

Article

Applicability of Weighting Method as Measure for Existing Manholes against Uplifting during Liquefaction

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Abstract: It has been confirmed that manholes may protrude from the road surface due to the liquefaction of the ground during a large earthquake. When the uplifting of a manhole occurs, it may bring about not only dysfunctions, such as the loss of the ability of sewage to flow, but also displacements, such as that of the pipeline connected to the manhole, which makes drainage difficult. However, effective and economic measures against the uplifting of existing manholes are still in the developmental stages. This study proposes a weighting method that increases the self-weight of the manhole as a countermeasure against the uplifting of manholes during an earthquake. The applicability of this weighting method will be clarified by conducting case studies from the viewpoint of the safety factor for manhole uplifting and the quantity of manhole uplifting. As a result, it is shown that, regardless of the shape of the manhole and the groundwater level, the risk of manhole uplifting during liquefaction can be reduced by implementing this weighting method.

Keywords: groundwater; liquefaction; manhole; uplifting; weighting method



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1. Introduction

It has been confirmed that manholes may protrude from the road surface, as shown in Figure 1, due to the liquefaction of the ground during a large earthquake. As a result, the sewerage pipeline that connects to the manhole underground can become damaged. The Great East Japan Earthquake of 2011 caused enormous damage to reclaimed coastal areas of Tokyo Bay and, according to the Ministry of Land, Infrastructure, Transport and Tourism, Japan, the total number of damaged manholes reached 6699 [1–3].

When the uplifting of a manhole occurs, it may bring about not only dysfunction, such as the loss of the ability of sewage to flow, which is the original function of sewerage, but also displacements, such as that of the pipeline connecting the manhole, which makes drainage difficult [4]. This also means that water cannot be used, which hinders people's lives and affects environmental hygiene. Therefore, it is necessary to improve the stability of manholes during earthquakes, because their instability could also cause traffic dysfunctions, such as the obstruction of important emergency transportation routes immediately after a disaster, which would take time to restore.

As measures against the liquefaction of sewerage pipeline facilities currently in use, the compaction of backfill soil, backfilling with crushed stones, improvement of the solidification of the backfill soil, and methods of releasing pore water pressure into manholes have been devised. However, effective and economic measures against the uplifting of existing manholes are still in their developmental stages.

Therefore, this study proposes a weighting method that increases the self-weight of the manhole as a countermeasure against the uplifting of manholes during earthquakes.

The applicability of this weighting method will be clarified by conducting case studies from the viewpoint of the safety factor F_S for manhole uplifting and the quantity (Δf) of the manhole uplifting.



(a)



(b)



(c)

Figure 1. Examples of manhole damage caused by earthquake. (a) Case of manhole uplifted due to earthquake (b) Case of ground subsidence around manhole (c) Case where ground and manhole move separately.

2. Overview of Manholes and Weighting Method

2.1. Manholes

A manhole is a vertical hole made to connect the surface of the ground with a sewer pipeline, or electric or communication cables buried underground [4,5]. It is mainly made for the purposes of the inspection, repair, and cleaning of underground facilities. Manholes usually have a cover to prevent anything or anyone from falling into them. Most manhole covers are made of steel. Many of them are circular in shape in order to prevent them from falling in [6]. Manhole covers are made to be very heavy to prevent them from being easily opened or stolen. The surface of these covers has irregularities to prevent them from being slippery. In addition, a small hole is made in advance in each cover to stop the cover from

being blown away due to pressure applied when a large amount of rainwater flows into the sewer pipeline.

The reinforced concrete manhole assembly basically consists of a single slanted wall at the top, straight walls in the middle and at the bottom, a steel cover, a receiving frame, an adjustment part, and so on. Each part is prefabricated at a factory and then installed on site. This type of manhole is easy to assemble and is widely used in sewerage projects. In 1989, it was certified by the Japan Sewage Works Association (JSWA) as a “manhole made of reinforced concrete for sewerage”, as shown in Table 1, as the domestic standard [7]. Manholes with an inner diameter of 750 to 2200 mm have been put into practical use. Furthermore, the height of all types of manholes varies from 1 to 4.5 m and is determined based on the individual site conditions.

