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# Effect evaluation of drainage condition and water content on cyclic plastic

# deformation of aged ballast and its estimation models

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#### 31 Abstract

32 With the ballast aging, the changes in the size and shape of the ballast particle reduce the drainage capacity, as 33 well as cause a greater permanent deformation of the railroad ballast. Therefore, it is meaningful to investigate 34 the effect of aging on the mechanical behavior of unsaturated ballast, and to estimate the cyclic plastic 35 deformation by considering the aging effects. Here, "aging effect" means the increase in fine fraction content 36 and the particle shape becomes rounded and smooth as compared with fresh ballast. In this study, the influence 37 of aging on the cyclic plastic deformation of unsaturated ballast was evaluated through a series of cyclic loading 38 triaxial compression tests. Test results indicate that the cyclic plastic deformation of ballast is seriously affected by water content, fine fraction content and drainage condition, and the increasing trend becomes more 39 40 remarkable at the water-rich aged ballast under the fully undrained condition since the effective confining 41 pressure decreases due to the generation of excess pore water pressure. Furthermore, the applicability of two 42 types of estimation models (i.e., a semi-empirical model named University of Illinois at Urbana-Champaign 43 (UIUC) model, and an elasto-plastic model named subloading surface extension (SSE) model) to the prediction 44 for cyclic plastic deformation of unsaturated ballast is also verified in this study by comparing with results of 45 cyclic loading triaxial compression tests. As the result, it is revealed that the UIUC model is suitable for 46 predicting the cyclic plastic deformation of fresh ballast (or slightly aged ballast) with different water contents 47 under the fully drained condition, and the SSE model shows good potential to estimate the cyclic plastic 48 deformation of fresh and aged ballasts by considering the effects of water content and drainage condition. The 49 findings of this study indicate that drainage conditions have a significant effect on predicting the cyclic plastic 50 deformation of aged ballast, and appropriate test conditions for triaxial compression tests (i.e., CD and CU tests) 51 should be selected according to hydraulic properties (i.e., permeability and water retentivity) of the aged ballast.

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Keywords: Aged ballast; Unsaturated soil; Cyclic plastic deformation; Laboratory element test; Estimation models.

#### 55 1 Introduction

56 The ballasted track structure (Fig. 1) is one of the typical track structures for traditional railways in Japan. 57 As passing tonnage of trains accumulates, clean or fresh ballast might be gradually contaminated with fouling 58 materials, which are finer than fresh ballast aggregates, due to the ballast abrasion, breakdown, and external 59 contamination (Indraratna et al., 2011; Selig and Waters, 1994). Selig and Waters (1994) pointed out that ballast 60 fouling is mainly due to the degradation of ballast particle size and shape, which is called "aging" in this study. It is worth noting that the definition of "aging" used in this study is different from the definition of "fouling" 61 62 commonly used in most previous studies. The aged ballast considers the changes in ballast particle size and 63 shape, while the fouled ballast does not consider the change in particle shape. Some past studies indicated that 64 the ballast fouling will cause a greater permanent deformation of ballasted tracks (Ebrahimi et al., 2015; 65 Indraratna et al., 2013a; Ishikawa et al., 2019). In addition, the increase in fine fraction content caused by ballast 66 fouling or aging affects the permeability and water retentivity of the ballast, which may cause an increase in 67 water content of the ballasted layer and further increase the cyclic plastic deformation of the ballasted track 68 (Indraratna et al. 2010; Tennakoon et al., 2012). The current Japanese design standard (RTRI, 2012) adopts a 69 semi-empirical formula to estimate the cyclic plastic deformation of ballast for the construction of new lines. 70 However, this formula cannot separately consider the adverse effects of water content and aging on the cyclic 71 plastic deformation of the ballast.



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Fig. 1. Schematic diagram of a typical ballasted track structure in Japan.

For cyclic triaxial tests, previous studies indicated that the cyclic plastic deformation of the aggregate materials is affected by the stress level, water content, fine fraction content, grading (Lekarp et al., 2000; Le Pen et al., 2013). For example, the increase in fine fraction content seriously alters the deformation-strength characteristics of the ballast, depending on the amount of fouling materials mixed with clean ballast (Dareeju et 78 al., 2015; Lackenby et al., 2007). Besides, Indraratna et al. (2013a) pointed out that with the increase in the fine 79 fraction content, the sleeper settlement of fouled ballasted track increases. Ebrahimi et al. (2015) indicated that 80 the water content of fouling materials has a significant effect on accelerating the cyclic plastic deformation and 81 changing the shape of deformational behavior of ballast from a small rate of plastic deformation to a high rate 82 of plastic deformation. Ishikawa et al. (2019) revealed that both water content and fine fraction content may 83 have serious influences on cyclic plastic deformation of the ballast. However, the effects of particle shape 84 changes and drainage conditions on cyclic plastic deformation have not been evaluated in previous studies on 85 fouled ballast so far.

86 For the semi-empirical model, many advanced phenomenological models (e.g., Abadi et al., 2016; Lekarp 87 et al., 2000; Monismith et al., 1975) for estimating the accumulative strain of geomaterials under cyclic loading 88 have been proposed by past researchers. In these models, the UIUC model is a simple model to predict the cyclic 89 plastic deformation of pavements under repeated traffic loads, because its input parameters can be easily 90 calculated by the shear strength parameters based on the monotonic triaxial test or the direct shear test instead 91 of the cyclic triaxial test (Chow et al., 2014a, 2014b; Qamhia et al., 2016). After that, the applicability of the 92 UIUC model was also verified for clean and fouled ballasts with different water contents and fine fraction 93 contents (Ishikawa et al., 2019). However, the applicability of this model to the prediction for the cyclic plastic 94 deformation of aged ballast has not been verified so far by considering the effect of drainage condition. On the 95 other hand, various constitutive models for granular materials have been developed so far (Hashiguchi and Ueno, 96 1977; Habiballah and Chazallon, 2005; Iwan, 1967; Mroz et al., 1981; Niemunis et al., 2005). In these models, 97 the subloading surface model shows a good ability to predict the cyclic plastic deformation behavior for metals 98 and clay (Hashiguchi and Ueno, 1977). After that, this model was modified by assuming an existence of the 99 elastic domain surface inside the subloading surface to realistically describe the inelastic deformation behavior 100 of coarse granular material under cyclic loading conditions. The validity of SSE model in predicting the 101 permanent deformation of air-dried clean ballast under cyclic loading was verified by comparing the test results 102 with the numerical results (Okayasu et al., 2014). However, the applicability of this model to predict the cyclic 103 plastic deformation of the aged ballast with various water contents and drainage conditions has not been 104 discussed so far.

105 To improve the track structure design and reduce maintenance costs, the main objective of this study is to 106 comprehensively investigate the effect of aging which includes changes in particle shape and particle size on 107 the cyclic plastic deformation of unsaturated ballast, and to estimate the cyclic plastic deformation of 108 unsaturated ballast by considering the aging effects. For these purposes, this study first evaluates the influence 109 of aging on cyclic plastic deformation of unsaturated ballast through a series of suction-controlled cyclic loading 110 triaxial compression tests for fresh and aged ballast. After that, the applicability of two types of estimation 111 models (i.e., UIUC model and SSE model) is verified to the prediction for the cyclic plastic deformation of fresh 112 and aged ballast with various water contents and drainage conditions.

