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Prediction of reinforced soil retaining wall deformations: A review of two procedures

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Abstract: A number of methods have been developed for designing geosynthetic reinforced soil (GRS) walls. Most concentrate on the internal and external stability of the structure, with little, if any, emphasis on deformation. The numerous factors that influence deformation and the limited number of instrumented case histories contribute to the difficulty of developing reliable deformation prediction methods. Two procedures that have been proposed for predicting reinforced soil wall deformations are by Christopher, et al. (1990), as modified by Christopher (1993), and Chew and Mitchell (1994). Sixteen case histories reported in the literature were used to assess the accuracy of these methods. Predicted deformations ranged from 40% to 460% of actual deformations for walls constructed with cohesionless soils.

1. INTRODUCTION

It has been thirty years since Reinforced Earth was introduced (Vidal, 1969) and more than twenty years since geosynthetics were first used in a reinforced soil wall (Bell and Steward, 1977). Since then, thousands of reinforced soil walls have been successfully designed and constructed. However design has been based on limiting equilibrium types of analyses that in principle do not account for wall deformations. This inability to predict wall deformations is one of the stumbling blocks that must be overcome before geosynthetic reinforced soil (GRS) walls can be routinely used in permanent (> 75 yr design life) applications.

Extension of common limit state design methods to address deformations has not proven successful (Bathurst and Koerner, 1988; Wu, et al., 1992). The finite element method (FEM) has been found effective for conducting parametric studies and for evaluating reinforced soil walls (Bathurst and Koerner, 1988; Wu, et al., 1992); however, because of its perceived complexity and the experience required for proper application, FEM has not been adopted by practitioners for routine GRS wall design. For regular application in engineering practice empirically or numerically developed design charts, of the nature commonly used in practice for designing other geotechnical structures, may be a practical alternate.

Two easy-to-use chart-based deformation prediction procedures that are not tied to a particular wall design method have recently been developed by Christopher (1993) and Chew and Mitchell (1994). These procedures are appealing in that they are simple to use and rationally based; however, the reliability of these procedures has not been independently assessed. In this paper these two procedures are applied to sixteen instrumented case histories in order to evaluate their accuracies.

2. CHRISTOPHER 1993 METHOD

Christopher, et al. (1990) presented a graph for estimating the lateral displacement that can be anticipated at the end of construction of simple reinforced soil structures constructed on firm foundations, Figure 1. Figure 1 was developed from full scale tests of 6 m high walls, FEM computer simulations, and centrifuge model studies. To use the chart only the L/H ratio (the ratio of reinforcement length L to wall height H) and the general classification of the reinforcing material (i.e., extensible or inextensible) are needed. With the exception of a recommendation to increase the predicted deformation by 25% for each 19.2 kPa (400 psf) of uniform surcharge supported by the wall, deformations due to application of external loads are not addressed.

To improve accuracy and account for differences in geosynthetic reinforcing material properties and vertical spacing of layers, Christopher (1993) recommended adjusting the values predicted from Figure 1 using Eq. 1.

$$\delta_{max} = \delta_R \left(\frac{H}{75 \log S_r} \right) \qquad (1)$$

where S_r is the global stiffness in 1000 lbf/ft^2 defined as:

$$S_r = \frac{JR_c}{S_v} \qquad (2)$$

and where:

J = reinforcing modulus per unit width (i.e., normalized with respect to thickness),

R_c = reinforcement coverage ratio (b/S_h) with b equal to the width of the reinforcement and S_h equal to the horizontal spacing, and

S_v = average vertical spacing of reinforcement layers, H/n, with H equal to the wall height and n equal to the number of reinforcement layers.

Figure 1 in combination with Eq. 1 will be referred to in the following discussion as the Christopher (1993) method. When Figure 1 is used but Eq. 1 is not applied the procedure will be referred to as the Christopher et al. (1990) method.

