needs to be high enough to compact the loose boundary of the inside of the cavity and should be less the pressure causing heaving failure. The compacting injection pressure is the minimum pressure which causes yielding at the boundary of the cavity (P_{min}) and the pressure causing heaving failure is the maximum pressure (P_{max}). The design of MGM also requires determining the magnitude of load on a plate to limit surface deformation.

2.2 Theoretical study

2.2.1 Minimum control pressure

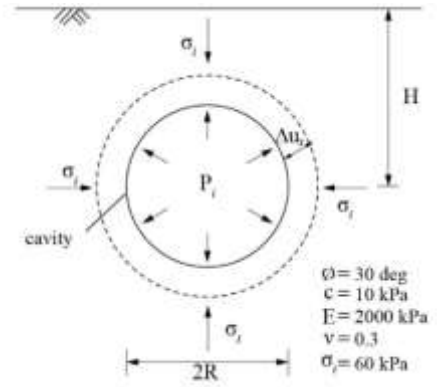
In the MGM, injection pressure applied inside the cavity compacts the loosened area along the inner boundary of the cavity. The behavior of the cavity can be evaluated with the cavity expansion theory (Zou *et al.* 2017, Thiyyakkandi *et al.* 2022). Since the cavities created in urban area generally are small enough compared to surrounding ground, the cavity can be idealized as a three-dimensional sphere in the ground.

Vesic (1972) established the three-dimensional cavity expansion theory under the conditions of isotropic expansion and central symmetry. Based on the Mohr-Coulomb criterion, the radial displacement (Δu_r) of the cavity due to the inner pressure ($r = r_p$, $\sigma_r = P_i$ at the inner boundary) is obtained as

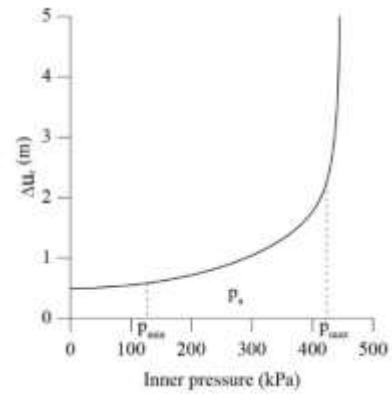
$$\Delta u_r = \frac{(1 + \nu)(\sigma_i - P_i)r^3}{2Er^2} \quad (1)$$

where ν : Poisson's ratio, E : Elastic modulus, r : radius of the cavity, σ_i : initial stress, P_i : inner pressure

The minimum inner pressure can be determined under the condition in which the cavity is fully filled, but the ground along the inner boundary of the cavity is not failed. When the grout is filled in the cavity, elastic expansion of the cavity occurs, and additional inner pressure will compact the boundary ground of the cavity. The inner pressure then can be increased until the ground reach failure condition at which pressure can be considered as the minimum pressure (P_{min}) required compact filling of the cavity (El-Kelesh *et al.* 2001).



(a) properties of ground



(b) cavity deformation-inner pressure

Fig. 5 Example determining minimum control pressure

$$P_{min} = \frac{3\sigma_i(1 + \sin\phi) + 4\cos\phi}{3 - \sin\phi} \quad (2)$$

The relevant volume changes due to the minimum inner pressure (ΔV) is obtained by combining the elastic and plastic volume changes.

$$\Delta V = \frac{4\pi}{3}(r^3 - r_i^3) = \frac{4\pi}{3} \left[r_p^3 - (r_p - \Delta u_{r(r=r_p)})^3 \right] + \frac{4\pi}{3}(r_p^3 - r^3)\delta \quad (3)$$

where $\Delta u_{r(r=r_p)}$: radial displacement increment, δ : coefficient of volume change.

To illustrate determination of the minimum control pressure inside the cavity, an example problem shown in Fig. 5(a) is considered. Properties were used of sandy soil. Based on the cavity expansion theory described above, the minimum inner pressure was calculated as 121.86 kPa. Fig. 5(b) shows the relationship between inner pressure and radial deformation. When the inner pressure is low, the slope of the relationship is mild. However, when the inner pressure exceeds a specific value, the radial deformation starts to increase rapidly, which is considered as failure state.

2.2.2 Maximum control pressure

Over-injection pressure can lead to heaving at the ground surface. Heaving generally occurs in the vertical direction, which has less confinement than other directions

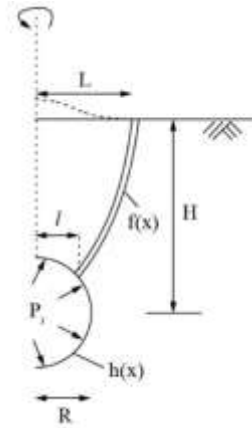


Fig. 6 Heaving failure mode due to inner cavity pressure

and may damage adjacent structures. It generally takes place in a low cover depth under high injection pressure. The heaving failure mechanism can be identified using the limit equilibrium theory or the upper limit theory.

Fig. 6 presents the conceptual model for the heaving failure due to the high inner pressure during grout injection. $f(x)$ is the function representing failure surface, $h(x)$ is the function presenting cavity shape, l is the horizontal distance from the failure surface, and L is the distance to the boundary crack caused by heaving at the ground surface. L represents the distance l where ground cracks occur, which is defined as the heaving range.

