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STUDY ON SOUNDNESS EVALUATION OF BRIDGE SLABS BY FALLING WEIGHT DEFLECTOMETER

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ABSTRACT: In proper maintenance for bridge slabs, deflection measurement of bridge slabs by falling weight deflectometer (FWD) is one of the soundness evaluation methods. The FWD is the non-destructive testing method for obtaining the slab deflections in-situ. In this research, we focused on the deflection area calculated from the deflection measurement as one of the soundness evaluation indexes for the bridge slabs and investigated it by elastic finite element (FE) analysis based on the thin plate theory simulating the fatigue damage by changing the flexural rigidity of reinforced concrete (RC) slabs. As the results, the deflection area in the transverse direction to the bridge axis correlated well with the deflection at the loading point, and the deflection area in the longitudinal direction was also found to be a good correlation with the deflection at the loading point by limiting its calculation length considering the characteristic of deflection curve. These relationships were similar not only in the simply supported slabs but also in the continuously supported slabs. Furthermore, in order to verify the analytical results, the deflection measurement was carried out on actual bridge slabs newly constructed. Then, the measured results had the same trend with the analytical results.

Keywords: Bridge slabs, Deflection area, Falling weight deflectometer, Soundness evaluation index

1. INTRODUCTION

Fatigue damages such as cracks and partial concrete falling (punching shear failure) out of reinforced concrete (RC) slabs began to emerge from the beginning of the 1960s in Japan, so the elucidation of the fatigue damage mechanism of RC slabs has been conducted by the wheel load running machine [1]. As a factor of the fatigue damage on the RC slabs, for example, designed by the Highway Bridge Design Specification published in 1956 [2], the slab thickness was thin and the amount of longitudinal reinforcing bars was little. In addition to this, it can be said that an increase in the number of heavy and overloaded vehicles was greatly influenced by the fatigue damage [3]-[5]. After that, the slab thickness, the amount of the longitudinal reinforcing bar, the design bending moment, and the allowable stress level of the reinforcing bar was reviewed many times so far, and the RC slab with the higher fatigue durability is realized nowadays. On the other hand, concrete cracking and reinforcing bar corrosion are becoming obvious due to some degradation factors such as the salt damage by spreading of deicing agent and the alkali-silica reaction. The proper maintenance for bridge slabs against the complex deterioration with the fatigue is required. As a method for evaluating the soundness of RC slabs, there are some methods such as evaluating cracks on the lower surface of RC slabs by visual observation based on the occurrence density (crack density), width and interval or directly measuring the deflection of RC slabs [6]. Some proposals have also been made to evaluate the soundness by measuring the deflection of RC slabs from the bridge surface by utilizing the equipment used for a method of the pavement soundness evaluation [7]-[11]. This is a method of dynamically measuring the deflection at the time by giving an impact load onto the bridge slab from the pavement surface, for example, by using a vehicle equipped with the falling weight deflectometer (FWD) testing machine (Fig.1).

In the FWD test, the deflection measurement sensors are placed at several points on the pavement surface in the transverse and longitudinal directions to the bridge axis, and the deflections at the time of dropping of the arbitrarily set weight are measured. In addition, since the entire bridge vibrates due to the loading of the impact load, in order to obtain the deflection of the bridge slab, the deflection values measured are corrected by using the deflection value measured on the main girders [12].

Conformity with the deflection values measured from the lower surface of RC slabs and by the FWD has been carried out in the literature.

Sekiguchi et al. [7], [8] evaluated the correlation between the soundness evaluation index based on the deflection measured by the FWD and the crack density from measured data at the existing bridge slabs. Abe et al. [9] showed linearity in the relationship between the deflection area and the deflection at the loading point of RC slabs, with reference to the deflection area recommended by AASHTO [13] when evaluating the soundness of concrete pavement. The deflection area calculated from the distribution of the deflection can evaluate the overall behavior of RC slabs in comparison with the other soundness evaluation indexes [8], [10].

