Evaluation of Prediction Methods for Lateral Deformation of GRS Walls and Abutments

Mahsa Khosrojerdi, S.M.ASCE[1]; Ming Xiao, M.ASCE[2]; Tong Qiu, M.ASCE[3];
and Jennifer Nicks, M.ASCE[4]

Abstract: Geosynthetic reinforced soil (GRS) walls and abutments are increasingly used to support transportation infrastructure. A pressing question in their response is the amount of horizontal deflection expected under service loads. This paper presents an evaluation of six methods for predicting the lateral deformation of GRS walls and abutments, namely the FHWA, Geoservice, CTI, Jewell-Milligan, Wu, and Adams methods. Field and laboratory performances of 17 GRS walls and abutments are compared with the predicted results from the six methods. A statistical analysis is then used to evaluate the conservativeness, accuracy, and reliability of these methods in predicting the maximum lateral deformation of GRS walls. The Adams method is the most accurate method for predicting the maximum lateral deformation if the amount of vertical deformation is reasonably known. Among the Geoservice, Jewell-Milligan, and Wu methods, which have the ability to predict the lateral deformation of GRS walls at various elevations where reinforcements are located, the Wu method is the most accurate and reliable method for predicting the lateral deformation of GRS walls. **DOI:** 10.1061/(ASCE)GT.1943-5606.0001591.

Author keywords: Abutment; Geosynthetic reinforced soil; Lateral deformation; Prediction method; Wall.

Introduction

In the design, construction, and maintenance of transportation infrastructure, demand is increasingly placed on reducing the cost, shortening the construction duration, and maintaining serviceability during its service life. Geosynthetic reinforced soil (GRS) abutments provide an economical solution to accelerated bridge construction that uses readily available materials and equipment and performs well (Adams et al. 2011a). Accordingly, GRS structures have gained increasing popularity in the world.

GRS consists of closely spaced layers of geosynthetic reinforcement and compacted granular fill material. The spacing of GRS reinforcement typically does not exceed 30 cm and is typically 20 cm (Adams et al. 2011a). Because GRS abutments support bridge structures, determining the amount of their horizontal and vertical deformations under service load is of great importance. Laboratory and field tests have been carried out to physically model the behavior of geosynthetically reinforced structures subjected to static loading. For example, Abu-Hejleh et al. (2000, 2002), Adams (1997), Adams et al. (2002), Ketchart and Wu (1997), Helwany (1993), and Helwany et al. (2001) performed field tests on geosynthetically reinforced bridge abutments with block facing and demonstrated that these structures have excellent performance characteristics and high load-carrying capacity. Benigni et al. (1996), Bueno et al. (2005), and Benjamim et al. (2007) evaluated the field performance of geosynthetically reinforced walls with wrap-around facing at the end of the construction stage, including the deformation of these walls and the strains in the reinforcement layers. The study of Benigni et al. (1996) showed that the top third of the wall moved almost rigidly forward under surcharge loading. Bueno et al. (2005) and Benjamim et al. (2007) concluded that the largest horizontal deformation and reinforcement strain under self-weight occurred toward the face of the structure, approximately at midheight of the wall. Bathurst et al. (2000, 2001) conducted laboratory model tests to evaluate the capacities and behaviors of geosynthetically reinforced walls and abutments under different loading conditions to identify possible sources of conservatism in current methods of analysis. The geosynthetically reinforced structures in the aforementioned studies had various reinforcement spacings from 15 to 60 cm.

Basic design guidelines for GRS abutments are available that outline recommended soil type, gradation, and level of compaction of the backfill soils, along with the vertical spacing, strength, stiffness, and length of reinforcement layers (Adams et al. 2011b; Nicks et al. 2013). Although these design guidelines are reasonably well established, the prediction of GRS walls and abutment deformation under applied service loads requires further investigation. A realistic estimation for deformations of GRS abutments is important because differential movements of bridge substructures can negatively affect the ride quality, deck drainage, and safety of the traveling public as well as the structural integrity and aesthetics of the bridge, which can lead to costly maintenance and repair measures (Modjeski and Masters 2015). Regardless of settlement uniformity, ensuring adequate clearance for bridge elevations is dependent on the total movement. Based on these reasons, the service limit state (SLS) often controls the design of shallow bridge foundations (AASHTO 2014; Samtani and Nowatzki 2006a, b). The SLS

---

[1] Graduate Student, Dept. of Civil and Environmental Engineering, Pennsylvania State Univ., University Park, PA 16802. E-mail: mahsa@psu.edu

[2] Associate Professor, Dept. of Civil and Environmental Engineering, Pennsylvania State Univ., University Park, PA 16802 (corresponding author). E-mail: mxiao@engr.psu.edu

[3] Associate Professor, Dept. of Civil and Environmental Engineering, Pennsylvania State Univ., University Park, PA 16802. E-mail: tqiu@engr.psu.edu

[4] Research Geotechnical Engineer, Turner Fairbank Highway Research Center, Federal Highway Administration, 6300 Georgetown Pike, McLean, VA 22101. E-mail: jennifer.nicks@dot.gov

Note. This manuscript was submitted on January 1, 2016; approved on June 10, 2016; published online on August 10, 2016. Discussion period open until January 10, 2017; separate discussions must be submitted for individual papers. This technical note is part of the ***Journal of Geotechnical and Geoenvironmental Engineering***, © ASCE, ISSN 1090-0241.

ensures the durability and serviceability of a bridge and its components under typical everyday loads, termed "service loads" (Mertz 2012). In SLS design, failure is often defined as exceeding tolerable displacements.

Horizontal deformation of abutments causes more severe and widespread problems for bridge structures compared to equal magnitudes of vertical movement (Modjeski and Masters 2015). The magnitude of deformations for GRS abutments depends on various factors, such as (1) backfill and foundation soil type, unit weight, and strength parameters; (2) geosynthetic type and its tensile strength properties; (3) reinforcement spacing and layout; (4) facing type; (5) connection between the reinforcement and facing; (6) geometry of bridge supports and their foundations; (7) native foundation and retained soil type, unit weight, and strength parameters; and (8) loading conditions.

Presently, six methods are available for predicting the lateral deformations of GRS walls and abutments; however, the accuracy of these prediction methods has not been evaluated. Among these methods, the FHWA, CTI, and Adams methods predict the maximum lateral deformation of GRS walls, and the Geoservice, Jewell-Milligan, and Wu methods have the ability to predict the deformation at elevations where reinforcements are located. In this study, the performances of 17 field and laboratory GRS walls and abutments with various applied surcharge loads were compared with the predicted results using the six methods. Statistical analyses were then conducted to evaluate the conservativeness, accuracy, and reliability of the six methods in estimating the maximum lateral deformation under service loads. The conservativeness, accuracy, and reliability of Geoservice, Jewell-Milligan, and Wu methods in predicting lateral deformations are also investigated. Most of the methods reviewed herein had been proposed long before the GRS concept was introduced; hence, in this study the "GRS wall" term refers to a geosynthetic-reinforced earth wall in general in which the vertical spacing between the reinforcement is not necessarily smaller than 30 cm.

Prediction Methods

The six methods evaluated in this paper are the FHWA method, Geoservice method, CTI method, Jewell-Milligan method, Wu method, and Adams method. Each method is briefly described in terms of applicability and parameters.

