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Frequency response analysis of reinforced-soil retaining walls

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ABSTRACT

The paper reports the results of a numerical investigation of the influence of height, reinforcement stiffness, reinforcement length and toe restraint condition on the predicted fundamental frequency of reinforced-soil retaining wall models. The study shows that some available closed-form solutions, based on linear elastic wave theory, provide a good estimation of the fundamental frequency of reinforced-soil wall models subjected to low-amplitude ground motion. The fundamental frequency of a reinforced-soil retaining wall model under low-amplitude ground motion is essentially defined by the magnitude of the shear wave velocity in the backfill material and the height of the wall. The results of numerical analyses showed no significant influence of the reinforcement stiffness or reinforcement length on the predicted fundamental frequency of the wall. However, the fundamental frequencies of the wall models showed some dependence on the intensity of input ground motion.

INTRODUCTION

Increases in the magnitude of lateral earth pressure acting on retaining walls due to the dynamic effect of ground motion can be significant. These additional horizontal forces may result in excessive lateral displacement of a wall or even damage or collapse of the structure. Significant lateral movements of bridge abutment retaining walls due to seismic loading have led to damage of bridge superstructures (Seed and Whitman 1970, Bakeer et al. 1990). Reinforced-soil walls constructed with metallic or polymeric reinforcement products have shown good performance during recent earthquakes when compared to traditional poured-in-place concrete gravity wall structures (Bathurst and Alfaro 1996, Tatsuoka et al. 1998). Nevertheless, dynamic behavior of these systems is not thoroughly understood (Bathurst and Hatami 1998). Reinforced-soil retaining walls with typical heights ($H < 10$m) and backfill material are generally considered to be short-period structures. Therefore, the response of the wall to ground motion is dominated by the fundamental frequency of the structure. In practice, the initial step for design against earthquake is to estimate the resonant frequency of the reinforced-soil wall structure. In the present study, the influence of the following parameters on the fundamental frequency of a typical reinforced-soil retaining wall is investigated: the wall height, H; the reinforcement stiffness, J; the reinforcement length to wall height ratio, L/H; wall toe restraint condition (i.e., pinned or free to slide); and, intensity level of ground motion characterized by peak ground acceleration, α_g. The two-dimensional, explicit dynamic finite difference program Fast Lagrangian Analysis of Continua (FLAC 3.40 - Itasca 1998) was used to carry out the numerical experiments.

DYNAMIC ANALYSIS OF RETAINING WALL MODELS

Numerical Grid and Problem Boundaries

The numerical grid for a typical wall model used in the study is illustrated in Figure 1. Numerical simulations represented an infinitely wide backfill of constant depth contained by a continuous panel wall with uniformly spaced reinforcement layers. The width of the backfill, B, was extended to a large distance beyond the back of the facing panel (Table 1) so as to contain the soil shear wedge (plastic zone) that develops behind the reinforced zone during base excitation. The vertical spacing between reinforcement layers was kept constant at $S_v = 1.0$m. The height of the wall models (H = 3, 6 and 9m) and the number of reinforcement layers are typical of actual structures in the field. The toe restraint condition of the wall models was either fixed (i.e., the toe of the wall was slaved to the foundation but was free to rotate) or free to slide horizontally *and* rotate about the toe. The results of a previous study (Bathurst and Hatami 1998) show that the lateral displacement of the wall and the magnitude and distribution of reinforcement load can be significantly affected by the toe restraint condition of the wall. For sliding cases, the wall model was seated on a thin layer of soil (0.05 m thick) that was extended across the entire width of the numerical grid. This layer performed a similar function to a sliding interface and was required to ensure that models representing walls without horizontal toe restraint (i.e., sliding-wall cases) were not artificially restrained during shaking. For the fixed-toe condition, the wall and soil regions were connected directly to a foundation base comprising of a 1 m-thick layer of very stiff material (Figure 1). Two values for the ratio of the reinforcement length to the wall height were selected to represent narrow (L/H = 0.4) and wide (L/H = 1) reinforced soil zones in the parametric analysis. This range of reinforcement ratios captures the range of values reported in the literature for actual structures in the field.