In this paper, the relationships between the deflection area and the deflection at the loading point were widely investigated by elastic finite element (FE) analysis based on the thin plate theory simulating the fatigue damage by changing the flexural rigidity of RC slabs. From the analytical results, we examined whether the deflection area becomes a soundness evaluation index for bridge slabs.

2. FE ANALYSIS AND SOUNDNESS EVALUATION INDEX

2.1 Analytical models and analytical cases

The analytical models were simply supported one-way RC slabs with a slab span length of 2 m, 3 m, and 4 m and each slab thickness were 190 mm, 230 mm, and 270 mm calculated as the minimum thickness from the Highway Bridge Design Specification [14], respectively. As simulating the fatigue damage, the flexural rigidity due to bending cracks occurring in the RC slab was reduced from the entire cross-section in the transverse direction (main reinforcing bar cross-section) and in the longitudinal direction (distribution reinforcing bar cross-section) with Young's modulus is a constant value (28 kN/mm^2). In the Steel Road Bridge Design Specifications [2] in 1956, the amount of the longitudinal reinforcing bar was specified at 25% or more against the amount of the main reinforcing bar. Moreover, in 1967, the Ministry of Construction, Road Bureau Director in Japan notified to raise the amount of the longitudinal reinforcing bar as 70% or more against the amount of the main reinforcing bar. From these provisions, the flexural rigidity when ignoring the tensile side concrete decreases to about 40% in the transverse direction and to about 20% in the longitudinal direction with respect to the flexural rigidity when the entire cross-section is effective. Therefore, in this study, the reduction ratios of the flexural rigidity in both directions were set to 20 combinations shown in Table 1.

Generally, as a circular loading plate having a diameter of 300 mm was used in the FWD measurement, the loading plate in this analysis was modeled with a square plate (265.9 × 265.9 mm) which is equivalent to the area and the loading area was spread to the distance to a half of the slab thickness by 45° distribution with a similar shape in the FE analysis. The influence of the asphalt pavement and the waterproofing was ignored in this study. The load value was determined from the loading area in each analytical case so that the ground pressure was kept as a constant value of 0.98 N/mm^2.

2.2 Deflection area for simply supported slabs

In the FWD tests, deflection measurement sensors are arranged arbitrarily as shown in Fig.2. The deflection area in the transverse direction is obtained from the deflection values measured by

Fig.1 A vehicle equipped with the FWD testing machine

Table 1 Combinations of flexural rigidities

Reduction ratio		I_x in the transverse direction 100%	80%	60%	40%
I_y in the longitudinal direction	100%	○	○	○	○
	80%	○	○	○	○
	60%	○	○	○	○
	40%	○	○	○	○
	20%	○	○	○	○

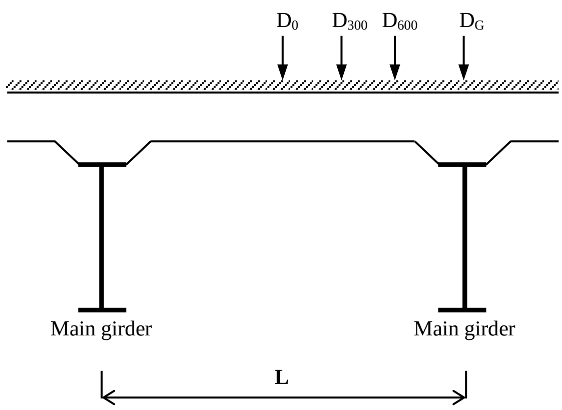


Fig.2 Arrangement of deflection measurement sensors in the transverse direction

the deflection measurement sensors placed between the main girders. On the other hand, since the shape of the deflection curve in the longitudinal direction is significantly different depending on the degree of damage of the RC slab, the calculation length of the deflection area in the longitudinal direction needs to be determined considering the shape of the deflection curve. In this study, the calculation length for the deflection area in the longitudinal direction was discussed based on the analytical results.