#### 113 2 Test materials

114 In general, most of the Japanese railroad ballasts are composed of angular, crushed, and hard andesite stone. 115 The grain size distribution of properly graded ballast in the Japanese railway standard ranges from 19 to 63 mm. 116 Fresh ballast or called clean ballast (CB) and aged ballast (AB) are used as test materials. In Fig. 2, the terms 117 "1/1CB" and "1/1AB" refer to the full-scale fresh ballast and full-scale aged ballast obtained from actual railway 118 tracks in Japan. Here, 1/1AB (Fig. 2) was extracted from heavily aged railway tracks. It should be noted that 119 field investigations on aged railway tracks in Japan show that the fine fraction content ( $F_c$ ) of in-situ aged ballast 120 is generally between 0 and 15%. Therefore, the maximum  $F_c$  value of 15% in the field investigation is used as 121 the basis for the laboratory test condition. However, in this study, the small-scale fresh ballast (1/2CB) and the 122 small-scale aged ballast (1/2AB) were employed as test samples due to the specimen size in the medium-size 123 triaxial apparatus. Both 1/2CB and 1/2AB have the half mean grain size of 1/1CB and 1/1AB with a parallel 124 gradation (Fig. 2). Some past researches (Indraratna et al., 1993; Le Pen et al., 2013; Wang et al., 2017) have 125 reported that a small-scaled ballast with the parallel gradation well reproduces the mechanical behavior of the 126 prototype ballast. It is noted that 1/2AB was prepared by the Los Angeles Abrasion (LAA) test using 1/2CB 127 with abrasion time (L) of 50 min (number of turns ( $N_t$ ) is 1650). The validity of the LAA test for preparing aged 128 ballast can be referred to previous research (Yang et al., 2021). Physical properties of test samples were listed 129 in Table 1.

130	Table 1 Physical properties of test samples.												
	Test	$G_{\rm s}$	$ ho_{ m dmax}$	$ ho_{ m dm}$	$D_{\rm cm}$	Wopt	$D_{50}$	$U_{c}$	LL	PL	PI	$F_{\rm c}$	$k_{ m s}$
	samples		$(g/cm^3)$	$(g/cm^3)$	(%)	(%)	(mm)	(mm/mm)	(%)	(%)	(%)	(%)	(m/s)
	1/2CB	2.73	1.652	-	-	3.3	21.4	1.42	NP	-	-	0	6.51×10 <sup>-2</sup>

1/2AB	2.73	2.162	-	-	7.5	12.2	384.9	21.4	17.6	3.8	14.6	3.39×10 <sup>-4</sup>
1/1CB	2.70	1.682	1.581	94.0	3.0	40.7	1.33	NP	-	-	0	-
1/1AB	2.70	2.185	2.198	101.0	7.8	20.3	-	22.0	16.3	5.7	15.0	-

 $G_{s}$ : specific gravity;  $\rho_{dmax}$  and  $w_{opt}$  are maximum dry density and optimum water content, obtained from compaction E-b method (JGS 0711-2009);  $\rho_{dm}$ : in-situ measured dry density;  $D_{cm}$ : in-situ measured degree of compaction;  $D_{50}$ : mean grain size;  $U_{c}$ : uniformity coefficient; *LL*, *PL*, and *PI*, are liquid limit, plastic limit, and plasticity index, respectively, obtained from test method for liquid and plastic limit of soils (JGS 0141-2009); *NP*: non-plastic;  $F_{c}$ : fine fraction content, means the percentage by weight of ballast material passing the 0.075 mm sieve;  $k_{s}$ : saturated coefficient of permeability at degree of compaction ( $D_{c}$ ) of 94% for 1/2CB, and 101% for 1/2AB, fitted by the results of saturated permeability tests with different  $D_{c}$  (Yang et al., 2021).



Fig. 2. Grain size distributions of test samples.

In general, fresh ballast is a free draining material with large voids. However, the infiltration of fouling material reduces the voids and restricts water drainage. Indraratna et al. (2010) proposed the Void Contaminant Index (*VCI*) to quantitatively evaluate the degree of fouling for fouled ballast, which can consider the differences in void ratio, specific gravity, and gradation between the fresh ballast and the fouling material.

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

where,  $e_b$ ,  $G_{sb}$ , and  $M_b$  are void ratio, specific gravity, and dry mass of fresh ballast, respectively;  $e_f$ ,  $G_{sf}$ , and  $M_f$ are void ratio, specific gravity, and dry mass of fouling material, respectively. Based on this definition, Fig. 3 shows the relationships between the *VCI* and  $F_c$  or  $N_t$  of 1/2AB. It should be noted that in addition to the 1/2AB used in this study, 1/2AB with three other different  $F_c$  was also prepared by the LAA tests with different  $N_t$  to examine the effectiveness of the LAA test for reproducing the lightly or heavily aged ballast with different  $F_c$  150 or VCI. Here, a lightly or heavily aged ballast refers to the difference in the aging level. For example, 1/2AB  $(F_c = 6\%)$  is considered a lightly aged ballast, and 1/2AB ( $F_c = 15\%$ ) is considered a heavily aged ballast. 151 Regarding the calculation parameters of VCI, the specific gravities ( $G_{sb}$ ,  $G_{sf}$ ) of fresh ballast and fouling material 152 153 are the same. Besides, the  $e_f$  and  $M_f$  of fouling material with different LAA test times can be calculated by 154 assuming that the initial dry mass of 1/2CB placed into the LAA test instrument is the same as the dry mass of 155 1/2AB regardless of abrasion time, and that the dry mass of fouling material for 1/2AB is the same as the dry 156 mass of the  $F_c$  for 1/2AB with the same abrasion time. As can be seen in Fig. 3(a), VCI of 1/2AB is about 32.8%, 157 and it increases approximately linearly with the increase of  $F_c$ . Besides, VCI also shows an overall increasing 158 trend as the  $N_t$  increases (Fig. 3(b)).



159 160

Fig. 3. Relationship between VCI and  $F_c$ ,  $N_t$ : (a) VCI- $F_c$ ; (b) VCI- $N_t$ .

#### 161 **3 Test method for cyclic loading triaxial compression test**

162 The cyclic loading triaxial compression (CL) test was performed by a medium-size triaxial apparatus (Fig. 163 4). The pressure membrane method was adopted in CL tests for unsaturated specimens to apply the matric 164 suction (s). Here, s is defined as  $s = u_a - u_w$ ,  $u_a$  is pore air pressure, and  $u_w$  is pore water pressure. As for more 165 information about this triaxial apparatus, Ishikawa et al. (2014) and Yang et al. (2021) can be referred. The 166 preparation method of a cylindrical specimen (H = 300 mm, D = 150 mm) in this test was as follows: an air-167 dried sample (1/2CB, w = 1.69%; 1/2AB, w = 2.01%) was put into the mold in five layers step by step. Each 168 layer was compacted by the vibrator to achieve the targeted  $D_c$  values similar to the actual track conditions 169 shown in Table 1. It is worth noting that according to field investigations, the measured  $D_c$  of aged ballast in 170 the field condition is close to or even greater than the maximum  $D_{\rm c}$  obtained from the compaction E-b method.