According to the upper limit theory, the energy dissipated by plastic deformation of the ground within the allowable velocity field is equal to the work done by the external load. In this case, the calculated failure load is always higher than the exact solution. If the failure load is the exact solution, the dissipated energy has a constant value. If a nonlinear ground failure criterion is assumed, the dissipated energy appears in the functional form of the failure surface function. When the variation principle is applied, the exact solution of the failure surface function and failure load can be obtained (Fraldi and Guarracino 2009, 2010, Yang and Huang 2011).

$$\Sigma W = W_D + W_Y + W_P \tag{4}$$

where W_D : dissipated energy, W_Y : gravity energy, W_P : inner pressure energy

Based on Eq. (4), using L and l , the inner cavity pressure causing heaving failure P_{max} can be calculated as follows

$$P_{max} = \frac{\gamma_c \left\{ \sin \phi \left[3 \cdot H \cdot l^2 + 2 \left((R^2 - l^2)^{\frac{3}{2}} - R^3 \right) \right] \omega + \cos \phi \cdot (L^3 - 3 \cdot L \cdot l^2 + 2 \cdot l^3) \right\} + 3 \cos \phi \cdot c \cdot (L^2 - l^2 \cdot \omega)}{3l^2 \omega \sin \phi} \tag{5}$$

where, $L = - \left\{ \frac{\omega}{\cot \phi} \sqrt{R_i^2 - l^2} - H \right\} + l$, $g = \frac{f(x)-1}{f(x)+1}$

$l = \frac{R_i}{\sqrt{g^2 + 1}}$ ($l \leq R_i$), horizontal distance from the failure surface,

$f(x)$: $f(x)$ of differential, $\omega = \frac{\cos \phi \cos \psi}{1 - \sin \phi \sin \psi}$,

R_i : radius of the cavity, H : tunnel depth, ϕ : friction angle, c : cohesion.

P_{max} is the inner pressure of the cavity to avoid surface heaving failure and can be defined as the maximum control pressure of the MGM.

2.2.3 Allowable injection pressure range and assessment

Allowable injection pressure (P_a) should be in between the pressure (P_{min}) filling and compacting the inner boundary of the cavity without failure of ground, which is considered as the minimum injection pressure, and the pressure causing heaving failure at the surface which is the maximum injection pressure (P_{max}). Therefore, allowable injection pressure (P_a) for the MGM must be controlled as the following range.

$$P_{min} < P_a < P_{max}$$

Example study to calculate the maximum control pressure was performed for the condition illustrated in Fig. 5, and the maximum pressure is calculated as 428.71 kPa.

Thus, the application of the MGM for the problem shown in Fig. 5 should be higher than 121.86 kPa to fill and compact the cavity and less than 428.71 kPa to avoid heaving failure.

3. Model tests

3.1. Model set up

Small scale model test was devised to evaluate the performance of the MGM. Considering the range of influence, the soil chamber was set to 600 mm in both width and length, and the model cavity was formed at 100 mm considering 1/10 scale effect. The selection of Jumunjin standard sand takes into account the characteristics of the sandy soil in the ground. and material properties of the soil are summarized in Table 1. The injection pressure was reproduced by using water pressure. To apply water pressure up to 40 kPa, a water tank connected to the membrane inside the cavity. Fig. 7 presents a schematic diagram of the model test.

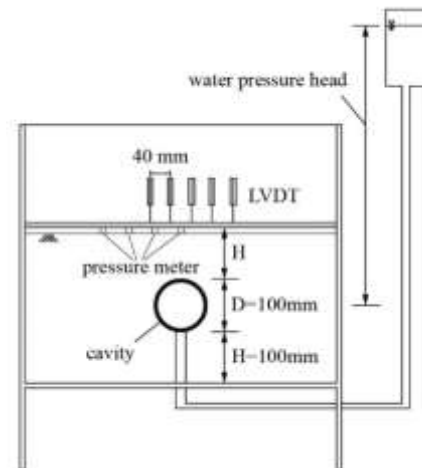


Fig. 7 Schematic diagram of the model test

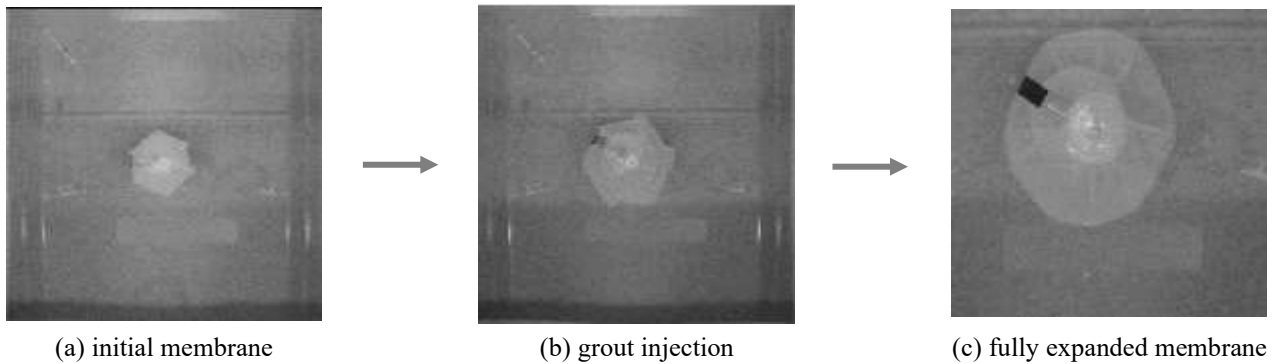


Fig. 8 Procedure of membrane expansion

Table 1 Soil properties

G_s	e	ω (%)	ϕ (°)	c (kPa)
2.65	0.911	9.36	32.7	1.58

To monitor the vertical behavior of ground, LVDTs are installed at 5 locations with intervals of 40 mm on the ground surface. For tests requiring confinement of ground heaving, a heaving prevention plate was placed to restrict vertical displacement. An earth pressure gauge was installed between the plate and ground surface.