The relationship between the deflection area in the transverse direction (A_t) and the deflection at the loading point (D_0) is shown in Fig.3. Both values increase with decreasing the flexural rigidity. It can be seen that the deflection area in the transverse direction has a good correlation with the deflection at the loading point in each slab span length. Here, in the FWD tests, the load can be determined arbitrarily and the response value of the deflection is influenced by the slab span length even with the same load. The unified soundness evaluation index is appropriate to consider without these influences. Therefore, it is considered that the deflection area is divided by the load value and the slab span length (A_t/PL), and the deflection at the loading point is divided by the load value (D_0/P). Then, the relationship between them can be shown in Fig.4. Consequently, all of the results are linearly plotted on a straight line.

Next, some results on the deflection curves in the longitudinal direction, for example, of RC slabs with several deteriorations in the longitudinal direction are shown in Fig.5. Then, there is the inflection point in the deflection curve at about a half of the slab span length from the loading point. The same trend can be seen in the analytical results for the other slab span lengths. In this study, the deflection area in the longitudinal direction and the deflection at the loading point are assigned to calculate between inflection points as shown in

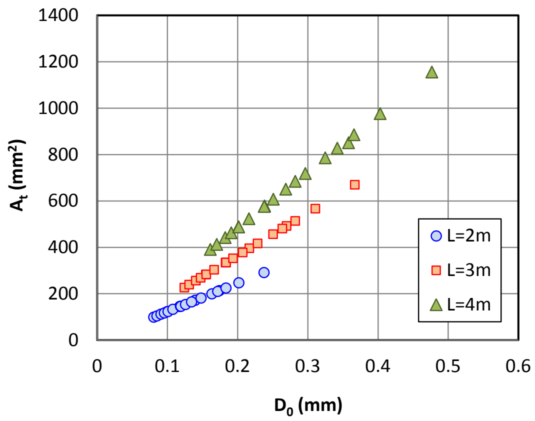


Fig.3 Relationship between the deflection area in the transverse direction (A_t) and the deflection at the loading point (D_0)

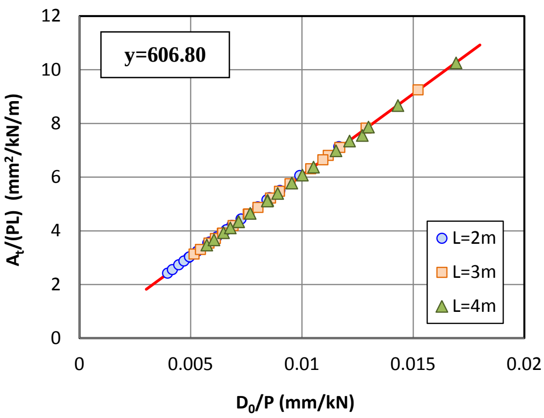


Fig.4 Relationship between the deflection area divided by the load value and the slab span length (A_t/PL) and the deflection at the loading point divided by the load value (D_0/P)

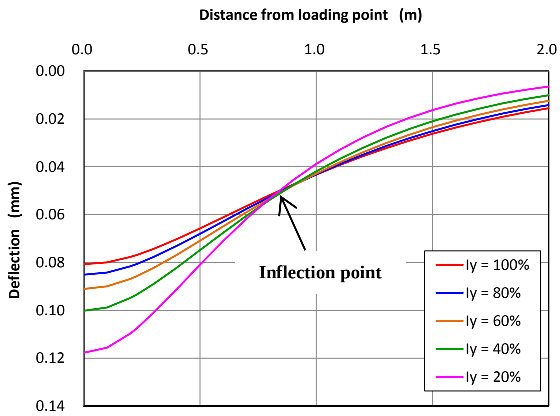


Fig.5 Deflection curves in the longitudinal direction of RC slabs (slab span length of 2 m) with several deteriorations

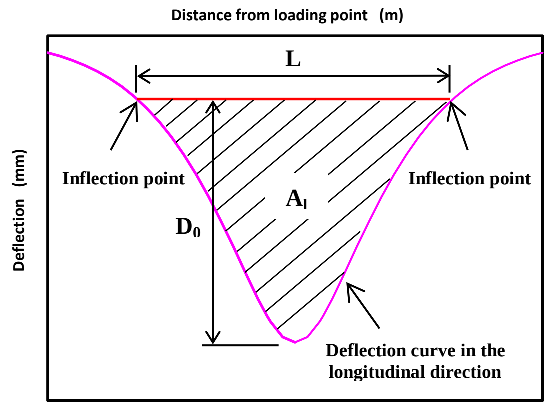


Fig.6 Deflection area in the longitudinal direction (A_l) and the deflection at the loading point (D_0^*) assigned to calculate between inflection points

