Using Geosynthetics To Reduce Surcharge-Induced Stresses on Rigid Earth-Retaining Structures

JOHN S. HORVATH

Results of a finite-element study are presented that indicate that it is possible to achieve significant reductions in surcharge-induced horizontal stresses on rigid earth-retaining structures (retaining walls, bridge abutments, etc.). This is achieved by using a new type of geosynthetic, called a geoinclusion, that is placed between the structure and retained soil. The geoinclusion functions as a relatively compressible inclusion that allows the retained soil to undergo controlled yielding to mobilize its inherent strength. In doing so, the soil resists a significant portion of the surcharge-induced stress increment rather than merely transmitting it to the wall. If, in addition to the geoinclusion, relatively stiff tensile reinforcement such as polymer geogrid or steel is placed within the retained soil, even greater reductions in surcharge-induced horizontal stresses can be achieved. These conclusions are consistent with previous studies that included both finite-element modeling and physical testing of the use of geoinclusions, either alone or with tensile reinforcement, under gravity-induced earth loads only.

A new application of geosynthetics that is attracting increasing attention from both practitioners and researchers is the reduction of horizontal earth pressures acting on relatively rigid retaining structures (basement and retaining walls, bridge abutments, navigation locks, etc.) to levels significantly below the at-rest pressure state (or greater, if compaction-induced stresses are considered) that would normally be used in the design of such structures. The author calls this the reduced earth pressure (REP)-wall concept. The element necessary to achieve this behavior is a new type of geosynthetic, called a geoinclusion, that is placed along the interior (soil-side) face of the structure. Some authors have referred to this material as "geoboard" (*1,2*). The primary function of the geoinclusion is to act as a relatively compressible inclusion that allows the retained soil to deform laterally without significant resistance. This movement simultaneously mobilizes the shear strength of the soil and reduces lateral earth pressures. The overall phenomenon is referred to as "controlled yielding." Both numerical (finite-element) modeling and physical testing, as well as limited application in practice, have verified this concept (*1,3–8*). It is also possible, and in most cases desirable, to incorporate additional functions into the geoinclusion, such as drainage, thermal insulation, and possibly the attenuation of noise and vibration. Therefore, for most applications the geoinclusion will be a geocomposite consisting of a highly compressible solid panel of variable thickness that is bonded to a thinner, permeable panel with nonwoven geotextile covering for drainage.

Carrying this concept further, the incorporation of horizontal layers of tensile reinforcement into the retained soil allows the horizontal earth pressures to be reduced even more (*5,7*). This is because tensile forces in the reinforcement are mobilized as the geoinclusion compresses and the retained soil undergoes controlled yielding. As a result, the retained soil is transformed into an otherwise conventional mechanically stabilized earth mass that is essentially independent of the rigid retaining structure. The author terms this application of combined geosynthetics (geoinclusion plus reinforcement) the zero earth pressure (ZEP)-wall concept, because lateral earth pressures approaching zero can be achieved using reinforcement of suitable stiffness. The use of a geoinclusion to allow the relatively unrestricted movement necessary to activate the tensile reinforcement is better than leaving a void behind the wall for this purpose. A void of the necessary width can be difficult to create during construction and might result in maintenance or other operational problems after the wall is in service (*9*). In addition, the geoinclusion can—and in most cases would—be designed to provide one or more additional functions, as in the REP-wall application.

PURPOSE AND SCOPE

In many situations, particularly in the transportation field, it is desirable to add or significantly increase a surface surcharge load adjacent to a wall. In transportation applications, in which a surface surcharge is generally used to simulate the effect of a live load, this might involve loads from motor vehicles, aircraft, or trains adjacent to a bridge abutment or retaining wall that are significantly in excess of the original design loads. Retrofitting a wall structurally for such increased loads can be expensive and difficult, as would be totally replacing it. The study summarized in this paper was undertaken to investigate if the REP- and ZEP-wall concepts could be used to limit the horizontal stress increase on rigid earth-retaining structures due to surface surcharges.

METHOD OF ANALYSIS

The research performed for this study consisted of finite-element modeling of a simple, hypothetical problem. The computer code used was SSTIPNH, a microcomputer con-

Manhattan College, Civil Engineering Department, Manhattan College Parkway, Bronx, N.Y. 10471.

version by the author of the well-known mainframe program SSTIPN. The general capabilities of SSTIPN are discussed in its user's manual (*10*), and the specific capabilities of SSTIPNH are discussed by Horvath (*11*).