FHWA Method

Christopher et al. (1990) developed empirical equations for calculating the lateral deformation of GRS walls during wall construction based on data collected from actual structures and estimated from computer simulation models. In this method, referred to as the FHWA method, maximum lateral deformation is calculated through a fourth-order polynomial equation

$$\delta_R = 11.81\left(\frac{L}{H}\right)^4 - 42.25\left(\frac{L}{H}\right)^3 + 57.16\left(\frac{L}{H}\right)^2 - 35.45\left(\frac{L}{H}\right) + 9.471 \quad (1)$$

$$\delta_{\max} = \frac{\delta_R H}{75} \quad \text{(extensible reinforcement)} \quad (2a)$$

$$\delta_{\max} = \frac{\delta_R H}{250} \quad \text{(inextensible reinforcement)} \quad (2b)$$

where δ_R = deformation coefficient of reinforced soil wall; L = reinforcement length; H = GRS wall height (including embedment depth); and $\delta_{\max}$ = maximum lateral deformation of GRS wall. These equations can be used for simple GRS structures placed on rigid foundations and reinforced with geosynthetics layers of the same size. The value of L/H should be between 0.3 and 1.175. These equations cannot directly be used for GRS walls with a surcharge load applied. Christopher et al. (1990) stated that for a 6.1 m (20 ft) high wall, each additional 19.15 kPa (400 psf) of surcharge load increases the relative deformation by about 25%; however, the surcharge effect may be greater for higher walls.

Geoservice Method

Eq. (3) describes the Geoservice method that Giroud (1989) developed based on a limit equilibrium analysis to calculate the lateral deformation of a GRS wall or abutment by using the maximum strain generated in reinforcement layers and assuming a triangular distribution of strain in the reinforcements

$$\delta_h = \frac{\varepsilon_d L}{2} \quad (3)$$

where δ_h = horizontal deformation of a GRS wall or abutment; and ε_d = strain limit or maximum strain in each layer of reinforcement. If the reinforcement strain is unknown, the lateral deformation can be calculated by first choosing a strain limit for the reinforcement that is usually less than 10% (Giroud 1989). The strain limit depends on a number of factors including the type of wall facing, the deformation tolerances, and the type of reinforcement.

CTI Method

Eq. (4) shows the semiempirical relationship Wu (1994) developed for calculating the lateral deformation of GRS walls and abutments in a study for the Colorado Transportation Institute (CTI)

$$\delta_{\max} = \varepsilon_d\left(\frac{H}{1.25}\right) \quad (4)$$

This equation has reasonable estimation for the strain limit from 1 to 3% for permanent walls and up to 10% for temporary walls (Wu 1994). The CTI method is a service-load-based method and was developed based on findings of instrumented full-scale GRS walls and finite element analyses

Eq. (4) applies only to walls with heights less than 6.1 m (20 ft) and very low facing rigidity such as wrapped-face walls. For GRS walls with higher facing rigidity such as modular block walls, the maximum lateral deformation is about 15% smaller than the predicted value by this method (Wu 1994).

Jewell-Milligan Method

Jewell (1988) and Jewell and Milligan (1989) proposed design charts to estimate the lateral deformation of GRS walls and abutments at different depths within the wall based on analysis of stresses and deformations in a reinforced soil mass. The charts present graphical relationships between a dimensionless displacement factor, $\delta_h K_{\mathrm{reinf}}/HP_{\mathrm{base}}$, and the ratio of depth below the crest of wall and the wall height, Z/H, for various backfill friction angles and dilation angles, where δ_h = lateral deformation of the wall at the face; K_{reinf} = stiffness of the reinforcement; P_{base} = calculated reinforcement force at the base of the wall; and Z = depth from the crest of the wall. Jewell and Milligan (1989) developed design charts for GRS walls placed on rigid foundations and reinforced with ideal or truncated length of reinforcement for both the uniform spacing and ideal spacing conditions. Jewell and Milligan (1989) stated that reinforcements have ideal length if they reach to the back of an imaginary line that extends with an angle of ϕ_{ds} with horizontal from toe of the wall through the backfill, where ϕ_{ds} = effective friction angle of soil from direct shear test. Wu et al. (2013) concluded that a wall has the ideal length of reinforcement when the ratio of L/H is equal or greater than 0.7. The wall has ideal spacing if the vertical spacing of reinforcements increases along the wall in a way that the reinforcement layers support the same amount of maximum force. The rigidity of the facing blocks is not considered in this method. The lateral deformation of the wall varies with wall depth, and the maximum lateral deformation is assumed to occur at the middle of wall height.

Wu Method

Wu et al. (2013) developed an analytical model for calculating the lateral deformation of GRS walls with $L/H \geq 0.7$. Eq. (5) shows the analytical expression Wu et al. (2013) derived from the graphs by Jewell (1988) and Jewell and Milligan (1989)

$$\Delta_h = \left(\frac{1}{2}\right)\left(\frac{P_{rm}}{K_{\text{reinf}}}\right)(H - z_i)\left[\tan\left(45° - \frac{\psi}{2}\right) + \tan(90° - \phi_{ds})\right] \tag{5}$$

where Δ_h = lateral deformation of GRS wall; P_{rm} = maximum reinforcement force at depth of z_i from crest; and ψ = dilation angle of soil. Eq. (5) can be used for walls with flexible facing because the rigidity of the wall is not considered.

Eqs. (6) and (7) show the equations Wu et al. (2013) developed for calculating the lateral deformation of GRS walls with modular block facing based on an analytical model. This method considers the rigidity of wall facing. Eq. (6) considers the effect of fiction between the back of modular block and soil, and Eq. (7) is a simplified form of Eq. (6) and neglects the friction (i.e., $\beta = 0$). According to Wu et al. (2013), lateral movement calculated by Eq. (7) will be slightly larger than the lateral movement calculated by Eq. (6)

$$\Delta_i = 0.5\left[\frac{K_h(\gamma_s z_i + q)S_v - \gamma_b b S_v \tan\delta(1 + \tan\delta\tan\beta)}{K_{\text{reinf}}}\right](H - z_i) \times \left[\tan\left(45° - \frac{\psi}{2}\right) + \tan(90° - \phi_{ds})\right] \tag{6}$$

$$\Delta_i = 0.5\left[\frac{K_h(\gamma_s z_i + q)S_v - \gamma_b b S_v \tan\delta}{K_{\text{reinf}}}\right](H - z_i) \times \left[\tan\left(45° - \frac{\psi}{2}\right) + \tan(90° - \phi_{ds})\right] \tag{7}$$

where K_h = horizontal earth pressure coefficient; γ_s = unit weight of soil; S_v = vertical spacing of reinforcement; γ_b = unit weight of modular block; b = width of facing block; δ = friction angle between modular block facing elements; and β = friction angle between back face of wall and soil. In this method, it was assumed that the wall face is vertical or nearly vertical and adjacent facing blocks are connected only through friction. When friction angles from direct shear test are not available, Eqs. (8) and (9) can be used to convert the friction angle of soil from triaxial test to plane strain test (Bowles 1988), and then from conditions representative of plane strain conditions to those representative of a direct shear test (Wu et al. 2013)

$$\phi_{ps} = 1.1\phi_{tr} \tag{8}$$

$$K_a = \frac{1 - \sin\phi_{ps}}{1 + \sin\phi_{ps}} = \frac{\tan(45 + \frac{\psi}{2} - \phi_{ds})}{\tan(45 + \frac{\psi}{2})} \tag{9}$$

where ϕ_{ps} = effective friction angle of soil from plane strain test; ϕ_{tr} = effective friction angle of soil from triaxial test; and K_a = active earth pressure coefficient.