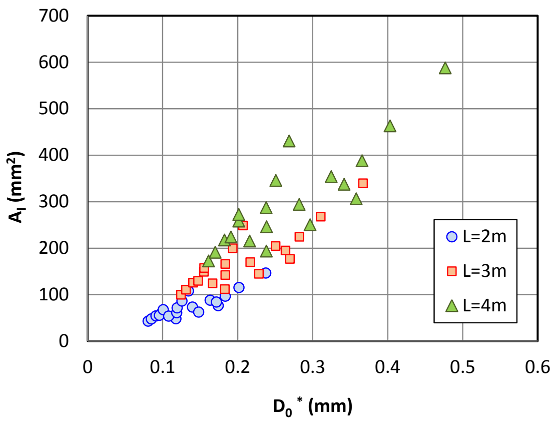


Fig.7 Relationship between the deflection area (A_l) in the longitudinal direction and the assigned deflection at the loading point (D_0^*)

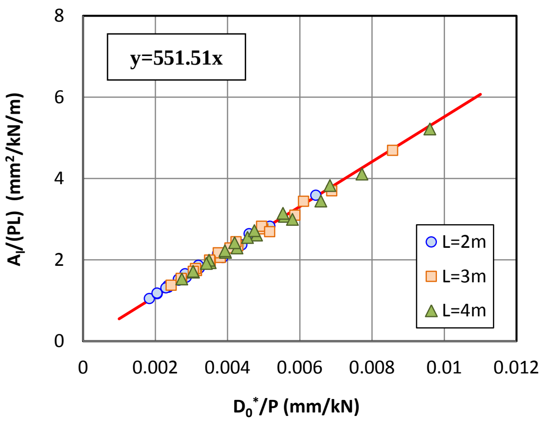
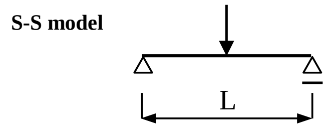


Fig.8 Relationship between the deflection area divided by the load value and the slab span length (A_l/PL) and the assigned deflection at the loading point divided by the load value (D_0^*/P)

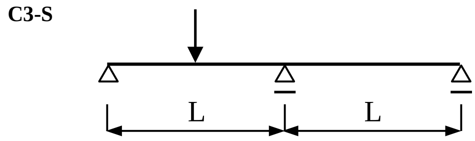
Fig.6. Then, the relationship between the deflection area in the longitudinal direction (A_l) and the assigned deflection at the loading point (D_0^*) is shown in Fig.7. And, as shown in Fig.8, the unified relationship between A_l/PL and D_0^*/P has a good correlation as is same with the transverse direction shown in Fig.4.

2.3 Deflection area for continuously supported slabs

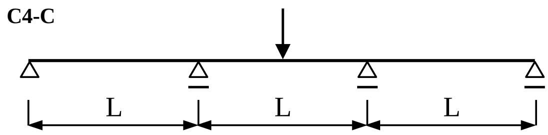
The analysis using models assuming continuously supported one-way slabs by three or four main girders shown in Fig.9 was also carried out. The slab span length was 2 m, 3 m, and 4 m and each slab thickness were 170 mm, 200 mm, and 230 mm, respectively, calculated as the minimum thickness from the Highway Bridge Design Specification [14]. The reduction ratios of



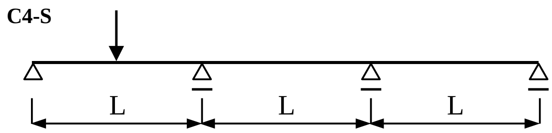
(a) Simply supported slab



(b) Continuous slab supported by three girders loaded at side span



(c) Continuous slab supported by four girders loaded at center span



(d) Continuous slab supported by four girders loaded at side span

Fig. 9 Analytical models for continuously supported slabs

Table 2 Combinations of flexural rigidities

Reduction ratio		I_x in the transverse direction 100%	80%	60%	40%
I_y in the longitudinal direction	100%	○	–	–	–
	80%	○	○	–	–
	60%	○	○	○	–
	40%	○	○	○	○
	20%	○	○	○	○

the flexural rigidity in the transverse and longitudinal directions were 14 combinations shown in Table 2.

