Predicting post-earthquake settlement of river embankments using parametric numerical

Kota Wakinaka[1*], *and Yuri* Yamamoto[1]

[1] Department of Architecture and Civil Engineering, National Institute of Technology, Kumamoto College, Kumamoto, Japan

Abstract. River embankments are critical flood control structures that protect human lives and property. To ensure safety during flood events, appropriate maintenance measures against seepage and erosion are required. In addition, embankments must maintain sufficient seismic performance to preserve their functionality after earthquakes. Currently, seismic safety assessments commonly rely on two-dimensional numerical analyses to predict post-earthquake settlements. However, these analyses are time-consuming and costly, which limits their applicability in preliminary evaluations. This study aims to develop a simplified prediction method by establishing a settlement prediction chart based on parametric analyses. Using numerical methods consistent with those applied in practical seismic assessments, a series of parametric simulations was conducted by systematically varying key factors influencing embankment settlements, including liquefiable layer thickness and liquefaction strength ratio. Based on the simulation results, a settlement prediction chart was constructed to estimate post-earthquake settlements under various embankment conditions. The validity of the proposed table was examined through deformation analyses of actual river embankment cross sections damaged during past earthquakes. The results showed that the predicted settlements were generally consistent with numerical analysis results, even for embankments with complex geometries. The proposed prediction chart can serve as an effective screening tool in seismic assessments, enabling efficient evaluation of levee performance and supporting decision-making for seismic countermeasures in river management.

1 Introduction

Research on liquefaction prediction is generally considered to have progressed significantly following the 1964 Niigata Earthquake. Subsequently, the 1995 Hyogo-ken Nanbu Earthquake (the Great Hanshin–Awaji Earthquake) generated strong ground motions of an unprecedented scale, which led to the introduction of the concept of Level 2 earthquake motions and the incorporation of performance-based design into the seismic design of civil engineering structures. In response to this advancement in seismic design philosophy, numerous methods have been developed to quantitatively predict deformations induced by liquefaction [1-3]. For evaluating deformation behavior of ground and structures associated with liquefaction, detailed numerical analysis methods, such as two-dimensional and three-dimensional effective stress analyses, have been established, and their high reproducibility has been demonstrated [4-6]. However, these methods require considerable effort for modeling and involve high computational costs, which limits their applicability to practical seismic inspections over large areas. In addition, practical assessments often involve uncertainties in the distribution of liquefiable layers and ground conditions, creating a demand for evaluation methods that balance simplicity and rationality.

In Japan, the total length of river embankments under direct national management is approximately 8,800 km, forming extremely long linear structures. As river embankments serve as critical disaster prevention facilities that protect human lives and property from floods and storm surges, it is essential to implement seismic countermeasures to ensure that their functionality is maintained during earthquakes. In seismic safety assessments of river embankments, a relatively simple static analysis method proposed by Yasuda et al. [1], hereafter referred to as ALID, is widely used to predict settlements. However, because river embankments extend over long distances and seismic inspections require the evaluation of numerous cross sections, applying detailed two-dimensional numerical analyses to all sections is not necessarily practical. Therefore, there is a strong need for the development of screening methods that can reasonably capture settlement trends due to liquefaction while simplifying the distribution of liquefiable layers and ground properties to a certain extent.

Numerous studies have investigated evaluation methods based on the relationship between liquefiable layer thickness and settlement, as well as ground strength assessments focusing on liquefaction resistance indices. For example, Tokimatsu and Seed [7] systematically organized methods for evaluating earthquake-induced settlements of sandy ground and clarified the relationship between settlement and ground conditions. Yoshimine et al. [8] focused on the undrained shear strength of sandy ground leading to flow failure and proposed useful indices for evaluating liquefaction strength. However, these studies primarily

* Corresponding author: k-wakinaka@kumamoto-nct.ac.jp

aimed at elucidating material-level behavior or conducting detailed evaluations, and their applicability as simplified screening methods for efficiently evaluating a large number of embankment cross sections in seismic inspections of long river embankments has not been sufficiently clarified in terms of applicability conditions and evaluation accuracy.

Therefore, this study aims to develop a simplified settlement prediction chart for practical screening during seismic inspections by conducting parametric analyses in which ALID is applied to simplified embankment models. Furthermore, analyses were performed on actual river embankment cross sections, and the validity and applicability of the proposed prediction method were evaluated. The results of these investigations are reported herein.

