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Technical note

Effect of shearing rate on the behavior of geogrid-reinforced railroad ballast under direct shear conditions

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ABSTRACT

A series of large-scale direct shear tests were conducted to investigate the behavior of unreinforced and geogrid-reinforced ballast at different rates of shearing. Fresh granite ballast with an average particle size (D_{50}) of 42 mm and five geogrids having different aperture shapes and sizes was used in this study. Tests were performed at different normal stresses (σ_n) ranging from 35 kPa to 140 kPa and at different rates of shearing (S_r) ranging from 2.5 to 10.0 mm/min. The laboratory test results revealed that the shear strength of ballast was significantly influenced by the rate of shearing. The internal friction angle of ballast (φ) was found to decrease from 66.5° to 58° when the shearing rate (S_r) was increased from 2.5 to 10.0 mm/min. It is further observed that the interface shear strength has improved significantly when the ballast was reinforced with geogrids. The interface efficiency factor (α), defined as the ratio of the shear strength of the interface to the internal shear strength of ballast, varies from 0.83 to 1.06. The sieve analysis of samples after the testing reveals that a significant amount of particle breakage occurs during shearing. The value of breakage, evaluated in terms of Marsal's breakage index (B_g), increases from 5.12 to 13.24% with an increase in shearing rates from 2.5 to 10.0 mm/min. Moreover, the influence of aperture shape and size of geogrid on the behavior of ballast-geogrid interfaces was also examined in this study.

1. Introduction

Ballast is one of the crucial components of a rail track and is responsible for distributing the applied wheel load to the sub-grade soil at an acceptable level while maintaining the track alignment. However, ballast owing to its unbound granular nature upon repeated application of stress arising due to the passage of trains undergoes differential track settlement and track misalignment, thereby affecting the track stability. Moreover, the extent of track deformations increases with the increase in train speed thereby further endangering the track stability. To rectify these issues, the rail authorities are compelled to carry out frequent maintenance operations that are not only expensive in nature but also disrupt the traffic. For instance, Indian railways spend around 600–700 million dollars annually on track maintenance and renewals operations, of which an estimated portion of 15–20% are for ballast related problems alone.

One of the promising approaches to arrest the lateral spreading of ballast and thus stabilize the tracks is to reinforce them with geosynthetics. Geogrids have been extensively used to reduce the settlement and lateral spreading of ballast (Bathurst and Raymond, 1987; Raymond and Ismail, 2003; Indraratna et al., 2006; Indraratna and Nimbalkar, 2013; Hussaini et al., 2015a, 2016; Liu et al., 2016; Chen et al., 2017; Esmaeili et al., 2017). The geogrid reinforcement helps in stabilizing the track by holding the ballast in position and thus inhibiting the lateral spreading of ballast that subsequently prevents track misalignment. The geogrids are commercially available in the market in different shapes (uniaxial, biaxial and triaxial) and of different aperture sizes. Dong et al. (2011) reported that geogrids with triangular aperture would provide uniform stress distribution and hence are more efficient than those with rectangular apertures. However, any improvement in performance depends on the interaction between the ballast and geogrid, which is a function of the relative sizes of ballast and apertures of the geogrid (Indraratna et al., 2012; Qian et al., 2015). Moreover, the interface between the two dissimilar materials acts as a medium for transferring the stresses from one body to another (Desai et al., 1984). Therefore, it is needed to explore the ballast-geogrid interface behavior to understand the behavior of ballast reinforced with geogrid.

Several researchers have studied the interface shear strength of granular medium using direct shear apparatus (Cancelli et al., 1992; Bakeer et al., 1998; Liu et al., 2009; Hussaini et al., 2012; Biabani and Indraratna, 2015; Mvelase et al., 2017). Liu et al. (2009) investigated the interface shear behavior of different soils (sand, gravel and laterite)

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against PET-yarn geogrids. Hussaini et al. (2012) captured the effect of the aperture size of geogrid to stabilize the ballast of a given gradation. Biabani and Indraratna (2015) have evaluated the interface behavior of sub-ballast stabilized with geogrid and geomembranes. Indraratna et al. (2012) is the only comprehensive literature that explicitly describes the shear behavior of various ballast-geogrid interfaces. They have established that the shear strength of ballast-geogrid interface is influenced by the geogrid aperture size (*A*). However, the study was conducted at a single and uniform shearing rate of 2.75 mm/min. While the effect of rate of shearing (S_r) on the behavior of sand specimens has been studied using cylindrical triaxial tests (Yamamuro and Lade, 1993), its effect on the behavior of ballast-geogrid interfaces has not been studied explicitly. It is well known that the extent of shear strain increases with the increase in the train speed (Indraratna et al., 2010; Thakur et al., 2013; Sun et al., 2014). In practice, a rail track under operating conditions may be subjected to different shear rates depending upon the magnitude of cyclic stress and the train speed. Therefore, there is a need to explore the role of rate of shearing (S_r) on the behavior of ballast-geogrid interfaces. In this context, large-scale direct shear tests were conducted to establish the effect of rate of shearing on friction angle and breakage of ballast.

2. Materials and method of testing

The material used in this current study was fresh granite ballast from a quarry near Pakud, Jharkhand, India. The particle size distribution adopted in the current study is as per the specifications of the Indian railway code (IRS-GE-1, 2004; Fig. 1). The maximum and the average particle size (D_{50}) of the ballast used are 65 and 42 mm respectively (Fig. 1). Five geogrids (labeled *G1* to *G5*) with different aperture sizes were used to reinforce the ballast in this study. The physical and technical specifications of the geogrids are summarized in Table 1.

