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Liquefaction countermeasures by shallow ground improvement for houses and their cost analysis

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ABSTRACT

A large number of houses suffered from liquefaction-induced damages in recent large earthquakes due to lack of economical countermeasures. In this study, the shallow ground improvement, up to several meters deep, was proposed as an economical liquefaction countermeasure for houses. Based on the case studies, the design criteria of allowable tilt angles and penetration settlements of houses were proposed for the required level of serviceability against moderate and large earthquakes. The results of questionnaire survey, airborne LiDAR survey and centrifuge model tests demonstrated that even a few meters of non-liquefiable layers in shallow ground could greatly reduce settlements and tilting of houses. A series of numerical analyses indicated that non-liquefiable layer of three meters thick below ground water table improved by solidification methods can prevent significant damages of houses. Furthermore, cost analyses were carried out for different ground improvement methods for both new and existing houses.

1. Introduction

Liquefaction-induced damages of civil engineering structures or large buildings are extremely small or none, if proper countermeasures are implemented. However, recent large earthquakes have proved that many of the private owned houses have suffered liquefaction-induced damages in contrast [11]. For example, more than 25,000 houses were severely damaged by liquefaction of the young reclaimed ground in the Tokyo Bay areas and the lowland areas along rivers due to the 2011 off the Pacific coast of Tohoku Earthquake, hereafter denoted as the 2011 Tohoku earthquake [17].

One of the pressing issues in order to mitigate these liquefaction-induced damages of houses is the development of economical countermeasures. Note that the current liquefaction countermeasures for civil engineering structures or large buildings request to improve the whole layers of saturated loose sand that are likely to liquefy, that are too costly for ordinary house owners.

In this paper, the shallow ground improvement technique is proposed as one of the most economical liquefaction countermeasures for houses. Some case histories showed that, the damages of buildings and houses on the ground were not serious or none if the non-liquefiable surface layer thicker than 3.0 m was found above the liquefiable layer [3]. In addition, if the shallow ground immediately below the mat foundations of houses is improved, settlements and tilting of houses by the liquefaction of the underlying layer should be significantly reduced. This is because this non-liquefiable surface layer would support the houses as a thick integrated base with relatively high stiffness. However, the required thickness of the shallow ground improvement, which satisfies appropriate performance criteria, has not been sorted out. In addition, although there are several kinds of methods available for the shallow ground improvement, the effectiveness as liquefaction countermeasure would be different from each other, which need to be considered in the proposal.

Various kinds of studies were carried out for the purpose to implement this proposal. Firstly, literature review and questionnaire survey were conducted to propose the design criteria for liquefaction countermeasures. Secondly, the performance of the

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shallow ground improvement against soil liquefaction was investigated by questionnaire survey, airborne LiDAR survey and centrifuge model tests. Thirdly, FEM analyses were conducted to determine the thickness of the improved layer required to prevent significant damages of houses. Furthermore, cost analyses were carried out for different ground improvement methods for both new and existing houses.

2. Design criteria for liquefaction countermeasures for houses

For the designs of liquefaction countermeasures, appropriate performance criteria should be set relevant to the houses, which are the allowable values of tilt angles and penetration settlements of houses for the required level of serviceability against the design earthquakes. Literature review was conducted for the current codes, standards and guidelines for foundation design of houses and buildings as well as for some investigation reports on the recent major earthquakes.

Table 1 shows the relationships between the tilt angles of houses and the relevant health problems [1]. The tilt angles exceeding 10/1000 certainly cause various disorders ranging from minor headache to serious health problems. Furthermore, the estimation of damaged houses, e.g., 'partially destroyed' and 'completely destroyed', is usually made as measuring the tilt angles of their foundations [2]. The 'partially destroyed' is designated for the tilt angles exceeding 1/100 (=10/ 1000), indicating the need for minor restorations. Whereas, the 'completely destroyed' is designated for the tilt angles exceeding 1/60 (=16.7/1000), indicating the need for repairs of major structural members or for rebuilding.

Table 1
Tilt angles of houses and health problems (after [1]).

