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VERTICAL LOADING TESTS ON LOCAL SCOURED SPREAD FOUNDATION ON ALUMINUM RODS MODEL GROUND

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ABSTRACT: In recent years, the damage to bridge foundations caused by heavy rainfall and scouring has increased. In some cases, the entire bridge is carried away, whereas, in others, damage mainly occurs in the foundation, such as settlement and inclination. In the latter cases, it is expected that the damaged bridge is shortly reused after minor repairs are performed only on the superstructure while retaining the residual displacement of the foundation. However, it is difficult to predict whether a foundation with residual displacement possesses the bearing capacity needed to resume emergency use of the damaged bridge. This study focuses on the residual bearing capacity of a shallow foundation after scouring. We performed vertical loading tests on scoured shallow foundations on an aluminum rod ground model to clarify the mechanism. The scouring of the ground was simulated by manually pulling out the aluminum rods. The residual displacement induced by the dead load was measured, and the loading was continued until the residual bearing capacity became clear. We systematically evaluated the effects of scouring volume and shape on the behavior of the foundation. It was found that the residual displacement increased with scouring, but the residual bearing capacity did not necessarily decrease. These findings suggest the possibility of expanding the conditions for the early resumption of damaged foundations and will be helpful for future emergency disaster operations of damaged river bridges.

Keywords: Bearing Capacity, Scour, Ground Spring Constant, Residual Performance, Image Analysis

1. INTRODUCTION

1.1 Background and Objective of Study

Scouring is caused by the erosive action of flowing water that removes the soil around hydraulic structures, such as bridge piers. This phenomenon often occurs with heavy rainfall and typhoons. The number of scouring disasters has been increasing in recent years owing to global warming. Half of the bridge scour cases are classified as medium-scale scours, which mainly damage foundations, such as settlements and inclinations without significant damage, for example, the outflow of girders [1].

Figure 1 shows an example of the medium-scale damage, the Hino Bridge across the Tama River, whose foundation has settled, owing to scours produced by the typhoon in Eastern Japan in October 2019. The road was closed because of settlement, and the transportation network was interrupted. The damaged pier was not reused because its long-term safety could not be guaranteed. Instead, the damaged pier and two girders were removed, and a new girder double the span length was fabricated and erected. It took seven months for the bridge to be reopened.

In this case, the bridge is partially rebuilt. However, it is unrealistic to apply the rebuilding operation to all damaged bridges in medium-scale scouring cases. In some cases, the bridge is expected to be used after immediate repair operations, even when its foundation is damaged, such as through settlements and inclinations. For early resume operations with the reuse of damaged piers, these resistances must be evaluated. However, most previous studies on bridge scouring have focused on predicting scour depth [2,3], and a few studies have focused on the bearing capacity of scoured foundations. Therefore, it is unclear whether residual resistance with residual displacement retains the bearing capacity required for reuse.

Fig. 1 Example of medium-scale damage

The target structure in this study was limited to a river bridge with a shallow foundation, and the target conditions were limited to local scours. By varying the local scour depth, we considered the expected condition in which the residual bearing capacity required for resuming operations will exist.

1.2 Performance of Residual Bearing Capacity of Scoured Foundation

This study focused on the residual bearing capacity of scoured foundations based on the following concept (Fig. 2) [1,4,5].

The load–settlement curve starting from the origin represents the performance of the bearing capacity before the disaster. After a scoured disaster, the performance changes, and the curves can have a wide variety of shapes. We believe that the performance of the residual bearing capacity can be determined by identifying the shape of the curve.

After the disaster, we can easily determine the residual settlement and dead load as a single point (Fig. 2). However, it is difficult to predict the following load–settlement curve from this single point; thus, it is almost impossible to determine whether the bridge pier can be repaired.