171	In E-B method, the number of compacted layers for a test sample was 3 layers, and each layer was dropped 92
172	times through a rammer (rammer mass is 4.5 kg) with the drop height of 450 mm. In this case, a larger $D_c$ (i.e.,
173	$D_{\rm c} = 101\%$ for 1/2AB) in the laboratory element test than the maximum $D_{\rm c}$ can be obtained by controlling the
174	vibration time of the sample. The uniformity of a specimen was ensured because the variations in the initial dry
175	density of the same sample were less than 1%. The test conditions of the CL tests in this study were shown in
176	Table 2. As shown in Table 2, CL tests were performed under three different water contents (air-dried,
177	unsaturated ( $s = 5$ kPa), and saturated) according to the standards of Japanese Geotechnical Society (JGS 0523-
178	2009; JGS 0524-2009; JGS 0527-2009). It is noted that the s of 5 kPa was selected under the unsaturated
179	condition because results of water retention tests (Fig. 5) showed that the water content of the two test samples
180	hardly decreases when the s was greater than 5 kPa. Besides, the effective confining pressure ( $\sigma'_c$ ) or net normal
181	stress ( $\sigma_{net}$ ) of 20 kPa was selected in CL test, which was referred to that in monotonic loading triaxial
182	compression (ML) test as shown in Table 3 (Yang et al., 2021). Here, $\sigma_{net}$ is defined as $\sigma_{net} = \sigma_c - u_a$ ( $\sigma_c$ : confining
183	pressure), and the $\sigma_{net}$ under the unsaturated condition was similar to the $\sigma'_c$ ( $\sigma'_c = \sigma_c - u_a$ ) under the air-dried
184	condition or $\sigma'_{c}$ ( $\sigma'_{c} = \sigma_{c} - u_{w}$ ) under the saturated condition. More importantly, the $\sigma'_{c}$ or $\sigma_{net}$ in CL tests was close
185	to the effective overburden pressure of the typical ballasted track in field conditions (Indraratna et al., 2013b;
186	Suiker et al., 2005).

Table 2 Test conditions a	and results of CL tests.
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Sample	Drainage condition	Water content	$\sigma'_{\rm c}, \sigma_{\rm net}$	$\rho_{\rm dc}$	$D_{\rm c}$	$S_{\rm r}$	$\mathcal{E}_{p, \max}$
	e		(kPa)	(g/cm <sup>3</sup> )	(%)	(%)	(%)
1/2CB	CD test	Air-dried	20.0	1.571	95.1	4.22	1.08
1/2CB	CD test	Unsaturated ( $s = 5$ kPa)	20.0	1.539	93.2	10.62	2.97
1/2CB	CD test	Saturated	20.0	1.541	93.3	100	3.53
1/2AB	CD test	Air-dried	20.0	2.220	101.6	21.7	0.65
1/2AB	CD test	Unsaturated ( $s = 5$ kPa)	20.0	2.198	100.6	67.2	6.40
1/2AB	CD test	Saturated	20.0	2.205	100.9	100	12.09
1/2AB	CU test	Air-dried	20.0	2.196	100.5	21.3	0.97
1/2AB	CU test	Unsaturated ( $s = 5$ kPa)	20.0	2.195	100.5	68.5	8.24
1/2AB	CU test	Saturated	20.0	2.199	100.6	100	Failed

Table 3 Test conditions and results of ML tests (Yang et al., 2021).

Sample	Drainage condition	Water content	$\sigma'_{\rm c}, \sigma_{\rm net}$	$\phi'$	с', с
Sample	Dramage condition	water content	(kPa)	(deg.)	(kPa)
1/2CB	CD test	Air-dried	20.0, 40.0	58.9	0
1/2CB	CD test	Unsaturated ( $s = 5$ kPa)	20.0, 40.0	55.3	1.6
1/2CB	CD test	Saturated	20.0, 40.0	55.3	0
1/2AB	CU test	Air-dried	20.0, 40.0	59.4	5.1
1/2AB	CU test	Unsaturated ( $s = 5$ kPa)	20.0	49.5	9.4
1/2AB	CU test	Saturated	20.0, 40.0	49.5	4.8

- 190  $\sigma'_{c}$  is the effective confining pressure under air-dried and saturated conditions;  $\sigma_{net}$  is the net normal stress in 191 unsaturated condition;  $\phi'$  is the effective friction angle; c' stands for effective cohesions under saturated and air-
- dried conditions; c stands for total cohesion under unsaturated condition, which is composed of two parts: one
- 172 und conditions, c stands for total concision under unsaturated condition, which is composed of two parts, one
- 193 is the effective cohesion (c') of the saturated soil, and the other is related to the matric suction, as shown in Eq.
- 194 (2) (Fredlund et al., 1978).

- $c = c' + (u_a u_w) \tan \phi^b \tag{2}$
- 196 where,  $\phi^b$  is the internal friction angle with respect to the matric suction.



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199 Fig. 4. Medium-size triaxial test apparatus for unsaturated soils: (a) schematic diagram; (b) structures of cap and pedestal

(after Yang et al., 2021).

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201



203

Fig. 5. Soil water characteristic curves of test samples (revised after Yang et al., 2021).

204 In a CL test, the consolidation process was conducted as follows. Under the air-dried condition, the 205 specimen after the preparation was isotropically consolidated under a designated  $\sigma'_{c}$  of 20 kPa. Under the 206 saturated condition, the de-aired water was supplied from the bottom end of the specimen, and the pore water 207 pressure  $(u_w)$  of 200 kPa was applied to ensure the pore water pressure coefficient B-value was above 0.96. 208 Following the saturation process, the specimen was isotropically consolidated under a specified  $\sigma'_{\rm c}$  of 20 kPa 209 for 24 hours with  $\sigma_c$  of 220 kPa and the  $u_w$  of 200 kPa. Under the unsaturated condition, the de-aired water was 210 immersed from the bottom of the specimen until the initial degree of saturation reached about 90%. Afterwards, 211 the specimen was isotropically consolidated under a prescribed  $\sigma_{net}$  of 20 kPa for 24 hours with  $\sigma_c$  of 220 kPa, 212 pore air pressure ( $u_a$ ) of 200 kPa, and  $u_w$  of 200 kPa. After the consolidation process, an unsaturated specimen 213 with the s of 5 kPa was prepared by reducing  $u_w$  while keeping both  $\sigma_c$  and  $u_a$  unchanged. Next, the shearing 214 process started after the equilibrium condition was reached in the suction process. The axial deviator stress ( $\sigma_d$ ) 215 in sinusoidal waveform ranged from 10 kPa to 80 kPa was cyclically applied to the test specimen of 1/2CB and 216 1/2AB under the different drainage conditions. In this study, the CL tests for the test specimen of 1/2CB were 217 conducted in CD tests due to its high permeability, while those of 1/2AB were conducted in both CD and CU 218 tests due to its low permeability as shown in Table 1. It is noted that under the unsaturated condition, both pore 219 water and pore air were allowed to drain in the CD test, while both were undrained in the CU test. The number 220 of loading cycles (N<sub>c</sub>) in the CL test was 10, 000 or the specimen was failed (permanent axial strain,  $\varepsilon_p > 15\%$ ), 221 and the loading frequency of 1 Hz was selected by referring to previous research on simulated train loads (Cai 222 et al., 2017; Chazallon et al., 2016).

