Floatation of Underground Structures during the M_w9.0 Tōhoku Earthquake of 11th March 2011

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SUMMARY:
In an earthquake, underground structures passing through liquefiable soil deposits are generally prone to floatation due to their lower submerged unit weight as compared to the surrounding saturated soil. This is evident from reconnaissance investigations following the M_w9.0 Tōhoku Earthquake on the 11th March 2011. In Urayasu city in Chiba prefecture, a large number of underground structures have floated above ground due to the widespread soil liquefaction in the city. Preliminary numerical analyses have been performed with FLAC, a finite difference program code, which produced similar uplift behaviour of buoyant structures. In addition, the analyses indicated that manholes are generally more prone to uplift as compared with buried domestic utility pipes. Both findings are in agreement with the field observations and theoretical force equilibrium analyses as presented in this paper.

Keywords: Liquefaction, floatation, manhole, pipeline, Tōhoku earthquake

1. INTRODUCTION

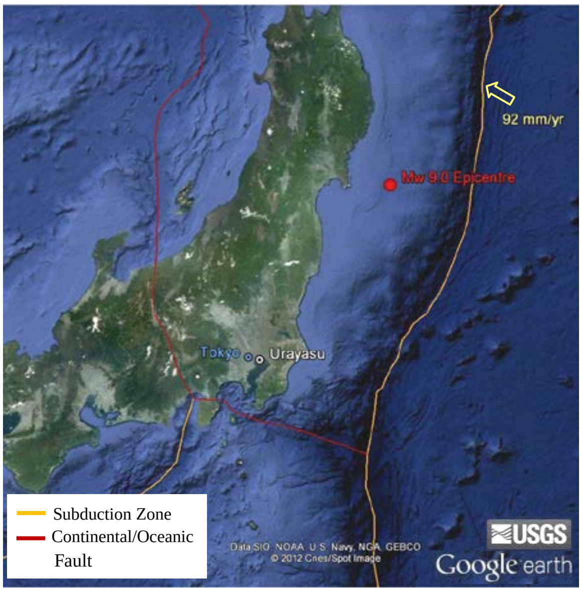
Underground infrastructure serving as vital lifelines for transport, utility and storage purposes has been a widespread alternative in redeveloping urban spaces to ease land congestion pressures. These underground structures include subway train and highway tunnels, gas and water pipelines, and fuel storage tanks. However, in the event of an earthquake, the functionality of these lifelines could be put in to jeopardy especially in soils susceptible to liquefaction.

Historical earthquake events including the recent 2011 Tōhoku earthquake have proven the damage susceptibility of manholes, pipelines and tanks. Observations from reconnaissance investigations after the earthquake showed significant damage to underground structures due to soil liquefaction at Shirakawa and Urayasu cities in Fukushima and Chiba prefectures respectively. In Shirakawa, manholes displaced 0.6m above ground, owing to the presence of high water table from nearby rice paddy fields (Chian *et al.*, 2012). At Urayasu city, widespread liquefaction was observed at the reclaimed land areas of the city (Tokimatsu *et al.*, 2011). Figure 1a indicates the location of Urayasu city in relation to the epicentre of the earthquake. The earthquake recorded at the K-NET station in Urayasu city showed a peak ground acceleration (PGA) of about 1.6m/s^2 and strong ground motion above 0.25 m/s^2 for about 120 seconds (Figure 1b). As a result of the strong and prolong earthquake, a large number of underground structures suffered damaged, in particular manholes which have floated above the ground surface, resulting in disruptions to water supply, electricity and sewerage flow.

Figure 2a shows an overview of the reclamation construction year and the locations with significant records of manhole uplift. Such type of failure occurred most at recent reclaimed areas. Based on the post-earthquake survey conducted by the Liquefaction Mitigation Investigation Committee of Chiba Prefecture, 7.6% of the total manholes (81 nos.) in reclaimed areas constructed between 1979 and 1980 suffered floatation as compared to 1.1% (31 nos.) in reclaimed areas constructed between 1968 and 1975. No significant uplift of manhole was observed in the native soil deposit.

As for pipelines, they usually fail at pipe-pipe and pipe-manhole connection joints. From borehole data (Figure 2b), it is understood that the reclaimed land is predominantly loose sand deposits with low N blow values. These layers of soil are highly liquefiable in the event of a strong earthquake.