Adams Method

Eq. (10) shows the equation presented by Adams et al. (2002) to calculate the maximum lateral deformation of GRS abutments in response to a vertical load

$$D_L = \frac{2b_{q,\text{vol}}D_v}{H} \tag{10}$$

where D_L = lateral deformation of GRS abutments; $b_{q,\text{vol}}$ = width of load along top of wall (including setback); and D_v = vertical settlement of GRS abutment. In this method, it is conservatively assumed that the volume change in a GRS abutment is zero, which represents the worst-case scenario for lateral displacement. Adams et al. (2002) assume that if the GRS wall is constructed properly (e.g., proper backfill soil, placement of reinforcement, and compaction), the soil and the reinforcement will deform laterally together and have the same amount of strain. Based on an assumption of a triangular lateral deformation and a uniform vertical deformation, the maximum lateral strain can be estimated by using Eq. (11) and should be limited to 1% (Adams et al. 2011a, b)

$$\varepsilon_L = \frac{D_L}{b_{q,\text{vol}}} = \frac{2D_v}{H} = 2\varepsilon_v \tag{11}$$

where ε_L = lateral strain; and ε_v = vertical strain at top of the wall.

Evaluation Methodology

To evaluate the six methods, the performances of 17 field and laboratory GRS walls and abutments were analyzed for the study. Table 1 presents a summary of these case studies. Among these cases, the two walls in Cases #5 and #6 were constructed in Brazil, the two walls in Cases #9 and #10 were constructed in France, and the rest of walls were constructed in North America. The estimated lateral deformations based on these methods were then compared to the measured deformations from the case studies. A statistical analysis was conducted to evaluate the conservativeness, accuracy, and reliability of these methods. In the statistical analysis, the bias λ, which is defined as the ratio of the measured value to the predicted value, was determined. A bias value of 1.0 means the prediction is the same as the measured (observed) deformation. A prediction method with a bias value smaller than 1.0 represents a conservative prediction method, whereas a prediction method with a bias value larger than 1.0 represents an unconservative method. The accuracy of a prediction method is represented by the deviation of the mean bias from unity; a mean bias that is much larger or smaller than unity represents a less accurate prediction method. The reliability of a prediction method is represented by the coefficient of variation (COV); a large COV value represents a prediction method that is less reliable.

For each prediction method, the statistical parameters such as the mean, standard deviation, and COV of the bias were calculated. Table 2 lists the measured values of the maximum lateral deformation and the corresponding predicted values using the FHWA method; the bias value for each case is also presented. The same approach is used for the rest of the prediction methods

Table 1. GRS Abutment and Wall Parameters of 17 Case Histories

Case number	H (m)	L (m)	S_v (m)	T_y (kN/m)	ϕ (degrees)	ψ (degrees)	Reinforcement type	Facing type	References and notes
1	3.6	2.5	0.6	20.4	40 (TT)	11	Biaxial geogrid	CMB	Hatami and Bathurst (2005) and Bathurst et al. (2009) Wall No. 1
2	3.6	2.5	0.6	10.2	40 (TT)	11	Biaxial geogrid	CMB	Hatami and Bathurst (2005) and Bathurst et al. (2009) Wall No. 2
3	3.6	2.5	0.9	20.4	40 (TT)	11	Biaxial geogrid	CMB	Hatami and Bathurst (2005) Wall No. 3
4	3.6	2.5	0.6	17.5	40 (TT)	11	Geogrid	CMB	Hatami and Bathurst (2006) and Bathurst et al. (2009) Wall No. 5
5	4.0	3.0	0.4	13	32 (DS)	14	Nonwoven geotextiles	Wrap-around	Bueno et al. (2005)
6	4.0	3.0	0.4	13	33 (TT)	0	Nonwoven geotextiles	Wrap-around	Benjamim et al. (2007)
7	5.0	2.0	0.5	27	40 (TT)	10	Geocomposite	Wrap-around	Benigni et al. (1996)
8	7.62	3.2–4.4	0.2	70	—	—	Nonwoven geotextile	CMB	Ketchart and Wu (1997)
9	4.35	1.3–3.6	0.3–0.6	25	—	—	Woven geotextile	CMB	Gotteland et al. (1997)
10	4.35	2.7–3.6	0.3–0.6	44	—	—	Nonwoven geotextile	CMB	Gotteland et al. (1997)
11	5.9	8–12	0.4	157.3	40 (DS)	—	Uniaxial geogrid	CMB	Abu-Hejleh et al. (2001) (section 800)
12	5.9	8–12	0.4	157.3	40 (DS)	—	Uniaxial geogrid	CMB	Abu-Hejleh et al. (2001) (section 400)
13	4.5	8–12	0.4	157.3	40 (DS)	—	Uniaxial geogrid	CMB	Abu-Hejleh et al. (2001) (section 200)
14	4.65	3.15	0.2	70	34.8 (DS)	—	Woven geotextile	CMB	Helwany et al. (2007) Wall section A (Amoco test)
15	4.65	3.15	0.2	21	34.8 (DS)	—	Woven geotextile	CMB	Helwany et al. (2007) Wall section B (Mirafi test)
16	6.1	4.3	0.6–1.0	39.2	40 (TT)	—	Biaxial geogrid	CMB	Bathurst et al. (1993)
17	12.6	9.75	0.38	from 31 to 186	43–47 (TT)	15	Geotextile	Wrap-around	Allen et al. (1992)

Notes: CMB = concrete modular block; DS = direct shear test; H = GRS wall height, L = reinforcement length, S_v = vertical spacing of reinforcement, T_y= ultimate tensile strength of reinforcement in accordance with ASTM D4595 test; TT = triaxial test; ϕ = friction angle of soil, ψ = dilation angle of soil; geocomposite material consists of a nonwoven polyester sheet on which woven polypropylene threads were knitted at constant spacing; for Cases #1, #2, #3, and #4, the facing deformations for each wall at some elevations and the magnitudes of surcharge load were reported using range bars that indicate the maximum, mean, and minimum values; the reported mean value of the range bar was selected as the measured value for the evaluation.

