様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科学研究費助成事業　　研究成果報告書

平成 ３０ 年　 ６ 月 １４ 日現在

機関番号：１４３０１
研究種目：基盤研究(B)（一般）
研究期間：2015～2017
課題番号：１５Ｈ０４０３７

研究課題名（和文）Experimental and theoretical diagnosis of arch collapse with liquefaction in embankment constructed on soft ground subjected to seismic loading

研究課題名（英文）Experimental and theoretical diagnosis of arch collapse with liquefaction in embankment constructed on soft ground subjected to seismic loading

研究代表者

ピパットポンサー　ティラポン（PIPATPONGSA, Thirapong）

京都大学・工学研究科・准教授

研究者番号：１０４０１５２２

交付決定額（研究期間全体）：（直接経費）　　13,500,000円

研究成果の概要（和文）：本研究では軟弱地盤上の盛土において地盤沈下による盛土内部の応力状態の変化が盛土の液状化抵抗に与える影響を検討するため、ウレタン地盤や剛体地盤を用いた動的模型実験を行った．実験の結果，高い締固め度の盛土では基礎地盤の凹状沈下による側方伸長変形で盛土中央底部の水平土圧が非常に小さくなることがわかった．また，盛土内部へのメトローズ供給によって発生する基礎地盤の沈下と供給部付近が緩むことにより，アーチ効果が発生し盛土中央底部の鉛直土圧が減少することが確認された．地震時において剛体地盤条件との比較からウレタン地盤上の盛土の液状化抵抗が沈下により減少したことが示唆された．

研究成果の概要（英文）：In this study, dynamic centrifuge model tests of an embankment placing on rigid base and soft base modelled by urethane were conducted to investigate the liquefaction resistance in association with the change of the stress distribution inside embankments due to basal subsidence. Experimental results reveal that lateral spreading deformation causes reduction in horizontal earth pressure along the bottom of highly-compacted embankments due to concave settlement of the base. Moreover, arch action was formed underneath the core of embankment as reduction in vertical earth pressure was observed due to the basal subsidence and loosening of inner zone after submersion in Metalose supplied inside the embankment. Comparisons between embankments built on rigid ground and those built on rigid ground imply that basal subsidence decreases liquefaction resistance in embankments during an earthquake.

研究分野：地盤工学

キーワード：アーチ効果　模型実験　液状化　盛土　主応力軸

１．研究開始当初の背景

After the 2011 Off the Pacific Coast of Tohoku earthquake, many researches have been conducted with an aim to answer why a large number of embankments and levees resting on non-liquefiable foundation soils were severely damaged. Despite Tohoku Regional Development Bureau of Ministry of Land, Infrastructure, Transport & Tourism (MLIT) had summarized that damages caused by liquefaction of the foundation ground involve basal settlement and saturated condition of loosening construction materials inside levees submerged under water, the failure mechanism has not been clearly understood because these explanations are not much different than what have been pointed out since the occurrence of the 1993 Off Kushiro-Oki earthquake. Okamura et al. (2013) have published their experimental works, successfully confirming the main causes of liquefaction mentioned earlier. In addition, they reported that stress at the lower part of the embankments was reduced after the embankments underwent subsidence due to the consolidation of the foundation clay. This result implies “soil arching”; however, they did not mention about “arching effect” in their paper. In fact, Trollope & Burman has already found that the settlement of embankments induces arch action across a basal deflection since 1980 in an attempt to explain the phenomenon of central pressure drop observed in granular heaps with a deflected base. They might not realize on that time this counter-intuitive observation could be related to the occurrence of liquefaction. Arching effect in embankments is separated into active and passive arch actions and the theory of active arch action has been achieved by Pipatpongsa et al. (2010). 1G embankment model with hysteretic loops of basal settlement has been conducted, confirming the downward basal deflection significantly induces passive arch and the lower-bound limit analyses in passive condition can characterize the pressure profiles with the pronounced dip.

２．研究の目的

Herein, the scope of research is limited to liquefiable embankments resting on the soft ground with the primary objective focusing on whether embankments constructed on deformable foundation is unsafe because passive arch action weakens the liquefaction resistance and insufficient confining pressure fails to prevent overstress in soil arching against seismic forces, or by other combined factors. Therefore, the following unclear mechanisms will be elucidated step by step during the research period using physical modelling and numerical analysis.