Given the evidence of extensive failures to these underground structures, there exists a need to conduct in-depth research to mitigate such damage and minimise disruptions to domestic utility services to communities following a major earthquake.



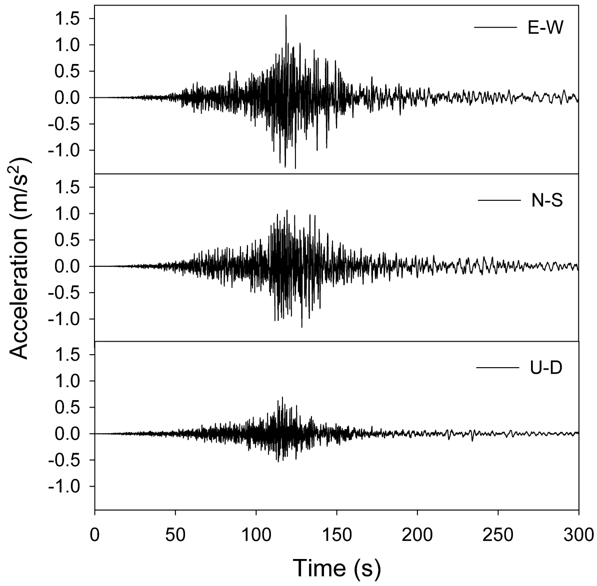


Figure 1a. (left) Location of earthquake epicentre and Urayasu city
Figure 1b. (right) K-NET earthquake motion record in Urayasu (Station CHB008)

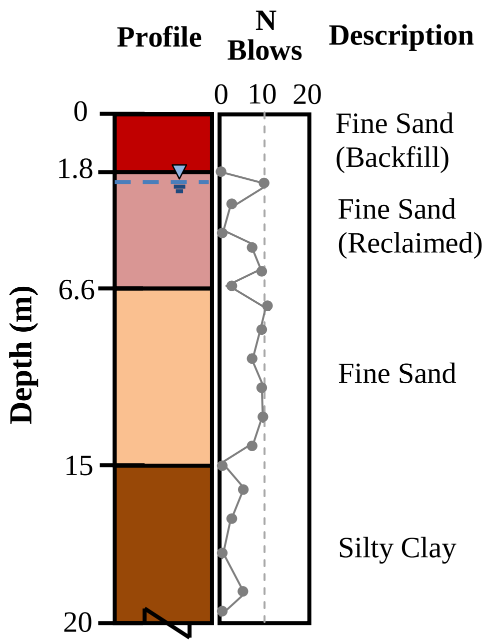


Figure 2a. (left) Overview of Urayasu city (shaded) with year of reclamation and locations of significant uplift of manhole (in white lines); from Liquefaction Mitigation Investigation Committee, Chiba Prefecture (2011)
Figure 2b. (right) Borehole data at the most recent reclaimed land region (location starred in Figure 2a); from Liquefaction Mitigation Investigation Committee, Chiba Prefecture (2011)

2. THEORETICAL FLOATATION MECHANISM OF UNDERGROUND STRUCTURES

2.1. Pipeline

A simplified mechanism for the floatation of a pipe can be adapted from static analysis. The resistance forces inhibiting the uplift force due to buoyancy ($F_{B,P}$) are provided by the weight of the pipe ($F_{S,P}$), the weight of the overlying soil ($F_{WS,P}$) and the shear developed in the soil ($F_{SP,P}$). However, in the event of soil liquefaction during an earthquake, the shear contribution could be reduced significantly. In addition, the excess pore pressure at the invert of the pipe can also contribute to the uplift force acting on the structure ($F_{EPP,P}$) as illustrated in Figure 3. When there is a positive net uplift force ($F_{NET,P}$) as shown in Eq. 1, the pipe may float as a result.