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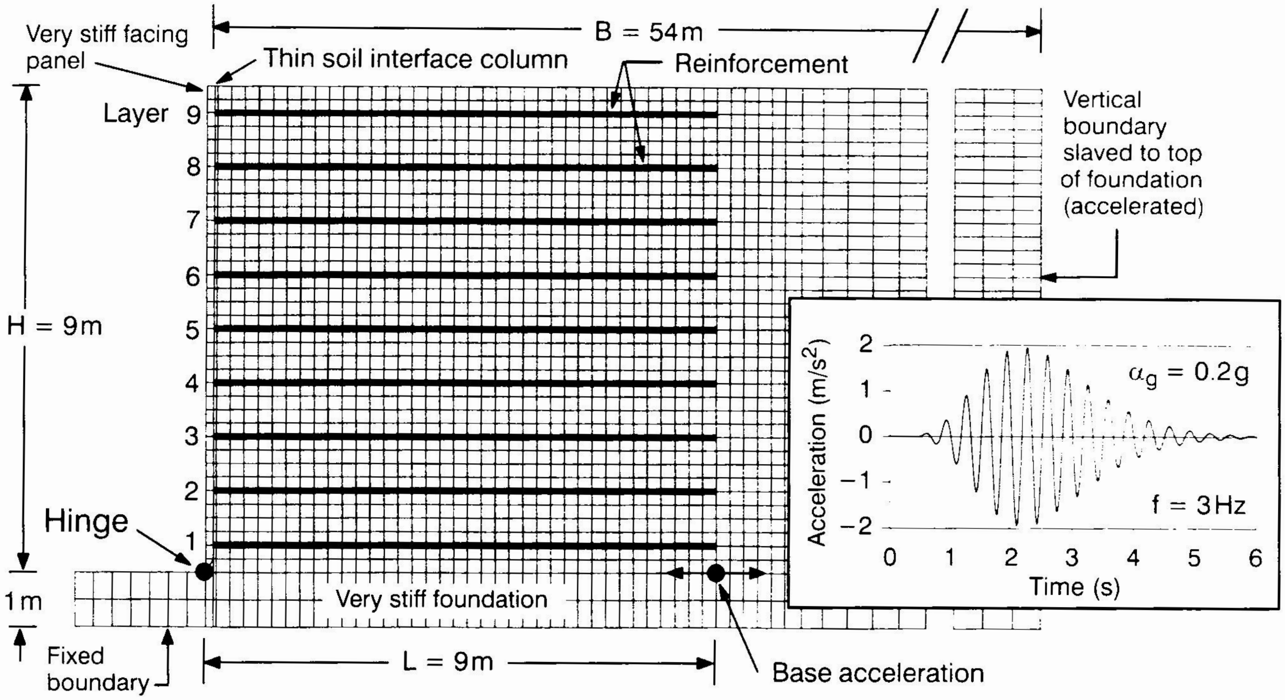


Figure 1. Example numerical grid for reinforced-soil wall with fixed toe condition.

