EXECUTIVE SUMMARY
NCHRP PROJECT 24-41

DEFINING THE BOUNDARY CONDITIONS FOR COMPOSITE BEHAVIOR OF GEOSYNTHETIC REINFORCED SOIL STRUCTURES

The overall objective of this report is to quantify the effect of adopting a closely-spaced reinforcement layout in geosynthetic-reinforced soil structures. While research since the early 1980s has identified the beneficial effect of closely-spaced reinforcement in reinforced soil structures, such improvement in performance is not accounted for in the simplified methodologies established by AASHTO. Considering the effect of closely-spaced reinforcement may be particularly relevant in critical structures, such as load-carrying geosynthetic-reinforced MSE (GMSE) bridge abutments, which eliminate the use of deep foundations to support the bridge loads. In fact, the adoption of closely-spaced reinforcement was identified as being particularly relevant for these type of structures, leading to specific design guidelines developed by FHWA for structures that became identified as Geosynthetic Reinforced Soil Integrated Bridge System, or GRS-IBS.

The terms "GRS," "MSE," and "GMSE" have been used since the 1980s, often indistinctly in the technical literature, to refer to mechanically stabilized earth structures that are reinforced with geosynthetics. For consistency with AASHTO, the term "GMSE" is adopted herein to refer to geosynthetic-reinforced soil structures, irrespective of the magnitude of its reinforcement vertical spacing. An expression that also requires clarification within the context of this report is the term "composite behavior." Accordingly, a GMSE structure is identified as showing a composite behavior when loading of a given geosynthetic reinforcement affects the deformation response and load magnitude of adjacent reinforcement layers. An important objective of this study is to unequivocally define the boundaries for such behavior. In addition, this study aims at proposing changes into AASHTO LRFD Bridge Design Specifications to account for such behavior.

An evaluation of the state-of-the-art on the different components of this study was conducted. The information was grouped into experimental, field monitoring, numerical, and design-related literature. The focus of this review was to summarize pertinent information published in technical venues that was deemed relevant to assess (1) the different components of the research and (2) the composite behavior of GRS structures.

A comprehensive summary of the state-of-the-practice was compiled to document the characteristics of the various components of geosynthetic-reinforced soil bridge abutments constructed worldwide. This is a type of structure for which closely-spaced reinforcement has often been adopted.Data on the characteristics of the geosynthetic-reinforced soil abutments used nationally and internationally was collected via a survey that targeted researchers, practitioners, wall system providers and geosynthetic reinforcement manufacturers. The wide range of characteristics of load-carrying GMSE bridge abutments, as obtained from the survey, is noteworthy, particularly considering the reasonably prescriptive nature of this type of structure as constructed in the US. Specifically, the majority of geosynthetic-reinforced soil bridge abutments in the US were constructed with smaller reinforcement vertical spacings than those adopted in most other abutments constructed worldwide. While the most common geosynthetic type is geogrids, the majority of US structures were constructed using woven geotextiles. Additionally, while the facing types utilized in geosynthetic-reinforced soil abutments varies widely around the world, the use of masonry block facing systems has prevailed in the US. A characteristic common to structures designed in the US and those designed abroad are the stringent requirements regarding the selection of backfill material.

Reinterpretation of data from FHWA's large-scale experimental structures was among the various sources of experimental and field data that, while collected as part of previous studies, was relevant to the objectives of the study. Since the 1970s, the FHWA has conducted extensive research to evaluate the behavior of reinforced soil structures, which led to the development of design guidelines first included in AASHTO in the early 1980s. These guidelines have continued evolving as additional research has been conducted and the number of reinforced soil structures built has increased. The current practice in the US relies largely on the latest design specifications developed by the FHWA in 2009 and also adopted by AASHTO. Recently, the FHWA developed a set of empirical and analytical design models for geosynthetic-reinforced soil structures constructed with small reinforcement spacings. These models were developed assuming that a geosynthetic-reinforced soil mass with close reinforcements behaves as a composite. The FHWA calibrated these models experimentally through a number of physical experimentation and field monitoring studies. To assess the reliability of the new approach, this study presents a reevaluation of a number of FHWA experimental structures and included models for bearing capacity, vertical and lateral displacements, and lateral earth pressures. This reevaluation indicated that the FHWA models provide reasonable predictions of the behavior of geosynthetic-reinforced soil structures. However, the scatter associated with these predictions was found to be reasonably high, especially at working stress ranges.

