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MECHANISM OF PROJECTION OF SEWERAGE MANHOLES ABOVE GROUND DUE TO SOIL LIQUEFACTION

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The projection of sewerage manholes above ground has been observed during earthquakes that have caused significant soil liquefaction. The force that moves a manhole upward can be attributed to the buoyancy caused by the liquefied soil, since no other reasonable causes are apparent. The weight of the manhole and the soil resistant force are the only forces that are in static equilibrium with the buoyancy. In this paper, we discuss the quantitative conditions for the possible projection of a manhole taking into consideration the above equilibrium of forces. The results should provide information helpful in the planning of countermeasures against damage to sewerage systems caused by projecting manholes.

Key Words : *earthquake, sewerage, manhole, soil liquefaction*

1. INTRODUCTION

The unusual sight of sewerage manholes being thrust above the ground during an earthquake never fails to attract public attention. This phenomenon, known as "projection" is associated with soil liquefaction. However, it should be noted that only a very small percentage of manholes in liquefied areas are ever projected. Also, almost all projecting manholes are simple cylindrical manholes. Together these facts suggest that the necessary conditions for the projection of a manhole are rather limited.

The force that moves a manhole upward is thought to be buoyancy caused by the liquefied soil. The forces that can resist this buoyancy are the weight of the manhole and soil resisting force against the manhole. Thus, the causes of manhole projection can be examined effectively by using a simple equilibrium model that takes into account the three forces acting on a cylindrical manhole.

In this paper, we quantitatively examine the necessary conditions for projection of a cylindrical manhole typical of those that have been projected above ground during past earthquakes.

2. MODEL FOR EXAMINING THE NECESSARY CONDITIONS FOR MANHOLE PROJECTION

Several manholes were projected above ground in Kushiro-cho during the Kushiro-oki Earthquake that took place on January 15, 1993. The maximum projection height was almost 1.5 m. These manholes were cylindrical ones having an inside diameter of 900 mm and were constructed by vertically placing a *C*-type centrifugal reinforced concrete pipe as described in the Japanese Industrial Standard.

The depth of the sewer pipes was 3.0 m to 4.5 m (Tanaka[1]) ; therefore, the total height of the manholes (*H* ; refer to **Fig.1**) was approximately 4 m to 5 m.

Photographs of other manholes projected during past earthquakes reveals similar cylindrical structures.

On the basis of an investigation of these manholes in Kushiro-cho, Mori[2] estimated that the depth of the liquefied layer was about 2 m.

The above facts present typical model of the equilibrium of forces such as the one shown in **Fig.1**, as well as the numerical conditions necessary to evaluate the appropriateness of such a model. Therefore, we will use a 900 mm diameter manhole made of *C*-type reinforced concrete pipe in our example of how to numerically calculate the projection conditions.

(1) Equilibrium of Forces Acting on a Cylindrical Manhole

The forces acting on a cylindrical manhole immersed in liquefied soil to a depth of l from the bottom and projected above ground by height h can be expressed as shown in **Fig.1**. The effect of buoyancy or soil restraining force acting on the connected sewer pipe is negligible, because those forces are very small due to the small diameter of the sewer pipe, as well as because the effects of such forces are very small due to the flexibility of a small diameter pipe.

The equilibrium of forces, or the necessary condition for projection, is given by the equation :

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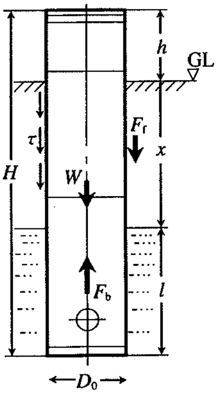

h : height of the projection
x : thickness of the non-liquefied layer
l : depth of immersion in the liquefied layer
D_0 : outside diameter of the manhole
τ : $=\tau(x)$; soil friction per unit area
W : weight of the manhole
F_b : buoyancy
F_f : soil resisting force

Fig.1 Three Forces Acting on a Projected Manhole

$$W+F_f \leqq F_b \cdots\cdots (1)$$

where W is the weight of the manhole, F_f is the force due to soil resisting force, and F_b is the buoyancy caused by the liquefied soil. The above three forces can be expressed by the following equations :

(1) Weight of the manhole, W

The weight of the manhole is given as a linear function of the height (H) of the manhole, with sufficient accuracy, as

$$W=aH+b \cdots\cdots (2)$$

where a and b are constants.

(2) Buoyancy, F_b

Buoyancy is expressed as follows :

$$F_b=\frac{\pi}{4}D_0^2 l \rho_s g \cdots\cdots (3)$$

where D_0 is the outside diameter of the manhole and ρ_s is the density of the liquefied soil or sand saturated with water.

(3) Soil resisting force, F_f

In this case, soil resisting force is expressed in the form of skin friction between the non-liquefied soil layer of thickness x and the surface of the manhole.