The deflection area was divided by the load and the slab span length, and the deflection at the loading point was divided by the load value as the same procedure mentioned above. The relationships between them in the transverse and longitudinal directions are shown in Fig.10 and Fig.11, respectively. From these results, it can be seen that these relationships are also well with the expression by a straight line regardless of the slab span length even if the loading position is located at the side span or at the center span.

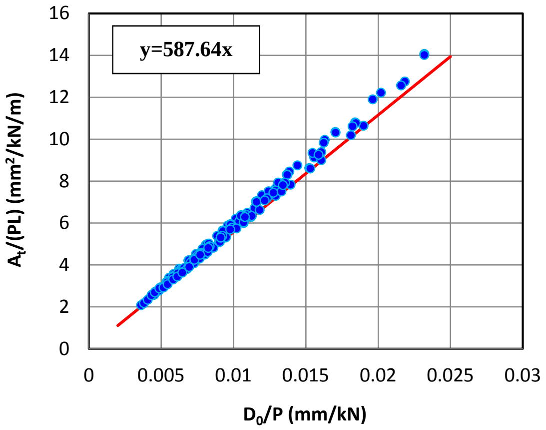


Fig.10 Relationship between the deflection area divided by the load value and the slab span length (A_t/PL) and the deflection at the loading point divided by the load value (D_0/P)

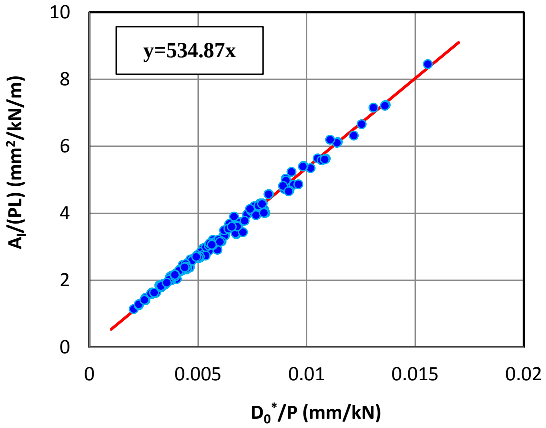


Fig. 11 The relationship between the deflection area divided by the load value and the slab span length (A_l/PL) and the assigned deflection at the loading point divided by the load value (D_0^*/P)

2.4 Soundness evaluation index

When diagnosing the soundness of RC slabs, it is required to provide a soundness classification from the beginning of construction to the serviceability limit state. Herein, it is assumed that the flexural rigidity when the entire cross-section is effective, that is when the reduction ratio of the flexural rigidity is 100% in this analysis, is at the beginning of construction (at the initial stage). Then, the deflection area and the deflection at the load point of all analytical cases were normalized by those of each initial stage. As the results, Fig.12 and Fig.13 can be obtained. Based on these normalized expression, it is considered that the soundness of RC slabs can be classified as the soundness evaluation index. In the present situation, however, the further data collection from