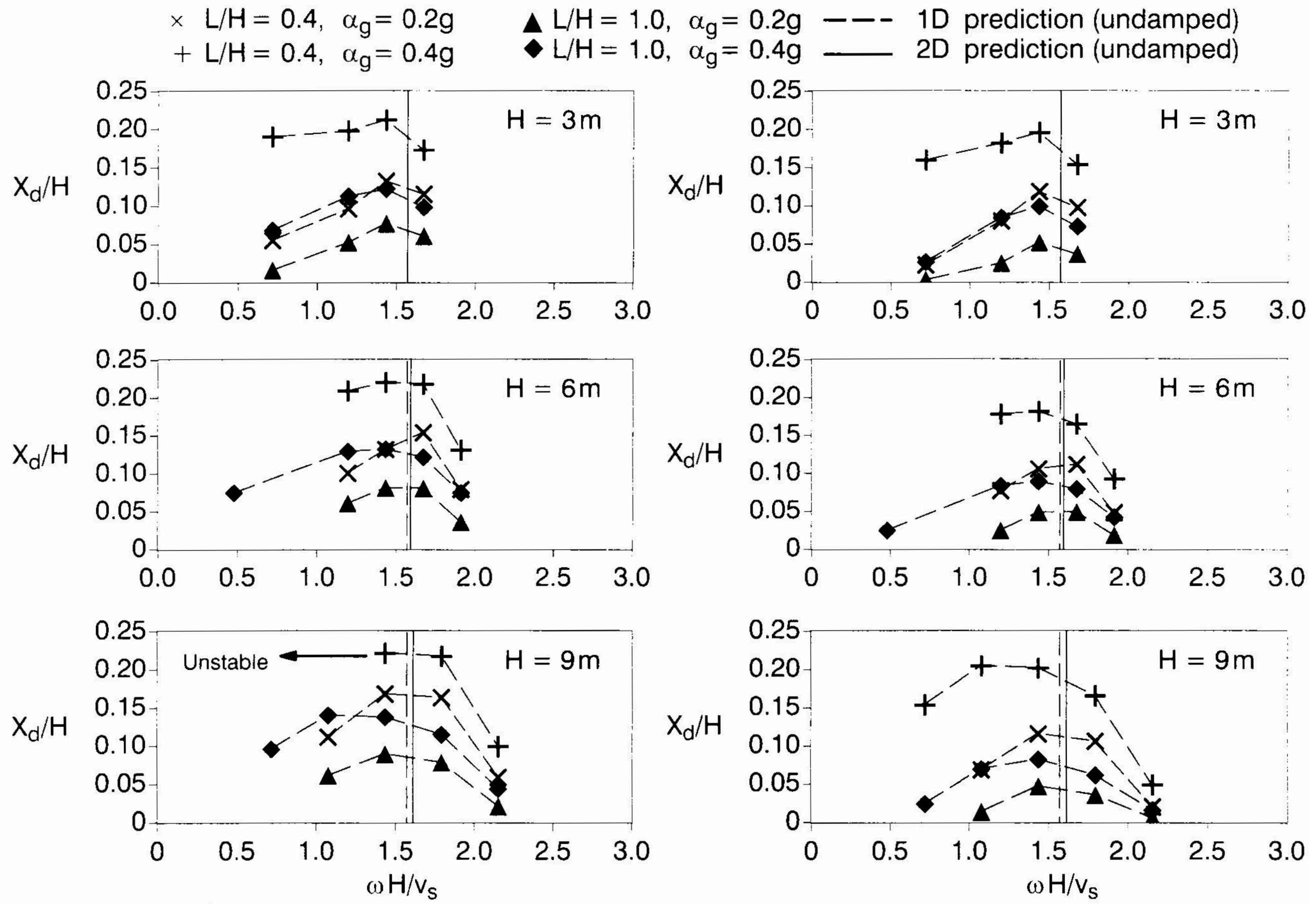
Material Properties

The wall facing was modeled as a continuous concrete panel with a thickness of 0.14m. The bulk and shear modulus values of the wall were K_W = 11,430MPa and G_W = 10,430MPa, respectively. Poisson's ratio for the panel material was taken as v_w = 0.15. The soil was modeled as a purely frictional, elastic-plastic material with a Mohr-Coulomb failure criterion (i.e., a granular soil). The friction angle of the soil was $\phi = 35°$, dilatancy angle $\psi = 6°$, and unit weight γ = 20kN/m³. The soil material was assigned constant values of bulk modulus K_s = 27.5MPa and shear modulus G_s = 12.7MPa. The foundation zone for fixed-toe cases was assigned the same material properties as the concrete facing panel. The wall-soil interface was modeled using a thin soil column (0.05m thick) directly behind the facing panel. A no-slip boundary was used between the thin soil column and the facing panel. The friction angle and the dilatancy angle of the interface soil column between the reinforced soil zone and the panel wall were set to $\phi_i = 20°$ and $\psi_i = 0$, respectively. The remaining soil properties of the interface soil column were the same as the properties of the backfill soil. The reinforcement layers were modeled using linear elastic-plastic cable elements with negligible compressive strength and an equivalent cross-sectional area of 0.002m². The equivalent linear elastic stiffness value for the reinforcement was taken as J = 500 or J = 10000kN/m (Table 1). The lower stiffness value represents an extensible (polymeric) geotextile reinforcement and the larger value a very stiff (polymeric) geogrid reinforcement material. The yield strength of the reinforcement in all cases was kept constant at T_y = 200kN/m, which is well above the magnitude of the maximum reinforcement load recorded in the simulations. Consequently, reinforcement rupture was not a possible failure mechanism in this study. The interface between the reinforcement (cable elements) and the soil was modeled with a grout material of negligible thickness and with an interface friction angle $\delta_g = 35°$. The bond stiffness and bond strength of the grout were taken as $k_b = 2 \times 10^3$ MN/m/m and $s_b = 1 \times 10^3$ kN/m, respectively. The interface and grout properties were selected to simulate a perfect bond between the soil and reinforcement layers. The end of each cable element was connected to a single grid point at the back surface of the continuous panel region to simulate a fixed reinforcement connection in the field.

