Multi-Scale Simulation for Fatigue Life Evaluation of Concrete Pavement subjected to Moving Load under Dry and Wet Conditions

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Abstract

In view of the life-cycle assessment of concrete pavement, three-dimensional behavioral simulation was conducted by integrating constitutive laws for cracked/uncracked reinforced concrete, modeling of pore water inside cracks and multi-yield surface plasticity for soil to investigate the fatigue life under high-cycle moving loads. Presented is a discussion that the balanced pavement requires thicker slabs than those required by current design codes on medium compacted soil foundations, but for too much looser foundation, it is over-designed, conversely. Then, a new design approach is proposed in terms of the slab thickness by considering nonlinear coupling with soil foundation. When the stagnant water exists on the slab with cracks, the numerical analysis shows the excessive pore water pressure in cracks at the upper layers of the concrete pavement. The engineering experience is proved such that the deterioration of concrete slabs is accelerated by water and the fatigue life is dramatically shortened compared to the dry situation.

1. Introduction

Concrete pavements have been increasingly utilized in highways and airfields around the world due to the primacy of life-cycle service and the load capacity. The fundamentals of design were developed based on the thin plate theory on the Winkler foundation (Westergaard 1927, 1933, 1947). Concrete slabs were considered as beams or plates on the elastic, isotropic and homogeneous supporting soil (Beskou and Theodorakopoulos 2011; Patil et al. 2013; Bing Sii 2014). Hence, the studies of concrete pavements are the concurrent interaction between concrete slabs and underneath soil foundations to ensure the smoothness and safety conditions for traffic as well as the time and cost saving in maintenance and construction work.

The fatigue life assessment of pavements is a key issue for maintenance as well as bridge slab decks. The service life was experimentally investigated by applying the fixed-point pulsating loads in laboratories. Meanwhile, traffic vehicles’ action of the reality is the repetitive loads in motion and it can not be represented by the fixed-point one. Maeda and Matsui (1984) demonstrated the significant reduction of fatigue life of concrete bridge decks under moving loads compared to the fixed-point by implementing the experiment of the wheel-type moving loads. Here, the reversed cyclic shear is produced along cracks and multi-directional cracking is introduced. They become a driving factor to accumulate the fatigue damage over the slabs (Maekawa et al. 2015). As can be seen in Fig. 1, the damage of the concrete slab under fixed-point load is just localized near the loading position.

On the contrary, under wheel traffic, this deterioration is dramatically distributed along the wheel paths. Maekawa et al. (2006) proposed the constitutive models and examined the decrease in fatigue life under moving loads by utilizing three-dimensional high-cycle fatigue simulation of reinforced concrete (RC). These constitutive models trace the transient damaging process by the direct path-integral scheme.

As previously stated, concrete pavement’s behavior is associated with an integrated nonlinearity of concrete and soil. Most of the works has adopted a simplified elastic foundation on which pavement is modeled as an elastic and homogeneous space of beams/plates (Mathews 1958; Kukreti et al. 1992; Kononov and Wolfert 2000; Lambaert et al. 2000; Huang and Thambiratnam 2001, 2002; Sun 2006; Steenbergen and Metrikine 2007) or half-space/plane layers (Eason 1965; Jones et al. 1998; Hung and Yang 2001; Krylov 2001; Rasmussen et al. 2001; Lin and Shen 2005; Ju 2009; Cao et al. 2010).

Nonlinear mechanics of soil consists of elastoplasticity. Wichtmann et al. (2009, 2010, 2016) challenged with the nonlinear theory of fatigue more than 10³ poly-cyclic loading. At the lower stress level, the failure mode of foundation may be attained through the quasi-elasticity, and the plasticity at the higher stresses is applied near failure (Lade 2005). Similar to the RC slab decks, the typical deterioration of concrete pavements is also distributed along the transverse or longitudinal direction of the slab in practice as shown in Fig. 1. Moreover, dowel bars of jointed concrete pavements can be broken when the joint sealant is damaged. The sup-
port of the dowel bar for the load transfer under the wheel loading is therefore dramatically reduced. In the event the soil foundation, the shear band zone under the concrete slab is challenging to observe details in practice. Hence, one pattern of soil-concrete interaction referred to the past experiment is selected to depict facts of the shear failure of the soil foundation in practice. First of all, in this study, a rational design for the pavement’s thickness is proposed based on the nonlinear soil-concrete interaction verified by small-scale mock-ups under the wheel-type loading. This is a starting point for the large-scale experiment in the future of the practical pavement design.

The ambient condition has a huge impact to the fatigue life of concrete pavements, too. If they are maintained under the freezing temperature, they are much degraded compared to the dry case (Gilkey 1926; Matsushita and Onoue 2006). The impact of water on the life of RC slab decks leads to the sharp decrease (Matsui 1987) as well. In engineering practice, water on the top surface of concrete slabs comes from the rain fall, and it can easily ingress and be stagnant in cracks if waterproof works would not be satisfied. Maekawa and Fujiyama (2013), Maekawa et al. (2015) and Nguyen et al. (2019a) depicted the intimate relations of the deformation and stagnant water inside concrete slabs and these behaviors have been integrated with crack-water interaction by Biot’s multi-phase theory (1941, 1955).

The stagnant water inside concrete migrates through solid-concrete skeletons and may activate pore pressure. Figure 1 illustrates the water kinetics in multi-scale chemo-physical platform to simulate the nonlinear mechanics of concrete slabs under moving loads (compression, tension, and shear transfer), and coupled with the stagnant water in crack spaces (Maekawa and Fujiyama 2013; Nguyen et al. 2019a). The damage of concrete slabs with water can be seen by examining the water pressure inside concrete. When cracks close, high pressure occurs inside cracks, and it can cause the internal force around cracks followed by further crack propagation (Shinmura and Sadowski 1997; Maekawa and Fujiyama 2013).

Then, as a second matter of this paper, three-dimensional fatigue analysis under moving loads is conducted to investigate the effects of stagnant water. The stagnant water in cracks is an exigent study to...
evaluate how the fatigue life is reduced. By incorporating the constitutive models of concrete and soil coupled with the multi-scale modeling for pore water inside cracks, the fatigue life of pavement system may be estimated, and it shows the dramatically shortened fatigue life.

