Soil-Pile Interaction Affected by Liquefaction and Lateral Flow

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SUMMARY

In the current routine practice the spring-supported beam model is widely used for designing foundation piles. If the soil is identified to develop liquefaction, the spring constant or coefficient of subgrade reaction is reduced by a factor of 1/6 - 2/3 according to the design code of bridge foundations in Japan. This is applied only to the case of vibratory movements of the ground during the main shaking of an earthquake. If the ground is inclined and starts to deform largely in a horizontal direction immediately after the main shaking, the piles embedded in such ground will undergo a lateral force which would be significantly different from that induced during the main shaking. In an effort to clarify this point several series of back-analyses have been made and the order of magnitude by which the coefficient of subgrade reaction is to be reduced was estimated. The results of the analyses showed that the coefficient of subgrade reaction be of the order of magnitude as small as 2×10^{-4} - 2×10^{-2} for the soil-pile interaction undergoing lateral flow of soils. This paper intends to present a summary of the previous works in the above context.

1. INTRODUCTION

When foundation piles are subjected to strong motions during earthquakes the piles would be deformed back and forth in unison with the movement of the surrounding ground. This facet of the seismic event may be termed vibratory or cyclic loading phase. If the ground moves largely, the piles may move concurrently and this may lead to some degree of injury due to excessive cyclic deformation. If soils in the neighbourhood develop liquefaction during the main shaking, the stiffness of the soils will be degraded further leading to much larger deformation of the ground which is sufficient to bring about injury to the piles embedded in such ground. According to the Japanese code of bridge design, it is stipulated that the soil-structure interaction be represented by the Winkler type model through the use of the coefficient of subgrade reaction, and the stiffness degradation due to liquefaction, if any, be taken into consideration by reducing this coefficient by a factor of 1/6 to 2/3. It has been known that the deformation of the pile in the cyclic loading phase is dominated by the movement of the surrounding ground, and there is practically little difference in the lateral displacements between the pile and the surrounding ground. This implied that even by the degraded stiffness of the above order of magnitude, the pile moves almost in unison with the surrounding soils. The features of the lateral displacement of a pile relative to the ground surface displacement are illustrated in Fig. 1 in which the displacement of 1.0 m is given on the surface with a linear distribution throughout the depth of the liquefied layer. Given this ground deformation, the pile deformation was computed by assuming various levels of stiffness degradation in the pile-soil interaction analysis by using the Winkler-type model as illustrated in Fig. 2. As indicated in Fig. 1, in the cyclic phase of the response, the displacement of the pile top is about the same as the displacement of the ground surface.

Towards the end of the main shaking and also during the period of low-intensity shaking that follows, the ground would start moving laterally if it is inclined and if soils have potential to develop flow-type deformation. This facet of the seismic event may be termed the phase of lateral flow or lateral spreading. One of the characteristic features of the pile-soil interaction in this phase is the fact that there exists a significant difference in the lateral deformation between the pile and the surrounding soils. In an extreme case, the pile can stand by itself almost underformed while the liquefied soils are moving largely in its neighbourhood. Such a large difference in displacement has been observed in many of the laboratory model tests and there have also been a number of field evidences in support of this in observed damage features of piles in the past-earthquakes (Yoshida and Hamada, 1991; Tokimatsu et al., 1997).

