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A NEW PSEUDO-DYNAMIC ALYSIS OF SOIL NAILIED WALLS

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SUMMARY

Soil nailing is an in-situ soil reinforcement technique that has been used during the last three decades mainly due to its flexibility, rapid construction and economical aspects compared with other conventional stability methods. Most of available analysis methods applied to reinforced retaining structures consider a global stability, while according to experiences gained from laboratory and field tests on soil-nailed structures, the local stability of nails is more critical and thus must be taken into account. The kinematical limit analysis of soil-nailed structures enables the designers to consider local stability. In this paper, a kinematical pseudo-dynamic analysis is presented for analysis of soil-nailed structures subjected to earthquake loading. The model is verified by available experimental data srom the field. A parametric study on the influence of the loading frequency shows that with increasing frequency the tension forces in nails decrease.

INTRODUCTION

Soil-nailed structures are coherent and flexible systems which can withstand larger deformation and as illustrated by post-earthquake observations on soil-nailed retaining structures (Barar, 1990; Felio et al., 1994). They also present high resistance to earthquake loading. Due to these advantages, soil-nailed structures are a valuable and cost-effective solution for geotechnical construction in seismic zones.
During the past three decades, only limited dynamic centrifuge tests (Vucetic et al., 1993; Sawada et al., 1993; Tufenkjian and Vucetic, 2000), shaking table tests (Richardson et al., 1977; Chida and Minami, 1982) and analytical methods (Sabhahit et al., 1996; Choukeir et al., 1997) have been conducted to investigate the seismic response of soil-nailed structures. However, to date, the interpretation of the available dynamic model test results has been primarily limited to a qualitative evaluation of the system performance and failure mechanisms.
Most of the design methods which are used for earthquake analysis of soil-nailed structures are based on the pseudo-static Mononobe-Okabe (M-O) analysis. There are two fundamentally different pseudo-static design methods namely global limit equilibrium analysis and working-stress analysis. The limit

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equilibrium analysis method extends available limit force equilibrium analysis to assess the seismic loading effect on the global safety factor. Also it doesn't allow for an estimate of the maximum tension and shear forces generated in the nails and, therefore, can't be used for local stability evaluation of soil-nailed structures at each nail level. These limitations led to the development of working-stress method. The working-stress design methods have been evaluated for static loading (Christopher et al., 1989; Juran and Elias, 1991; Clouterre, 1993) through comparisons with laboratory models, full-scale experiments and field monitoring of structures. Only limited studies have been conducted to evaluate experimentally the available working-stress design methods for the seismic design of soil-nailed structures (Richardson et al., 1977; Seed and Mitchell, 1981; Dhouib, 1987; Segrestin and Bastick, 1988; Choukeir et al., 1997) in order to evaluate the seismic loading effect on the mobilized forces in the nails with pseudo-static analysis.

In the current pseudo-static design methods, a single loading parameter (maximum amplitude of the horizontal ground acceleration) is used to characterize the seismic loading. This analysis method overstimates tension forces in nails subjected to earthquake loading. Therefore, the results of a pseudo-dynamic analysis are more reliable than the pseudo-static analysis results.

Sabhahit et al. (1996) presented a pseudo-dynamic limit force equilibrium approach which incorporates a finite shear wave velocity based on the assumption that the shear modulus is constant and only the phase not the magnitude of acceleration was varying with depth. This method gives only a global safety factor and thus can't be used to determine the local safety factor for each nail. This paper remedies limitations of pseudo-static methods and the mentioned pseudo-dynamic method and thus its advantahes in evaluating nail forces and local stability of nailed slope is obvious.

PROPOSED WORKING-STRESS PSEUDO-DYNAMIC DESIGN METHOD

The proposed pseudo-dynamic analysis (Karbor, 2003) approach for soil-nailed structures is derived as an extension of the kinematical working-stress design method developed by Juran et al. (1990) for static loading of soil-nailed structures. The applicability of this working-stress design method under static loading has been described in details by Juran and Elias (1991) and is incorporated in several design codes (FHWA report No. RD-89-0431, 1989; CLOUTERRE, 1993).