$$F_{NET,P} = (F_{B,P} + F_{EPP,P}) - (F_{S,P} + F_{SP,P} + F_{WS,P}) \tag{1}$$

2.2. Manhole

Similar to the manhole, the shear developed in the soil and the weight of the pipe are present in the force equilibrium, indicated as $F_{SP,M}$ and $F_{S,M}$ respectively in Eq. 2 and Figure 4. However, it is noted that the resistance from the weight of the overlying soil (F_{WS}) is absent in the case of manholes as illustrated in Figure 4. This implies that the soil's contribution against floatation now lies solely on the shear resistance ($F_{SP,P}$). In addition, the shear contribution ($F_{SP,M}$) is now governed by the soil-structure friction interface rather than friction between soil grains. Typical, the lining of the manholes used in Japan is concrete which gives a soil-concrete frictional coefficient of μ=0.4 as compared to soil-soil coefficient of about 0.7 (assuming friction angle of 35° at large strains). It is therefore expected that manholes would suffer from a lower shear resistance against floatation as compared to pipelines at identical buried depths. Furthermore, manholes generally possess a greater buoyancy force due to larger cross-sectional area than pipelines based on Archimedes Principle. The above factors could hence contribute to the higher susceptibility to floatation of manholes as documented by government officials in Urayasu city.

$$F_{NET,M} = (F_{B,M} + F_{EPP,M}) - (F_{S,M} + F_{SP,M}) \tag{2}$$

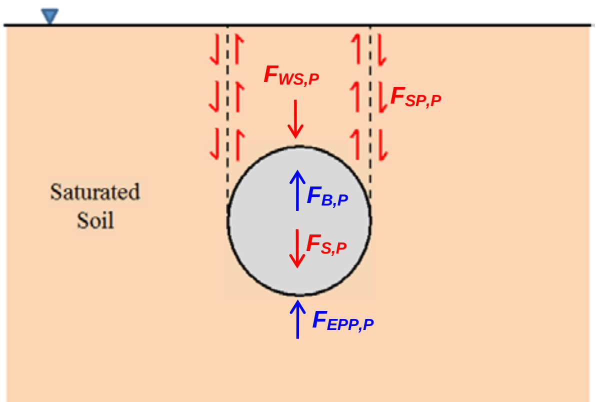


Figure 3. Forces acting on a pipe in liquefied soil

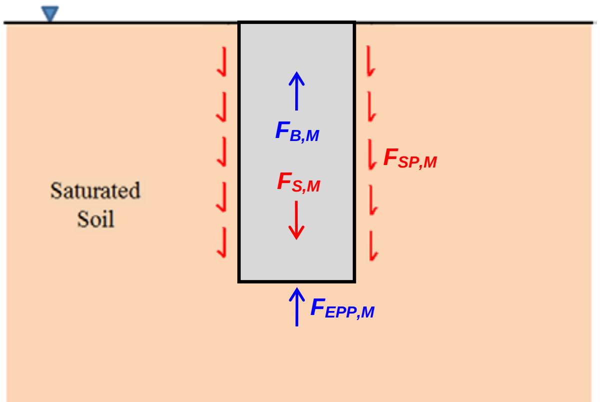


Figure 4. Forces acting on a manhole in liquefied soil

3. NUMERICAL ANALYSIS

Preliminary numerical analyses had been performed using FLAC (Fast Lagrangian Analysis of Continua), a finite difference program code developed by Itasca Consulting Group as a general two-dimensional analysis of geotechnical/geological media for computing large deformations (Itasca, 2011). The Wang model (Wang, 1990; Wang *et al.*, 1990), a non-linear, bounding surface plasticity constitutive model for sand, specifically formulated to capture the contraction and dilation induced by shear stress was applied in the numerical analysis for the simulation of soil liquefaction condition. The soil properties used in these analyses are presented in Table 1. The constitutive model-dependent parameters, namely the modulus coefficient defining the small strain elastic shear modulus (G_o), the reduction of shear modulus with increasing strain amplitude (h_r) and the blow count related k_r and d were calibrated to produce similar contractive and dilative responses as cyclic laboratory tests of Toyoura sand before applying to the analysis. Details of the constitutive model are discussed by Wang and Makdisi (1999).

It is noted that soil variability exist at the site and these values are merely representative of a typical liquefiable soil deposit as a general study. Both the manhole and pipe are assumed as rigid and have an overall specific gravity of 0.5. The problem was taken as a plane strain in this preliminary analysis.

