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Special Contribution

Residual bearing capacity of scoured shallow foundations and their reinforcement effect by press-in sheet piles

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1. Introduction

There have been increasing cases of damage to bridges that cross rivers as flood disasters have become more severe due to climate change in recent years. Many of the bridges built in Japan prior to World War II are still in use today, but many of these bridges are supported by shallow-spread foundations or wood piles, making them particularly susceptible to scouring. Large displacement occurs in scoured foundations, making the bridge impassable even if the bridge does not collapse. The following two contradictory points need to be considered when managing the restoration of bridges, which are important infrastructure, for a country or local community to steadily rebuild after a disaster. The first is for paths to be made temporarily accessible as soon as possible after a disaster, even in cases of limited performance to some extent. The second is to ensure the structure to be strengthened so that the damage does not happen again.

Fig. 1. View during the flood [1]

This article introduces examples where this form of management was successful in railway bridges in Japan [1],[2]. **Fig. 1** shows the situation during flooding, where a shallow foundation was scoured, resulting in a residual settlement of approximately 300 mm and a residual inclination of approximately 50/1000. Emergency restoration was implemented at an early stage (approximately one month after the disaster) after confirming with loading tests up to 90% of the maximum train load (**Fig. 2**) that the structure had the minimum bearing capacity to withstand slow train operation. In this case, in exchange of forgoing foundation reinforcement work, train speeds were restricted, and an electronic monitoring system was also used, thereby ensuring safety. Afterwards, steel pipe piles were pressed in around the scoured foundation in order to reinforce and integrate the structure (**Fig. 3**). These types of reinforcement work were carefully conducted during periods of low rainfall (autumn and winter in Japan) while trains were running. The reinforcement work was completed, and the train speed restrictions and electronic monitoring systems were lifted approximately six months after the disaster.

Fig.2. View of Static loading test by water tank [2]

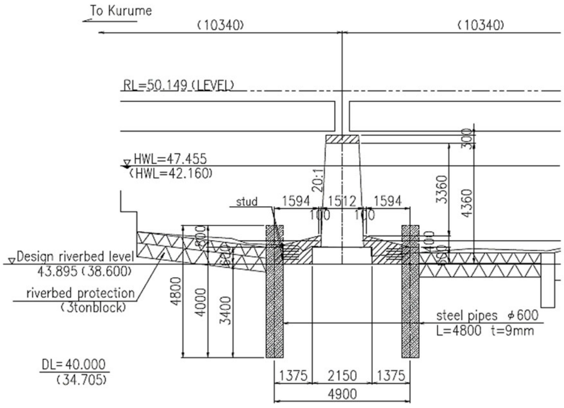

Fig.3. General drawing of the restoration with Press-in Steel pipe piles [1]

Generalizing this form of good practice experience requires clarifying the mechanism by which the residual bearing capacity of shallow foundations is expressed even after being damaged by scouring and establishing quantitative design methods for the reinforcement effect by press-in sheet piles. In this article, we introduce model experiments using an aluminum-rods model ground that we are conducting for these purposes.

2. Overview of experimental technology using aluminum-rods model ground

The aluminum-rods model ground is a mixture of aluminum rods (specific gravity 2.7) of different diameters of several millimeters and stacked together with the rods aligned in the same direction as shown in **Fig. 4**, where a two-dimensional granular material is simulated. The nonlinearity of the stress-strain relationship and the dilatancy properties are similar to those of a medium dense sand. Another major advantage is that the information on displacement and porosity changes in the model ground can be easily obtained from the end face of the aluminum rod through image analysis. Because of these features, aluminum-rods model ground has sometimes been used as one of the basic techniques for conducting model experiments targeting two-dimensional boundary value problems in the field of geotechnical engineering since the 1960s[3],[4].

In this experiment, we used a mixture of three types of aluminum rods with diameters of 1.5 mm, 2.0 mm, and 3.0 mm in a weight ratio of 1:1:1. A comparison of its grain size distribution with that of Toyoura sand, which is widely used in model experiments in Japan shows that the uniformity coefficient U_c is similar, with a mean diameter D_{50} of around 2 mm, which is about 10 times that of Toyoura sand. Furthermore, the unit weight of the aluminum rods model ground with this grain size distribution is still within a relatively narrow range of around 21–22 kN/m^3 even after changing the compaction method and degree. Additionally, the grain size effect should be noted in conditions where clear shear bands tend to occur in the ground, such as in bearing capacity tests. This grain size effect is thought to occur because the shear band thickness is proportional to the grain diameter. For example, Toyosawa et al. reported from bearing capacity tests in centrifuge model tests using dense river sand that the bearing capacity may increase due to the grain size effect in cases where the breadth of footing B is less than 50 times the D_{50} value[5]. Using this as a reference, then when conducting bearing capacity tests with a shallow foundation in this aluminum-rods model ground with these grain size distributions, then the breadth of footing B should be at least 100 mm (approximately 50 times the D_{50} value).

