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Mechanical behaviour of coarse grains/fines mixture under monotonic and cyclic loadings

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ABSTRACT

Micro-ballast/fines mixtures were tested at various contents of coarse grains in triaxial cells under monotonic and cyclic loadings. X-ray μCT scans were undertaken to visualise the coarse grains distributions in the compacted samples. Results show that inclusion of coarse grains has significant effect on the mechanical behaviour of micro-ballast/fines mixture. While the volumetric content of coarse grains f_v increases, the cohesion decreases, the friction angle increases, the dilatancy becomes more pronounced, the maximum deviator stress increases, the permanent deformation decreases, the resilient modulus increases and the damping ratio decreases. There is a characteristic volumetric content of coarse grains f_{v-cha}, that defines two zones: when $f_v < f_{v-cha}$, the mechanical behaviour is governed by the fines proportion. On the contrary, when $f_v > f_{v-cha}$, the mechanical behaviour is controlled by the coarse grains proposition. This is totally supported by the X-ray μCT scans which revealed that when f_v varies from 0% to 10% (below f_{v-cha}), the fine particles constitute the skeleton of the sample, with coarse grains drowned in the matrix of fines. When f_v increases to 20% (still below f_{v-cha}), the connections between coarse grains start to develop. As $f_v > 35\%$ (beyond f_{v-cha}), almost all coarse grains are connected to form a skeleton of grain-grain contacts.

Introduction

The French railway network is composed of ballasted tracks. In addition, the high-speed lines represent 6% only, most lines being conventional lines which were constructed one hundred years ago. As opposed to the high-speed lines which were constructed with a layer of sub-ballast beneath the ballast layer, allowing fine migration from subgrade to ballast layer, the conventional lines were constructed by simply putting the ballast layer directly on natural soils. As a result, under the effect of long term circulation of trains, there has been interpenetration of ballast and subgrade, forming an interlayer that corresponds to a dense mixture of ballast and subgrade [23,16]. Duong et al. [5] developed a physical model to investigate the mechanism of interlayer creation. Results showed that it depends on the dry density or stiffness of subgrade. While the subgrade is dense, interlayer creation occurs by interpenetration. By contrast, while the subgrade is loose, it is rather the mud pumping that takes place [6]. Cui et al. [2,3] reported that the density of the interlayer reached 2.4 Mg/m^3 in the Sénissiat site. With such high density, its mechanical behaviour is expected to be favourable to the global track behaviour under the effect of dynamic loading of train. For this reason, the French railway company decided to keep this interlayer in the substructure when executing the renewal program for the conventional lines. Indeed, it has been revealed that this layer can greatly affect the dynamic response of substructure in terms of stress distribution [29] and strain development [30]. As the interlayer was formed with natural soils, it exhibits a large variability in terms of clay fraction and clay mineralogy or soil nature. In addition, the water content or degree of saturation can be also quite different from site to site. The effects of water content and fines contents were investigated by Duong et al. [7] on the hydraulic behaviour, and by Trinh et al. [23] and Duong et al. [4,8] on the mechanical behaviour. Results revealed the predominant effect of fines on both the hydraulic behaviour and mechanical behaviour: it is the suction developed within the fines that is the driving force for the water transfer in the ballast/fines mixture; it is also the suction within the fines that reduces the permanent deformation and increases the resilient modulus.

It is worth noting that the aforementioned studies involved a ballast/fines mixture that is characterised by a microstructure defined by a full contact of ballast grains with the proportion of fines contained mainly in the pores between the ballast grains. However, further examination of the interlayer showed that there is a gradient of ballast grains over depth: the fraction of ballast grains in the mixture is decreasing with depth. Thereby, in the upper part of interlayer, there is full contact of ballast grains, while in the lower part the ballast grains are drowned in a fines matrix, without predominant contacts between them. Recently, Wang et al. [24–26] performed monotonic and cyclic

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triaxial tests on micro-ballast/fines mixture in order to well understand the effect of ballast grains content. They identified a characteristic volumetric micro-ballast content that separates an overall mechanical behaviour controlled by the contacts of coarse gains from that controlled by the fines matrix. In this paper, the recent related works about the effect of coarse grains on mechanical behaviour of coarse grains/fines mixtures are reviewed and re-examined, allowing an overall view of the samples preparation, the samples characterisation by X-ray μCT and the identification of the influence of micro-ballast content on the shear strength, permanent deformation, resilient modulus and damping ratio. The results obtained constitutes a database not only for further constitutive and numerical modelling, but also for the assessment of the mechanical response of interlayer with decreasing ballast grains content over depth.

Materials and methods

Owing to the difficulty in obtaining intact interlayer soil, the tested samples were prepared by compaction of reconstituted mixture with fines and coarse grains.

For the fines constitution, the proportions of 9 different commercial soils were selected, simulating the grain size distribution curve of the fines collected from Sénissiat site (Fig. 1). A mixing machine was used to prepare a mixture with respective masses of the soils, at 4% water content. The grain size distribution curve of the fabricated fines was measured after preparation (see Fig. 1). A good agreement was obtained with the in-situ one, justifying the fines reconstitution protocol adopted. The reconstituted soil of fines has a liquid limit of 32% and a plasticity index of 20%. According to the Unified Soil Classification System, it is a lean clay (CL).

