



SEISMIC DESIGN OF HIGHWAY BRIDGE FOUNDATIONS FOR LIQUEFACTION-INDUCED GROUND FLOW

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ABSTRACT: The liquefaction-induced ground flow inflicted serious damage to various engineered structures including highway bridges in the Kobe Earthquake of 1995. This paper summarizes the estimation of ground flow force acted on highway bridge foundations and the design technique developed to secure seismic safety of bridge foundations for liquefaction-induced ground flow, which was incorporated into the Design Specifications for Highway Bridges in Japan.

Key Words: Liquefaction-induced ground flow, foundation, highway bridge, seismic design

INTRODUCTION

The Hyogo-ken Nanbu (Kobe) Earthquake, which occurred on January 17, 1995, caused extensive soil liquefaction over a wide area of offshore reclaimed lands and natural deposits (Japan Society of Civil Engineers 1996). Besides that, near the water's edge, liquefaction induced ground flow with the movement of quaywalls or seawalls. Aerial photogrammetry revealed that the maximum residual displacement due to ground flow reached 3 to 4m (Hamada *et al.* 1995, Committee on Highway Bridge Damage Caused by the Hyogo-ken Nanbu Earthquake 1995). Liquefaction and its associated ground flow exerted serious influence on various engineered structures. Although highway bridges did not suffer fatal damage due to liquefaction, liquefaction-induced ground flow caused large deformation of bridge foundations. For example, a pier of the Shin-Shukugawa Bridge that crosses a watercourse between reclaimed lands was moved toward the watercourse by approximately 1m, which resulted in rupture of bearings on the pier (Otsuka *et al.* 1997).

To estimate the influence of liquefaction-induced ground flow on bridge foundations, it was assumed that the surface layer, which did not liquefy, was conveyed by the liquefied layer spreading underneath, and both layers caused force to a bridge foundation. The ground flow force was estimated so that the displacement at pile head is consistent with the residual displacement of bridge foundation (Tamura *et al.* 1996). As an experimental approach, Tamura and Azuma (1997) also conducted a series of shake table tests. In this experiment, models of a quaywall and its backfill soil were prepared in a large soil container. Pile models were installed in the ground, and the force acted on the piles were measured. Based on those results, a seismic design technique of bridge foundations for liquefaction-

induced ground flow was developed and incorporated into the Design Specifications for Highway Bridges in Japan (Japan Road Association 1996, Kawashima *et al.* 1997).

ESTIMATION OF GROUND FLOW FORCE BY BACK ANALYSIS

The force acted on a bridge foundation due to the liquefaction-induced ground flow was estimated by back analyses of bridges that suffered residual horizontal displacements (Tamura *et al.* 1996). The result for a bridge pier, which was located at the north edge of Rokko Island, is presented herein. This pier was a 2-story steel rigid frame pier and was supported by cast-in-place concrete piles, 1.5m in diameter. The bearings on this pier were fixed for the watercourse-side girder and movable for the inland-side girder. The soils were composed of sandy artificial fill, alluvial clay and alternation of diluvial sand and clay. The residual horizontal displacement of this pier was 0.9m. The ground water level of the site was 3.3m below the ground surface, and the liquefaction was judged to occur in the sandy artificial fill below the ground water level. Fig. 1 shows an overview of the analyzed foundation and the distribution of applied force in the following analysis.