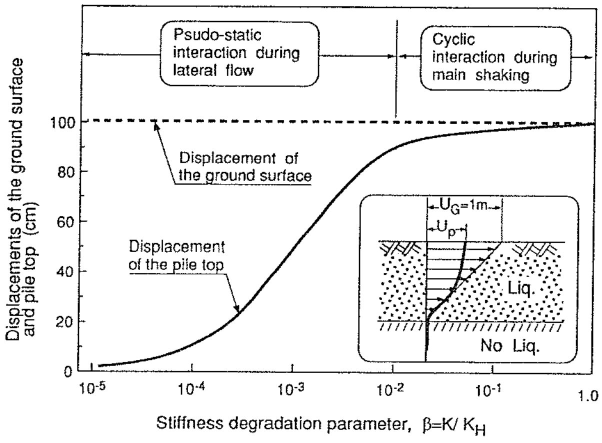

Fig. 1 Pile top displacement relative to the ground versus soil stiffness

These situations can be understood by looking again at the curve in Fig. 1 where the pile displacement relative to the assigned 1 m value of the ground displacement tends to decrease with increasing value of the stiffness degradation parameter β. If such large relative displacement is to be incorporated in the design analysis in the same line of the current approach using the Winkler-type model, the reduction of the stiffness of the order of 1/6 to 2/3 is not sufficient and much more stiffness reduction will be needed. Thus, it has become necessary to examine the order of magnitude by which the stiffness of soils is to be degraded when they are put in a state of lateral flow following liquefaction. In this context, cases of injury were studied and multiple series of back-analyses were carried out for foundation piles damaged as a result of lateral spreading at the time of the 1995 Kobe earthquake. The following is the summary of these results.

2. BACK ANALYSES OF DAMAGED PILES

The majority of reinforced concrete pile foundations used hitherto in Japan may be classified roughly into two groups, that is, the precast reinforced concrete piles and the cast-in-place reinforced concrete bored piles. The precast concrete piles have an annular cross section with a diameter of 30 - 40 cm and their length is 10 - 20 m. They are used to support medium-weight structures such as buildings and warehouses. Four to six piles are connected in a group at their top to a small-size footing slab about 2×2 m in plan. The footing slab embedded in the ground to a depth of 1.0 - 1.5 m is connected to the neighbouring slab through underground horizontal beams.

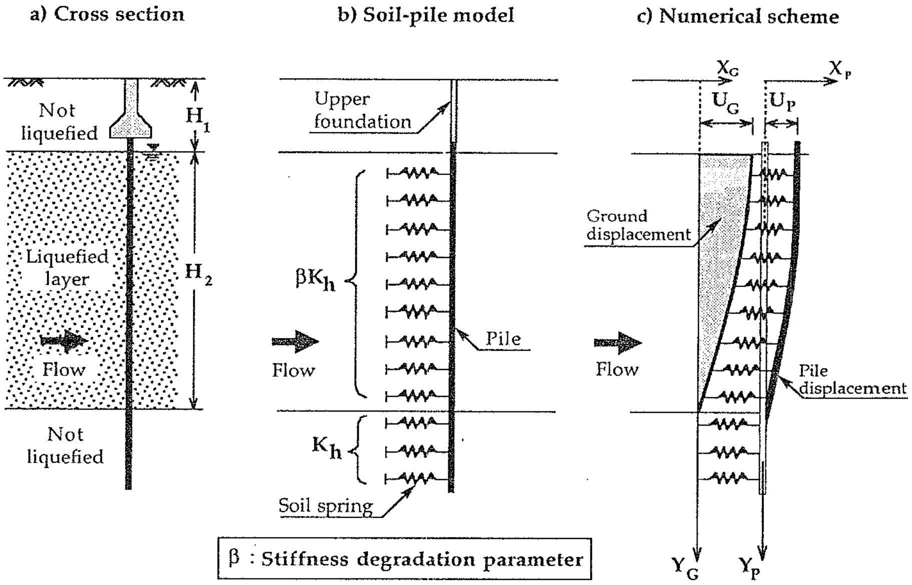

Fig. 2 Winkler-type model of soil-pile interaction

The cast-in-place reinforced concrete piles have a large diameter of 1.0 - 2.0 m and their length is 30 - 40 m. These piles are constructed by what is called the benoto excavation method. They are used to support large structures such as piers of highway bridges and heavy-weight buildings. A massive reinforced concrete footing is placed on top of the pile group consisting of 20 - 30 bored piles. The thickness of the footing is 2-4 m and the whole body is embedded into the ground.