#### 223 4 Test results and discussions

#### 4.1 Stress-strain relationship of aged ballast

225 Fig. 6 and Fig. 7 present the relationships between axial strain ( $\varepsilon_a$ ) and axial deviator stress ( $\sigma_d$ ) of 1/2CB 226 and 1/2AB with various water contents at different number of loading cycles ( $N_c$ ) in CD and CU tests. When 227 other test conditions except the water content are constant, the elastic and plastic strains of both samples increase 228 with the increment of water content. Besides, when comparing stress-strain relationships for both samples in 229 CD tests under unsaturated and saturated conditions, the stiffness of 1/2AB is softer than that of 1/2CB, and the 230 plastic strain rate of 1/2AB is greater than that of 1/2CB, though the stress-strain relationships of both samples 231 are almost similar under air-dried condition. On the other hand, when comparing test results for 1/2AB in CD 232 and CU tests, the difference in the stress-strain relation becomes clear with increasing the water content, and 233 the saturated 1/2AB in the CU test has the largest plastic stain rate. It is worth noting that the stress-strain 234 relationships for unsaturated samples are different in CD and CU tests, since both pore water pressure and pore 235 air pressure change in the CU test due to the fully undrained conditions. In this case, the net normal stress (or 236 effective confining pressure) is not constant in the CU test, while it remains constant in the CD test. Furthermore, 237 as shown in Fig. 6(b), Figs. 7(c) and (d), when comparing the stress-strain relations at different  $N_c$  ( $N_c$ =10 and 238 1000), the area of the stress-strain hysteresis curve decreases as the  $N_{\rm c}$  increases, regardless of test samples, 239 water contents, and drainage conditions. More importantly, the changing trend of the stress-strain relationship 240 is more significant for 1/2CB, which indicates that aging changes the development trend of plastic deformation 241 of ballast. These results indicate that the water content, drainage condition, and ballast aging have significant 242 influences on the plastic strain of ballast. As the water content increases, the aged ballast with much fine fraction 243 content and rounded particle shape might reduce the interlock between particles, thereby the lubricating effect 244 of water content and fine fraction content changes the stress-strain relationship of the ballast. Besides, the 245 reduction of  $\sigma'_{c}$  in CU tests further increases the development of plastic strain, which will be discussed in a later 246 section.



Fig. 6. Stress-strain relationship for 1/2CB with different water contents /  $N_c$  in CD tests: (a)  $N_c = 1000 \sim 1005$ ; (b)  $N_c = 10$ and 1000.





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Fig. 7. Stress-strain relationships for 1/2AB with different water contents /  $N_c$  in CD and CU tests: (a) CD test, N<sub>c</sub>=1000~1005; (b) CU test, N<sub>c</sub>=1000~1005; (c) CD test, N<sub>c</sub>=10 and 1000; (d) CU test, N<sub>c</sub>=10 and 1000.



For the plastic deformation of the granular material, the "shakedown theory" (Arnold et al., 2002; Werkmeister et al., 2004; Xiao et al., 2017) was commonly used to describe the plastic deformation and breakage rules of the granular material under cyclic loading. In general, the shakedown behavior of the granular material under cyclic loading includes three stages (Werkmeister et al., 2004): plastic shakedown (steady

259 deformation behavior), plastic creep (failure at a large number of loading cycles), and incremental collapse (failure at a small number of loading cycles), as shown in Fig. 8(a). In addition, Werkmeister et al. (2004) 260 261 pointed out that the relationship between the plastic strain rate and the plastic strain can be used to distinguish 262 these three types of shakedown behavior, as shown in Fig. 8(b). Region A indicates the plastic shakedown stage, 263 where the plastic strain rate decreases sharply as the plastic strain increases. Region B reveals the plastic creep 264 stage, where the plastic strain rate decreases sharply at first, and then tends to be stable with an increase in 265 plastic strain. Region C indicates the incremental collapse stage, where the plastic strain rate decreases slightly 266 as the plastic strain increases. For the plastic strain rate of railway ballast, previous studies (Mamou et al., 2017; 267 Sun et al., 2019) illustrated that there is a threshold stress level above which significant accumulation of plastic 268 strain and generation of excess pore pressure occurs, especially in undrained conditions. It is noted that Xiao et 269 al. (2017) pointed out that the fresh ballast is generally in a plastic shakedown or plastic creep state after 270 hundreds of loading cycles.



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Fig. 8. Typical shakedown behaviors of granular materials under cyclic loading: (a) schematic diagram of the shakedown
 theory (revised after Werkmeister et al., 2004); (b) relationship between plastic strain rate and plastic strain.

Fig. 9 shows the relationships between the permanent axial strain ( $\varepsilon_p$ ), volumetric strain ( $\varepsilon_v$ ), resilient axial strain ( $\varepsilon_{res}$ ) and number of loading cycles ( $N_c$ ) up to 10, 000 cycles for test specimens of 1/2CB and 1/2AB with various water contents and drainage conditions. Here,  $\varepsilon_p$  represents permanent axial strain (cyclic plastic strain) at unloading, and  $\varepsilon_{res}$  represents the resilient axial strain between the loading and unloading. The  $\varepsilon_p$  of all specimens shows a rapid growth trend in the initial cyclic loading process, and then the increasing trend of  $\varepsilon_p$ becomes stable as the  $N_c$  increases, irrespective of test conditions. Besides, when comparing the  $\varepsilon_p$  under the

280 same test conditions except the water content, the  $\varepsilon_p$  of all specimens increases with the increment of water 281 content, irrespective of test samples. In CD tests for 1/2AB, the  $\varepsilon_p$  under the air-dried condition shows a stable 282 trend with the increment of  $N_c$ , while the  $\varepsilon_p$  under unsaturated and saturated conditions reveal an approximately 283 linear growth trend with the increment of  $N_c$ , as shown in Fig. 9(c). For the dilatancy behavior in CD tests, the 284 volume of unsaturated and saturated specimens is dilated, while the volume of the air-dried specimen is 285 compressed as the  $\varepsilon_p$  increases with the increment of  $N_c$ , irrespective of test samples. The reason for this 286 phenomenon is that the volumes of the fresh and aged ballasts are firstly compressed at axial strain ( $\varepsilon_a$ ) about 287 1%, followed by dilation with the increase in  $\varepsilon_a$  during the shear process (Yang et al., 2021). When other 288 conditions are unchanged, the specimen under the higher degree of saturation shows an upward trend in the 289 dilation due to the larger  $\varepsilon_p$ . Besides, the  $\varepsilon_{res}$  of both samples in CD tests increases by the sequences in air-dried, 290 unsaturated, and saturated specimens, though the differences in  $\varepsilon_{res}$  under different water contents are not 291 remarkable as those in the  $\varepsilon_p$ . Moreover, with the increment of  $N_c$ , the  $\varepsilon_{res}$  shows an increasing trend under the 292 air-dried condition, while it decreases under the unsaturated and saturated conditions. This is because the 293 unsaturated and saturated specimens have larger plastic deformation, which leads to an increase in density and 294 thus greater stiffness. The above results indicate that the permanent/residual axial and volumetric strains of fresh 295 and aged ballast in CD tests are affected by the water content. On the other hand, as shown in Fig. 9(e), the  $\varepsilon_{\rm p}$ 296 of 1/2AB under the air-dried condition presents a stable trend with the increment of  $N_c$  in CU tests, while  $\varepsilon_p$ 297 under unsaturated and saturated conditions shows an approximately linear increasing trend with the increment 298 of  $N_c$ . It is noted that under the saturated condition, 1/2AB is failed at the  $N_c$  of 5, 000 in the CU test. Besides, 299 as shown in Fig. 9(f),  $\varepsilon_{res}$  in CU tests increases by in the order of air-dried, unsaturated, and saturated specimens. 300 These results indicate that the cyclic plastic deformation of aged ballast is significantly affected by the water content in both CD and CU tests, and the effects of water content on the cyclic plastic deformation are more 301 302 significant in CU tests.



