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Predicting seismic performance of geogrid-reinforced slopes

D.Y.Lin, S.S.Lin & S.H.Kuo
Department of Harbor and River Engineering, National Taiwan Ocean University, Keelung, Taiwan

ABSTRACT: The seismic response of a 49 ft high geogrid reinforced slope was studied using the available finite element computer code FLUSH. Both fixed horizontal boundaries and with transmitting boundaries were considered in the analysis to evaluate the maximum relative displacement and maximum absolute acceleration of the slope under different frequencies of horizontal seismic loading. The seismic loading produced axial forces along each reinforcement layer was also evaluated to check the possibility of breakage.

1 INTRODUCTION

One of the major applications of geosynthetics in Taiwan is for new town development. Many high geosynthetic reinforced walls or steep geosynthetic reinforced slopes were built along hillside areas. Since seismic activities occur very frequently in Taiwan, a dynamic analysis becomes necessary in order to evaluate the stability and safety of these geosynthetic reinforced walls or slopes.

In addition to pseudo-static analytical method, the finite element method is one of the most popular methods on seismic analysis of reinforced structures, Either the equivalent elastic method or the incremental elastic method is used on analysis (Yogendrakumar et al, 1991). However, the existing analytical methods, in general, do not provide the frequency dependent boundary conditions to simulate the exact dynamic effects of the semi-infinite viscoelastic horizontal layered soil system beyond the finite element region.

The study reported here presents a seismic analysis result for a 49 ft high geogrid reinforced steep slope built at Taipei county for a housing development project. The computer code, FLUSH (Lysmer et al, 1975), is used to evaluate the performance of this slope under seismic loading. The isoparametric quadrilateral element and linear beam element are used to model soil continuum and geogrid, respectively. In addition, the Lysmer-Waas boundary conditions are considered to represent the exact dynamic effect of the semi-infinite viscoelastic horizontally layered soil system beyond the soil element region. The equivalent linear method is used to account the nonlinear effects of soil during earthquakes. The material properties for the geogrids are assumed to be strain-independent and the cross sectional properties specified are those corresponding to a one foot width perpendicular to the plane of the model. The relative displacement between soil and geogrid during earthquake motion is neglected.

2 SLOPE INVESTIGATED

The considered slope, 49 ft high, was constructed by the side of a terrace in Taipei county, where a new housing development, with total developing area 255,000 ft^2, was planned over the top of the terrace. In general, the slope over the housing development area is dipping north towarding south about 30 degree from horizontal plane. The geological condition is an andesite or tuff rock layer, with thickness 75 ft to 128 ft, topped over sedimentary bedrock layer. The unconfined compressive strength is about 12,730 and 140 psi for intact andesite and intact tuff, respectively.

However, the top portion of the tuff and andesite rock layer is highly weathered. This top surface layer is covered by some reddish brown color clayey silt and some yellow brown color sandy silt or silty clay. The thickness is about 8.7 to 59 ft deep. The standard penetration test N value is between 3 to 30. The natural water content is between 14 to 53%. The in situ density test showed the density is about 0.067 pound/in^3. The liquid limit is 0 to 72, and the plasticity index is 0 to 44. The designed slope is 49 ft high along the hillside of the terrace and found on tuff or andesite covered rock layer. This slope was reinforced by Tensar SR 110 geogrids and Tensar SR 80 for the top sixteen and the bottom fourteen layers, respectively. Borrowed granular soil was used as reinforced slope backfilling material. This backfilled granular soil is with internal friction angle 30^0.

After the slope was built, a seismic analysis was considered to be necessary, because the slope is located on an area where is susceptible of seismic loading due to earthquake.

3 MATHEMATICAL MODEL REVIEW

The problem of consideration involves geogrid-soil interaction behavior during seismic analysis. A computer program, FLUSH (Lysmer et al 1975), often used for dynamic soil-structure interaction problems is adopted for this study. The computational model used in the considered slope is shown in Fig. 1. The isoparametric quadrilateral elements and the beam elements were used to model the soil continuum and geogrid reinforcements, respectively. Considering the geogrid reinforced slope as two dimensional plane strain condition, the equation of motion for the finite element representation of the system can be written as (Lysmer et al 1975):

$$[M]\{\ddot{u}\} + [K]\{u\} = -\{m\}\,\ddot{y} - \{V\} + \{F\} - \{T\} \qquad (1)$$

where $\{u\}$ are the displacement of the nodal points relative to the rigid base, [M] and [K] are the usual plane strain mass and stiffness matrices, respectively, of a slice of unit thickness and {m} is a vector related to [M] and the direction of the given bed rock motion, $\ddot{y}\,(t)$. Material damping can be included by forming [K] from complex moduli.