For the coarse grains, in order to match the dimensions of the cyclic triaxial cell (100 mm diameter and 200 mm height), a micro-ballast with the maximum grain size $D_{\max}^{m}$ of 20 mm was adopted, 5 times smaller than the diameter of the sample. Fagnoul and Bonnechere [9] and Pedro [18] reported that when the ratio of sample size to the maximum grain size is larger than 5, the sample size effect can be ignored. The grain size distribution of the micro-ballast was determined following a simple similitude method: the grain sizes of the two materials share the same percentage of passing. Anagnosti [1], Indraratna et al. [12] and Pedro [18] reported that using this similitude method, the fabricated material can well represent the prototype one in terms of mechanical behaviour. This method is expressed by Eq. (1):

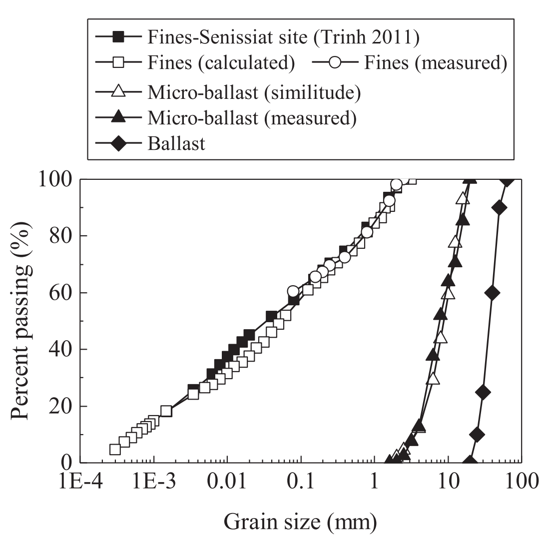

Fig. 1. Grain size distributions of fines and micro-ballast.

$$\frac{D^{b}-D_{\min}^{b}}{D^{m}-D_{\min}^{m}}=\frac{D_{\max}^{b}-D_{\min}^{b}}{D_{\max}^{m}-D_{\min}^{m}}=A \quad (1)$$

where $D_{\max}$, $D_{\min}$ and D are the maximum, the minimum and a given grain sizes, respectively. Superscripts b and m represent the ballast and micro-ballast, respectively. A is a constant.

The range of real ballast grain size varies from 20 mm to 63 mm (Fig. 1). As the minimum grain size of micro-ballast $D_{\min}^{m}$ is chosen as 1.6 mm (defined by the minimum size of the materials used for micro-ballast preparation), the constant A is equal to 2.337 according to Eq. (1). Thereby, for a given grain size of ballast D^{b}, the grain size of micro-ballast D^{m} can be calculated. From the similitude method, the percentage of ballast grains passing through 35 mm is 43.7%. At the same percentage of passing, the micro-ballast size is 8 mm. The grain size distribution curve of micro-ballast determined is shown in Fig. 1. Three commercial coarse soils were used to fabricate the micro-ballast based on its grain size distribution curve. A mixing machine was used for this purpose. The grain size distribution curve of this fabricated micro-ballast was also measured (Fig. 1). A very good agreement can be observed between the target curve and the measured one.

To quantify the coarse grains in a sample, a parameter namely volumetric content of coarse grains f_v is adopted, representing the ratio of the volume of coarse grains V_c to the volume of the total sample V_{total} [18,20]. V_{total} can be calculated by the size of the sample. Given f_v, V_c can be determined accordingly. Then, using the dry unit mass of coarse grains ρ_{s-c}=2.68 Mg/m^3 [22], the dry mass of coarse grains can be obtained. On the other hand, the volume of fines V_f can be calculated by:

$$V_f = V_{total}-V_c = V_{s-f} + V_{w-f} + V_{a-f} \quad (2)$$

where V_{s-f}, V_{w-f} and V_{a-f} are the volume of soil solid, water and air in the fines, respectively. As the soil suction is expected to be controlled by the state of fines, the optimum water content w_{opt-f} and maximum dry density $\rho_{d\max-f}$ of fines were kept as the same when preparing the samples by compaction. Note that all grains with diameter smaller than 2 mm (instead of 1.6 mm) were defined as fines in this study. It is believed that this does not change the analysis because as Fig. 1 shows, the proportion of grains in the range from 1.6 mm to 2 mm is negligible.

Six f_v values (0%, 5%, 10%, 20%, 35% and 45%) were considered. For the sample preparation, water was added and mixed with the fines to reach the optimum water content (13.7%). Then, the fines were conserved in a container for 24 h for moisture homogenization. Afterwards, the fines were mixed with dry coarse grains of pre-determined mass. Finally, static compaction was applied in three layers to prepare a soil sample of 100 mm diameter and 200 mm height.

X-ray μCT scans were performed on the middle part of as-compacted samples (100 mm in diameter, 120 mm in height) to visualise the distribution of coarse grains inside the samples. The samples were scanned using a two-turn helical mode and the scanning source was a Hamamatsu L10801 which was set at 170 kV, 100 μA, with a voxel size of 58.5 μm. The imager was a Paxscan Varian 2520 V with 1960 × 1536 photosites and a size of 127 μm. After scanning, the images were reconstructed using the software X-act (RX Solutions), producing 1 900 cross-sectional slices for each sample. To have a better understanding of the coarse grains distribution, the ImageJ software (version 1.6.0_24) was used to eliminate the pixels representing the fines (diameter < 2 mm). The procedures of resetting the threshold range were then followed to remove the outliers and finding edges of the coarse grains. Thus, the slices were expected to only exhibit the coarse grains after this operation. The threshold range chosen for the sample with f_v = 10% was from 176 to 254 to ensure the clear brightness of soil grains. This range can be a little different for different samples. By stacking all the processed slices for each sample, the three-dimensional (3D) views of the coarse grains distribution were then built, as shown in Fig. 2. It is observed that when f_v varies from 0% to 10%, the fine particles constitute the skeleton of the sample, with coarse grains