Fig. 9.  $\varepsilon_p$ ,  $\varepsilon_v$ , and  $\varepsilon_{res}$  of test samples with different water contents: (a)  $\varepsilon_p$  and  $\varepsilon_v$  of 1/2CB in CD tests; (b)  $\varepsilon_{res}$  of 1/2CB in CD tests; (c)  $\varepsilon_p$  and  $\varepsilon_v$  of 1/2AB in CD tests; (d)  $\varepsilon_{res}$  of 1/2AB in CD tests; (e)  $\varepsilon_p$  and  $\varepsilon_v$  of 1/2AB in CU tests; (f)  $\varepsilon_{res}$  of 1/2AB in CU tests.

309 4.3 Effects of drainage condition, water content, and aging on permanent axial deformation

#### 310 *4.3.1 Effect of drainage condition*

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311 Considering that the drainage condition may affect the permanent axial deformation of aged ballast due to 312 its low permeability, thus both CD and CU tests were conducted for the test specimen of 1/2AB. In this case, 313 Fig. 10(a) shows the comparisons of  $\varepsilon_p$  for 1/2AB between CD tests and CU tests. The  $\varepsilon_p$  of 1/2AB in CU tests 314 is larger than those in CD tests, irrespective of water contents. Besides, under the air-dried condition,  $\varepsilon_p$  of all 315 specimens is small, irrespective of drainage conditions. However, the differences in  $\varepsilon_p$  under unsaturated and 316 saturated conditions are remarkable between the two types of test conditions, especially under the saturated 317 condition. These findings indicate that in the high degree of saturation condition, the drainage condition has a 318 significant influence on the permanent axial deformation of aged ballast. For a clearer explanation, Fig. 10(b) 319 presents the relationship between the  $\varepsilon_{p, max}$  and  $S_e$  of 1/2AB. Here,  $\varepsilon_{p, max}$  means the maximum permanent axial strain at  $N_c$  of 10, 000, and the effective degree of saturation ( $S_e$ ) is the normalized water content between the 320 321 saturated state and the residual degree of saturation (Brooks and Corey, 1964).

$$S_{\rm e} = \frac{S_{\rm r} - S_{\rm rr}}{S_{\rm rs} - S_{\rm rr}} \tag{3}$$

where,  $S_{rs}$  is the degree of saturation under saturated conditions, and  $S_{rr}$  is the residual degree of saturation. It is noted that the  $S_e$  of the soil in the air-dried state in this study is considered to be zero. As can be seen in this figure, the  $\varepsilon_{p, max}$  in CU tests is larger than those in CD tests, regardless of  $S_e$ . More importantly, the difference in  $\varepsilon_{p, max}$  is greater as the water content increases. This indicates that the effect of drainage condition on the permanent axial strain becomes more significant at the higher water content.





Fig. 11 shows the changes in  $u_w$  and  $\varepsilon_p$  for 1/2AB in CU tests. It is worth mentioning that the increasing 330 trend of excess pore water pressure in the saturated condition is larger than that in the unsaturated condition, 331 332 which is a probable reason why the saturated specimen is failed at the  $N_c$  of 5, 000. It can be inferred that the 333 excess pore water pressure generated in the CU test is one of the factors that affect the permanent axial 334 deformation of the aged ballast. In addition, the water content itself can reduce the shear strength of aged ballast, 335 and induce a greater permanent axial deformation. Besides, the excess pore water pressure shows a whole increasing trend with the N<sub>c</sub>, though it shows a downward trend in the initial loading process, irrespective of 336 337 water content. It is noted that the excess pore water pressure is generated even for the unsaturated sample, since 338 the degree of saturation of 1/2AB under the unsaturated condition is about 70% (Fig. 5). This indicates that due 339 to the low permeability of the heavily aged ballast, the excess pore pressure is easily generated even in an 340 unsaturated state under the repeated train loads, which is consistent with the phenomenon of aged railway tracks 341 under the field condition.

342 Similar to the increasing trend of excess pore water pressure with the increment of  $N_c$  in CU tests, the  $\sigma'_c$ 343 of 1/2AB shows a whole decreasing trend with the increment of  $N_c$ , though an increasing trend is observed in 344 the initial loading process, as shown in Fig. 12. To be specific, when the  $N_c$  is greater than 500, the  $\sigma'_c$  decreases 345 as the increment of the  $N_c$  and the final values of  $\sigma'_c$  in CU tests are smaller than those in CD tests, regardless of 346 water contents. The decrease in  $\sigma'_{c}$  in CU tests is a reason why the  $\varepsilon_{p}$  in CU tests under the same initial test 347 condition is higher than that in CD tests. Besides, the change in  $\sigma'_{c}$  in CU tests is related to the dilatancy trend 348 of the test specimen. When comparing the final values of  $\sigma'_{c}$  under different water content conditions, the final 349 value of  $\sigma'_{c}$  of the saturated specimen is lower than those of unsaturated and air-dried specimens. This is because 350 the positive dilatancy trends become stronger by the sequences in air-dried, unsaturated, and saturated 351 specimens. These results demonstrate that the permanent axial strain of aged ballast is affected by the drainage 352 condition. Considering that the high  $S_{\rm rr}$  and low permeability of the aged ballast, the in-situ aged ballast is almost 353 under a partially or fully undrained condition with a high degree of saturation. In general, the cyclic loading 354 tests for fresh and fouled ballasts in an air-dried condition have been carried out in the past researches so far. However, these results indicate that the cyclic loading tests for unsaturated and saturated specimens in partially 355 356 and fully undrained conditions should be adopted for the accurate estimation of cyclic plastic deformation of 357 heavily aged ballast, though the cyclic loading tests for an air-dried specimen in fully drained condition is



358 suitable for evaluating the permanent deformation of fresh or slightly aged ballast.





Fig. 11. Changes in pore water pressure/permanent axial strain of 1/2AB in CU tests.





362

Fig. 12. Changes in effective confining pressure of 1/2AB in CU tests.

363 *4.3.2 Effect of water content* 

To evaluate the effect of water content on the  $\varepsilon_{p}$ , Fig. 13(a) shows the effect of water content on  $\varepsilon_{p}$  for both samples in CD tests. When the other initial test conditions are constant except for the water content, the  $\varepsilon_{p}$ increases with the increase in water content, irrespective of test samples. Furthermore, the wetting causes aged ballast to increase  $\varepsilon_{p}$  dramatically as compared with fresh ballast. As shown in Fig. 13(b), the  $\varepsilon_{p, max}$  appears a remarkable increasing trend under the higher  $S_{e}$ , regardless of test samples and drainage conditions. These results reveal that the water content has serious influence on permanent axial deformation of both samples, especially for the aged ballast.



Fig. 13. Effect of water content on  $\varepsilon_p$  and  $\varepsilon_{p, max}$ : (a)  $\varepsilon_p - N_c$ ; (B)  $\varepsilon_{p, max} - S_e$ .

