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STUDIES ON SEVARAL COUNTERMEASURES AGAINST LIQUEFACTION-INDUCED FLOW AND AN APPLIVATION OF A MEASURE TO EXISTING BRIDGES IN TOKYO

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ABSTRACT: In Japan, studies on liquefaction-induced flow started just after the 1983 Nihonkai-chubu earthquake and were accelerated after the 1995 Hyogoken-nambu earthquake. Several prediction and countermeasure methods have been proposed. At Metropolitan Expressway, detailed study was conducted to evaluate the safety against the flow. Then, four sites were selected to reduce the effect of the flow by applying a countermeasure. The applied method was to install steel pipes between bridge foundations and sea walls.

Key Words: Liquefaction, Ground flow, Countermeasure, Earthquake, Pile foundation, Bridge

INTRODUCTION

Liquefaction-induced flow brought severe damages to structures during past earthquakes such as the 1964 Niigata and the 1983 Nihonkai-chubu earthquakes in Japan. Studies on the flow started just after the Nihonkai-chubu earthquake. However, the 1995 Hyogoken-nambu earthquake accelerated the study because of the damage to bridges and buildings were severe. After the earthquake many studies have conducted based on inverse analyses of damaged structures, shaking table tests and analyses. Several prediction and countermeasure methods have been proposed and introduced in several design codes.

The developed countermeasure methods have been applied to existing structures. Among them, the method to install steel pipes between existing bridge foundations and sea walls was applied to Metropolitan Expressway in Tokyo. Effectiveness of this method was demonstrated by conducting centrifuge tests and residual deformation analyses.

HISTORY OF STUDIES ON LIQUEFACTION-INDUCED FLOW

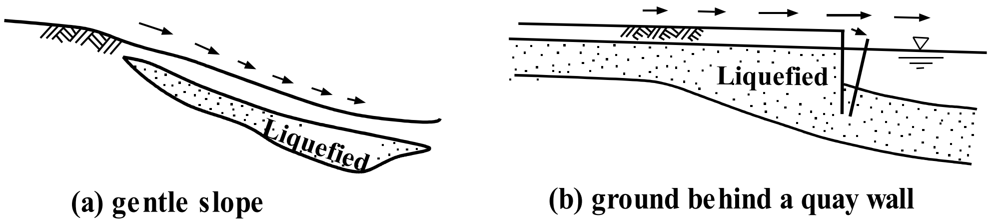


Fig.1 Patterns of liquefaction-induced flow

Studies before the 1995 Hyogoken-nambu earthquake

In 1964, many structures suffered severe damage due to liquefaction in Niigata City. Buildings, timber houses, oil tanks settled. Railway embankments and river levees slid and settled. Sewage manholes and underground tanks floated. Not only these damages, but also liquefaction-induced flow occurred and brought more severe damages to bridges and buried pipes along Shinano River and other several areas. However, no attention had been paid to damages due to the liquefaction-induced flow before 1983 Nihonkai-chube earthquake because the actual amount of ground displacement was not clear.

Many buried pipes suffered severe damage due to liquefaction-induced flow at gentle slopes in Noshiro City during the Nihonkai-chubu earthquake. After the earthquake, a trial was carried out to measure the displacement of the ground surface due to the flow by comparing two aerial photo sets taken before and after the earthquake. This study revealed that very large amount of displacement up to 5 m occurred at the gentle slopes in Noshiro City. The same measure was conducted for the flow in Niigata City during the 1964 Niigata earthquake and clarified that more large displacement up to 10 m occurred along Shinano River (Hamada et al., 1986).

Based on these measurements, studies on mechanism of the liquefaction-induced flow was discussed by conducting case studies of past earthquakes, shaking table tests, laboratory tests and analyses, by mainly technical committees organized in Association for the Development of Earthquake Prediction for about ten years. Then it was recognized that liquefaction-induced ground flow can be divided into two classes, as illustrated in Fig.1: i) ground flow on gentle slopes, and ii) ground flow behind quay walls. Damage to buried pipes occurred in the first situation during the 1983 Nihonkai-chubu earthquake. In contrast, pile foundations suffered severe damage due to the second type of flow during the 1964 Niigata earthquake along Shinano River. Several ideas on the mechanism of the flow were proposed: i) flow occurs due to the decrease of shear modulus, ii) flow occurs because the soil changes to viscous material, etc. Based on these ideas, a few analytical methods to predict the flow had been proposed before the Hyogoken-nambu earthquake.