Reinterpretation of data generated as part of a KDOT field investigation involving the use of secondary reinforcements was also useful to assess the effect of closely-spaced reinforcement. Specifically, three MSE wall sections reinforced with geogrids were constructed and monitored by KDOT: (1) an MSE wall section with uniaxial geogrids as primary and secondary reinforcements; (2) an MSE wall section with uniaxial geogrids as primary reinforcements, with biaxial geogrids as secondary reinforcements; and (3) an MSE wall section with uniaxial geogrids as primary reinforcements only (i.e., the control section). Earth pressure cells, inclinometers, and foil-type strain gauges were used in test wall sections to measure the vertical and lateral earth pressures, lateral wall facing deflections, and strains of primary and secondary geogrids, respectively. A reevaluation was conducted of the collected data with focus on the effect of vertical spacing. Based on an analysis of the field test results, the following conclusions were drawn: (1) the secondary reinforcements reduced the wall facing deflections as compared with those in the control section; (2) the measured vertical earth pressures were consistent with the computed trapezoid stresses and increased with construction of the wall; (3) the distribution of measured lateral earth pressures in the control section increased linearly with depth, while the distribution of the measured lateral earth pressures in the sections with secondary reinforcements were approximately uniform with depth; (4) the measured tensile strains at the connection in all sections were comparatively small; and (5) the use of secondary reinforcements was found to reduce the maximum tensile strains in the primary geogrids.

Research conducted at the University of Delaware in the 1990s and 2000s was also reinterpreted, as it focused directly on the effect of reinforcement vertical spacing on the behavior of geosynthetic-reinforced soil structures. Data from that research was synthesized as part of this study and the relevant findings from that study were integrated with recent ones related to the effect of reinforcement vertical spacing. Specifically, an experimental testing program conducted in the 1990s on geosynthetic-reinforced soil unit cells was reevaluated to gain insight of the effect of reinforcement vertical spacing with focus on the soil arching phenomenon. In this testing program, a pullout testing device was developed to evaluate the displacement and strain fields within a reinforced soil unit cell. Two testing series were carried out: pullout of single reinforcement layers, and pullout of two reinforcement layers connected to a rigid facing panel. The tests conducted to assess the influence of a single reinforcement layer indicated that if the vertical spacing is less than twice the arching zone, contiguous reinforcement layers interact with each other and tend to behave as a single composite material. A field evaluation was also conducted as part of that study, which included field pullout tests on two geosynthetic-reinforced soil walls. Results showed that wall displacements, reinforcement strains and lateral pressure on the facing were small and the soil confined between reinforcements acted as a monolithic block, which was consistent with observations from the experimental program. Lastly, a numerical simulation was conducted to assess the effect of reinforcement spacing. The effect of closely-spaced reinforcements was observed to increase with increasing backfill shear strength. The results indicated that interaction of the various wall components may affect wall performance. Overall, even though it is not considered in common design methodologies, soil arching was found to affect the behavior of geosynthetic-reinforced soil.

A substantial number of centrifuge models involving geosynthetic-reinforced soil structures, previously tested to assess different performance aspects were also reevaluated as part of this study. An advantage of centrifuge modeling is that the stress state of reduced-scale models corresponds to that of prototypes because of the increased gravitational field. Consequently, centrifuge tests are suitable to validate several design aspects experimentally, including the effect of reinforcement vertical spacing. While the centrifuge experimental studies conducted in the past were tailored to address specific aspects of geosynthetic-reinforced soil design, they were collectively found to provide a relevant source of experimental data that was mined as part of this study to assess additional aspects of geosynthetic-reinforced soil behavior. Accordingly, this study included the compilation of a large volume of data generated by testing geosynthetic-reinforced soil models in geotechnical centrifuges, from which a portfolio was created of centrifuge data on geosynthetic-reinforced soil structures, with an emphasis on data in which reinforcement vertical spacing was varied. Overall, the results from these studies collectively indicate that the impact of reinforcement vertical spacing on the behavior of geosynthetic-reinforced soil structures is not strictly proportional to the impact of reinforcement mechanical properties (e.g. stiffness, ultimate tensile strength), but that it outweighs the relevance of the mechanical properties for particularly small values of vertical spacing.