Table 2. Predicted and Measured Maximum Lateral Deformations of GRS Walls Using FHWA Method

Case number	Measured (mm)	Predicted (mm)	Bias (measured/predicted)	Notes
1	5.2	48.4	0.11	Results are obtained at the end of construction
1	9.3	68.0	0.14	Results are obtained under 30 kPa
1	13.5	80.8	0.17	Results are obtained under 50 kPa
1	31.4	93.5	0.33	Results are obtained under 70 kPa
2	7.9	48.4	0.16	Results are obtained at the end of construction
2	12.0	68.0	0.18	Results are obtained under 30 kPa
2	35.0	80.8	0.43	Results are obtained under 50 kPa
2	58.4	93.5	0.62	Results are obtained under 70 kPa
3	6.0	48.4	0.12	Results are obtained at the end of construction
4	10.5	68.0	0.15	Results are obtained under 30 kPa
4	20.3	80.8	0.25	Results are obtained under 50 kPa
4	29.6	93.5	0.32	Results are obtained under 70 kPa
5	15.7	50.6	0.31	Results are obtained at the end of construction
6	12.2	50.6	0.24	Results are obtained at the end of construction (measured data are read after 200 days)
7	2.1	135.3	0.02	Results are obtained at the end of construction
7	8.0	172.4	0.05	Results are obtained under 21 kPa
7	29.5	209.3	0.14	Results are obtained under 42 kPa
7	82.7	283.6	0.29	Results are obtained under 84 kPa
16	38.8	81.3	0.48	Results are obtained at the end of construction
16	91.7	106.7	0.86	Results are obtained under 23 kPa (measured data are read after 11,280 h of applying load)
17	127.4	155.2	0.82	Results are obtained at the end of construction
17	137.0	270.7	0.51	Results are obtained under 57 kPa

and the corresponding tables are provided as Supplemental Data (Tables S1–S5). The number of data points used in the analyses for predicting the maximum lateral deformation is 22, 13, 12, 15, 12, and 12 for the FHWA, Geoservice, CTI, Jewell-Milligan, Wu, and Adams methods, respectively. The numbers of data points are different because not all methods were applicable to all the case studies. For instance, the FHWA method is applicable to simple GRS walls in which the length of reinforcement layers are constant; therefore, this method could only be used for case histories 1, 2, 3, 4, 5, 6, 7, 16, and 17. Conditions applicable to each of the six methods have been explained in the "Prediction Methods" section.

The accuracy, conservativeness, and reliability of Geoservice, Jewell-Milligan, and Wu methods for predicting the deformation at different elevations along the height of the wall are evaluated. Tables S6–S8 list the measured and the corresponding predicted values of lateral deformation using these three methods. The number of data points used in the analyses for predicting the lateral deformations is 62, 84, and 62 for the Geoservice, Jewell-Milligan, and Wu, respectively.

Results

In this section, the six prediction methods for estimating the maximum lateral deformation of GRS walls and abutments are first discussed, and the three methods that can predict the lateral deformations along the wall height are then evaluated.

Maximum Lateral Deformation

Table 3 summarizes the statistical analyses of the six prediction methods for maximum lateral deformation of GRS abutments and walls. For the FHWA method, the mean λ value is 0.30, which suggests the method is highly conservative, and the predictions on average overestimate the lateral deformations by a factor of 3.2. The COV value of 0.76 indicates a fair reliability. Because this method requires few input parameters (height of the wall and length of reinforcement), it can be used for a rough estimation of the maximum lateral deformation of GRS walls even before construction.

For the Geoservice method, the mean λ value is 1.82, which suggests that this method is unconservative, and the predicted lateral deformations are on average 55% of the actual measured values. The relatively high COV value (0.93) indicates a relatively low reliability. If actual values of the reinforcement strains are not available, a strain limit should be assumed based on previous related experiments, which may further reduce the reliability and accuracy of this method.

For the CTI method, the mean λ value is 0.67, which suggests that this method is conservative and on average overestimates the lateral deformation by a factor of 1.49. The COV value of 0.49 indicates a good reliability. Similar to the Geoservice method, if an

Table 3. Summary of Statistical Analyses of Prediction Methods for Maximum Lateral Deformation

Statistical parameters	FHWA method	Geoservice method	CTI method	Jewell-Milligan method	Wu method	Adams method
Number of data points	22	13	12	15	12	12
Mean bias	0.30	1.82	0.67	0.27	0.61	1.13
SD	0.23	1.69	0.49	0.15	0.42	0.57
COV	0.76	0.93	0.73	0.56	0.70	0.51

assumed value of the strain limit is used, the accuracy and reliability of this method may further decrease.

For the Jewell-Milligan method, the mean λ value is 0.27, which suggests that this method is highly conservative and on average overestimates lateral deformation by a factor of 3.70. The relatively low COV value (0.56) indicates a good reliability. For the Wu method, the mean λ value is 0.61, which suggests that this method is conservative and on average overestimates lateral deformation by a factor of 1.64. The relatively low COV value (0.70) indicates a fair reliability. One of the important advantages of the Jewell-Milligan and Wu methods is that the vertical displacement of wall or the reinforcement strain after construction is not needed for predicting lateral deformations.

For the Adams method, the mean λ value is 1.13, which suggests that this method is slightly unconservative, and the predicted lateral deformations are on average 88% of the actual measured values. The low COV value (0.51) indicates a good reliability. One limitation of this method is that for predicting the maximum lateral deformation of an abutment or a wall, the amount of vertical settlement of the structure must be known.

Lateral Deformation along Wall Height

Table 4 summarizes the statistical analyses of the three prediction methods for estimating lateral deformation of GRS walls at different elevations. For the Geoservice method, the mean λ value is 2.51, which suggests that this method is unconservative, and the predicted lateral deformations are on average 44% of the actual measured values. The relatively high COV value (1.30) indicates a relatively low reliability. For the Jewell-Milligan method, the mean λ value is 0.29, which suggests that this method is highly conservative and on average overestimates lateral deformation by a factor of 3.45. The COV value of 1.09 also indicates a low reliability. For the Wu method, the mean λ value is 0.55, which suggests that this method is conservative and on average overestimates lateral deformation by a factor of 1.82. The COV value of 1.07, although the lowest among the three methods, still indicates a low reliability.

Discussion

The underlying mechanisms behind the different levels of accuracy of the six methods are discussed in this section. The Adams method is the most accurate method for predicting the maximum lateral deformation with a mean bias closest to unity and a small COV. This is because the maximum lateral deformation is calculated based on the vertical settlement of GRS walls and abutments in this method; unlike the other five methods, the Adams method cannot be used for blind prediction prior to construction of GRS walls and abutments. The Adams method is slightly unconservative likely because of the slight lateral movement of facing blocks that can occur independently of the reinforced soil deformations.

Table 4. Summary of Statistical Analyses of Prediction Methods for Lateral Deformations along a GRS Wall or Abutment

Statistical parameters	Geoservice method	Jewell-Milligan method	Wu method
Number of data points	62	84	62
Mean bias	2.51	0.29	0.55
SD	3.25	0.31	0.59
COV	1.30	1.09	1.07

The Wu method improves the Jewell-Milligan method by including the effect of wall facing rigidity; this improvement is reflected by the generally observed higher level of accuracy of predicting lateral deformations of GRS abutments in the Wu method. Wu et al. (2013) noted that the two methods produce nearly identical lateral wall movement for weightless facing blocks. As the facing blocks become heavier, the lateral wall movement becomes smaller; for very heavy facing blocks, the maximum lateral wall movement can be 35% smaller than a wall with negligible facing rigidity.

The CTI method has a relatively high accuracy because it is a service-load-based method and actual strains in the reinforcement from the case histories were used in Eq. (4). For the design of GRS walls and abutments, the accuracy of the maximum lateral deformation estimated from the CTI method is largely dependent on the accuracy of the estimate of the maximum strains in the reinforcements. The Geoservice method also relies on an estimate of the maximum strain in the reinforcements; however, this method is not as accurate as the CTI method in estimating the lateral deformation under working load conditions because the Geoservice method is based on limit equilibrium analysis at the stress limit state.

The FHWA method is the most conservative method likely for a combination of two reasons. First, it is based on regression analysis of data collected from actual GRS structures and numerical simulations up to 1990, which include different design and construction conditions than those in recent case histories used in this study. Second, the geometry of the GRS wall and abutment is the only input needed in this method [Eq. (1)]; hence, this method is generally not as accurate as those that incorporate the strains in reinforcement.