In this paper the method of Juran et al. (1990) is extended to the analysis of the seismic loading effect on the magnitude of the maximum resisting forces (tension and shear forces) mobilized in the nails. The main design assumptions of the kinematical analysis are summarized below (Fig. 1):

1- Failure occures by a quasi-rigid body rotation of the active zone, which is limited by a log-spiral failure surface.
2- The locus of the maximum tension and shear forces at failure coincides with the failure surface developed in the soil.
3- The shearing resistance of the soil, defined by Coulomb's failure criterion, is entirely mobilized along the sliding surface.
4- The shearing resistance of stiff inclusions, defined by Tresca's failure criterion, is mobilized in the direction of the sliding surface in the soil.
5- The horizontal components of the interslice forces are equal.
6- The effect of a slope (or horizontal surcharge), at the upper surface of the nailed soil mass, on the tension forces in the nails is linearly decreasing along the failure surface.

The extension of the kinematical design method for pseudo-dynamic stability analysis involves the following assumptions:

1- Earthquake acceleration is simulated by a sinusoidal acceleration which acts at the base of the slope and its phase varies along the slope height.
2- Shear modulus of the soil is constant along the depth.
3- Shear strenght parameters of the soil are constant during earthquake loading.
4- The soil is not saturated and thus no effect of pore water pressure is present.

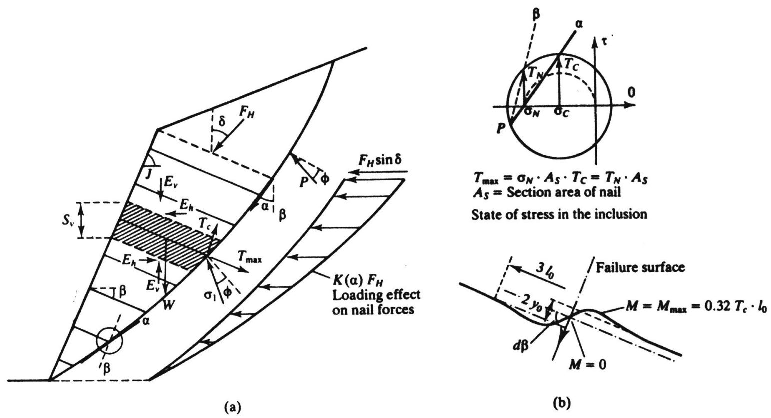

Fig. 1 Kinematic limit analysis; (a): Failure mechanism and design parameters; (b): Theory of infinite inclusion for nails

The normal soil stress along the failure surface is calculated using Kotter's equation. The mobilized nail forces are determined by satisfying the horizontal equilibrium of forces acting on each nailed slice, as shown in Fig. 2. In this figure, F_h=horizontal interslice force, F_h=vertical interslice force, T_{max}=maximum tension force of nail, w_i=slice weight, k_v =vertical earthquake aceleration coefficient, β =nail inclination, c=soil cohesion, ϕ =soil friction angle, $a_i(z,t)$=acceleration at each nail level as a function of time and depth, F_{Hi}=force deduced as the effect of slope at the upper surface of nailed soil mass, $\sigma(a)$=normal stress along the failure surface.

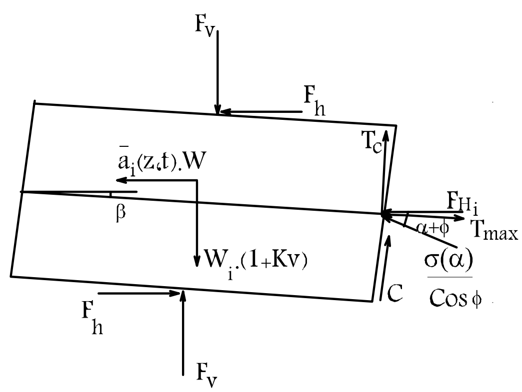

Fig. 2 Forces applied to each soil nailed slice

A unique failure surface can be found to satisfy the equilibrium condition. In order to stablish this failure surface, it is necessary to determine the two kinematical parameters α_o and α_f where these are inclination angles of the failure surface at the top and the bottom of the reinfoced soil mass respectively. For flexible nails the failure surface is practically vertical at the top (α_o = 0), whereas for perfectly rigid nails, it is perpendicular to the nail. Parameter α_f is computed from moment equilibrium of the active zone. posion of the failure surface at the upper ground surface.