Studies after the 1995 Hyogoken-nambu earthquake

During the 1995 Hyogoken-nambu earthquake, large displacement such as 4 m occurred in the liquefied ground behind sea walls in and around Kobe City. The large displacement brought severe damage to bridges, buildings and etc. Then, attention has focused mainly on flow and associated damage to pile foundation behind sea walls. Immediately after the earthquake, inverse analyses for the damaged highway bridges of Hanshin Expressway were conducted and a new design method to consider the effect of of liquefaction-induced flow was proposed. This method, so called earth pressure method was introduced in the new design code for highway bridges in Japan (Japanese Road Association, 1996).

In Japanese Geotechnical Society, a Technical Committee on “Liquefaction-induced Flow and Permanent Deformation of the Grounds and Earth Structures during Earthquakes (Chairman: Susumu Yasuda, Professor of Tokyo Denki University)” was organized just the same time of the Hyogoken-nambu earthquake and made research from 1995 to 1998. The committee studied the following five themes on liquefaction-induced flow: 1) case histories during past earthquakes in and out Japan, 2) mechanism, 3) prediction methods, 4) design methods, 5) countermeasures. Results of the studies were summarized in one volume (JGS, 1998).

Studies on the liquefaction-induced flow have been conducted by not only the technical committee in JGS but also many researchers in Japan. Based on these researches, the liquefaction-induced flow has been introduced in several design codes. For examples, a new design procedure based on seismic deformation method was adopted to the seismic design code for high pressure gas facilities (High Pressure Gas Safety Institute of Japan, 2000). Moreover, susceptible zones for liquefaction-induced flow in Tokyo Metropolitan area has been estimated and used for the real-time disaster mitigation system for gas supply system (Yasuda et al., 2004).

Current design methods of pile foundations for liquefaction-induced flow

Based on recent studies, the following four approaches have been proposed to consider the effect of ground flow in the design of piled foundations (Yasuda and Berrill, 2000):

a) Evaluating the deformation of both piles and ground simultaneously,

b) Evaluating the pressure acting on piles due to the ground flow first, then evaluating the resulting deformation of the piles (earth pressure method),

c) Estimating ground displacement first, and then evaluating the deformation of piles (seismic deformation method)

d) Estimating pile deformation, assuming that the liquefied ground behaves as a viscous fluid.

The first approach is logically correct, but it is not an easy one, even by the latest effective-stress response methods of analysis, because of the difficulty of incorporating large ground displacements and interaction between the ground and structure. The second approach is simple and was introduced immediately after the Hyogoken-nambu earthquake in the new specification for highway bridges in Japan as mentioned above. The third approach is also simple and can be applied to complex topographical conditions of the ground and sea walls. In this approach, the displacement of the ground during flow must be estimated first. Then, horizontal forces are applied to the pile through soil springs. Therefore, both ground displacement due to flow and the value of soil-spring stiffness for the liquefied ground must be evaluated in some way. This approach was also developed after the Hyogoken-nambu earthquake, and has been adopted recently in the design codes for High Pressure Tanks in Japan. Application of the fourth approach is still experimental, and it has not yet been introduced into design codes.

Current countermeasure methods against liquefaction-induced flow

In Japan, some studies on the countermeasure against liquefaction-induced flow have already started few years ago before Kobe earthquake as mentioned above. But many studies on the countermeasure were initiated after the Kobe earthquake by model tests and analyses. Table 1 shows the ideas of the countermeasures summarized by the technical committee in JGS (JGS 1998, Kanatani et al. 2000). There are three categories of countermeasures against the damage to structures due to the liquefaction associated ground flow. Most reliable measure is to improve the ground in all area to prevent the occurrence of liquefaction. However this measure is uneconomical and can not be applied under or near existing structures. The second measure is to strengthen a sea wall not to trigger the ground flow, if the liquefaction of the ground behind the sea wall is induced. Strengthening of the ground with a wall, sand piles or densification of a narrow zone of the ground also prevents or decreases the ground flow even though liquefaction occurs in the ground. The third measure is strengthening of structures, for example strengthening of pile foundation by additional piles, to prevent damage even though the liquefaction and associated flow of the ground occurs. Among the countermeasures, some methods have been applied to sea walls and expressways in Tokyo, Kobe and Osaka.