All cases in this study were constructed as test walls, which may lead to smaller displacements compared to typical walls in the field because of special attentions in the test wall constructions. The measured wall deformations in some cases reported in this study in themselves include statistical variations. The evaluation and results of this study are based on 17 cases that are currently available; the conclusions may be further strengthened or revised with more case histories that become available in the future. Moreover, only one case has a wall height larger than 8 m; the six methods remain to be evaluated for walls higher than 8 m.

Conclusions

This paper presents an evaluation of six methods for predicting the lateral deformation of GRS walls and abutments, namely the FHWA method, Geoservice method, CTI method, Jewell-Milligan method, Wu method, and Adams method. Field and laboratory performances of 17 GRS walls and abutments were compared with the prediction results using the six methods. Statistical analysis was used to evaluate the conservativeness, accuracy, and reliability of these methods. Interpretations of the results of this study should consider that the number of measured data points may be statistically small because of the limited available case histories in the literature, particularly for the evaluation of maximum deformation prediction. The following conclusions are reached based on the 17 case histories.

For estimating the maximum lateral deformation of GRS walls and abutments, the FHWA and Jewell-Milligan methods are the most conservative methods whereas the Geoservice method is the most unconservative method. The Adams method is the most accurate method for predicting the maximum lateral deformation with a mean bias closest to unity and a small COV. The Adams method can be used as a prediction tool assuming the designer can adequately estimate vertical settlement. The CTI and Wu methods are conservative and relatively reliable methods for predicting the maximum lateral deformation of GRS walls and abutments without knowing the vertical deformation.

Among the three methods that can estimate the lateral deformations along the height of a GRS abutment or wall, the Wu method is conservative and relatively accurate; although its reliability is the highest among the three available methods, its high COV value still indicates a relatively low reliability.

Acknowledgments

Support of this study was provided by the Federal Highway Administration (FHWA) under Contract No. DTFH6114C00012. This support is gratefully acknowledged. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and not necessarily the views of the FHWA.

Supplemental Data

Tables S1–S8 are available online in the ASCE Library (http://www.ascelibrary.org).

References

AASHTO. (2014). *AASHTO LRFD bridge design specifications*, 7th Ed., Washington, DC.

Abu-Hejleh, N., Wang, T., and Zornberg, J. G. (2000). "Performance of geosynthetic-reinforced walls supporting bridge and approaching roadway structures." *Advances in transportation and geoenvironmental systems using geosynthetics*, ASCE, Reston, VA, 218–243.

Abu-Hejleh, N., Zornberg, J. G., Wang, T., and Watcharamonthein, J. (2002). "Monitored displacements of unique geosynthetic-reinforced soil bridge abutments." *Geosynth. Int.*, 9(1), 71–95.

Adams, M., Nicks, J., Stabile, T., Wu, J. T., Schlatter, W., and Hartmann, J. (2011a). "Geosynthetic reinforced soil integrated bridge system interim implementation guide." *Rep. No. FHWA-HRT-11-026*, Federal Highway Administration, Washington, DC.

Adams, M., Nicks, J., Stabile, T., Wu, J. T., Schlatter, W., and Hartmann, J. (2011b). "Geosynthetic reinforced soil integrated bridge system synthesis report." *Rep. No. FHWA-HRT-11-027*, Federal Highway Administration, McLean, VA.

Adams, M. T. (1997). "Performance of a pre-strained geosynthetic reinforced soil bridge pier." *Proc., Int. Symp. on Mechanically Stabilized Backfill*, J. T. H. Wu, ed., Balkema, Rotterdam, Netherlands, 35–53.

Adams, M. T., Lillis, C. P., Wu, J. T. H., and Ketchart, K. (2002). "Vegas Mini Pier experiment and postulate of zero volume change." *Proc., 7th Int. Conf. Geosynthetics*, Swets and Zeitlinger, Lisse, Netherlands, 389–394.

Allen, T. M., Christopher, B. R., and Holtz, R. D. (1992). "Performance of a 41-foot high geotextile wall." *Washington State Final Rep. No. WA87-03*, Washington State Dept. of Transportation, Olympia, WA, 72.

Bathurst, R. J., Jarrett, P. M., and Benjamin, D. J. (1993). "A database of results from an incrementally constructed geogrid-reinforced soil wall test." *Proc., Soil Reinforcement: Full Scale Experiments of the 80s*, ISSMFE/ENPC, Paris, 401–430.

Bathurst, R. J., Nernheim, A., Walters, D. L., Allen, T. M., Burgess, P., and Saunders, D. D. (2009). "Influence of reinforcement stiffness and compaction on the performance of four geosynthetic reinforced soil walls." *Geosynth. Int.*, 16(1), 43–59.

Bathurst, R. J., Walters, D. L., Hatami, K., and Allen, T. M. (2001). "Full-scale performance testing and numerical modelling of reinforced soil retaining walls." *Proc., 4th Int. Symp. on Earth Reinforcement, IS Kyushu*, H. Ochiai, J. Otani, N. Yasufuku, and K. Omine, eds., Vol. 2, Balkema, Rotterdam, Netherlands, 777–799.

Bathurst, R. J., Walters, D. L., Vlachopoulos, N., Burgess, P. G., and Allen, T. M. (2000). "Full-scale testing of geosynthetic reinforced walls." *Proc., Advances in Transportation and Geoenvironmental Systems Using Geosynthetics, Geo-Denver*, J. G. Zonrberg and B. R. Christopher, eds., ASCE, Reston, VA, 201–217.

Benigni, C., Bosco, G., Cazzuffi, D., and Col, R. D. (1996). "Construction and performance of an experimental large scale wall reinforced with geosynthetics." *Earth reinforcement*, H. Ochiai, N. Yasufuku, and K. Omine, eds., Vol. 1, A. A. Balkema, Reston, VA, 315–320.

Benjamim, C. V. S., Bueno, B. S., and Zornberg, J. G. (2007). "Field monitoring evaluation of geotextile-reinforced soil-retaining walls." *Geosynth. Int.*, 14(2), 100–118.

Bowles, J. E. (1988). *Foundation analysis and design*, 5th Ed., McGraw-Hill, New York.

Bueno, B. S., Benjamim, C. V. S., and Zornberg, J. G. (2005). "Field performance of a full-scale retaining wall reinforced with Nonwoven geotextiles." *Slopes and retaining structures under seismic and static conditions*, M. Gabr, J. J. Bowders, D. Elton, and J. G. Zornberg, eds., ASCE, Reston, VA, 2617–2625.

Christopher, B. R., Gill, S. A., Giroud, J. P., Mitchell, J. K., Schlosser, F., and Dunnicliff, J. (1990). "Reinforced soil structures. Vol. 1: Design and construction guidelines." *Rep. No. FHWA-RD 89-043*, Federal Highway Administration, Washington, DC.

Giroud, J. P. (1989). "Geotextile engineering workshop-design examples." *Rep. No. FHWA-HI-89-002*, Federal Highway Administration, Washington, DC.

Gotteland, P., Gourc, J. P., and Villard, P. (1997). "Geosynthetic reinforced structures as bridge abutment: Full scale experimentation and comparison with modelisations." *Proc., Int. Symp. on Mechanically Stabilized Backfill*, J. T. H. Wu, ed., Balkema, Rotterdam, Netherlands, 25–34.