3.2 Test cases

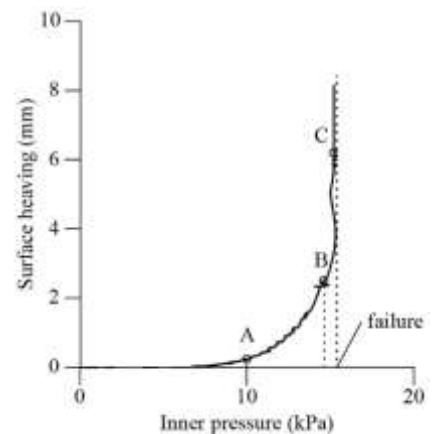
The cavity was formed using a flexible plastic sphere in the ground. Fig. 8 shows the process of the membrane expansion (MGM) during cavity remedial work.

Two types of tests were planned: the unconfined surface (US) condition without surcharge and the confined surface (CS) condition with a surcharge. In the US tests, the inner pressure was applied into membrane pocket in the cavity without surface confinement. Meanwhile, in the CS tests, the surface deformation was restricted by using heaving prevention plate. During the tests, and the surface displacement, heaving pressure, and heaving range (distance from the center of cavity to the circular crack due to heaving) were monitored.

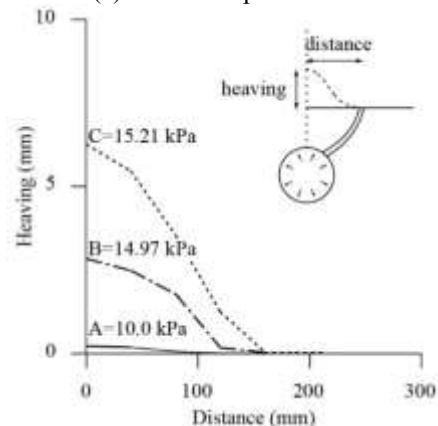
Influencing factors involved in the MGM are several. However, in the model test, only the cavity depth and surface confinement are considered. For the US tests, 3 cases of cavity depth are considered, in which the cover depth to the cavity diameter are 0.5(HP-0.5), 1.0(HP-1.0) and 1.5(HP-1.5). In the UC test, only the case in which the cover depth to cavity diameter is 1.0 is considered (OP-1.0).

3.3 Test results

In the US tests, the inner pressure applied was increased constantly by up to about 0.025 kPa~0.03 kPa. Fig. 9(a) presents the surface heaving with an increase in inner pressure for the case of HP-1.0. The heaving range expanded until the ground reaches a failure state as shown in Fig. 9(b). However, when the inner pressure reaches the



(a) surface displacement



(b) heaving

Fig. 9 Results of US tests (HP-1.0)

highest value which indicates ground failure, only the vertical displacement occurred without further increase in lateral extension of heaving range.

Fig. 10 compares the surface displacement at the failure state for the test case of HP-0.5, HP-1.0, and HP-1.5. The shape of deformation is similar to Gaussian probability distribution curve which observed at the ground surface during tunnel excavation.

Fig. 11 shows plan view of the heaving process for the test cases of HP-0.5, HP-1.0, and HP-1.5. Initially, cracks occurred only locally at the surface just above the cavity, however as the inner pressure increased, the heaving

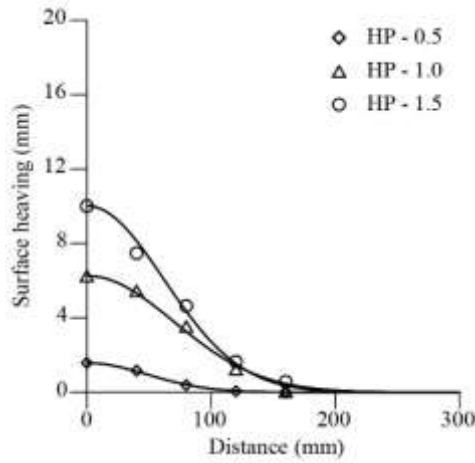


Fig. 10 Surface displacements at failure (US-tests)