Field monitoring data from the Founders/Meadows bridge, constructed in Castle Rock, Colorado in 1999, was also reassessed as part of this study. This structure is the first load-carrying GMSE abutment constructed on a major highway in the US. The abutments were extensively instrumented and monitored during construction and for approximately 5 years following opening to traffic. Because these abutments are the largest and among the oldest geosynthetic-reinforced soil structures in service, they have been used in several numerical studies to extend the range of parameters beyond those strictly collected from field monitoring performance of geosynthetic-reinforced soil abutments. The field monitoring data collected for the Founders/Meadows abutments were compiled and reevaluated in this study considering the current understanding of the behavior of geosynthetic-reinforced soil under bridge loads. This reevaluation examined the data collected on the outward movements of the abutment, settlement of the abutment, reinforcement strains, differential settlement between the abutment and approaching roadway, temperature and moisture changes, and vertical and lateral stresses within the geosynthetic-reinforced soil mass. The monitored vertical stress distribution revealed the pattern of stress propagation within the geosynthetic-reinforced soil mass. It was determined that temperature variations, construction sequence and construction season may have significant effect on the behavior of load-carrying GMSE bridge abutments.

Field monitoring data from five additional load-carrying GMSE bridge abutments was also reevaluated in order to synthesize information relevant to the impact on behavior of reinforcement vertical spacing. The five load-carrying GMSE abutments included three structures designed following GRS-IBS guidelines. Particular attention was paid to the response of these structures (constructed in Colorado, Delaware, Minnesota, and Louisiana) in relation that specifically monitored as part of this study in Virginia. Overall, the field monitoring data revealed that the profile of maximum reinforcement tension showed a relatively uniform distribution with depth, particularly for the case of closely-spaced reinforcement vertical spacings. Also, the profile of connection loads was found to also show a reasonably uniform distribution with depth for different reinforcement vertical spacings. The connection load values in the observed uniform distribution were found to fall within the range of the values that would be obtained using a triangular distribution considering the maximum unit tension in the reinforcements. Also, field monitoring data revealed that the vertical stress distribution shows similar trends and magnitude consistent with those predicted by conventional stress distribution methods (AASHTO 2:1 and Boussinesq). As expected, settlements in the structures were observed to increase with an increase in abutment height.

The experimental component of this study included the development of a new device to comprehensively assess the soil-reinforcement composite interaction under both working stress and failure conditions. This new equipment was able to assess the mechanical behavior of a geosynthetic-reinforced soil mass considering varying reinforcement vertical spacings. It also facilitated investigating interface shear stress transfer mechanisms. The device provided suitable measurements of the strains developed in both actively tensioned and adjacent reinforcement layers. It allowed direct visualization of the kinematic response of soil particles adjacent to the geosynthetic reinforcement layers, which facilitated evaluation of the soil displacement field via digital image analysis. Evaluation of the soil displacement field allowed quantification of the extent of the zone of shear influence around a tensioned reinforcement layer. Finally, the device allowed monitoring of dilatancy within the reinforced soil mass, providing additional insight into the effect of reinforcement vertical spacing on the reinforced soil mass.

A newly developed experimental device was used to conduct a comprehensive testing program. The experimental plan was tailored to evaluate the effects on the interaction among neighboring reinforcements in relation to: (1) the normal stress at the soil-reinforcement interface; (2) the vertical spacing between reinforcements; (3) the reinforcement properties; and (4) the fill type. Analysis of the experimental results revealed that the existence of the zone of shear influence and its extent can be directly related to the interaction between contiguous reinforcement layers. The interaction between adjacent reinforcement layers was found to increase with decreasing reinforcement vertical spacing. A minimum reinforcement vertical spacing threshold was identified below which the interaction between adjacent reinforcements develops fully. In addition, a maximum reinforcement vertical spacing threshold was identified beyond which the interaction between adjacent reinforcements becomes negligible. For the testing program implemented in this study, the minimum and maximum threshold vertical spacings were identified as 0.10 and 0.20 m (4 and 8 in.), respectively. Therefore, according to these experimental results, the zone of shear influence extends an average distance of 0.15 m (6 in.) from the soil-geosynthetic interface. That is, interaction between adjacent reinforcements could be observed for a vertical spacing value corresponding to 0.30 m (12 in.), or twice the average distance from the reinforcement for which interaction occurs.

