- Technical Paper -

EFFECT OF SOIL DENSITY ON WATER COUPLED CRACKS FOR LIFE PERFORMANCE OF CONCRETE PAVEMENT UNDER MOVING LOAD

Hung H. Q. NGUYEN*1 and Koichi MAEKAWA*2

ABSTRACT

The three-dimensional nonlinear simulation is implemented based on the coupled code of constitutive laws for multi-directional cracked concrete, multi-yield surface plasticity modeling for soil, and multi-phase modeling for pore water inside concrete to examine the reduction in life of the concrete pavement. The FEM analyses are also emphasized on the supportive capacity of the dense/very dense compaction of soil for life-cycle assessment of the pavement when stagnant water resides at the top surface of 10cm of the slab. Other positions of condensed water show the less impact of soil density.

Keywords: concrete pavement, fatigue life, high cycle, moving load, pore water pressure

1. INTRODUCTION

The design of concrete pavements is mechanically coupled between concrete slabs and soil foundations to provide the safe and long-term service for highways and airfields. The basic theory for this design was originally developed based on the linear beams/plates on the Winkler foundation by Westergaard [1]. Another point is the loading type in the existing studies. The life-cycle assessment for the concrete pavement is currently conducted based on the fixed-point pulsating loadings in laboratories and the existing design codes [2]. However, the traffic vehicles in reality are the repetitive loadings in motion and theirs cannot be represented by the fixed-point one [2]. Maeda and Matsui presented the reduction in life of the reinforcement concrete (RC) slabs on bridges under the moving load compared to the fixed-point one by implementing the moving wheel load experiments [3,4]. Maekawa et al. proposed the constitutive models and investigated the decrease in fatigue life of RC bridge slabs under moving loads by using the three-dimensional high cycle fatigue simulation [5]. As can be seen in Fig. 1, the damage of the concrete slab is only localized near the loading point under the fixed-point load. Conversely, the distributed deterioration of the concrete slab can be observed along the moving wheel load. It is due to that the reversed cyclic shear is produced along cracks and multi-directional cracking is introduced. They become an accelerated factor of the concrete damage over the slabs [6]. These models have been extended to consider the effects of ambient environments for life-cycle assessment of concrete slab decks.

In the consideration of fatigue life for concrete pavements, the behavior of integrated nonlinear soil and concrete slabs is approached. Most of the works have tackled a simplified elastic foundation on which pavement is modeled as an elastic and homogeneous space of beams or plates. This principle design associated with the concentrated load cause the localized damage of soil only as shown in Fig. 1. It cannot be applied to the reality due to the difference of the failure mode and loading types. Nguyen et al. have coupled the high cycle fatigue of soil and concrete slabs based on the small-scale mock-ups [2]. Under the nonlinear theory of high cycle as 10^3 poly-cyclic loading, the failure of soil can take place on both shear and volumetric fatigue [2]. The damage of soil under the moving load is more severe and distributed along the moving wheel compared to the fixed-point one as shown in Fig. 1. By focusing on the constitutive models for the nonlinear soil integrated concrete slabs, the fatigue life of concrete pavements shows the dramatic reduction under the moving loads.

Another point is the effects of the ambient conditions. Fatigue life of concrete pavements as well as the bridge slabs can be significantly reduced if the water is stagnant at the top surface of the slab. Maekawa and Fujiyama [6] and Nguyen et al. [7] illustrate the close relations of the deformation and condensed water inside concrete cracks and these behaviors have been integrated with crack-water interaction by Biot's multi-phase theory. Figure 1 shows the multi-scale chemo-physical platform to simulate the nonlinear mechanics of concrete pavements under the moving loads coupled to the condensed water in crack spaces [6,7]. Under the moving loads, cracks may form and existing ones can propagate. When cracks close, the high-water pressure occurs inside cracks and it can rapidly accumulate the deterioration.

In this paper, the authors introduce the three-dimensional high cycle fatigue analysis to investigate the effects of the condensed water with a mass of soil density, i.e loose, dense and very dense compaction by incorporating the constitutive models of nonlinear soil and concrete slab coupled to the multi-scale modeling for pore water inside cracks.