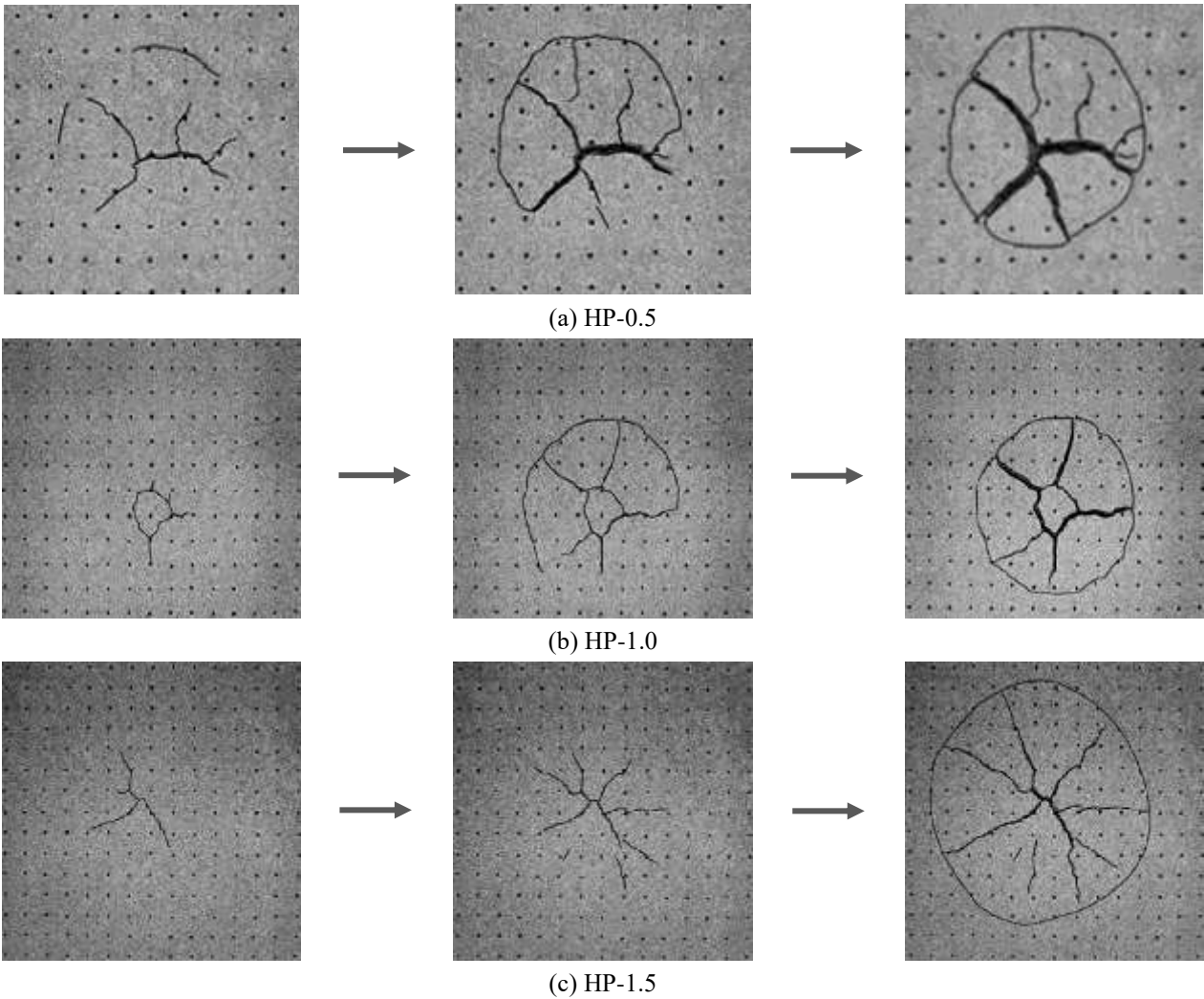


Fig. 11 Surface heaving procedure (US-tests)

ranges(cracks) have gradually expanded. Once the inner pressure reached a certain ultimate pressure, the heaving range did not expand further. It is shown that the increase of cavity depth increases the range of heaving due to the dilative behavior of sand.

The maximum surface displacement for different cavity depths is shown in Fig. 12(a). The maximum inner pressure increases with an increase in cover depth. The heaving pressures from model tests were compared with those from theory in Fig. 12(b), and both results showed good agreement.

