- *Technical Paper* -

NUMERICAL SIMULATION OF CONSTRUCTION-JOINT EFFECTS FOR FATIGUE-LIFE ASSESSMENT OF CONCRETE PAVEMENT SUBJECTED TO TRAVELING WHEEL-TYPE LOAD

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ABSTRACT

The coupled code program for analysis of soil and concrete slab to be verified by the small-scale experiment has been implemented by integrating constitutive models for concrete and soil under the moving load to assess the life-cycle of jointed and continuously reinforced concrete. The behavioral simulation is discussed to emphasize the drastic reduction of fatigue life of jointed concrete due to the localized damage of concrete slab and soil. The effects of reinforcement ratios, thickness of concrete slab and relative density of soil have been investigated as the sensitivity factors of modeling.

Keywords: concrete pavement, fatigue life, joints, moving load, numerical simulation

1. INTRODUCTION

A concrete pavement is designed to provide the safe and durable road surfaces and the study of this one is the coupling of soil and concrete slab interaction for the purpose of examining the fatigue life to serve construction and maintenance works. There were a lot of researches [1-3] based on the fixed-point pulsating loads to check the service time of concrete slabs. It is supposed not to reflect real working conditions due to the fact that the behaviors of concrete pavement are mainly affected under the moving loads of traffic vehicles. Maeda and Matsui implemented the first experiment to check how different the fatigue life of reinforced concrete (RC) bridge decks is in case of moving loads compared to fixed-point pulsating ones [4,5]. The experimental results showed the dramatic decrease of fatigue life under the moving loads. Maekawa et al. has proposed concrete constitutive models to investigate the fatigue life of RC slabs on deck by tracing the exact transient process of gradual damages under the repeated loading [6]. By utilizing the three-dimensional high-cycle simulation, Maekawa et al. has successfully demonstrated the significant reduction of fatigue life of RC bridge slabs [6].

In the event of concrete pavement, the accuracy of prediction for the fatigue life is thought to be based on the coupling of concrete slabs and base soil. It is clearly seen that previous studies have been conducted based on a simplified method to suppose the soil foundation as beams or plates on elastic homogeneous spaces [7]. Meanwhile, nonlinear mechanics of soil consists of elasticity and plasticity to be dealt with by using constitutive models [8].

By analyzing the three-dimensional high-cycle fatigue of soil-concrete pavement slab, Nguyen et al. [9] implemented the coupling of soil behaviors (shear and volumetric issues) and concrete (compression, tension and shear transfer) to show how the fatigue life of concrete pavement has been reduced in the case of moving loads compared to fixed ones. The details of this scheme are shown in Fig.1.

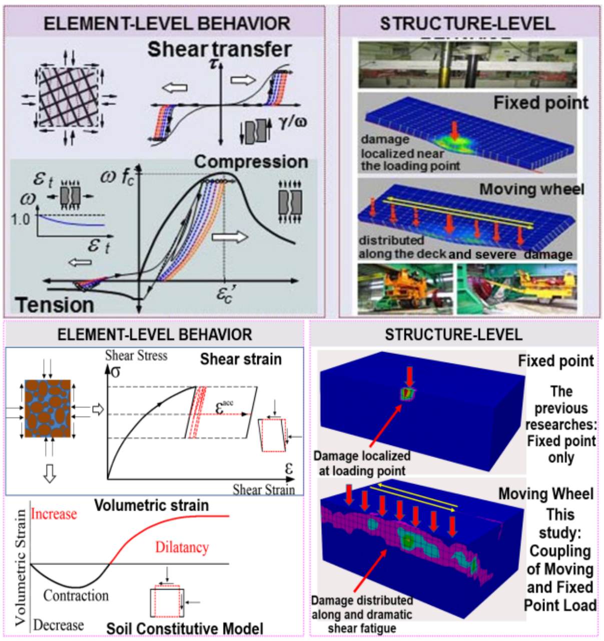

Fig.1 Model scheme of concrete slab and soil foundation [9]

In the case of fixed-point loads, the damage of concrete slabs and soil is focused on the load-point position only. On the contrary, under the moving loads, the damage is clearly distributed along the moving wheel and the shear fatigue is more severe compared to fixed-point load.