---

*1 Ph.D. Candidate, Graduate School of Urban Innovation, Yokohama National University, JCI Student Member
*2 Professor, Faculty of Urban Innovation, Yokohama National University, Dr. E., JCI Member

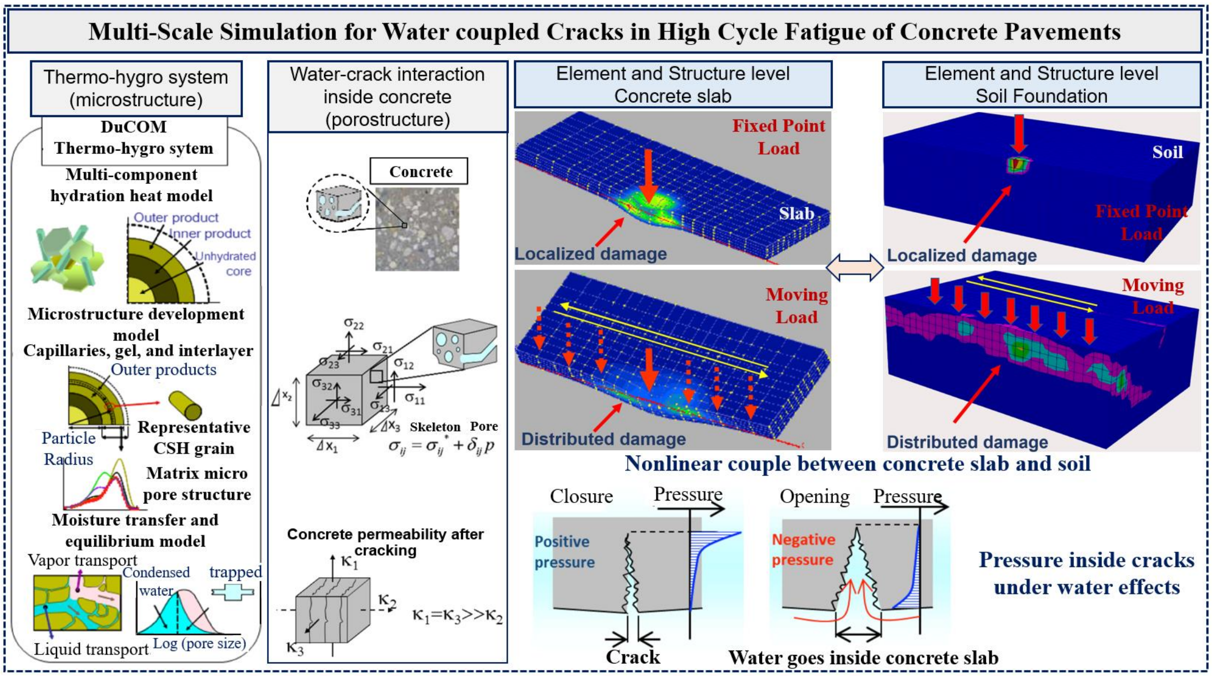


Fig. 1 Muti-scheme simulation of water coupled crack in concrete pavements [6],[7]

2. CONSTITUTIVE LAWS OF CONCRETE STRUCTURES, SOIL AND PORE WATER INSIDE CRACKS

To simulate the behaviors of concrete pavement in the case of dry and wet concrete slab, the integrated multi-scale, multi-chemo-physical analysis of soil and concrete slab has been developed. This coupled code has been validated by experiments of each scale, i.e., the high cycle fatigue of RC slab decks [5], the shear band of the soil [8], and the motion of water in cracked concrete [6]. Referring to the study of the nonlinear behavior of soil under high cyclic loading by Witchmann et al., the small-scale mock-ups under wheel-type moving loads were implemented to clarify the high cycle interaction of soil and concrete slab [2].