PROBLEM STUDIED

Geometry

Figure 1 shows the overall geometry of the problem studied and the finite-element discretization used. Both the retained soil and geoinclusion (if present) were modeled using rectangular solid elements. Because a perfectly rigid wall was assumed, it was not necessary to model the wall explicitly. Instead, the nodes on the left side of the modeled continuum were simply fixed against movement. The reinforcement (if present) was modeled using zero-thickness linear springs, which will be discussed in more detail subsequently. Not shown, because of space limitations, are the one-dimensional interface elements that were used above and below each layer of reinforcement to simulate the frictional interface between soil and reinforcement.

SSTIPNH allows for the simulation of incremental construction. In this study, the geoinclusion (if present) was placed full-height on the wall, followed by the repetitive placement of 1-ft-thick layers of retained soil and a sheet of reinforcement (if present).

Surface Surcharge

The simulated surcharge is also shown in Figure 1; it was an infinite strip load parallel to the wall that approximated a Cooper E-80 railroad loading assumed to be uniformly distributed over the bottom of an 8-ft-wide tie. In the computer simulation, this load was applied in two increments of equal magnitude.

Soil Properties

SSTIPNH allows for nonlinear stress-strain behavior of solid elements using the familiar hyperbolic model for both Young's modulus and the bulk modulus, with Poisson's ratio calculated from these two parameters. Elastoplastic one-dimensional elements are also available to model the interface between dissimilar materials. The various model parameter values used in this study were based on data from Clough and Duncan (*12*), Duncan et al. (*13*), and other sources. Values are given in Tables 1 and 2 for the soil and soil-concrete interface for the free-field case of no geoinclusion or reinforcement. To approximate the effect of soil compaction during placement, each layer was assumed to be overconsolidated with a K_o = 1 immediately after placement. This is not a rigorous simulation of the compaction process [see papers by Duncan and Seed (*14*) and Seed and Duncan (*15*) for thorough discussion of this topic], but it was judged to be a reasonable approximation that was within the capabilities of SSTIPNH.

Geosynthetic Properties

The geoinclusion was modeled as a linear-elastic solid. The Young's modulus was based primarily on the test data reported by Partos and Kazaniwsky (*1*). The values of the hyperbolic-model parameters used to approximate this behavior are given in Tables 3 and 4. It was assumed that the geoinclusion composite was covered with a nonwoven geotextile on the field (soil) side. The soil-nonwoven geotextile interface was modeled using one-dimensional interface elements with the values given in Tables 3 and 4. These values were based primarily on ones given by Koerner (*16*).

The three types of reinforcement evaluated [woven geotextile, polymer grid (geogrid), and steel] were each modeled as chains of linear-elastic spring elements of zero thickness using what are called nodal link elements in SSTIPNH. The nodal link spring stiffness can have a transverse component

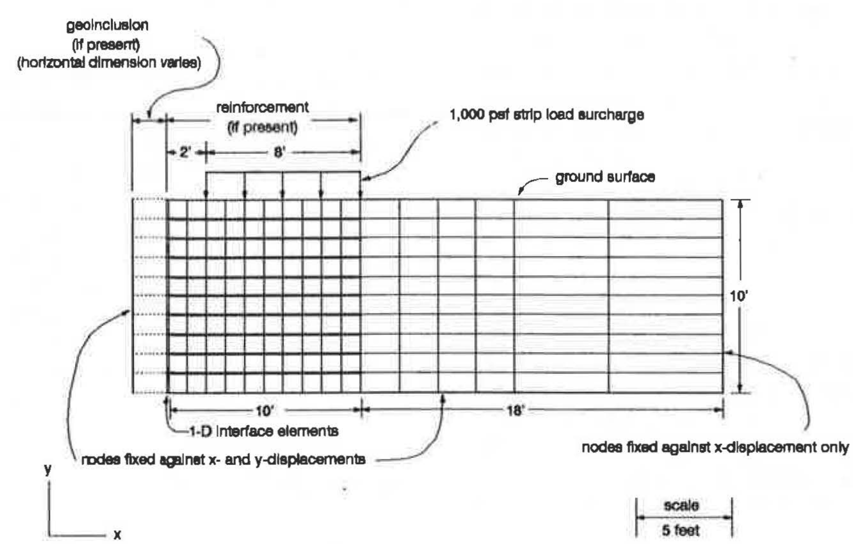

FIGURE 1 Problem geometry and finite-element mesh.