2. Interaction of concrete pavement and soil foundation

2.1 Numerical code

For behavioral simulation of concrete pavement with/without stagnant water and cracks, the authors integrated these issues in multi-scale, multi-chemo-physical analysis of combined soil and concrete, which consists of cement hydration, micropore structure formation, and mass transport in concrete from nano to micro-meter, and mesoscale to deal with structural concrete from millimeter to meter scales (Maekawa et al. 2015). The meso-scale model of stagnant water inside concrete cracks has been coupled as well (Maekawa and Fujiyama 2013). This program has been developed and validated by experiments of each scale, i.e., the high-cycle fatigue for concrete slab decks (Maekawa et al. 2006), the shear band of the soil foundation (Soltani and Maekawa 2015) and the water transport in cracks (Maekawa and Fujiyama 2013). The nonlinear deformation of soil was also observed under the high-cyclic loading (Wichtmann et al. 2009, 2010, 2016) and modeled by elasto-plasticity.

Having these results, we propose a structural modeling for concrete slab on soil foundation under the wheel track loading. Firstly, the fatigue life and failure mode of concrete slabs and soil foundations are focused on by implementing small-scale experiments. Secondly, the behavior of water coupled cracks in RC slabs is discussed in the case of submerged slabs. Then, we try to propose the improved way to rationally decide the thickness of concrete pavement.

2.2 Small-scale mock-up under wheel running loads

The authors conducted two types of small-scale mock-ups for validation of computational codes, focusing on both soil’s shear failure and damage of concrete slabs. To computationally capture the shear failure of soil, its loose compaction is privileged. It is also the unfavorable case of pavement in reality. The relative density of soil was set up 50% in the experiment. The thickness is a key determinant for slab deterioration. If the thick concrete slab of normal strength is coupled with soil foundation under moving loads, the failure primarily attributes to the localized shear of soil. In contrast, the severe damage may occur in the case of thin slabs on medium compacted soil. Then, two thicknesses of concrete slabs were selected in small-scale experiments of 50 mm and 20 mm as shown in Fig. 2 (Nguyen et al. 2019b).

The concrete slab for validation of the simulation code was 300 × 150 mm in plane and the thickness was 20 mm and 50 mm, respectively. The track length 150 mm of the moving wheel was applied along the center of the slab. The speed was kept constant at 21 round trips per minute during experiments until 75 220 cycles owing to the capacity and specification of the wheel load testing equipment. The rolling wheel load in both cases was 1029 N. The load was first applied at the slab center to balance during the passage of traveling wheel. The mix proportion of concrete used are shown in Fig. 2. Soil foundation was made by sand from Ohigawa river and contained in a formwork which has three steel sides and the rest is a plastics to observe the shear band. To avoid the warping of the form under the compaction, two steel bars were placed in front of the plastic side. We had the same dimension of the soil container of 300 × 360 mm in plane and 200 mm in depth.

Three-dimensional numerical analyses were carried out as shown in Fig. 2. The small thickness of the concrete slab was aimed to seize the concrete failure. However, after finishing 75 220 cycles, the slab of 20 mm did not fail. Then, one load level of 98 N was further applied. As a result, the slab was fully damaged just after some cycles as shown in Fig. 2a. As the plain concrete slab was utilized, cracking is critical no matter where it comes. Figure 2a shows the comparison of the computed displacement and failure mode with experimental ones. It can be seen from the numerical simulation that when the load level increased 98 N, the bending tension at the bottom side of concrete slabs gets severe and causes cracking. It is clearly seen that the computed failure mode and displacement are fairly close to the experimental results.

Figures 2b and 2c indicate the shear deformation and the displacement (50 mm thickness). As mentioned above, the thick concrete slab can cause the severe damage of soil, and it is experimentally confirmed. The localized shear of soil significantly developed beneath the slab with similarity of the behavioral simulation. The computed displacement at the slab center is fairly close to the experiment.

These two experiments show the critical cases of pavement on the loose soil foundation. The failure mode and the displacement have been examined as imperative factors to assess the fatigue life. The simulation is consistent with the experiment. Thus, this program code may be applied to investigate the fatigue life of the pavement system. The experiments are reported in detail (Nguyen et al. 2019b).

2.3 Impact of water on concrete slab

Matsui (1987) tested the RC slab deck of 2000 mm × 3000 mm in plane and 190 mm thickness. The deck was supported vertically along one longitudinal and two transverse edges. The moving wheel load of 80 kN was applied at the center of the deck. The speed of the rolling wheel was 7.7 km/h. The track length of the moving load was 2000 mm. The water was supplied from the
top of the deck and pooled on it. It was reported that the existence of water causes tremendous decrease (1/200th of the dry state) in fatigue life. Maekawa and Fujiyama (2013) and Maekawa et al. (2015) utilized the coupled simulation code with the constitutive laws of cracked concrete and concrete-water interaction. The computationally derived S-N diagram for RC deck was fairly close to the reality. Then, the authors also use this nonlinear analysis coded by COM3 for the life assessment of concrete pavement on the nonlinear soil foundation.

3. Numerical Analysis

3.1 High cycle fatigue of structural concrete

The fundamentals for high-cycle fatigue of concrete in the simulation system were developed with regard to the constitutive models for cracked concrete (Maekawa et al. 2006). As illustrated in Fig. 3, the life-simulation starts from the cement hydration. The CSH hydrates are evolved and micro pore structures are formed and expressed by means of statistical density functions in terms of the size of pores. The thermodynamic equilib-

Fig. 2 Small-scale experiments for concrete slab and soil foundation: (a) slab thickness = 20 mm and (b), (c) concrete slab thickness = 50 cm (Nguyen et al. 2019b).
rium is satisfied with regard to the moisture transport in micropores as well as cracks in accordance with the pore water pressure gradient. The mechanical interaction of concrete solid skeleton and pore pressure is calculated over the pore size from $10^{-6}$ m to $10^{-3}$ m. This calculation scheme is upscaled to the macro-structural level expressed by the constitutive model of cracked concrete consisting of compressive kinetic, tension and shear transfer along crack planes.

One dimensional stress-strain relations are incorporated into the 3D spaced-averaged constitutive model. Each constituent model as shown in Fig. 3 is time-strain-path dependent. Concrete in compression undergoes the progressive plasticity and gradual loss of its elastic stiffness as damaging (Maekawa and Fujiyama 2013). Then, the elasto-plastic and fracture concept was explicitly applied (Maekawa and El-Kashif 2004; Maekawa et al. 2006). The total stress denoted by $\varepsilon$ in compression is a sum of plastic $\varepsilon_p$ and elastic strain $\varepsilon_e$ strains as,

$$\varepsilon = \varepsilon_e + \varepsilon_p \quad (1)$$

The compressive stress is associated with the elastic strain and fracture parameter $K_c$ as,

$$\sigma = E_0 \varepsilon_e K_c \quad (2)$$

where $E_0$ is initial stiffness of concrete.