2.1 Small-Scale mock-up under wheel-type moving loads

The authors have conducted the small-scale experiments to investigate the mechanism of the soil and concrete slab interaction under the high cycle fatigue subjected to the wheel moving load. The selection for the testing dimension depended on the specifications of the wheel load testing equipment and the size effects for the soil and concrete slabs. The concrete slab was 300x150mm in plane and thickness of 20mm and 50mm. The water to cement ratio of the slab was 55%. Soil was Ohigawa river sand contained in a formwork of 300x360mm in plane and 200mm in depth having a plastic transparent side to seize the shear band of soil. The relative density of soil was 50% and 75%. The wheel type loads were 513N and 1,029N and applied at the slab center along the longitudinal direction. The speed of the moving wheel was 21 round trips per minute until 75,220 cycles of the capacity of testing facilities. The three-dimensional FEM analyses were implemented. The computed displacement and failure mode are fairly close to the experimental results. Details of these experiments can be referred in [2].

2.2 Water-crack interaction in concrete slab

The nonlinear analysis code for the impacts of water on concrete slab was coupled by Maekawa and Fujiyama [6] based on the experiment of RC slab decks submerged in water under the moving wheel load by Matsui [4]. The authors also utilize this nonlinear code for the evaluation of fatigue life of the concrete slab on the nonlinear soil foundation in this study.

2.3 Constitutive laws for concrete, soil and pore water in cracks

(1) High cycle fatigue of concrete

The constitutive model for high cycle fatigue of cracked concrete was proposed by Maekawa et al. [5] by incorporating one-dimensional stress-strain into 3D spaced-averaged constitutive model consisting of compression, tension and shear transfer along crack planes. Each constituent model is time-strain path-dependent. Maekawa et al. have 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. The tension and shear models have been also enhanced the cumulative damage. In this study, the high cycle fatigue for concrete has been incorporated in the verified code. Details of this model can be referred in [2], [5].

(2) High cycle fatigue of soil

The multi-yield surface plasticity modeling is approached to reproduce the shear failure of the soil foundation. This constitutive model was originally developed by Towhata and Ishihara [9] and integrated with the nonlinear analysis of concrete structures by

Soltani and Maekawa [8]. Under the high cycle moving load, nonlinear behavior of soil exhibits the shear and volumetric fatigue. The volumetric fatigue strain consists of dilatancy and contraction. The multi-yield plasticity modeling has been incorporated in the coupled code utilized in analysis of this study. Details of this model can be referred in [2],[8].

(3) Pore water inside concrete

The intimate relation of the condensed water inside concrete and the deformation has been observed by Maekawa and Fujiyama based on Biot's multi-phase model for the liquid-solid composites from nano-scale 10^{-9}m to 10^{-3}m [6]. Concrete is assumed as two-phase composites as skeleton and pore water. The total density of saturated concrete can be determined based on those. It is noted that there are two trends of water in nano-scales of concrete material as isotropic manner in pre-cracking and anisotropy in post-cracking owing to the orientation of cracks [6]. Under the moving loads, cracks can open and close consequently [6]. When cracks close with water, the water pressure rises. It can cause phase change as vaporization when opening. Therefore, the damage of cracks can be accelerated. This model has been integrated in the coupled code with soil and concrete slab to investigate the impact of the condensed water on life-cycle assessment of concrete pavements. Detail of this model can be referred in [6],[7].

3. FATIGUE ANALYSIS OF CONCRETE PAVEMENT UNDER CONDENSED WATER EFFECTS

This section demonstrates the three-dimensional FEM analysis to investigate the fatigue life of concrete pavement under the effects of the condensed water. The sensitivity of model is focused on the support of soil density to the life-cycle assessment. This study has never been verified and validated previously owing to the complexity of integrating soil into the composite system.