Table 1. Types of manholes in practical use in Japan (Japan Sewerage Association).

Name	No. 0	No. 1	No. 2	No. 3	No. 4	No. 5
Inner diameter (mm)	750	900	1200	1500	1800	2200

2.2. Weighting Method

As shown in Figure 2, a weighted ring is installed around the upper part of the manhole body, and a joint fitting is placed between the manhole body and the receiving frame where the manhole cover is installed. By joining the receiving frame and the manhole body via a joining member, the weighted ring and the manhole body are connected, and the space between the weighted ring and the manhole body is filled with non-shrink mortar and then floated by integration. The features of the weighting method are that it is low in cost, saves space due to its range in construction, causes no effect on buried objects, and that the weighted ring can be adjusted from one to three steps [8].

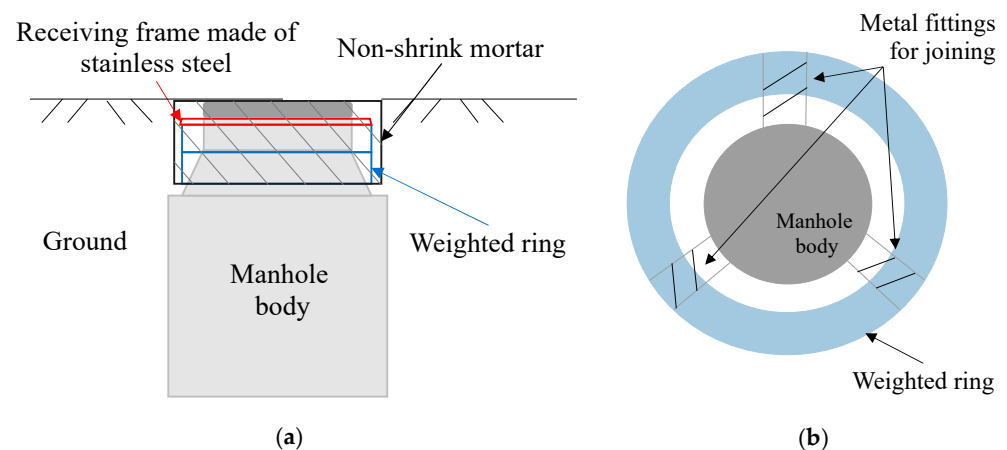


Figure 2. Outline of structure of weighting method. (a) Cross-sectional view (b) Plan view.

3. Method for Evaluating Stability of Manholes during Liquefaction

3.1. Mechanism of Manhole Uplifting

Liquefaction of the ground is a phenomenon in which the loosely deposited saturated sandy ground receives repeated shear loads due to an earthquake or similar event, such that the pore water pressure between the sand particles increases and the shear resistance (effective stress) of the sand particles decreases. That is, the ground behaves like a liquid. When liquefaction occurs, sand boils (a phenomenon in which sand is blown up to the surface of ground) and fountains are seen, and the ground is compressed and subsides. Then, the fluidized backfill soil wraps around the bottom of the manhole, the frictional force on the peripheral surface of the manhole is reduced, and the (self-weight of manhole + frictional force on peripheral surface) becomes smaller than the uplifting pressure, causing manhole

uplifting. Figure 3 shows the mechanism of the occurrence of manhole uplifting due to liquefaction generated by an earthquake [9–14].

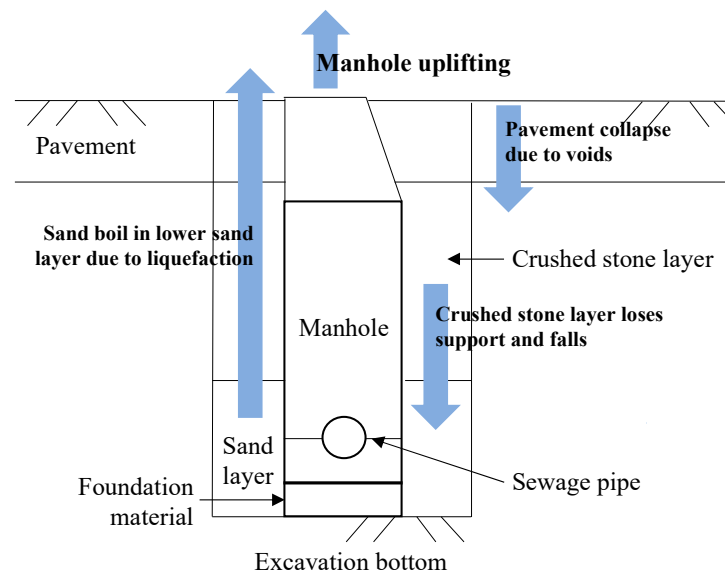


Figure 3. Mechanism of occurrence of manhole uplifting due to earthquake.