For considering time-dependent plasticity, fracturing and cyclic fatigue damage, we install the fracture parameter $K_c$ by the full differential form as,

$$dK_c = \left( \frac{\partial K_c}{\partial t} \right) dt + \left( \frac{\partial K_c}{\partial \varepsilon_e} \right) d\varepsilon_e \quad (3)$$

Thus, we have the cyclic fatigue damage for compression as,

$$\frac{\partial K_c}{\partial \varepsilon_e} = \lambda \text{ when } F_k < 0 \quad (4)$$

$$\frac{\partial K_c}{\partial \varepsilon_e} = -\left( \frac{\partial F_k}{\partial \varepsilon_e} \right) \left( \frac{\partial F_k}{\partial K} \right) + \lambda \text{ when } F_k = 0 \quad (5)$$

where $F_k$ is damage potential formulated for unconfined normal strength concrete. The fracture degradation rate $\lambda$ represents the impact of elastic strain and we have,

$$\lambda = \frac{K^0}{2} \left( 1 - K^0 \right)^{g-R} \quad (6)$$

where $g$ is the damage parameter chiefly to represent the lower stress paths, and $R$ to cover the higher one.

The tension model is also expressed by $\varepsilon$ and $\sigma$ (Gong and Maekawa 2018) and the tension strain also consists of the elastic strain $\varepsilon_e$ and the fracture parameter $K_T$ as,

$$\sigma = E_0 \varepsilon_e K_T \quad (7)$$

where $K_T$ indicates the decreasing tension stiffness related to bond fatigue, and we have,

$$dK_T = Fdt + Gd\varepsilon + Hd\varepsilon \quad (8)$$

where $F$ is the rate factor, $G$ is a function for idealizing cyclic fatigue damage, and $H$ is a function for instantaneous evolution of tension fracture.

We apply the the contact density model (Li et al. 1987, 1989) for crack shear. Under the cyclic shear along a crack plane, aggregate interlock is gradually

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**Fig. 3 Constitutive models for concrete** (Maekawa and Fujiyama 2013; Gong and Maekawa 2018).
degraded (Maekawa and Fujiyama 2013). The relation of the shear stress and the relative displacement of crack planes is denoted by,
\[
\tau = \int R_c(\omega, \delta, \theta) \sin \theta \, d\theta
\]
where \( \theta \) is the orientation of the minimal contact unit of which the rough crack consists, \( R_c \) is the interlocking force acting on the contact plane \( \theta \), and \( (\delta, \omega) \) are the shear slip and the width. The accumulated path function \( X \) is added to the contact density model as above to depict the reduction of transferred shear associated with cyclic fatigue damage as,
\[
\tau = X \tau_{\text{cr}}(\delta, \omega)
\]
\[
X = 1 - \frac{1}{10} \log_{10} \left[ 1 + \int \| \delta / \omega \| \right] \geq 0.1
\]
where \( \tau \) is the transferred shear stress, \( \tau_{\text{cr}} \) is original stress computed by contact density model.

3.2 High cycle fatigue of soil
In this study, the multi-yield surface plasticity modeling is applied to reproduce the shear failure of foundation. The constitutive model used for soil was conceptually proposed and codified by Towhata and Ishihara (1985a, 1985b, 2008) and Gutierrez et al. (2011). Afterwards, it was incorporated in the simulation platform with structural concrete (Soltani and Maekawa 2015). Soil is assumed as an assembly of finite numbers of elasto-plastic components. Under the high-cyclic moving loads, nonlinearity exhibits shear and volumetric modes. The volumetric fatigue strain compri3ses both the dilatancy and contraction. The dilatancy provoked by shear is further divided into recoverable and unrecoverable strains. Both modes of soil are verified and integrated with constitutive models for concrete in the programed code. The multi-yield plasticity modeling for soil underneath concrete pavements is summarized in Fig. 4.

The tangential stiffness \( (D_i) \) is calculated from the shear stress \( (\tau_i) \) and shear strain \( (\gamma_i) \) relation. As each component has its own sub-strength, all components will yield at different shear strains (Soltani and Maekawa 2015). The elastic shear stiffness \( (G_{0m}) \) and the sub-yield strength \( (F_{refm}) \) are inversely obtained from the total shear stiffness. Next, the volumetric fatigue strain in dilatancy \( (\varepsilon_{vd}) \) and contraction \( (\varepsilon_{vc}) \) can be assumed. The dilatant volumetric strain is composed of the recoverable strain \( (\varepsilon_{vd}) \) and the nonrecoverable one \( (\varepsilon_{vc}) \). These values are calculated with experimental data as,
\[
\varepsilon_{vd} = \eta \left( J_{2v} - \frac{1 - e^{-e_{vd}}}{a} \right), \quad a = 50
\]
\[
J_{2v} = \sqrt{\frac{1}{2} e_{ij} e_{ij}}, \quad \eta = 0.5 \left( \frac{\varepsilon_{vd} + \varepsilon_{vd,\text{lim}}}{\varepsilon_{vd,\text{lim}}} \right)
\]
where \( e \) is void ratio. \( e_{ij} \) is deviatoric tensor of total strain. \( J_{2v} \) is total shear strain intensity. Then, we have,
\[
\varepsilon_{\text{w}} = \varepsilon_{\text{w,ini}} \left(1 - \exp\left(-3\left(J_{2,p} + J_{2,p,ini}\right)\right)\right) - \varepsilon_{\text{w,ini}}
\]

\[
J_{2,p} = \int dJ_{2,p}, \quad \int dJ_{2,p} = \frac{1}{2} \beta S_{ij} d\varepsilon_{ij}
\]

\[
\beta = \frac{J_{2}}{\sqrt{p}}, \quad J_{2} = \frac{1}{2} S_{ij} S_{ij}
\]

where \(J_{2,p}\) is the accumulated shear strain invariant and subscript of ‘ini’ implies the initial state of soil, and \(\varepsilon_{\text{w,ini}}\) is the intrinsic volumetric strain as,

\[
\varepsilon_{\text{w,ini}} = -0.1 \left(\log_{10} |p|^{0.6} + 1\right) < 0
\]

\[
\varepsilon_{\text{w,ini}} = \varepsilon_{\text{r,ini}} \left(1 - \exp\left(-3J_{2,p,ini}\right)\right)
\]

where \(p\) is the volumetric nonlinear of the soil skeleton as,

\[
p = 3K \left(\varepsilon_{0} - \varepsilon_{v} - \varepsilon_{p}\right)
\]

where \(\varepsilon_{0}\) is the total volumetric strain and equal to \((\varepsilon_{1} + \varepsilon_{2} + \varepsilon_{3})/3\), and \(K\) is defined as the volumetric bulk stiffness of soil particles and we have,

\[
K = \frac{2(1+\nu)}{3(1-2\nu)} G_{0} \chi^{0.5}
\]

where \(\nu\) is elastic Poisson’s ratio and \(\chi\) is the confinement index to represent the size of the yield surface on the corresponding deviatoric plane. The volumetric plasticity of consolidation is calculated as,

\[
\varepsilon_{p} = 0.01 \left(\varepsilon_{\text{v,lin}} \left(|p|_{\text{max}} - \varepsilon_{\text{w,lin}}\right)\right)
\]

where \(|p|_{\text{max}}\) is the maximum mean stress.