3.1 FEM analysis model

The finite element discretization of full-scale behavioral simulation for water-crack interaction is shown in Fig. 2. The half-domain of concrete pavement with X-direction (the moving load direction) is applied as a symmetric axis. The plane dimension of the concrete slab is 3000x4000mm and 250mm thickness. The soil foundation dimension is 3000x8000mm in plane and 2000mm in depth. The cyclic moving load of 156kN is produced by applying nodal forces at the symmetric axis. The concrete slab consists of five layers of 50mm. Water to cement ratio of the slab is W/C=55% (fine aggregate = 850 kg/m^3, coarse aggregate = 1000 kg/m^3, and entrained air = 4%). It is equivalent to the normal one in practices and concrete flexural strength is 4.1 MPa (or 600psi) which is recommended in Guideline of thickness design for concrete highway and street pavements of Portland Cement Association. The nonlinear mechanics of RC slab in this study is considered through a three-dimensional multi-directional smeared crack model which reinforcing bars may be reflected by the reinforcement ratios. The reinforcement ratio (pt) of the slab is 0.1% to depict the weakest case of the concrete slab (equivalent to 47.1 kg/m^3).

To cover a wide range of frictionally restrained interlayer condition, the erosion potential and the nonlinear interaction between the slab and soil foundation under stagnant water from the top to bottom slab integrated to the foundation, the most severe case is the unbonded interface condition utilized in the FEM analysis. The displacement normal to the side boundaries is restrained as plain strain. Soil foundation is sandy having the three typical density as the loose (RD=50% - sandy soil cohesion = 0MPa and internal friction $\phi=40^0$), dense (RD=75% - sandy soil cohesion = 0MPa and internal friction $\phi=45^0$), and very dense (RD=95% - sandy soil cohesion = 0MPa and internal friction $\phi=45^0$) compaction to examine how the soil density can support fatigue life if stagnant water resides in cracks. The properties of the soil foundation at each density are calculated based on the multi-yield surface plasticity modeling in which the tangential stiffness is the first input to determine the fatigue failure (shear and volumetric fatigue) under the repetitive loading.

In this paper, the effects of condensed water are investigated as the top layer of 5cm, 10cm, whole depth (25cm of the slab) as well as the fully dry slabs. The drying shrinkage has been automatically reproduced as the thermo-hygro action develops in order that it may equilibrate with ambient relative humidity of 60% and the temperature of 20^0C.

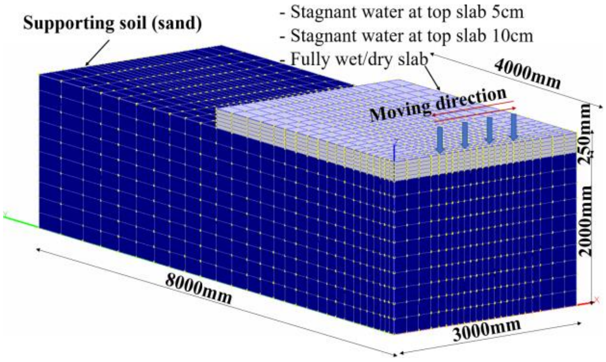


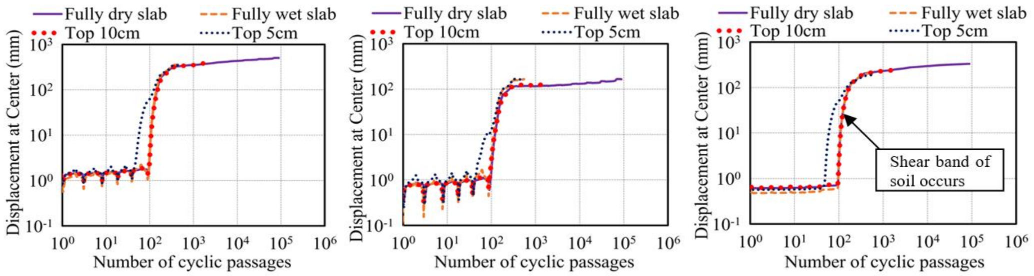
Fig. 2 The full-scale FEM analysis for water-crack interaction of concrete pavements

