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Centrifuge Modeling for Uplift of Buried Structures by Liquefaction : A New Measure for Uplift

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Synopsis

Many types of damage of buried structures occur due to liquefaction during an earthquake, such as flotation, settlement, bending and buckling of buried pipes. Among those, this paper focuses only on uplift of sewerage manholes. Uplift behavior of buried structures with and without a measure for uplift is investigated in model tests which are dynamically tested in a centrifuge modeling. In this study, effectiveness of the new measure for uplift which is to dissipate the excess pore water pressure is investigated to mitigate uplift displacement of the manhole during earthquakes (Konishi et al. 2008). The measure consisted of two configurations which are a filtering net and pipe. The tests showed that the mechanism of the uplift behavior and the effects of the measure for the uplift, but the uplift amount may be still too large (8% of the length of the manhole) when it is applied in practice.

Keywords: Buried structure, Earthquakes, Liquefaction, Centrifuge modeling test

1. Introduction

After the 1964 Niigata earthquakes in Japan, uplifting phenomenon of a sewerage system has been reported frequently. Among sewerage systems, sewerage manholes have been frequently damaged by liquefaction during earthquakes in Japan. Uplift of manholes has become a serious matter because ejected manhole obstructs not only the flow of sewerage systems as a lifeline for a long period after earthquake but also road traffic. Especially, high uplifted manholes from the surface of road, in a few instances, block emergency vehicles just after the earthquake when these were most needed.

In 1964 Niigata earthquake, Japan, 37% of coverage of sewerage systems was uplifted (Konishi et al. 2008), and uplift of about 20 sewerage manholes that maximum uplift displacement was 1.5 m from the ground surface was induced in 1993 Kushiro-oki earthquake. In 1993, another earthquake, the Hokkaido-nansei-oki earthquake, fifty-five manholes were uplifted about 10 to 57 cm. 1994 Hokaido-toho-oki earthquake, also, caused uplift of sewerage manholes in several cities (Yasuda and Kiku, 2006). Damage to the sewerage manholes grew rapidly after 2004 Niigata-ken Chuetsu earthquake. More than 1,400 manholes were uplifted and maximum uplift displacement was about more 1 m from the ground surface during the earthquake.

In this present study, a new measure for uplift which is to dissipate the excess pore water pressure was proposed to mitigate the uplift of sewerage manhole for future earthquakes (Konishi et al. 2008). The measure is targeting both newly and existing manholes. In order to study the mechanism of uplift and verify the effect of the new measure for uplift, centrifuge tests were conducted with and without the measure.

2. Model design

Model ground

The model is scaled down to 1/20. Silica sands were used to make model ground. Physical and mechanical properties of these soils are listed in TABLE 1. The ground model was prepared in a rigid container, with nominal inside dimensions of 0.45, 0.15 and 0.30 m with a transparent front window installed in the container, through which the in-flight model behavior can be monitored as shown in Fig. 1.

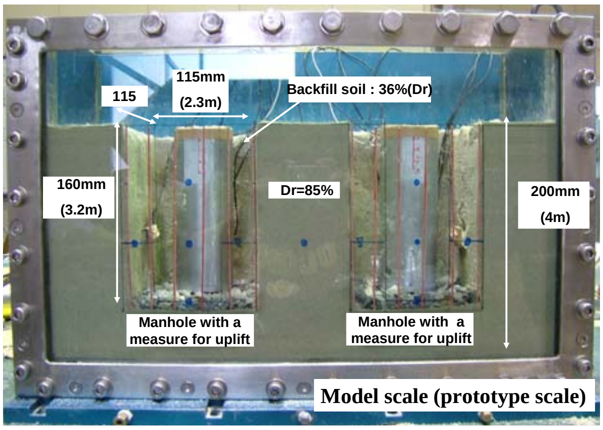

Fig. 1 Model manholes installed in the excavated ground before back-filling with loose soils

Table 1 Properties of silica sand

Silica sand (Grade – 7)			
Specific gravity	G_s	2.56	
Maximum void ratio	e_{max}	1.19	
Minimum void ratio	e_{min}	0.71	
Wet sand	γ_t	14.8	kN/m^3
Saturated sand	γ_{sat}	18.1	kN/m^3

The original subsoil layer of relative density, Dr ≈ 85%, was first prepared by compacting moist silica sands. Then, to install the model manholes, a trench of volume 2.3 × 2.3 × 3.2 m was excavated. The manhole was placed on gravel with thickness of 0.2 m at the bottom of the trench (Fig. 1). The same silica sand as the original model ground was air-pluviated in the trench with viscous water to form a loose deposit (Dr ≈ 36%).