When the lower sand layer is locally liquefied, the upper crushed stone layer (fluidized backfill soil) loses its bearing capacity. Therefore, the upper crushed stone layer (fluidized backfill soil) and the pavement fall due to the loss of support from below, resulting in depressions in the ground surface. In addition, although it depends on the relationship between the depth of the manhole and the groundwater level, the manhole alone cannot maintain stability against buoyancy. Therefore, even if liquefaction does not occur, manhole uplifting may occur if the restraint from the surrounding ground is lost.

3.2. Safety Factor for Manhole Uplifting (F_S)

When a manhole with a certain diameter exists from a predetermined depth to the surface of the ground, the safety factor (F_S) for manhole uplifting can be estimated using Equation (1).

$$F_S = \frac{W_S + W_B + Q_S + Q_B}{U_S + U_D} \quad (1)$$

where F_S is the safety factor for manhole uplifting, W_S is the load of overlaid soil on the surface of the ground, W_B is the self-weight of the manhole, Q_S is the shear resistance of the overlaid soil, Q_B is the frictional resistance on the side surface of the manhole, U_S is the uplifting pressure due to hydrostatic pressure loading on the bottom of the manhole, and U_D is the uplifting pressure due to excess pore water pressure loading on the bottom of the manhole.

3.2.1. Load of Overlaid Soil on Surface of Ground (W_S)

The load of the overlaid soil on the surface of the ground (W_S) is the load of the soil to be placed on the upper part of the deck; this is estimated using Equation (2).

$$W_S = \sum \{ (A_i \times h_i - V_i) \times \gamma_{ti} \} \quad (2)$$

where A_i is the loading area (m^2), h_i is the layer thickness (m), V_i is the member volume (m^3) with respect to the layer thickness, and γ_{ti} is the unit volume weight of the soil (kN/m^3).

3.2.2. Self-Weight of Manhole (W_B)

The self-weight of the manhole (W_B) is estimated with Equation (3) in consideration of the weight applied by the weighting ring.

$$W_B = W_M + W_W \quad (3)$$

where W_M is the weight of the manhole (kN) and W_W is the weight applied by the weighting ring (kN).

3.2.3. Shear Resistance of Overlaid Soil (Q_S)

The shear resistance (Q_S) of the overlaid soil on the upper part of the deck is estimated from the total shear resistance in each layer for the overlaid soil; it is estimated with Equation (4).

$$Q_S = \Sigma \{ K_{0i} \times \sigma_{Vi} \times A_{si} \times \tan \phi_i \} \quad (4)$$

where K_{0i} is the coefficient of earth pressure at rest, σ_{Vi} is the effective overburden pressure at the center of the layer (kN/m²), A_{si} is the lateral surface area of the layer (m²), and ϕ_i is the internal friction angle (°). In principle, Q_S for the overlaid soil is not considered in the liquefied ground; thus, the Q_S of the liquefied ground (ground deeper than the groundwater level) is regarded as 0.

3.2.4. Frictional Resistance on Side Surface of Manhole (Q_B)

The frictional resistance force (Q_B) on the side surface of the manhole is estimated from the total frictional resistance force on the side surface of the manhole in each layer using Equation (5).

$$Q_B = \Sigma \left\{ K_{0i} \times \sigma_{Vi} \times A_{mi} \times \tan \frac{2}{3} \phi_i \right\} \quad (5)$$

where A_{mi} is the lateral surface area of the manhole (m²). In principle, the Q_B on the side surface of the manhole is not considered in a liquefied ground; thus, the Q_B of the liquefied ground (ground deeper than the groundwater level) is regarded as 0.