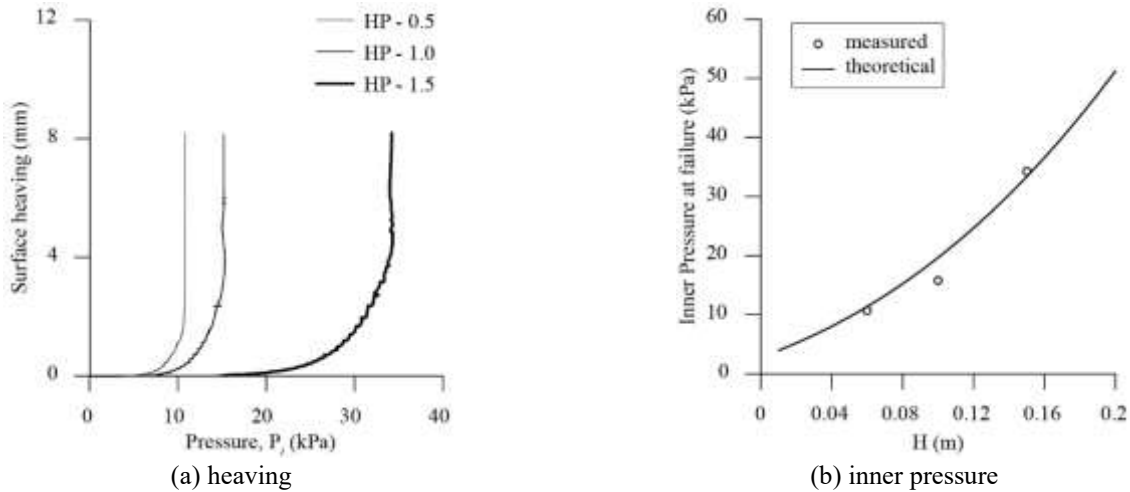


Fig. 12 Effect of cavity depth

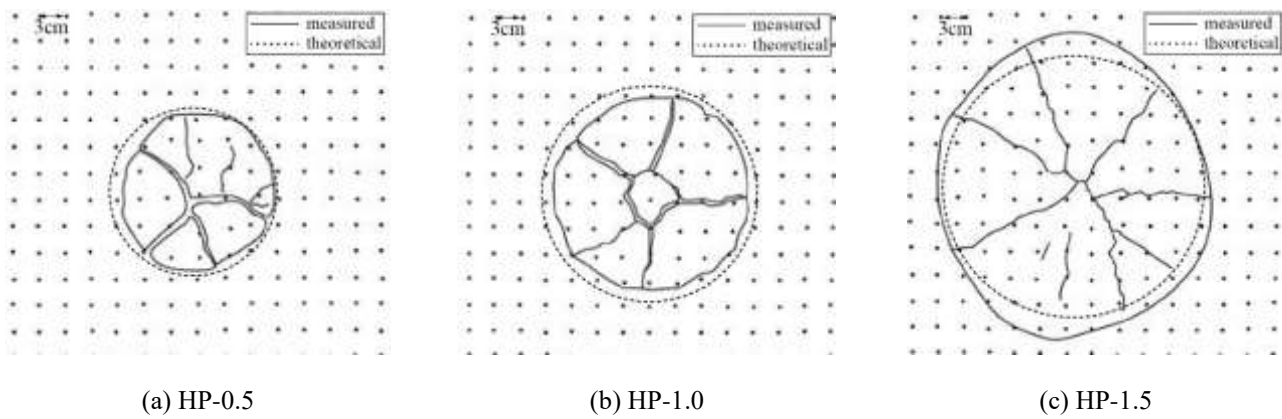


Fig. 13 Comparison of heaving ranges at failure

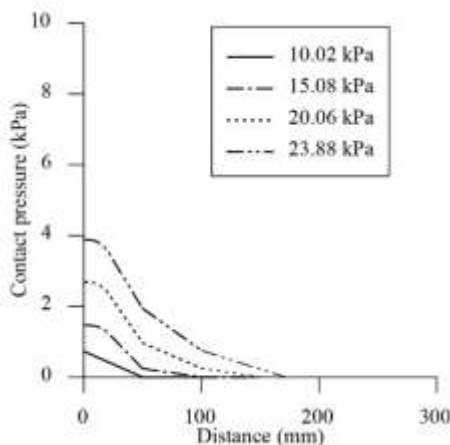


Fig. 14 Contact pressures during pressurization (OP-1.0)

Fig. 13 compares the plan views of the heaving range for the model test and theoretical analysis. They also show good agreement.

Test under the CS condition in which a loading plate was set on the surface to confine surface displacement were performed only for the case of $H/D=1$ (OP-1.0). Fig. 14

shows the contact pressure between the plate and ground surface during pressurization. The contact pressure was concentrated at the plate's center. This implies that to restrict surface heaving in practice, center-oriented surcharge or center-enhanced stiffness loading plate can effectively control the heaving deformation.

4. Numerical study on influencing factors

4.1 Numerical modelling of contact behavior between cavity and membrane

Implementing the MGM requires modelling of the contact behavior between the membrane and the ground. If the grout injection pressure is low, interaction between the membrane and the ground can be neglected. However, if the injection pressure causes yielding of surrounding ground, the contact and sliding behavior between the membrane and the ground becomes significant. The contact behavior can be determined by the relative position and defined by the gap function. The sliding behavior between membrane and ground can be identified by Coulomb's law (Lauren 2002).

Table 2 Analysis cases

Variable Parameter	Ground properties				Shape factor	
	E_g (MPa)	ϕ (°)	ψ (°)	c (kPa)	H/D^*	b/a^{**}
Representative Properties	20	30	0	10	0.5	1
Range	10, 20, 30, 100, 1000	20, 25, 30, 35, 40	0	0, 5, 10, 15, 20	0.3, 0.5, 1, 1.5, 3	0.25, 0.64, 1, 1.6, 4

* H/D =cavity relative depth, H =cover depth, D =cavity diameter

** b/a , a =vertical radius, b =lateral radius

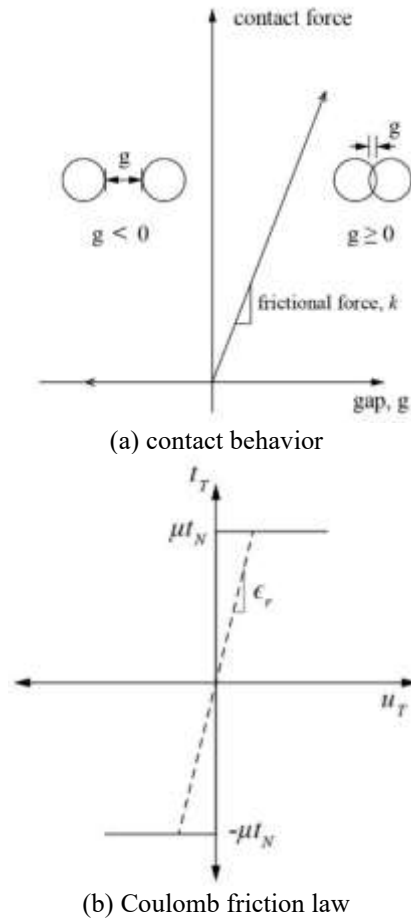


Fig. 15 Schematic illustration of contact modelling

$$F_T < \mu \cdot F_N: \text{stick condition} \quad (6)$$

$$F_T \geq \mu \cdot F_N: \text{slip condition} \quad (7)$$

where F_N : vertical contact force, F_T : tangential contact force, μ : coefficient of friction