2 Analysis method

In this study, all deformation analyses were conducted using ALID [1] to investigate settlement behavior of river embankments induced by liquefaction. The ALID model used in this study is a simplified analytical method proposed to evaluate ground deformation induced by liquefaction during earthquakes. The model estimates deformation by considering the reduction in shear modulus and volumetric strain characteristics associated with liquefaction. In this model, it is assumed that soil modulus decreases due to the reduction in effective stress caused by liquefaction, and the resulting deformation is calculated based on the properties of each soil layer. In particular, ground deformation is assumed to be predominantly governed by shear deformation, and surface displacement is obtained by integrating the accumulated shear strain in each layer. The target of the analyses was river embankment cross sections in which the liquefaction-prone zone was limited to the foundation ground, in order to clearly identify the influence of ground conditions on settlement behavior due to liquefaction. Based on this concept, simplified models were developed to systematically organize the effects of ground conditions. In this chapter, Section 2.1 first presents the parametric analysis procedure using the simplified models and the methodology for constructing a settlement prediction chart, with the aim of extracting ground conditions considered to be dominant factors controlling settlements. Subsequently, Section 2.2 describes analyses using actual river embankment cross sections and examines the applicability of the settlement prediction chart based on the simplified models.

2.1 Parametric analysis using simplified model

The simplified models were designed assuming a typical river embankment, with an embankment height of 4 m and a crest width of 5 m. To evaluate the influence of slope gradient, three models with slope ratios of 1:2, 1:3, and 1:4 were prepared. First, preliminary analyses were conducted to identify the relative importance of each ground parameter on settlement. In the preliminary

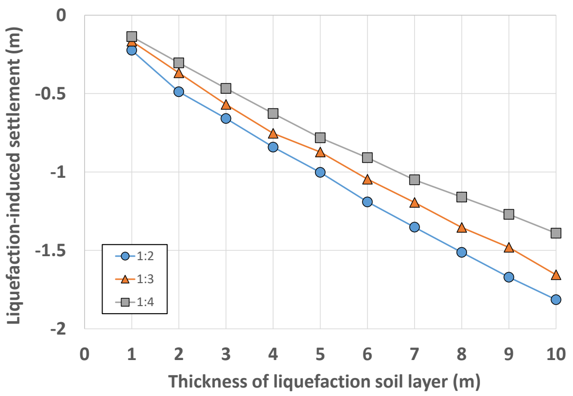

Fig. 1(a) Relationship between liquefaction layer thickness and settlement.

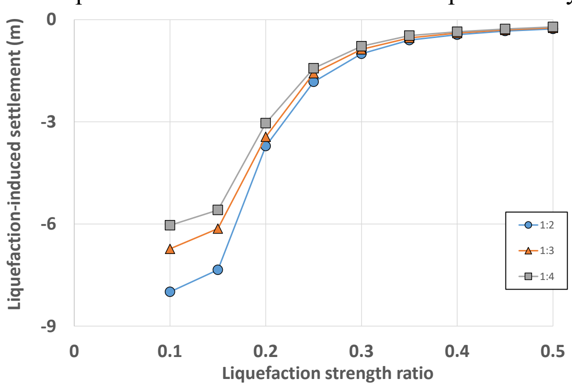

Fig. 1(b) Relationship between liquefaction strength ratio and settlement.

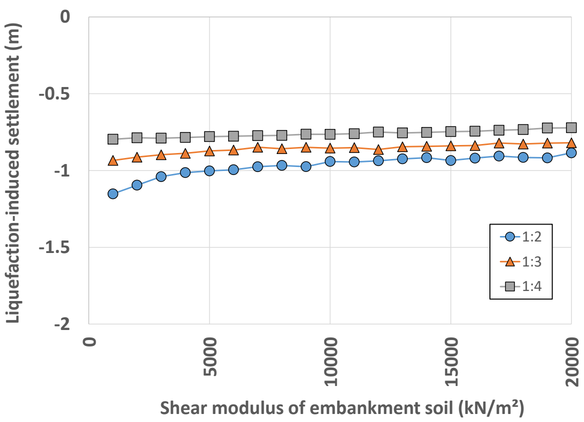

Fig. 1(c) Relationship between shear modulus of embankment soil and settlement.

