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Shaking table tests on mitigation of liquefaction vulnerability for existing embedded lifelines

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Abstract

The 2011 off the Pacific Coast of Tohoku Earthquake caused significant damage to underground sewage lifelines in the Tokyo Metropolitan area. The importance of the earthquake- and liquefaction-resistance of embedded pipelines was recognised, as a significant amount of time passed before the commencement of temporary operations was resumed. One of the lessons learned was the liquefaction vulnerability of relatively inexpensive structures such as embedded sewage pipelines whose seismic resilience is important for the robustness and quick repair of urban infrastructures. The same problem is likely to occur in other regions where strong earthquakes are expected in the near future. Despite the urgency of this situation, it is not possible these days to excavate pipes and improve backfills quickly due to financial limitations. Hence, less expensive measures, such as mechanical constraints, the partial injection of grout, the installation of drain pipes, and the insertion of sheath pipes, are proposed in this paper. In the present study, shaking model tests were conducted for the purpose of validating those measures by which retrofitting may be achieved at reduced construction costs and in a shorter time frame. Through the tests, the proposed measures exhibited the satisfactory performance of mitigating liquefaction-induced damage to sewage pipelines. The results of the shaking table tests on different mitigation measures were discussed considering their practical applications.

Keywords: Earthquake; Liquefaction; Lifelines; Model test; Mitigation

1. Introduction

The damage to lifeline facilities caused by the 2011 off the Pacific Coast of Tohoku Earthquake was extremely detrimental to post-earthquake operations in modern cities near Tokyo Bay. Details of geotechnical problems related to liquefaction have been reported (Sasaki et al., 2012; Yasuda et al., 2012). Typical examples of liquefaction-induced damage in underground lifelines are shown in Fig. 1. The significant floating of manholes and pipes was observed over a wide area. The disconnection of pipe joints was also a serious problem, as it introduced liquefied backfill sand into the pipes. As a result, the resumption of operations was delayed due to the significant efforts required to clean out the clogged pipes. After the

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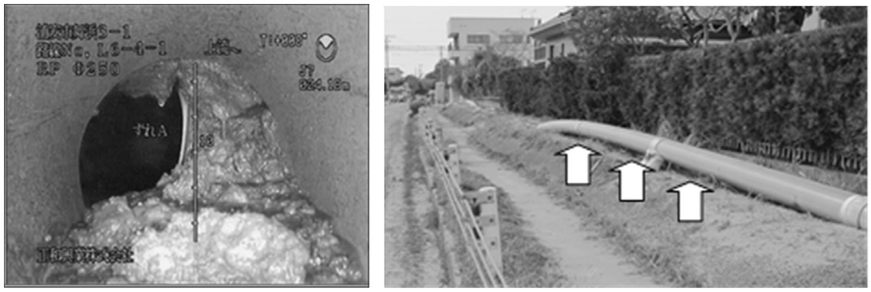

Fig. 1. Clogging and floating of embedded pipes.

earthquake, discussions began on the risk of future large earthquakes that may hit other regions of the nation.

Another important issue is the ageing and deterioration of embedded sewage lifelines. According to a survey conducted in 2009, approximately 19% of the existing sewage pipes (totalling 430,000 km) in Japan have been in operation for more than 30 years, and risks of damage due to deterioration in sewage facilities are known to increase after 30 years of operation (Investigative Committee on Entrusted Management of Sewerage Facility Maintenance, 2012). Moreover, the proportion is expected to increase further, up to 40%, by 2019. Thus, the replacement or the rehabilitation of these deteriorated pipes is urgently required for the extension of their usable life.

2. Previous mitigation measures and proposed methods

The mechanism of the liquefaction-induced floating of buried pipes has been studied (Koseki et al., 1997, 1998). After the Niigata Chuetsu Earthquake of 2004, the following three backfilling methods were recommended to restore the damaged sewage pipelines: compacted sand, aggregates, and cement mixed soil (Technical Committee on Earthquake Resistant Design of Sewage Lifelines, 2004). The first method is simple and has been employed widely in practice. However, some problems due to a lack of compaction have been reported (Technical Committee on Earthquake Resistant Design of Sewage Lifelines, 2008). The second method relies on the high permeability of the aggregate backfill to ensure that the excess pore water pressure will dissipate quickly during earthquakes. The third method showed good performances during the Niigata-ken Chuetsu-oki Earthquake of 2007 (Miyake et al., 1998; Technical Committee on Earthquake Resistant Design of Sewage Lifelines, 2008). However, difficulty in the re-excavation of the backfill for maintenance works is problematic.

The performance of these conventional measures requires the excavation of backfill soil over long distances, which necessitates considerable time and construction costs. This is a significant drawback for urgent earthquake retrofitting in other parts of the nation. Hence, the amount of excavation should be reduced and the development of less expensive and easier technology for existing lifelines is desired. The present study proposes four types of mitigation measures (Fig. 2), namely, (1) mechanical constraint using vertical bars (horn structure), (2) vertical drain pipes, (3) chemical grouting, and (4) the insertion of sheath pipes. These mitigation measures require a partial excavation or no excavation at all; thus, they would be economical and quick. Among the four measures, the insertion of sheath pipes has been proposed to revitalise old deteriorated pipes in which new internal pipes are installed. The aim of this measure is to maintain the flow of sewage water even if the external pipes are disconnected during earthquakes. In a companion paper, Otsubo et al. (2016) proposed several alternative mitigation measures for damaged or new pipelines by backfilling with industrial waste.

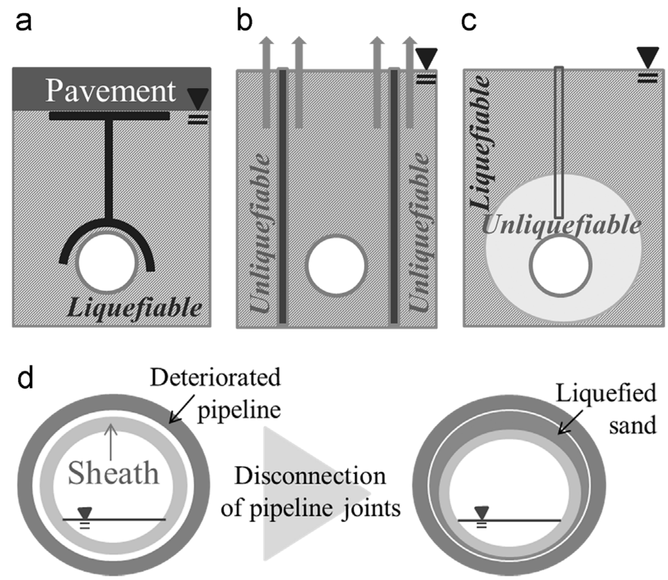

Fig. 2. Proposed mitigation measures without overall excavation: (a) horn-like structure, (b) vertical drain pipes, (c) chemical grouting, and (d) insertion of sheath pipe.

3. Method of shaking model tests

3.1. Model ground and similitude law

A 1-g shaking table and a rigid soil container were used in this research in which a model ground, L270 × W40 × D50 cm, was prepared using silica sand no. 7 (Specific gravity $Gs=2.64$, mean diameter $D_{50}=0.206$ mm, uniformity coefficient $C_u=2.00$, maximum void ratio $e_{max}=1.243$, and minimum void ratio $e_{min}=0.743$). The same sand was used for all the experiments to reproduce the loose backfill ($Dr=30\%$). Gravel ($D_{50}=3.34$ mm and $C_u=2.07$) was also used to reproduce the permeable pavement. To reduce the effect of the rigid lateral boundaries, cushions were used at both ends.