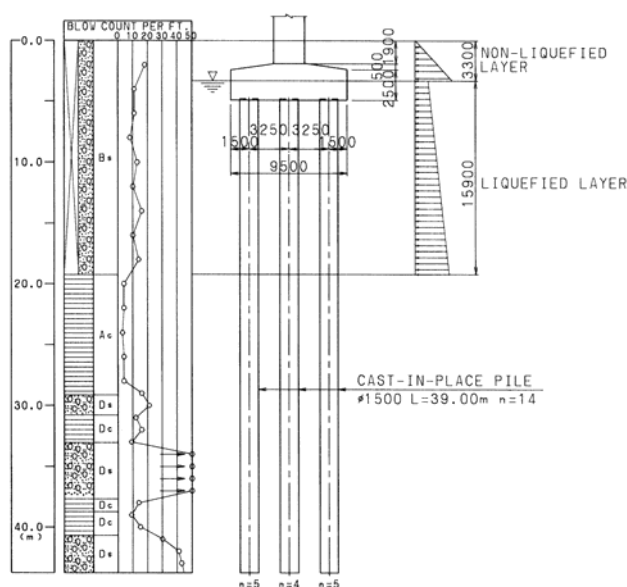


Fig. 1 Overview of analyzed foundation and applied force

In the estimation of the force applied to a bridge foundation due to the liquefaction-induced ground flow, it was assumed that the surface non-liquefied layer was conveyed by the liquefied layer spreading underneath, and both layers caused force to a bridge foundation (Tamura *et al.* 1996). Since the non-liquefied layer was considered to move toward the structure and exert force on it, the force equivalent to the passive earth pressure was assumed to act on a bridge foundation in the non-liquefied layer. The liquefied layer was considered to move fluidly around the structure, and the force corresponding to a certain portion of overburden pressure was assumed to act on a bridge foundation in the liquefied layer. This portion was estimated by back analyses of bridge piers with residual displacements.

Fig. 2 illustrates the assumption taken in the analysis for a bridge foundation. A rigid footing is supported by piles, and piles by soil springs. This assumption allows nonlinear features of pile bodies and soils to be implemented separately (Japan Road Association 1995). Besides that, the soil resistance was ignored for the non-liquefied and liquefied layers that were considered to move when the ground flow occurred. The width for which the ground flow force applied was set as the width of structure for a pier and footing, and the projected width between the end piles for pile bodies.

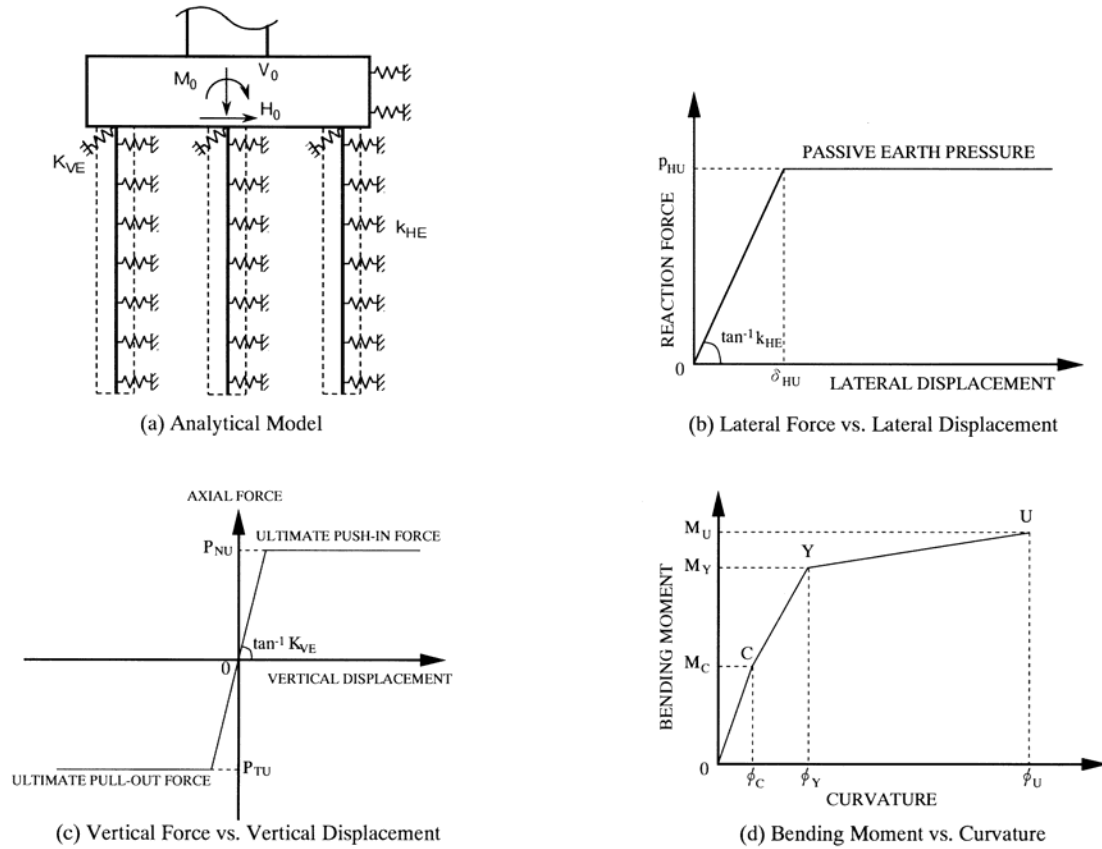


Fig. 2 Idealization of pile foundation for nonlinear analysis

Since some portion of the overburden pressure of the liquefied layer acted on a bridge foundation as lateral force, this portion was estimated in a way that the obtained pile top displacement was eventually identical to the observed residual displacement. The result is shown in Fig. 3. The total force that caused the residual displacement of 0.9m to this pier was estimated as 22.11 MN (2,256tf); 5.67 MN (578tf) for non-liquefied layer and 16.44 MN (1,678tf) for liquefied layer. The ratio of the force applied in the liquefied layer to the overburden pressure was calculated as 0.32 for this pier. Similar analyses were conducted for the four bridge piers on the Route 5 of the Hanshin Expressway, and the contribution factor of overburden pressure was estimated approximately as 0.3.