3.2 Fatigue life of concrete pavement with RD=50%

Figure 3 shows the fatigue life of concrete pavement with/without water effects with RD=50%. It can be seen that under the effects of condensed water, fatigue life (i.e. the fully wet case: 5.72×10^2 cyclic passages) is dramatically decreased compared to the case of the dry slab (8.81×10^4 cyclic passages). The displacement of the concrete pavement at the early stage significantly rises nearly equal to the final cycle of the dry case (Fig. 3 (a), (b) and (c)). The relation of the displacement at the center of the slab and the number of cyclic passages is divided into Fig. 3 (a), (b),

(c) for the purpose of determining the predominant fatigue failure of the slab and/or the soil foundation. The failure modes therefore depict the severe deterioration of the concrete slab. In case of the dry slab, the damage of the slab is not serious, and the fatigue failure focuses on the shear band of the soil. One critical point that the damage of the slab depended on the positions of stagnant water. If the water is stagnant at the top layer slab of 5cm, the severe damage may develop around this position. It is a similar trend to the existing of the condensed water at the top layer slab of 10cm, the damage is focused on the top slab only. This assumption is also observed in the case of the fully wet slab. The serious deterioration of the slab is mainly concentrated at the top slab as the case of condensed water at top layer slab of 5cm, 10cm. The bottom surface shows the less impact of the stagnant water. As a result, there is no decay of the slab at this position (see failure mode in Fig. 3). In the studies of water effects to the RC slab decks, Maekawa and Fujiyama showed that the rise of the pore pressure in cracked concrete under the moving loads just affects the wet-upper deck [6]. In case of the concrete pavement, the same characteristics is discovered.

It can be seen in Fig. 3 ((a),(b), and (c) – the number of cyclic passages (fatigue life) and displacement relation), when the stagnant water exists in the slab, the top layer of 10cm shows the longer fatigue life compared to other cases (the top layer of 5cm and the fully wet slab). The fatigue life of water effects at the top layer of 5cm and the fully wet slab is nearly identical. The water at the top layer of 5cm illustrates the faster progress of the displacement compared to the case of 10cm. The fatigue life is therefore reduced. We can say that the water effects at the locations near the top surface of the slab is more critical than further ones. As previously stated, cracks can open and close under the moving load and the water pressure will be repeatedly negative or positive. When cracks close, the high-water pressure appears and causes the increase in the internal stresses in micro-pores of concrete. Under the repetitive moving loads, the water pressure highly rises over a large number of passage and it results in increasing principal strains accompanying the erosion. The loose soil foundation (RD=50%) depicts the insufficient support to the fatigue life of the pavement when the condensed water exists in the cracked concrete.



(a) Total displacement of the slab and soil (b) Displacement of the slab only (c) Displacement of soil only

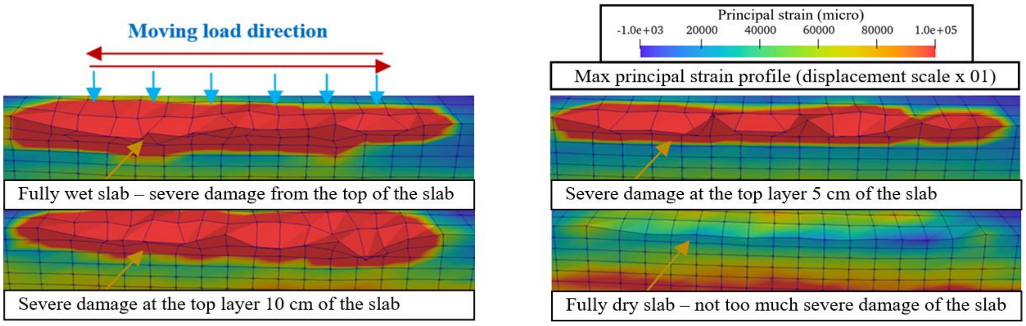
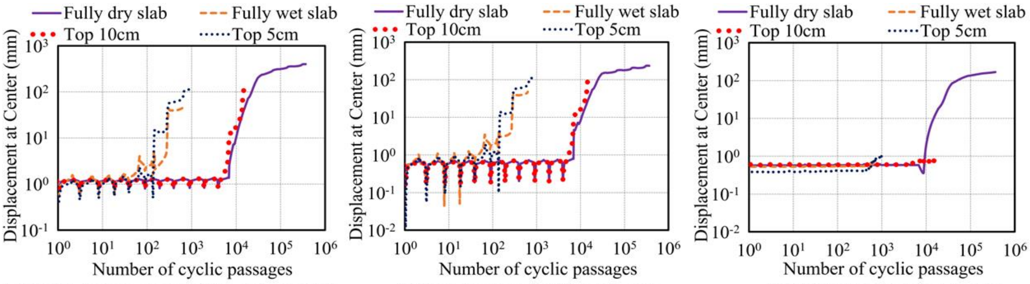