Table 1. Soil properties used in numerical analyses

Parameter	Values
Dry Density (ρ_d)	1700 kg/m^3
Bulk Modulus (K)	1.5×10^7 Pa
Shear Modulus (G)	5.5×10^6 Pa
Internal Friction Angle (ϕ)	35°
Cohesion (c)	0 Pa
Initial Void Ratio (e)	0.8
Permeability	1×10^{-4} m/s
Small Elastic Shear Modulus Coefficient (G_o)	300
Shear Modulus Reduction Coefficient (h_r)	0.3
Effective Stress Coefficient (k_r)	0.06
Cyclic Pore Pressure Coefficient (d)	3.0

Based on past experimental studies of underground structures in centrifuge tests (Chian, 2012), it was suggested that a buoyant structure floats only in the presence of high pore water pressure. This is due to the reduced shear strength of the soil which permits floatation to occur. As such, a few cycles of earthquake has to take place before the floatation can occur. Investigation of such response was carried out using the FLAC software which showed similar uplift response of the underground structure in liquefiable soil after an earthquake. The model layout is shown in Figure 5.

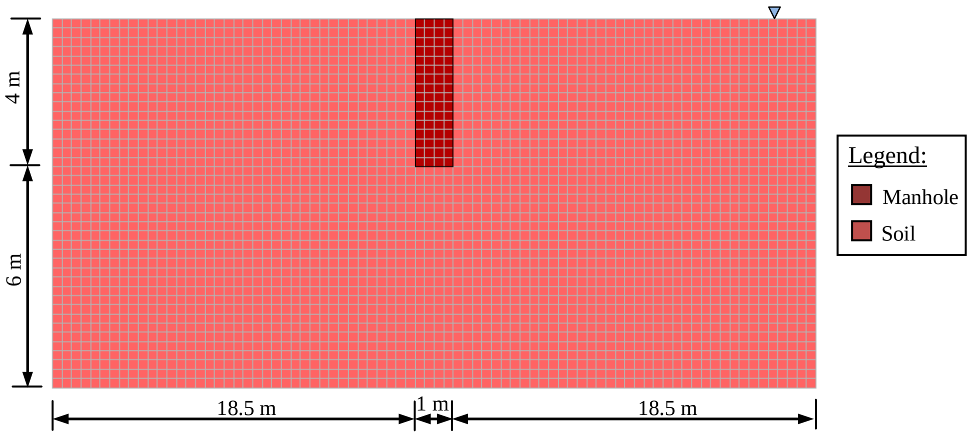


Figure 5. Model layout with manhole

Figure 6 shows the arbitrary input earthquake motion applied to the model. Similar to observations in centrifuge experiments, the numerical analysis demonstrates that the floatation of the manhole occurs shortly after the first couple of earthquake cycles and ceases floating as soon as the earthquake stops, despite the retention of high excess pore pressure present in the soil immediately after the earthquake. This infers that the uplift of manholes in liquefiable soil should not be assumed as a buoyant structure in viscous fluid, which would otherwise show continual floatation of the manhole.

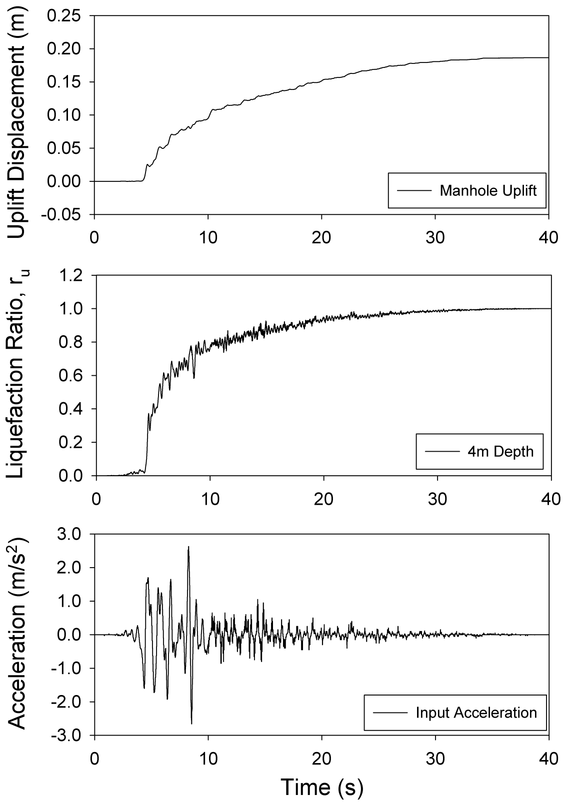


Figure 6. Uplift displacement of manhole, base input motion and liquefaction ratio at 4m depth 1.5m away from manhole

