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Deformations of geosynthetic reinforced soil under bridge service loads

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A B S T R A C T

This paper evaluates the results of 13 large scale Geosynthetic Reinforced Soil (GRS) column load tests, also known as performance tests (PT) or mini-pier tests, to study the effect of tensile strength (T_f), vertical reinforcement spacing (S_v), facing elements, and backfill properties on the deformations of GRS at 200 kPa, typical bridge bearing pressures, and also at 400 kPa. The results indicate that GRS performs well under service conditions. A semi-empirical expression is proposed for prescribed bearing pressures to limit vertical strain to 0.5% of the abutment height. In addition, recommendations for estimating lateral deformation for GRS bridge abutments are also provided. At 200 kPa surcharge for this series of tests, vertical settlements ranged from 8.3 to 33.9 mm (or from 0.4% to 1.7% axial strain); lateral deformations ranged from 3.0 mm to 10.1 mm (or 0.6%–2.0% lateral strain); and reinforcement strain ranged from less than 1% during construction to less than 3% during loading. The lateral deformation results indicate that the maximum displacement occurs in the top third region of the wall face. Comparing the vertical and lateral displacement data shows that most GRS models experienced negligible positive volume changes up to about 1% under typical bridge service loads.

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1. Introduction

During the past decade, the use of closely-spaced (≤0.3 m) geosynthetic reinforced soil (GRS) technology to support bridges has become more common because it is cost-effective, quick to build, exhibits excellent performance, and reduces life-cycle maintenance activities (FHWA, 2015). The AASHTO LRFD Bridge Design Specifications (2014) defines three limit states for bridge foundations: service, strength, and extreme limits. The strength limit of GRS has been studied with a closed-form semi-empirical equation proposed and validated to predict bearing resistance and required reinforcement strength for these closely-spaced systems (Wu and Pham, 2013; Adams et al., 2011a, 2014). Other studies have been performed on the seismic behavior of GRS investigating the extreme limit state (Liu, 2009; Lee et al., 2012; Liu et al., 2011; Helwany et al., 2012; Vieira et al., 2011, 2012; Lee and Chang, 2012; Liu et al., 2014; Ruan and Sun, 2014). As with many other geotechnical features, the service limit state (SLS) of GRS abutments, however, is not largely understood or defined.

The SLS for GRS abutments primarily includes vertical settlement, lateral deformation, and reinforcement strain. Currently, the Federal Highway Administration recommends a GRS performance test (PT), also known as a mini-pier experiment, to empirically measure settlement. This information can then be used to predict in-service performance of a GRS abutment, including an estimate of maximum lateral deformation based on the postulate of zero volume change (i.e. the volume lost due to settlement is equal to the volume gained due to lateral deformation; Adams et al., 2002, Adams et al. 2011a, 2015). Compared to settlement and lateral deformation measurements of in-service bridges, this method produces reasonable approximations (Adams et al., 2011b); however, a performance test is specific to the GRS composite tested (i.e. unique to the combination of backfill, reinforcement spacing and properties, and facing element). One problem is that these large scale PTs require specialized equipment and knowledge to perform. The method is atypical for most GRS bridges designed with different backfills and geosynthetics from what has already been tested (Adams et al., 2011a; Nicks et al., 2013); rather, a simple methodology is needed to estimate deformations without conducting mini-pier experiments. In addition, there are no guidelines

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to estimate the in-service reinforcement strain; however, for GRS, it is often assumed that the soil and the reinforcement strain together.

The performance of a GRS abutment is primarily a function of the backfill material, reinforcement spacing (S_v), compactive effort, reinforcement properties, and facing rigidity. By volume, the backfill is the largest component in a GRS composite. The structural backfills specified for abutment design are typically either an open-graded or a well-graded aggregate, with fines less than 12% and friction angles greater than 38 degrees (Adams et al., 2011a). GRS pier dead load test results indicated that GRS composites constructed with open-graded aggregates (OGAs) are slightly less stiff with more settlement as compared to a well-graded aggregate of similar strength; however, this difference is minor, less than 0.1% of the initial 2 m height, or 2 mm, under applied pressures of 245 kPa (Adams and Nicks, 2014). A numerical analysis by Helwany et al. (2007) of a GRS abutment with 0.2 m vertical reinforcement spacing showed that a 6° (or approximately 18%) increase in the backfill friction angle (from 34° to 40°) resulted in a 35% improvement in vertical settlement and a 45% reduction in lateral wall face deformation.

Proper placement of the structural backfill is critical to the performance of a GRS abutment. During construction, the development of compaction induced stresses stiffens GRS composites (Wu et al., 2013; McGown et al., 1998; Chou and Wu, 1993). In effect, compaction preloads the geosynthetic within the backfill, thus restraining lateral movement, locking-in internal stress and confinement to the soil, and strengthening the composite. Nicks et al. (2013) compared the results of an uncompacted and compacted GRS performance test. In these tests, the applied stress resulting in 0.5% vertical strain for the uncompacted sample was 15 kPa, whereas for the compacted sample with the same materials, the applied stress was 147 kPa, an increase in the load carrying capacity at the SLS by a factor of almost 10.