A) Before earthquake: basal settlement → arch action → weakening liquefaction resistance

B) After earthquake: soil liquefaction → drop of confining pressure + seismic force → arch collapse → failure of embankment

Therefore, this research serves two purposes. Firstly, to associate the arching phenomena in soils with the mechanisms of weakening resistance against liquefaction of partially saturated embankments resting on deformable ground. Secondly, to develop the experimentally realizable theory bridging the criteria of arch collapse and the failure of embankment due to liquefaction and strong ground motions. A series of both 1G model tests in static loading and centrifugal model tests of embankment in dynamic loadings is carried out to diagnose the mechanisms of arch collapse.

３．研究の方法

Regarding the soil for modelling the embankment using centrifugal modelling, Hiroshima sand and Silica sand No.7 were used. Note that, Hiroshima sand was sieved with the maximum size of 1 mm. The curve of grain size distribution for these sands is displayed in Fig.1. In addition, the compaction tests indicated the maximum dry density of Hiroshima sand and silica sand No.7 are $\gamma_{d.max}$=17.3 kN/m3 and $\gamma_{d.max}$ =14.1 kN/m^3, respectively.

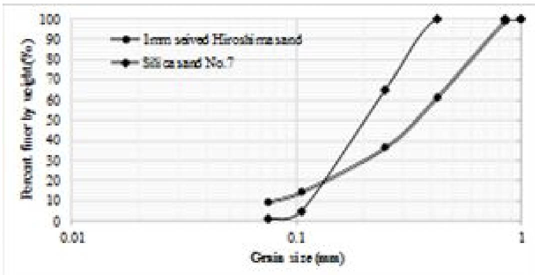

Fig.1: Grain size distribution of the sandy soil

The model configuration and instrumentation is shown in Fig.2. The deformable ground was modelled by Urethane. The basal subsidence was recorded by a couple of laser sensor transducers. One pointed directly on the crest surface to measure the total subsidence while the other pointed on the wooden rod connected with the base to measure basal subsidence separately. Two pore water transducers were used together with three earth pressure gauges to measure both vertical and horizontal earth pressures for observing the occurrence of arching effect.

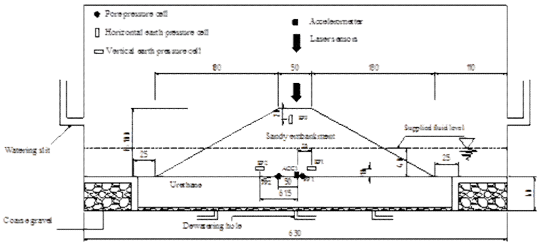

Fig.2: Model configuration and instrumentation

The fluid was prepared by dissolving Metolose with water to achieve 50 cSt kinematic viscosity fluid for centrifuge tests at acceleration of 50g. Due to the softness of the Urethane, the input seismic loading could not fully propagate to the Urethane underneath the embankment, but almost half of seismic loading transferred to the base of the embankment. Thus, only the amount of seismic loading underneath embankment for each test was considered.

The embankment was frozen and thawed before starting centrifugal acceleration. The sequence of the experiment is set into five steps, i.e. Step 1: prepare the deformable ground made of Urethane (some supplement metal frame was used to stabilize the ground to the watering process and seismic loading; Step 2: prepare the embankment using wooden mold then frozen the model by refrigerator, after frozen the embankment, remove the model from its mold and put on the prepared ground and wait until the model was completely thawed at the room temperature; Step 3: increase the gravitational acceleration until reaching the designated value (50g in this case); Step 4, watering and dewatering the model to the expected initial pore water pressure; finally Step 5: apply the seismic loading.

４．研究成果

The bulging mechanism was observed from the series of some tests, e.g. UB.90.D.I-1,2,3 as seen in Fig. 3, Fig.4, Fig.5 and Fig.6.