Because liquefaction-liable soils are mostly sandy and sandy soils are commonly used for backfilling the manhole, cohesion of the soil as a constituent of friction can be neglected. Assuming that the magnitude of friction per unit area (τ) is proportional to the horizontal earth pressure, the value of τ can be expressed by the following equation as a function of thickness x :

$$\tau=K\rho g x \tan\phi \cdots\cdots (4)$$

where K is the earth pressure coefficient, ρ is the density of non-liquefiable soil, and ϕ is the angle of friction. There can in fact be other causes besides friction that may either increase or decrease soil resisting force. However, we will assume that the effect of such causes is represented by the varying value of K in Eq.(4), while the value of ϕ remains unchanged (then, the constant, K, can be called the equivalent earth pressure coefficient).

Total soil resisting force is then given by integrating Eq.(4) with respect to the region, $0 \leqq x \leqq x$, as

$$F_f=\frac{\pi}{2}D_0 K \rho g x^2 \tan\phi \cdots\cdots (5)$$

By substituting the respective forces in Eqs.(3), (4), and (5) in Eq.(1), we obtain the following equation to determine the relationship between variables x and l :

$$l \geqq \frac{4}{\pi D_0^2 \rho_s g}\left(aH+\frac{\pi}{2}D_0 K \rho g x^2 \tan\phi + b\right) \cdots (6)$$

Relationships such as those between h and H, and h and l, can be obtained by replacing the variables in Eq.(6) in accordance with the following equation :

$$H=h+x+l \cdots\cdots (7)$$

(2) Manhole Dimensions and Soil Characteristic Constants for a Sample Numerical Calculation

We will assume the following values for the dimensions of the manhole and the constants for soil characteristics.

a. Outside diameter of the manhole

The outside diameter of a 900 mm C-type concrete pipe is specified in the Japanese Industrial Standard as

$D_0=1.05$ m

b. Weight of the manhole

The weight of the above concrete pipe, per unit length (constant a in Eq.(2)), is given in the same standard as

$a=567\ (\mathrm{kg/m}) \times g=5.56\ \mathrm{kN/m}$.

The sum of the weight of manhole components such as the bottom plate, the manhole cover (600 mm diameter), and the iron frame which do not depend on the length of the manhole (constant b in Eq.(2)), is estimated as

$b=357.5\ (\mathrm{kg}) \times g=3.50\ \mathrm{kN}$.

c. Constants for soil characteristics

We will assume that the values of the constants for the soil characteristics in Eq.(6) are

$\rho_s=2{,}000\ \mathrm{kg/m^3}$

$\rho=1{,}600\ \mathrm{kg/m^3}$

$\phi=30$ deg

(3) Conditions for the Occurrence of Projection and Subsequent Discussion

By substituting the values assumed above for the corresponding constants in Eq.(6), we obtain equations expressing the conditions for the occurrence of projection in the form of relationships between H, l, and x. In this study, we will calculate assuming two extreme values for K. The first case is

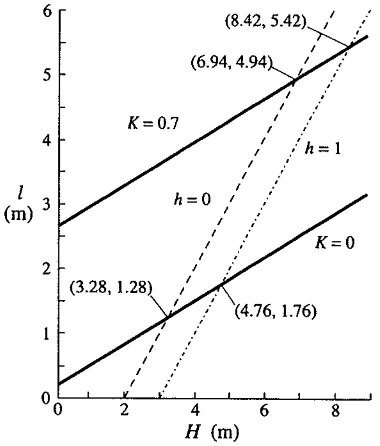

Fig.2 Relationship between H, l, and K to Determine the Conditions for Projection

when $K=0$, which represents a state of no soil resistance at all ; and the second case is when $K=0.7$, which is approximately equivalent to the value of the coefficient of earth pressure at rest for sufficiently compacted sandy soil. Most actual cases are thought to be represented by a value of K between 0 and 0.7.

The results are as follows :

$K=0$:

$$l \geqq 0.327H+0.206 \quad (8)$$

$K=0.7$:

$$l \geqq 0.327H+0.952x^2+0.206 \quad (9)$$

Equation (7) should be added to the above two equations to finally determine the overall condition for manhole projection.

In this case, the necessary conditions for projection are examined for a case where $x=2$ m, which according to Mori[2] is similar to the case at Kushiro-cho. This value of x is considered to be very probable in coastal areas where low lands such as alluvial plains and reclaimed land tend to be formed and where the level of groundwater tables tend to be high.

Fig.2 illustrates the relationships between H and l by the solid lines that have been calculated from Eqs.(8) and (9). The two broken lines illustrate the relationships between H and l given by Eq.(7) for two different projection heights, $h=0$ m and $h=1$ m.

The points of intersection of the solid lines and the broken lines provide combinations of the smallest possible values of H and l for the designated values of h and K.

This figure indicates the following facts :

1) Even when there is no soil resisting force ($K=0$), the bottom of the manhole would have to be immersed in the liquefied soil by more than about 1.3 m, in order for the projection to initiate. In order for the manhole to project by a height of $h=1$ m, the immersion depth (l) would have to be more than about 1.8 m. This means that the immersion depth would have to be more than 2.8 m, before the initiation of projection. This also means that the thickness of the liquefied layer would have to be greater than 2.8 m. If the liquefied layer is not as thick as this value, the bottom of the manhole will reach the underlying non-liquefied layer. As a result, projection will not take place because buoyancy cannot be created in such a state.