The forces {V} originate from the viscous boundaries on the planar sides of the slice. As shown by Lysmer et al (1975), these forces are

$$\{V\} = \tfrac{1}{L}[C]\Big(\{\dot{u}\} - \{\dot{u}\}_f\Big) \qquad (2)$$

where L is the thickness of the slice, [C] is a matrix depends on the properties of the free field, and $\{\dot{u}\}_f$ are the known free field velocities.

The {F} are the forces act on a vertical plane in the free field and they involve no horizontal transmission of wave energy. These forces are

$$\{F\} = [G]\{u\}_f \qquad (3)$$

where [G] is a frequency independent stiffness matrix formed from the complex moduli in the free field.

The forces related to the energy transmission are

$$\{T\} = ([R] + [L])\Big(\{u\} - \{u\}_f\Big) \qquad (4)$$

where [R] and [L] are the frequency dependent boundary stiffness matrices.

The equation of motion of Eq. 1 can be solved by the complex response method which assumes that the input motion can be written as a finite sum of harmonics, i.e. a truncated Fourier series (Lysmer et al. 1975)

$$\ddot{y}\,(t) = Re \sum_{s=0}^{N/2} \ddot{Y}_s \exp(i\omega_s t) \qquad (5)$$

where N is the number of digitized points in the input motion. Also, it implies that the response can be written as Fourier series (Lysmer et al. 1975)

$$\{u\} = Re \sum_{s=0}^{N/2} \{u\}_s \bullet \exp(i\omega_s t) \qquad (6)$$

and

$$\{u\}_f = Re \sum_{s=0}^{N/2} \{u_f\}_s \bullet \exp(i\omega_s t) \qquad (7)$$

The free field motions, $\{u\}_f$, are computed separately on the assumption that the free field consists of horizontal soil layers and that the seismic excitation consists of vertically propagation p or s waves. The computations are performed in the frequency domain in terms of the free field amplitudes as

$$\{u_f\}_s = \{A_f\}_s \bullet \ddot{Y}_s\,,\ s = 0, 1, \ldots, \tfrac{N}{2} \qquad (8)$$

where $\{A_f\}_s$ is a vector containing the amplification values from the rigid base accelerations to layer displacements. The computer program determines

Table 1 : Material Types of Input Data

		Poisson Ratio	Unit Weight (lb/ft^3)	Shear Modulus (kips/ft^2)
Soil Types	Clay	0.37	127.4	—
	Sand	0.35	121	—
Reinforcement Types		0.45	56.16	24,827.6
Total Number of Layer in Free Field			50	
Total Number of Nodal Point			1,421	
Direction of Control Motion for EQ.			Horz.	
Both Transmitting Boundary and Fixed Boundary were Considered.				