The total shear stress \(S_{ij}\) is a sum of the component stresses \((\sigma_{ij})\), which derives from the plastic strain \((\varepsilon_{pl,ij})\), elastic shear stiffness \((G_{0} F^{m})\), and yield strength \((F^{m})\) as,

\[
S_{ij} = \sum_{m=1}^{n} S_{ij}^{m} (\varepsilon_{pl,ij}^{m}, G_{0} F^{m})
\]

\[
ds_{ij} = 2G_{0} d\varepsilon_{ij}^{m} = 2G_{0}^{m} (d\varepsilon_{ij} - d\varepsilon_{ij}^{m})
\]

\[
d\varepsilon_{ij}^{m} = \frac{s_{ij}^{m}}{2F^{m}} d\varepsilon_{ij}, \quad d\varepsilon_{ij}^{m} = \frac{s_{ij}^{m} d\varepsilon_{ij}}{F^{m}}
\]

where \(d\varepsilon_{ij}^{m}\) and \(d\varepsilon_{ij}\) are deviatoric tensors of plasto-elastic strains of the \(m\)-th component, respectively. Then, we have the total stress (\(\sigma_{ij}\)) as,

\[
\sigma_{ij} = s_{ij} + p \delta_{ij}
\]

where \(\delta_{ij}\) is Kronecker’s delta and \(p = (\sigma_{ij} + \sigma_{ji} + \sigma_{33})/3\). Details of the constitutive model for the soil foundation can be referred in Nguyen et al. (2019b).

### 3.3 Water infilled crack

The water infilled crack model in cracked concrete is used (Maekawa and Fujiyama 2013; Maekawa et al. 2015) based on Biot’s two-phase theory (1941, 1955) as well as the effective stress model of soil. Here, we have the total density of saturated concrete as,

\[
\rho = (1-n)\rho_{c} + n\rho_{f}
\]

where \((1-n)\rho_{c}\) is for concrete skeleton and \(n\rho_{f}\) for the pore water, \(\rho_{c}\) is the density of concrete skeleton, \(\rho_{f}\) is the density of pore water and \(n\) is the pore volume ratio. Thus, the total stress of uncracked concrete denoted by \(\sigma_{ij}\) is a sum of the skeleton stress and the isotropic pore water pressure as,

\[
\sigma_{ij} = \sigma_{ij}^{s} + \delta_{ij} p
\]

where \(p\) is pore pressure and \(\sigma_{ij}^{s}\) is the effective stress tensors on the solid skeleton. It is noted that the pore water inside concrete in Eq. (21) is assumed to be isotropic. Hence, this formula is applied to the stagnant water inside capillary pores.

After cracking, we have water substantially located in a thin layer surrounded by a couple of crack planes. Then, the impact of the pore pressure gets anisotropy in nature (Maekawa and Fujiyama 2013) which is directed normal to a pair of parallel crack planes. The sensitivity of crack mouth opening has conducted in the experiment by Wang et al. (Maekawa and Fujiyama 2013). Then, the permeability of cracked concrete along \(l\)-axis is assumed as,

\[
K_{l} = k \left\{1 + \left(\frac{\varepsilon_{p} + \varepsilon_{pl}}{a}\right)^{4}\right\}
\]

where \(K\) is the intrinsic water permeability of uncracked concrete, \(\varepsilon_{p} + \varepsilon_{pl}\) is the mean transverse in plane strain and the constant denoted by \(a\) indicates the sensitivity (Maekawa and Fujiyama 2013). Then, we have the dynamic equilibrium with dragging forces rooted in the permeability \(K\) of pore water in each direction - \(i\) through micro-pores and crack gaps as (Maekawa and Fujiyama 2013),

\[
\sigma_{ij} + \rho g_{i} = \rho u_{i,tt} + \rho_{f} w_{i,tt}
\]

where \(\rho g_{i}\) is the gravity force, \(u_{i,tt}\) is the acceleration of skeleton, and \(w_{i,tt}\) is the acceleration of water. The dynamic equilibrium equation for fluid materials in skeleton is given as,

\[
\rho_{f} + \rho_{f} g_{i} = 1/k_{w} w_{i,tt} + \rho_{f} (u_{i,tt} + w_{i,tt}/n)
\]
where $1/K_{wi,tt}$ is the viscosity, $\rho_f (u_{i,tt} + w_{i,tt}/n)$ is the inertia force equal to the mass × acceleration. The value of $n$ is a constant before loading and considered as capillary pore porosity of concrete mixture. The pore pressure denoted by $p$ is calculated as,

$$p = \tanh \left( K_i \left( w_i + \varepsilon_i \right) \right) - \frac{dp}{d(w_i + \varepsilon_i)} K_i \left( w_i + \varepsilon_i \right) \left( w_i + \varepsilon_i > 0 \right)$$

where $p = 0$ means the atmospheric pressure as standard, $p < 0.0$ is normal compression, and $0.0 < p < 1.0$ is negative, $w_{i,tt} + \varepsilon_i$ is the volumetric strain of stagnant water inside pores and voids, and $K_i$ is the averaged substantial linear stiffness and related to the bulk stiffness of concrete matrix and pure water.

When cracks close with water, water pressure rises and it turns to negative and/or vaporization when opening. Then, the damage of concrete is accelerated since the pore pressure is transmitted to the capillary pores mostly located around the interface of aggregates and cement pastes. For RC bridge decks, water was reported as a cause of severe erosion and disintegration (Maekawa et al. 2015). In case of the concrete pavement, in this study, we try to apply this behavioral simulation as summarized in Fig. 5 on the interaction of water and traffic loads like the previous discussion on bridge RC slabs.