2.1 Analyses of Small Diameter Precast Concrete Piles

The back-analyses for small-diameter precast concrete piles have been done for several cases of injury incurred at the time of the Kobe earthquake (Ishihara, 1997; Ishihara and Cubrinovski, 1998). The outcome of the analyses was expressed in terms of the stiffness degradation parameter, β, for given relative displacements between the pile and the ground observed at the time of the earthquake. The parameter, β, is defined simply as

$$\beta = \frac{\text{k-value of soils under lateral spreading}}{\text{k-value of soils without liquefaction}}$$

where k is the coefficient of subgrade reaction. The results of the back-analyses are demonstrated in Fig. 3 where the stiffness degradation parameter, β, is plotted versus the relative displacement $U_G - U_P$ divided by the thickness of the liquefied layer H_2. As illustrated in the inset of Fig. 3, U_P and U_G denote the displacements of the pile top and the ground surface, respectively. In performing the analyses the soil-pile interaction was represented by the spring-beam model as shown in Fig. 2, and the lateral force in the unliquefied surface layer generated by the relative displacement was ignored. The pile was assumed to be fixed at the bottom. It was also assumed that the pile was extended upwards to the ground surface and characteristics of the footing slab were taken into consideration. In the analyses, the ground displacement with a given values U_G on the surface and a cosine distribution versus depth was given to the spring system, and the deformation of the pile body was calculated for various values of the stiffness degradation parameter. Among several pile top displacements computed, the stiffness degradation parameter matching the observed or estimated displacement was chosen as the true value representing the realistic scenario of the pile-soil interaction during the lateral spreading. The results of the analyses shown in Fig. 3 indicate that the stiffness degradation lies in the range as small as 2×10^{-4} - 1×10^{-2} for the pile-soil interaction under the condition of lateral spreading. It is seen as well that the β-value tends to increase with decreasing value of the relative displacement. This observation is to be taken as granted because the large relative displacements are considered to be the case in the soil deposit which is softened to a great extent as a result of liquefaction.

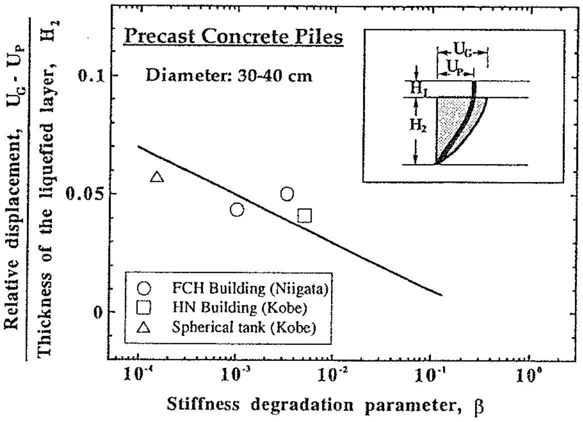

Fig. 3 Relative displacement between the ground and pile versus the stiffness degradation parameter for the case of precast concrete piles

2.2 Analyses of Large Diameter Bored Piles

Back-analyses were also performed for large-diameter cast-in-place reinforced concrete bored piles which were injured at the time of the Kobe earthquake. In view of the presence of a massive footing, the passive earth pressure was assumed to be applied on the back side wall of the footing. The results of the analyses are presented in Fig. 4 in which the computed β-values are plotted versus the relative displacement divided by the thickness of the liquefied layer H_2. It may be seen as well that the stiffness degradation parameter stays as small as 2×10^{-4} - 2×10^{-2} and tends to increase with decreasing relative displacement between the pile and the ground. The results of the analyses for the large diameter piles are shown superimposed to those for the small diameter piles in Fig. 5. It may be seen that the large diameter bored piles with greater stiffness require less degree of reduction in the stiffness as compared to the low-stiffness small-diameter precast concrete piles in order to induce the same level of relative displacement between the pile and the ground on the surface. This implies that, to achieve a given magnitude of relative displacement, the level of required stiffness degradation is less for the large diameter concrete pile resulting in greater magnitude of the lateral force induced on the pile body, as compared to the small diameter precast concrete piles where the larger stiffness degradation leads to a smaller magnitude of the lateral force applied to the pile body.