Fig. 15 illustrates the contact and sliding behavior based on relative positions of bodies. In numerical analysis, the modelling of contact behavior generally involves the use of the contact force method and the frictional force method. The contact force method is applied to strictly prevent any inter-element penetration, ensuring precise adherence to contact constraints (Lin *et al.* 2016). In this study, the frictional force method is used, as it allows inter-element penetration by imposing contact stiffness.

To simulate the MGM, the expansion of the membrane element inside the cavity was considered as a contact problem. The membrane element is assumed to be elastically expanding to fulfill the entire cavity. The modelling range was set to 5 times the cavity diameter in consideration of the membrane grouting impact. The initial stress around the cavity was implemented by adding a process of excavating the cavity, and the Mohr-Coulomb model was used.

The effects of the design parameters of the MGM were investigated using the contact modelling method. The factors considered are the ground properties and cavity geometry such as depth and flatness. Analysis cases are listed in Table 2.

4.2 Results of the analysis

The effects of parameters are investigated with respect to heaving pressure (p_h) which is injection pressure causing heaving failure, heaving range (L_h), contact pressure (p_c) and failure mode of ground. Heaving range is normalized by representative heaving range (L), L_h/L and injection pressure (p_i), p_c/p_i respectively.

4.2.1 Effect of the ground stiffness

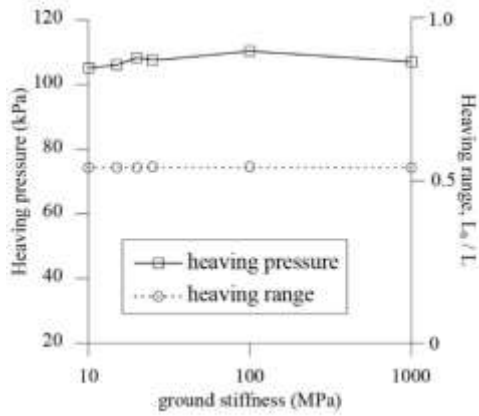
Fig. 16(a) shows the results of heaving pressure and heaving range under the US condition. It shows that the effects of ground stiffness are not significant. Fig. 16(b) presents the failure mode which develops upward without lateral expansion.

Contact pressure between plate and ground surface under the CS condition is shown in Fig.17. It shows that as the ground stiffness increases, the contact pressure decreases, which means less surcharge is required to confine ground displacement.

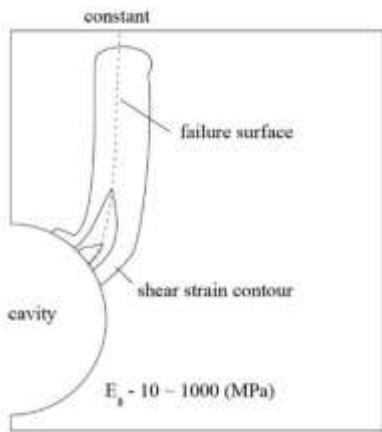
4.2.2 Effect of angle of shear resistance

Fig. 18(a) presents the effect of the shear resistance angle under the US condition. The pressure causing heave has slightly increased, as the angle of shear resistance increases. However, the heaving range decreased as the angle of shear resistance increased, and the failure mode gradually moved toward the surface as shown in Fig. 18(b).

Under the CS condition, the contact pressure decreases as the shear resistance angle increases. This is because increase in the shear resistance angle strengthens the ground, so that the inner pressure reaching the ground surface decreases. Therefore, it can be concluded that the effect of shear resistance angle on the MGM is significant.

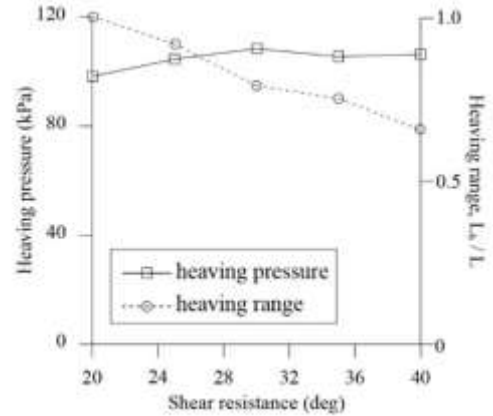


(a) heaving pressure and range

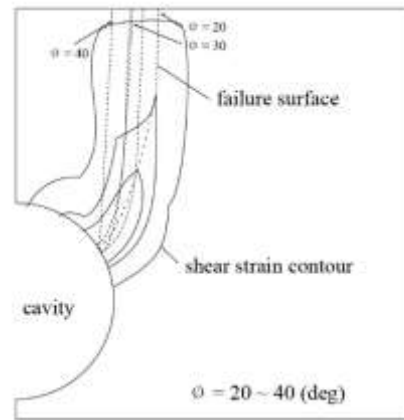


(b) failure mode

Fig. 16 Effect of ground stiffness (US condition)