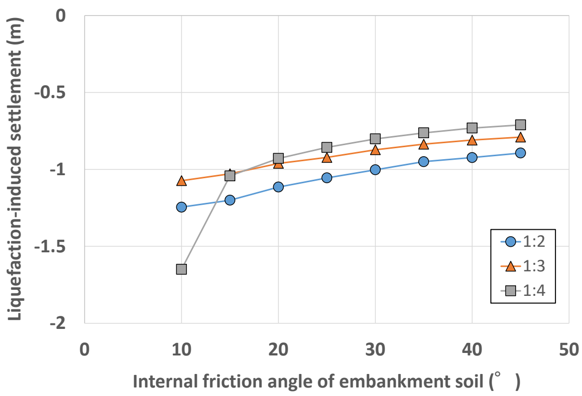

Fig. 1(d) Relationship between internal friction angle of embankment soil and settlement.

analyses, four parameters—shear modulus, internal friction angle, liquefaction strength ratio, and thickness of the liquefaction layer—were considered. The liquefaction strength ratio represents the resistance of soil against cyclic shear stress induced during earthquakes. It is used as an index to evaluate liquefaction potential, and liquefaction is considered to occur when the cyclic shear stress ratio exceeds the liquefaction strength ratio. Only one parameter was varied at a time, while the other parameters were fixed at representative values near their median. The ranges of these parameters were determined based on realistic conditions, covering ground conditions from vulnerable to relatively good, assuming actual damage cases of river embankments. Specifically, the thickness of the liquefaction layer was varied from 1 m to 10 m at 1 m intervals, the liquefaction strength ratio from 0.10 to 0.50 at increments of 0.05, the internal friction angle from 10° to 45° at 5° intervals, and the shear modulus from 1,000 kN/m² to 20,000 kN/m² at intervals of 1,000 kN/m². These intervals were selected to ensure sufficient resolution to capture trends in settlement behavior. The analysis parameters, their ranges, and intervals are summarized in Table 1. The analysis results for each parameter under the slope conditions of 1:2, 1:3, and 1:4 are shown in Figs. 1(a)–(d).

Table 1. Intervals and ranges of analysis parameters.

	Interval	Analysis Range
Thickness of liquefaction soil layer (m)	1	1-10
Liquefaction strength ratio	0.05	0.10-0.50
Internal friction angle of embankment soil (°)	5	10-45
Shear modulus of embankment soil (kN/m^2)	1000	1,000-20,000

The preliminary analyses confirmed that the shear modulus and internal friction angle are not dominant factors governing liquefaction-induced settlement. In contrast, the thickness of the liquefaction layer and the liquefaction strength ratio were found to have a significant influence on settlement. Moreover, comparison of the results for different slope gradients showed that the differences in settlement were small under all conditions. Therefore, under the analysis conditions of this study, the influence of slope gradient on settlement was judged to be limited, and a slope ratio of 1:3 was adopted as a representative value in the subsequent analyses.

Based on these preliminary results, the main parametric analyses focused on the two parameters identified as dominant: the thickness of the liquefaction layer and the liquefaction strength ratio. A representative simplified model is shown in Fig. 2. Although Fig. 2 illustrates the case with a liquefaction layer thickness of 10 m, ten cases with thicknesses ranging from 1 m to 10 m were considered, and the layers below the liquefaction layer were assumed to be non-liquefied. The liquefaction strength ratio was varied from 0.10 to 0.50 at intervals of 0.05, resulting in nine cases. In total, 90 analysis cases were conducted. Based on these two parameters, a settlement prediction chart was constructed. The dimensions of the simplified model and the ground parameters are summarized in Table 2.

It has been pointed out that deep liquefaction layers in the foundation ground tend to contribute excessively to settlement in numerical analyses. Therefore, in this study, the depth-dependent stiffness correction method proposed by Wakinaka et al. [9] was applied. Wakinaka et al. [9] showed, through back-analyses of damaged embankments using ALID, that although the influence of deep liquefaction layers on embankment settlement is limited in actual damage, conventional analyses tend to overestimate their contribution to deformation. To correct this tendency, they proposed a method in which the shear modulus of deep liquefaction layers is gradually increased using the vertical effective stress as an index, thereby suppressing unrealistic deformation in deep layers. Following this concept, the same correction was applied in the analyses of both the simplified models and the actual embankment cross sections in this study, enabling a more realistic evaluation of settlement behavior.