Fig. 3 Fatigue life and failure mode of concrete pavements under water effects with RD=50%

3.3 Fatigue life of concrete pavement with RD=75%

Figure 4 demonstrates the fatigue life of the pavement with/without water effects under RD=75%. As discussed in section 3.2, the top layer of 5cm and the fully wet slab are the most critical cases when the stagnant water exists. This assumption can be applied in the case of RD =75%. By comparing the fatigue life of concrete pavements in Fig. 3 and 4, it can be seen that fatigue life of the condensed water at the top layer of 5cm and fully wet slab in case of RD =75% is moderately similar to the case of RD=50%. But, irrespective of the serious damage of the slab and the similarity of fatigue life, the displacement of the slab with water at top layer 5cm or fully wet slab shows the lower value compared to the case of RD=50%. We can say that the dense foundation cannot upgrade fatigue life of the slab if the water at these positions. However, the extended fatigue life in the case of water at the top layer of 10cm or fully dry slab under RD=75% can be observed. The failure mode of the dry case is less severe than the case of stagnant water in the slab, and the damage is thus distributed under the moving load only. In case of the dry slab, the shear band of soil occurs, the fatigue failure is therefore the coupling of the soil and concrete slab damage. In the event of the condensed water at the top layer of 10cm, the displacement of the slab is nearly similar to the case of the dry slab. However, the slab damage is more critical, the failure mode is thus governed by the slab deterioration only. As the preceding section, due to the fast development of the principal strain caused by the rise of the pore water pressure, the damage of the slab is accelerated (the detail is discussed in section 3.5).



(a) Total displacement of the slab and soil (b) Displacement of the slab only (c) Displacement of soil only

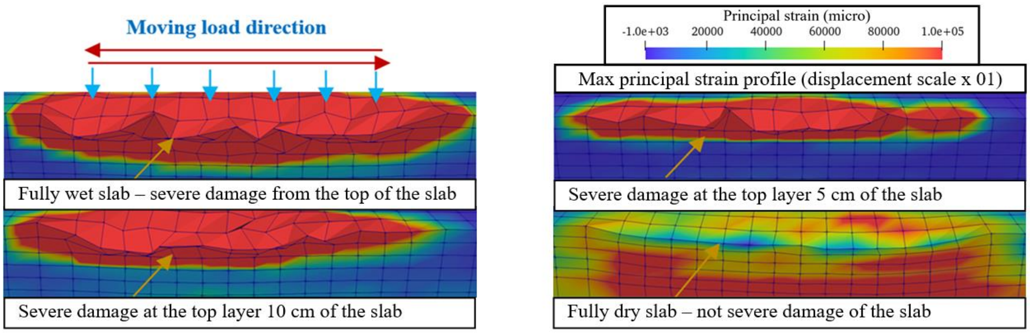


Fig. 4 Fatigue life and failure mode of concrete pavements under water effects with RD=75%

3.4 Fatigue life of concrete pavement with RD=95%

Figure 5 shows fatigue life of the pavements with/without water effects under RD=95%. It is interesting that due to the very dense compaction of the foundation, the shear band of soil will not occur both the dry and wet slabs. The failure mode is primarily governed by the fatigue damage of the slab. It is similar to the case of RD=50% and 75%, the damage of the slab is severe at the top surface of the slab under the condensed water impacts. As seen in Fig. 5, fatigue life of the case of water at the top layer of 5cm or fully wet slab is identical to the case of RD=50% and 75%. However, the displacements are obviously less critical. Another point is that owing to the very compacted soil (RD=95%), the sudden increase of the displacement in the dry case occurs at the later stage compared to the case of water at the top layer 10cm. The fatigue life and displacement of the case of water at the top layer of 10cm is similar to the case of RD=75%. Comparing to other cases, we can say that fatigue life of the pavement is dramatically enhanced if the stagnant water resides at the top layer of 10cm under the compacted soil (RD=75% and 95%). Furthermore, the bottom slab shows less influence in three cases of density no matter how the wet slab is. This computed simulation is consistent with the experiment of the RC slab decks [6].