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There are two typical types of concrete pavement as jointed (either plain or reinforced) and continuously reinforced concrete. The systems of jointed concrete can be longitudinal or transverse direction, and it is found that the critical stresses occurred more severely at transverse joints compared to longitudinal ones [10]. Results of a survey in Japan show that the initiation of longitudinal cracks of concrete pavement under wheel paths started at transverse joints [11]. In addition, three major types of joints can be defined as contraction, expansion and construction joints. Construction and expansion joints are both used between pavement and adjacent roads, meanwhile, the contraction joints are used as a weakened plane while curing process [10].

The dowel bars in between two concrete slabs at the joint position can be installed to support the load transfer under traffic moving loads [12]. In the case of no existence or the failure for supporting the load transfer of dowel bars, each concrete slab apparently endure the fully applied load and it is the most critical case which affects the fatigue life of concrete pavement. There are less previous researches in view of comparing the fatigue life of jointed concrete slabs without dowel bars and continuously reinforced concrete.

In this paper, the authors show the three-dimensional high-cycle fatigue for soil and concrete slab by coupling the constitutive models of both cases to investigate the decrease of fatigue life in the case of existing construction joints (transverse direction) without dowel bars (or failure for supporting of dowel bars) compared to continuously reinforced concrete. The typical construction joint is 20mm in width [10] and applied in this study as shown in Fig.2.

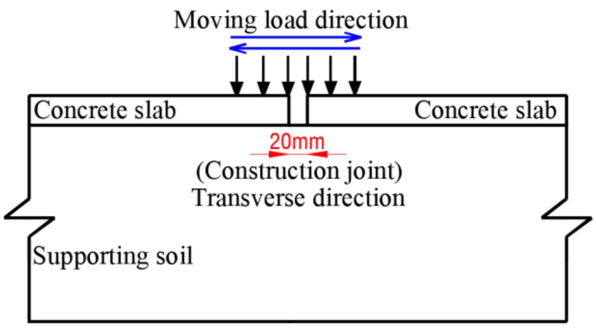

Fig.2 Construction joint used in this study

2. COUPLED ANALYSIS FOR CONCRETE SLAB AND SOIL

As preceding section, the high cycle fatigue for concrete bridge slabs on deck has been investigated by using the constitutive models [6]. Furthermore, the nonlinear soil-structure interaction was considered for examining the shear failures of soil foundation [13]. By combining two above separate codes to be verified and validated at each scale of experiments, the coupled code was developed based on the multi-scale platform coded as DuCOM-COM3 [14]. This coupled code is currently used to simulate the three-dimensional high-cycle fatigue modeling of concrete pavement in case of jointed reinforced concrete without dowel bars and continuously reinforced concrete. The reliability and accuracy of this simulation platform has been examined based on experiments and partly applied to designs and maintenance works in practical engineering.

2.1 The small-scale experiment for verification of soil-concrete slab interaction

The small-scale experiment was aimed to verify and validate the mechanism couple of supporting soil and concrete slab under the vehicular moving load. Wichtmann showed that soil is considered as high cycle fatigue when the number of cyclic passages is over 10^3 cycles with a small relative amplitude [15]. Based on this experiment, the authors recommended and conducted the small-scale experiment for concrete pavement by using wheel-track loading test facilities. Concrete slab was 300mm x150mm in plane and 50mm thickness. The track length of the moving wheel was 150mm and applied at the center along the longitudinal direction.

The wheel-type load was 1029N, and the speed of moving wheel was kept at 21 round trips per minute during the experiment until 75,220 cycles owing to the restriction of experimental facilities. The water to cement ratio of concrete slab was 55% (normal concrete). Sand was used as the supporting soil from Ohigawa river contained in a formwork with one plastic side to investigate the failure mode after applying load. The relative density of soil was 75% to illustrate the dense condition of soil foundations. Details of experimental models are shown in Fig.3.