APPLIVCATION OF A REMEDIAL MEASURE TO EXISATING BRIDGES OF METROPOLITAN EXPRESSWAY IN TOKYO

Figure 2 shows the route map of Metropolitan Expressway. Bay Shore Route and other several

Table 1 Countermeasures against liquefaction-induced flow behind quay walls (Kanatani et al., 2000)

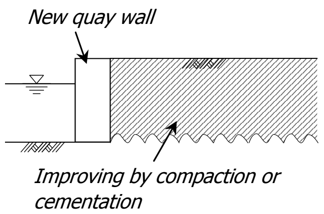
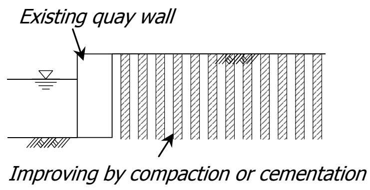
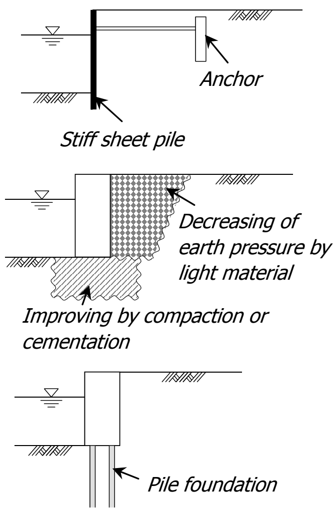
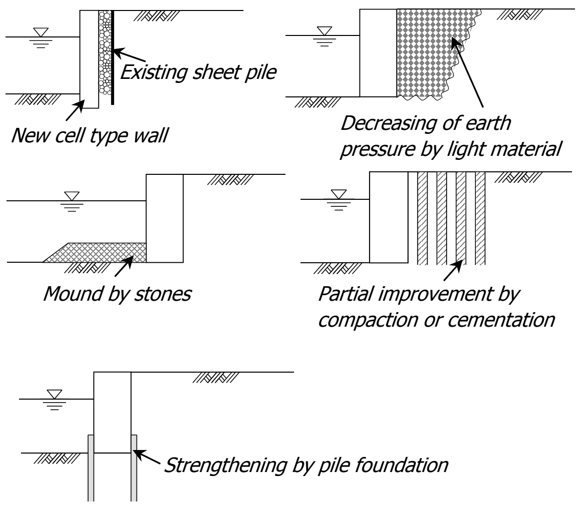
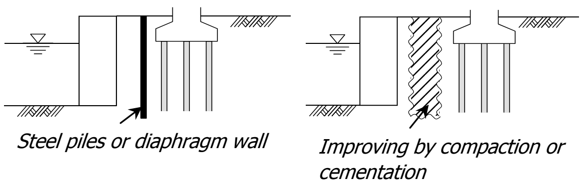
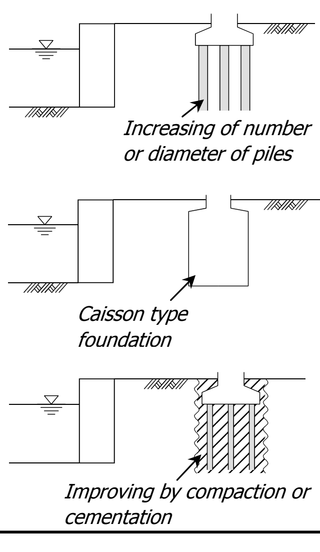
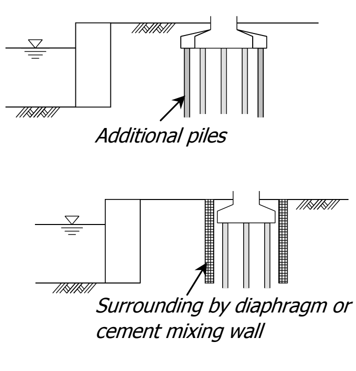
Concept of countermeasure	New structure	Existing structure
Prevention of the occurrence of liquefaction	<New quay wall> 	<Existing quay wall> 
Prevention of the occurrence of flow though liquefaction occurs	<New quay wall> (1)Construction of stable quay wall 	<Existing quay wall> (1)Strengthening quay wall  (2)Decreasing of displacement of the ground behind quay wall 
Keeping of serviceability though liquefaction-induced flow occurs	<New pile foundation> 	<Existing pile foundation> 