The ALID model used in this study is essentially a simplified analytical method intended for small to moderate deformation and is not strictly formulated to handle large-strain conditions. However, previous studies have reported that the deformation predicted by ALID is generally consistent with observed ground deformations in actual earthquake damage [9], indicating that the method has been applied in practice to a certain extent even in cases involving relatively large deformation. In this study, although large deformations are analyzed using ALID, the evaluation is conducted based on such empirically established applicability.

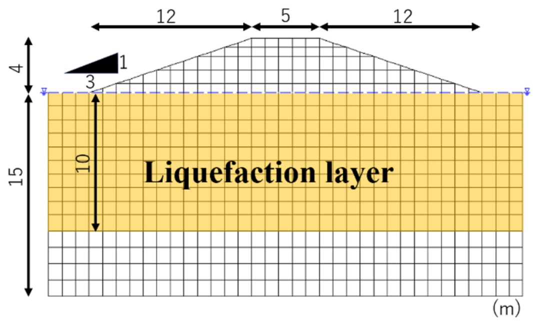

Fig. 2 Simplified model.

Table 2. Dimensions and soil parameters.

Slope gradient	1:3
Internal friction angle of embankment soil (°)	30
Shear modulus of embankment soil (kN/m^2)	10,000
Crest height (m)	4
Crest width (m)	5

2.2 Analysis using actual river embankments

Next, in order to verify the validity of the settlement prediction chart developed based on the simplified models, analyses were conducted using actual river embankment cross sections. The target cross sections were selected from river embankments that had suffered earthquake damage in the past, focusing on cases in which only the foundation ground had liquefied. The cross sections were chosen by considering the embankment geometry and the distribution characteristics of the liquefiable layers, and six representative cross sections were selected so as to cover a variety of conditions. The geological cross sections of the six selected cases are shown in Figs. 3(a)–(f).

The selected cross sections include cases with very simple liquefaction layer distributions, such as those shown in Figs. 3(c), (e), and (f), as well as cases in which non liquefied layers are interbedded between liquefaction layers, resulting in discontinuous distributions, as shown in Figs. 3(a) and (b). In addition, the cross sections were selected to cover a variety of conditions in terms of slope gradient, embankment height, and embankment width. For these cross sections, models reflecting the actual ground conditions were constructed, and liquefaction analyses were performed using the same input ground motion as that applied in the simplified model analyses. By comparing the resulting settlements with those estimated from the settlement prediction chart, the applicability of the table and the tendency of prediction errors were evaluated.

As pointed out by Wakinaka et al. [10], deep liquefaction layers have a limited contribution to embankment settlement in actual damage cases, whereas conventional numerical analyses tend to overestimate their influence on deformation. Therefore, simply summing the thicknesses of all liquefaction layers may result in an unrealistically large effective liquefaction thickness and lead to an overestimation of settlement. For this reason, in this study, when multiple liquefaction layers were present and separated by non-liquefied layers, the liquefaction layer thickness was not defined only by the simple sum of all liquefaction layers. Instead, the average thickness of the upper and lower liquefaction layers was adopted as a representative value. At the same time, the total thickness obtained by simply

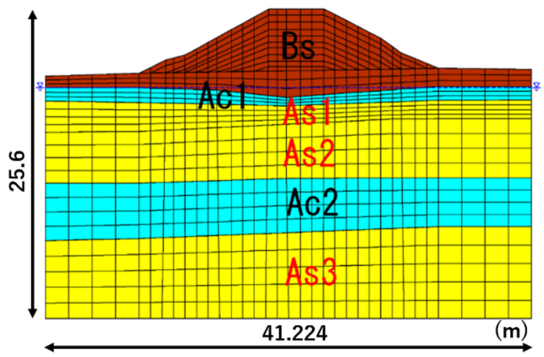

Fig. 3(a) Hokkaido-nansei-oki earthquake, Shiribeshi-Toshibetsu river.

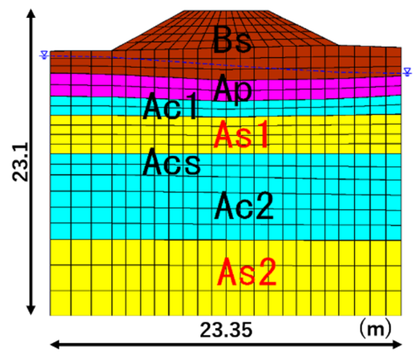

Fig. 3(b) Hokkaido-nansei-oki earthquake, Shiribeshi-Toshibetsu river.