Hatami, K., and Bathurst, R. J. (2005). "Development and verification of a numerical model for the analysis of geosynthetic-reinforced soil segmental walls under working stress conditions." *Can. Geotech. J.*, 42(4), 1066–1085.

Hatami, K., and Bathurst, R. J. (2006). "Numerical model for reinforced soil segmental walls under surcharge loading." *J. Geotech. Geoenviron. Eng.*, 10.1061/(ASCE)1090-0241(2006)132:6(673), 673–684.

Helwany, S. M. (1993). "Long-term soil-geosynthetic interaction in geosynthetic-reinforced soil structures." Ph.D. thesis, Univ. of Colorado, Boulder, CO.

Helwany, S. M., Budhu, M., and McCallen, D. (2001). "Seismic analysis of segmental retaining walls. I: Model verification." *J. Geotech. Geoenviron. Eng.*, 10.1061/(ASCE)1090-0241(2001)127:9(741), 741–749.

Helwany, S. M., Wu, J. T., and Kitsabunnarat, A. (2007). "Simulating the behavior of GRS bridge abutments." *J. Geotech. Geoenviron. Eng.*, 10.1061/(ASCE)1090-0241(2007)133:10(1229), 1229–1240.

Jewell, R. A. (1988). "Reinforced soil wall analysis and behavior." *The application of polymeric reinforcement in soil retaining structures*, Kluwer, Netherlands.

Jewell, R. A., and Milligan, G. W. E. (1989). "Deformation calculation for reinforced soil walls." *Proc., 12th Int. Conf. on Soil Mechanics and Foundation Engineering*, Vol. 2, Taylor & Francis, Abingdon, U.K., 1259–1262.

Ketchart, K., and Wu, J. T. H. (1997). "Performance of geosynthetic-reinforced soil bridge pier and abutment, Denver, Colorado, USA." *Proc., Int. Symp. on Mechanically Stabilized Backfill*, Wu, J. T. H., ed., Balkema,, Rotterdam, Netherlands, 101–116.

Mertz, D. (2012). "Steel bridge design handbook: Limit states." *Rep. No. FHWA-IF-12-052-Vol.10*, Federal Highway Administration, Washington, DC.

Modjeski and Masters, Inc. (2015). "Bridges for service life beyond 100 years: Service limit state design." *SHRP 2 Rep. No. S2-R19B-RW-1*, Transportation Research Board of National of Academies, Washington, DC.

Nicks, J. E., Adams, M. T., Ooi, P. S. K., and Stabile, T. (2013). "Geosynthetic reinforced soil performance testing—Axial load deformation relationships." *Rep. NO. FHWA-HRT-13-066*, Federal Highway Administration, Washington, DC.

Samtani, N. C., and Nowatzki, E. A. (2006a). "Soils and foundations reference manual: Volume I." *Rep. No. FHWA-NHI-06-088*, Federal Highway Administration, Washington, DC.

Samtani, N. C., and Nowatzki, E. A. (2006b). "Soils and foundations reference manual: Volume II." *Rep. No. FHWA-NHI-06-089*, Federal Highway Administration, Washington, DC.

Wu, J. T. (1994). "Design and construction of low cost retaining walls: The next generation in technology." *Rep. No. CTI-UCD-1-94*, Colorado Transportation Institute, Denver, CO.

Wu, J. T., Pham, T. Q., and Adams, M. T. (2013). "Composite behavior of geosynthetic reinforced soil mass." *FHWA Rep. No. FHWA-HRT-10-077*, McLean, VA.

ASCE *Journal of Geotechnical and Geoenvironmental Engineering*

Evaluation of Prediction Methods for Lateral Deformation of GRS Walls and Abutments

Mahsa Khosrojerdi, Ming Xiao, Tong Qiu, and Jennifer Nicks

DOI: 10.1061/(ASCE)GT.1943-5606.0001591

Supplemental Data

Tables S1–S8 contain predicted and measured maximum lateral deformations of GRS walls and abutments using the Geoservice, CTI, Jewell-Milligan, Wu, and Adams methods; and the predicted and measured lateral deformations of GRS walls and abutments at various elevations using the Geoservice, Jewell-Milligan, and Wu methods.

Table S1. Predicted and Measured Maximum Lateral Deformations of GRS Walls and Abutments using Geoservice Method

Case #	**Measured (mm)**	**Predicted (mm)**	**Bias, λ** $\frac{\text{Measured}}{\text{Predicted}}$	**Notes**
1	5.2	8.9	0.58	Results are obtained at the end of construction
2	7.9	12.3	0.64	Results are obtained at the end of construction
3	6.0	9.4	0.64	Results are obtained at the end of construction
5	15.7	9.6	1.64	Results are obtained at the end of construction
6	12.2	16.4	0.74	Results are obtained at the end of construction (measured data are read after 200 days)
7	82.7	47.5	1.74	Results are obtained under 84 kPa
8	14.3	2.6	5.50	Results are obtained under 131 kPa
9	83.3	111.3	0.75	Results are obtained under 190 kPa
10	106.7	244.2	0.44	Results are obtained under 190 kPa
11	4.0	23.8	0.17	Results are obtained under 115 kPa
16	38.8	11.6	3.34	Results are obtained at the end of construction
16	91.7	24.9	3.68	Results are obtained under 23 kPa (measured data are read after 11280 hours of applying load)
17	137.0	36.1	3.79	Results are obtained under 57 kPa

Table S2. Predicted and Measured Maximum Lateral Deformations of GRS Walls and Abutments using CTI Method

Case #	Measured (mm)	Predicted (mm)	Bias, λ $\frac{\text{Measured}}{\text{Predicted}}$	Notes
1	5.2	17.3	0.30	Results are obtained at the end of construction
2	7.9	23.8	0.33	Results are obtained at the end of construction
3	6.0	18.3	0.33	Results are obtained at the end of construction
5	15.7	20.5	0.77	Results are obtained at the end of construction
6	12.2	20.5	0.60	Results are obtained at the end of construction (measured data are read after 200 days)
7	82.7	190.0	0.44	Results are obtained under 84 kPa
8	14.3	8.8	1.63	Results are obtained under 131 kPa
9	83.3	180.4	0.46	Results are obtained under 190 kPa
10	106.7	398.2	0.27	Results are obtained under 190 kPa
11	4.0	16.4	0.24	Results are obtained under 115 kPa
16	38.8	22.9	1.28	Results are obtained at the end of construction
16	91.7	49.2	1.41	Results are obtained under 23 kPa (measured data are read after 11280 hours of applying load)

Table S3. Predicted and Measured Maximum Lateral Deformations of GRS Walls using Jewell-Milligan Method

Case #	**Measured (mm)**	**Predicted (mm)**	**Bias, λ** $\frac{\text{Measured}}{\text{Predicted}}$	**Notes**
1	5.2	20.6	0.11	Results are obtained at the end of construction
1	9.3	30.8	0.14	Results are obtained under 30 kPa
1	13.5	37.6	0.17	Results are obtained under 50 kPa
1	31.4	44.4	0.33	Results are obtained under 70 kPa
2	7.9	41.2	0.16	Results are obtained at the end of construction
2	12.0	61.6	0.18	Results are obtained under 30 kPa
2	35.0	75.2	0.43	Results are obtained under 50 kPa
2	58.4	88.8	0.62	Results are obtained under 70 kPa
3	6.0	20.6	0.12	Results are obtained at the end of construction
4	10.5	96.0	0.15	Results are obtained under 30 kPa
4	20.3	117.2	0.25	Results are obtained under 50 kPa
4	29.6	138.4	0.32	Results are obtained under 70 kPa
5	15.7	164.9	0.31	Results are obtained at the end of construction
6	12.2	200.6	0.24	Results are obtained at the end of construction (measured data are read after 200 days)
17	137.0	1412.4	0.51	Results are obtained under 57 kPa