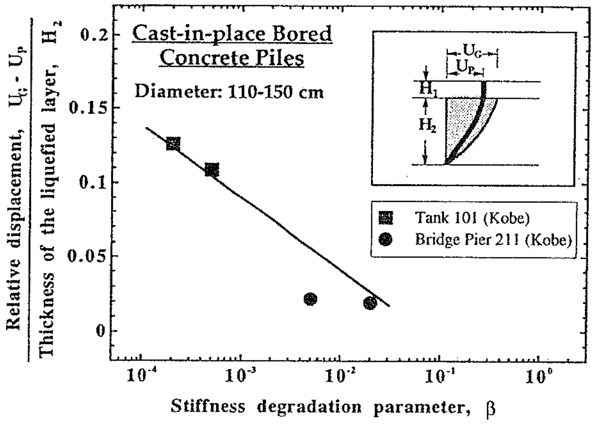

Fig. 4 Relative displacement between the ground and pile versus the stiffness degradation parameter for the case of cast-in-place concrete piles

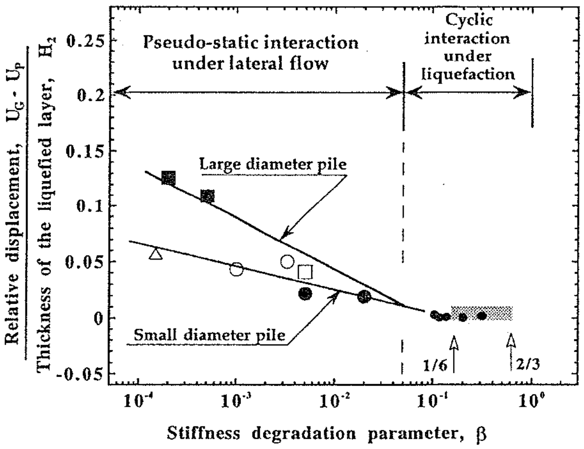

Fig. 5 Summarized relations between the normalized relative displacement and stiffness degradation parameter

3. DISCUSSIONS

Coming back to the initial phase of the seismic load application as mentioned above, it was pointed out that the stiffness degradation would probably be in the range of $\beta = 1/6\text{-}2/3$ according to the Japanese code of bridge design. It may be postulated with good reasons that the value of the global strain as defined by $(U_G - U_P)/H_2$ would be less than about 1%. If their value is plotted versus the $\beta = 1/6\text{-}2/3$ in Fig. 5, the data would be located within the range indicated by the shaded area. There are some unpublished data in the above context obtained from effective stress analyses of pile behaviour in liquefied deposits in Port Island using the finite element technique. The results of these analyses are also shown in Fig. 5 by small bold circles where it can be seen that the data from the effective stress analyses also lie well within the zone established for the values from the design code. Thus, no matter whichever is the vibratory or laterally moving phase the relation between the relative displacement and the stiffness degradation parameter may be defined almost uniquely and expressed by a single curve for a given type of the pile.

4. CONCLUDING REMARKS

As a result of back-analyses for precast reinforced concrete piles and also for cast-in-place reinforced concrete piles damaged at the time of the Kobe earthquake, it was disclosed that when the piles are subjected to lateral spreading, the coefficient of subgrade reaction in the soil-pile interaction model needs to be reduced by a factor of 2×10^{-4} - 2×10^{-2} from the values established for non-liquefaction conditions. The cast-in-place large-diameter bored piles are shown to require less reduction in the coefficient of subgrade reaction than the precast small-diameter piles in order to produce equal degree of pile deformation relative to the deformation of the surrounding ground. It was also shown that, whichever the type of piles, the reduction of the coefficient of subgrade reaction should become more pronounced as the displacement of the pile increases in comparison to that of the surrounding ground.

5. REFERENCES

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