3.2.5. Uplifting Pressure Due to Hydrostatic Pressure Loading on Bottom of Manhole (U_S)

The uplifting pressure on the bottom of the manhole (U_S), due to the hydrostatic pressure acting on it, is estimated using Equation (6).

$$U_S = \gamma_w (Z_B - Z_W) \times A \quad (6)$$

where γ_w is the unit volume weight of water (kN/m³), Z_B is the depth to the bottom of the manhole (m), Z_W is the depth to the water table (m), and A is the area relative to the outer diameter of the manhole (m²).

3.2.6. Uplifting Pressure Due to Excess Pore Water Pressure Loading on Bottom of Manhole (U_D)

The uplifting pressure on the bottom of the manhole (U_D) due to excess pore water pressure loading is estimated using Equation (7).

$$U_D = \Delta u \times A = L_u \times \sigma'_V \times A \quad (7)$$

where Δu is the excess pore water pressure (kN/m³), A is the area relative to the outer diameter of the manhole (m²), σ'_V is the effective loading pressure (kN/m²) in the soil at the same depth as the bottom surface of the manhole under hydrostatic pressure, and L_u is

the excess pore water pressure ratio. Excess pore water pressure ratio L_u is estimated with Equation (8) using the resistance value (F_L) against liquefaction [4,5].

$$\left. \begin{aligned} L_u &= F_L^{-7} & (F_L \geq 1) \\ L_u &= 1 & (F_L < 1) \end{aligned} \right\} \quad (8)$$

In this study, U_D is estimated based on the assumption that the ground is liquefied with a resistance value of $F_L < 1$ against liquefaction.

The weighting method is a construction method in which the F_S is estimated using the balance of forces in the vertical direction at the time of an earthquake, as described above, and the vertical load is increased by the self-weight of the manhole, such that the F_S is equal to or greater than the predetermined value. Therefore, the physical significance is relatively clear.

This study adopted a value of 1.1 as the standard for evaluating the F_S , because $F_S \geq 1.1$ is one of the design criteria for manholes set by the Japan Sewage Works Association (JSWA). The change in F_S and the effect of the weighting method on F_S are considered.

3.3. Quantity of Manhole Uplifting (Δf)

The quantity (Δf) of manhole uplifting can be estimated using Equation (9) [15], assuming that the backfill soil is completely liquefied, and the excavation range is sufficiently larger than the diameter of manhole, as shown in Figure 4.

$$\Delta f = \left(1 - \frac{\gamma_m}{\gamma_{sat}}\right)h - \left(1 - \frac{\beta\gamma_t}{\gamma_{sat}}\right)d - \frac{F_S}{\pi\gamma_{sat}}\left(\frac{2}{c}\right)^2 \quad (9)$$

where Δf is the quantity of displacement for manhole uplifting, γ_m is the manhole unit volume weight, γ_{sat} is the soil saturation unit volume weight, h is the vertical length of the manhole, β is the excess pore water pressure ratio, γ_t is the unit volume weight of the non-liquefied soil layer shallower than the groundwater level, d is the depth of the groundwater level from the ground surface, F_S is the frictional force acting on the peripheral surface of the manhole, and c is the diameter of the manhole.

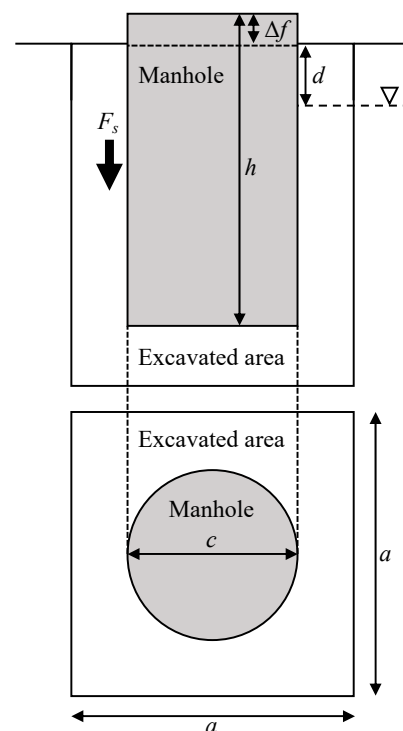


Figure 4. Relative relationship between excavation range and manhole assumed in analysis.