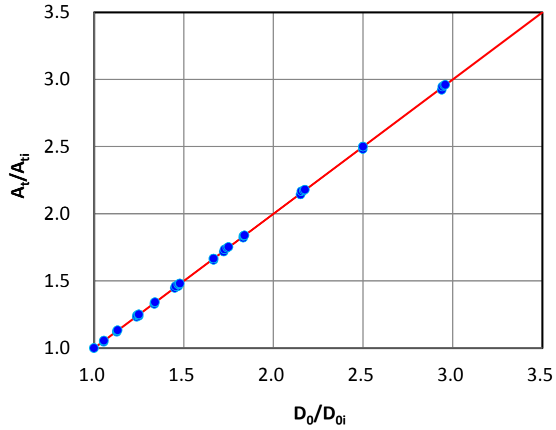


Fig.12 Relationship between A_t/ A_{ti} and D_0/ D_{0i}

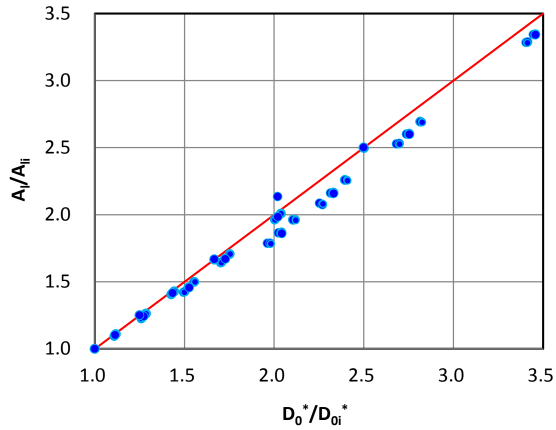
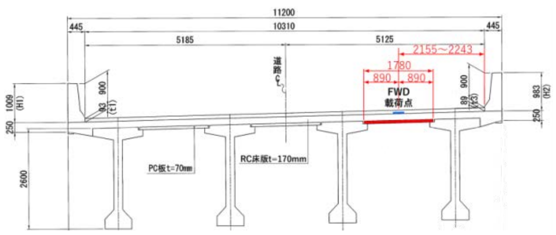


Fig.13 Relationship between A_l/ A_{li} and D_0^*/ D_{0i}^*

(a) PCT composite bridge

(b) FWD measurement



(c) Cross section of PCT composite bridge

Fig.14 Actual PCT composite bridge

FWD tests on actual bridge slabs and the analytical considerations are needed to suggest the soundness classification.

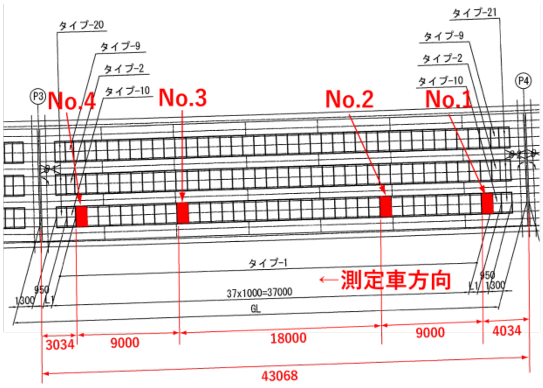


Fig.15 Positions of FWD measurements

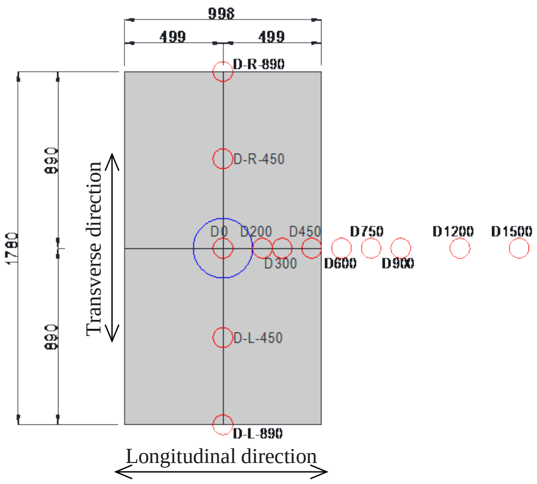


Fig.16 Loading position and deflection measuring points on PC panel

3. DEFLECTION MEASUREMENT IN PCT COMPOSITE BRIDGE SLABS

3.1 Deflection measurement

The actual PCT composite bridge with four main girders was constructed in 2017 as shown in Fig.14. The deflection measurement by the FWD was carried out before construction of asphalt pavement at two slab panels (No.1 and No.4) closer to the piers and other two slab panels (No.2 and No.3) at a quarter of the girder span length as shown in Fig.15. The loading position and the deflection measuring points on each panel are shown in Fig.16. The loading point (blue circular) was at the center of the panel and the deflection measurement sensors were placed at the positions circularly represented and the value described beside the circle means the distance from the