Model manhole and its insertion into model ground

(1) New measure system

Fig. 2 shows the schematic view which can illustrate the mechanism for the new measure. The measure for uplift constitute a filtering net which is installed at a part of connection of a sewerage pipe and manhole, and a pipe installed at the part of filtering net in the manhole as shown in Fig. 2 (Konishi et al. 2008). Before earthquakes, water level in the pipe is the same to underground water depth around the manhole because the filtering net is connected with the pipe as shown in Fig 2 (a). However, during earthquakes, excess pore water pressure in the ground around the manhole gradually increases, and the pressurized pore water is guided into the manhole through the filtering net and pipe due to the increased excess pore water pressure in the ground around the manhole as shown in Fig. 2 (b). Therefore, the uplift of the manhole is mitigated because of decreasing buoyancy force acting at the bottom of the manhole by dissipating excess pore water pressure into the manhole and increasing weight by added water in the manhole.

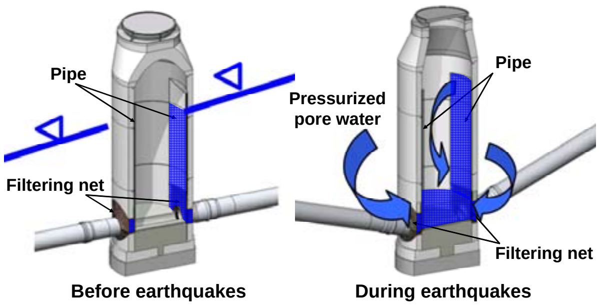

Fig. 2 Schematic view for a countermeasure (Konish, 2008)

(2) Model manhole

Target prototype manhole is standard No. 1 Manhole (JSWA, 2001), hollow cylinder, reinforced concrete manholes, typical of modern manhole in Japan. Standard No. 1 manhole consisted of 5 segments which are cab, inclined wall, vertical wall, body and base slab. Unit weight of model manhole is 1.16 times lager than that of No.1 manhole because unit weight of aluminium is lager than that of reinforced concrete. Therefore, uplift amount of the centrifuge modeling tests may be slightly overestimated.

Three types of the manholes (one is no measure and two are with a measure for uplift), which are scaled down to a twentieth of Standard No. 1 Manhole (JSWA. 2001), were used in the centrifuge modeling tests. Fig. 3 shows model manholes with and without the measure used in the centrifuge modeling tests. The models are with outer diameter of 55 mm, length of 150 mm and a wall thickness of 5 mm in model scale. They nominally named Model No. 1 for manhole without the measure [Fig. 3 (a)] and Model. No 2 and Model No. 3 for a rmeasures [Model No. 2: Fig. 3 (b) and Model No. 3: Fig. 3 (c)].

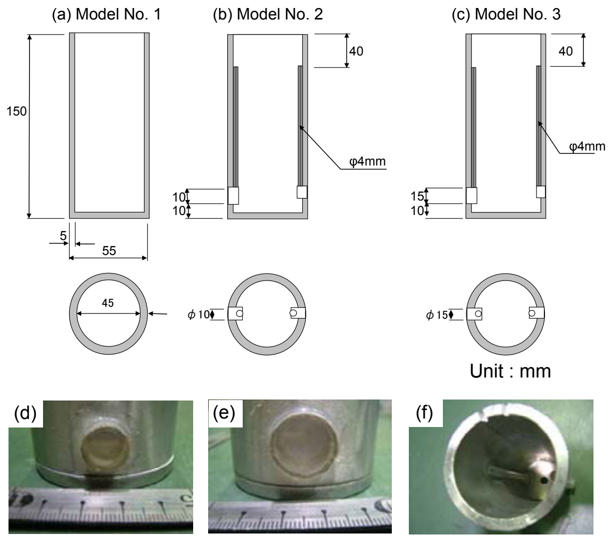

Fig. 3 Model manhole and countermeasures used in the tests; (a)–(c): plans of model manholes, (d) and (e): filtering nets installed Manhole No. 2 and Manhole No. 3, respectively and (f): a pipe installed in the manhole.