### 4. Fatigue kinetics of pavement system

#### 4.1 Failure mode of pavement system

For investigating the fatigue kinetic of pavement system in this section, we will use six mock-ups presented for verifying the failure mode of concrete slabs and soil foundation (Nguyen et al. 2019). Here, the key note for these series was the high load level of 1029 N with the relative density (RD for short) of 50% and 75%. At the same load amplitude and thickness, RD of 75% shows the immediate damage of the slab just after the static load. Meanwhile, soil’s RD of 50% depicts better coupling with the concrete slab and the total displacement gets smaller than the case of the thicker one. Interestingly, this result is opposite to the current design principle (Nguyen et al. 2019). Then first, we present the full-scale nonlinear simulation, and second, the pavement thickness required by some current guidelines will be reviewed and compared with the full nonlinear solution. The summary for the research methodology of the new proposal for the slab’s thickness is shown in Fig. 6.

#### 4.2 Proposal of rational design approach

The guidelines on design thickness of concrete pavements are discussed as such, the Guide for the Design of Pavement Structures proposed by American Association of State Highway and Transportation Officials (AASHTO 1993), Thickness Design for Concrete Highway and Street Pavements by Portland Cement Association (PCA 1984), a newer design program named as the Mechanistic-Empirical Pavement Design Guide (MEPDG) (AASHTO 2008; Jenjiwattanakul and Sano 2011; Papagiannakis and Masad 2012; SUDAS 2019), and the ACI 325 Guide for Design of Jointed Concrete Pavements for Streets and Local Roads reported by American Concrete Institute (ACI 32.5.12R-02 2002).

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**Fig. 5 Summary of the coupled code for concrete, soil and pore water inside cracks.**
**Small-Scale Mock-ups**
- RD 50% shows the better result compared to RD 75% at the thin slab’s thickness (20mm).
- RD 50% shows the better result at the thin slab’s thickness 20mm compared to the thick one 50mm.

The balanced slab thickness is necessary in the pavement design.

**Small-Scale Simulation**

**Nonlinearly Coupled Code**

Constitutive laws of high-cycle fatigue for concrete

\[
\sigma = E_K \varepsilon_n \quad \text{Fatigue damage}
\]
\[dN_c = \frac{dN}{dE} = \frac{1}{E_c} \text{elastic-plastic damage} \quad \text{(Decrease of stiffness and plasticity accumulation by continuous fracture propagation)}
\]

Constitutive law of high-cycle fatigue for soil

\[
\varepsilon = \frac{E_0}{E_c} \varepsilon_n \quad \text{Fatigue damage}
\]
\[dN_c = \frac{dN}{dE} = \frac{1}{E_c} \text{elastic-plastic damage} \quad \text{(Decrease of tension stiffness)}
\]

Shear Fatigue

\[
\sigma_{xy} = \tau_{x+y} \quad \text{Shear Stress}
\]
\[\text{Time} \quad \text{Shear stress}
\]

\[
\varepsilon_{vol} = \frac{1}{3} \text{tr} \varepsilon \quad \text{Volumetric Strain}
\]
\[\varepsilon_{vol} \text{ (positive)} \quad \text{Contraction (negative)}
\]

DuCOM-COM3

Input (Strains)

Output

Total stress \( \sigma_{ij} \)

Multi-directional fixed crack modeling

Multi-yield surface plasticity modeling

**Full-Scale FEM Analysis for All Cases of Soil’s Density**

- Full-scale FEM analysis for each soil’s density (loose, medium dense, dense and very dense compaction).
- The sensitivity parameters of modeling: the diversity of the slab’s thickness: 120mm, 150mm, 180mm, 200mm, 220mm, 250mm.
- The moving load, boundary conditions: kept constant all cases.

The balanced slab’s thickness has been newly proposed and compared to the current design codes.

Fig. 6 Research methodology for the prediction and assessment of the thickness in the pavement.
The AASHTO Design Guide provides the fundamentals for pavement design practice and requires a number of design parameters. It is therefore called as the empirical approach (Jenjiwattanakul and Sano 2011; Delatte 2014; SUDAS 2019). The basis of the PCA design (PCA 1984) is on the elastic theory of pavement (Westergaard 1927; Pickett and Ray 1951) and finite element analysis. The criteria for the design procedures in PCA is based upon a comprehensive analysis of pavement’s resistance to fatigue and displacements. The design factors are thus simpler than the AASHTO’s method, focused on the flexural strength of concrete, the soil’s density and the weight as well as types of truck axle loads. The PCA method is called as the mechanistic approach (PCA 1984; Jenjiwattanakul and Sano 2011; Delatte 2014). The MEPDG method utilizes the failure potential for a given thickness with huge dataset. Each paving association provides its different software and specific inputs are required (SUDAS 2019). The MEPDG does not depict the particular pavement thickness. ACI 325 [ACI 325.12R-02, (2002)] provides the slab thickness to achieve an acceptable pavement system for streets and local roads. The concepts of ACI 325 is based on the principles developed by PCA and others (AASHTO and ASTM) to analyze the concrete slab supported by the elastic slab over a dense liquid subgrade. It can be said that the mechanistic method for pavement thickness is approached via PCA and ACI 325.

Regarding the four current guidelines, soil is modeled as the linear, isotropic, homogeneous and elastic foundation and the failure mode is just focused on the damage of concrete. In reality, under the high-cycle fatigue of moving traffics, the shear and volumetric failure of the soil foundation appear and they are also the key issues of decayed life as the behavioral simulation previously indicated. Here, PCA and ACI 325 are first selected to be compared with the nonlinear simulation. We propose the critical cases for comparison; the high average daily traffic in both directions with all vehicles, the maximum axle load, the strength of concrete, and the pavement thickness without curb and gutters or shoulders (unsupported edges). The state of soil foundation is considered in four cases; poor (loose), poor to fair (medium dense), fair to good (dense) and good to excellent (very dense).

ACI 325 shows the guide for the design of pavements for streets and local roads under the low volumes of traffic. The required safety factor is 1.1 which is lower than PCA. There are seven street classifications outlined in ACI 325, and the recommendation for the pavement thickness in business streets with traffic classification of ADTT 800 (ADTT: Average Daily Truck Traffic) is selected due to its carriage for both expressways and arterials. As instructed in ACI 325, concrete flexural strength (MOR, Modulus of Rupture) in the range of 3.8 to 4.8 MPa at 28 days is regarded as economical. Owing to the normal concrete used in simulation and practices (W/C = 55%), MOR = 4.1 MPa is selected (equivalent to 600psi, also recommended in PCA). Based upon the modulus of subgrade reaction (k) for the soil, the equivalent soil’s density is determined from RD = 50% to 95%.

