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Modeling of interfaces in finite element analyses of geosynthetically reinforced walls

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ABSTRACT: Some results of extensive finite element parametric analyses performed on mathematical models of geosynthetically reinforced walls are presented. The focus of these results is the characterization of interfaces in the modeling of such walls and the consequences associated with improper modeling techniques. The conclusions reached will prove useful to analysts of geosynthetically reinforced walls.

1 INTRODUCTION

Due to their cost-effectiveness and increasing acceptance, a large number of geosynthetically reinforced soil structures are being designed and constructed throughout the world. In order to gain better insight into mechanisms affecting the behavior of such structures, engineers are turning to numerical (approximate) analyses. Currently the most popular numerical analysis technique in use is the finite element method. This powerful analytical tool holds much promise for simulating the behavior of geosynthetically reinforced soil structures, especially under "working stress" conditions. The finite element method is not without limitations, and it is imperative that the analyst be aware of these. Failure to do so may lead to incorrect mathematical models which, when analyzed, may yield erroneous results. These in turn may lead to an unsafe design.

The most practical manner in which to study the significance and consequences of various modeling assumptions is to perform systematic numerical studies of specific classes of reinforced soil structures. In these studies the structures are modeled using a minimum number of assumptions and are analyzed as boundary value problems. The results obtained give insight into the behavior of the structure.

In order to gain insight into the behavior of geosynthetically reinforced soil walls under working conditions, a series of numerical parametric studies were recently performed (Xi 1992). These studies systematically investigated the consequences of various assumptions made in modeling such structures. This paper presents some results from these studies. The focus of these results is on the mathematical characterization of material interfaces.

2 DESCRIPTION OF MODELS ANALYZED

The major components comprising a reinforced soil wall are: the backfill soil, the reinforcement, the facing units and the foundation soil. The mathematical modeling of any physical problem requires that each major component be represented as accurately as possible. Failure to do so will introduce further uncertainty into an analysis which already is approximate. The modeling of reinforced soil walls thus requires accurate characterization of the backfill and foundation soils, the reinforcement, and the facing units. Also the interaction, particularly the relative motion or "slip" between the soil and reinforcement and between the soil and facing units, must be accounted for. Finally, the actual sequence of construction must accurately be simulated.

The parametric studies described herein centered around a so-called "standard wall configuration" (SWC). In each set of analyses the value of one parameter was varied while holding the remaining parameters fixed at values associated with the SWC.

The reinforced soil walls analyzed in the present work were idealized as two-dimensional continua under a state of plane strain. The analyses were limited to quasi-static "working stress" (non-failure) conditions. As such, infinitesimal displacements and displacement gradients were assumed. The reason for restricting analyses to working stress conditions is quite simple: if a numerical analysis technique cannot successfully simulate behavior under working stress conditions, it certainly cannot be expected to yield valid results at higher loads leading to failure.

All computations associated with the present work were performed using a modified version of the REA computer program (Herrmann 1978a). REA performs two-dimensional (plane strain) quasi-static analyses of soil structures. The presence and coupling of pore fluid is not accounted for in the program.

The height of the standard wall was chosen to be 10 meters. Based on the results of several preliminary analyses, the right boundary of the backfill was located a distance of 25 meters from the wall. In this manner, the presence of this boundary had no effect on the response of the wall/reinforcement/soil system. The length of the reinforcement was assumed to be 7 meters. The vertical spacing of the reinforcement was chosen to be 1.0 meter. Along the right boundary the backfill soil was free to settle vertically but not laterally. Mathematically this boundary was idealized with roller supports. Underlying the base of the backfill was assumed to be a firm foundation. The finite element model of the standard wall configuration is shown in Figure 1.