Table 1. Parametric values used in the evaluation of the fundamental frequency of wall models

Wall height H (m)	Model width B (m)	Reinforcement ratio L/H	Base condition	Reinforcement stiffness J (kN/m)	Peak ground acceleration α_g (g)	Input frequency f_g (Hz)
3	30	0.4, 1.0	Fixed	500, 10000	0.2, 0.4	3, 5, 6, 7
6	42	0.4, 1.0	Fixed, Sliding	500, 10000	0.2, 0.4	1, 2.5, 3, 3.5, 4
9	54	0.4, 1.0	Fixed	500, 10000	0.2, 0.4	1, 1.5, 2, 2.5, 3

Notes: Reinforcement spacing S_v = 1.0m; damping ratio ξ = 5%.



a) J = 500 kN/m

b) J = 10000 kN/m

Figure 2. Variation of the normalized lateral displacement of the wall crest at the end of seismic loading with normalized frequency of input ground motion (Note: vertical lines are predicted fundamental frequency values from linear elastic wave theory).

Seismic Loading

The staged construction of each wall model was simulated by placing the backfill and the reinforcement in layers, while the continuous panel was braced horizontally using rigid external supports. The panel supports were then released in sequence from the top to the bottom of the structure as is done in the field. After static equilibrium was achieved (end of construction stage), the full width of the foundation was subjected to the variable-amplitude harmonic ground motion record illustrated in Figure 1. This acceleration record was applied horizontally to all nodes at the bottom and the right-hand side (truncated) boundary of the backfill soil zone at equal time intervals of $\Delta t = 0.05$ s. The mathematical expression for the accelerogram is given by:

$$\ddot{u}(t) = \sqrt{\beta e^{-\alpha t} t^{\zeta}}\ \sin\,(2\pi f t) \qquad (1)$$

where: $\alpha = 5.5$, $\beta = 55$, and $\zeta = 12$ are constant coefficients, f is frequency and, t is time. The resulting peak amplitude, α_g, using these parameters is 0.2g, where g is the acceleration of gravity. Coefficient terms were adjusted to give a peak amplitude $\alpha_g = 0.4$g representing a stronger earthquake. The variable-amplitude input ground motion from Equation 1 was chosen over simple harmonic acceleration because it simulates the rise and time decay of an idealized accelerogram. The applied acceleration at the truncated boundary was based on the assumption of uniform distribution of horizontal acceleration over the depth of the backfill at a large distance from the facing panel. A viscous damping ratio of $\xi = 5\%$ was chosen for both the soil and facing panel regions in the parametric analyses.

RESPONSE OF WALL MODELS TO INPUT GROUND MOTION

Wall Displacements

Figure 2 summarizes the variation of the calculated normalized lateral displacement of the wall crest (due to dynamic loading only) at the end of seismic loading with normalized frequency of input ground motion. The toe restraint condition