The pavement thickness for the high traffic volumes is proposed in PCA with four strengths as low, medium, high and very high foundation. Due to the frequency of heavy trucks, safety factor 1.2 is recommended. It is similar to ACI 325, MOR 600 psi as normal use of concrete, and the modulus of subgrade reaction (k) demonstrates the property of soil. The axle-load category 3 in PCA shows the heavy average daily traffic (ADT) and truck traffic (ADTT) in both directions, and it is also the popular case. The maximum ADTT in this category at each soil’s density has been selected to be compared with the proposed pavement thickness by the numerical simulation (PCA 1984, Chapter 3: Design Procedure).

The soil foundation is classified by (RD = 50%), medium dense (60%), dense (65% to 80%), and very dense (85% to 95%) compaction. The balanced thickness of each density is picked up from a mass of simulated thickness based on the current design code as 120, 150,

![Fig. 7 The full-scale numerical modeling for the new approach of pavement thickness.](image-url)
180, 200, 220 and 250 mm. As a matter of course, the pavement thickness in simulation corresponds to 1.0 safety factor. The full-scale FEM analysis for the new proposal and concept of the balanced pavement thickness are demonstrated in Fig. 7.

In the theory for the basis of ACI 325 and PCA, the thickness design method can be used for plain or reinforced pavements because the presence or lack of the distributed reinforcement has no significant effect on loaded slab behaviors as it pertains to thickness design. Based on this recommendation, the nonlinear FEM modeling is carried out with a light reinforcement ratio (abbreviated here as “pt”) of 0.1% for the purpose of investigating the weakest/most critical case of the concrete slab.

Figures 8 and 9 show the comparison of the low volume of traffic (ACI 325) and the high one (PCA) with numerical simulation, respectively. The selection for the balanced thickness of the slab in nonlinear FEM analysis is determined at the optimum performance for the fatigue failure of the concrete slab and soil. Depending on the relative density of soil, the failure point can take place earlier either soil or the concrete slab, or both of them simultaneously. The best selection of optimized fatigue life in the concrete pavement can be obtained in FEM analysis at each slab’s thickness in terms of the failure mode of the slab and/or the soil foundation. The methodology to approach the balanced thickness of concrete slab in nonlinear FEM analysis at each relative density of soil is typically illustrated in Fig. 8b for RD = 50% and 65%, respectively. Another soil density is similarly considered to attain the balanced thickness of concrete slab. It can be seen that the reduction for the required thickness in both guidelines is linear with the increase in soil’s density. It attributes to the principle of Westergaard’s theory of elasticity, where no shear band of soil is considered. As discussed above, under the highly repeated traffic, the shear and volumetric fatigue of soil appear concurrently and become one of the key factors of reduced service time of the pavement (Nguyen et al. 2019b). The results of numerical simulation in both cases show three fatigue failure modes at each soil’s density. When the soil is the loose and the medium dense as RD = 50% and 60%, the shear band is more critical than the damage of concrete slabs (see Fig. 10a). Here, the fatigue failure is limited on the soil foundation. Thus, the large thickness of the concrete slab is not necessary due to more burden for the soil (Nguyen et al. 2019b). In consideration of nonlinear

![Fig. 8 Balanced thickness of concrete slab to maximize the fatigue life of pavement system and the specified recommended thickness by ACI 325.](image)

![Fig. 9 Balanced thickness of concrete slab to maximize the fatigue life of pavement system and the specified recommended thickness by PCA.](image)
mechanics of the loose and medium dense soil, the pavement thickness is thought to be reduced compared to the guideline by ACI 325 and PCA.

In the event of dense soil foundation (RD = 65% to 75%), the numerical simulation conversely gives the need of larger thickness. It attributes to the integrated failure of both concrete and soil. The surface soil is more confined by the slab’s presence when its thickness is the larger. These analytical results have been similarly observed in the experiments (Nguyen et al. 2019b). In contrast to soft foundations as discussed above, the thicker slab is required in the case of RD = 75%. The numerical simulations demonstrate the nonlinearly varying required thickness with regard to the soil density. This is a key of discussing code revision.

When the soil foundation is very hard and compacted (RD = 80% to 95%), the shea r band of soil will not appear (see Fig. 10c). Then, the fatigue failure is primarily governed by the damage of concrete. As a result, the balanced thickness in numerical simulation is nearly similar to the ACI 325 and PCA.

4.3 Numerical model for water-crack interaction

We have similar discretization for the full-scale behavioral simulation of coupled water and cracks as shown in Fig. 7. The half-domain of concrete pavement with X-coordinate (moving load direction) is applied as the symmetric axis. The dimension of the soil foundation is 3000 mm × 8000 mm in plane and 2000 mm in depth, and the concrete slab is 3000 mm × 4000 mm in plane and 250 mm (25 cm) thickness. The moving load of 156 kN is produced by applying nodal forces at the symmetric axis (X-direction). The total nodal force is kept constant. The concrete slab consists of five layers of 50 mm.

Three main variables are considered, i.e., reinforcement ratio and locations of stagnant water in concrete slabs and the soil’s relative density. Four reinforcement ratios are specified, i.e., 0.1, 0.3, 0.5 and 1.0%. The effect of saturation is examined at the top layer slab of 5 cm, 10 cm, the whole depth (five layers of 25 cm of the slab) and fully dry slabs. The foundation is assumed as sand with relative density 50% and 75% to illustrate the loose and dense compaction, respectively.

The magnified direct path integral was applied in simulation by utilizing binary increasing magnification with each passage along the slab axis (Maekawa et al. 2006). There are around 60 time-steps implemented in one single pass and about 2000 time-steps for the entire path of simulation. The multi-frontal direct linear sparse matrix solution in the FEM solution was also applied to accumulate the time calculation. The drying shrinkage has been automatically reproduced as the thermo-hydro action develops so that it may equilibrate with ambient relative humidity of 60% and the temperature of 20°C.

4.3.1 Reinforcement ratio and stagnant water positions

The four specific cases of reinforcement ratios are shown from Figs. 11 to 15. In these figures, the fatigue life and failure mode of the concrete pavement with the loose soil foundation (RD = 50%) are observed under the stagnant water and the dry condition. The fatigue failure of concrete pavements is determined based on the limit state either the concrete slab or shear failure of soil, or both of them simultaneously. The load-carrying mechanism in the concrete slab may evolve due to crack-to-crack interaction and this results on a reduced area of diagonal shear fracture planes. The load cycle at failure is estimated by observing the mode of out-of-plane deformation and displacement at the center of the slab. Another point is the soil foundation which is characterized by the shear and volumetric fatigue under the repetitive loading. The fatigue failure is analyzed by the shear band and the large displacement of soil. The maximum failure state of pavement system may be obtained when diagonal shear fracture planes of concrete slabs and the shear band of soil occur concurrently.