TABLE 1 SOIL AND SOIL-CONCRETE INTERFACE PROPERTIES, SOLID ELEMENTS

material	γ_t (pcf)	c (psf)	ϕ (deg)	$\Delta\phi$ (deg)	K_0	K	n	R_f	K_b	m
sand	115	0	40	0	1	1000	0.5	0.8	300	0.25

TABLE 2 SOIL AND SOIL-CONCRETE INTERFACE PROPERTIES, INTERFACE ELEMENTS

material	c_a (psf)	δ (deg)	$\Delta\delta$ (deg)	K_n	K_s	K_{sur}	n	R_f
concrete	0	32	0	$1x10^9$	$4x10^4$	$6x10^4$	1	0.9

TABLE 3 GEOINCLUSION AND SOIL-GEOSYNTHETIC INTERFACE PROPERTIES, SOLID ELEMENTS

material	γ_t (pcf)	c (psf)	ϕ (deg)	$\Delta\phi$ (deg)	K_0	K	n	R_f	K_b	m
geoinclusion	1	1	0	0	0	2.17	0	0	0.72	0

TABLE 4 GEOINCLUSION AND SOIL-GEOSYNTHETIC INTERFACE PROPERTIES, INTERFACE ELEMENTS

material	c_a (psf)	δ (deg)	$\Delta\delta$ (deg)	K_n	K_s	K_{sur}	n	R_f
nonwoven geotextile	0	36	0	$1x10^6$	$1x10^3$	$1.5x10^3$	1	0.9
woven geotextile	0	32	0	$1x10^6$	$1x10^3$	$1.5x10^3$	1	0.9
polymer geogrid	0	25	3	$1x10^6$	$1x10^3$	$1.5x10^3$	1	0.9
steel	0	40	0	$1x10^9$	$4x10^4$	$6x10^4$	1	0.9

as well as an axial (longitudinal) component. The transverse component was used in this analysis to approximate the tension that develops in reinforcement as a result of differential vertical deflection (*17*). The values used for reinforcement stiffness are given in Table 5. They were derived from typical moduli reported in the manufacturer's literature around early 1989, when this study was begun, and rounded off for simplicity. The goal here was to approximate the stiffness of generic types of reinforcement rather than duplicate specific products. It is recognized that the relative difference in stiffness between geogrids and some woven geotextiles may be less than the 10:1 ratio assumed.

The frictional interface between reinforcement and soil was modeled using one-dimensional interface elements, with separate interfaces above and below each layer of reinforcement. For the geogrid and steel, a technique suggested by Human et al. (*17*) was used to account for the fact that there is at least partial continuity of soil through the reinforcement. This was accomplished by forcing the nodes of the solid soil elements immediately above and below the reinforcement to have the same horizontal displacement. This was not done with the woven geotextile, because it was assumed to behave as an effective separator between soil above and below it. Thus, there could be relatively lateral displacement between the soil above and below the geotextile. Values for the interface-model parameters are given in Table 2; they were adapted from Koerner's (*16*) for the woven geotextile, those of Human et al. (*17*) for the geogrid, and the author's assumptions for the steel.

TABLE 5 REINFORCEMENT STIFFNESS PARAMETERS

Reinforcement	Spring Stiffness (lb/ft/ft of wall)	
	Longitudinal	Transverse
woven geotextile	2,000	1
polymer geogrid	20,000	10
steel	2,000,000	1,000

DISCUSSION OF RESULTS

General Comments

The primary results of interest discussed in this section are the stress increases on the wall caused by application of the surcharge. These results are plotted in a dimensionless form, with the vertical axis being the relative depth below the top of the wall (actual depth divided by the wall height of 10 ft) and the horizontal axis being the actual horizontal stress increase divided by the 1,000-psf vertical surcharge.