3.5 Pore pressure and principal strain

Figure 6 depicts the pore pressure and concrete principal strain at the top layer of 5cm, 10cm, and fully wet slab to examine how the stagnant water affects the fatigue life of the pavement under RD=75%. We can see that the pore water pressure suddenly increases in case of condensed water at the top layer of 5cm and fully wet slab. Consequently, the principal strain also rises at the early stage, and the displacement of the concrete pavement is increased concurrently. The rise of the principal strain accompanies with the accelerated erosion due to the fast development of internal stresses in the concrete slab [6]. In case of the condensed water at the top layer of 10cm, the pore water pressure increases at the later stage and it causes the later rise of the principal strain. The fatigue life of the slab is therefore prolonged compared to the case of water at the top layer of 5cm or fully wet slab. Water kinetics in cracked concrete is thought to be the main reason to reduce fatigue life of the pavement under water.

4. CONCLUSIONS

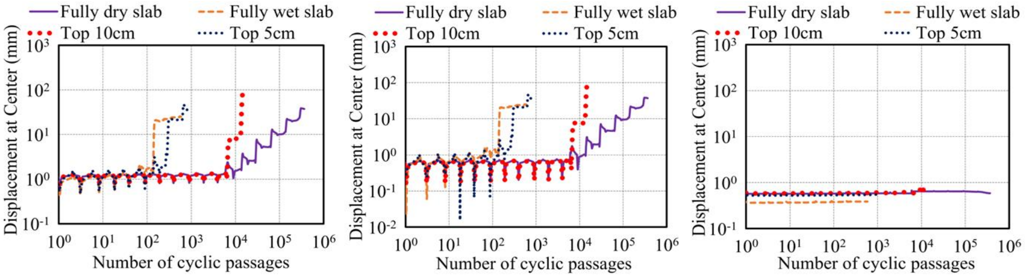
The effects of the stagnant water in cracked concrete are computationally concentrated in terms of the fatigue life of concrete pavement. The three-dimensional FEM analyses of nonlinear concrete slab, soil and pore water in cracks were integrated, and the following conclusions are earned as;

(1) The presence of the stagnant water in cracks of concrete slabs is computationally confirmed as a key factor to dramatically reduce the fatigue of the concrete pavement under moving loads.

(2) The pore pressure aggravated by the crack kinetics evolves in micro-pores in concrete. The history of the pore pressures and principal strain shows that the damage of concrete slabs is accelerated by the rise of the pore water pressure in crack gaps.

(3) Compared to other cases, the pore water pressure

gradually rises at the top surface slab of 10cm. Therefore, the dense and very compacted foundation solely have great support on the increase of the fatigue life for the concrete pavement if the condensed water resides at this position.



(a) Total displacement of the slab and soil (b) Displacement of the slab only (c) Displacement of soil only

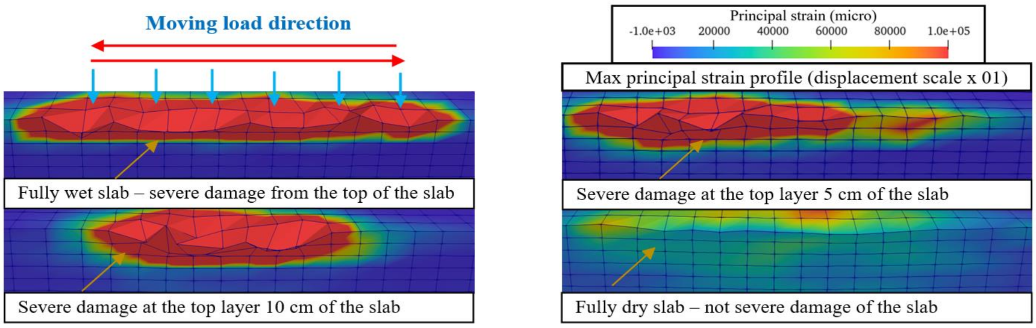


Fig. 5 Fatigue life and failure mode of concrete pavements under water effects with RD=95%