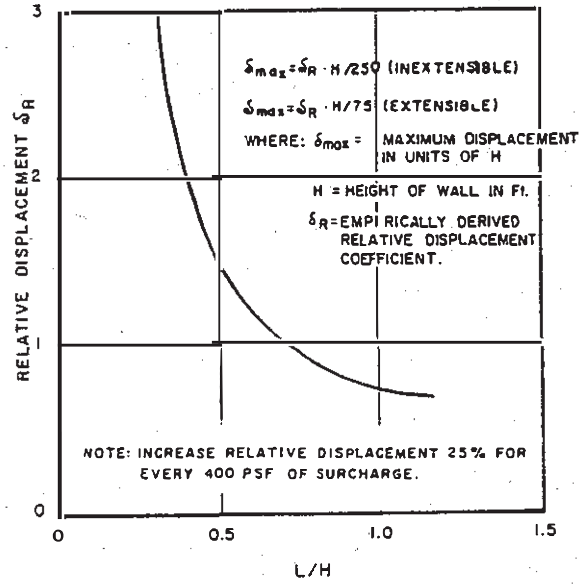


FIGURE 1: Empirical curve for estimating lateral displacement that occurs during construction of reinforced soil structures (after Christopher, et al., 1990).

3. CHEW AND MITCHELL METHOD

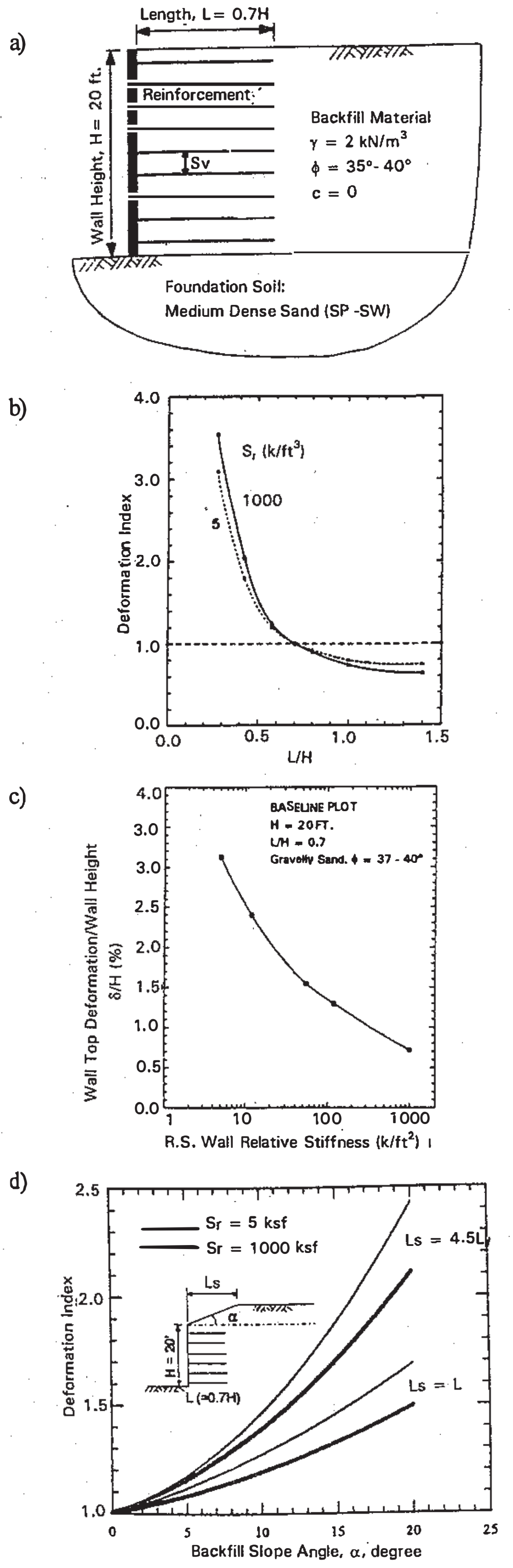
Chew and Mitchell (1994) developed a deformation prediction procedure using detailed finite element analysis and parametric studies, Figure 2. As with the Christopher method this procedure uses the reinforcement length to wall height ratio, L/H, as the base parameter for predicting deformations. However, Chew and Mitchell also provide means to adjust predicted deformations for various wall heights, the global stiffness ratio, S_r (as defined in Eq. 2), the effect of uniform and sloping surcharges, and the application of strip loads. In this method, deformation of a wall is predicted by first estimating the deformation of a "baseline" wall and adjusting for differences between this baseline and the wall being evaluated. The baseline case represents a 6.1 m high wall with L/H equal to 0.7, uniform reinforcement spacing, moderate compaction, level backfill and no external loading. Soil friction angle is assumed to be between 35° and 40°.