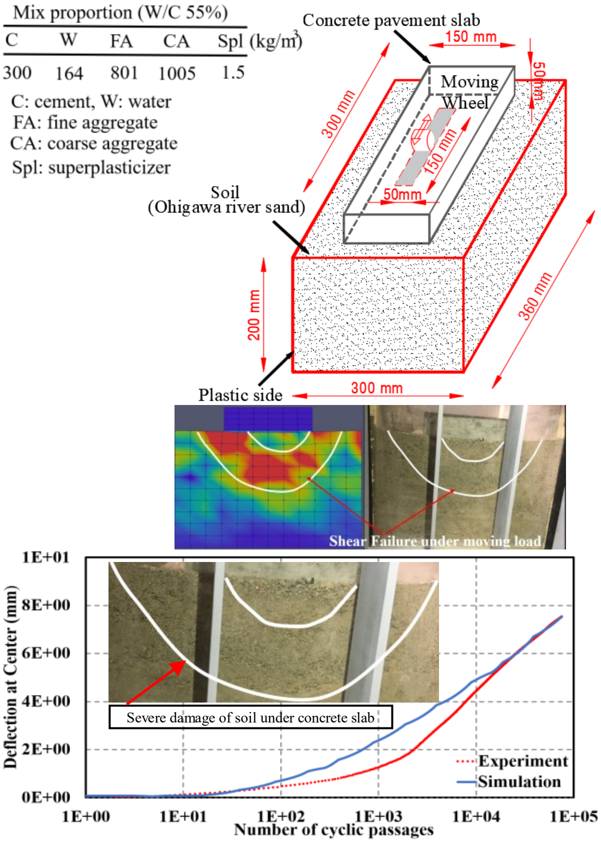

Fig.3 Analysis for the small-scale concrete pavement modelling of experiment and simulation

To clearly elucidate the coupling code of soil and concrete slabs, the authors implemented the three-dimensional behavioral simulation. As can been seen in Fig.3, the computed deflection is moderately close to the experimental one. Another point is the observation of the failure mode of soil in case of experiment and numerical simulation. The shear failure of soil was significantly distributed under the concrete slab. It is similar to the computed deflection that the simulated failure mode is also fairly close to the experimental result. Therefore, the coupled code for soil and concrete slab can currently be applied to examine the fatigue life of concrete pavement under the moving loads.

2.2 Multi-scale modelling of soil-concrete slab interaction

(1) Constitutive model for high-cycle fatigue of concrete

As stated previously, Maekawa et al. proposed the constitutive law for high-cycle fatigue based on the research from the multi-directional fixed crack modelling by coupling one dimensional stress-strain relations of concrete in tension, compression and shear [6]. Each constituent modeling is strain and time path dependent. Maekawa et al. extracted the accumulated fatigue damage of concrete solid by experimentally subtracting the component of time dependent deformation and reformulated more generic constitutive model for compression. It is similar to compression, tension stiffening/softening and shear models have to be enhanced to consider the cumulative fatigue damage [9]. In this study, the high-cycle fatigue for concrete slab has been integrated in the verified code. Details of this model can be observed in [6].

(2) Constitutive model for high-cycle fatigue of supporting soil

The constitutive model for soil utilized in this study was conceptually developed by Towhata and Ishihara [16] and coupled with concrete into the integrated analysis by Soltani and Maekawa [13]. By using the theory of multi-yield surface plasticity modeling, soil is simply characterized as an assembly of finite numbers of elasto-perfectly plastic components [13]. The multi-yield surface modeling is actualized to collect the data from strains as input parameters and sum up the total stresses as output ones. Under the moving loads, nonlinear mechanics of soil consists of shear and volumetric fatigue. Volumetric strain can be divided into two components as dilatancy (positive) and contraction (negative). The dilatancy volumetric strain is also divided as negative dilation (unrecoverable strain) and positive one (recoverable strain).

These behaviors (shear and volumetric issues) of soil have been coupled in the code program used for analysis. Details of this model can be obtained in Fig.4 and in [9,13,17].