4. Stability Evaluation against Liquefaction

4.1. Analysis Patterns and Conditions

To make a comparison based on the manhole shape, the applicability of the weighting method will be examined using circular manholes, Nos. 1, 2, and 3, presented in Figure 5 and Table 1. The upper floor slab type is adopted as the shape of each circular manhole, and the analysis is performed on a saturated ground where the risk of liquefaction is high. In addition, for the No. 1 circular manhole, in order to examine the effect of the groundwater level in the ground around the manhole, the groundwater level is set to 0, 0.5, 1.0, 1.5, and 2.0 m, respectively.

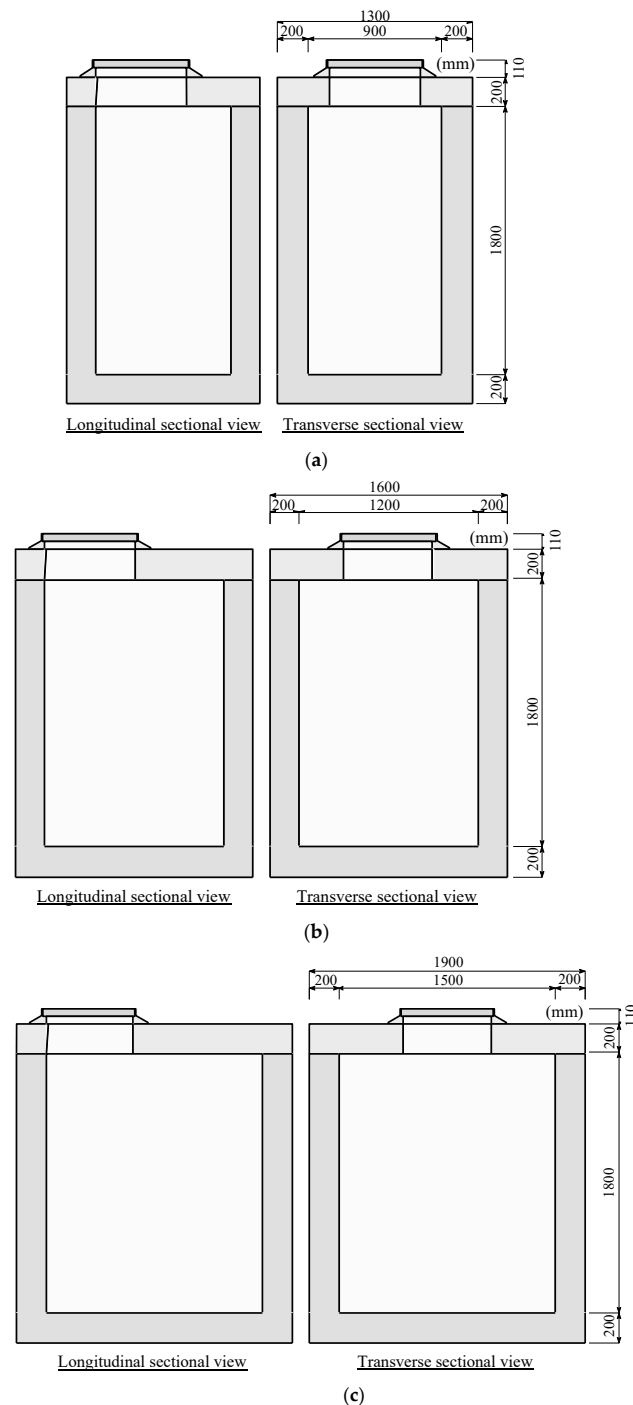


Figure 5. Specific dimensions of manholes Nos. 1, 2, and 3 in analysis. (a) No. 1 manhole (b) No. 2 manhole (c) No. 3 manhole.

The analysis conditions for the manholes are set as given in Table 2. The ground conditions around the manholes are shown in Table 3. When calculating the F_S and the Δf , it is assumed that the ground around the manholes below the groundwater level was liquefied ground. Figure 6 shows a schematic diagram of the analysis conditions.