Chew and Mitchell (1994) propose the following design methodology for using their charts (Figure 2):

1. Design the basic reinforced soil (Figure 2a) wall using current limit state design methods.
2. Compute the stiffness ratio, S_r for the wall using Eq. 1.
3. Determine $(\delta/H)_{base}$ for the wall using Figure 2b.
4. Determine the deformation index factors, DI, for the wall being evaluated:
   a) $DI_{L/H}$, for the L/H ratio, Figure 2c,
   b) DI_H, for the wall height, H, Figure 2d,
   c) DI_q, for uniform surcharges (see Chew, et. al., 1991),
   d) DI_{slope}, for sloping surcharges, Figure 2e,
   e) DI_{other}, to account for other influences.
5. Compute the wall face deformation, δ, using Eq. 3:

$$\frac{\delta}{H} = \left(\frac{\delta}{H} \right)_{base} \cdot DI_{L/H} \cdot DI_H \cdot DI_q \cdot DI_{slope} \cdots \qquad (3)$$

6. Evaluate the reduced system stiffness due to material creep and/or corrosion, if any. Chew and Mitchell (1994) suggest that the long term δ/H of geosynthetic walls could be estimated by using a $(\delta/H)_{base}$ determined from a reduced stiffness ratio with reduced reinforcement strength properties that account for creep.



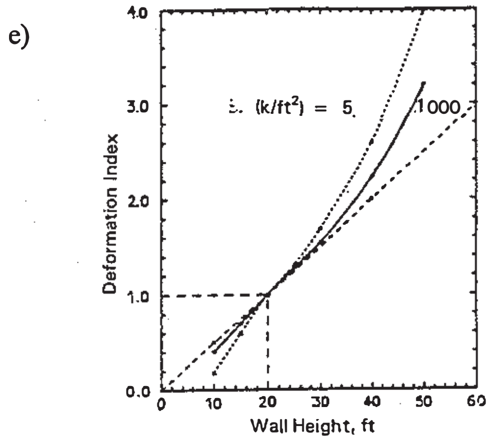


FIGURE 2: GRS wall deformation prediction charts as developed by (Chew and Mitchell, 1994): a) baseline configuration, b) $(\delta/H)_{base}$ vs. S_r, c) $DI_{L/H}$, d) DI_H, and e) DI_{slope}.

4. DISCUSSION

Christopher (1993) and Chew and Mitchell (1994) both recognized the reinforcement length to wall height ratio, L/H, and the stiffness ratio, S_r, as principal factors affecting wall deformations. Because neither method is tied to specific design procedures and since both are simple to use, we were able to compare the displacements each method predicted with those measured in instrumented walls, see Table 1. Except for those walls included in Table 1 that were part of the program used to calibrate the Christopher chart [Adib (1988), walls 1 - 6], an exact match of predicted and actual deformations should not be expected. Soils, facing materials, and construction methods used in the instrumented walls may differ from those for which the deformation prediction methods were developed. Furthermore, although both procedures were developed for granular soils, three of the walls included in this evaluation were constructed with cohesive soils.