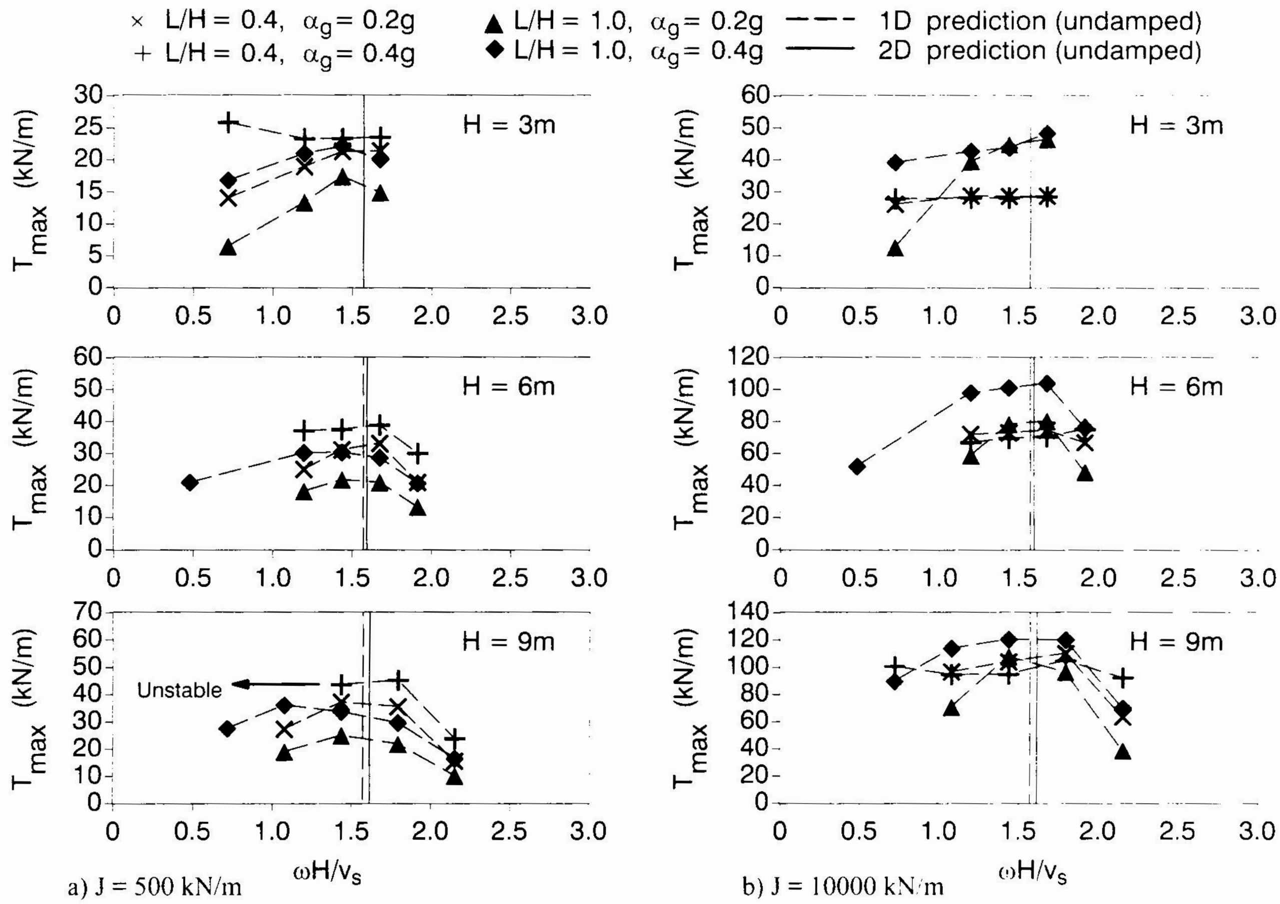
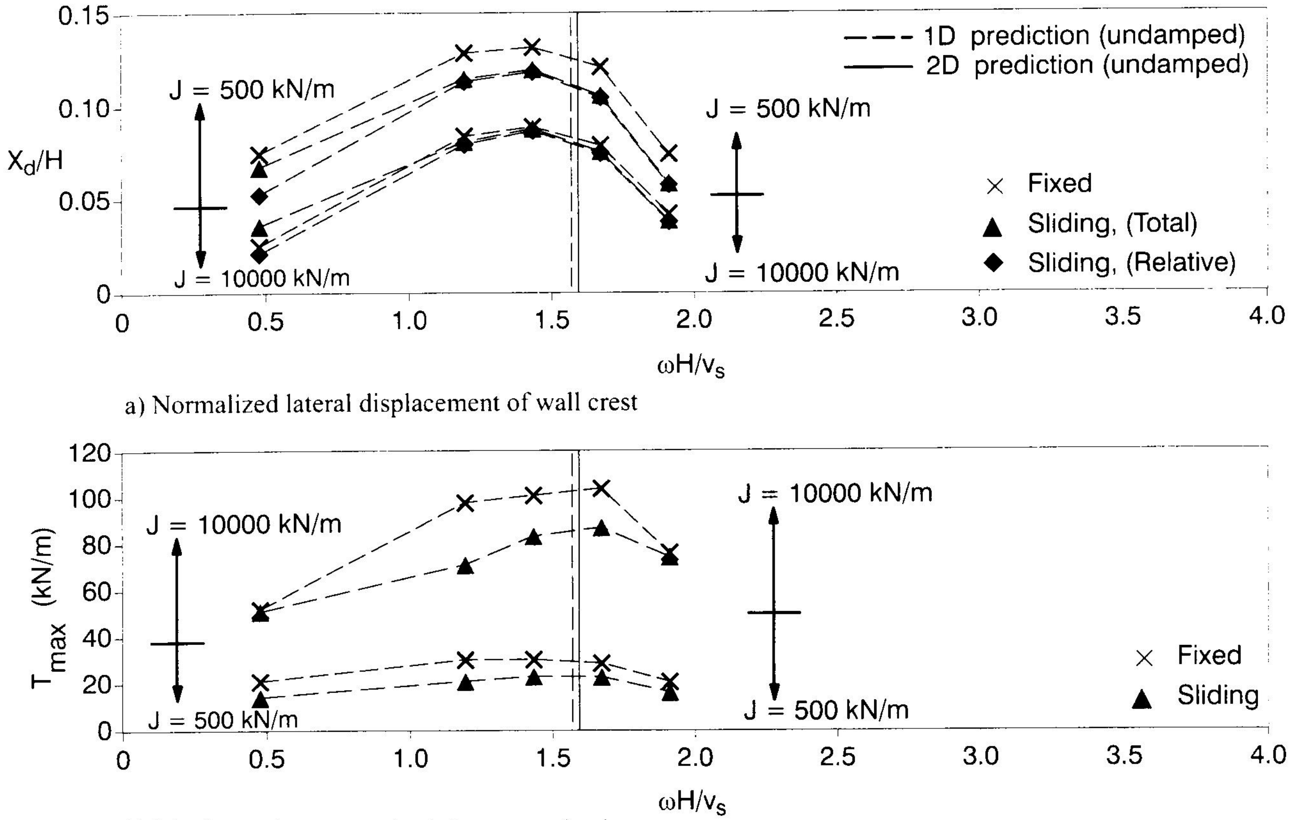