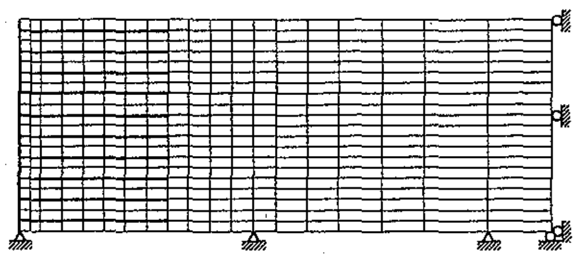

Figure 1. Finite Element Model of the Standard Wall Configuration

For all analyses, the backfill soil was assumed to be free-draining and cohesionless. It was idealized as a quasi-linear elastic (hyperbolic) continuum. The constitutive model used was based on the original formulation of Duncan and Chang (1970), with modifications as described by Duncan (1980) and by Herrmann (1978a). The advantages and disadvantages of a quasi-linear elastic idealization are well-known (Duncan 1980). Since the present study was restricted to working stress conditions, the choice of constitutive model is thought to be justified. The values of the hyperbolic model parameters were determined by matching experimental results for clean Ottawa sand (Marcozzi 1988). These values were: $K = K_{ur} = 600$, $n = 0.40$, $\phi = 35°$, $c = 1.0$ kPa, $R_f = 0.80$, $P_{atm} = 101.4$ kPa, $K_b = 300$, and $m = 0.40$. The unit weight of the material was assumed to be 18 kN/m^3.

The backfill soil mass was discretized using standard four-node isoparametric quadrilateral elements. In computing approximate strains and stresses, reduced (one-point) numerical quadrature was used.

In the present study the process of "incremental construction" (Clough and Woodward 1967) was employed. The backfill soil was discretized in layers of quadrilateral elements 0.5 meter in height. Each layer of soil elements, and each reinforcing layer was placed in a separate solution increment. Investigations performed in conjunction with the present studies indicated that failure to "place" a reinforcement layer and the soil layer directly below it in separate solution increments resulted in the presence of a fictitious pre-stressing force in the reinforcement. Depending on the location of the reinforcement within the soil mass, this pre-stress could lead to forces whose magnitudes differed from actual values by more than 50 percent. Furthermore, the resulting distributions of reinforcement forces were erratic ("saw tooth") and thus counter to experimentally measured distributions.

The reinforcement was assumed to possess stress-strain characteristics typical to a geogrid. The cross-sectional and strength parameters describing the geogrid were taken directly from actual product specifications. One-dimensional bending (flexural-axial) elements were used to represent the reinforcement. The material was idealized using a bi-linear stress-strain relationship with isotropic hardening. The necessary material parameters were obtained based on the manufacturer's stiffness specifications. The self-weight of the reinforcement was assumed to be negligible.

Although geogrids would naturally be expected to have negligible bending stiffness, this assumption was not made a priori. Instead, actual values for the cross-sectional and material parameters were used in defining the characteristics of the bending elements. In all analyses performed, the computed bending moments were negligible, thus confirming the suspected behavior.

The facing associated with the SWC was assumed to consist of modular, 0.20 meters thick concrete units. These relatively flexible units were represented by one-dimensional bending (flexural-axial) elements. A bi-linear stress-strain relationship with isotropic hardening was used to idealize the concrete.

During the simulated construction sequence, the facing units were "placed" in the same solution increment as the adjacent soil. To better represent the actual (albeit small) resistance to rotation provided at the connection between facing units, this connection was idealized by a nodal hinge with a relatively weak rotational spring. Failure to include the nodal spring results in spurious tensile stresses being predicted near the top of the soil mass (Xi 1992).

The bending elements used to model both the reinforcement and the facing included the provision for relative movement (slippage) between themselves and the surrounding continuum elements. The approach used to account for this slippage was described by Herrmann (1978b). According to this approach the soil and reinforcement experience the same normal displacement. The tangential displacements differ by the relative movement δ. In the case when the attainable bond stress has been fully mobilized, the relative movement δ is the resulting slippage. When the bond has not broken down, the relative movement δ is resisted by the fictitious uniformly distributed bond springs. If the stiffness of the fictitious springs is made very large, the non-slip relative movement can be made effectively zero. When the maximum attainable tangential bond stress has been developed (this being governed by a Mohr-Coulomb type failure criterion), slippage is resisted by applying this stress (as suitable nodal loads) to the contacting surfaces. For the SWC the cohesion c along the interfaces was assumed to be zero; the friction coefficient was set equal to $f = 0.8 \tan \phi = 0.8 \tan 35^\circ = 0.560$.