Free-Field

Initially, a "free-field" analysis was made to investigate the stresses acting on the wall in the absence of any geoinclusion or reinforcement. The increase in horizontal stress on the wall caused by the surcharge is shown in Figure 2. The results are relatively insensitive to the assumed soil-wall friction. Normally, friction effects with rigid earth-retaining structures are ignored in design practice because it is assumed that soil-wall friction cannot develop in the absence of any wall movement. However, as discussed by Horvath (*11*) and Duncan et al. (*18*), significant levels of soil-wall friction can develop as a result of even slight (fraction of 1 in.) settlement of the retained soil that will occur during the soil placement and compaction process. The rapid decrease in calculated stresses near the bottom of the wall is the result of the perfectly rough boundary condition that was assumed in the finite-element model. Also shown is the theoretical stress increased based on the usual design method of doubling the solution for a homogeneous, isotropic elastic half-space. The rationale behind this approach is discussed in detail by Tschebotarioff (*19*). The actual solution used was taken from work by Poulos and Davis (*20*). Identical results were obtained using the solution in the PILE BUCK Design Manual (*21*). The difference between calculated and theoretical results is consistent with observed behavior (*22*).

Geosynthetics

Analyses were performed using the geoinclusion alone (REP wall) as well as combined geosynthetics, that is, geoinclusion plus reinforcement (ZEP wall). The results of these analyses are summarized in Figures 3, 4, and 5, each of which shows, for a different type of reinforcement, the increase in horizontal stress on the wall caused by the surcharge, both without and with reinforcement, with the frictional free-field results for comparison. In Figure 3, the explanation of the unex-

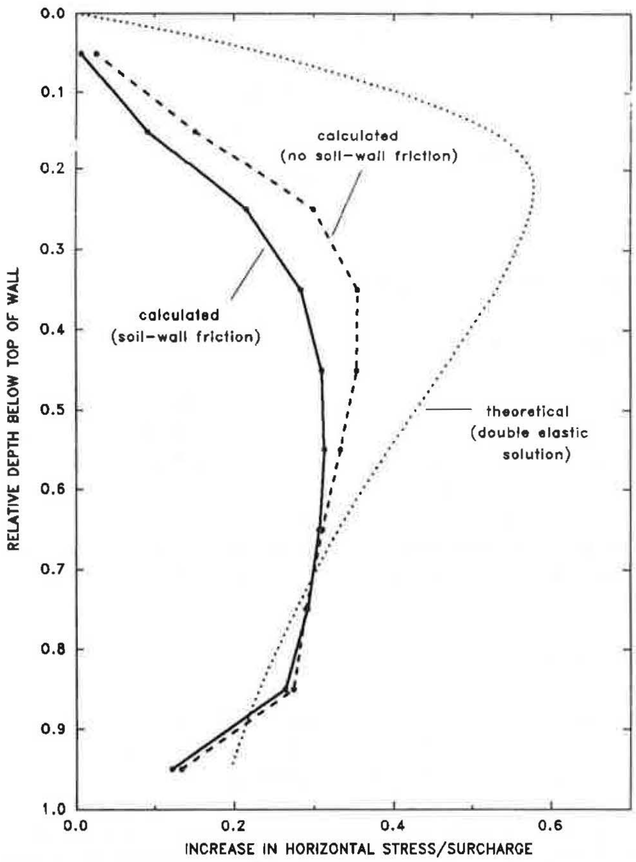

FIGURE 2 Horizontal stress increase on wall caused by surcharge under free-field conditions—no geoinclusion or reinforcement.