Table S4. Predicted and Measured Maximum Lateral Deformations of GRS Walls using Wu Method

Case #	**Measured (mm)**	**Predicted (mm)**	**Bias, λ** $\frac{\text{Measured}}{\text{Predicted}}$	**Notes**
1	9.3	7.3	1.27	Results are obtained under 30 kPa
1	13.5	17.0	0.79	Results are obtained under 50 kPa
1	31.4	30.6	1.03	Results are obtained under 70 kPa
2	12.0	14.6	0.82	Results are obtained under 30 kPa
2	35.0	34.0	1.03	Results are obtained under 50 kPa
2	58.4	61.2	0.95	Results are obtained under 70 kPa
4	10.5	22.8	0.46	Results are obtained under 30 kPa
4	20.3	52.7	0.39	Results are obtained under 50 kPa
4	29.6	95.4	0.31	Results are obtained under 70 kPa
5	15.7	158.4	0.10	Results are obtained at the end of construction
6	12.2	177.6	0.07	Results are obtained at the end of construction (measured data are read after 200 days)
17	137.0	2182.3	0.06	Results are obtained under 57 kPa

Table S5. Predicted and Measured Maximum Lateral Deformations of GRS Walls and Abutments using Adams Method

Case #	**Applied Pressure (kPa)**	**Measured (mm)**	**Predicted (mm)**	**Bias, λ** $\frac{\text{Measured}}{\text{Predicted}}$	**Notes**
7	84	82.7	73.4	1.13	None
8	131	14.3	15.2	0.94	None
9	N/A	8.6	11.4	0.75	Results are obtained at EOC
10	N/A	11.1	15.3	0.73	Results are obtained at EOC
11	115	10	5.6	1.79	None
12	115	9	12.7	0.71	None
13	115	7	16.0	0.44	None
14	207	23.4	16.3	1.44	None
	475	57.3	41.8	1.37	
15	214	36.4	27.5	1.32	None
	317	57.8	45.4	1.27	
	414	113.4	69.2	1.64	

Note: Since the amount of vertical displacement for cases #1-6 and #16-17was not known, Adams method cannot be used for predicting maximum lateral deformation of these cases.

Table S6. Predicted and Measured Lateral Deformations of GRS Walls and Abutments using Geoservice Method

Case #	**Elevation (m)**	**Measured (mm)**	**Predicted (mm)**	**Bias, λ** $\frac{\text{Measured}}{\text{Predicted}}$	**Notes**
1	3.3	1.5	0.7	2.11	Results are obtained at the end of construction (EOC)
	2.7	5.1	2.4	2.12	
	2.1	5.2	3.0	1.74	
	1.5	5.0	8.9	0.56	
	0.9	3.7	7.4	0.51	
	0.3	2.4	6.9	0.34	
2	3.3	6.3	4.5	1.39	Results are obtained at EOC
	2.7	8.0	5.9	1.35	
	2.1	6.4	6.9	0.93	
	1.5	4.7	12.3	0.38	
	0.9	3.8	9.9	0.39	
	0.3	1.2	7.2	0.17	
3	3.1	2.1	9.4	0.22	Results are obtained at EOC
	2.2	6.0	8.7	0.69	
	1.3	5.2	8.4	0.62	
	0.5	2.1	6.6	0.32	
5	2.8	9.8	7.2	1.36	Results are obtained at EOC
	2	15.7	9.6	1.64	
	1.2	8.6	0.9	9.56	
	0.4	13.1	6.0	2.18	
6	3.6	2.4	0.2	12.0	Results are obtained at EOC
	2.8	8.3	7.3	1.14	
	2	12.2	9.6	1.27	
	1.2	5.4	3.0	1.80	
	0.4	5.0	6.0	0.83	
7	4.5	81.5	47.5	1.72	Results are obtained under 84 kPa
	4	82.1	44.0	1.87	
	3.5	82.7	42.5	1.95	
	3	78.2	44.0	1.78	
	2.5	71.1	33.5	2.12	
	2	60.3	28.5	2.12	
	1.5	45.1	21.5	2.10	
	1	31.5	11.0	2.86	
	0.5	18.9	6.5	2.91	
8	6.5	8.0	2.1	3.81	Results are obtained under 131 kPa
	5.9	8.0	2.6	3.08	
	5.1	14.0	2.2	6.36	
9	3.8	83.3	111.3	0.75	Results are obtained under 190 kPa
	2.6	57.7	46.6	1.24	
	1.5	21.6	30.2	0.71	
	0.6	7.2	15.7	0.46	
10	3.8	106.7	244.2	0.44	Results are obtained under 190 kPa
	2.6	96.9	182.2	0.53	
	1.5	21.8	53.6	0.41	
	0.6	0.9	8.8	0.10	

Table S6. (*continued*)

Case #	**Elevation (m)**	**Measured (mm)**	**Predicted (mm)**	**Bias, λ** $\frac{\text{Measured}}{\text{Predicted}}$	**Notes**
11	2.4	1.1	19.8	0.06	Results are obtained under 115 kPa
	4	4.0	23.8	0.17	
	4.8	4.0	7.4	0.54	
16	5.2	38.3	2.6	14.73	Results are obtained at EOC
	3.4	36.8	10.3	3.57	
	2.0	32.7	11.6	2.82	
	0.8	20.7	11.0	1.88	
	0.2	11.2	4.1	2.73	
16	5.2	90.7	6.0	15.12	Results are obtained under 23 kPa (measured data are read after 11280 hours of applying load)
	3.4	89.0	21.3	4.18	
	2.0	77.1	24.9	3.10	
	0.8	60.7	18.5	3.28	
	0.2	36.8	3.7	9.94	
17	9.5	63.9	36.1	1.77	Results are obtained under 57 kPa
	6.1	137.0	26.3	5.21	
	3.0	66.7	24.9	2.68	
	1.1	15.5	21.9	0.71	

Note: All predicted values are based on measured maximum reinforcement strain at each elevation.