Figure 3. Variation of maximum reinforcement incremental load at the end of seismic loading with normalized frequency of input ground motion (Note: vertical lines are predicted fundamental frequency values from linear elastic wave theory)

is fixed in all the cases presented in Figure 2. The input frequency is non-dimensionalized in the form of $\omega H/v_s$ where ω is the input circular frequency and v_s is the speed of shear wave propagation in the backfill material.

Progressive outward displacement of the wall facing was observed during all the parametric simulation runs. Post-construction wall lateral displacements due to base shaking were significant in all the analysis cases although the magnitude of outward displacement was less for the stiffer reinforcement cases. A shear failure wedge was formed behind the reinforced zone which covered a considerable portion of the backfill. The observed wedge angle, in general, showed good agreement with the predicted value according to the Mononabe-Okabe theory considering amplification of acceleration over the height of the wall (Bathurst and Hatami 1998). However, the frequency response curves in Figure 2 indicate that the fundamental frequency of wall models subjected to moderately strong ground motion (α_g=0.2g) can still be predicted satisfactorily based on linear elastic wave theory. The prediction becomes less accurate for a stronger ground motion (α_g=0.4g). The predicted fundamental frequency based on the two-dimensional (2D) analysis of the backfill as a continuum model (Wu and Finn 1996) is very close to the calculated value using the one-dimensional (1D) approximation because of the large width of the backfill used in the numerical models (e.g., B/H>5). The undamped predominant frequencies of the wall models were calculated based on the wall geometry and material properties (Bathurst and Hatami 1998) as: f_3 = 6.67 Hz, f_6 = 3.38 Hz and f_9 = 2.28 Hz where f_H is the predominant frequency of the wall model with height H. Comparison of the frequency response curves shown in Figure 2 reveals almost no influence of the reinforcement stiffness or reinforcement length on the predicted fundamental frequency of a wall model of given height and backfill material. However, the fundamental frequencies of the wall models shift towards lower frequencies under a stronger input ground motion (cf. cases of 0.4g and 0.2g in Figure 2). This observation is attributed to the decrease in the magnitude of the modulus of the backfill material at larger strain levels which has also been observed in experimental studies (Richardson and Lee 1975). The equivalent viscous damping ratio of the backfill increases with increasing strain level. This also contributes to reduce the fundamental frequency of the retaining wall structure under strong ground motion to a value less than that predicted using linear elastic analysis. The dependence of fundamental frequency of the wall on ground motion intensity is a nonlin-



b) Maximum incremental reinforcement load

Figure 4. Influence of toe restraint condition and reinforcement stiffness on frequency response of wall models ($H = 6$ m, $L/H=1.0$) to input ground motion ($\alpha_g = 0.4$ g) (Note: vertical lines are predicted fundamental frequency values from linear elastic wave theory)