Model No. 2 [Figs. 3 (b) and (d)] has the filtering net with diameter of 10 mm, while Model No. 3 [Figs. 3 (c) and (e)] has that of 15 mm in model scale. The length of the pipe which is connected at the filtering net in the manhole is 100 mm in model scale [Fig. 3 (f)]. To verify the effects of the measure for uplift, the tests were conducted with deeper underground water depth of 1 m so that the pore water doesn't flow into the manhole before shaking. A mesh (75 μm) which made from steel was attached at the filtering net to prevent sandy soil incoming into the manhole as shown in Figs 3 (d) and (e).

To insert the model manhole, prepared original subsoil with Dr ≈ 85% excavates a range of about 2 times (2.3 × 2.3 m) of outer diameter of the manhole pushing an aluminium plate in the ground surface to prevent the excavation wall from collapsing during excavating.

Instrumentation

Three types of electronics instruments were used: (1) accelerometers (SSK, A6H-50) to record dynamic motions on the ground surface, structure and container, (2) pore water pressure transducers (SSK, P306A-2), (3) laser displacement transducers (Keyence, LBP-080) to measure the uplift displacement of the manholes. Fig. 8 shows the general location of all instrumentation.

A0 was installed on the shake table to measure dynamic motion. A1~A2 (without measure) and A5~A6 (with measure) were installed at the top (A1 and A5) and bottom (A2 and A6) of the manhole to record the dynamic motion of the manholes. A3 and A7 were installed on the backfill soil, and A4 was installed on the ground surface.

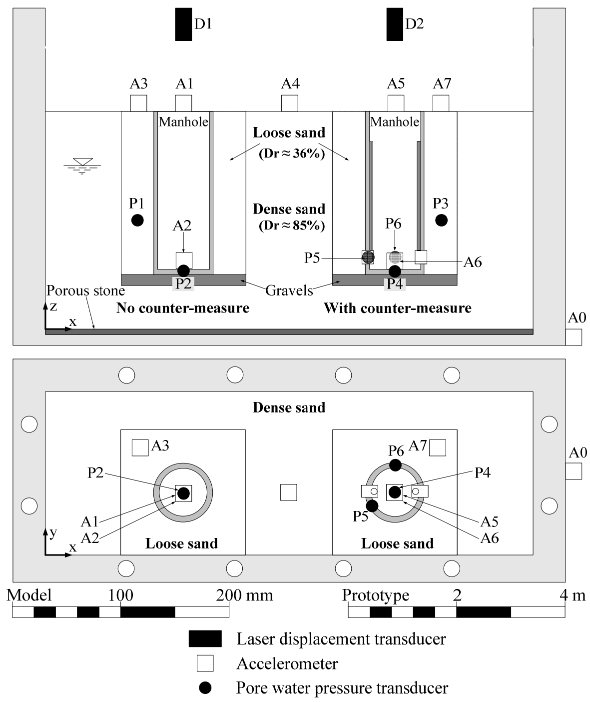

Fig. 4 Centrifuge model test set-up

Pore water pressure transducers were oriented perpendicular to the direction of shaking to minimize the influence of sloshing of a liquefied soil during shaking. P1 (without measure) and P3 (with measure) were located in the backfill soil at depth of 2 m from the ground surface. P2 (without measure) and P4 (with measure) were installed at the bottom of the manhole to measure buoyant force that the liquefied backfill soil moved laterally toward the bottom. In order to evaluate the effects of the measures (filtering net) proposed in this study, P5 was set up beside the filtering net and P6 was installed perpendicular to the filtering net at the back of the manhole at the same depth to compare with P5 as shown in Fig 4.

To measure the uplift displacement of the manhole, D1 (no measure) and D2 (with measure) that the capacity is ±25mm at a spot of 80 mm from the transducer were installed as shown in Fig. 4.

3. Tests procedures

The geotechnical centrifuge at the Disaster Prevention Research Institute (DPRI), Kyoto University, was employed. The centrifuge has a 5-m radius and was equipped with one-dimensional shake table capable of gravitational accelerations of up to 50 g during shaking. The applied centrifugal acceleration was 20 g in the centrifuge modeling tests.