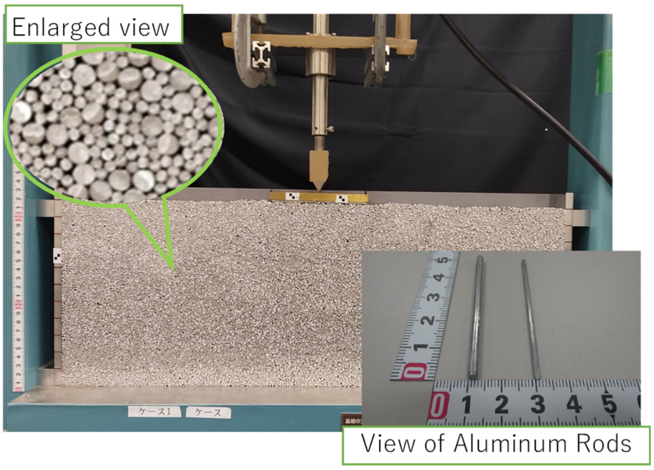

Fig. 4. Overview of aluminum rods model ground

The internal friction angle of the aluminum rods model ground is often easily estimated by an angle of repose test in which an aluminum rod is placed in a sample box and tilted, and the angle of repose obtained as the tilt angle at the time of collapse is around 29–33°. Additionally, back calculation using the Rankine earth pressure equation from the passive coefficient of earth pressure and active coefficient of earth pressure obtained from a retaining wall earth pressure experiment conducted separately yielded an internal friction angle of 28–31°, which is about the same as the angle of repose[6]. Furthermore, back-calculation of the bearing capacity factor N_γ, and N_q from bearing capacity tests on the same aluminum rods model ground also resulted in an internal friction angle in the range of 29-30 degrees.[7]

Additionally, in model experiments using aluminum rods model ground, the ground materials themselves considerably differ, making it difficult to determine a scaling factor of various physical quantities based on a strict similarity rule. Therefore, the similarity rule in aluminum-rods model ground generally uses the idea that a dimensionless quantity (e.g., bearing capacity factor N_γ, N_c, N_q, coefficient of earth pressure K) for the physical phenomenon to be reproduced is made equal between the prototype and the model as needed.

3. Bearing capacity tests of scoured shallow foundation

We conducted vertical loading tests under conditions that artificially simulated the condition in which the ground at the bottom of the foundation was washed away by scouring in order to determine the relationship between scour depth and residual bearing capacity exerted after a disaster [8],[9].

Fig. 5. shows a reproduction of scouring. The condition in which a hole is created by scouring on the upstream side of a

bridge pier is reproduced by removing an aluminum rod, and the scour depth *d* is used as the main parameter. After the scouring was simulated, vertical load was applied by using a jack, and the relationship between the vertical load and settlement was measured. Fig. 6 shows the results.

In **Fig. 6**, the settlement was set to zero before simulating scouring (extracting aluminum rod). Additionally, the dead load (65 N) was approximately 1/3 of the ultimate bearing capacity under conditions where no scouring occurs. The displacement when this dead load was applied represents the residual displacement after a disaster. The results showed that the residual displacement after a disaster increased with increasing scour depth *d*.

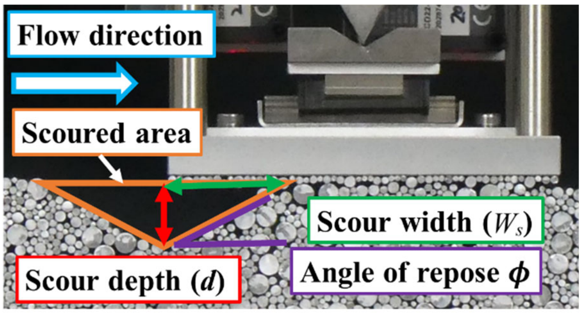

Fig. 5. Modeling scour by removing aluminum rods

Meanwhile, as the loading continued, the load tended to increase from the vicinity of the residual displacement, showing that the maximum load (i.e., residual bearing capacity after disaster) increased to about the same level as in the case with no scouring. In other words, even if scouring caused damage that induced residual displacement, the expected residual bearing capacity itself after the disaster may not decrease by much. This is consistent with the actual cases of emergency restoration shown in **Figs. 1–3**, where the residual bearing capacity needed for train operation could be expected without reinforcing the foundation.