If the damaged bridge is reused, emergency restoration, such as jacking up and additional repair concrete, will be performed. Therefore, safety confirmation loading tests, such as static loading tests and slow train passing tests, were conducted in this study. In addition, the settlement was measured to obtain information as a second point in the load–settlement curve.

Through this process, it is possible to limit the candidates for the load–settlement curve of the damaged foundation. The performance of the residual bearing capacity after a disaster can then be evaluated.

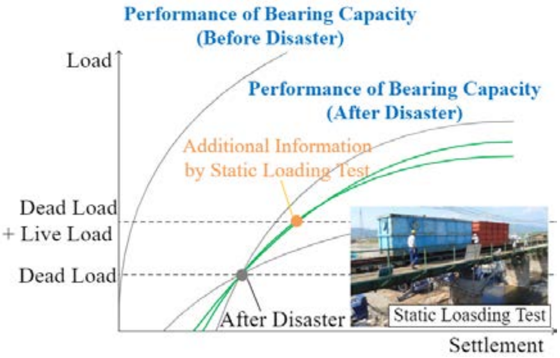


Fig. 2 Concept of change in performance of bearing capacity by scouring disaster

2. RESEARCH SIGNIFICANCE

In this study, we performed vertical loading tests on a scoured foundation on an aluminum rod ground model to reveal the mechanism of the residual bearing capacity of a scoured foundation. We also performed an image analysis to clarify the mechanism.

The findings of this study suggest the possibility of expanding the conditions for the early resumption of bridges with damaged foundations and is valuable for future emergency disaster operations of damaged river bridges. Finally, these findings will improve the resilience of transportation networks.

3. VERTICAL LOADING TESTS ON ALUMINUM RODS

3.1 Experimental Devices

In this study, the aluminum rod ground model, which is often used to evaluate the two-dimensional behavior of granular soils such as sand and gravel [6-10], was used. The experimental devices used for the vertical loading tests are shown in Figs. 3 and 4. The aluminum rod ground model was produced by mixing two types of aluminum rods with diameters of 1.6 and 3.0 mm and layered with 60% and 40%

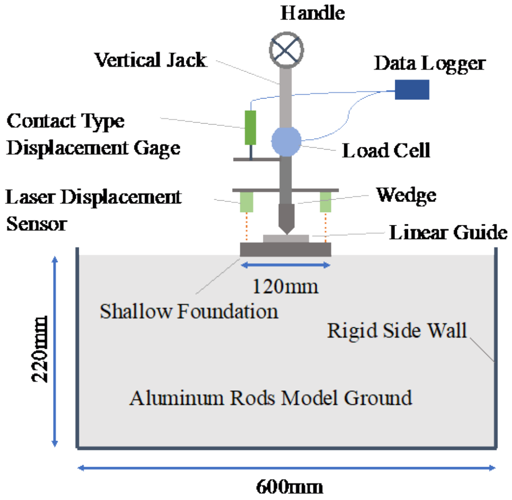


Fig. 3 Outline of experimental devices

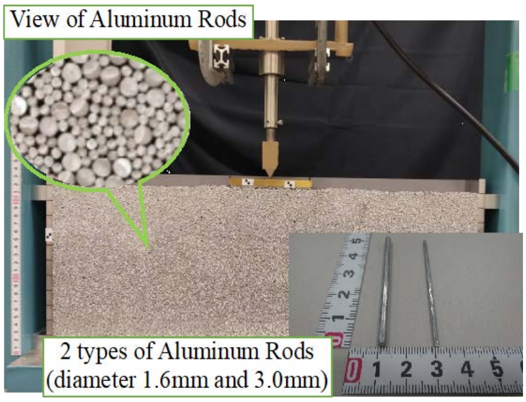


Fig. 4 Aluminum rod ground model

weight content, respectively. This particle size distribution was identical to that of previous studies [6-9].