Fig.3: Top view of the embankment after shaking of test UB.90.D.I-1

Fig.4: Front view of the embankment after shaking of test UB.90.D.I-1

Fig. 5: Top view of the embankment after shaking of test UB.90.D.I-2

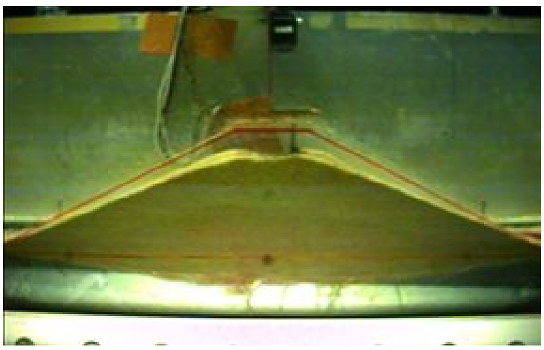

Fig.6: Front view of the embankment after shaking of test UB.90.D.I-2

The typical characteristics of the bulging mechanism could be clarified as that: the lower part of the embankment was bulging while the lateral displacement is small as stated by Sadeghi (2014). The excessive crest settlement was appeared on such failure mode e.g. such amount of test UB.90.D.I-2 was found as much as 0.665m. Note that either complete liquefaction or the limited liquefaction solely occurred in the zone 1 - underneath the crest (See Fig.7) as indicated in Fig.8 and Fig.9 for tests UB.90.D.I-1 and UB.90.D.I-2, respectively.

Conversely, the amount of excess pore pressure buildup in the zone 2 - underneath the slopes(See Fig.7) was negligible in these models e.g. UB.90.D.I-1, UB.90.D.I-2 as shown in Fig.10 and Fig.11, correspondingly.