Table 2. Assumed conditions for manhole.

Name of Manhole	No. 1	No. 2	No. 3
Circular manhole cover “circular iron cover 600 T25”, weight (kN)	0.908	0.908	0.908
Circular floor slab “outer diameter \times 600 \times 200”, weight (kN)	5.099	8.434	12.553
Side wall and bottom plate, unit volume weight (kN/m ³)	23.00	23.00	23.00

Table 3. Assumed conditions for ground around manhole (sandy soil).

Unit volume weight shallower than groundwater level of soil, γ_t (kN/m ³)	18.0
Saturation unit volume weight of soil, γ_{sat} (kN/m ³)	19.0
Unit volume weight of groundwater, γ_w (kN/m ³)	10.0
Internal friction angle, ϕ (°)	30
Coefficient of earth pressure at rest K_0	0.5

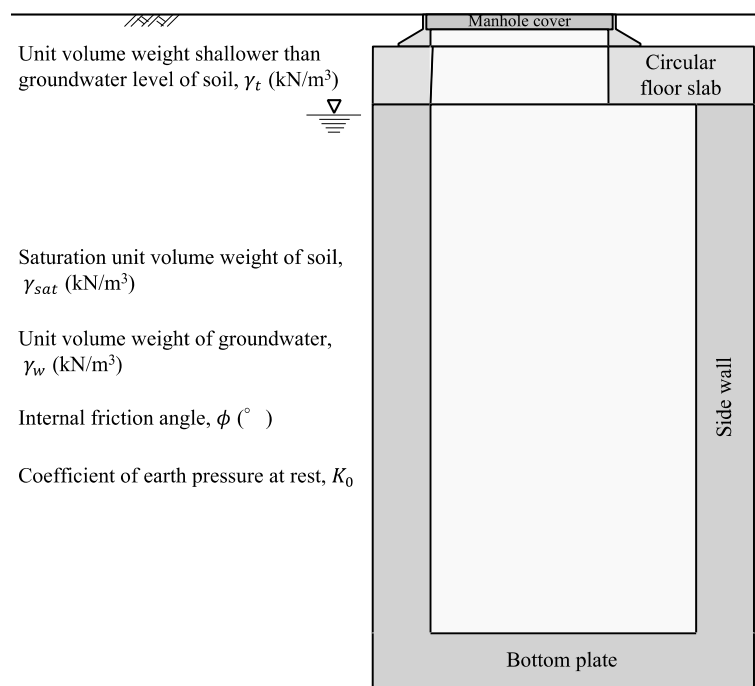


Figure 6. Schematic diagram of analysis conditions.

4.2. Comparison by Manhole Shapes

Figures 7 and 8 show the analysis results for the F_S and the Δf , respectively, of circular manholes Nos. 1, 2, and 3. When the weighting method is not applied to a manhole, the F_S is below 1.1, the standard for evaluating all shapes, and the Δf is also confirmed to be more than 0. In other words, not applying the weighting method creates an analysis condition with a very high risk of manhole uplifting when liquefaction occurs. In addition, the F_S increases and the Δf decreases as the weight applied by the weighting ring is increased in the weighting method for all shapes, so the weighting method can suppress the risk of manhole uplifting when liquefaction occurs. Moreover, the larger the manhole diameter, the higher the risk of manhole uplifting. By implementing the weighting method for a manhole in the ground where the manhole is likely to experience uplift when liquefaction occurs, the risk of manhole uplifting can be reduced regardless of the shape of the manhole.