#### 373 *4.3.3 Effect of aging*

374 As for the effect of aging on the  $\varepsilon_p$  of ballast, the different tendency of  $\varepsilon_p$  between fresh and aged ballasts is due to their plastic strain rate being in different "Regions", as shown in Fig. 8(b). It is noted that the plastic 375 strain rate for the fresh and aged ballast was calculated by the increment of plastic strain at each loading cycle 376 during the whole cyclic loading. As illustrated in this figure, the plastic strain rate of the fresh ballast is generally 377 378 in the Region A, while the plastic strain rate of the aged ballast is generally in the Region B or the Region C. 379 These indicate that the aging significantly changes the tendency of the plastic strain of the ballast from plastic 380 shakedown to incremental collapse stage, though the cyclic stress level of different samples is the same in this study. Furthermore, Fig. 14(a) presents the relationship between the  $\varepsilon_{p, max}$  and  $F_c$ . As can be seen in this figure, 381 382  $\varepsilon_{p, max}$  of 1/2AB is higher than those of 1/2CB in unsaturated and saturated conditions, though the opposite trend 383 appears in the air-dried condition. The changing trend of the  $\varepsilon_{p, max}$  with various water contents is similar to that 384 of maximum principal stress ratio  $((\sigma'_1/\sigma'_3)_{max})$  in the same condition shown in Fig. 14(b) (Yang et al., 2021). 385 These results indicate that the both water content and aging synergistically affect the permanent axial strain of 386 the ballast, and the increase in water content caused by ballast aging negatively enhances the adverse effects on 387 the permanent axial strain. In addition, it should be emphasized that the effects of particle shape changes and 388 increase in fine fraction content on the permanent axial strain of aged ballast are considered simultaneously in 389 this study, though the effect of particle shape changes was not evaluated in previous studies on fouled ballast 390 (Indraratna et al., 2011; Ishikawa et al., 2019). Compared with previous studies, test results in this study indicate 391 that aged ballast has an unexpected smaller permanent axial strain than those of fresh and fouled ballasts in the

392 air-dried condition, while it has a larger permanent axial strain than those of fouled ballast in unsaturated and 393 saturated conditions. The reasonable explanation for this phenomenon is that the smaller and rounder particles 394 produced in the process of ballast breakdown and abrasion might provide a weakening effect in the aggregate matrix by preventing contact between large particles thus greatly reducing the aggregate matrix in the 395 396 unsaturated and saturated conditions, though the fine particles can also provide a stabilizing effect by filling the 397 voids among larger particles in the air-dried condition. Conclusively, the difference in permanent axial strain 398 between fouled ballast and aged ballast demonstrates that when evaluating the permanent axial strain of aged 399 ballast, it is essential to consider the influence of particle shape, fine fraction content, and water content 400 comprehensively.



401 402

Fig. 14. Effect of aging on  $\varepsilon_{p, \max}$ ; and  $(\sigma'_1/\sigma'_3)_{\max}$ : (a)  $\varepsilon_{p, \max}$ ; (b)  $(\sigma'_1/\sigma'_3)_{\max}$  (after Yang et al., 2021).

403 From the above analysis, the results of ML tests and CL tests illustrate that the  $\tau_{\rm f}$  and  $\varepsilon_{\rm p, max}$  are affected by 404 the water content and ballast aging. Thus, the relationships between the  $\varepsilon_{p, max}$  and  $\tau_{f}$  with various water contents 405 and drainage conditions are shown in Fig. 15. As expected, the samples with a lower  $\tau_{\rm f}$  appear a higher  $\varepsilon_{\rm p, max}$ , 406 irrespective of test samples and drainage conditions. This indicates that the water content and aging have similar 407 effects on the shear strength and permanent axial strain of ballast, that is the increase in water content or aging 408 might cause a decrease in shear strength and an increase in permanent axial deformation of ballast, and the 409 downward/upward trend of shear strength/permanent axial deformation is more remarkable for aged ballast 410 under the high-water content condition.



426

Fig. 15. Relationship between  $\varepsilon_{p, max}$  and  $\tau_{f}$ .

### 413 5 Estimation of permanent axial deformation of unsaturated ballast

#### 414 5.1 Estimation of permanent axial deformation by UIUC model

The UIUC model belongs to a semi-empirical model, and its input parameters can be obtained from ML tests (Qamhia et al., 2016). Therefore, in this section, the applicability of the UIUC model is evaluated by comparing the predicted results by this model with measured results from CL tests. For this model, the permanent axial strain can be calculated as follows:

419 
$$\varepsilon_{\rm p} = A N_{\rm c}^{\ B} \sigma_{\rm d}^{\ C} \left(\frac{\tau_{\rm f}}{\tau_{\rm max}}\right)^D \tag{4}$$

420 where,  $\varepsilon_p$  is the permanent axial strain corresponding to  $N_c$  applications (%);  $\sigma_d$  is the axial deviator stress (kPa); 421 *A*, *B*, *C*, *D* are regression parameters. Besides,  $\tau_f$  and  $\sigma_f$  are the applied effective shear stress and applied effective 422 normal stress acting on failure plane calculated by Eq. (5) and Eq. (6), respectively;  $\tau_{max}$  is the maximum 423 effective shear stress at  $\sigma_f$  calculated by Eq. (7) determined by ML tests.

424 
$$\tau_{\rm f} = \sqrt{\left(\frac{\sigma_{\rm d}}{2}\right)^2 - \left(\sigma_{\rm f} - \left(\sigma_{\rm 3}' + \frac{\sigma_{\rm d}}{2}\right)\right)^2} \tag{5}$$

425 
$$\sigma_{\rm f} = \frac{2\sigma_3' + 2\tan^2 \phi' \sigma_3' + \sigma_{\rm d} + \tan^2 \phi' \sigma_{\rm d} - \sqrt{\tan^2 \phi' \sigma_{\rm d}^2 + \tan^4 \phi' \sigma_{\rm d}^2}}{2(1 + \tan^2 \phi')} \tag{6}$$

$$\tau_{\rm max} = c + \sigma_{\rm f} {\rm tan} \phi' \tag{7}$$

427 where  $\sigma'_3$  is the minimum effective principal stress, which is equal to  $\sigma'_c$  in CL tests; *c* stands for total cohesions 428 of both samples with different water contents, as shown in Table 3. It is noted that the *c* of test samples in air-429 dried and saturated conditions is equal to the effective cohesion (*c'*).

430 The input parameters and the corresponding regression parameters of UIUC model for 1/2CB and 1/2AB 431 are shown in Table 4 and Table 5, respectively. It is noted that the input parameters of c and  $\phi'$  for 1/2CB were 432 determined by CD tests, while c and  $\phi'$  for 1/2AB are determined by CU tests. The regression parameters in 433 Table 5 were obtained by fitting the results of CL tests at different water contents for each test sample. As shown 434 in Table 5, 1/2AB has the higher A and D values than those of 1/2CB. It means that the aged ballast shows a 435 higher initial permanent axial deformation, and that the effect of  $(\tau_{\rm f}/\tau_{\rm max})$  on permanent axial strain becomes 436 more pronounced for the aged ballast as compared with fresh ballast. These indicate that it is feasible to predict the permanent axial strain of fresh and aged ballasts with various water contents by the UIUC model. 437



#### Table 4 Input parameters of UIUC model.

	1/2CB	1/2CB	1/2CB	1/2AB	1/2AB	1/2AB
Input Parameters	Air-dried,	s=5 kPa,	Saturated,	Air-dried,	s=5 kPa,	Saturated,
	CD test	CD test	CD test	CD test	CD test	CD test
$\sigma_{\rm d}$ (kPa)	80	80	80	80	80	80
$\sigma_{ m f}( m kPa)$	25.77	27.11	27.11	25.57	29.58	29.58
$\tau_{\rm f}({\rm kPa})$	20.69	22.77	22.77	20.36	25.98	25.98
<i>c</i> (kPa) (Yang et al., 2021)	0	1.6	0	5.1	9.4	4.8
$\phi'$ (deg.) (Yang et al., 2021)	58.9	55.3	55.3	59.4	49.5	49.5
$ au_{ m max}( m kPa)$	42.64	40.73	39.16	48.34	44.04	39.44
$ au_{ m f}/ au_{ m max}$	0.485	0.559	0.581	0.421	0.590	0.659

Table 5 Regression parameters of UIUC model.