(a) heaving pressure and range



(b) failure mode

Fig. 18 Effect of shear resistance (US condition)

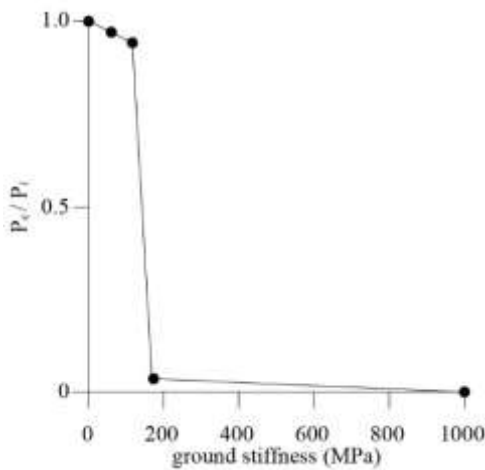


Fig. 17 Effect of ground stiffness on contact pressure (CS condition)

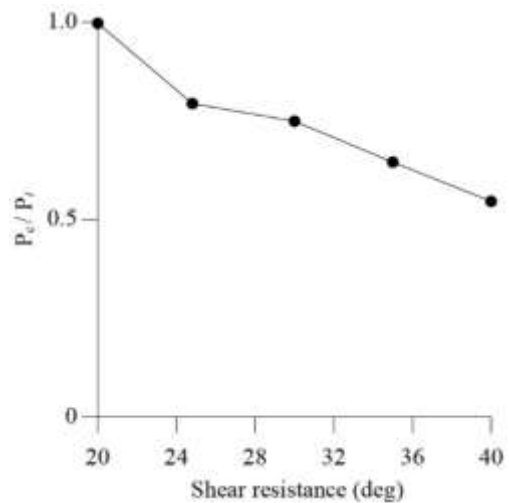
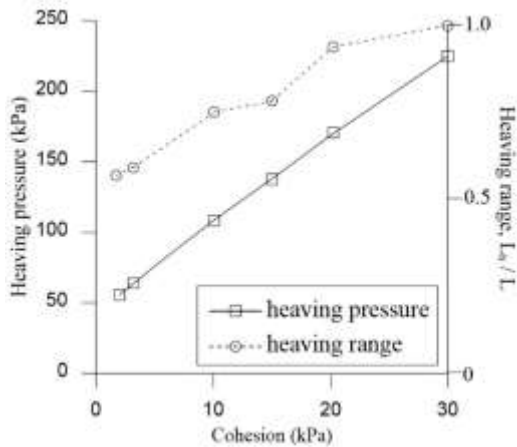


Fig. 19 Effect of shear resistance angle on contact pressure (CS condition)

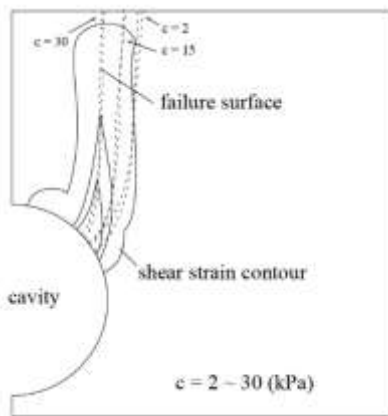
4.2.3 Effect of cohesion

Fig. 20 presents the effect of the cohesion. In the US condition, the heaving pressure and range have increased with an increase in cohesion. According to the limit theory, the cohesion is independent of the shape of the failure surface. However, the effect of cohesion on the failure mode became apparent when the friction force is mobilized at the interface between membrane and ground.

Under the CS condition, the contact pressure decreases with an increase in cohesion (Fig. 21). Increase in cohesion increases the contact pressure by up to approximately 25% or more. This indicates that as cohesion increases, elastic zone becomes wider and consequently the injection pressure is directly transmitted to the ground surface in a more linear and vertical direction.



(a) heaving pressure and range



(b) failure mode

Fig. 20 Effect of cohesion (US condition)

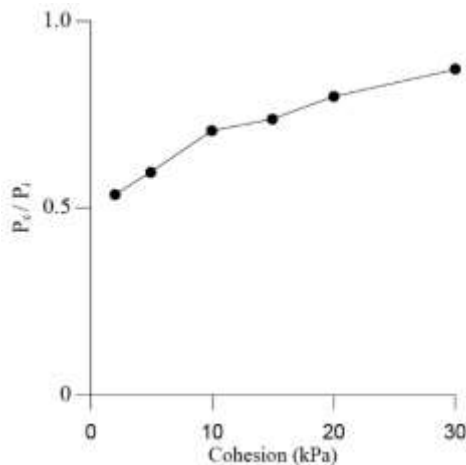


Fig. 21 Effect of cohesion on contact pressure (CS condition)

4.2.4 Effect of cavity relative depth

Fig. 22 shows the results of the analysis on the effect of cavity depth under the US condition. The heaving pressure and range exhibit a linear relationship with the cavity depth. This finding is consistent with the results of the theoretical analysis, indicating that a deeper cavity requires a higher injection pressure to fill it.