The above facts also indicate that the height of the manhole (H) should be greater than 4.8 m, in order for the projection to take place when there is no soil resisting force, and when the thickness of the surficial non-liquefied layer (x) is 2 m.

2) If soil resisting force is as great as in the case for $K=0.7$, the minimum height of the manhole (H) should be at least about 7 m for the projection height of $h=0$; at the same time, the immersed depth in the liquefied layer (l) as well as the thickness of the liquefied layer would have to be greater than 5 m. In order for the manhole to project by a height of $h=1$ m, the above values of H and l would have to be increased by 1 m. Such a great thickness of liquefied layer would seldom be realized in the existing ground. Thus the condition for manhole projection would be quite limited if sufficiently great soil resisting force could be expected.

3) The question arises in the above calculation as to why the manhole in Kushiro-cho could project by a height of $h=1.5$ m, despite its small length ($H=5$ m or less) and the great thickness of non-liquefied layer compared to the length H($x=2$ m, approximately).

A possible answer to this is as follows : it is highly likely that a small gap was produced around the surface of the manhole at the lower part of the non-liquefied layer, due to the differential motion between the manhole and the ground. The pressurized pore water in the liquefied layer then found its way up through the gap, forming a cylindrical film of water around the manhole. This film of water can contribute to buoyancy even though it may be very thin. As a result, the effective depth of immersion (l) increased and the effective thickness of the non-liquefied layer (x) decreased. In addition, the differential motion between the manhole and the ground may have decreasse the skin friction. Above all, it can naturally be supposed that the liquefied soil layer was sufficiently thick so that the bottom end of the manhole was completely immersed in the liquefied soil.

4) As shown above, the possibility of projection or the overall condition for manhole projection is very limited. This fact suggests that the projection of manholes above ground can be prevented by implementing fairly simple measures.

3. SEWERAGE SYSTEM BEHAVIOR AND COUNTERMEASURES FOR PREVENTING MANHOLE PROJECTION

(1) Sewerage System Behavior Other than Manhole Projection

Sewer pipes are also frequently subject to the buoyant effects of liquefied soils. In many cases, they move upward, forming a gentle arch, rising several centimeters to several tens of centimeters at the midway point between two manholes that do not move at all. The apparent density of a concrete sewer pipe filled with water is 1,300～1,500 kg/m^3 (depending on the diameter of the pipe). This value is reasonably high when compared to the density of liquefied soils, which is estimated to be 1,800～2,000 kg/m^3 on average. However, when a sewer pipe is empty, its apparent density will be half the above value or less, and the sewer pipes will be subject to significantly higher buoyancy.

The fact that manholes do not usually move upward while sewer pipes often do suggests that the manholes are securely restrained, in general, by the non-liquefied surface soil layer, while no restricting forces are expected for sewer pipes from the surrounding soils. This result reinforces the appropriateness of the model illustrated in **Fig.1**, as well as the above discussions based on the same model.

(2) Measures to Prevent Manhole Projection

The calculations in the preceding chapter (the results are expressed in Eqs.(8) and (9), and in **Fig.2**) indicate that the magnitude of soil resisting force that can prevent a manhole from projecting need not be very great ; the buoyancy acting on the manhole of diameter 900 mm is approximately 10 kN/m (1,000 kgf/m) for the part immersed in the liquefied layer. Therefore, securing friction between the non-liquefiable soil layer and the manhole surface should be sufficient to prevent projection, if the thickness of the non-liquefiable layer (x in **Fig.1**) is not too thin. If the value of x is expected to be very small, some other means to securely fix the manhole to the non-liquefiable layer may become necessary. Replacing the liquefiable soils around the manhole with non-liquefiable soils, to a suitable depth and width is one such means.

4. CONCLUSION

Our study demonstrates that the criterion for the projection of cylindrical sewerage manholes can be determined on the basis of a simple mechanistic model expressing the equilibrium of three forces : buoyancy caused by the liquefied soil, the weight of the manhole, and the restrictive force due to the non-liquefiable surface soil layer. Our study also revealed that the necessary conditions for manhole projection are very limited. This discovery explains why most manholes have not projected during past earthquakes, even in those areas sustaining severe liquefaction. This fact also assures us that the manhole projection can be prevented by simple means based on the evaluation of the equilibrium of forces such as that illustrated in **Fig.1**.

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地盤液状化時の下水道マンホールの浮上に関する考察

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これまで，いくつかの地震において，地盤液状化による下水道マンホールの浮上が観察されている．ほとんどの場合，浮上は円筒形の簡易なマンホールに生じている．本文では，簡単な力の釣り合い条件にもとづき，マンホールが浮上する条件について考察を加えた．その結果，浮上を生じ得る条件は非常に限られたものであり，マンホールに対する地盤の拘束力を確保する程度の対策で，浮上は十分に防ぐことができることが示された．