Firstly, the lightest reinforcement ratio (pt = 0.1%) is examined as illustrated in Fig. 11. As the fatigue life is dramatically shortened under water, the displacement of the concrete pavement significantly rises almost equal to the final cycle of the dry case. The concrete slab is severely damaged. In case of the dry slab, however, the
deterioration of concrete is not serious. If the slab is immersed at the top layer of 5 cm, the severe damage may develop around this position. The same trend can be seen for 10 cm zone with water. In the fully saturated event, the damage of concrete slab is concentrated mainly on the top layer.

Interestingly, the stagnant water at the bottom layer of the slab has less impact to the failure. We can say that the damage of concrete pavement chiefly attributes to the decay of the top layer on which bending compression develops. In the previous studies of RC decks, the rising pore pressures under high-speed wheel movement were detected at the wet-upper deck only (Maekawa and Fujiyama 2013; Nguyen et al. 2019a). Here, the similarity is found. It is also consistent with the previous experiment (Isobe et al. 2015; Fathalla et al. 2019) which shows the horizontal cracks just appearing nearby the top layer of dry concrete bridge decks (see Fig. 12). Stagnant water therefore mainly affects the slab at this position. The total fatigue life is then dramatically increased compared to the stagnant water case.

The water at the top layer of 5 cm causes displacement in rapid progress near the final failure than the case of 10 cm and consequently, the less fatigue life is brought about. It can be said that the effect of water is more critical near the slab’s surface, and the rising pore water pressure leads to the disintegration of the concrete composite system. When water is allowed over the top layer of 10 cm, it can escape to the bending tension zone. When the stagnant water exists inside the top 10 cm of the slab, water suction inside cracks in open mode occurs. As a result, stagnant water goes through the bending tension zone when flexural cracks open. The water pressure is therefore decreased (negative pressure) com-

![Fig. 12 Horizontal cracking at the top surface of concrete bridge deck under moving load.](image)

![Fig. 11 Fatigue life and failure mode of concrete pavement under water effects with pt = 0.1%.](image)
pared to the case of water at top 5 cm zone where bending compression primally develops. This is one of the targets for more discussion in future to investigate the most severe case under water effects of FEM analysis. Then, the pressure rise gets a little mild. However, provided that the whole volume of cracked concrete would be filled by water, water transport is stucked and the pressure rise reaches the whole volume over the member (Maekawa and Fujiyama 2013). The explanation for this point will be discussed more details in Section 4.4.

The light reinforcement ratio (pt = 0.1%) hardly enhances the fatigue life if the stagnant water resides. Figure 13 shows the fatigue life and failure mode of concrete pavement under water effects with pt = 0.3%. We have a bit increase in the fatigue life for the case of top layer of 10 cm. Other cases are almost similar to the case of pt = 0.1%. The fully wet slab demonstrates the most severe damage and its deterioration is distributed just on the top surface. It is similar to the slab of pt = 0.1%. We have no deterioration of the bottom layer’s concrete.

The total displacement of this pavement evolves suddenly in the case of fully wet slab compared to other cases in Fig. 13. The dramatic increase in the principal strain can be seen as well. Owing to the higher reinforcement ratio, the damage of the fully dry slab at the final stage is not severe compared to pt = 0.1% as shown in Fig. 13. The displacement of the dry slab is also smaller. Figure 13 shows the diminutive support of the case of pt = 0.3% in stagnant water just at the top layer of 10 cm. We can say that the upgrade of reinforcement ratio from 0.1 to 0.3% is worthless under the stagnant water at cracked concrete.

The medium reinforcement ratio of 0.5% is investigated as shown in Fig. 14. Under the stagnant water, the fatigue life is more or less similar to the slab of 0.3%. The devastation of concrete slabs is distributed at the top layer slab (5 cm or 10 cm) depending on the positions of stagnant water as the other cases of reinforcement ratio.

In the event of fully wet slab, the damage of concrete is limited just on the top surface, and we have no dete-

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**Number of cyclic passages:**
- **Fully dry:** $8.81 \times 10^4$
- **Fully wet:** $1.50 \times 10^5$
- **Top 5 cm:** $7.63 \times 10^2$
- **Top 10 cm:** $3.15 \times 10^3$

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**Fig. 13 Fatigue life and failure mode of concrete pavement under water effects with pt = 0.3%**.
ioration at the bottom side of the slab in this simulation. It can be noted that the medium reinforcement ratio of 0.5% has quite less impact to the fatigue life with stagnant water. The heavy reinforcement ratio of 1.0% is also investigated as shown in Fig. 15. The displacement of the concrete slab with the stagnant water at the top of 5 cm and the fully saturated rapidly increases compared to the stagnant water at the top of 10 cm. Irrespective of the heavy reinforcement ratio, water at the top of 5 cm and the whole slab are shown as the critical cases.

In the case of water at the top of 10 cm, the increased displacement almost coincides with the fully dry slab at the first thousand cycles. However, the displacement suddenly rises at the final stage. Thus, the fatigue life is dramatically reduced. The heavy reinforcement clearly shows the benefit in the fully dry slab. But under water, the expected life is just the same magnitude of low reinforcement ratio.

The failure mode of the dry slab from Figs. 11 to 15 is strongly governed by the shear band of the loose soil foundation. In case of the water effects in concrete slabs, the flexural failure of the slab is more severe than the shear band of soil. The maximum principal strain of concrete slabs with a displacement scale $\times 0.1$ is shown at the failure cycle of the concrete slab.

4.3.2 Effects of relative density of soil
In case of the slab immersed in water, the damage is severe and the displacement of the concrete pavement quickly grows. To investigate the sensitivity of reinforcement to the fatigue life, a series of 0.1 to 1.0% is examined under water. The total fatigue life was nearly similar for any scale of reinforcement. It can be seen that the effect of reinforcement ratio is inconsiderable and it can be negligible when the stagnant water exists in cracked concrete under moving loads.

Another variable is the relative density of soil. The lightest reinforcement ratio of 0.1% and the heaviest one of 1.0% are numerically checked with the dense soil foundation of $RD = 75\%$ as shown in Figs. 16 and 17, respectively. It can be seen that the dense foundation has a great contribution to the fatigue life in case of the top

![Fig. 14 Fatigue life and failure mode of concrete pavement under water effects with $pt = 0.5\%$.](image-url)
layer 10 cm immersed. As previously stated, the stagnant water at the top layer 5 cm and the whole slab are defined as the critical positions. It is identical to the case of RD = 75%. Irrespective of the dense soil foundation or reinforcement ratio, the fatigue life in these two cases is nearly coincidental to the RD = 50%.