After confirming that all equipment and sensors functioned well, centrifugal acceleration was increased gradually up to 20 G. To properly consolidate the model ground before shaking, the model was put under 20 G for 5 minutes. After settlement of the sand layers had completed, centrifugal acceleration was increased up to 20 G again to apply the dynamic motion to the ground and manhole. The input motion is a sinusoidal with frequency of 1.25 Hz in prototype scale for all cases.

TABLE 2 shows test cases carried out in the centrifuge test. Total tests are 4 cases (CS1 ~ CS4). CS1 to 3 were conducted for Model No. 2 to evaluate the effects of the measure for uplift. CS4 was conducted for Model No. 3 to evaluate the effects of the filtering net size comparing with tests for Model No. 2. The underground water depth had been kept at the depth of 1.0 m form the ground surface. The maximum input accelerations observed on the shake table had gotten a range of 0.63 ~ 0.67 g. Uplift displacements and settlements were directly measured by a ruler (Fig. 5) before and after each experiment when the uplift amount exceeded an allowable range of laser displacement transducer.

Table 2 Summary of centrifuge manhole tests

	Manhole type (Model No.)		G.W.L	Relative density		Max. input Acc.
Case No.	Without measure	With a measure	m	Original subsoil (%)	Backfill soil (%)	g
CS1	1	2	1	Dense sand (85 %)	Loose sand (36 %)	0.63
CS2	1	2	1			0.671
CS3	1	2	1			0.635
CS4	1	3	1			0.645

Fig. 5 Uplifted model manhole for CS4

4. Test results

Behavior of manhole and backfill during uplifting

Figs. 6–7 show the results of the centrifuge modeling tests. Fig. 6 is without measure (Model No. 1), and Fig. 7 is with measure (Model No. 3) for CS4. As shown by the vertical broken lines in individual figures, the manhole started to lift up (D1 and D2) at 7 s when the excess pore water pressure in the middle of the backfill [P1: Fig. 6 - 7(b)] and that of the bottom of the manhole, σ_{vm}', [P2: Fig. 6 – 7 (c)] exceeded the initial effective vertical stress. Uplifting stops at the end of shaking and a slight downward movement was investigated after shaking.

To study the uplift behaviour of a manhole in detail, acceleration amplification factors and phase differences are investigated (Fig. 8). The amplification factors are obtained by dividing the peak values of A1 to A4 by corresponding peak values of the input acceleration (A0). While the phase differences are computed from the difference of arrival time of peaks from the corresponding peaks of A0 through the following equation;

$$\Delta\theta = \frac{t_{An} - t_{A0}}{T} \times 360^\circ \ (n=1, 4) \qquad (1)$$

where $\Delta\theta$ is phase difference, t_{An} is arrival time of the peak at sensor An (n=1, 4) corresponding to the peak in the input acceleration, and T is the period of input motion (=0.8 s). In Fig. 8(a), amplification of the surface of original subsoil (A4/A0) is nearly 2, while that of surface of backfill (A3/A0) is gradually decreasing from 1.4 to 0.9 with large fluctuation. Considering that the fluctuation starts 7 s when the manhole started lift up [Fig. 6(a)], the acceleration of backfill might be disturbed by the motion of the manhole. The factor of A1/A0 (top of the manhole/input) is slightly larger than that of A2/A0 (bottom of the manhole/input). Namely, larger inertial force is acting at the top of the manhole. This suggests rocking behaviour of the manhole during uplift. As shaking continues, there appears phase difference exceeding 90° in Figs. 8 (e) to (h). Phase difference of the backfill surface keeps 90° [Fig. 8 (f)] suggesting complete liquefaction of the backfill.

Fig. 9 shows the relationship between excess pore water pressure and uplift displacement of the manhole for CS4. Fig. 9 (a) is pore water pressure measured at the bottom of the manhole [P1] and (b) is a pore water pressure measured in backfill [P2]. Fig. 9 (c) is the two pore water pressures are compared.

Although, the pore water pressure at the bottom of the manhole is decreased during uplifting, the manhole uplifts with pore water pressure in backfill as shown in Fig. 9. It indicates that the manhole is uplifted by the liquefaction of backfill and decreased pore water pressure at the bottom of the manhole is increased during vacant place by uplift of the manhole was placed by liquefied backfill soil.