Fig. 2 Route map of Metropolitan Expressway and treated sites

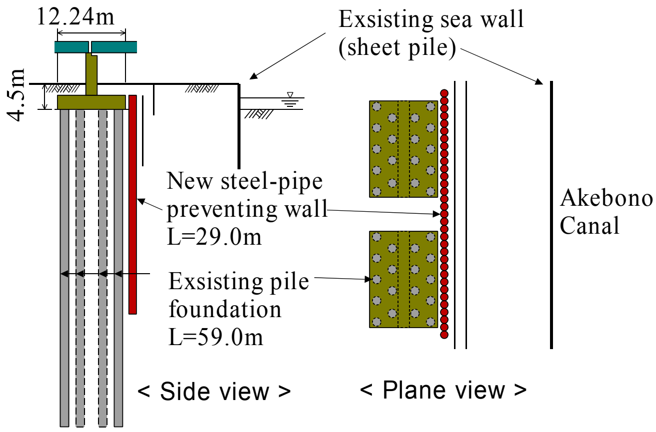


Fig. 3 Countermeasure method applied for Metropolitan Expressway at Akebono district (Kinoshita et al., 1999)

routes run along or cross coasts, canals and rivers. Damage to existing bridge foundations due to liquefaction-induced flow was concerned. Then a technical committee (Chairman: Yukitake Shioi, Prof. of Hachinohe Institute of Technology) was organized to study the possibility of the damage, appropriate countermeasure methods and design procedure of the measures, from 1995 to 1997 after the Kobe earthquake. In the study, several kinds of countermeasures against liquefaction-induced flow were listed and compared by focusing on their effectiveness, adaptability and cost. Then a treating method to install steel pipes to make a preventing wall between bridge foundations and sea walls was selected because this method is economic. Effectiveness of this method was confirmed by conducting several analyses and centrifuge tests (Ogasawara et al., 1999). Then, the method was applied to Akebono, Ariake, Katsushima and Ayasegawa sites as shown in Fig.2.

In the design procedure decided by the technical committee, deformation of pile foundations is estimated by the seismic deformation method, in which ground displacement is estimated first, and then horizontal force is applied to piles through soil springs. The ground displacement is estimated by residual deformation analysis in which reduction of shear modulus due to liquefaction is considered. In soil springs, reduction of the springs due to liquefaction is also considered. Allowable displacement of the top of the pile foundation was defined as twice of the displacement which causes yield of the pile.

At Akebono site, liquefiable sandy layer is deposited from ground surface to the depth of about 10 m. A bridge with a length of about 150 m crosses over Akebono Canal. Two bridge foundations founded on 18 cast-in place concrete piles, are located about 20 m behind a sea wall as shown in Fig.3. The sea wall is a sheet pile type wall and is estimated as not stable during future earthquakes. Figure 4 shows the analyzed deformation of the ground due to liquefaction. The estimated displacement on the surrounding ground surface of the bridge foundations was 1.2 m. If the surrounding ground moves 1.2 m, the displacement of the top of the piles become about 4.5 times of the allowable displacement. But if the ground displacement can be reduced less than 50 cm, the displacement of the top of piles can be settled in the allowable displacement. Then the size of the installing steel pipes was designed to reduce the ground displacement less than 50 cm. The selected size of the installing steel pipes was 1200 mm in diameter, 22 mm in thickness and 29 m in depth as shown in Fig.3. The steel pipes were installed continuously to make a preventing wall as shown in Photo 1.

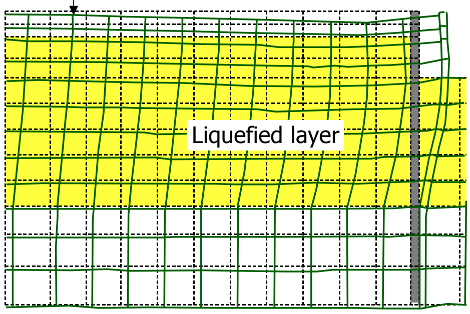


Fig. 4 Analyzed liquefaction-induced deformation of the ground at Akebono district

Photo 1 Installation work of steel pipes

CONCLUSION

Studies on countermeasure methods against liquefaction-induced flow in Japan are summarized, and an application of a remedial measure to existing bridges is introduced. Several types of the remedial measures have been developed after the 1995 Hyogoken-nambu earthquake in Japan. Among them, a countermeasure method to strengthen the ground with a preventing wall by steel pipes was adopted to four bridges of Metropolitan Expressway in Tokyo, recently.

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