Laboratory investigations were conducted using large-scale direct shear apparatus specifically designed to test railway ballast in IIT Patna (Fig. 2). It consists of two 450 mm × 450 mm square boxes having an overall depth of 300 mm. The upper box is free to move while the lower box is fixed in position. The capacity of load cells employed to measure the applied normal stress and shear stress is 300 kN/m^2. The maximum shear displacement that could be allowed using this apparatus is up to 100 mm. The equipment is designed for testing granular materials at high strain rates and normal loading. The samples were prepared by weighing the required proportion of different sized particles and then thoroughly mixing them to match the gradation curve adapted in this study (Fig. 1). Subsequently, the mixed sample was placed in the shear box and compacted in three layers of approximately 100 mm height with the help of electric vibrator to achieve a desired density of 1470 kg/m^3. A 7 mm thick rubber membrane was placed beneath the electric vibrator to minimize the breakage of ballast during compaction. After the compaction of first 100 mm layer, additional 50 mm was compacted to fill the lower box and the geogrid was placed at the interface of upper and lower boxes of the shear box. Subsequent to the placement of geogrid at the interface, the box was filled with 50 mm of ballast and compacted again which was followed by the placement and compaction of the third layer. The tests were conducted at different normal pressures of 35, 70, 100 and 140 kPa and different shearing rates (S_r) of 2.5, 5.0 and 10.0 mm/min. The different shear strain rates considered here in effect simulates the passage of trains at different speeds wherein the increasing train speeds are simulated by higher rates of shear strain and vice-versa. All tests were conducted up to a shear displacement of 67.5 mm that corresponds to the horizontal strain of 15%. The shearing load required to cause the horizontal displacement was measured automatically by means of a load cell and the corresponding vertical displacement was measured with the help of LVDTs.

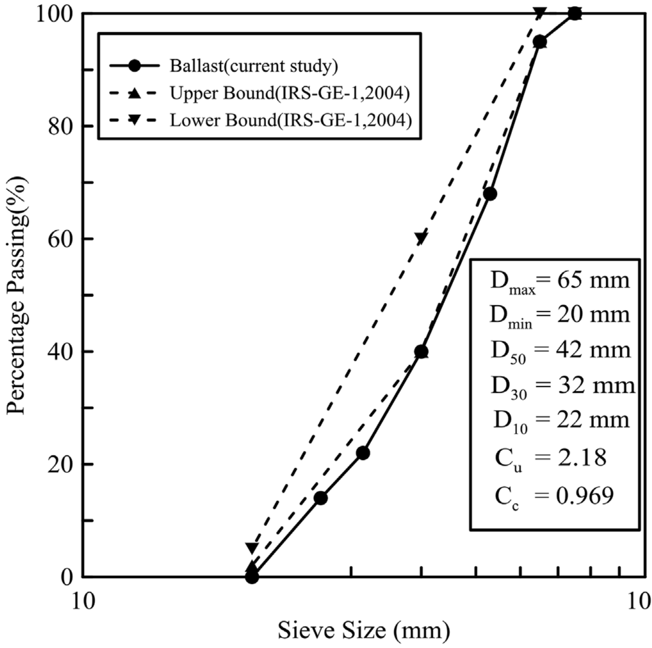

Fig. 1. Particle size distribution of ballast used in current study.

3. Results and discussion

3.1. Shear behavior of ballast and ballast-geogrid interfaces

The shear behavior of unreinforced ballast and that reinforced with different geogrids is plotted in the form of stress ratio (τ/σ_n) and vertical displacement (d_v) with horizontal displacement (d_h) (Fig. 3). It is found from Fig. 3 that the inclusion of geogrids *G1*, *G3*, *G4* and *G5* increases the stress ratio (τ/σ_n) in comparison to unreinforced ballast for an applied normal stress (σ_n) of 70 kPa and shearing rate (S_r) of 10.0 mm/min. This is primarily due to the interlocking of particles within the geogrid apertures. On the other hand, the geogrid *G2* shows a lower value of stress ratio as compared to unreinforced ballast (Fig. 3a). This may be due to the lack of interlocking of particles within the apertures of geogrids owing to the smaller aperture size of the geogrid. The stress ratio (τ/σ_n) of reinforced ballast initially increases up to a horizontal displacement of about 30–40 mm and then decreases marginally thereafter. The fluctuation seen in τ/σ_n may be attributed to the sudden loss of interlock or breakage of interlocked particles. The particle breakage was measured by conducting the sieve analysis after the tests and will be discussed in the latter sections of the paper. The vertical displacement behavior (d_v) shows initial compression of the sample until a horizontal displacement of about 10 mm followed by dilation (Fig. 3). It is further observed that geogrids also reduce the extent of dilation which is in line with the results from various past studies (Indraratna et al., 2012; Hussaini et al., 2012; Biabani and Indraratna, 2015). A similar kind of interface behavior was exhibited by ballast at other rates of shearing but is not shown here for reasons of brevity. Replicate tests were conducted to ensure the consistency in results. It is observed that replicate tests closely match with the original tests (Fig. 3b).

3.2. Friction angle of ballast (φ)

3.2.1. Effect of shearing rate on the friction angle (φ)

Fig. 4 represents the variation of friction angle of geogrid-reinforced ballast with the rate of shearing (S_r) at a constant normal stress (σ_n) of 35 kPa. It is observed that the friction angle of unreinforced ballast (φ) decreases from 66.5° to 64.73° when S_r increases from 2.5 to 10.0 mm/min. This may be primarily attributed to quicker sliding of particles that