The field monitoring component of this study involved a GRS-IBS structure constructed by the Virginia Department of Transportation's (VDOT), Staunton District in an area primarily characterized as a dry stream bed. The dimensions of the structure (2.4 m [8 ft] high and 9 m [30 ft] wide) were consistent with mini-pier tests constructed by FHWA as part of the development of the GRS-IBS system. The main focus of the field monitoring evaluation was on understanding the stress and strain distributions within the structure, as well as the lateral movements of the facing, as they relate to both sections of the structure constructed using reinforcement vertical spacings of 0.2 m (8 in.) in the primary reinforcement zone and 0.1 m (4 in.) in the bearing bed zone. The structure was designed and constructed by VDOT in accordance with FHWA guidelines. This included the use of woven geotextiles, AASHTO No. 8 aggregate and facing blocks. The two abutments were instrumented, with one of them constructed with a beam seat of 0.6 m (2ft.) and the other with a beam seat of 1.2 m (4 ft.). The instrumentation program aimed at understanding: (1) the stress and strains distribution behind the facing blocks; (2) the differences between the stress and strain distributions anticipated within the primary and bearing bed zones (i.e. zones with different vertical reinforcement spacing); and (3) the effect of the beam seat width (or contact stresses) on the stress distribution within the abutment. Instrumentation included vertical and horizontal earth pressure cells, strain gages, extensometers (placed in geotextiles and soil), settlement cells and survey targets. Field monitoring results also aimed at providing information suitable for calibration of the numerical model conducted as part of the numerical component of the project.

Data generated at different construction stages was evaluated as part of the field performance: self-weight of the backfill material, placement of the bridge slab, and loading of the slab with a truck after construction. Additionally, loading tests were conducted in stages during construction by placing Jersey barriers 0.3 m (1 ft.) away from the facing blocks of select layers. The results showed that the presence of secondary reinforcements (with comparatively small vertical spacing) led to a reduction in vertical and lateral stresses, reinforcement strains and backfill deformation. The vertical stress distribution due to the slab load was observed to agree with the theoretical AASHTO 2:1 and Boussinesq stress distribution methods. Overall, the profile of lateral earth pressures was found to be relatively uniform, with magnitudes of stresses comparatively higher those estimated using GRS-IBS design guidelines. The maximum measured strains in the geotextile were below 0.5% and connection load values ranging from 0.8 to 1.2 kN/m (4.6 to 6.9 lb/in). The reinforcement strain and connection load distribution with depth were also found to be reasonably uniform. Foundation settlement and lateral facing displacements were comparatively small and below the maximum vertical and lateral deformations allowed per GRS-IBS design guidelines. As expected, the abutment constructed with a wider beam seat exhibited a comparatively smaller magnitude of vertical stresses and facing displacements.

Numerical simulations were carried out under both serviceability and limit strength states to broaden the range of parameters adopted in the experimental and field components of this project. Numerical models were initially calibrated and validated against laboratory and field test data to provide reliable and accurate simulations of the behavior of GMSE structures in general and load-carrying GMSE bridge abutments in particular. After model calibration, three series of numerical parametric studies were conducted to investigate the effects of key parameters (e.g. wall height, reinforcement spacing, backfill and reinforcement properties, facing rigidity, foundation conditions, and loading conditions) on the behavior of GRS structures. The parametric studies included numerical investigations: (1) of soil-geosynthetic interaction tests; (2) of GRS piers; and (3) of GRS-IBS structures. In addition, this study investigated the effect of boundary conditions on the behavior of GRS structures and the stability of GRS structures under the strength limit state.

A numerical analysis of GRS mini-pier tests indicated that the impact of decreasing the reinforcement spacing was more significant than that increasing the reinforcement stiffness while maintaining a stiffness/spacing ratio constant. However, a numerical evaluation of GRS-IBS structures revealed similar behavior between two structures simulated with the same stiffness/spacing ratio. The main difference between the GRS mini-pier and GRS-IBS was their boundary conditions. A numerical investigation on the effect of boundary conditions showed that the impact of the stiffness/spacing ratio depends on the dominant internal stability mechanism (i.e. reinforcement pullout or breakage). When reinforcement pullout controls the performance, a structure with small reinforcement spacing and low reinforcement stiffness showed better performance than a structure with large reinforcement spacing and high reinforcement stiffness (for a constant stiffness/spacing ratio). However, when reinforcement pullout does not control performance, the two structures required essentially the same reinforcement tension capacity for different reinforcement spacings and stiffness values selected using a constant stiffness/spacing ratio.