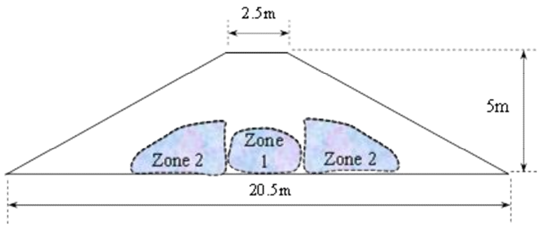

Fig.7: Liquefiable zones inside the embankment

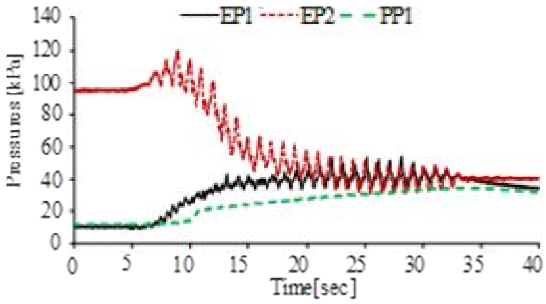

Fig.8: Onset of liquefaction occurrence of test UB.90.D.I-1

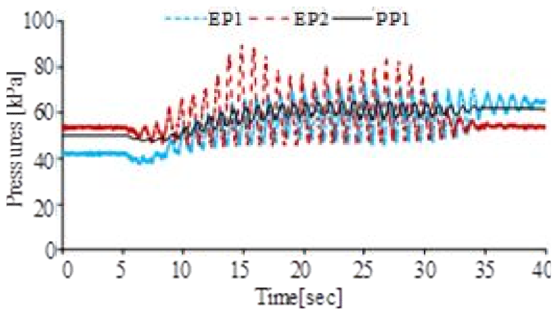

Fig.9: Onset of liquefaction occurrence of test UB.90.D.I-2

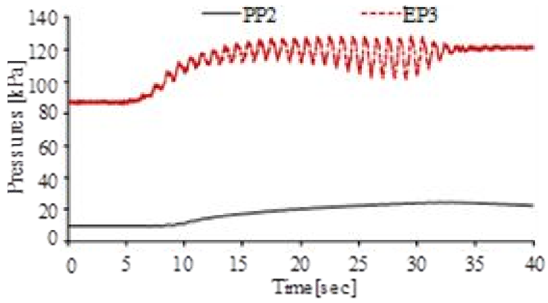

Fig.10: Excess pore pressure buildup in zone 2 of test UB.90.D.I-1

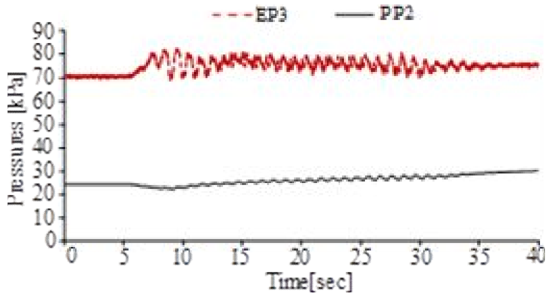

Fig.11: Excess pore pressure buildup in zone 2 of test UB.90.D.I-2

The underlying mechanism accounted for such failure mode could be conjectured as that: as the liquefaction solely occurred in the zone 1; therefore, the shear resistance in this zone turns to almost zero; consequently, the supportive force to its above upper part of the embankment is erased and turn such upper part to be very susceptible against seismic loadings. On the other hand, the sliding mode was not able to take place; since the liquefaction could not have occurred in this area, i.e. zones 2, whereby the shear resistance in the sides of the embankment was not deteriorated by the seismic loading and strong enough to prevent the sliding occurred. As a result, the upper part was prone to cave in the liquefaction zone. If the current conditions turn the cave-in into reality; the arch collapse mechanism is obtained. Otherwise, the bulging on the slope is observed, since the upper part attempted to cave in the liquefaction zone 1 making the side of the embankment bulging. Hence, the appearance of embankment under such bulging failure mode is clarified, and this failure mode has been schematized in Fig.12. The appearance of the test UB.90.D.I-2 is elaborate to exemplify the trend of approaching the arch collapse mechanism from the bulging failure mode since it was most close to the arch collapse pattern as exhibited in Fig.5 and Fig. 6. In fact, the arch has not been collapsed in this test as the value of EP3a and EP3b, which located symmetrically far away from centerline a distance of 3.08m, was not dropped but increased during and after the course of the shaking as shown in Fig.13. This evidence confirms that the arch has not been collapsed.

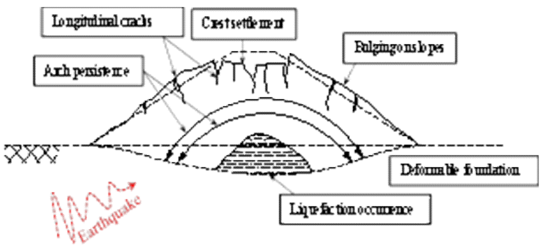

Fig.12: Mechanism of bulging mode

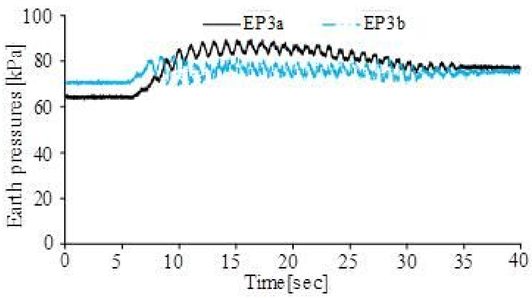

Fig.13: Responses of earth pressure during shaking of tests UB.90.D.I-2

As foregoing discussion, there are two mechanisms to activate the arch action inside the embankment, viz. basal subsidence whereby the arch action occurred right after starting of the acceleration process, and the arch action induced by the pore fluid supplying process by which the arch action occurred under the full prototype scale or 50g centrifugal acceleration. It is necessary to note that the basal subsidence has presumably increased the liquefaction susceptibility on three aspects simultaneously, i.e. (i) loosening the soil density, (ii) enlarge the saturated area at the lower part of the embankment due to the concave base, and (iii) probably triggering the arch action inside the embankment reducing the mean effective confining stress on the central vicinity of the lower part which lessens the liquefaction resistance of the embankment. To dominate the role of arch action on the increase of the potential of liquefaction triggering, such role has to be isolated from the three consequent effects of the basal subsidence.

With regard to the first effect on the soil density loosening, as stated in the foregoing chapter based on the elastic solution, the basal subsidence has substantially reduced the soil density since the volume of the embankment was expanded under the effect of the basal subsidence. Such fact has been numerically measured by taking into account the Young’s modulus reduction corresponding to the amount of the basal subsidence under the exponential function. This fact is indisputable for the increasing of the liquefaction susceptibility; and it affected on the rate of excess pore pressure buildup as stated by Okamura et al. (2011), (2013).

In conclusion, through such series of centrifugal model tests, some characteristics of dynamic response of the sandy embankment have been revealed: (i) the arch action was not only activated by the basal subsidence but also triggered by the fluid supplying process and (ii) the arch action appearance has substantially increased the potential of liquefaction triggering.

５．主な発表論文等

（研究代表者、研究分担者及び連携研究者には下線）

〔雑誌論文〕（計 5 件）

① T. Nguyen, T. Pipatpongsa, T. Kitaoka and H. Ohtsu, Stress distribution in conical sand heaps at incipient failure under active and passive conditions, International Journal of Solids and Structures, 查読有, 印刷中
https://doi.org/10.1016/j.ijsolstr.2018.04.001

② B. Ukritchon, R. Ouch, T. Pipatpongsa and M.H. Khosravi, Experimental studies of floor slip tests on soil blocks reinforced by brittle shear pins, International Journal of Geotechnical Engineering, 查読有, 印刷中
https://doi.org/10.1080/19386362.2017.1314126