There was considerable scatter in predicted versus measured values for the two methods, Figure 3a. The Christopher (1993) procedure did well for the walls used in its development, and in general for walls over 5 m. It overpredicted deformations by 250% for the 2.9 m high Mur Ebal wall (Balzier, et al., 1991) and underpredicted by 60% to 80% for the 4.65 m Tucson wall (Berg, et al., 1986) and the three cohesive soil walls (Djarwadi and Wong, 1994). The improvement in accuracy of the Christopher (1993) method in comparison to the Christopher, et al., (1990) method is evident in Figure 3b. For 5 m and higher geosynthetic

Table 1: Reinforced soil walls used in evaluation.

Description	Reference	H(m)	L/H	ϕ_{tx}	$S_R(k/ft^2)^1$	$\delta_{meas.}$(mm)
Tucson wall	Berg, et al. (1986)	4.65	0.80	34	120	65
Lithonia wall		6.0	0.60	40	120	65
Gaspe seawall	Berg, et al. (1987)	5.3	0.70	?	120	40
Wall 1	Adib (1988) and Christopher (1993)	6.1	0.70	40	1500	24
Wall 2		6.1	0.70	40	56	25-50
Wall 3		6.1	0.70	40	1000	23
Wall 4		6.1	0.70	40	1000	20
Wall 5		6.1	0.70	40	1000	23
Wall 6		6.1	0.70	40	10	100
Malaysa wall	Hajiali (1991)	7.5	0.80	40	1000	25
Rainier wall	Holtz, et al (1990)	12.6	0.77	43	30	100-130
MurEbal	Balzier, et al. (1991)	2.9	0.70	39	6-12	11
Websol wall	Won, et al. (1994)	8.4	0.64	41-44	≈50?	50-100
Apron wall	Djarwadi and Wong (1994)^2	8.0	1.11	15	95	100
Chute wall		4.75	1.11	c=16kN/m^2	95	90
Stilling wall		10.8	1.11		95	160

[1] Stiffness Ratio, S_R, in kips/ft^2 to permit direct application of this ratio in the Chew and Mitchell (1994) and Christopher (1993) procedures.

[2] Friction angle and cohesion apply to all three walls reported by Djarwadi and Wong (1994).

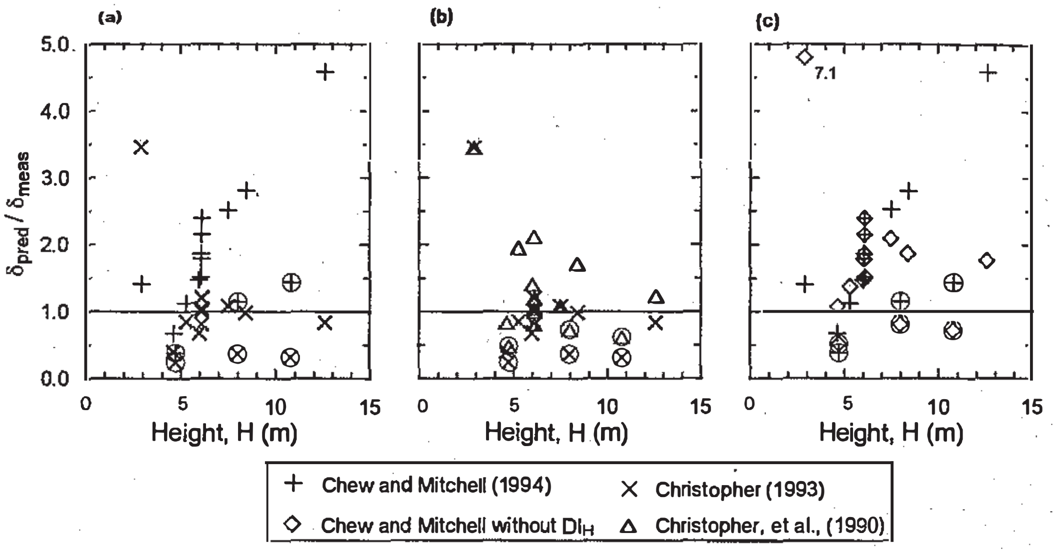


FIGURE 3: $\delta_{predicted} / \delta_{measured}$ vs. wall height:

a) Chew and Mitchell (1994) and Christopher (1993),

b) Christopher (1993) and Christopher, et al. (1990), and

c) Chew and Mitchell (1994) with and without DI_H.