The ground model was generated in an experimental container with a width of 600 mm and a depth of 220 mm. These ratios to the foundation width of 120 mm are 5.0 and 1.83, respectively. Preliminary loading tests with different depths of the model ground have confirmed that the effect of the bottom of the container on the load–settlement relationship is sufficiently insignificant at this size [11].

Compaction was performed for each spreading depth of 50 mm using a hand vibrator machine. The weight per unit volume and angle of repose ϕ_r of the ground model wewaseasured using a measuring box (width = 250 mm; depth = 50 mm). Here, the angle between the measuring box tilt and the aluminum rod collapse (Fig. 5) is defined as the angle of repose ϕ_r. After five tests, avethe rage values of γ = 21.3 kN/m^3 and ϕ_r = 29° were obtained.

A rigid plate with a thickness of 10 mm, a width of 120 mm, and a length of 50 mm was used as the shallow foundation model. A linear guide was installed on the top surface of the foundation to enable the foundation to rotate and slide horizontally. It was loaded vertically using a wedge at the point of the vertical displacement-controlled jack (Fig. 6).

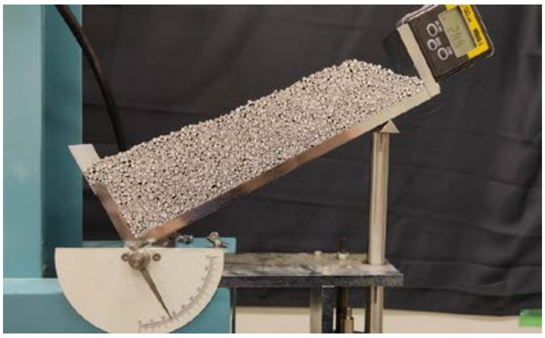


Fig. 5 Measurement of angle of repose

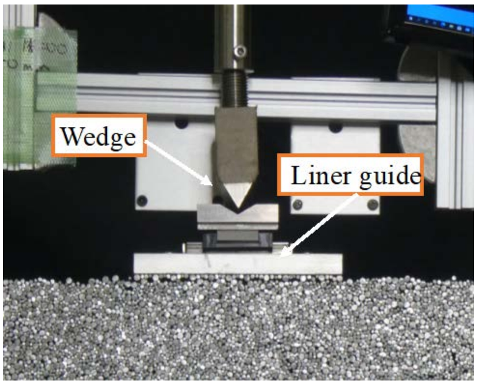


Fig. 6 Connection structure between load jack and foundation model

The load cell was set between the wedge and the vertical jack to measure the vertical load. In this experiment, the actual load resistance was the total load value output by the data logger and the self-weight of the foundation (3.9 N) because the foundation was not connected to the vertical jack. The displacement of the jack was measured using a contact-type displacement transducer. The angle of inclination of the foundation was obtained by measuring the displacement of both sides of the foundation using laser displacement transducers.

3.2 Loading Procedure

After the aluminum rod model ground was produced, the foundation was placed on the ground. At this time, the values of the load and settlement were zero. First, a 22.5 N load was applied to simulate a dead load. This condition represents the state of the foundation before the scouring damage occurs. This value of the dead load was obtained by dividing the ultimate bearing capacity obtained in the previous experiment without scouring by a safety factor of 3.

During the tests, loading and unloading were repeatedly applied several times until the displacement of the jack exceeded 10% of the foundation width. The loading speed in each settlement phase was controlled to 0.25 mm/min in 0–3 mm, 0.5 mm/min in 3–6 mm, and 1 mm/min in more than 6 mm. Figure 7 shows the variations in the settlement and load with time for vertical loading tests performed for the model before scouring.

