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Experimental investigation on porosity reduction of a coarsely crushed rock layer subject to vertically cyclic loading

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ABSTRACT

The long-term cyclic loadings from traffic and maintenance may weaken the occurrence of buoyancy-driven natural convection of the pore air in the coarsely crushed rock layer during winter months and the effectiveness of cooling down the embankment and underlying foundation soils, thus resulting in instability and failure of the highway/railway embankment structure. Obviously, successful application of the coarsely crushed rock embankments in cold regions has to study both theoretically and experimentally the impact of cyclic loadings on the particle shape, grain size distribution and rearrangement of the crushed rock aggregates and the porosity variation of coarsely crushed rock layer. Therefore, some experiments on the crushed rock samples with dimensions of $75 \times 75 \times 87$ cm under vertically cyclic loadings have been carried out. Three coarsely crushed rock samples with initial grain sizes of 16–40, 25–50 and 50–80 mm were used to measure the related parameters to study their variations in cooling capability after the vertically cyclic loadings, respectively. The experimental approach on examining the particle shape and grain size distribution variations and the rearrangement of the crushed rock aggregates and the porosity reduction of the crushed rock layer under vertically cyclic loadings is developed. The porosities of three crushed rock samples with vibrating loading cycles have been measured using the water flooding approach.

The results show that the cyclic vibrating loadings can cause the breakage and abrasion of the particles and their edges in the coarsely crushed rock layer and the particles also tend to be rounding and non-angular. These result in rearranging of particles and decreasing of particle size and increasing of fines content in the coarsely crushed rock layer, thus reducing the porosity of the crushed rock layer. Compared with the initial average porosities before cyclic loading, the reduction rates of final average porosity in three crushed rock samples after cyclic loading with 18,000 cycles reach to 6.53, 7.45 and 8.08% corresponding to initial grain sizes of 16–40, 25–50 and 50–80 mm, respectively. These reduction rates of the final average porosities in the vibrated crushed rock samples after cyclic loading increase relatively with increasing of an initial grain size. Under such conditions, the long-term cyclic loadings from traffic and maintenance can weaken the effectiveness of cooling down the embankment and underlying foundation soils due to natural convection in the coarsely crushed rock layer during winter months.

1. Introduction

Under such conditions of the currently proposed scenarios of climate warming and the warm and ice-rich nature of the seasonally frozen soils and sensitive permafrost on the Qinghai-Tibet Plateau, the sustainable thermal stability of embankments is considered of utmost importance in the operation of the Qinghai-Tibet Railway and the construction of the proposed Qinghai-Tibet Expressway (Cheng et al., 2007, 2008; Lai et al., 2012; Li and Sheng, 2008; Li et al., 2009; Liu et al., 2012; Ma et al., 2011; Qin and Hiller, 2011; Qin and Zhang, 2010; Wu et al., 2011; Zhang et al., 2008). Hence, new techniques to cool the ground temperature for avoiding instability and failure of the embankment due to thaw settlement will be utilized in construction and maintenance of highway/railway embankments in cold regions. These new techniques involve utilizing the coarsely crushed rock embankment (triggering natural convection of the pore air during winter months due to a high air permeability of the crushed rock matrix) (Goering and Kumar, 1996; Lai et al., 2006a, 2006b; Lebeau and Konrad, 2009; Ma et al., 2009, 2011; Rooney, 1997; Saboundjian and Goering, 2003; Sun et al., 2005a, 2007), the insulating thermal material, thermosyphon and ventilation pipe embankments (Chataigner et al., 2009; Liu and Tian, 2002; Niu et al., 2008, 2011; Wen et al., 2008; Yu et al., 2008; Zhang et al., 2008, 2011b) and the embankments combined with multiple cooling mechanisms (Dong et al., 2010; Goering, 2003; Jørgensen et al., 2008; Lai et al., 2004, 2012; Sun et al., 2011; Wu et al., 2010; Xu and Goering, 2008; Yang et al., 2008, 2012; Zhang et al., 2011a). Among these, the combined techniques

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with multiple cooling mechanisms have a significantly enhanced cooling capability of the embankment and underlying foundation soils.

The scientific research of crushed rock embankments in permafrost regions began in the early 1960s. By the late 1990s, researchers had already found that buoyancy-driven natural convection of the pore air occurs in reaction to the unstable air-density stratification developing in the crushed rock layer due to lower surface temperatures during winter months and the upward heat loss removed from the crushed rock embankment and underlying foundation soils in winter is greater than heat intake in summer dominated by heat conduction alone (Goering and Kumar, 1996; Harris and Pedersen, 1998; Rooney, 1997). By the 2000s, there were many studies on the natural convection cooling effectiveness in the coarsely crushed rock embankment and revetment during winter months (Arenson et al., 2007; Cheng et al., 2007, 2008; Dong et al., 2010; Goering, 2003; Lai et al., 2004, 2006a, b; Lebeau and Konrad, 2009; Li et al., 2006; Ma et al., 2006, 2008, 2009; Mu et al., 2010, 2012; Qian et al., 2012; Quan et al., 2006; Saboundjian and Goering, 2003; Springman and Arenson, 2008; Sun et al., 2005a, b, 2007, 2009, 2010, 2011; Wu et al., 2007, 2008; Xu and Goering, 2008; Yu et al., 2004; Zhang et al., 2006, 2008, 2009). Efforts were initiated to study the techniques to cool the ground temperature on the basis of natural convection occurring in the coarsely crushed rock layer during winter-time, both experimentally and theoretically and to improve the measures for ensuring the thermal stability of the highway/railway embankment in permafrost regions. Cheng et al. (2007) stated that the cooling mechanism of closed and sloping crushed rock layers is in the form of natural convection, while that of open and inclined crushed rock layers are via the chimney effect and forced convection. Adopting such an idea of buoyancy-driven convection of the pore air during winter months, the coarsely crushed rock embankment and revetment has been applied in the construction of the Qinghai-Tibet Railway (Cheng et al., 2007, 2008; Ma et al., 2006, 2008; Mu et al., 2010, 2012; Zhang et al., 2008). The in-situ observed data were also indicated to be consistent with theoretical analyses (Ma et al., 2008, 2011; Mu et al., 2010, 2012; Sun et al., 2005b; Wu et al., 2007, 2008).