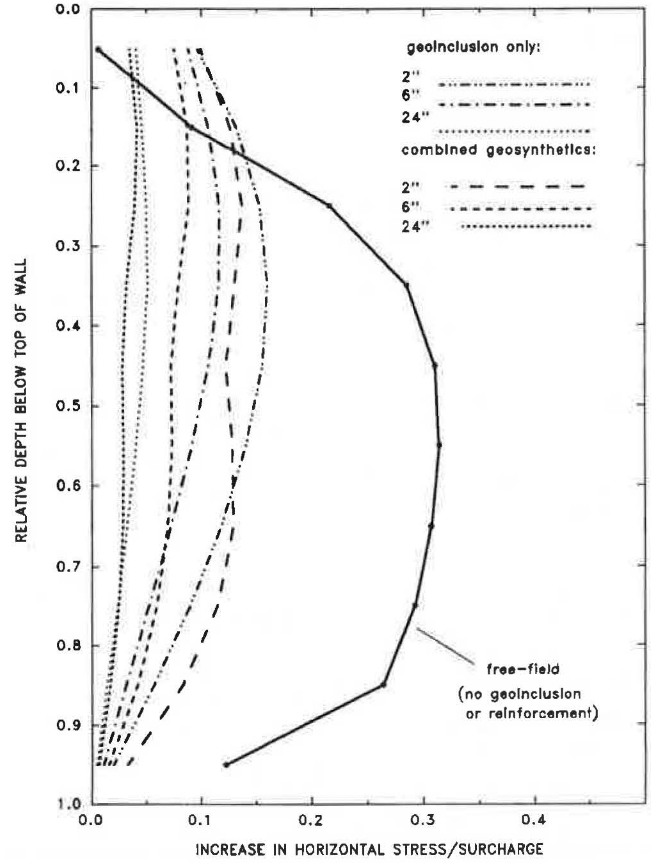

FIGURE 3 Horizontal stress increase on wall caused by surcharge—geotextile reinforcement.

pected result of slightly greater stresses near the bottom of the wall using woven geotextile reinforcement as opposed to no reinforcement is not readily apparent.

To provide some idea of the horizontal deformations that occur, the horizontal compression of the 24-in. geoinclusion for the cases studied is shown in Figure 6. Note that this shows the total compression of the geoinclusion under combined earth plus surcharge loads.

The reductions in horizontal stress increase achieved using geosynthetics are summarized in Figure 7. This shows the percentage reduction of the peak horizontal stress increase caused by the surcharge, using the frictional free-field results as the basis of comparison (i.e., 100 percent). It should be noted that the relative depth at which the peak stress occurs differs between the free-field condition and when geosynthetics are used (the depths are always shallower in the geosynthetics cases). However, the results plotted in Figure 7 do provide some insight into the effectiveness of geosynthetics in achieving stress reductions.

CONCLUSIONS

The conclusions drawn from these results are as follows:

1. The use of even a relatively thin geoinclusion alone provides a significant reduction in the increase in horizontal stress on the wall caused by the surcharge.
2. The use of woven geotextile reinforcement of the stiffness assumed provides slight improvement over the geoinclusion alone. The relative improvement would be greater for a stiffer geotextile.
3. The geogrid reinforcement produces more significant reductions in horizontal stresses than the geoinclusion alone.
4. The steel reinforcement produces dramatic reductions in the horizontal stress increase in comparison with the geoinclusion alone and effectively achieves a condition of a zero earth pressure increase.

In all cases, the trends are the same as those observed for the behavior under earth loading alone (*5,7*).

RECOMMENDATIONS

Applications

Potential applications of the REP- and ZEP-wall concepts to situations in which surcharge loading is involved include new construction and existing structures. In new construction, sometimes it is not desirable or economical to design the retaining structure for soil plus surcharge loads, particularly if the surcharge load might exist only for a limited time—for example, during construction that is of short duration compared with the design life of the structure.