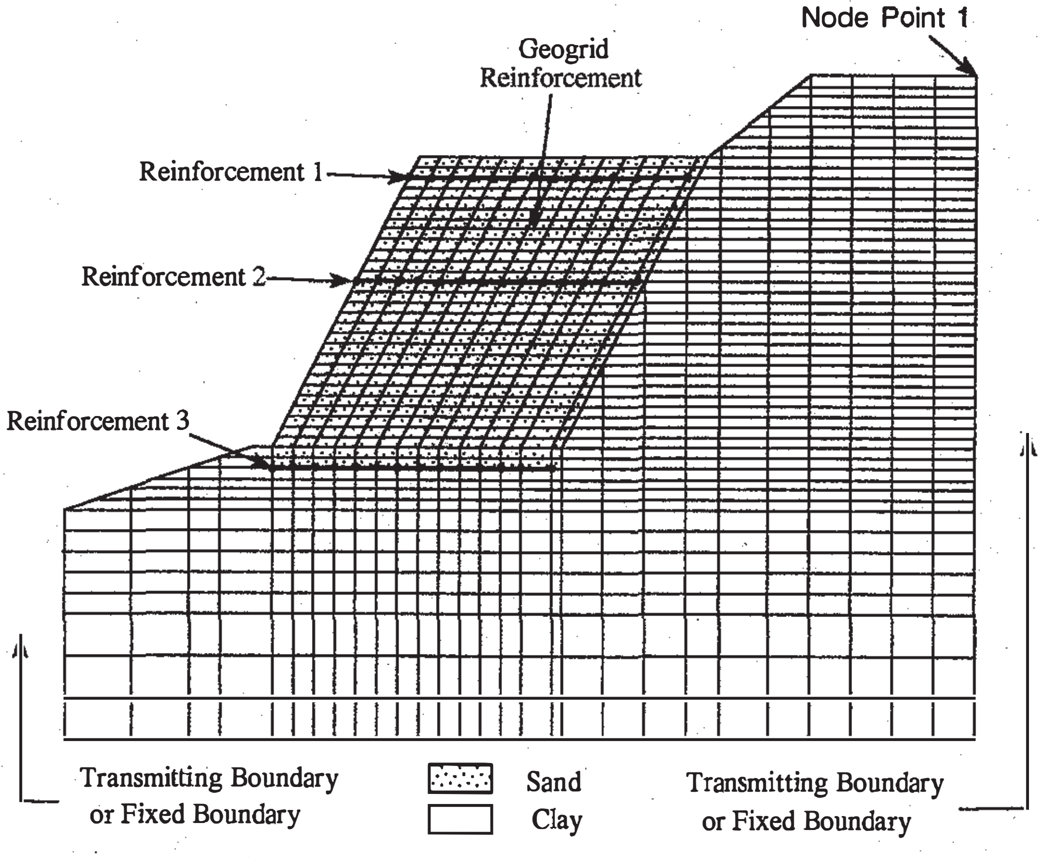

Fig 1. Finite Element Mesh of Investigated Slope

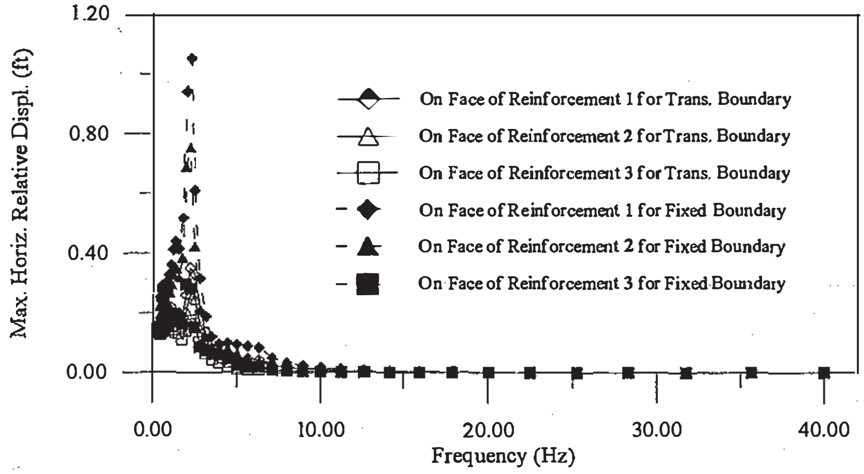

Fig. 2 Max. Horizontal Relative Displacement V.S. Frequency

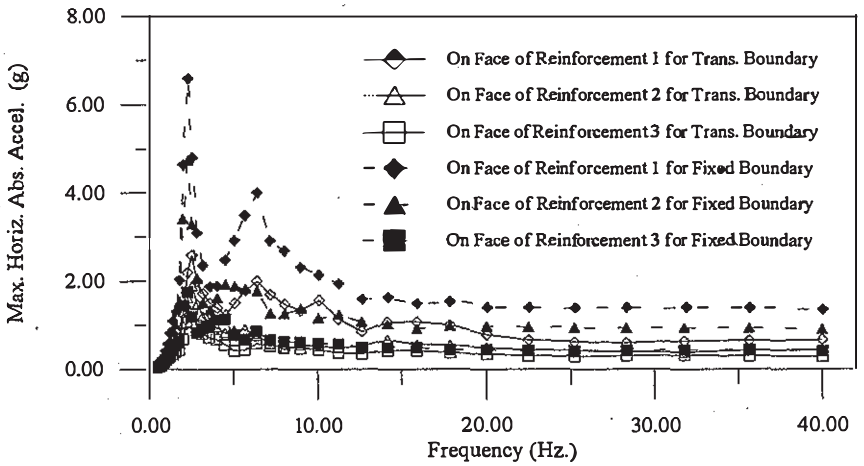

Fig. 3 Max. Horizontal Absolute Acceleration V.S. Frequency

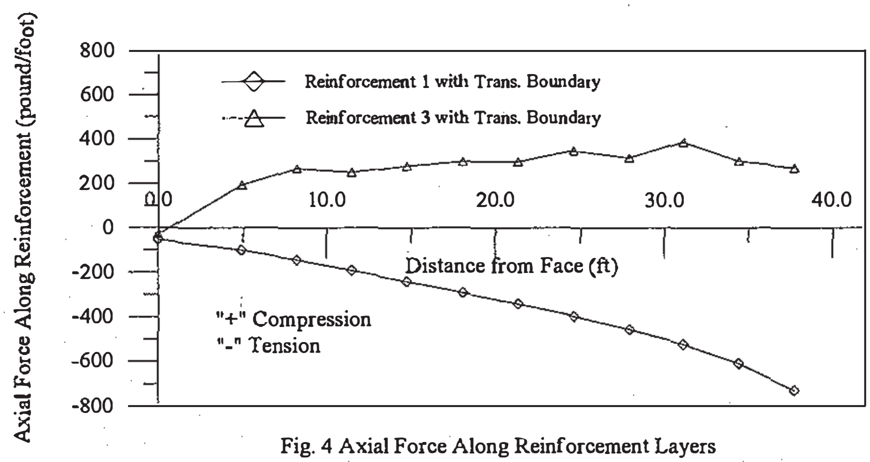

Fig. 4 Axial Force Along Reinforcement Layers

the rigid base acceleration from the inverse of Eq. 8, i.e.

$$\ddot{Y}_s = U_{js}/A_{js};\ s = 0, 1, \ldots, \tfrac{N}{2} \qquad (9)$$

where U_{js} and A_{js} are the jth components of $\{U_f\}_s$ and $\{A_f\}_s$, respectively.

The equivalent linear method was used in FLUSH as solution procedure. According to this method an approximate nonlinear solution can be obtained by a linear analysis provided the stiffness and damping used in the analysis are compatible with the effective shear strain amplitudes at all points of the system.

4 FINITE ELEMENT MODELING

The finite element mesh of the considered problem is shown in Fig. 1. The soils were modeled 2D elements whereas the geogrid was modeled as beam element. The horizontal soil layers in the free field was specified as Lysmer-Waas boundary conditions or fixed. Some important input parameters for the finite element mesh shown in Fig. 1 are listed in Table 1.

5 RESULTS OF ANALYSIS

Some rigid base accelerations were considered in the analysis. However, only horizontal bedrock motion with maximum acceleration 0.267g, which was considered to be the most severe case, was reported in the paper. Figs. 2 and 3 showed the maximum horizontal relative displacement and maximum horizontal absolute acceleration on the slope face v.s. seismic frequency, respectively. As shown in the figures, if both ends of the boundary were fixed, the relative displacement and the absolute acceleration are higher than the case with transmitting boundaries. However, both cases showed the maximum relative displacement and the maximum absolute