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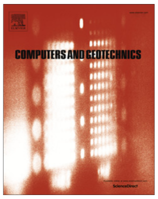

A constitutive model for coal-fouled ballast capturing the effects of particle degradation

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ABSTRACT

Rail tracks undergo degradation owing to particle breakage and fouling of ballast by various fines including coal and subgrade soil. As the ballast becomes fouled, its strength and drainage capacity are compromised, sometimes resulting in differential settlement and reduced track stability. This paper demonstrates a continuum mechanics based framework to evaluate the detrimental effect of fines on the strength, deformation and degradation of coal-fouled ballast under monotonic loading. An elastoplastic constitutive model that considers the effect of fines content and energy consumption associated with particle breakage during shearing is presented. This multiphase constitutive model is developed within a critical state framework based on a kinematic-type yield locus and a modified stress-dilatancy approach. A general formulation for the rate of ballast breakage and coal particle breakage during triaxial shearing is presented and incorporated into the plastic flow rule to accurately predict the stress–strain response of coal-fouled ballast at various confining pressures. The behaviour of ballast at various levels of fouling is analysed and validated by experimental data.

1. Introduction

Ballast is the most common material supporting rail tracks due to its economy, rapid drainage and ease of maintenance [1,2]. Fouling is the term commonly used in railway practice to indicate the contamination of ballast by intruding and subsequently accumulated fines. Fouling of ballast over time is one of the primary reasons why track geometry deteriorates. Coal spilling from moving wagons, fine particles resulting from ballast breakage and soft subgrade (soil) pumping are the major causes of fouling. As a result, the pore matrix of ballast changes by reducing the particle interlock (i.e. frictional resistance), which in turn reduces the shear strength and promotes plastic deformations. Thus, the compressibility of the ballast layer becomes a serious concern, which subsequently leads to unfavourable track conditions and high maintenance costs.

Ballast breakage has been identified as the most significant source of fouling [2,3], while it is known that the degradation of particles influences the strength and deformation behaviour of granular media [4–6]. However, in countries like Australia and the United States, coal spilling from wagons and subgrade soil pumping are also common sources of ballast fouling [7]. A few studies have reported the adverse effects of coal fouling on the strength of ballast [8–11].

While numerous constitutive models for coarse granular materials have been proposed in the past [4,12–14], there have been few rigorous attempts to capture the effects of ballast breakage and fouling. Ueng and Chen [15] proposed an energy based criterion which models particle crushing upon shearing as a function of the surface area. Indraratna and Salim [16] later extended this approach by linking the energy consumption with Marsal's [17] breakage index rather than an increase in the surface area. In the present study, the above criterion has been extended to incorporate the additional energy consumption due to degradation of the

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Nomenclature

I_{Bb}	ballast breakage index
I_{Bc}	coal breakage index
PSD	particle size distribution
VCI	void contaminant index
$\delta\varepsilon_v^p$	plastic volumetric strain increment
$\delta\varepsilon_s^p$	plastic shear strain increment
e, e_g	void ratio and intergranular void ratio of coal-fouled ballast, respectively
e_b, e_f	void ratio of clean ballast and fouling material, respectively
fc_f	ratio of the weight of coal fines to the total weight of the sample of fouled ballast
fc_b	ratio of the weight of ballast fines to the total weight of the sample of fouled ballast
G	elastic shear modulus of fouled ballast
v	poisson's ratio of fouled ballast
V_υ, V_f, V_g	volume of voids, fines, and host soil, respectively
V_{bf}, V_{cf}, V_b	volume of ballast fines, coal fines, and ballast, respectively
V_T	total volume
G_s	specific gravity of coal-fouled ballast
G_{sb}, G_{sf}	specific gravity of the ballast and the fouling material, respectively
G_{sh}	specific gravity of the host soil
M_b, M_f	dry mass of the clean ballast and the fouling material, respectively
M_{bf}, M_{cf}	dry mass of ballast fines and the coal fines, respectively
M_s, M_T	dry mass of solids and total mass, respectively
γ_b	bulk unit weight of ballast
ρ_w	density of water
q, p'	deviator and effective mean stress, respectively
p'_o, p'_{cs}	effective mean stress at the commencement of loading and at the critical state, resp.
$\delta\varepsilon_1^p$	incremental axial plastic strain
$\delta\varepsilon_s^e, \delta\varepsilon_v^e$	incremental elastic distortional strain and volumetric strain, respectively
δE_{Bb}, δE_{Bc}	incremental energy spent on the breakage of ballast and coal particles, respectively
ϕ'_f, ϕ'_{fF}	basic friction angle of clean ballast and coal-fouled ballast, respectively
χ, μ	material parameters defining the rate of ballast breakage
ε_3, ε_1	lateral and axial strain, respectively
ξ, θ	material parameters defining the rate of coal breakage
υ_g	specific volume of coal-fouled ballast
κ_g	swelling/recompression constant
h, g	hardening and plastic potential function, respectively
δf	differential of a function $f = 0$ that defines the yield locus
α	model constant relating to the initial stiffness of coal-fouled ballast
M	slope of critical state line in (p', q) diagram
λ_{gcs}	slope of critical state line in $(\ln p'–\upsilon_g)$ diagram
Γ_g	Intergranular specific volume (υ_g) at $p' = 1$ kPa
κ_g	swelling/recompression constant
β, γ	breakage parameters
E	modulus of elasticity of rail
I	moment of inertia of rail
C	foundation modulus
V	train velocity
t	thickness of the rubber membrane
σ'_3	effective confining pressure