3 THE REINFORCEMENT-SOIL INTERFACE

One of the key issues associated with the numerical simulation of reinforced soil walls is the importance of accounting for the relative displacement ("slippage") between the reinforcement and the backfill soil. In order to gain insight into this issue, the SWC was first analyzed using the previously mentioned values of the interface parameters c and f. Keeping all remaining parameters equal to values associated with the SWC, analyses were next performed in which f was set equal to $0.6 \tan \phi$ and $1.0 \tan \phi$. Finally, the SWC was re-analyzed without allowing relative displacement between the reinforcement and the backfill soil.

Based on the results of these analyses, as well as on those associated with other investigations, the following conclusions were drawn:

1. In the process of numerically "constructing" the soil/reinforcement/wall system, relative displacement between a reinforcement layer and the backfill soil occurred in the vicinity of the wall. This displacement was initiated as the next layer of soil was "placed" above the reinforcement, causing outward lateral displacement of the wall and tensioning of the reinforcement. Away from the wall, sufficient friction was present along the soil-reinforcement interface so as to prevent relative displacement. With the increase in normal (vertical) stress due to the placement of subsequent soil layers, the relative displacement in the vicinity of the wall ceased.

2. The results obtained using values of f equal to $0.6 \tan \phi$ and $1.0 \tan \phi$ gave results essentially identical to those associated with the SWC. As such these results are not included in the subsequent figures.

3. Failure to account for the possibility of relative displacement between the reinforcement and the soil results in different magnitudes and distributions of reinforcement forces. As shown in Figure 2, this difference is confined to a region in the vicinity of the wall. That is, in that region where relative displacement is realized during the simulated construction sequence.

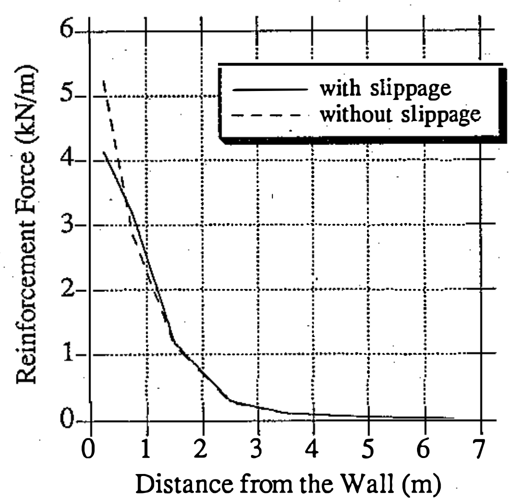

Figure 2. Distribution of Reinforcement Force 0.5 m Above Base of Wall

4. As shown in Figure 3, the relative displacement between the reinforcement and the soil has a negligible effect on the distribution of lateral earth

pressure acting against the wall. The rather abrupt increase in pressure near the base of the wall requires further explanation. This phenomenon is attributed to the presence of a hinge boundary condition at the toe of the wall. It is important to understand that this does not imply a larger force in the lower layers of reinforcement that is required to counterbalance this pressure, but instead that the hinge takes a larger portion of the horizontal force.

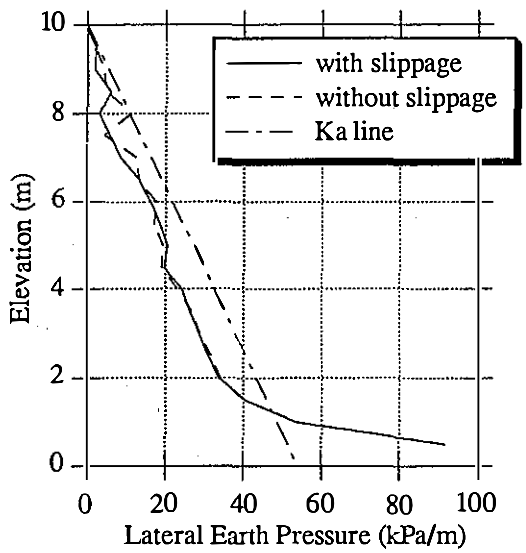

Figure 3. Lateral Earth Pressure Acting on Wall

5. The relative displacement between the reinforcement and the soil has also a negligible effect on the lateral displacement of the wall (Figure 4). This is explained by the fact that under working conditions, the relative displacement is of low magnitude and fairly localized.