Symbols corresponding to walls constructed with cohesive soil are circled.

reinforced walls constructed with cohesionless soils, the use of Eq. 1 in general provided better estimates of wall deformation. Christopher, et al., (1990) performed only noticeably better for the 4.65 m Tucson wall.

With the exception of the 4.65 m Tucson wall the Chew and Mitchell procedure overpredicted deformations. Even for situations that could be considered idea–inextensible reinforcement in walls with L/H ratios equal to the baseline case of 0.7 [Adib (1988), walls 1, 3, 4, and 5]–the Chew and Mitchell procedure overpredicted deformations by as much as 140%. Although it might be expected that deformation prediction procedures based upon cohesionless soils would underpredict deformations of GRS walls constructed with cohesive soils, that was not necessarily the case. Chew and Mitchell overpredicted deformations by as much as 45% for the 8 m and 10.8 m high cohesive soil walls.

As wall height increased above the 6.1 m baseline case, the amount of overprediction increased substantially. Predicted deformations were 2.8 and 4.6 times greater than those measured for the 8.4 m Malaysian wall (Hajiali, 1991) and the 12.6 m Rainier Avenue wall (Holtz, et al., 1990), respectively. In fact, without application of the wall height factor, DI_H (Figure 2d), the deformations predicted for these high walls is closer to the actual deformations, Figure 3c. If DI_H is not applied to walls shorter than the baseline case, the predicted deformations are greater than would be predicted using the complete procedure. For the 2.9 m high Mur Ebal wall (Balzier, et al., 1991), failure to apply DI_H grossly over estimates wall deformation. Thus, when using the Chew and Mitchell charts, it appears that the wall height factor should be applied only to walls less than 7 m high.

The difference in accuracy of the Christopher (1993) and Chew and Mitchell (1994) methods may be partially due to the different approaches used to develop them. The Chew and Mitchell charts were primarily developed using numerical methods., which requires accurate modelling of material properties, construction effects, foundation conditions, etc. Errors in modelling any of these parameters would influence the solutions obtained. The better performance of the Christopher (1993) method, which also used numerical methods in its development, probably results from the correlations with empirical observations from field and laboratory studies. Thus, errors in numerical modelling of material properties may have been compensated for when the FEM solutions were "calibrated" using the measured values.

In addition to the large number of variables that may affect wall deformations, the difficulties experienced in predicting reinforced soil wall deformations may be related to the relatively small displacements that these walls undergo. Figure 1 predicts GRS wall deformations to be only three times larger than steel reinforced soil walls. Furthermore, maximum displacements of GRS walls with L/H ratios in the typical range of 0.6 to 1.0 are only 1.6% to 0.9% of the wall height. If deformations can be controlled in the field through careful construction techniques, the Christopher (1993) and Chew and Mitchell (1994) deformation prediction methods may prove adequate with only slight modifications.

5. CONCLUDING REMARKS

In light of the large number of factors that influence GRS wall behaviour and the difficulty in accounting for all effects, it is not surprising that there was substantial scatter in the results. The design chart presented by Christopher, et al. (1990) and modified by Christopher (1993) is simple to use and relatively accurate for walls higher than 5 m. The charts developed by Chew and Mitchell (1994) are also easy to use and address more loading conditions; however, they are very conservative and tend to seriously overpredict deformations. For the cases investigated, accuracy was improved by not applying the height adjustment factor for walls higher than 7 m. While the less accurate of the two methods, the Chew and Mitchell procedure has the potential for more practical application since it permits consideration of various typical applied loads; additional charts may be constructed for various backfill soil friction angles and loading conditions. Neither method should be applied to walls constructed with cohesive soils.

We suggest that engineering judgement be used when predicting GRS wall deformations using these procedures until additional calibration information, especially additional case histories, becomes available and the two methods are further refined. Until then, designers must be prepared for actual deformations being substantially different than those estimated using these procedures.

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