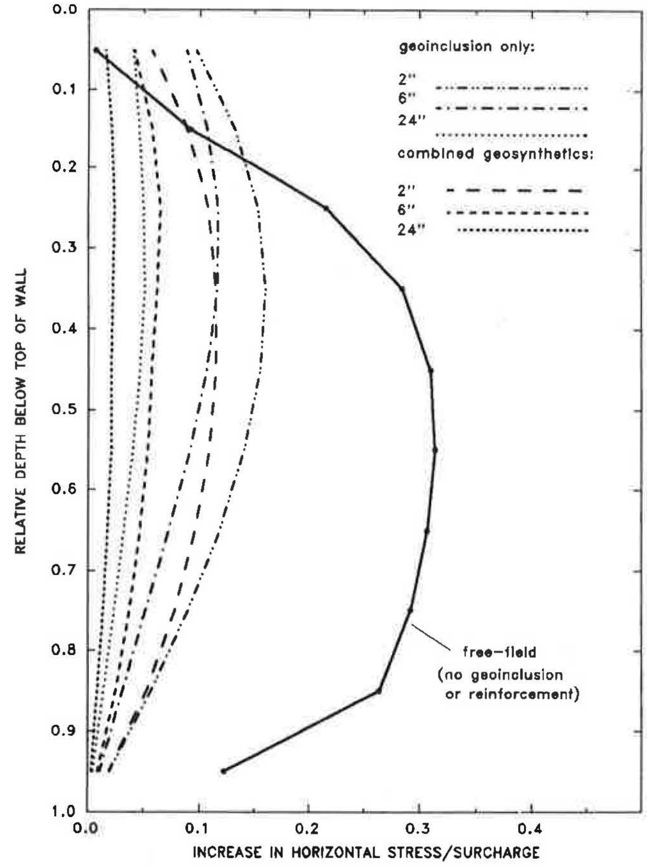

FIGURE 4 Horizontal stress increase on wall caused by surcharge—polymer geogrid reinforcement.

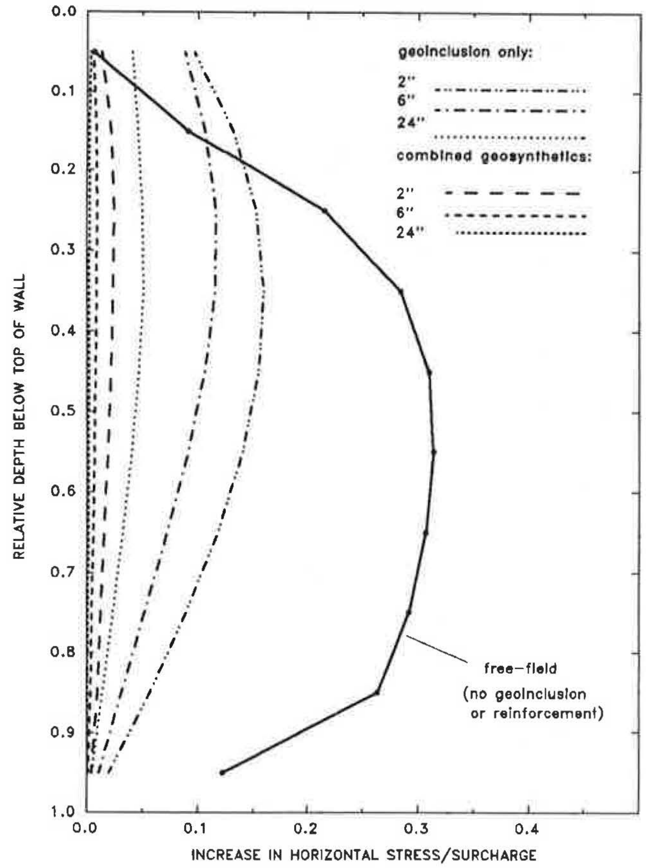

FIGURE 5 Horizontal stress increase on wall caused by surcharge—steel reinforcement.

As far as existing structures, typical situations in which a structure is subjected to surcharge stresses that exceed its allowable capacity were mentioned earlier in this paper. It may be more economical to reduce these stresses permanently using geosynthetics than to strengthen the wall structurally or replace it.

Future Study

At this point in the development of the use of geoinclusions, either large-scale model or full-scale field testing is required to verify the theoretical results presented in this paper. The primary area of investigation with regard to surcharge loading is evaluating the effect on the surcharge-induced stresses of long-term creep, modulus changes, and nonrecoverable deformation of the geosynthetics, particularly the geoinclusion, and nonrecoverable deformations of the retained soil when subjected to many cycles of live load. Testing reported by Sherif and Mackey (*22*) indicates that horizontal stresses caused by a surcharge can increase significantly after many load cycles even without geosynthetics.

SUMMARY

Numerical modeling suggests that it is possible to achieve significant, even total, reduction in surcharge-induced horizontal stresses on rigid earth-retaining structures. This is done by using either a new type of geosynthetic called a geoinclusion or a combination of geoinclusion and synthetic reinforcement of the retained soil. These are referred to as the REP- and ZEP-wall concepts, respectively. Although it appears that a geoinclusion alone will produce significant benefits, physical testing is required to investigate whether its effectiveness may be diminished as a result of nonrecoverable deformations and modulus increase after many cycles of surcharge applications that would occur in most actual installations. It may be that the use of synthetic reinforcement is necessary to sustain the effectiveness of the stress reductions. The nonrecoverable and creep deformations of polymer reinforcement (woven geotextiles and geogrids) also must be studied. However, these issues are design details and should not detract from this interesting advancement and application of geosynthetics technology.