coal particles by adopting the ballast breakage index [6]. Using a critical state framework, a multiphase constitutive model has been developed which is based on a kinematic type yield locus and a modified stress-dilatancy approach. The advantage of this approach is its ability to simulate the deformation and degradation of coal-fouled ballast by considering the contribution made by each phase, i.e. the primary contribution from the ballast and the secondary contribution from the coal. The proposed model has also been compared and validated with large-scale triaxial data.

2. Laboratory work

2.1. Assessment of ballast fouling

In rail practice, fouling material is often defined as particles smaller than 9.5 mm accumulated in the ballast voids [3]. The degree of coal fouling was determined using the Void Contaminant Index (*VCI*) proposed in earlier studies [18] as represented by Eq. (1).

$$VCI = \frac{(1+e_f)}{e_b} \times \frac{G_{sb}}{G_{sf}} \times \frac{M_f}{M_b} \times 100 \qquad (1)$$

where e_b is the void ratio of clean ballast, e_f is the void ratio of the fouling material, G_{sb} is the specific gravity of the ballast, G_{sf} is the specific gravity of the fouling material, M_b is the dry mass of clean ballast, and M_f is the dry mass of the fouling material. Defining volume fractions $F_b = V_b/V_T$, $F_{cf} = V_{cf}/V_T$ for the (clean) ballast and for the coal fines respectively, Eq. (1) is represented by:

$$VCI = \frac{\upsilon_{cf} F_{cf}}{1 - F_b} \times 100 \qquad (2)$$

where V_{cf} is the volume of coal fines, V_b is the volume of ballast and V_T is the total volume (Fig. 1). e_{cf} and $\upsilon_{cf} = 1 + e_{cf}$ are void ratio and specific volume of the coal fines, respectively. In the current study, *VCI* ranging from 0% to 100% is considered. The *VCI* can exceed 100% if the granular assembly displaces such that some of the grains totally segregate and lose their original inter-particle contacts, and subsequently allow this dilated space to be filled with the fouling material. However, this is extremely rare situation. A *VCI* of 100% means that the original granular assembly still remains intact without any grain segregation, and all the voids within the granular assembly are completely filled with the fouling material.

The ballast was thoroughly cleaned, dried and sieved through a set of standard sieves (aperture size 53: 13.2 mm). The clean ballast was compacted in six equally thick layers to simulate the appropriate field density and void ratio ($\gamma_b = 15.3$ kN/m^3, $e_b = 0.72$–0.74) for heavy haul tracks. A rubber pad (4 mm thick) was used to minimise the risk of particle degradation during vibratory compaction. The pulverised wet coal fines were then added to the top of each layer and lightly vibrated to promote steady infiltration into the ballast voids. This process mimics the infiltration of falling coal from moving freight carriages in a real track, and also avoids disturbance to the ballast structure. The visual inspection