Geotextiles and Geomembranes 44 (2016) 344–357

Contents lists available at ScienceDirect

Geotextiles and Geomembranes

journal homepage: www.elsevier.com/locate/geotexmem

Reinforcement and mud-pumping benefits of geosynthetics in railway tracks: Numerical analysis

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ARTICLE INFO

Article history:
Received 12 May 2015
Received in revised form
4 October 2015
Accepted 17 January 2016
Available online 8 February 2016

Keywords:
Geosynthetics
Railway track
Laboratory tests
Finite element analysis
Reinforcement
Mud-pumping

ABSTRACT

Laboratory tests were conducted on track materials to evaluate constitutive parameters for three different sets of constitutive relationships, namely, non-linear analysis, straight analysis and coupled analysis. The model test results of finite element analyses using various constitutive relationships are compared. The coupled analysis provided a better prediction of the measured results compared to the non-linear and straight analyses. A detailed parametric study of a prototype track was then performed using the coupled analysis to evaluate the effects of geosynthetics on track reinforcement and mud-pumping reduction.

Geogrid reinforcement was found to significantly reduce tie displacement only at low subgrade modulus values and effective subgrade shear strength parameters. Geogrid reinforcement was equally effective at reducing tie displacement within the subballast thickness range of 450–1000 mm. High excess pore water pressure coupled with low effective cohesion gives rise to mud-pumping problems in silty soil subgrades. The provision of geotextiles at the subgrade surface facilitates quick in-plane drainage and dissipation of pore water pressure. Thus, excess pore water pressure was observed to be lower in a geotextile-stabilized track compared to that in an unreinforced track, indicating reduction in mud-pumping potential in the former.

1. Introduction

Several subgrade failures and mud-pumping problems have been reported on tracks laid on silty and clayey soil subgrades, respectively, after heavy monsoon rains on heavily trafficked routes in India. In spite of the wide extent of mud-pumping problems across several national railways (Hayashi and Shahu, 2000), very little information is available on mud-pumping in the current literature. Geosynthetics provide a means to improve track support structure, thereby reducing track maintenance and operation costs of train delays. However, for decision-making and proper utilization, it is necessary to evaluate the benefits of geosynthetics on various aspects of track improvement, such as mitigation of mud-pumping problems, track strengthening, subballast thickness reduction, and maintenance cycle reduction. Presently, no study on mud-pumping benefits of geosynthetics in the track is available.

All numerical analyses require geotechnical characterization of tracks and evaluation of the constitutive parameters of different track materials and interfaces. The difficulties in track characterization are compounded due to the different sizes of track materials and the relatively large number of interfaces, especially when both geogrids and geotextiles are used in the track. Some studies have been carried out on the deformational behavior of fouled railway ballast using large scale triaxial tests (Indraratna and Tennakoon, 2014; Ebrahimi and Tinjum, 2015). However, in general, very little information is available on track characterization in the literature, especially for nonlinear and time-dependent analyses.

Research on unreinforced railway tracks has resulted in several numerical studies on railway tracks. A majority of these studies assumes linear track substructure and analyzes it using two- or three-dimensional finite element simulations (Selig et al., 1979; Stewart and Selig, 1982; Shahu et al., 1999). However, experimental data have shown that a track support structure exhibits both stress-dependent and traffic time-dependent nonlinear responses (Desai and Siriwardane, 1982; Sadeghi, 2008). Presently, no

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http://dx.doi.org/10.1016/j.geotexmem.2016.01.006

time-dependent non-linear finite element analysis of track is available.

A two-dimensional, plane strain finite element analysis of geosynthetic-reinforced track has been carried out by Indraratna and Nimbalkar (2013). A plane strain analysis utilizes an unrealistic stress distribution inside of the track with the characteristics of a line load with very little stress dissipation with depth. A three-dimensional, linear-elastic finite element analysis of a single sleeper box model with geosynthetic reinforcement was carried out by Jirousek et al. (2010). Leshchinsky and Ling (2013) presented a three-dimensional finite element analysis of a railway track reinforced with geocells wherein the soft soil was considered to be linear-elastic, and the ballast and subballast layers were represented by an elasto-plastic, Drucker–Prager constitutive relationship.

The present study investigates the benefits of the use of geosynthetics on tracks laid on fine-grained soil subgrades. The study is presented in two parts: the first portion includes model testing and is presented in a companion paper; the second portion, which is presented in this paper, involves the geotechnical evaluation and three-dimensional finite element analyses of the prototype track. First, the constitutive parameters of the model and prototype track materials are evaluated. Next, the results of the finite element analyses using various constitutive relationships for track materials are compared with the model test results carried out in the first portion. Based on this comparison, a coupled time-dependent finite element formulation was chosen. Use of coupled analysis gives important insight into the dissipation of pore water pressure in the track and thus brings out the mud-pumping benefits of geosynthetics in the track. Finally, a detailed parametric study of a typical prototype track is performed using the coupled, time-dependent finite element formulation to evaluate the effects of geosynthetics on track reinforcement and mud-pumping reduction.