The behavior of GRS depends on development of compaction induced stresses and to some degree the facing rigidity. Chou and Wu (1993) studied the contribution of facing with large scale experiments and finite element simulations. Gravely silty sand was used to build 3.6 m high test walls with reinforcement spacing of 0.3 m. They modeled four types of facing elements for this study including timber/plywood, wrap-around geosynthetic, a continuous concrete panel, and modular concrete blocks. Their results indicated that among all the cases, modeled with uniform surcharges up to 34.5 kPa, the panel facing exhibited the smallest wall movement and tensile strain in the reinforcement layers. The plywood and modular blocks behaved similarly, exhibiting more lateral displacement than the rigid panel facing. The flexible wrap-around facing had the largest lateral displacement, about 20% more than the plywood and modular blocks in this study. This may be due to the greater ability of more rigid facings to lock-in compaction induced stresses and their stiffness.

Recent studies showed that the vertical and lateral deformations of GRS structures increase with increased reinforcement spacing (Adams et al., 2011a; Wu et al., 2006). Finite element analysis supports this observation; under 200 kPa surcharge, results suggest that an increase in the vertical spacing from 0.2 m to 0.4 m and from 0.2 m to 0.6 m leads to a 25% and 50% increase in vertical and lateral displacements, respectively (Helwany et al., 2007). You-Chang et al. (2009) also examined the impact of reinforcement frequency on the response of small-scale unconfined models (i.e. 0.15 m high). The results indicated that the closer the reinforcement spacing, the more stress the model could support at an equivalent axial strain.

To study the load deformation characteristics of GRS, 13 large-scale column experiments, or performance tests, on different GRS and larger-spaced composite columns were conducted to failure (Table 1). This paper focuses on the lateral and axial deformation of these specimens at 200 and 400 kPa; typical service loads for bridges are 200 kPa, which is the recommended allowable bearing pressure for GRS abutments. This analysis also examines performance at 400 kPa for additional information about composite behavior beyond the 200 kPa service criterion for potential extreme loading conditions. As indicated in Table 1, the series of experiments performed were part of a parametric analysis of GRS composites built with different backfill materials, reinforcement strengths, and reinforcement spacing; the effect of facing was also measured with some composites tested with concrete masonry units (CMU) face elements in place and some without (i.e. no facing). Note that the nomenclature for the Test ID in Table 1 is defined according to the aggregate type, the reinforcement strength, the reinforcement spacing (in mm) and with or without facing.

2. GRS models

Figs. 1 and 2 illustrate the dimensions of the performance tests. The experiments had a base (B) to height (H) ratio of 0.5, where the square base was 1.0 m^2 and H was 2.0 m. Each test was constructed in the same way on a rigid concrete slab. The first course of block was placed level and centered within the position of the reaction assembly. Next, aggregates were infilled using a front-end loader or a concrete dump hopper and compacted to approximately 100% of maximum dry density per Standard Proctor (AASHTO T 99) for the well-graded aggregate tested, which was verified using a nuclear density gauge for each lift. Note that open-graded aggregates were also used in a few PT experiments; compaction was performed until no vertical movement was observed. Once final compaction was achieved and before placement of the next course of CMU block, any remaining aggregates were brushed off the facing blocks so that a smooth surface existed to prevent point loading and ensure even placement of next course of facing element. Depending on the reinforcement schedule within the performance test, a layer of geotextile was then placed over the aggregate with a facing element coverage ratio of at least 85% of the width of CMU block.

To facilitate construction, two sets of ratchet straps were placed around the top 2 rows of facing blocks to secure and maintain block alignment during compaction. This served to mimic the development of compaction induced stresses that would be expected during field construction of GRS abutments (reinforcement spacing $\leq$ 0.3 m) which have more area to distribute the energy and maneuver compaction equipment without significantly displacing the facing elements. During each layer of GRS construction, the lower ratchet strap was removed and then used to band the new upper course of block. The process was repeated until the mini-pier was completed (Figure 3a). For the tests with no facing (Figure 3b), the CMU blocks were removed after construction and the geotextile fabric was trimmed flush with the exposed GRS composite (Nicks et al., 2013). The series of tests were designed to examine the contributions of backfill type, reinforcement strength and spacing, and facing condition to the strength and serviceability of GRS composites, with deformations and strains the focus of this analysis.

3. Material properties

3.1. Reinforcement properties

Table 1 summarizes the reinforcement strength and reinforcement spacing for the various GRS composites tested. Biaxial woven polypropylene geotextiles were used in all of the experiments with reported ultimate MARV strength values varied between 20 kN/m to 70 kN/m; the vertical spacing ranged from 97 mm to 388 mm.