3. FATIGUE ANALYSIS OF CONTRUCTION JOINT EFECTS

This section shows the three-dimensional fatigue

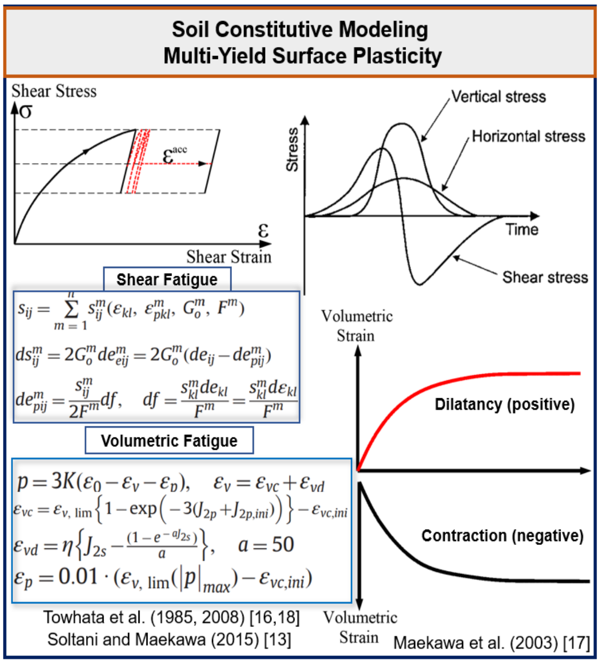

Fig.4 Constitutive modeling for supporting soil of concrete pavement

simulation to compare the fatigue life of concrete pavement under the moving load in case of no existence or failure for supporting of dowel bars at transverse joint and continuously reinforced concrete. The sensitivity of model is also investigated the mechanism focused on the thickness and reinforcement ratios of concrete slab as well as the relative density of soil.

3.1 Analysis model for soil and concrete slab interaction

Model used for simulation of construction joint effects in concrete pavement is presented in Fig.5. The half-domain of concrete pavement is applied by using the X-coordinate as the symmetric axis. The plane dimension of concrete slab is 8000mm (length) + 20mm (construction joint) + 8000mm (length), and 3000mm (width). The thickness is changed as 120mm, 150mm, 180mm, 200mm and 250mm. The reinforcement ratio (RR) is 1.0% and 0.1%. The plane dimension of soil is 20000mm x 3000mm x 2000mm as length, width and depth, respectively. The relative density (RD) of soil is 50% (loose supporting foundation) and 75% (dense one).

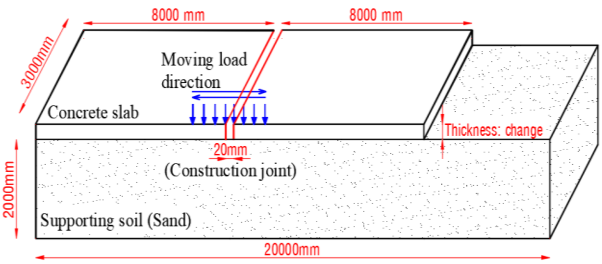

Fig.5 Simulation model for investigation of construction-joint effects to fatigue life

The cyclic moving load 16tf is applied between two concrete pavement slabs. Due to the fact that this coupled code program has been applied the binary increasing magnification with each passage along the slab axis [6], 60 time-steps are conducted in one single pass and around 2,000 time-steps for the entire path of simulation. The multi-frontal direct linear sparse matrix solution in FEM is also applied. The drying shrinkage has been automatically reproduced owing to the development of the thermo-hydro action in order that it can equilibrate with ambient relative humidity 60% and temperature 20^{0}C.

To fully investigate the impacts of construction joints to the fatigue life of model, continuously reinforced concrete has been also simulated. The properties of concrete slab and soil are similar to the jointed concrete slab.

3.2 Computation for fatigue life of jointed and continuously reinforced concrete

Fig.6 illustrates the comparison of fatigue life between the continuous and jointed concrete pavement in the event of reinforcement ratio 1.0% (equivalent to 471 kg/m^3, 376 kg/m^3, 339 kg/m^3, 282 kg/m^3 and 226 kg/m^3 of thickness 250mm, 200mm, 180mm, 150mm, and 120mm, respectively), and relative density of soil 50% and 75%, respectively.