Tilt angles of houses			Health problems
Deg	Rad.	Inclination	
0.29	1/200	5/1000	Feeling of tilting
0.34	1/167	6/1000	Feeling of differential settlement
0.46	1/125	8/1000	Strong feeling of tilting, Frequent complaints
0.6	1/100	10/1000	Need to level a floor
~1	~1/60	~16.7/1000	Feeling of heaviness in head and loss of balance
2–3	1/30–1/20	33.3–50/1000	Serious disorder of dizziness, headache, nausea and anorexia
4–6	1/15–1/10	66.7–100/1000	Serious disorder of fatigue and sleep

For the purpose to investigate the threshold values of tilt angles for the residents to ask for repair works of levelling their inclined houses by soil liquefaction, questionnaire survey was conducted to several major house manufacturers who were involved in the restoration works after the 2011 Tohoku Earthquake. In this survey, the tilt angles and the differential settlements of 355 repaired houses were collected. Fig. 1 show the relationships between the tilt angles and the differential settlements of the repaired houses with strip footings and mat foundations, respectively. Excluding a datum for the mat foundations of exceptionally values, the minimum values of tilt angles and differential settlements are 6/1000 and 50 mm, respectively, regardless of neither the foundation types nor the areas. Considering the data scattering, it may be justified to conclude that the threshold values of tilt angles are 8–10/1000 to ask for repair works.

Based on the above literature review and questionnaire survey, the performance criteria are proposed regarding the earthquake motion levels and tilt angles of houses as follows:

1. For moderate earthquake that is assumed to be experienced more than once during the lifetime of the house, the tilt angles should not exceed 10/1000 so as not to pose any health problems to the residents.
2. For large earthquakes that is maximum earthquake to be considered, the tilt angles should not exceed 16.7/1000 so that the residents can return to their normal lives by minor restoration works.

However, these tilt angles of houses are not suitable criteria for verification of designing liquefaction countermeasures, because the effectiveness of shallow ground improvement against soil liquefaction would be confirmed and verified by practical experiments and numerical analyses using simple symmetrical models (i.e., [5]). Therefore the relevant values of penetration settlement of houses should be designated which can be correlated with the above criteria. In this paper, the penetration settlement denotes the extent of sinking of the house into the ground, i.e., the difference between the total settlement of the house and the settlement of the surrounding level ground.

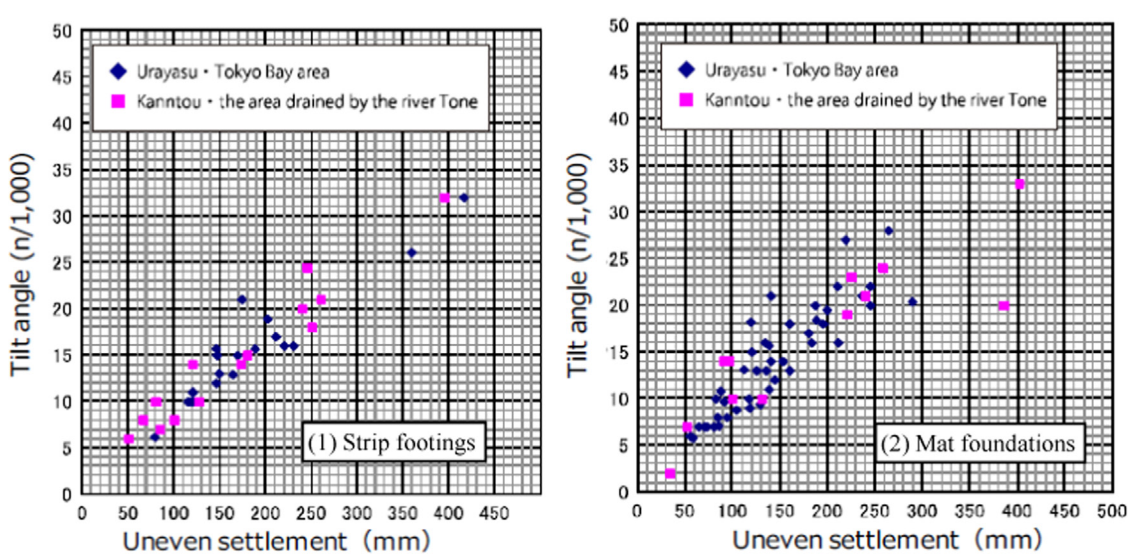

Fig. 1. The relationships between the tilt angles and the differential settlements of the repaired houses after the 2011 Tohoku Earthquake with (1) strip footings and (2) mat foundations.