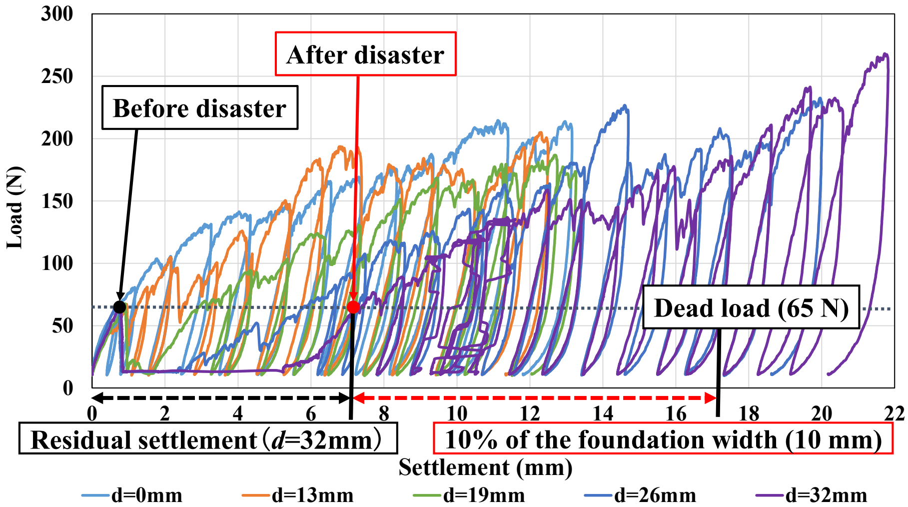

Fig. 6. Load-settlement curves after scour

4. Bearing capacity test of shallow foundation reinforced with press-in sheet piles

The restoration of foundations damaged by scouring (or preventative reinforcement prior to the disaster) requires work in rivers, so construction methods that do not use cement or concrete (or use only a small amount) are advantageous for water quality conservation, and the use of press-in construction methods is expected. Sheet pile foundations that combine sheet piles and footings have previously been developed[10],[11],[12], and they are also used to reinforce river bridge piers[1]. In general, sheet piles and footings should be rigidly connected and integrated in order to obtain high reinforcement effect with less material. However, in the case of reinforcement for scoured foundations in the river, construction efficiency and economy can be improved by eliminating the construction period, cost, and space required for integrating the existing footing with the additional sheet pile. Therefore, an experiment was conducted to confirm the reinforcement effect when integration with the existing footing was omitted (however, the heads of the added sheet piles were connected)[13].

Fig. 7 shows the experimental setup. A sheet pile model (aluminum plate) was installed around the footing with a breadth of footing *B* = 100 mm, and a vertical load was applied. The sheet piles and footing were not connected, but the sheet piles on both sides were connected at the head. The main experimental parameter was the penetration length L of the sheet pile model.