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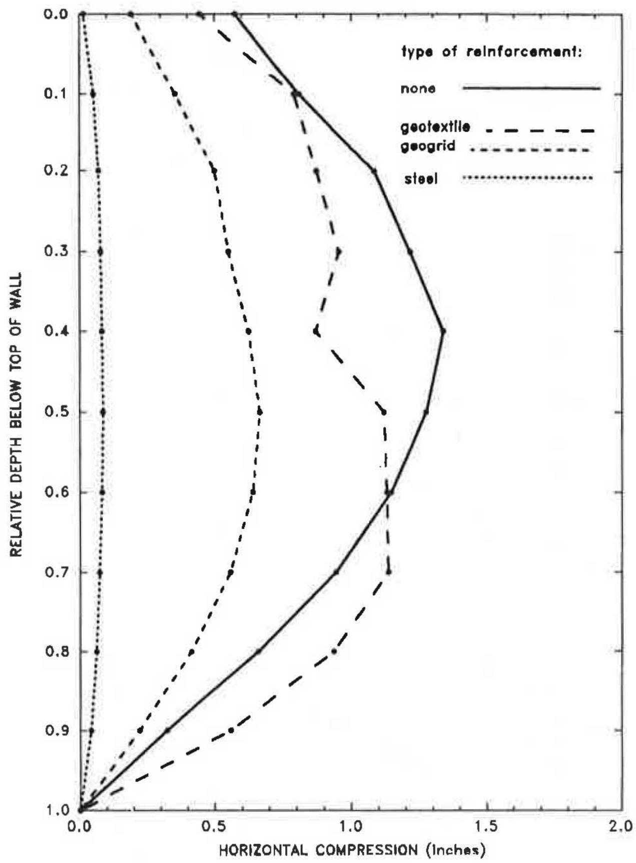

FIGURE 6 Total compression of 25-in. geoinclusion after application of surcharge.

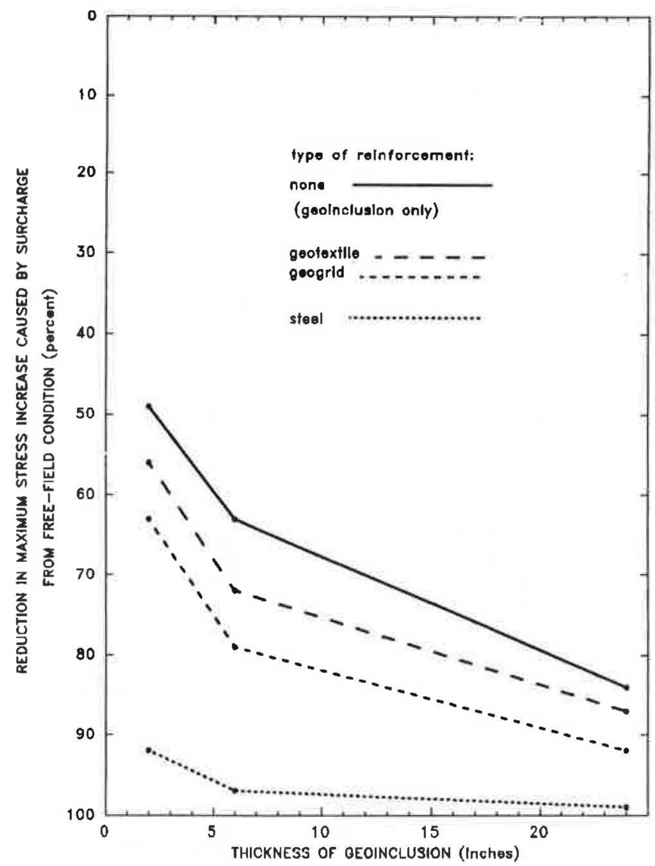

FIGURE 7 Effectiveness of geosynthetics in reducing horizontal stress increase caused by surcharge.

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