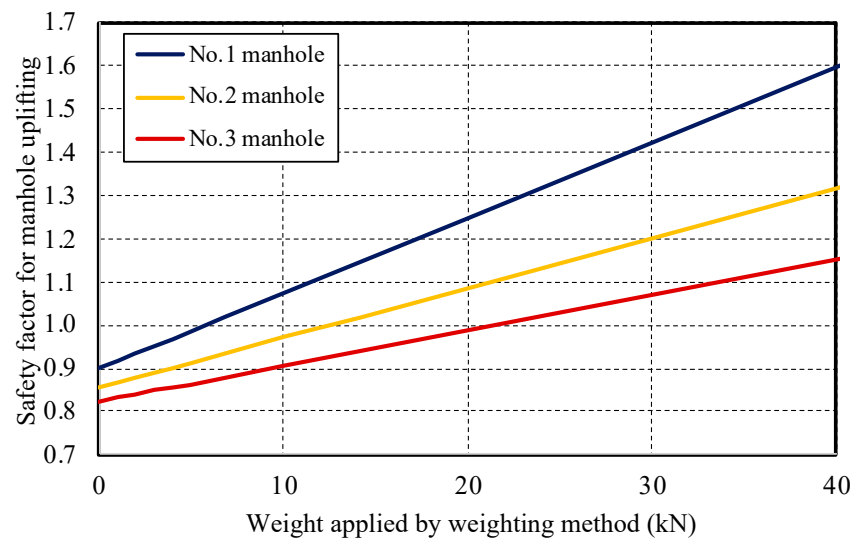


Figure 7. F_S for circular manholes Nos. 1, 2, and 3.

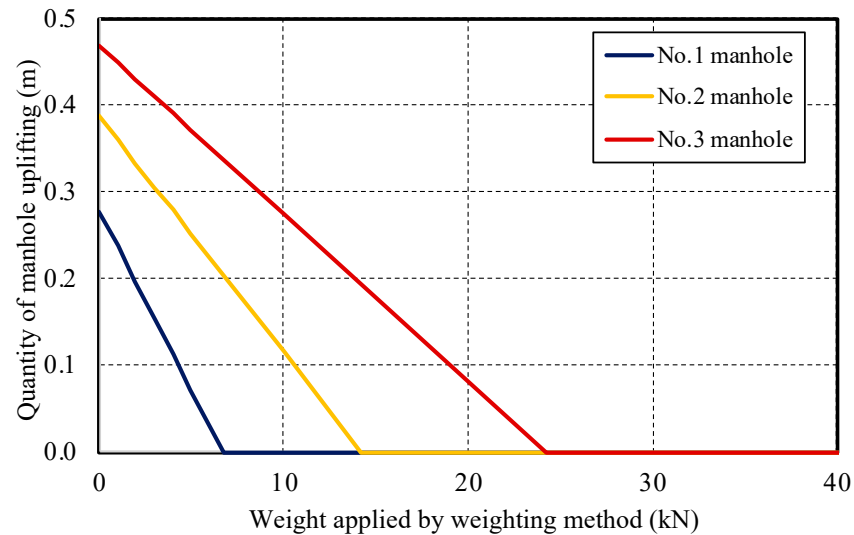


Figure 8. Δf for circular manholes Nos. 1, 2, and 3.

4.3. Comparison by Groundwater Level

Figure 9 shows the analysis results of the F_S for the No. 1 circular manhole when the groundwater level of the ground around the manhole is changed, while Figure 10 shows the analysis results of the Δf for the No. 1 circular manhole when the groundwater level of the ground around the manhole is changed. It is confirmed that the F_S increased and the estimated Δf decreased as the groundwater level decreased. The major factors for this are considered to be the decrease in lifting pressure due to the decrease in the groundwater level and the effect of the generation of shear and frictional resistance below the groundwater level. In addition, the increasing rate of the F_S and the decreasing rate of the Δf , accompanying the increase in weight applied by the weighting ring, are almost equal at each groundwater level. The effect of the weighting method on manholes of the same shape is considered to be independent of the groundwater level. From the above, it is considered that the weighting method can reduce the risk of manhole uplift regardless of the groundwater level of the ground around the manhole.