ear characteristic of the structure under severe excitation. This shift of frequency was more pronounced for taller wall models. This may be attributed to larger strain levels being developed in 9 m models as compared to 3 m models. On the other hand, significant displacement response was observed at lower input frequencies in a few cases with L/H=0.4 in taller wall models under the input ground motion with α_g=0.4 g (Figure 2). This is mainly due to insufficient length of the soil reinforcement for the case L/H=0.4. Design codes such as FHWA (1996) recommend a minimum of L/H=0.7 for the reinforcement length of reinforced-soil walls under static loading. The wall response to input ground motion with a frequency lower than the fundamental frequency of the wall approaches the response of the wall due to static lateral earth pressures. Accordingly, a wall with under-designed reinforcement length undergoes significant lateral displacement and possible instability due to the short width of the reinforced zone. In the current study, some cases of instability in the numerical models with L/H=0.4 and J=500 kN/m subjected to α_g=0.4 g ground motion were observed (Figure 2).

Reinforcement Loads

Figure 3 summarizes the variation of the maximum reinforcement incremental load at the end of dynamic loading, T_{max}, with normalized loading frequency (T_{max} = total maximum force less tensile force recorded at end of construction). The maximum load at each reinforcement layer was observed at the connection with the facing panel. However, contrary to the lateral displacement of the wall that was greatest at the wall crest, the maximum reinforcement incremental load was observed in different reinforcement layers depending on the parametric case (Bathurst and Hatami 1998). In general, the overall maximum incremental load, T_{max}, was observed in lower reinforcement layers for stiffer reinforcement, shorter reinforcement length geometries and stronger input ground motion cases. Cases with L/H=0.4 resulted in larger incremental loads at lower frequencies which can be attributed to the shorter reinforcement lengths. Nonetheless, the frequency response of the incremental load also shows a maximum in the vicinity of the predicted fundamental frequency based on linear elastic analysis (with better accuracy for a moderately strong ground motion, α_g=0.2 g). The data in Figure 3 and Figure 4b show that for otherwise identical cases, reinforcement loads were greater for wall models with stiffer reinforcement but the fundamental frequency remained insensitive to reinforcement stiffness values in this study.

Effect of toe restraint condition

Frequency responses of lateral displacement of the wall crest and maximum reinforcement incremental load are shown in Figures 4a and 4b, respectively. The results are shown for 6m-high wall models with L H=1 and α_g=0.4g. Both total and relative displacements of the wall crest (relative to the base of the wall) are presented in the figure. Comparison of the magnitude of lateral displacement of the wall for fixed and sliding conditions indicates that the wall subjected to horizontal ground motion undergoes a larger lateral displacement at the top when the toe is restrained from lateral movement. This also results in a somewhat larger maximum incremental load being developed in the reinforcement. However, the frequency responses of both the displacement and reinforcement load do not show any observable influence of the toe restraint condition on the fundamental frequency of the wall models. Furthermore, the measured fundamental frequency values inferred from the figures for α_g=0.4g are consistently lower by about the same amount from theoretical values based on linear elastic theory.

CONCLUSIONS

Parametric seismic analyses were carried out on a set of reinforced-soil wall models simulating reinforcement materials with different stiffness values and reinforcement length. The wall models had three heights of 3, 6 and 9m. Two different toe restraint conditions are included for the 6m-high wall models. The foundation of each wall model was subjected to a variable-amplitude, harmonic input acceleration record with a range of frequencies in the vicinity of predicted critical values according to linear elastic analysis. Two ground motion intensity levels characterized by peak ground acceleration values were also included in the study. The results of analyses showed that the fundamental frequency of a reinforced-soil retaining wall with a sufficiently large uniform backfill extending beyond the wall facing and subjected to a moderately strong ground motion can be estimated satisfactorily using one-dimensional linear elastic theory. Predicted values based on a two-dimensional continuum model are close to values using one-dimensional theory for wide backfills (e.g., B H>5). The soil reinforcement stiffness, reinforcement length and toe restraint condition did not show any significant effect on the fundamental frequency of the reinforced-soil wall models. The intensity of the input ground motion, represented by the magnitude of the peak acceleration showed some influence on the fundamental frequency of the retaining walls. The fundamental frequencies of wall models were less for the stronger of the two input acceleration records used. Finally, it should be noted that the current study is restricted to the rigid foundation condition. The influence of foundation depth and stiffness on dynamic response of simulated reinforced-soil retaining wall structures is currently under investigation by the writers.

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