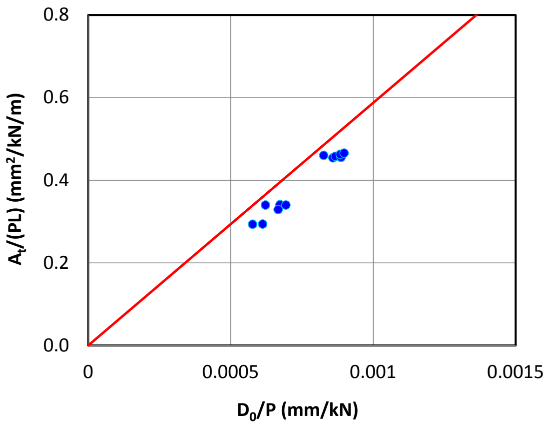


Fig.17 Relationship between the deflection area divided by the load value and the slab span length (A_t/PL) and the deflection at the loading point divided by the load value (D_0/P)

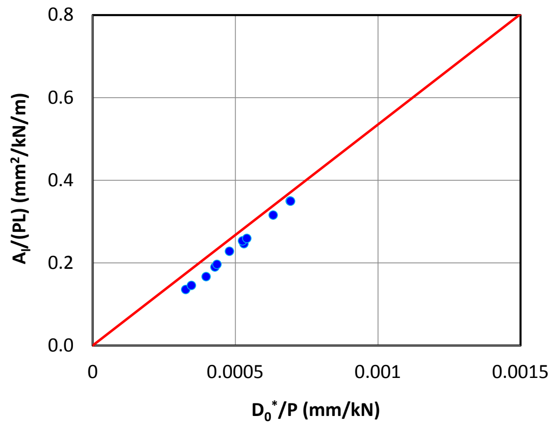


Fig.18 Relationship between the deflection area divided by the load value and the slab span length (A_l/PL) and the assigned deflection at the loading point divided by the load value (D_0^*/P)

loading point. The applied load at each point was 49kN, 78kN, and 98kN and the data was acquired eight times for each load level. The first sampling data were excluded as preliminary loading and three data combinations with the smallest variation coefficient of the deflection at the loading point were extracted among the remaining seven data sets. Consequently, the average data was obtained from those three data.

3.2 Deflection area

In this PCT composite bridge, the width of the slab panel (1780 mm) was used as the slab span length as shown in Fig.14. In addition, for the deflection area in the longitudinal direction, the calculation length was from the loading point to 900 mm and the obtained value was twice considered as a symmetrical proportion. The relationships between the deflection area in the transverse and longitudinal directions and the deflection at the loading point calculated with the same procedure mentioned above were obtained. The relationships between the deflection area divided by the load value and the slab span length and the deflection at the loading point divided by the load value are shown in Fig.17 and Fig.18. In both figures, a red line shows the line obtained from the regression analysis in Fig.10 and Fig.11. Then, these data before construction of the asphalt pavement can be almost plotted close to the straight line obtained from the analytical results mentioned above. The analytical results were verified from the deflection measurements on the actual bridge slabs. However, the deflection values obtained from newly constructed bridge slabs were very small. It can be said that the further FWD measurements carried out on existing damaged bridge slabs are needed.

4. CONCLUSIONS

In this study, by the elastic FE analysis based on the thin plate theory, the relationship between the deflection area and the deflection at the loading point of RC slabs was examined to suggest the soundness evaluation index by the FWD tests. The findings obtained are summarized below.

(1) The deflection area (A_t) in the transverse direction was a good correlation with the deflection at the loading point. Since the deflection area (A_l) in the longitudinal direction is influenced by the calculation range. From the deflection curves, the calculation range was determined to be the length between the inflection points which was almost same with the slab span length.

(2) The deflection area divided by the load value and the slab span length was a good correlation with the deflection at the loading point divided by the load value in the transverse and longitudinal directions.

(3) When compared with the test results measured on the actual PCT composite bridge slabs, the relationships obtained from the FE analysis were verified well.

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