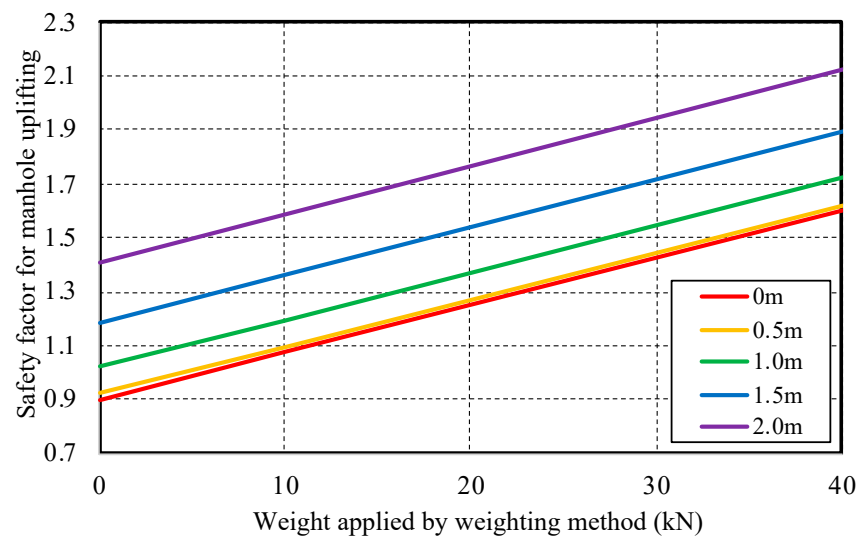


Figure 9. F_s for No. 1 circular manhole when groundwater level is changed.

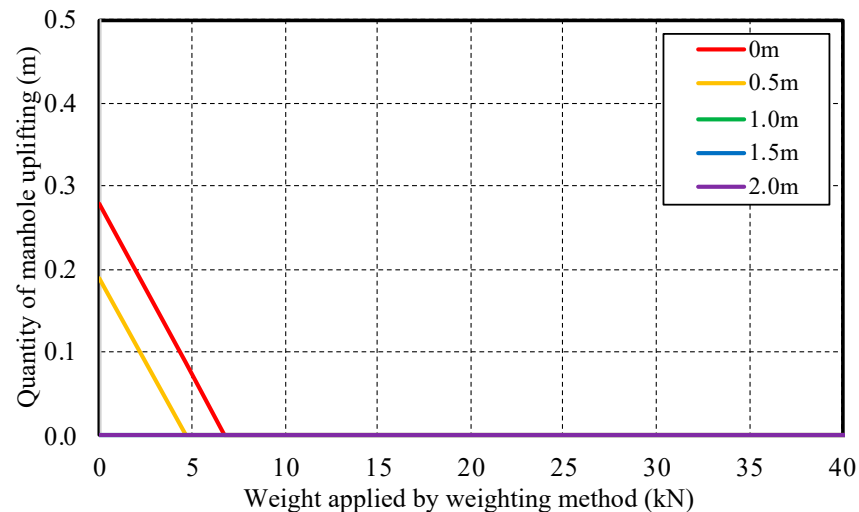


Figure 10. Δf for No. 1 circular manhole when groundwater level is changed.

5. Conclusions

In this study, the authors proposed and examined a weighting method as a countermeasure against the uplift of existing manholes due to liquefaction. The results obtained are as follows.

- (1) Regardless of the shape of the manhole, by implementing the weighting method, the risk of manhole uplifting during liquefaction can be reduced.
- (2) The weighting method can reduce the risk of manhole uplifting during liquefaction regardless of the groundwater level in the ground around the manhole.

It is thought that the weighting method is effective as a suppressive countermeasure against manhole uplifting due to the liquefaction of the ground around manholes. In countries where earthquakes occur frequently, it is indispensable to take measures against manhole uplifting brought about by the liquefaction of the ground around manholes. By applying the weighting method and adjusting the weight of the weighted ring according to the site conditions, it is possible to take the appropriate suppressive measures against manhole uplifting due to the liquefaction of the ground around manholes at each location. Minimum functionality must be ensured at sewerage facilities, including manholes, in the event of an earthquake or other natural disaster. In addition, it is necessary to take

measures to prevent manhole uplifting so that such manhole uplifting does not interfere with rescue and disaster recovery activities in the event of such disasters.

Many measures against manhole uplifting due to liquefaction have been proposed, and the effects of each measure need to be clarified. Therefore, the application of each measure can be clarified not only by static analysis, but also by dynamic analysis. In addition, the Δf during an earthquake changes greatly depending not only on the soil characteristics and vibration characteristics of the ground, but also on the groundwater level, excavation width, earthquake motion amplitude, vibration duration, and frequency characteristics. The process of the stability analysis in this study did not consider subsidence after manhole uplifting. Therefore, the Δf may change depending on each individual case.

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