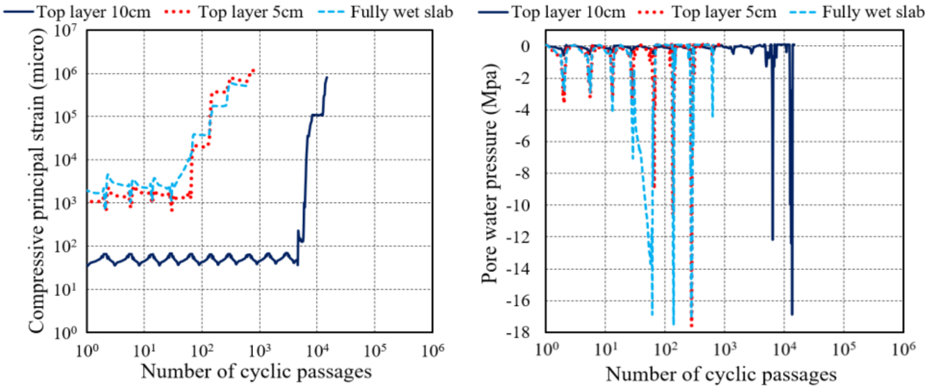


Fig. 6 Principal strain and pore water pressure of concrete slab at the top surface with RD=75%, pt=0.1%

REFERENCES

[1] Westergaard, H.M.,”Theory of Concrete Pavement Design,” Proceedings of Highway Research Board, 7 (Part 1), 1927, pp. 175–181.

[2] Nguyen, H.Q.H., Komatsu, S., and Maekawa, K.,”High-Cycle Fatigue Interaction between Soil Foundation and Concrete Slab under Moving Wheel-type Loads,” Engineering Structures,2019a. vol. 209, 109931.

[3] Maeda, Y. and Matsui, S.,”Fatigue of Reinforced Concrete Slabs under Trucking Wheel Load,” Proceedings of JCI, (6), 1984, pp. 221–224.

[4] Matsui, S.,”Fatigue Strength of RC-Slabs of Highway Bridge by Wheel Running Machine and Influence of Water on Fatigue,” Proceedings of JCI, (9(2)), 1987, pp. 627–632.

[5] Maekawa, K., Gebreyouhannes, E., Mishima, T., and An, X.,”Three-Dimensional Fatigue Simulation of RC Slabs under Traveling Wheel-Type Loads,” Journal of Advanced Concrete Technology, 4 (3), 2006, pp. 445–457.

[6] Maekawa, K. and Fujiyama, C.,”Rate-Dependent Model of Structural Concrete Incorporating Kinematics of Ambient Water Subjected to High-Cycle Loads,” Engineering Computations, 30(6), 2013, pp. 825–841.

[7] Nguyen, H.Q.H., Maekawa, K., and Komatsu, S.,”Effects of Water-Coupled Cracks on Life-Cycle Assessment of Concrete Pavement under Moving Load,” Proceedings of Airfield and Highway Pavements, ASCE, 2019b, pp. 110–121.

[8] Soltani, M. and Maekawa, K.,”Numerical Simulation of Progressive Shear Localization and Scale Effect in Cohesionless Soil Media,” International Journal of Non-Linear Mechanics, 69, 2015, pp. 1–13.

[9] Towhata, I. and Ishihara, K., ”Undrained Strength of Sand Undergoing Cyclic Rotation of Principal Stress Axis,” Soils and Foundations, 25(2), 1985, pp. 135–147.