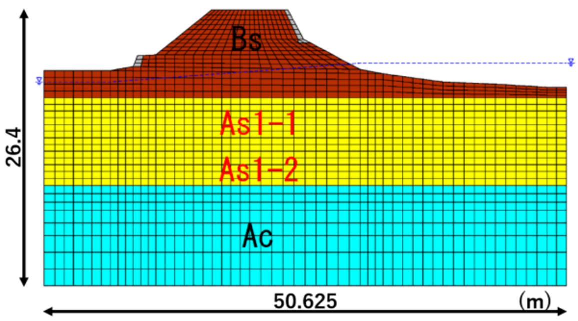

Fig. 3(c) The great Hanshin-Awaji earthquake, Yodo river.

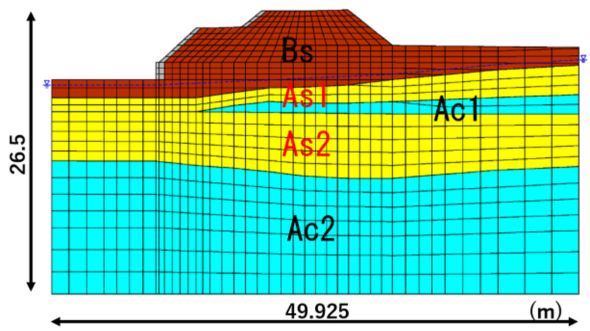

Fig. 3(d) The great Hanshin-Awaji earthquake, Yodo river.

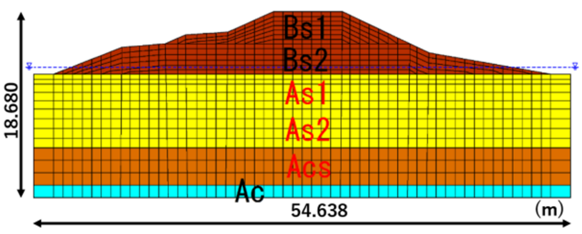

Fig. 3(e) Miyagiken-oki earthquake, Kitakami river.

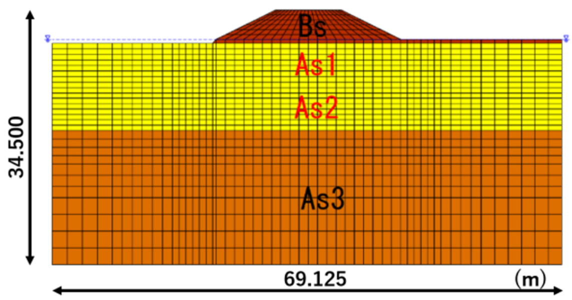

Fig. 3(f) Niigata earthquake, Agano river.

summing all liquefaction layers was also used, and the validity of the settlement prediction chart was evaluated using both definitions. This treatment was intended to reflect the limited contribution of deep liquefaction layers to surface deformation and embankment settlement, while also examining the influence of the definition of liquefaction layer thickness on the prediction results. In addition, when multiple liquefaction layers were present, the liquefaction strength ratio was defined as the simple average of the liquefaction strength ratios of the individual liquefaction layers and was used as a representative value in the application of the settlement prediction chart.

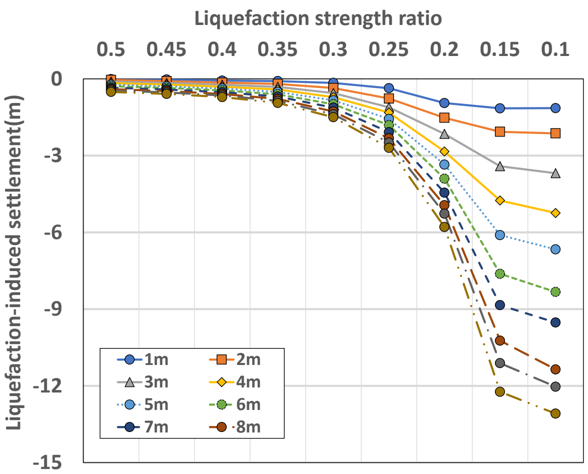

Fig. 4. Liquefaction-induced settlement prediction chart.