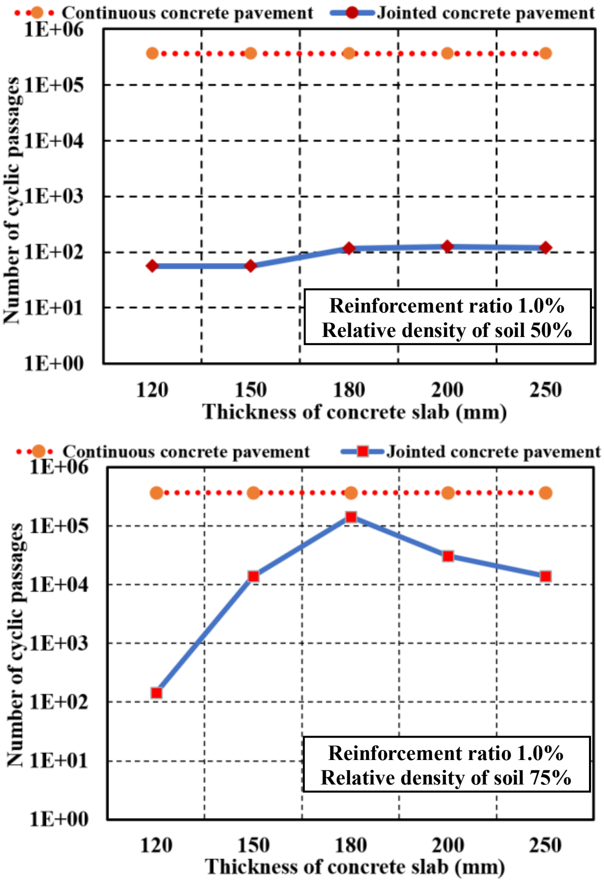

Fig.6 The comparison of fatigue life between continuous and jointed concrete pavement (RR 1.0%)

As can be seen in Fig.6, the fatigue life of jointed concrete pavement is dramatically reduced compared to continuous one. It is pointed out that the fatigue life of continuous concrete pavement is similar to all cases irrespective of thickness or the status of soil foundations (RD 50% or 75%). On the contrary, in the case of RD 50% of jointed concrete pavement, there is less difference of the fatigue life from thickness 120mm to 250 mm. Meanwhile, there exists a distinction of fatigue life of jointed concrete pavement if relative density of soil is 75%. The underneath soil is a key determinant to support the life-cycle of concrete pavement.

One critical and interesting thing is the fact that under the dense supporting foundation (RD 75%) and strong concrete slab (reinforcement ratio 1.0%), the longest fatigue life of jointed concrete of pavement is the one of thickness 180mm. It can be explained by the observation of the failure mode as shown in Fig.7. In the event of thickness 180mm of jointed concrete pavement, the shear band of soil becomes more dispersed and the drastic damage of concrete occurred at two edges of concrete slab concurrently. Meanwhile, the other cases showed the severely localized damage of soil and the deterioration of concrete only took place at one slab. It is clearly necessary to design the rational thickness for jointed concrete slab under the dense supporting soil. Large thickness (200mm or 250mm) or thin one (120mm) is not the optimized method in design. This is a discussing point of future study.