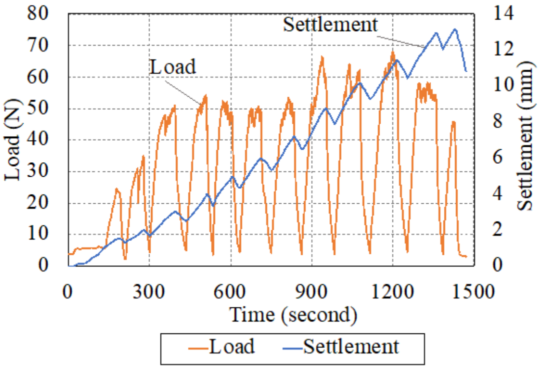


Fig. 7 Time-history curves of load and displacement of the model before scouring

3.3 Modeling of Local Scour

The local scour around the pier is generally known to be deeper on the upstream side of the pier [11-14]. Therefore, aluminum rods in the local scour area were removed to simulate a situation in which local scouring occurred just below the foundation on the upstream side (Fig. 8). The shape

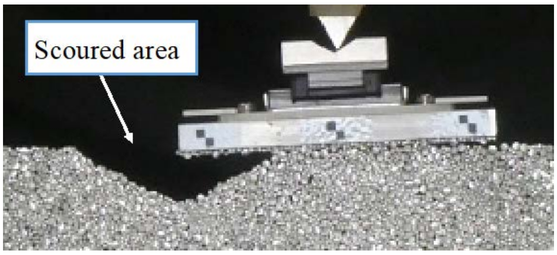


Fig. 8 Modeling of Local scour by removing aluminum rods

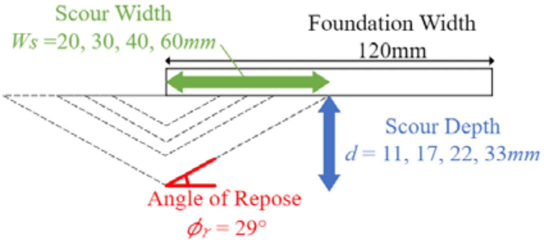


Fig. 9 Test cases of local scour area

of the local area was an isosceles triangle with an angle of repose (29°) and the depth of the local scour. This shape was determined by referring to the method for estimating the local scour area in the Japanese maintenance standards for railway structures[12]. The loading tests were performed for four cases by varying the local scour depth, d = 11, 17, 22, and 33 mm (Fig. 9).

While the displacement of the vertical jack was maintained, aluminum rods were removed to simulate local scouring. During the removal of the aluminum rods, most of the reaction force was lost because the position of the vertical jack was fixed. Subsequently, the displacement of the vertical jack increased again, and the load–settlement curve after the disaster was plotted.

In practice, the dead load is eccentric because the foundation is inclined after a local scour appears. However, this eccentricity was not modeled in our study because of the following reasons. In emergency restorations, the girders are generally jacked up and moved horizontally to return to their original position and then fixed by adding repair concrete (Fig. 10). In other words, the loading position of the live load before and after the disaster remained unchanged.

4. EXPERIMENTAL RESULTS

4.1 Load-Settlement Curves

The load–settlement curves obtained from the tests are shown in Fig. 11. For d = 33 mm, the curve could not be plotted because the foundation could not carry its self-weight and moved by rotating from its initial position during the aluminum rod removal. In the other three cases, each curve showed a slight gradient during the initial loading phase. However, from the middle phase of loading, the curve warped up, indicating a high load value. This increase occurred when all foundation base widths reached the ground after the foundation was inclined along the slope owing to local scouring.