3 Analysis results

In this chapter, the analysis results obtained under the analysis conditions defined in Chapter 2 are presented, and discussions on these results are provided. Section 3.1 presents the results of the parametric analyses using the simplified models and discusses the influence of each parameter on settlement. Section 3.2 applies the developed settlement prediction chart to actual river embankment cross sections and examines the validity and applicability of the proposed prediction method through comparisons with the analyzed settlements.

3.1 Parametric analysis using simplified model

Fig. 4 shows the relationship between the liquefaction strength ratio and settlement for each liquefaction layer thickness, based on the prediction chart. The figure indicates that settlement increases as the liquefaction strength ratio decreases and as the liquefaction layer becomes thicker. This trend can be attributed to an increase in the accumulation of shear deformation and strain within the liquefaction layer. Moreover, for cases with larger liquefaction layer thickness, the rate of increase in settlement with decreasing liquefaction strength ratio becomes greater. This result suggests that, as the liquefaction layer thickness increases, the relationship between settlement and liquefaction strength ratio is no longer simply proportional. In addition, it was confirmed that the trend of settlement increase changes markedly around a liquefaction strength ratio of approximately 0.2. In the range where the liquefaction strength ratio is greater than about 0.2, the increase in settlement is relatively gradual, whereas under conditions below 0.2, the settlement tends to increase rapidly. This suggests that, under the analysis conditions of this study, a liquefaction strength ratio of around 0.2 may represent a transition point in settlement behavior. Furthermore, in the low-strength range where the liquefaction strength ratio is 0.15 or less, a tendency for scatter in settlement was observed even under the same layer thickness conditions. This is considered to be due to the fact that, under low strength ratio conditions, deformation within the liquefaction layer becomes unstable and is more susceptible to the influence of localized deformation.

3.2 Analysis using actual river embankments

Next, in order to verify the validity of the settlement prediction chart developed based on the simplified models, a comparison was made with the analysis results obtained using actual river embankment cross sections. Fig.5 shows the relationship between the analyzed settlements for the actual cross sections and the settlements estimated from the prediction chart. For the cases shown in Figs. 3(c), (e), and (f), although multiple liquefaction layers exist, they are continuous and not separated; therefore, the results evaluated using the average liquefaction settlement and the total liquefaction settlement are plotted at the same positions and overlap. When evaluated using the total liquefaction settlement, the predicted settlements tend to be overall larger than the analyzed settlements. This is considered to be because the influence of liquefaction layer thickness is strongly reflected in the prediction chart, leading to an overestimation of the deformation of deep liquefaction layers. On the other hand, when evaluated using the average liquefaction settlement, the predicted settlements show values close to the analyzed settlements, and many of the plotted points are distributed near the one-to-one correspondence line compared with the total liquefaction settlement case. Settlement due to liquefaction does not arise from localized deformation at a specific layer or position, but from the accumulation of deformation occurring throughout the liquefied ground. Therefore, these results indicate that an evaluation based on the average thickness and representative properties of the liquefaction layers is effective.

Using the averaging-based evaluation method, the mean error between the settlements obtained from the analyses and those predicted by the prediction chart was 0.57 m, which is comparable to or smaller than the prediction accuracy reported in previous back-analyses of damage cases [9]. From this result, although the proposed settlement prediction chart does not aim to reproduce the absolute values of settlement with high precision, it can be considered to have sufficient validity as a simplified method for grasping the scale of settlement and the relative level of risk.

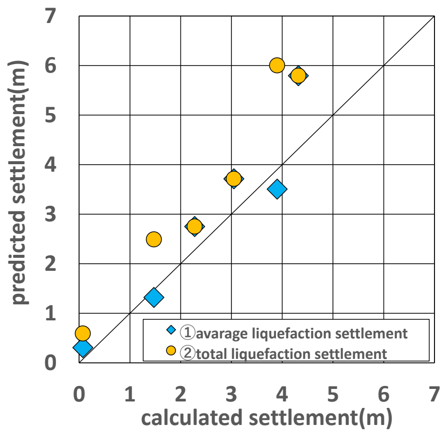

Fig. 5. Predicted settlement and calculated settlement.