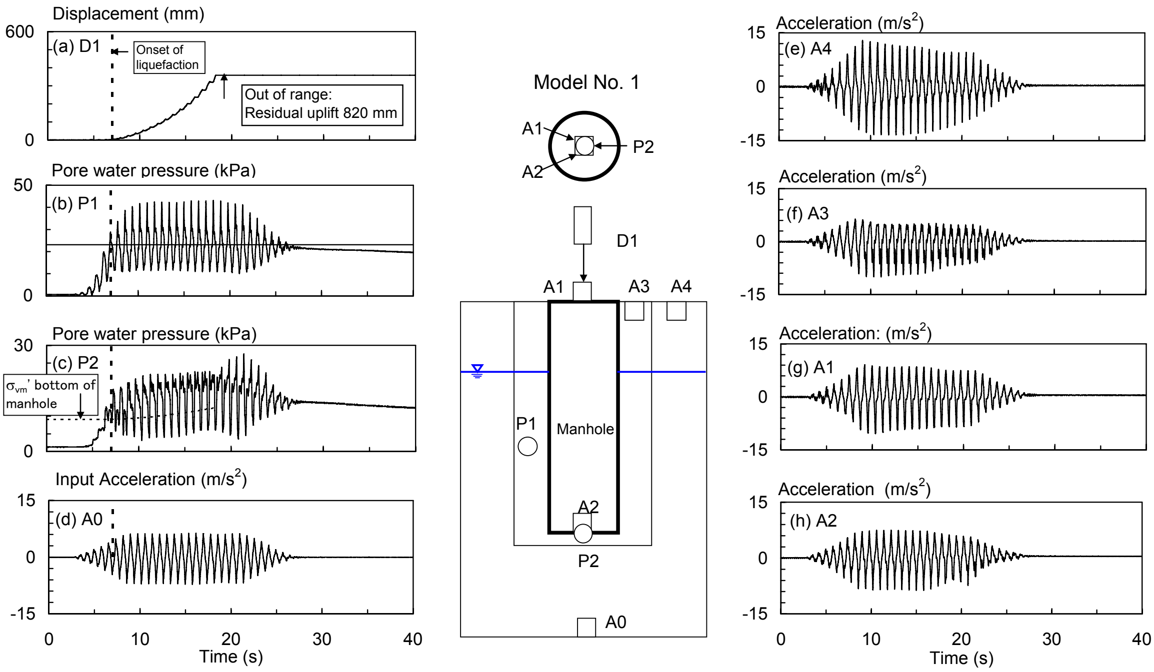

Fig. 6 Results of centrifuge model tests without measure (CS4): Groundwater depth, GL = −1.0 m