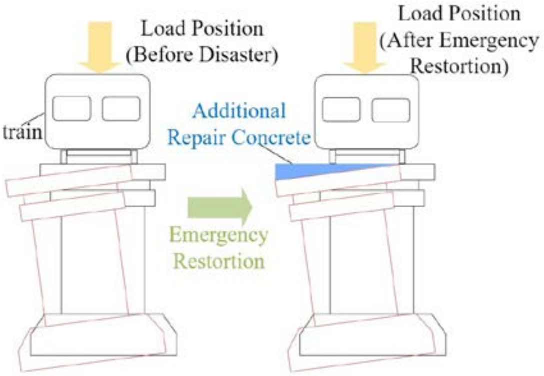


Fig. 10 Modeling of loading position after emergency restoration

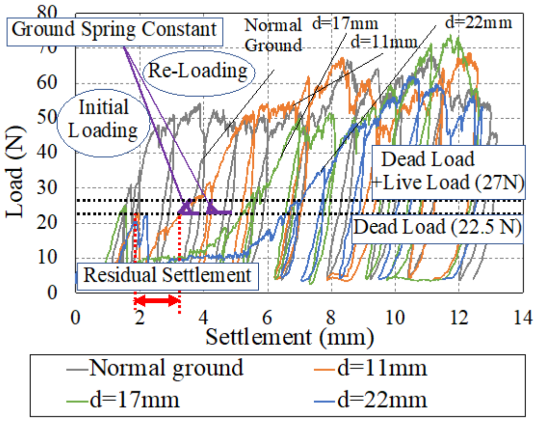


Fig. 11 Load–settlement curves

4.2 Residual Settlement and Residual Inclination

In Fig. 12, the horizontal axis indicates the local scour depth, and the vertical axis represents the settlement and inclination when the load reaches the dead load after local scouring. These settlements and inclinations correspond to the residual settlement and inclination that occur in actual situations after a foundation is damaged by disasters because of the settlement and inclination increase with local scouring under dead loads. The graphs indicated that the residual settlement and inclination increased with the local scour depth.

Figure 13 shows the changes in the inclination of the foundation with increasing settlement. The filled circles in the graph represent the state when the dead load is loaded after removing the aluminum rods. These plots indicate the residual settlement caused by the dead load immediately after the scouring disaster. In each scouring case, the inclination of the foundation under the dead load decreased gradually, and it decreased by at least 1° after the test when the settlement reached 12 mm. It was assumed in this study that repair would be conducted to return the loading position (which moved slightly owing to scouring) to the initial position (Fig. 10). The inclination of the foundation returned to the stable direction, suggesting that there is minimal concern about exceeding the limit state of inclination when the foundation is reused with appropriate repair (Fig. 13).

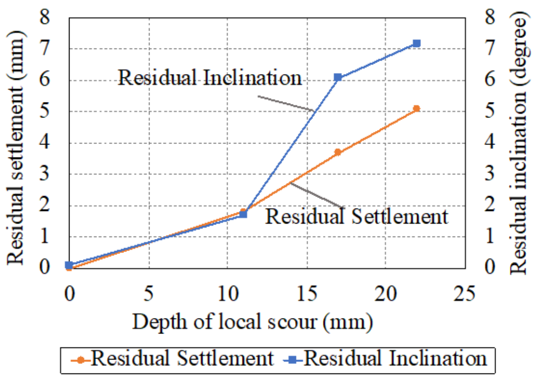


Fig. 12 Changes in residual settlement and inclination with the depth of local scour

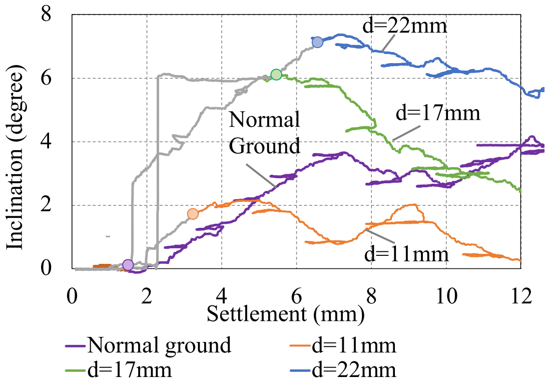


Fig. 13 Changes in inclination of foundation with settlement

4.3 Ultimate Bearing Capacity and Ground Spring Constant

In Figure 14, the horizontal axis indicates the local scour depth, and the left vertical axis shows the ultimate bearing capacity. In this study, the ultimate bearing capacity was defined as the maximum value of the load before the settlement reached 12 mm, which was 10% of the foundation width. The ultimate bearing capacity maintained a steady value (Fig. 14), almost the same as normal ground loading.