The fatigue life of pt = 1.0% slab in stagnant water (5 and 10 cm from the top surface) is nearly resembling with RD = 50%. However, a huge gap of the life time is seen with stagnant water with supporting soil of RD = 75%. The displacements of the fully wet slab and water at the top layer 5 cm slab are rapidly increased at the nearly final cycle, and it is virtually equal to the displacement of the concrete slab with water at top layer 10 cm. The displacement of the slab with stagnant water at the top layer of 10 cm is accompanied by the displacement of the dry slab. Under the light reinforcement ratio of 0.1%, the damage evolution of the wet-top layer of 10 cm is faster than the slab of pt = 1.0%. The pore pressure is also assumed to increase more and faster than the slab of pt = 1.0%.

Compared to the case of wet-top layer of 10 cm with RD = 50%, more critical deterioration of concrete can be seen in the case of RD = 75%. However, the much longer life is foreseen in RD = 75%. It is explained due to the small shear failure of the soil foundation. The shear band of the soil foundation in the case of RD = 75% occurred at the late stage. Hence, the damage of the pavement depends on the position of water in the slab. Meanwhile, RD = 50% shows the coupled damage of concrete and underneath soil. Therefore, the damage can be seen in both concrete and soil.

For the dense soil foundation, the effect of reinforcement ratio is clearly seen in case of water at top layer 10 cm of the slab compared to the loose foundation. The longer fatigue life in the case of dry slab pt = 0.1% with soil RD = 75% is computationally simulated rather than the case of RD = 50%. The fatigue life of pt = 1.0% under the water at the top layer of 10 cm of the slab is also extended in comparison with pt = 0.1% and RD =

![Fig. 15 Fatigue life and failure mode of concrete pavement under water effects with pt = 1.0%](image-url)

**Number of cyclic passages:**
- Fully dry: $3.66 \times 10^5$
- Fully wet: $3.68 \times 10^3$
- Top 5 cm: $2.02 \times 10^3$
- Top 10 cm: $2.72 \times 10^3$
75%. The critical locations of wet concrete are either the whole volume or the top layer of 5 cm of the slab. If the stagnant water resides at these positions, strengthening of both slab and soil is imperceptible. But, there is less occurrence of damage at the bottom side of the slab even no matter how wet the slab is. This is also consistent with the experience of bridge concrete decks (Maekawa and Fujiyama 2013).

The failure mode of the dry slab in Figs. 16 and 17 shows the coupling damage of the concrete slab and soil (the flexural failure of the slab and the shear band of soil occur simultaneously and later than the case of the loose foundation). Under the water impacts, the severe damage of the slab is observed compared to the soil failure. The maximum principal strain of concrete slabs with a displacement scale × 01 is shown at the failure cycle of the concrete slab.

4.4 Pore pressure and principal strain
To evaluate the effects of stagnant water, the pore water pressure and concrete principal strain at the top layer of 5 cm, 10 cm and fully saturated slab are investigated as shown in Fig. 18. It can be seen that when the concrete slab is fully wet, the pore water pressure suddenly increases faster than other cases of stagnant water impacts. As a result, the principal strain also rises at the earliest stage. The high water pore pressure causes the fast development of internal stresses in the concrete slab which accelerates the disintegration of structural concrete concurrently (Maekawa and Fujiyama 2013). In case of the stagnant water at the top layer of 5 cm, the pore water pressure increases faster than the case of the wet top layer of 10 cm. The principal strain and the concrete damage proceed at the earlier stage than the case of the wet top layer of 10 cm. Water kinetics in cracked concrete is thought to be the main reason for the reduced fatigue life under water.

4.5 Fatigue life: fully dry and saturated wet slab
To investigate the effects of water on the fatigue life of concrete pavement, one representative case of the concrete slab with \( \text{pt} = 0.1\% \) and soil’s density \( \text{RD} = 75\% \) is

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**Fig. 16 Fatigue life and failure mode of pavement under with water for \( \text{pt} = 0.1\% \) and \( \text{RD} = 75\% \).**
focused. Figure 19 offers the computed S-N diagram for the concrete pavement under the wheel-moving passages of fully dry and saturated concrete slabs. The computed fatigue life is dramatically reduced under submerged conditions as much as the case of RC decks on bridge girders (Maekawa et al. 2006). In fact, the deterioration of concrete slabs under submerged conditions is faster than two or three orders compared to the dry conditions under lower magnitude of loads. But, for the greater amplitude, the decay of the fatigue life is comparatively less. It is due to the minor effect of the shear transfer (Maekawa et al. 2006). The computationally derived S-N diagram matches the one of bridge slabs (Matsui 1987). The open-closure of crack planes with sandwiched water may govern the disintegration of concrete rather than the accumulated damage of crack shear transfer.

5. Conclusions

The impact of stagnant water residing in cracked concrete is computationally estimated from the point of view of the fatigue life of the concrete pavement on the nonlinear soil foundation. In reference to the experimental facts, nonlinear three-dimensional finite element analyses of plain and reinforced concrete slabs were systematically conducted with nonlinear soil foundations, and the following conclusions are earned with different ambient states as;

(1) The required pavement thickness on the loose soil foundation is found to be thinner than the medium/dense one. This is opposite to the on-going design concept based upon the linearity of soil foundation. A key factor can be presented in discussing the rationale of design principle of concrete pavement. In other words, the thickness of the pavement on the medium compacted soil shall be increased than the current design requirement.

(2) The stagnant water in cracks of concrete slab is computationally confirmed to be a great impact on the rapid decrease of the fatigue life like the cases of RC bridge decks under moving loads.

Fig. 17 Fatigue life and failure mode of concrete pavement with water for pt = 1.0% and RD = 75%.
(3) The pore pressure aggravated by the crack kinetics evolves in micro-pores in concrete. Computationally, the history of the pore pressure and principal strain signifies that the damage of the concrete slab is accelerated by the high pore pressure in crack gaps.

(4) The water can produce the high pore pressures in concrete and its effect may reach the concrete near the surface in bending compression. Hence, the damage caused by the pore pressures does not approach the bottom surface of slabs.

(5) Reinforcement ratio is computationally simulated to have an inconsiderable impact on the fatigue life of pavements if the stagnant water lie on the slab. The balanced thickness of the concrete slab on the nonlinear soil in this study is proposed based on the results of small-scale mock-ups and the full-scale FEM analysis. This study can be fundamental for future discussion when the analytical results are compared to real-size experiments. This is a strategic point to revise the existing design codes of concrete pavements.

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