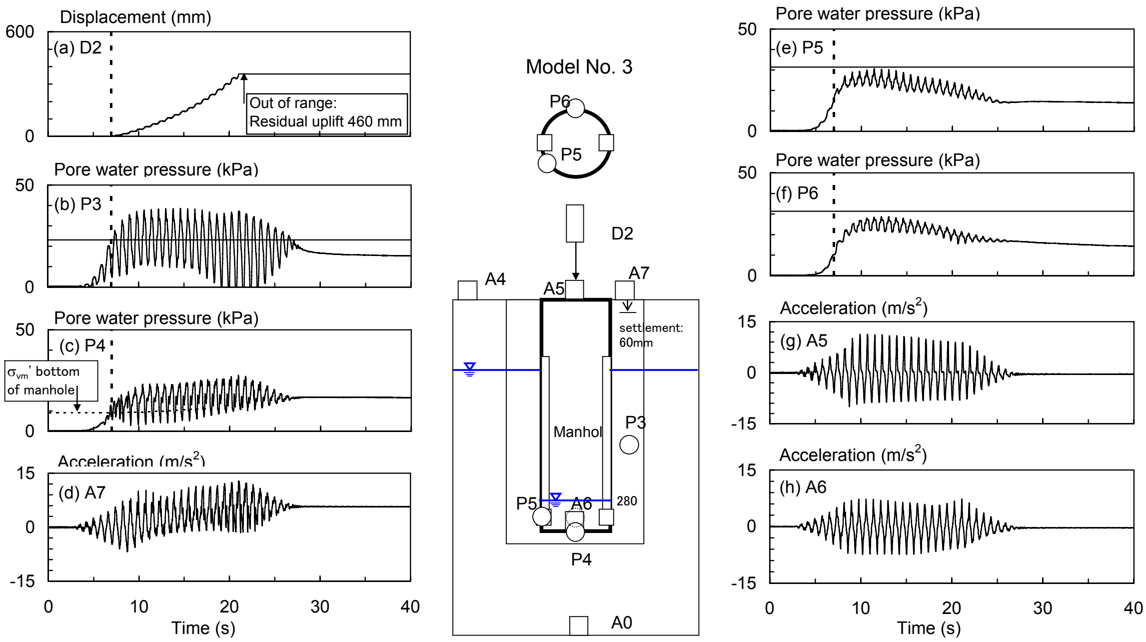

Fig. 7 Results of centrifuge model tests with measure (CS4): Groundwater depth, GL = −1.0 m

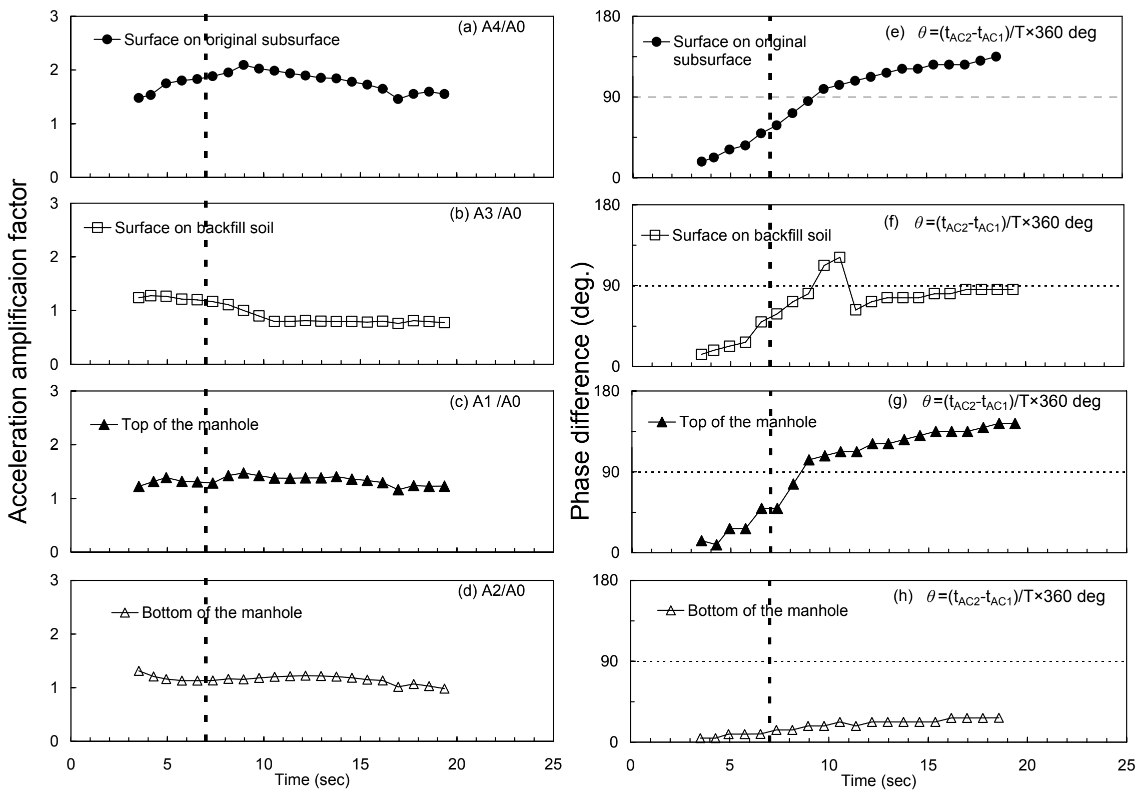

Fig. 8 Time history of acceleration amplification factor [(a) to (d)] and phase difference [(e) to (h)]: no measure of CS4