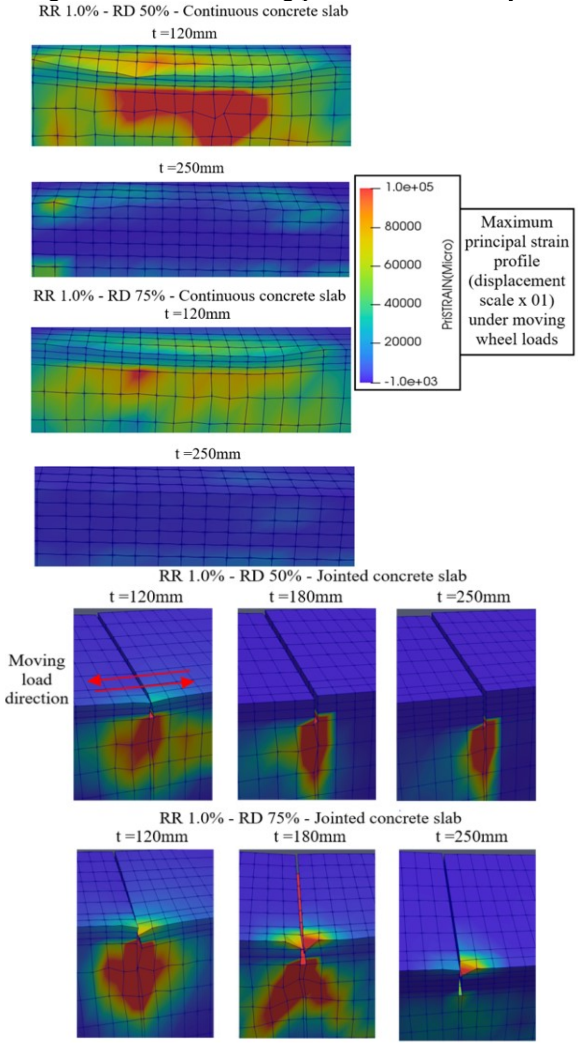

Fig.7 The comparison of failure mode between continuous and jointed concrete pavement (RR 1.0%)

The effect of loose soil (RD 50%) demonstrates that the fatigue life of jointed concrete pavement may not be supported by the thickness or reinforcement ratio of concrete slab. The shear failure of soil plays an important role to reduce the fatigue life as clearly seen in the differences of elevation in between two concrete slabs under the moving load. There is no damage of concrete slabs, even in the case of thin slab (120mm).

By investigating the typical failure modes of some cases as shown in Fig.7, the most critical position of concrete slabs can be defined as the edges between the transverse joints where the shear failure of soil as well as the deterioration of concrete slabs are localized.

To check the effects of reinforcement ratio, a light one 0.1% (equivalent to 47.1 kg/m^3, 37.6 kg/m^3, 33.9 kg/m^3, 28.2 kg/m^3 and 22.6 kg/m^3 of thickness 250mm, 200mm, 180mm, 150mm, and 120mm, respectively) was applied to compare with 1.0%. As shown in Fig.8, in the case of RD 50% of soil, there is less different in the fatigue life of jointed concrete pavement (RR 0.1% compared to 1.0%), especially in the thick slabs (200mm or 250mm). There is clear diversity in fatigue life if supporting soil for jointed concrete slab is the dense one (75%), because reinforcement ratio shows its influence on the dense soil of concrete pavement by the significant decrease of fatigue life in the event of RR 0.1% compared to RR 1.0%.

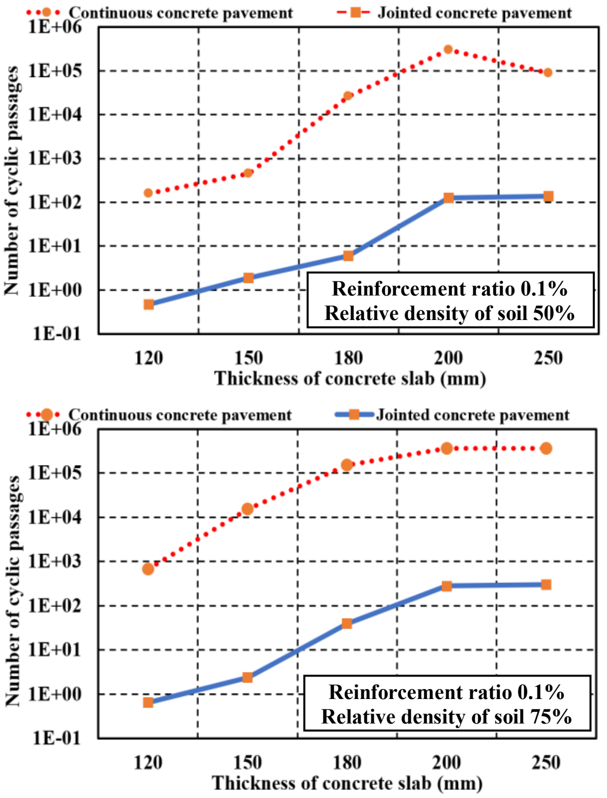

Fig.8 The comparison of fatigue life between continuous and jointed concrete pavement (RR 0.1%)

In view of the design, under the moving load, the fatigue life of jointed concrete cannot be supported if the loose soil is applied irrespective of RR 1.0% or 0.1%, or even the thickness of concrete slab 200mm or 250mm. This is the fact that the damage of concrete slab and soil is localized nearby the edges of slabs between construction joints as shown in the failure mode. The lower reinforcement ratio 0.1% shows more severe damage than 1.0%.