acceleration occur at the same frequency. In addition, the results of Figs. 2 and 3 showed the maximum relative displacement and the maximum absolute acceleration are higher on the top of the slope than those on the bottom of the slope. Furthermore, the maximum relative displacement occurs at frequency about 2.5 Hz, as in Fig. 2. The fixed boundary case produced the largest relative displacement 1.05 ft on top reinforcement layer. The ratio of this 1.05 ft displacement with the height of the slope 49 ft is about 2%. For rigid reinforced earth wall, the allowable horizontal displacement v.s. wall height ratio is usually considered to be 1%. Since the 2% ratio was produced under severe seismic loading and under fixed boundary condition, the design is considered to be appropriate from safety point of view. In addition, the 1% is considered for rigid wall case, while the analyzed slope adopted flexible face while should be able to sustain larger displacement than that of rigid face design. The maximum absolute acceleration obtained from Fig. 3 can be used for designing of the structures to be built on the top of the terrace.

The variation of maximum axial force for all the cases analyzed along the reinforcements 1 and 3 is shown in Fig. 4, with transmitting boundaries considered. As shown in the figure, the top and bottom reinforcement layers are subjected to tension and compression forces, respectively. Both forces are considered to be small, which will not cause the breakage of the geogrid.

6 CONCLUSIONS

The response of a 49 ft high geogrid reinforced slope subjected to earthquake loading was investigated by an available finite element analysis code, FLUSH. The maximum relative displacement of the slope under the considered earthquake loading is considered on the safe side after the analysis. In addition, the breakage of reinforcement will not happen, based on the analytical result.

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