Table S7. Predicted and Measured Lateral Deformations of GRS Walls and Abutments using Jewell-Milligan Method

Case #	Elevation (m)	Measured (mm)	Predicted (mm)	Bias, λ $\frac{\text{Measured}}{\text{Predicted}}$	Notes
1	3.3	1.5	7.4	0.20	Results are obtained at EOC
	2.7	5.1	15.6	0.33	
	2.1	5.2	20.6	0.25	
	1.5	5	20.6	0.24	
	0.9	3.7	15.6	0.24	
	0.3	2.4	7.4	0.32	
1	3.3	9.3	11.1	0.84	Results are obtained under 30 kPa
	2.7	7.2	23.4	0.31	
	2.1	6.5	30.8	0.21	
	1.5	5.2	30.8	0.17	
	0.9	3.3	23.4	0.14	
	0.3	1.4	11.1	0.13	
1	3.3	12.2	13.5	0.90	Results are obtained under 50 kPa
	2.7	13.0	28.6	0.45	
	2.1	11.7	37.6	0.31	
	1.5	7.6	37.6	0.20	
	0.9	2.3	28.6	0.08	
	0.3	0.6	13.5	0.04	
1	3.3	31.3	16.0	1.96	Results are obtained under 70 kPa
	2.7	31.0	33.7	0.92	
	2.1	26.4	44.4	0.59	
	1.5	16.5	44.4	0.37	
	0.9	8.9	33.7	0.26	
	0.3	2.8	16.0	0.18	
2	3.3	6.3	14.8	0.43	Results are obtained at EOC
	2.7	7.9	31.2	0.26	
	2.1	6.4	41.2	0.16	
	1.5	4.7	41.2	0.11	
	0.9	3.8	31.2	0.12	
	0.3	1.2	14.8	0.08	
2	3.3	11.4	22.2	0.51	Results are obtained under 30 kPa
	2.7	11.6	46.8	0.25	
	2.1	10.5	61.6	0.17	
	1.5	7.1	61.6	0.12	
	0.9	3.9	46.8	0.08	
	0.3	2.4	22.2	0.11	
2	3.3	29.8	27.0	1.10	Results are obtained under 50 kPa
	2.7	34.8	57.2	0.61	
	2.1	32.3	75.2	0.43	
	1.5	24.0	75.2	0.32	
	0.9	14.8	57.2	0.26	
	0.3	5.8	27.0	0.21	

Table S7. (*continued*)

2	3.3	45.7	32.0	1.43	Results are obtained under 70 kPa
	2.7	57.3	67.4	0.85	
	2.1	51.5	88.8	0.58	
	1.5	37.4	88.8	0.42	
	0.9	23.9	67.4	0.35	
	0.3	9.5	32.0	0.30	
3	3.1	2.1	10.7	0.20	Results are obtained at EOC
	2.2	6.0	20.6	0.29	
	1.3	5.2	20.6	0.25	
	0.5	2.1	10.7	0.20	
4	3.3	10.4	34.6	0.30	Results are obtained under 30 kPa
	2.7	10.4	73.0	0.14	
	2.1	7.8	96.0	0.08	
	1.5	6.1	96.0	0.06	
	0.9	3.7	73.0	0.05	
	0.3	1.4	34.6	0.04	
4	3.3	19.5	42.1	0.46	Results are obtained under 50 kPa
	2.7	19.4	89.2	0.22	
	2.1	16.1	117.2	0.14	
	1.5	11.5	117.2	0.10	
	0.9	7.5	89.2	0.08	
	0.3	2.7	42.1	0.06	
4	3.3	27.6	49.9	0.55	Results are obtained under 70 kPa
	2.7	29.7	105.1	0.28	
	2.1	24.8	138.4	0.18	
	1.5	17.8	138.4	0.13	
	0.9	11.3	105.1	0.11	
	0.3	3.7	49.9	0.07	
5	3.6	0.79	63.8	0.01	Results are obtained at EOC
	2.8	9.8	53.8	0.18	
	2.0	15.7	164.9	0.10	
	1.2	8.6	138.3	0.06	
	0.4	13.1	58.6	0.22	
6	3.6	2.4	78.0	0.03	Results are obtained at EOC
	2.8	8.3	172.7	0.05	
	2.0	12.2	200.6	0.06	
	1.2	5.4	172.7	0.03	
	0.4	5.0	78.0	0.06	
17	9.5	63.9	1412.4	0.05	Results are obtained under 57 kPa
	6.1	137.0	1091.4	0.13	
	3.0	66.7	271.1	0.25	
	1.1	15.5	128.4	0.12	

Table S8. Predicted and Measured Lateral Deformations of GRS Walls and Abutments using Wu Method

Case #	**Elevation (m)**	**Measured (mm)**	**Predicted (mm)**	**Bias, λ** $\frac{\text{Measured}}{\text{Predicted}}$	**Notes**
1	3.3	9.3	0	NA	Results are obtained at 30 kPa
	2.7	7.2	0	NA	
	2.1	6.5	3.2	2.03	
	1.5	5.2	7.2	0.72	
	0.9	3.3	7.3	0.45	
	0.3	1.4	3.4	0.41	
1	3.3	12.2	4.9	2.49	Results are obtained at 50 kPa
	2.7	13.0	12.9	1.01	
	2.1	11.7	16.9	0.69	
	1.5	7.6	17.0	0.45	
	0.9	2.3	13.1	0.18	
	0.3	0.6	5.4	0.11	
1	3.3	31.3	26.4	1.18	Results are obtained at 70 kPa
	2.7	31.0	30.5	1.02	
	2.1	26.4	30.6	0.86	
	1.5	16.5	26.9	0.61	
	0.9	8.9	19.0	0.45	
	0.3	2.8	7.3	0.38	
2	3.3	11.4	0	NA	Results are obtained at 30 kPa
	2.7	11.6	0	NA	
	2.1	10.5	6.4	1.64	
	1.5	7.1	14.4	0.49	
	0.9	3.9	14.6	0.27	
	0.3	2.4	6.4	0.37	
2	3.3	29.8	9.8	3.04	Results are obtained at 50 kPa
	2.7	34.8	25.8	1.35	
	2.1	32.3	33.8	0.95	
	1.5	24.0	34.0	0.70	
	0.9	14.8	26.2	0.49	
	0.3	5.8	10.8	0.54	
2	3.3	45.7	52.8	0.86	Results are obtained at 70 kPa
	2.7	57.3	61.0	0.94	
	2.1	51.5	61.2	0.84	
	1.5	37.4	53.8	0.69	
	0.9	23.9	38.0	0.63	
	0.3	9.5	14.6	0.44	
4	3.3	10.4	0.0	NA	Results are obtained at 30 kPa
	2.7	10.4	0.0	NA	
	2.1	7.8	10.0	0.78	
	1.5	6.1	22.4	0.27	
	0.9	3.7	22.8	0.16	
	0.3	1.4	10.6	0.13	

Table S8. (*continued*)

4	3.3	19.5	15.3	1.28	Results are obtained at 50 kPa
	2.7	19.4	40.2	0.48	
	2.1	16.1	52.7	0.31	
	1.5	11.5	53.0	0.22	
	0.9	7.5	40.8	0.18	
	0.3	2.7	16.8	0.16	
4	3.3	27.6	82.3	0.34	Results are obtained at 70 kPa
	2.7	29.7	95.1	0.31	
	2.1	24.8	95.4	0.26	
	1.5	17.8	83.9	0.21	
	0.9	11.3	59.2	0.19	
	0.3	3.7	22.8	0.16	
5	3.6	0.79	57.0	0.01	Results are obtained at EOC
	2.8	9.8	133.0	0.07	
	2.0	15.7	158.4	0.10	
	1.2	8.6	132.9	0.06	
	0.4	13.1	57.0	0.23	
6	3.6	2.4	63.9	0.04	Results are obtained at EOC
	2.8	8.3	149.2	0.06	
	2.0	12.2	177.6	0.07	
	1.2	5.4	149.2	0.04	
	0.4	5.0	64.3	0.08	
17	9.5	63.9	2182.3	0.03	Results are obtained under 57 kPa
	6.1	137.0	1149.7	0.12	
	3.0	66.7	255.6	0.26	
	1.1	15.5	108.8	0.14	