The right vertical axis in Figure 14 represents the ground spring constant *k* which is defined as the slope of the load-settlement curve from the dead load to 1.2 times the dead load. This load increment was simulated as a live load, for example, a trainload. We calculated two types of ground spring constants (Fig. 11): at the initial loading immediately after local scouring and during reloading. On the one hand, the ground spring constant at the initial loading can be used to calculate the increase in settlement during restoration work, such as the jack-up, adding repair of concrete, and static loading tests. On the other hand, the ground spring constant at reloading can be used to evaluate the behavior under live load after the resumption of service.

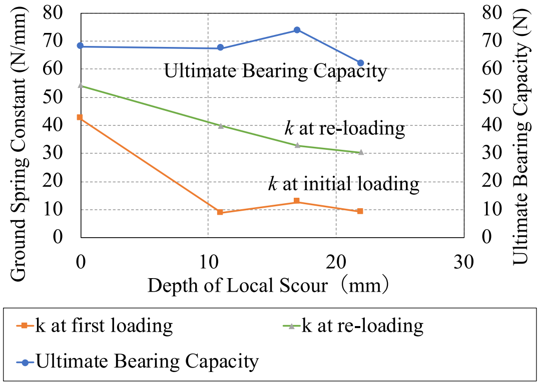
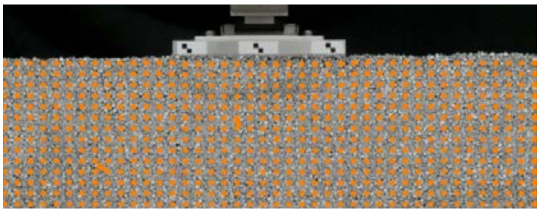


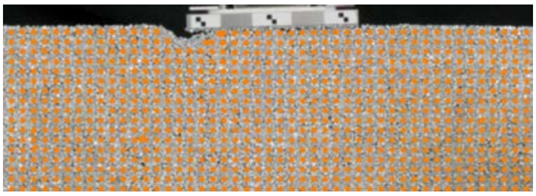
Fig. 14 Changes in ultimate bearing capacity and ground spring constant with local scour depth

Both ground spring constants tended to decrease with local scour depth (Fig. 14). Although the ground spring constant at the initial loading decreased significantly, the incremental settlement at the restoration work was smaller than the overall residual settlement owing to the dead load only (Fig. 11). This increment can be handled easily through restoration work. Moreover, the ground spring constant at reloading had a higher value than the ground spring constant at the initial loading in all cases. The effect of the local scour depth on the ground spring constant at reloading was less significant than that at initial loading.

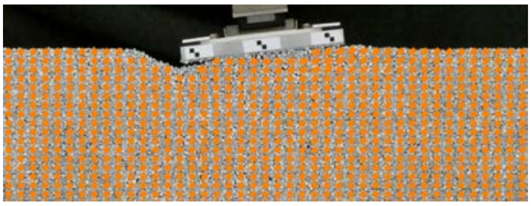
In summary, in cases where the foundation does not collapse under the dead load, it is likely for its ultimate bearing capacity not decrease even if it is damaged by local scouring. Therefore, the bridge's foundation might be safe, with there also the possibility of its reuse. In addition, the decrease in the ground spring constant at reloading is expected to remain within the acceptable range after the resumption. However, the sum of the residual deformation and increment at initial