Most of the researches mentioned have been focused on triggering natural convection of the pore air in the crushed rock embankment and revetment and the cooling capability of embankment and underlying foundation soils during winter months; however, some have also been focused on the physical properties of crushed rock matrix (He et al., 2007; Lai et al., 2006a; Lebeau and Konrad, 2009; Yang et al., 2007; Yu et al., 2004; Zhang et al., 2006). It is due to the fact that the cooling capability of crushed rock layer due to natural convection during winter months is directly dependent upon the porosity of crushed rock matrix. Further, the porosity of a crushed rock layer depends directly on the particle shape, arrangement and grain size distribution of crushed rock aggregates. On the other hand, the long-term cyclic loadings from traffic and maintenance may affect on the particle shape, arrangement and grain size distribution of crushed rock aggregates in the coarsely crushed rock layer. Hence, the long-term cyclic loadings may have impact on the cooling capability of crushed rock due to natural convection in the coarsely crushed rock embankment during winter months, resulting in instability and failure of the embankment structure. However, less study in the effect of the long-term cyclic loadings from traffic and maintenance on the cooling capability of crushed rock due to natural convection is carried out. The purpose of this work is to study both theoretically and experimentally the impact of cyclic loading on the particle shape, rearrangement and grain size distribution of crushed rock aggregates and the porosity of the coarsely crushed rock layer. The factors affecting on weakening the occurrence of natural convection of the pore air motion in the coarsely crushed rock layer during winter months and the cooling effectiveness of the highway/railway embankment and underlying foundation soils due to long-term cyclic loadings are also discussed.

2. Theoretical formulations

2.1. Governing equations

Natural convection in the coarsely crushed rock layer of the embankment during winter months is a heat transfer problem of a two-phase system consisting of a porous granular rock matrix saturated with a single incompressible air phase, which may be subjected to an airflow regime (Goering, 2003; Goering and Kumar, 1996; Sun et al., 2005a, 2007, 2010). In permafrost regions of the Qinghai-Tibet Plateau, the yearly mean wind velocity is about ranging from 3.0 m/s to 6.0 m/s. This implies that the pore air motion in the coarsely crushed rock layer with a high air permeability must consider the drag effect of non-Darcy flow (Nield and Bejan, 1999; Yang et al., 2007; Zhang et al., 2006, 2009). Therefore, assumptions such as Boussinesq approximation, non-Darcy's law considering an inertia loss term, local thermal equilibrium and isotropy of heat transfer are applicable in the theoretical analysis (Lai et al., 2006b; Sun et al., 2005a, 2010; Yang et al., 2007). Under such assumptions, the governing equations based on conservation of mass, momentum and energy for natural convection heat transfer in the coarsely crushed rock layer can be expressed as:

$$\nabla \cdot \mathbf{u} = 0, \tag{1}$$

$$\mathbf{u} = -\frac{K}{\mu}\{\nabla p - \rho_0[1-\beta(\theta-\theta_0)]\mathbf{g}\} - \frac{\rho_0 c_F K^{1/2}}{\mu}|\mathbf{u}|\,\mathbf{u}, \tag{2}$$

$$C_e\frac{\partial\theta}{\partial t} - \nabla\cdot(\lambda_e\nabla\theta) = -C_a\mathbf{u}\cdot\nabla\theta, \tag{3}$$

where θ and t are the temperature and time, p is the pore air pressure, $\mathbf{u}$ and $|\mathbf{u}|$ are the velocity vector of the pore air flow in the crushed rock layer and its absolute value, θ_0 and ρ_0 are the reference values for the temperature and relevant density of the pore air, C_e, λ_e and K are the volumetric heat capacity, thermal conductivity and air permeability of the crushed rock layer, C_a, β and μ are the volumetric heat capacity, thermal expansion coefficient and dynamic viscosity of the pore air, $\mathbf{g}$ is the gravitational vector (i.e. the z-axis is positive to be chosen upwards), c_F is the dimensionless drag coefficient of the pore air motion (i.e. Ergun constant) and ∇ is the Hamilton operator, respectively.

The semi-empirical Fair–Hatch formula is available for evaluating the air permeability of the coarsely crushed rock media with angular particle shapes (Yang et al., 2007). This relation can be expressed as (Bear, 1972; Saboundjian and Goering, 2003):

$$K = \frac{n^3}{5(1-n)^2}\left(\frac{\alpha_1}{100}\sum\frac{N}{d_n}\right)^{-2}, \tag{4}$$

where n is the porosity of the crushed rock layer, N is the percentage of crushed rock particles held between adjacent size limits of the sieve plate, d_n is the geometric mean size between adjacent size limits of the sieve plate and α_1 is the particle shape parameter in the coarsely crushed rock matrix, respectively.

2.2. Porosity of coarsely crushed rock media

We assume that the pore space distribution in the coarsely crushed rock media is uniform and isotropic and all the pore space is connected each other. It is easy to see that the porosity n of coarsely crushed rock layer may be defined as (Bear, 1972; Nield and Bejan, 1999):

$$n = \frac{V_p}{V} = 1 - \frac{V_s}{V}, \tag{5}$$

where V_p, V_s and V are the pore volume of the coarsely crushed rock