Thus, based on the present working stress analyses, the most significant consequence of neglecting the relative displacement between the soil and reinforcement is a difference in the magnitude and distribution of reinforcement forces in the vicinity of the wall.

4 THE FACING-SOIL INTERFACE

Although sometimes overlooked in the mathematical modeling of reinforced soil walls, the characteristics of the interface between the facing units and the backfill soil can significantly influence the resulting numerical simulations.

In order to better understand the importance of correctly representing this interface, the SWC was re-analyzed with no relative displacement permitted between the facing units and the soil. The values of all other parameters remained unchanged. In Figure 5 the deformed soil/reinforcement/wall system associated with this analysis (magnified 1.5 times) is superimposed on the undeformed configuration.

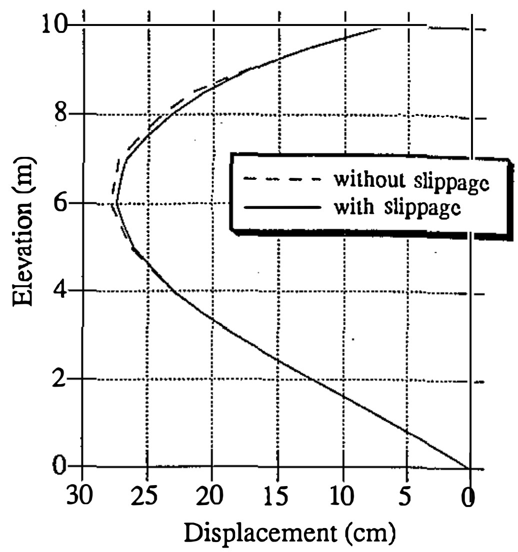

Figure 4. Lateral Displacement of Wall

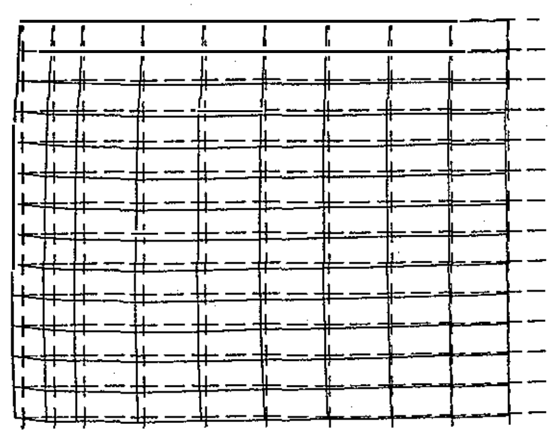

Figure 5. Magnified View of Deformed and Undeformed Finite Element Grids

To better understand this figure, note that relative to the soil the facing units possess large axial stiffness. Thus if relative displacement is not permitted between the facing and the soil, the soil elements in contact with the elements modeling the facing cannot "settle" (displace vertically) as much as the neighboring elements representing the soil mass. As a result, the facing elements (particularly near the top of the wall) displace outward only slightly and rotate in a clockwise manner. The net result is a reduction in lateral displacement of the wall due to an inward rotation near the top of the wall (Figure 6). Not only is this inward rotation contrary to the expected response (i.e., outward wall displacement accompanying settlement of the backfill soil), but it places a portion of the soil mass near the top of the wall in tension.

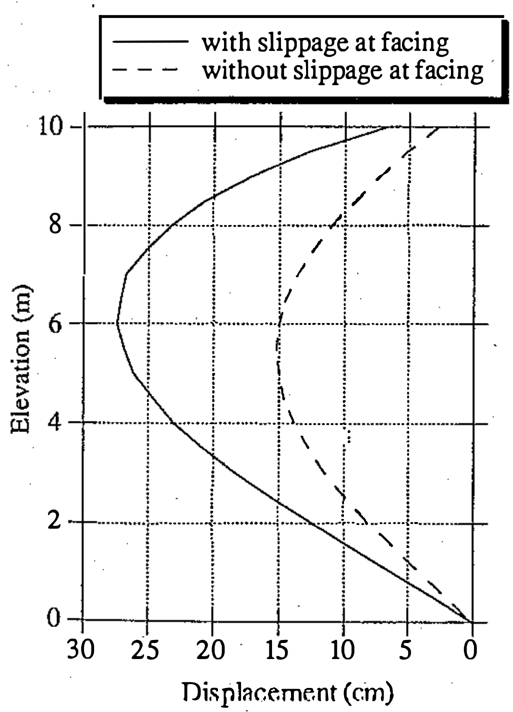

Figure 6. Lateral Displacement of Wall

The result is a reduction in lateral stress acting on the wall (Figure 7). This, however, is counter to the expected response; i.e., an increase in lateral pressure due to the reduction in lateral displacement of the wall.