③ B. Ukritchon, R. Ouch, T. Pipatpongsa and M.H. Khosravi, Investigation of stability and failure mechanism of undercut slopes by three-dimensional finite element analysis, KSCE Journal of Civil Engineering, 查読有, 22(5), 2018, 1730-1741.
https://doi.org/10.1007/s12205-017-2011-x

④ R. Ouch, B. Ukritchon, T. Pipatpongsa and M.H. Khosravi, Finite element analyses of the stability of a soil block reinforced by shear pins, Geomechanics and Engineering, 査読有, 12(6), 2017, 1021-1046
https://doi.org/10.12989/gae.2017.12.6.1021

⑤ M.H. Khosravi, T. Pipatpongsa and J. Takemura, Theoretical analysis of earth pressure against rigid retaining walls under translation mode, Soils and Foundations, 査読有, 56(4), 2016, 664-675
https://doi.org/10.1016/j.sandf.2016.07.007

〔学会発表〕(計 9 件)
① T. Nguyen, T. Pipatpongsa, T.Kitaoka, H. Ohtsu, Stress redistribution in embankments induced by basal subsidence based on the isogeometric analysis using elastic model, 第 23 回計算工学講演会, 査読無, 2018, G-10-03

② T. Nguyen, T. Pipatpongsa, T.Kitaoka, H. Ohtsu, Numerical investigation of arch action in sand heap using elastic model based on isogeometric analysis method, 第 21 回応用力学シンポジウム講演概要集, 査読無, 35-36, 2018

③ 南出奏, ピパットポンサー・ティラポン, 北岡貴文, 大津宏康, 掘削途中の斜面における表面移動速度の逆数を用いた斜面崩壊予測手法について, 第 45 回岩盤力学に関するシンポジウム講演論文集, 査読有, 2018, 185-189

④ K. Fang, T. Pipatpongsa, T. Kitaoka and H. Ohtsu, Preliminary tests for evaluating suitability of materials used in centrifuge modeling of slopes, Proceedings of the 45th Symposium on Rock Mechanics, 査読有, 2018, 149-154

⑤ T. Nguyen, T. Pipatpongsa, T. Kitaoka and H. Ohtsu, Stress redistribution in embankment due to basal subsidence using centrifuge models, 第 52 回地盤工学研究発表会, 査読無, 2017, 95-796

⑥ 南出奏, ピパットポンサー・ティラポン, 北岡貴文, 大津宏康, 表面移動速度の逆数を用いた法尻掘削斜面における斜面崩壊予測手法の検討, 第 52 回地盤工学研究発表会, 査読無, 2017, 823-824

⑦ 加納武司, 堃方, ピパットポンサー・ティラポン, 北岡貴文, 大津宏康, 傾斜面に沿った横抵抗を受けた土塊の滑り条件, 第 52 回地盤工学研究発表会, 査読無, 2017, 829-830

⑧ K. Fang, T. Kanou, T. Pipatpongsa, T. Kitaoka and H. Ohtsu, Physical models on base failure of slope subjected to surcharge loading, 第 52 回地盤工学研究発表会, 査読無, 2017, 831-832

⑨ T. Nguyen, T. Pipatpongsa, T. Kitaoka and H. Ohtsu, Stress distribution in elastic embankment using isogeometric analysis under Bézier extraction, The 6th Japan-Korea Geotechnical Engineering Workshop, Japanese Geotechnical Society Special Publication, 査読有, 4(4), 2016, 78-83

〔図書〕(計 0 件)
〔産業財産権〕
○出願状況(計 0 件)

○取得状況(計 0 件)

〔その他〕
ホームページ等
http://georisk.kuciv.kyoto-u.ac.jp

6. 研究組織

(1)研究代表者
ピパットポンサー ティラポン (PIPATPONGSA, Thirapong)
京都大学・大学院工学研究科・准教授
研究者番号: 10401522

(2)研究分担者
木村 亮 (KIMURA, Makoto)
京都大学・大学院工学研究科・教授
研究者番号:30177927

澤村 康生 (SAWAMURA, Yasuo)
京都大学・大学院工学研究科・助教
研究者番号:20738223

竹村 次朗 (TAKEMURA, Jiro)
東京工業大学・環境・社会理工学院・准教授
研究者番号:40179669

竹山 智英 (TAKEYAMA, Tomohide)
神戸大学・大学院工学研究科・准教授
研究者番号:00452011

(3)連携研究者
なし
(4)研究協力者
なし