Another test was conducted with a pipe buried at the same depth under similar soil and earthquake conditions. A large pipe of 1m diameter is selected to provide a higher buoyancy to compare with the manhole as shown in Figure 7. The vertical displacement and pore water pressure time history plots are presented in Figure 8. Based on the results, the pipe floats minimally as compared to the displacement of the manhole. This suggests that the uplift response between the pipe and manhole is not proportional to their cross-sectional area ratio and hence deviating from the idealised assumption of liquefied soil as a viscous liquid in this case. Apart from the smaller cross-sectional area, the lower uplift of the pipe is also attributed to the overlying soil weight and higher shear resistance of the soil suppressing the buoyancy. In addition, the uplifting of the structure may also induce soil dilation near its crown which further discourages significant uplift (Chian and Madabhushi, 2011). Due to the low stiffness of the overlying soil, the soil can displace laterally away from the crown of the pipe as supported by the analysis which showed negligible soil upheaval. This indirectly implies that a damaged underground pipeline due to floatation may not be noticeable at the soil surface.

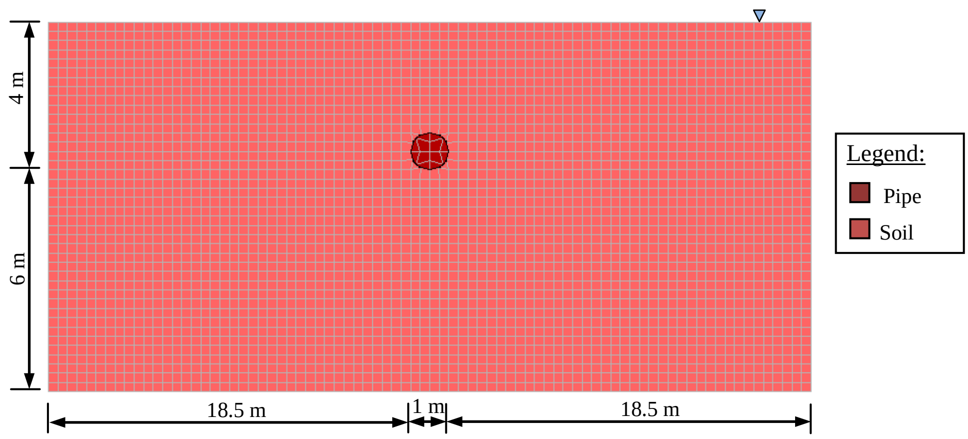


Figure 7. Model layout with buried pipe

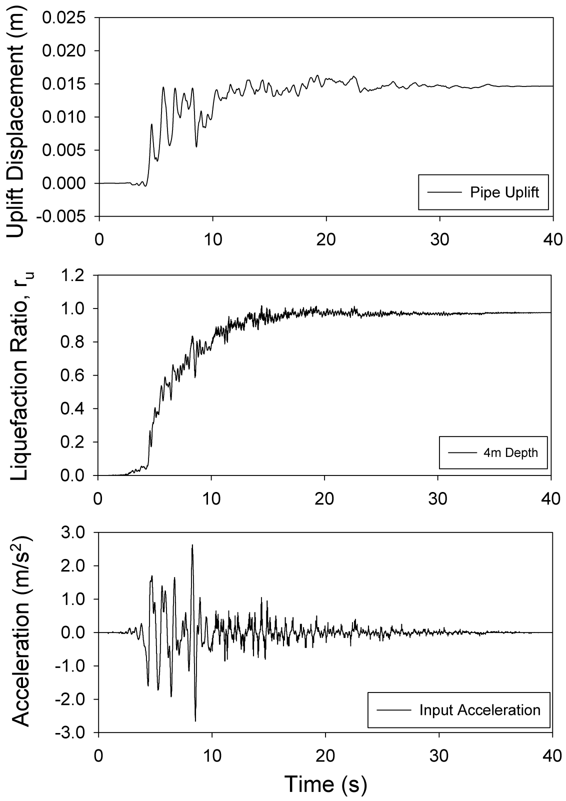


Figure 8. Uplift displacement of pipe, base input motion and liquefaction ratio at 4m depth 1.5m away from pipe

Similar to the manhole, the uplift displacement of the pipe came to a constant which clearly indicate the high dependency of the uplift response to the input earthquake motion. This is in agreement with the hypothesis that earthquake shaking has to persist to cause force inequality which leads to the continual floatation of underground structures in liquefied soil. As soon as the earthquake ceases, the inequality is no longer present. This is in contrast with the commencement of floatation which is highly dependent on the pore water pressure instead.