On the contrary, soil foundations play a key role to increase in the fatigue life of continuous concrete pavement. If concrete slab is thin as 120mm, 150mm or 180mm, the assistance of soil to increase the service time is inconsiderable. But, in case the thick slabs (200mm or 250mm) and the dense soil applied, there is almost the same fatigue life of continuous concrete pavement RR 0.1% compared to RR 1.0%. The actual working condition of concrete pavement under the loose or dense soil with different reinforcement ratios or thickness of concrete slabs should be coupled in concrete pavement design and maintenance works.

Fig.9 depicts the comparison of the failure mode between the continuous and jointed concrete pavement in the event of reinforcement ratio 0.1%.

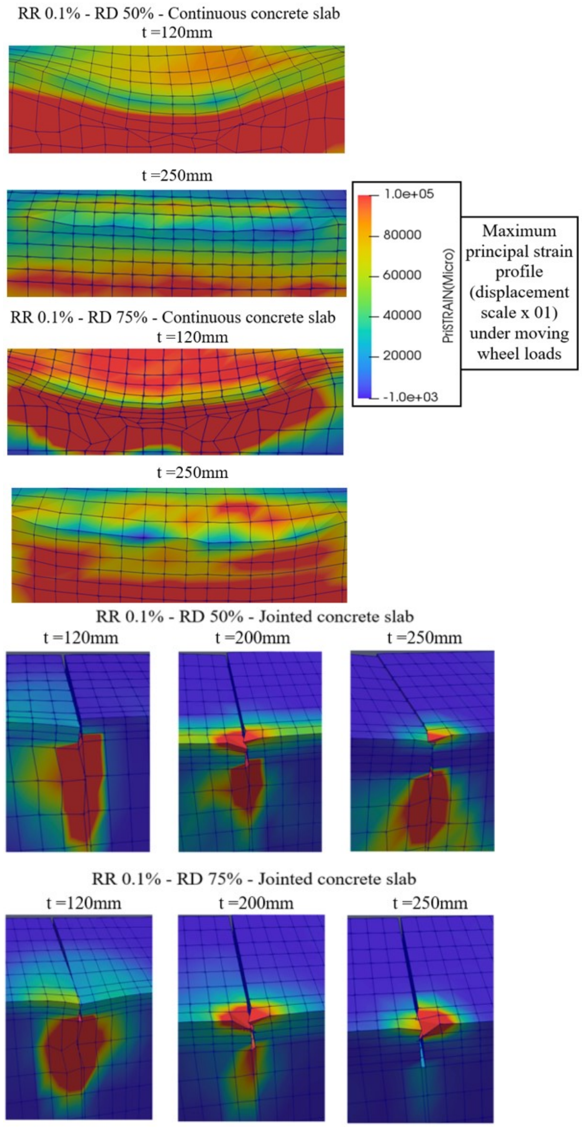

Fig.9 The comparison of failure mode between continuous and jointed concrete pavement (RR 0.1%)

It can be clearly seen that the failure modes of reinforcement ratio 0.1% for jointed concrete pavement are fairly close in all cases irrespective of soil conditions. This is also the coupling of localized damage of soil and concrete slab at the joint construction. The failure mode of continuous concrete shows the clear impacts of thickness by the critical deflection of concrete slab (thickness 120mm) compared to the thick one (thickness 250mm) as shown in Fig.9.

4. CONCLUSIONS

The effects of construction joint in transverse direction is computationally investigated by utilizing the three-dimensional high-cycle fatigue for coupling of soil and concrete slabs. The numerical analysis shows the drastic decrease in the fatigue life of jointed concrete pavement compared to continuous one, and the following conclusions are obtained.

(1) The existence of construction joints may cause the dramatic reduction of fatigue life due to the localized damage of soil and concrete slabs at the edges.
(2) Reinforcement ratio is computationally estimated to have a major effect to the fatigue life in both cases of jointed and continuous concrete pavement.
(3) Soil foundations may be a sufficient tool to support the fatigue life of jointed concrete pavements if dense soil and the rational thickness of concrete slab are examined concurrently. The failure of dowel bars to support the load transfer between the construction joints has been computationally investigated. It shows the primacy of continuously reinforced concrete compared to jointed one in the life-cycle assessment.

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