The settlement prediction chart proposed in this study aims to provide a simplified evaluation of liquefaction-induced settlement trends using a limited set of ground parameters, namely the thickness of the liquefaction layer and the liquefaction strength ratio. Therefore, this method is not intended for detailed design verification, but is assumed to be applied as a screening tool at the initial stage of seismic inspections of river embankments. On the other hand, in cases where the distribution of the liquefaction layer thickness is extremely uneven, or where deformation of localized weak layers governs the settlement behavior, the applicability of this method may be reduced. Accordingly, based on the evaluation results obtained from this prediction chart, it is important to conduct detailed deformation analyses using actual cross sections as necessary.

4 Conclusion

In this study, with the aim of developing a simplified damage prediction method for use in the seismic inspection of river embankments, parametric analyses using simplified models were conducted and a settlement prediction chart for liquefaction-induced settlement was developed. Furthermore, the validity of the proposed prediction method was examined through comparisons with analysis results obtained for actual river embankment cross sections. From this study, the following findings were obtained.

1) Based on the results of the preliminary analyses using the simplified models, it was confirmed that, within the range of analysis conditions considered in this study, the shear modulus, the internal friction angle, and the slope gradient do not have a dominant influence on liquefaction-induced settlement.
2) The thickness of the liquefaction layer and the liquefaction strength ratio were identified as the principal parameters that have a significant influence on settlement, and by organizing these parameters in combination, it was possible to capture the overall trends of liquefaction-induced settlement behavior.
3) Comparison with analyses using actual river levee cross sections revealed that the method of evaluating the liquefaction layer thickness by averaging provides higher prediction accuracy for settlement than the method that simply treats the liquefaction layer thickness as the total sum. This result is considered to reflect the fact that settlement due to liquefaction manifests not as localized deformation at a specific layer or position, but as the cumulative effect of deformation occurring throughout the liquefied ground as a whole.
4) Although the settlement prediction chart proposed in this study is not intended to evaluate detailed deformation behavior, it has been shown to be potentially useful as a simplified evaluation method for initial-stage screening in seismic inspections of river levees and for identifying cross sections that should be subjected to detailed analysis.

References

1. S. Yasuda, N. Yoshida, K. Adachi, H. Kiku, S. Gose, T. Masuda, Simplified practical method for evaluating liquefaction-induced flow. J. JSCE, **638**, III-49, 71–89 (1999). (in Japanese)
2. S. Iai, Y. Matsunaga, T. Kameoka, Strain space plasticity model for cyclic mobility. Soils Found., **32**, 2, 1–15 (1992). https://doi.org/10.3208/sandf1972.32.2_1
3. F. Oka, A. Yashima, A. Tateishi, Y. Taguchi, S. Yamashita, A cyclic elasto-plastic constitutive model for sand considering plastic-strain dependence of shear modulus. Géotechnique, **49**, 5, 661–680 (1999). https://doi.org/10.1680/geot.1999.49.5.661
4. S. Iai, T. Morita, Y. Matsunaga, K. Abiko, Response of a dense sand deposit during the 1993 Kushiro-Oki earthquake. Soils Found., **35**, 1, 115–132 (1995). https://doi.org/10.3208/sandf1972.35.115
5. S. Yasuda, H. Nagase, H. Kiku, Y. Uchida, The mechanism and a simplified procedure for the analysis of permanent ground displacement due to liquefaction. Soils Found., **32**, 1, 149–160 (1992). https://doi.org/10.3208/sandf1972.32.149
6. H. Liu, Z. Yang, J. Zhang, Numerical investigation of liquefaction-induced ground deformation considering soil–structure interaction. Soil Dyn. Earthq. Eng., **130**, 105998 (2020). https://doi.org/10.1016/j.soildyn.2020.105998
7. K. Tokimatsu, H.B. Seed, Evaluation of settlements in sands due to earthquake shaking. J. Geotech. Eng., **113**, 8, 861–878 (1987). https://doi.org/10.1061/(ASCE)0733-9410(1987)113:8(861)
8. M. Yoshimine, P.K. Robertson, C.E. Wride, Undrained shear strength of clean sands to trigger flow liquefaction. Can. Geotech. J. 36, 891–906 (1999). https://doi.org/10.1139/t99-047
9. K. Wakinaka, M. Ishihara, T. Sasaki, Recurrence numerical analysis of liquefaction damage of river bank considering aging effects in Proceedings of the 49th Annual Conference of the Japanese Geotechnical Society (2014), pp. 1643–1644. (in Japanese)