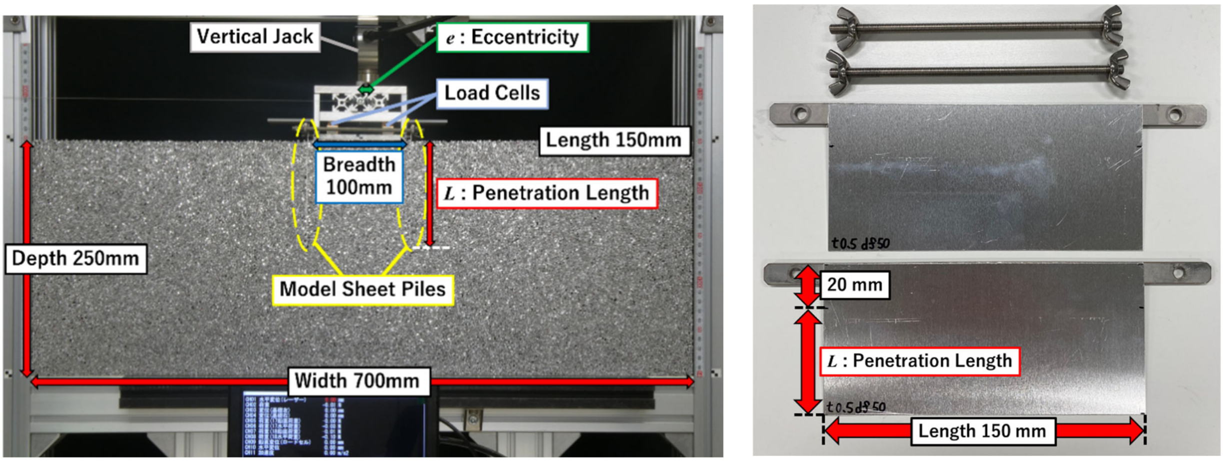

Fig. 7. Experimental setup for confirming reinforcement effect by sheet piles

Fig. 8 shows the load-displacement relationship from unreinforced cases (Case L0) to cases reinforced with sheet piles with penetration length *L* = 20–140 mm (0.2–1.4 times the breadth of footing *B*) (Case L20–Case L140). It can be confirmed in the figure that the bearing capacity increases due to penetration.

Fig. 9 shows the relationship between penetration length L and ultimate bearing capacity (maximum vertical load up to 10 mm settlement). The results confirmed that the reinforcement effect is not proportional to penetration length L but rather changes in a step-wise manner with 0.8 times the breadth of footing *B* (*L* = 80 mm) as the boundary.

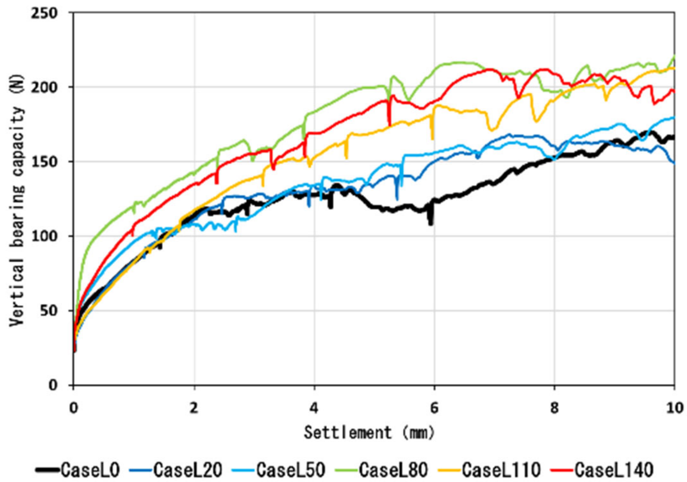

Fig. 8. Load-settlement curves (effect of penetration length *L*)

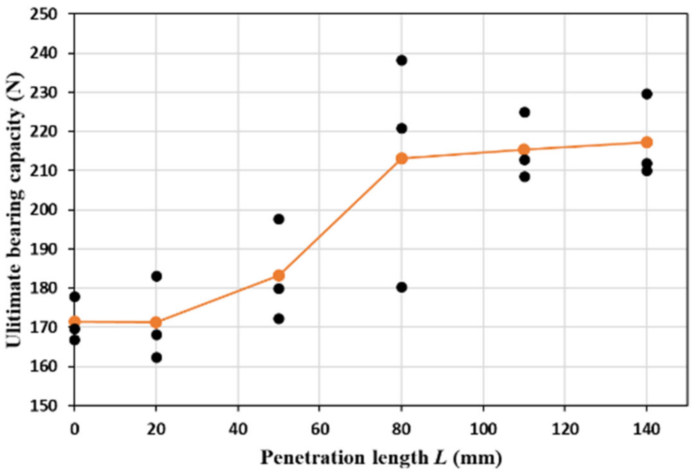

Fig. 9. Relationship between *L* and ultimate bearing capacity

5. Conclusion

The press-in construction method is very much suited for post-disaster restoration and preliminary reinforcement work for river bridge pier foundations, where there is increasing risk of scouring damage, but there is still insufficient accuracy of evaluating the mechanical performance before and after reinforcement. In this article, we introduced experimental examples of residual bearing capacity immediately after a disaster and the effects of advance reinforcement. Evaluations are currently limited to those that are independent from each other, but in the future, we plan to conduct combined evaluations as well as consider seismic performance after reinforcement. We hope to continue these examinations and establish a logical evaluation and design method to contribute toward the realization of a safe and more secure society.

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