Samula	During as a solution	Regression	Regression parameters						
Sample	Drainage condition	A	В	C	D	$R^2$			
1/2CB	CD test	0.1938	0.1306	1.2130	6.5239	0.9801			
1/2AB	CD test	0.3162	0.6843	0.1066	7.5684	0.9960			
1/2AB	CU test (S)	0.3162	0.6843	0.1066	7.5684	-			
1/2AB	CU test (D)	0.6020	0.6266	0.1022	6.8378	0.9397			

440 CU test (S) and CU test (D) mean that the same and different regression parameters from CD tests were adopted in CU 441 tests.

Fig. 16 compares the measured and estimated permanent axial strains of 1/2CB with various water contents. The estimated values by the UIUC model using the same regression parameters (Table 5) are consistent with measured values even though the water contents are different. This indicates that the effect of water content on permanent axial deformation of fresh ballast can be effectively estimated by UIUC model. Then, in order to evaluate the applicability of this model to the prediction for the permanent axial deformation of aged ballast,

447 Fig. 17 compares the measured and estimated permanent axial strains of 1/2AB with different water contents and drainage conditions. It is noted that the regression parameters of 1/2AB are different from those of 1/2CB 448 449 as shown in Table 5. In addition, the input parameters of  $\sigma_d$ ,  $\tau_f$ , and  $\tau_{max}$  in Eq. (4) in CU tests are changed due to the change in the  $\sigma'_3$ , which can be calculated by the Eqs. (5) ~ (7). Subsequently, the permanent axial strain 450 451  $(\varepsilon_{p,i})$  at different  $N_{c,i}$  in CU tests can be calculated with different  $\sigma_{d,i}$ ,  $\tau_{f,i}$ , and  $\tau_{max,i}$  by Eq. (8). The reason for the 452 fluctuation of the predicted values seen in Fig. 17(b) is that the input parameters of  $\sigma_{d,i}$ ,  $\tau_{f,i}$ , and  $\tau_{max,i}$  are changed as the  $\sigma'_3$  changes in CU tests, while these input parameters are constants adopted for the estimation of CD tests 453 454 (Table 4).

455 
$$\varepsilon_{p,i} = \varepsilon_{p,i-1} + A \left( N_{c,i} \right)^B \sigma_{d,i}^C \left( \frac{\tau_{f,i}}{\tau_{\max,i}} \right)^D - A \left( N_{c,i-1} \right)^B \sigma_{d,i}^C \left( \frac{\tau_{f,i}}{\tau_{\max,i}} \right)^D$$
(8)

456 where,  $N_{c,i}$  represents the  $N_c$  is ith;  $N_{c,i-1}$  represents the  $N_c$  is (i-1)th;  $\varepsilon_{p,i}$  is the permanent axial strain at the  $N_{c,i}$ ; 457  $\varepsilon_{p,i-1}$  is the permanent axial strain at the  $N_{c,i-1}$ ;  $\sigma_{d,i}$ ,  $\tau_{f,i}$ , and  $\tau_{max,i}$  are the axial deviator stress, effective shear stress, 458 and effective shear strength at the  $N_{c,i}$ . It can be seen that the estimated permanent axial strains of 1/2AB by 459 UIUC model are consistent with measured values in CD tests (Fig. 17(a)), irrespective of water contents, while 460 the estimated values are different from measured values in CU tests (Fig. 17(b)). The possible reason is that the 461 UIUC model cannot reproduce the effect of the change in excess pore water pressure (Fig. 11) caused by cyclic 462 loading in CU test on the mechanical behavior of ballast. On the other hand, when using different regression 463 parameters from those for CD tests, the estimated values by the UIUC model are consistent with measured 464 values in air-dried and unsaturated conditions, though the estimated value is smaller than the measured value in 465 the saturated condition, as shown in Fig. 17(c). These results prove that the permanent axial deformation of 466 fresh and aged ballasts with various water contents in CD tests can be well estimated by UIUC model by using 467 the same regression parameters, while the applicability of UIUC model to the prediction for permanent axial 468 deformation of aged ballast may be limited in CU tests, since it is difficult to predict the change in excess pore 469 pressure under cyclic loading.



Fig. 16. Comparison of  $\varepsilon_p$  for 1/2CB with various water contents in CD tests.





472

474 Fig. 17. Comparison of  $\varepsilon_p$  for 1/2AB with various water contents: (a) CD test; (b) CU test (S); (c) CU test (D). 475 5.2 Estimation of permanent axial deformation by SSE model

476 The reliability of the SSE model is discussed by comparing the results of CL tests for fresh and aged 477 ballasts under various water contents with the numerical results. The input parameters of SSE model for 1/2CB 478 and 1/2AB under various water contents and drainage conditions were listed in Table 6. Here, the  $\sigma_c'$  can be 479 determined from the CL test.  $F_0$  can be determined from the ML test (Wood, 1990).  $\mu$  can be determined from the ML test (Qi et al., 2020).  $\phi'$  can be obtained from the ML test.  $\lambda$  and  $\kappa$  can be determined from the isotropic compression test, which refers to previous study on air-dried ballast (Okayasu et al., 2014). In accordance with observations reported in Alonso et al. (1990),  $\lambda$  depends on the matric suction (*s*), which can be determined from CL tests. Besides,  $p_i$ , U(R), U(Re), and  $R_e$  are material constants independent on water content, while  $R_{emax}$ changes depending on the water content, all of which can be fitted by the results of CL tests.

485

Table 6	Input parame	eters of SSE model
1 4010 0	mput putum	

Sample	1/2CB	1/2CB	1/2CB	1/2AB	1/2AB	1/2AB
Drainage condition	CD test CD test, CU test					
Water content	Air-dried	s=5 kPa	Saturated	Air-dried	s=5 kPa	Saturated
$\sigma'_{c}$	20	20	20	20	20	20
$F_0$	1078	887	842	1186	895	792
μ	0.3	0.3	0.3	0.3	0.3	0.3
$\phi'$	58.9	55.3	55.3	59.4	49.5	49.5
λ	0.05	0.07	0.09	0.05	0.07	0.09
K	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
$p_i$	45	45	45	45	45	45
U(R)	20	20	20	150	150	150
$U(R_{\rm e})$	4	4	4	25	25	25
Re	0.001	0.001	0.001	0.001	0.001	0.001
R <sub>emax</sub>	0.150	0.067	0.060	0.047	0.037	0.022

486  $\sigma'_c$  is the effective confining pressure;  $F_0$  is an initial value of the size of the normal yield surface;  $\mu$  is the Poisson ratio;  $\lambda$ 487 and  $\kappa$  are the slopes of the normal-consolidation and swelling line;  $p_i$ , U(R), and  $U(R_e)$  are material constant;  $R_e$  is a ratio 488 of the size of the elastic boundary surface to the size of the normal-yield surface;  $R_{emax}$  is the maximum value of the  $R_e$ . 489 Fig. 18 compares the permanent axial strain of 1/2CB with various water contents between simulations and 490 tests. It can be found that the predicted values by SSE model are consistent with measured values, regardless of 491 water contents. These results prove that the applicability of the SSE model to the prediction for the permanent 492 axial deformation of fresh ballast by considering the effect of water content.



493



Fig. 18. Comparison of  $\varepsilon_p$  for 1/2CB in CD tests between simulations and tests.