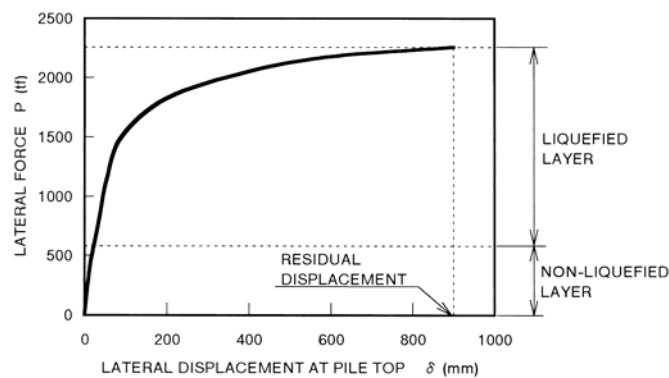


Fig. 3 Relationship between lateral force and displacement at pile top

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When the liquefaction-induced ground flow that may affect the seismic safety of bridge is likely to occur, this influence has become to be considered in the Design Specifications for Highway Bridges since 1996 (Japan Road Association 1996, Kawashima, K. *et al.* 1997).

The case in which the ground flow that may affect seismic safety of bridge is likely to occur is generally that the ground is judged to be liquefiable and is exposed to biased earth pressure, e.g., the ground behind a seawall. The effect of liquefaction-induced ground flow is modeled as the static force acting on structure. This method premises that the surface soil is of the non-liquefiable and liquefiable layers, and the forces equivalent to the passive earth pressure and 30% of the overburden pressure are applied to the structure in the non-liquefiable layer and liquefiable layer, respectively, as shown in Fig. 4. Since the magnitude of ground flow decreases as the distance from the water's edge increases, modification by distance is incorporated in the estimation of the ground flow force. Modification by the degree of liquefaction is also established.

The seismic safety of a bridge foundation is verified by confirming the displacement at the top of foundation caused by ground flow does not exceed an allowable value. The allowable displacement of foundation may be taken as two times the yield displacement of foundation. In this process, the inertia force of structure is not necessary to be considered simultaneously, because the liquefaction-induced ground flow may take place after the principal ground motion ends.

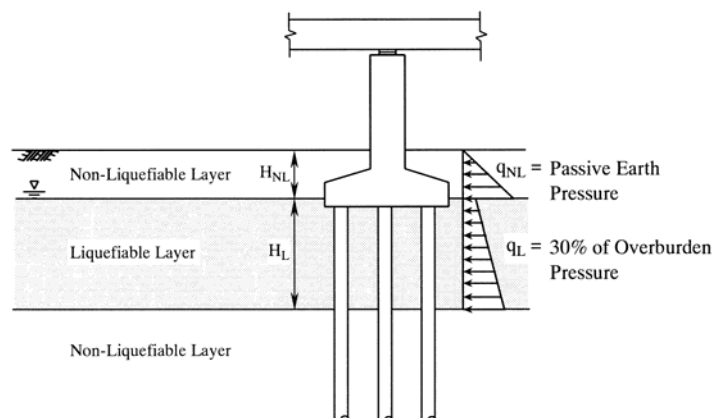


Fig. 4 Idealization of ground flow force for seismic design of bridge foundation

CONCLUSIONS

The estimation of liquefaction-induced ground flow force on bridge foundation and its application to the seismic design of highway bridges were presented. The principal conclusions of the present work may be summarized as follows:

- 1) According to the back analyses of damaged bridge foundations by liquefaction-induced ground flow in the 1995 Kobe Earthquake, the ground flow force acting on bridge foundation can be approximately estimated as the sum of the passive earth pressure of the surface non-liquefiable layer and 30% of the overburden pressure of the liquefiable layer.
- 2) Based on the back analyses and shake table tests performed separately, a simple and practical seismic design technique of bridge foundations for liquefaction-induced ground flow was developed and incorporated into the Design Specifications for Highway Bridges in Japan.

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