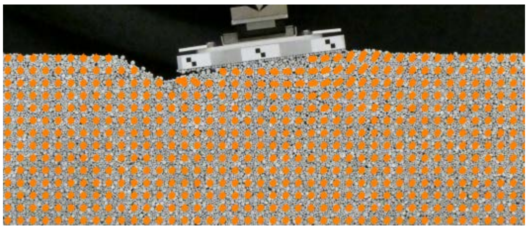
a) Case of normal ground



b) Case of d = 11 mm

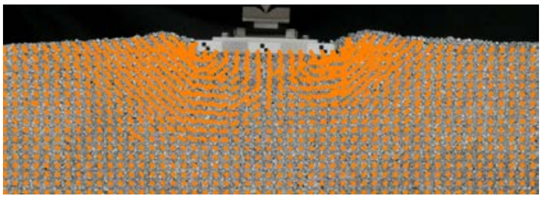


c) Case of d = 17 mm

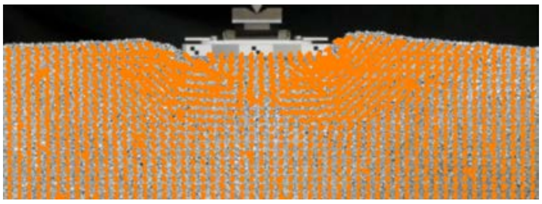


d) Case of d = 22 mm

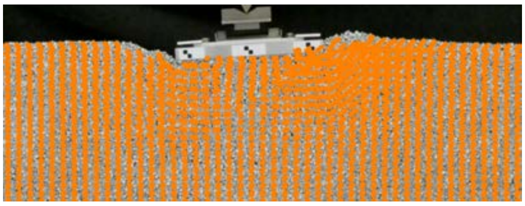
Fig. 15 Ground displacement at residual settlement



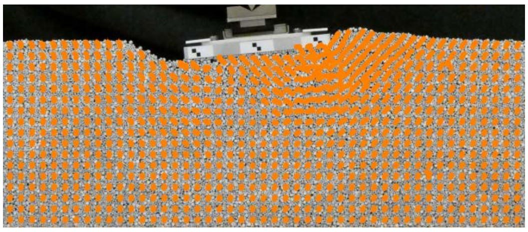
a) Case of normal ground



b) Case of d = 11 mm



c) Case of d = 17 mm



d) Case of d = 22 mm

Fig. 16 Ground displacement from residual settlement to 12 mm

loading must be less than the maximum limit value that the restoration work can accommodate.

4.4 Image Analysis

We performed image analyses to calculate the displacement and visualize the slip lines on the ground for all cases. In the image analysis, tracking points were set on the image for the tests on the aluminum rod ground model. The displacements at each point were calculated by changing the points. In addition, slip lines were observed to chase the trajectories of each point.

Figures 15 and 16 show the image analysis results, and we compared the changes in the slip lines under the dead load and 10% of the foundation width (12 mm). In all cases under the dead load, tiny slip lines were observed. In contrast, at 12 mm settlement, more extensive slip lines appeared than those under the dead load. For d = 17 and 22 mm, significant slip lines were observed at the unscoured side (right side) of the foundations, as shown in Fig. 16. On the scoured side, a slip surface was observed, although the movement was slight. This surface indicated that the ground resistance at the scoured area at the bottom of the foundation recovered. It was also confirmed from the image analyses that the bearing capacity increased during the loading tests, even when the foundation was scoured.

5. CONCLUSION

In this study, we performed vertical loading tests on a scoured spread foundation on aluminum rods and conducted image analysis to clarify the mechanism of the bearing capacity of the locally scoured foundation.

The results suggest that it is possible to resume the service of bridges because the ultimate bearing capacity will remain, even if the foundation is damaged if the residual settlement and inclination are recoverable through simple emergency restoration and if the reduction in the ground spring constant is limited. Additionally, the inclination of the foundation will be gentle, and the settlement will not increase when the repair, such as fixing the loading position to the original location before resuming, is performed.

In future research, we will perform tests by varying the diameters of aluminum rods and the size distributions of the aluminum rods. Moreover, we will analyze the bearing capacity mechanism in detail through image analysis.

6. ACKNOWLEDGEMENTS

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