495 On the other hand, Fig. 19 compares the simulated and measured permanent axial strains of 1/2AB in 496 different drainage conditions. As can be seen in Fig. 19(a), the permanent axial strains of 1/2AB with various 497 water contents in CD tests can be well predicted by SSE model. However, as shown in Fig. 19(b), there is a 498 certain difference between the estimated and measured permanent axial strain of 1/2AB in CU tests, and with 499 increasing Sr, the difference becomes larger due to the generation of excess pore water pressure. This is because 500 only a mechanical model in numerical simulations is adopted in this study, which causes the SSE model cannot 501 accurately predict the change in excess pore water pressure under cyclic loading. These results prove that the 502 SSE model can well predict the permanent axial deformation of fresh and aged ballasts with various water 503 contents in CD tests, and there is a possibility for improving the prediction accuracy of the SSE model for aged 504 ballast in CU tests by employing a hydro-mechanical model.





506

Fig. 19. Comparisons of  $\varepsilon_p$  for 1/2AB between simulations and tests: (a) CD test (b) CU test.

507 To analyze the influence of water content on input parameters of SSE model for both samples, the changes 508 in normalized input parameters with the effective degree of saturation ( $S_e$ ) for 1/2CB and 1/2AB are shown in 509 Fig. 20. It is noted that this figure only plots input parameters that change with S<sub>e</sub>, instead of all input parameters. 510 Here, the value of each input parameter of 1/2CB in the air-dried condition is taken as the standard value, and 511 the values of normalized input parameters under various test conditions are the ratio of original values to 512 standard values. It shows that the  $F_0$  decreases with the increase in water content, regardless of test samples. As 513 for the U(R),  $U(R_e)$  and  $R_e$ , they are unchanged with various water contents, regardless of test samples. Besides, 514 the  $R_{\rm emax}$  decreases with the increment of  $S_{\rm e}$ , irrespective of test samples and drainage conditions. As for the  $\phi'$ 515 in the unsaturated condition, Fredlund et al. (1978) proposed that an increase in matric suction (s) results in an

516 increase in the apparent cohesion while maintaining the same  $\phi'$  as the saturated soils. In this case, when other test conditions are constant, the  $\phi'$  maintains constant, even though the S<sub>e</sub> changes, except in the air-dried 517 518 condition. Moreover, as the  $S_e$  increases, the  $\lambda$  increases while the  $\kappa$  does not change, which is consistent with 519 the results of Alonso et al. (1990). On the other hand, previous study (Yang et al., 2021) revealed that the  $S_e$  of 520 the fresh ballast is generally below 0.016 and the  $S_e$  of the aged ballast is generally above 0.66 in the field 521 conditions. In this case, the input parameters of the fresh ballast under the air-dried condition can reproduce actual conditions for a new railway line, while the input parameters of the aged ballast under the saturated 522 523 condition can simulate actual conditions for an old railway line since when the  $S_e$  is greater than 0.66, the 524 normalized input parameters of the aged ballast show a small change with the water content.



Fig. 20. Relationship between normalized input parameters and S<sub>e</sub> of test samples: (a): 1/2CB in CD tests; (b) 1/2AB in
 CD and CU tests.

### 528 6 Conclusions

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In this study, the influence of aging on cyclic plastic deformation of unsaturated ballast was evaluated by performing a series of the CL tests. After that, the applicability of the UIUC model and the SSE model was verified to the prediction for the cyclic plastic deformation of unsaturated ballast by considering aging effects. The following findings can be mainly obtained:

• The permanent axial deformation of ballast increases with the increase in water content, irrespective of test samples and drainage conditions, and wetting has a more significant impact on the permanent axial deformation of aged ballast as compared with fresh ballast. It can be inferred that the water content and aging effect synergistically affect the permanent axial deformation of ballast, and this is the reason why the aged ballast with a high degree of saturation would appear a greater permanent axial deformation than that of fresh
ballast with a low degree of saturation at the field condition.

• For the aged ballast, the permanent axial deformation in CU tests is larger than that in CD tests, regardless of water contents. Besides, the effect of drainage conditions on the cyclic plastic deformation for aged ballast becomes more significant as the degree of saturation increases since the excess pore water pressure increases significantly at higher degree of saturation.

• The shear strength and permanent axial deformation are affected by the water content and aging. When other test conditions are constant, the unsaturated ballast with the lower shear strength in the monotonic loading condition has the higher permanent axial deformation in the cyclic loading condition, irrespective of test samples and drainage conditions. The decreasing/increasing trend of shear strength/permanent axial deformation is more remarkable, in case of both the water content and fine fraction content increase.

Aged ballast has smaller permanent axial strain than that of fouled ballast under the air-dried condition, while
 it has a larger permanent axial strain than that of fouled ballast under unsaturated and saturated conditions.
 Thus, the difference in permanent axial strain between fouled ballast and aged ballast demonstrates that when
 evaluating the permanent axial strain of aged ballast, it is essential to consider the influence of particle shape,
 fine fraction content, and water content comprehensively.

In CD tests, the influence of water content on the permanent axial deformation of fresh and aged ballasts can
 be well estimated by the UIUC model with the same regression parameters, even though water contents are
 different. However, in CU tests, the applicability of the UIUC model to the prediction for the permanent
 axial deformation of aged ballast is limited, since it is difficult to predict the change in excess pore pressure
 under cyclic loading.

• The SSE model can well predict the permanent axial deformation of fresh and aged ballasts with different water contents in CD tests. Thus, the input parameters of the fresh ballast under the air-dried condition can reproduce actual conditions for a new railway line. On the other hand, the effect of water content on the permanent axial deformation of aged ballast in CU tests could not accurately predict by the SSE model, since a mechanical model was adopted in this study. However, the input parameters of the aged ballast under the

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saturated condition may simulate actual conditions for an old railway line when the hydro-mechanical analysis is adopted.

565 The findings of this research indicate that it is necessary to consider the effects of the drainage condition and water content on the hydro-mechanical behavior of the aged ballast, due to the low permeability and high 566 567 residual degree of saturation. For the fresh ballast, the air-dried specimen in triaxial tests under the fully drained 568 condition can reproduce the actual conditions. However, for the aged ballast, the unsaturated and saturated 569 specimens in triaxial tests under partially and fully undrained conditions can reproduce the actual conditions. 570 Therefore, for the actual design, when evaluating the cyclic plastic deformation of the aged ballast, it is important to first consider the hydraulic properties (i.e., permeability and water retentivity), and select 571 572 appropriate test conditions (i.e., CD and CU tests) based on these properties. For example, when the fine fraction content of aged ballast exceeds a threshold (i.e.,  $F_c > 15$ ) or when the coefficient of permeability of aged ballast 573 574 is less than a threshold (i.e.,  $k_{s} < 10^{-4}$ ), the undrained test conditions should be selected. Besides, the UIUC model is suitable for predicting the permanent axial deformation of fresh ballast or slightly aged ballast under the 575 576 drained condition, and the SSE model shows good potential to estimate the permanent axial deformation of 577 fresh and aged ballasts under different drainage conditions when the hydro-mechanical analysis is adopted, 578 although the applicability of the SSE model in this study is verified only based on the mechanical analysis under 579 the drained condition. However, the findings in this study were obtained under limited test conditions (only one 580 unsaturated state, fine fraction content, and confining pressure). Further laboratory element tests (triaxial 581 compression test, water retention test, and permeability test) considering more different degrees of saturation, 582 fine fraction contents, and confining pressures need to be conducted in the future to investigate the hydro-583 mechanical behavior of aged ballast, and to further determine the threshold value between heavily and sightly 584 aged ballast. More importantly, the applicability of the UIUC model and the SSE model to the prediction for 585 the permanent axial deformation of aged ballast in the undrained condition still needs further study.

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