Finally, as a consequence of the predicted tensile stresses in the soil mass, some portions of the reinforcement near the top of the wall are subjected to compressive forces, or to tensile ones very near zero. Furthermore, the distribution of these forces are somewhat erratic (Figure 8). This of course is counter to observed behavior.

Thus based on the above observations it is evident that failure to correctly account for relative displacement between the facing units and backfill soil can lead to inconsistent results.

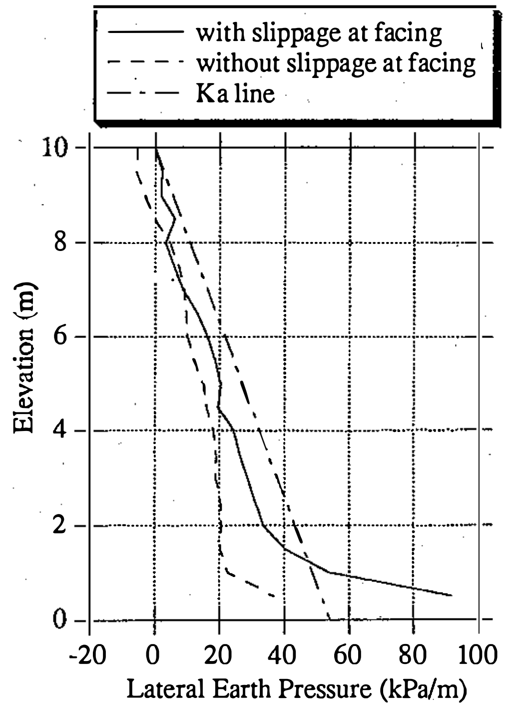

Figure 7. Lateral Pressure Acting on Wall

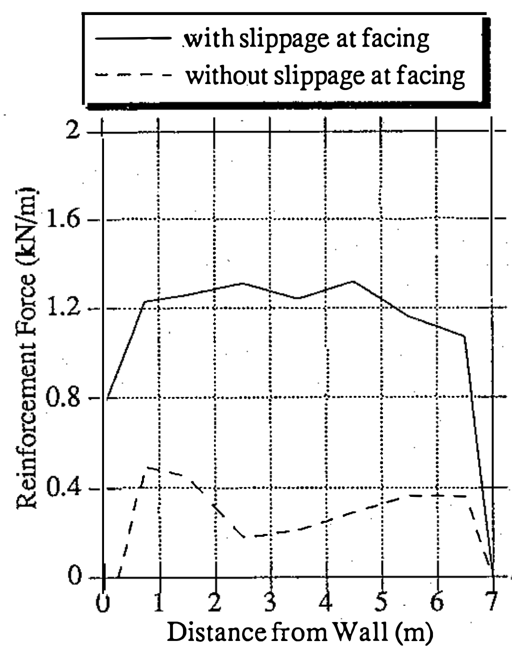

Figure 8. Distribution of Reinforcement Force 0.5 m Below Top of Wall

5. CONCLUSION

This paper has focused on the consequences of correctly modeling interfaces in the finite element analysis of geosynthetically reinforced soil walls under "working stress" conditions.

It was shown that failure to account for relative displacement between the reinforcement layers and backfill soil has somewhat localized consequences. Namely, only the magnitude and distribution of the reinforcement force in the vicinity of the wall are practically affected.

Of possibly greater importance is the representation of the interface between the facing units and the adjacent soil. Failure to account for relative displacement along such an interface leads to: (a) Non-conservative under-estimations of lateral displacement of the wall; (b) A reduction in the lateral pressure acting against the wall, with a rather significant region of tensile stresses within the soil mass; and, (c) Portions of the reinforcement layers near the top of the wall being subjected to compressive, or near zero tensile forces.

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