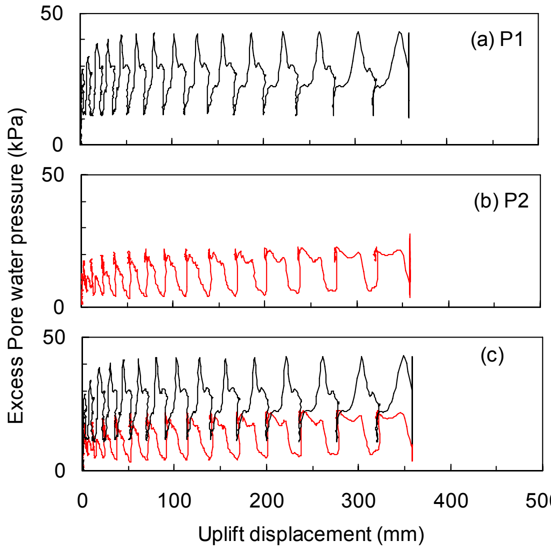

Fig. 9 Relationship between excess pore water pressure and uplift displacement for no measure of CS4 : (a) is pore water pressure measured at the bottom of the manhole, (b) is pore water pressure measured in backfill and (c) is the two pore water pressures are compared

Effect for a new measure for uplift

A new measure against the uplift of the manhole proposed in this study (Konishi et al. 2008). The measure system can dissipate the pressurized water by liquefaction into the manhole. Results of the centrifuge modeling tests show that the measure has an effect on the uplift of the manholes.

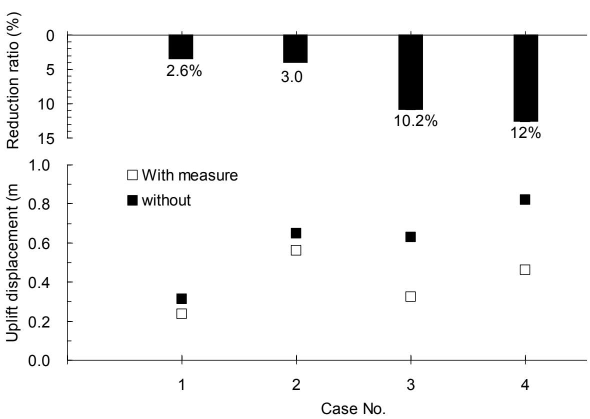

Fig. 10 uplift displacement and reduction ratio by the mitigation measure.

Fig. 10, which plotted the relationship between the uplift displacement and Case No. for 4 cases, shows some effects of the measure. Uplift amount for the manholes with the measure was smaller than that of the manholes without the measure for all tests. CS1 to 3 for the model No. 2 show that the uplift amount had been reduced up to 2.6, 3.0 and 10.2% for the manhole length (3 m), respectively. CS4 for the model No.3 show that the uplift amount had been reduced up to 12.0. Model No. 3 with filtering net of diameter of 15 mm had gotten the best reduction ratio (12.0%).

5. Conclusions

A study was performed to study the mechanism of the uplift of a manhole and to evaluate the effectiveness of the new countermeasure against the uplift of a manhole through geotechnical centrifuge modeling tests. The tests were conducted with and without countermeasure, synchronously. The countermeasure is consisted of a filtering net and pipe to guide pressured water into a manhole during earthquakes.

The manhole started to lift up when the excess pore water pressure in the middle of the backfill and that of the bottom of the manhole exceeded the initial effective vertical stress. The uplift of the manhole with the countermeasure was decreased up to 12.0% for the length of the manhole [Fig. 10, Model No. 3]. However, the amount of uplift may be still too large (8% of the length of the manhole) when it is applied in practice. To introduce the measure for uplift to the design, further investigation for effective measures is required.

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液状化による埋設構造物の浮上に関する遠心模型実験
：浮上量の低減に関する対策

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要　旨

大地震時に液状化による埋設構造物の浮き上がりが生じた事例は数多く報告されている。2004年新潟県中越地震では，長岡市，小千谷市などで1,400箇所以上のマンホールの浮き上がりが発生し，緊急車両の通行が阻害されるなど，市民生活に大きな影響を与えた．マンホールの浮上防止対策についても，埋戻し土の締固め，固化改良，砕石による埋戻し，間隙水圧をマンホール内に逃がす方法（小西ら，2008）などが考案されている。しかし，既存のマンホールに対する浮上防止対策については，有効かつ経済的な方法がいまだ模索されている。本研究では，遠心模型実験を用い，既存および新設のマンホールに対して間隙水圧をマンホール内に逃がす方法の有効性を評価した。その結果，浮き上り量は対策なしよりマンホール長さの12%まで低減された。

キーワード：地震，液状化，埋設構造物，遠心模型実験