The results of stability analyses showed that the shape of the critical slip surface was different for structures simulated with reinforcement spacing of 0.2 m (8 in.) and 0.6 m (16 in.). in the first case, the critical slip surface initiated from the wall toe and followed a Rankine slip plane up to approximately 2/3 of the wall height, then extending vertically to the edge of the bridge bearing seat. The tensile strength of the reinforcements was mobilized in both primary reinforcement zone and the bearing reinforcement zone (with smaller reinforcement vertical spacing). The maximum tension in the reinforcements showed an essentially uniformly distributed trend with depth. For the case with a vertical spacing of 0.6 m (24 in.), the slip surface was found to initiate at the wall toe and extend to the end of the bearing reinforcement zone. The required tensile strength of the reinforcement was not uniform and was only mobilized in the primary reinforcements.

Recommendations to modify the existing design procedures were finally compiled based on the wealth of experimental, field monitoring and numerical data generated in this study. Focus was on implementation of the recommendations into Section 11.10 AASHTO LRFD Bridge Design Specifications (AASHTO 2017). The proposed design procedure accounts for the boundaries identified for the composite behavior of GMSE structures established in the experimental research component of the study. Specifically, a zone of influence ranging from 0.1 to 0.2 m (4 to 8 in.) on each side of the geosynthetic is recommended for cases where the coefficient of interaction exceeds 0.8 and free draining fill materials are adopted in construction. The results from the field monitoring component and numerical component of this study were used to reassess current approaches, including correlations established by the FHWA regarding the effect of vertical spacing. This information allows proper integration of the findings of this project into the current AASHTO LRFD framework. With this background in mind,

A total of five design aspects were identified for possible revision into current guidelines to facilitate incorporation of the effect of reinforcement vertical spacing into the design of GMSE structures in general and load-carrying GMSE abutments in particular. The identified design aspects that deserve reevaluation and specific revisions to current design methods regarding these aspects are as follows:

1 **Effect of the vertical reinforcement spacing on the magnitude and distribution of maximum reinforcement tension**: A uniform distribution of maximum reinforcement tension with depth is recommended for GMSE structures with closely-spaced vertical reinforcement spacing. This recommended distribution has cost-effectiveness implications for the case of structures designed using the same vertical reinforcement spacing and reinforcement design strength in the entire height of the GMSE structure.

2 **Effect of vertical spacing on the magnitude and distribution of connection loads**: A uniform distribution of reinforcement connection load with depth is recommended for GMSE structures with closely-spaced vertical reinforcement. This recommended distribution also

has cost-effectiveness implications for the case of structures designed using the same vertical reinforcement spacing and reinforcement design strength.

3 **Effect of vertical spacing on stress distribution and the design of the bearing seat**: Increased density of reinforcement is recommended in this under the bearing seat of load-carrying GMSE abutments (including GRS-IBS structures). In particular, a reinforcement vertical spacing of 0.1 m (4 in.) was shown to result in improved performance

4 **Effect of vertical spacing on the structure's vertical and lateral deformation**: Improvement of structural stiffness is observed in structures with closely-spaced reinforcement, as it relates to comparatively decreased lateral displacements of the overall structure. A model is proposed for preliminary prediction of maximum lateral displacements.

5 **Effect of vertical spacing on the "bump at the end of the bridge:"** The use of closely-spaced reinforcement is recommended as it was verified to lead to a decreased bump at the end of the bridge for the case of load-carrying GMSE bridge abutments (including GRS-IBS structures).

Specific revisions to appropriate articles in AASHTO's Section 11 are provided for incorporation of each of these structural advantages into the specific design aspects. Additionally, modifications to the current Article 11.10.10.1, Concentrated Load Conditions, are also proposed for the case of load-carrying GMSE bridge abutments in general and for the case of GRS-IBS structures in particular, due to the uniqueness of the approach and documented performance. The research basis supporting the proposed revisions to incorporate the vertical spacing as an additional variable in design procedures are summarized. In reviewing the acceptance of the design advances proposed for use with closely-spaced reinforcements, consideration should also be given to several inherent benefits that improve the overall conservatism of the structure, which should offset any uncertainties resulting from the proposed modifications. These include increased redundancy in the system, comparatively better control of lift thickness and overall better backfill compaction control.