3. ANALYSIS OF MANHOLES IN URAYASU CITY

Numerical analysis with the same manhole model used in the above example was performed with the 2011 Tōhoku earthquake motion recorded at the K-NET station in Urayasu. The mesh used in this case was coarser to accommodate the expected large soil deformation. The K-NET earthquake motion was first outcropped with the site condition of the station before applying to the model. Figure 9 shows the applied earthquake motion at the base of the model. The uplift displacement of the manhole derived from the analysis was approximately 0.71m, which lies in the upper range of manhole uplift displacement values measured on site (93% of the measured uplift distribution). The largest uplift displacement measured on site was about 0.9m.

Floatation continued till the end of the time history in the presence of the residual input earthquake motion (about 0.08m/s^2). However, it is evident that the rate of uplift has reduced significantly. Such significant uplift is likely attributed to the higher water table in the model. The water table in the analysis lies at the soil surface rather than at the 2m depth measured in the newly reclaimed regions in Urayasu. Despite a lower PGA as compared to the previous analysis, the Tōhoku earthquake produced a greater overall uplift displacement of the manhole due to longer earthquake duration. In addition, the higher frequency of the earthquake motion may similarly increase the uplift displacement of underground structures.

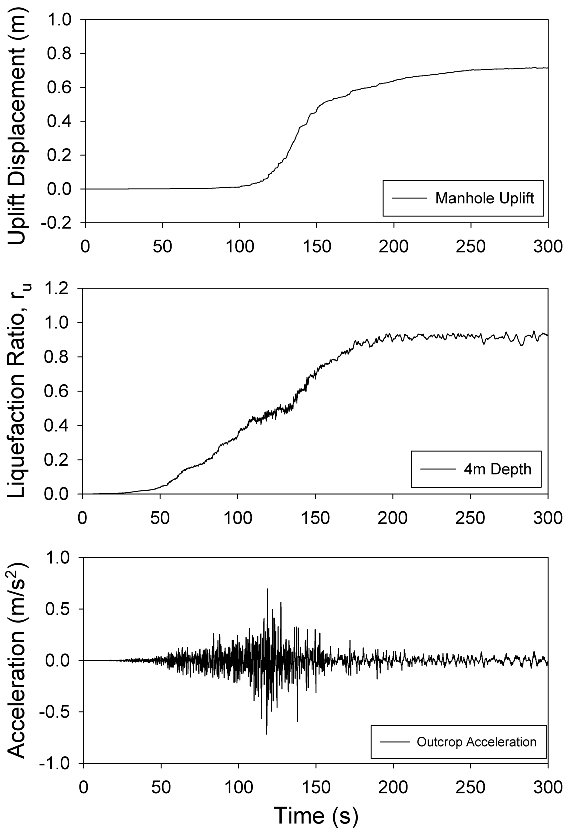


Figure 9. Uplift displacement of manhole, base input motion and liquefaction ratio at 4m depth, obtained from analysis representing the Tōhoku earthquake at Urayasu

Based on the analyses presented, it is evident that the use of FLAC analysis with appropriate liquefaction constitutive model can produce reasonable estimate of uplift displacement of manholes in liquefiable soil. Such analysis may therefore be extended to investigate more case histories of earthquake induced floatation of underground structures.

4. CONCLUSION

Preliminary numerical analysis with FLAC using the Wang model has shown to be capable of replicating the floatation of underground structures such as manholes and pipes in liquefiable soil. Based on theoretical force analysis, a manhole is generally more susceptible to floatation than a pipe due to the absence of the overlying soil weight, lower shear resistance and greater buoyancy. This is substantiated with numerical analysis which showed a substantially larger uplift displacement of the manhole under identical earthquake and soil condition. Results also showed that these underground structures float in the presence of high pore water pressure, but cease floating when the earthquake shaking stops. These observations clearly indicate the unsuitability of assuming liquefied soil as a high viscous fluid in these scenarios. Further application of the analysis to the 2011 Tōhoku earthquake showed reasonable uplift displacement of manholes in comparison with the field measurements which highlights the prospects of extending such numerical analysis for geotechnical problems associated with the floatation of underground structures in liquefiable soil.

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