2. Laboratory tests

The details of the model tests are provided in the companion paper. The laboratory tests were performed on ballast and subballast materials, subgrade soils, and geotextile and geogrid used in the model tests. The tests were also performed to evaluate mechanical characteristics of different interfaces present in the model tracks. The details of these tests are given below.

2.1. Track materials

Consolidated drained (CD) triaxial tests were performed on relatively permeable materials of ballast and subballast to evaluate effective shear stress parameters. The tests on ballast material were performed on 380-mm-diameter and 760-mm-high fully saturated specimens prepared in a split mold by vibration at a relative density of 87% ($\gamma_d = 16.1$ kN/m^3). The tests on subballast material were performed on 100-mm-diameter and 200-mm-high fully saturated specimens prepared in a split mold by tamping at a relative density of 72% ($\gamma_d = 14.5$ kN/m^3). Consolidated undrained triaxial tests with pore water pressure measurements ($\overline{CU}$ tests) were performed on 38-mm-diameter and 76-mm-high fully saturated specimens of Delhi silt ($\gamma_d = 16.5$ kN/m^3) and Dhanaury clay ($\gamma_d = 15.3$ kN/m^3) prepared in a split mold by kneading compaction. Full saturation in $\overline{CU}$ tests was ensured by performing the consolidation stage under an elevated back-pressure (=250 kPa) for 24 h. The dry densities of the ballast, subballast and subgrade soil specimens were the same as the placement densities of the corresponding layers in the model tracks.

2.2. Geotextile and geogrid

A biaxial geogrid (GG) and a non-woven geotextile (GT) were used in the model tracks. The geogrid was made of high density polyethylene (HDPE) with an aperture size of 30 mm × 30 mm, rib thickness of 2 mm, secant stiffness at 5% strain of 513 kN/m and ultimate tensile strength of 49.9 kN/m. The geotextile was a 2.2 mm thick, non-woven, heat-bonded, polypropylene (PP) fabric with apparent opening size of 0.14 mm, secant stiffness at 5% strain of 90 kN/m and an ultimate tensile strength of 49.6 kN/m. The strength and stiffness characteristics mentioned above were determined by a wide width tensile test as per relevant ASTM standards (ASTM D6637; ASTM D4595).

2.3. Interface properties

A typical railway track structure consists of several layers of different materials. However, constitutive parameters of different track layer interfaces are not available in the literature. Therefore, in this study, direct shear tests were conducted to determine the interface normal stiffness and shear stiffness between different track materials, namely, sleeper–ballast, ballast–geogrid, geogrid–subballast, subballast–geotextile, geotextile–subgrade, ballast–subballast and subballast–subgrade. A small size direct shear apparatus with box dimensions of 60 mm × 60 mm × 50 mm was used for the interfaces with maximum particle sizes of the constituent materials of both layers of less than 10 mm (i.e., for subballast–geotextile, geotextile–subgrade and subballast–subgrade interfaces). For the remaining interfaces, a large size direct shear apparatus with box dimensions of 30 cm × 30 cm × 22.5 cm was used.

3. Constitutive parameters

As mentioned earlier, track support structure exhibits both stress-dependent as well as traffic time-dependent nonlinear responses. Based on this, the following types of analyses were performed.

3.1. Types of analysis

Pre-failure stress–strain law as well as failure criteria can be stated in terms of either drained or undrained or coupled parameters. 'Coupled' analysis relates to modeling of time-dependent processes of excess pore pressure dissipation and consolidation (Biot, 1941). For low permeability materials (subgrade soils), undrained or coupled parameters can be used; for high permeability materials (ballast and subballast), drained or coupled parameters can be used. Thus, there are potentially four options, namely, linear drained/undrained (termed here as straight analysis employing drained parameters for upper layers and undrained parameters for subgrade), nonlinear drained/undrained (termed here as non-linear analysis employing drained parameter for upper layers and undrained parameters for subgrade), linear coupled (termed here as coupled analysis employing coupled parameters for all layers) and nonlinear coupled analysis (employing coupled parameters for all layers). Since non-linear coupled analysis is not readily available, it is not performed here. The details of other three analyses are given below:

(i) *Non-linear analysis*: Since track support structure exhibits stress-dependent non-linear responses, this particular analysis has been performed. In this case, the ballast, subballast and subgrade soils all were simulated by a non-linear,