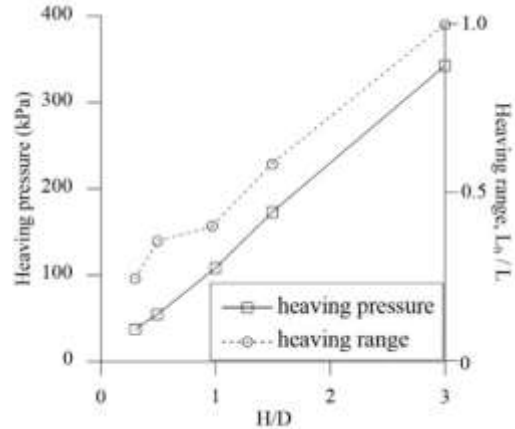


Fig. 22 Effect of cavity depth on heaving (US condition)

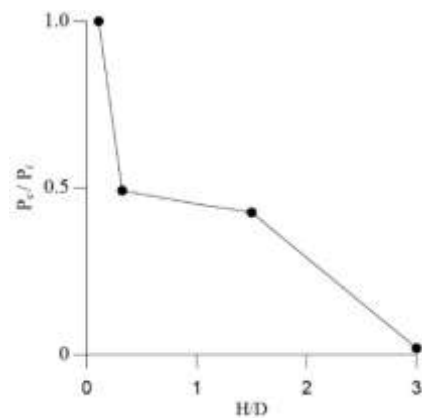


Fig. 23 Effect of cavity depth on contact pressure (CS condition)

In the CS condition, the magnitude of the contact pressure decreased by up to 16% or more with an increase in cavity depth (Fig. 23). As the cavity depth increases, the injection pressure transmitted to the ground surface is widely distributed, resulting in a smaller impact on the ground. Therefore, it can be concluded that the relative depth of the cavity is the most significant factor in the design of the MGM.

4.2.5 Effect of cavity flatness

Results for the cavity geometry (flatness) are shown in Fig. 24. As the flatness increases, the heaving pressure and range increased. This is because of the increase in the failure area above the cavity. In the case of a flatness of 0.25, the failure surface did not reach the surface, but just was formed around the cavity. However, when the flatness increased, the heaving pressure increased, and the heaving range widened as the failure area increased.

Under the CS condition, as the inner pressure increased, the contact pressure has decreased. This behavior is related to the ground failure mode: a cavity with small flatness transmits the inner pressure to the ground surface near the cavity, meanwhile a cavity with large flatness transfers the inner pressure to the surface in wider range of the ground, which reduces the contact pressure.

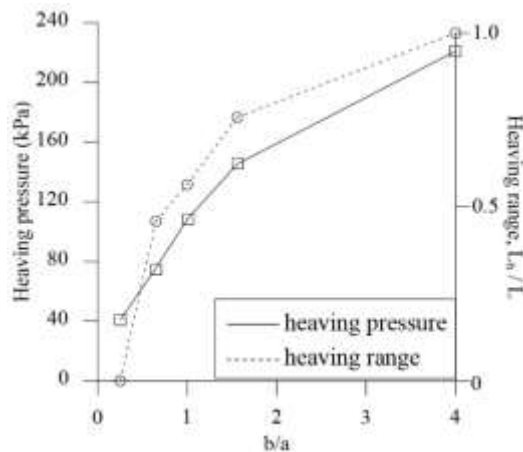


Fig. 24 Effect of flatness (US condition)

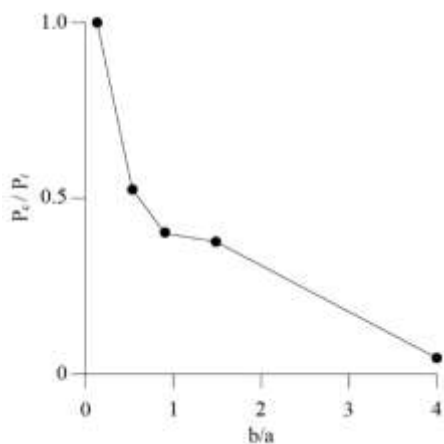


Fig. 25 Effect of flatness on contact pressure (CS condition)

5. Conclusions

In this study, to measure problems facing at the cavity remedial work, a new cavity remediation method termed as membrane grouting method (MGM) was proposed. The effects of various factors were investigated for the application of the MGM.

The behavior of the ground during cavity injection was investigated using the cavity expansion and the limit theories, then a series of model tests were performed to validate the proposed method. A numerical parametric study was conducted to evaluate the effects of design parameters. The results can be summarized as follows:

a. Implementation of the MGM requires controlling the injection pressure. The pressure should be higher than yielding stress of the inner boundary of the cavity, and less than the pressure causing surface heaving failure.

b. The key control parameter of the MGM is the injection pressure, and its minimum and maximum values can be obtained by cavity expansion theory and limit equilibrium method respectively.

c. Surface heaving can be confined by introducing loading plate with surcharge. Increase in cavity depth, cavity flatness and ground stiffness significantly reduce the contact pressure between the plate and ground surface.

d. Numerical parameters study on the design factors showed that the effects of cavity geometry such as depth and flatness are significant. Meanwhile the effects of ground properties except ground stiffness are relatively small.

If a cavity is identified in advance and is considered to recover the cavity, the MGM can be a more economical and eco-friendly restoration than the trench-based cut & cover remediation. Particularly, in urban area where small and large cavities occur frequently, the proposed MGM can be effectively applicable as a rapid and non-destruction remedial method.

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