The derivation and presenting the mathematical procedue here makes the paper lengthy and the reader may reffer to Karbor (2003). A comprehensive computer program was also developed to determined all parameters involved. In this paper only limited data determined from this program are presented. Further data are available in Karbor (2003).

VERIFICATION

Example 1

To the best knowledge of the authors, no dynamic test data are available to present local forces in nails. Thus the model is verified with static data. In first example, the full scale experiment prformed at the C.E.B.T.P., at Saint-Remy is considered. Before construction of the 7 m high nailed wall, a slightly cohesive sand embankment, was constructed on a Fontainebleau sand foundation.The soil was Fontainebleau sand with a small amount of fine grained material, and was placed and compacted to become medium dense with a relative density of D_r=0.6. At this density, soil shear strength parameters c =3 kPa and ϕ=38^o were determined in the laboratory. Aluminium tube nails were used with inclination angle of 10^o to the horizontal direction. The spacing of the nails in the horizontal and vertical directions was S_h=1.15 m and S_v=1.00 m respectively. The results of this experiment and the proposed method are shown in Fig. 3 where T_{max} (kN) is the maximum tension force for each nail and Z/H is the relative depth of nails (Z=depth from the slope top and H=slope height).

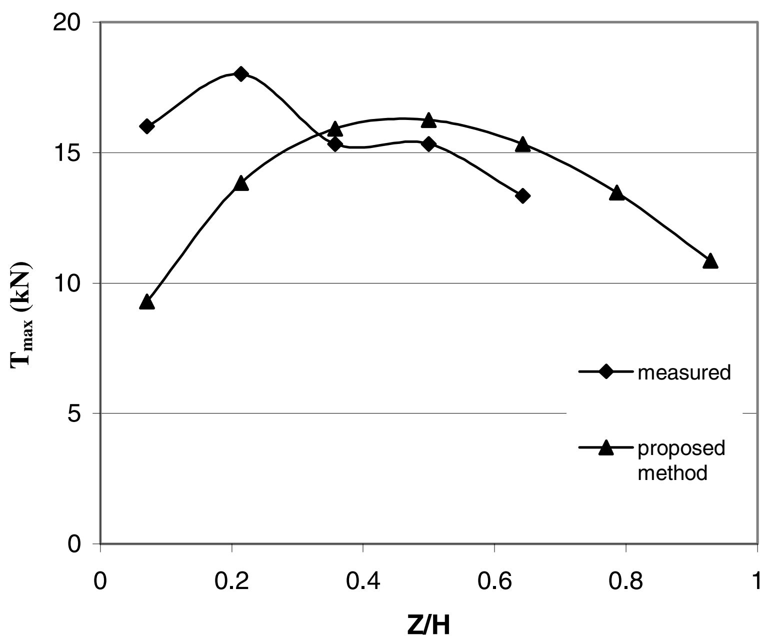

Fig. 3 Comparison of measured and computed forces in nails versus depth

Example 2

The design parameters of a full scale vertical wall in Seattle, Washington are height of wall (H) = 16 m, unit weight of soil (γ) = 21.6 kN/m^3, inclination angle of nails = 15^o, number of nails=9, horizontal and vertical spaces of nails (S_h, S_v) =1.8 m, ϕ=40^o, and c=9.6 kN/m^2. The amounts of dimensionless parameter TN =T_{max} /(γ.H.S_v.S_h)) for each nail level are plotted versus their relative depths in Fig. 4.

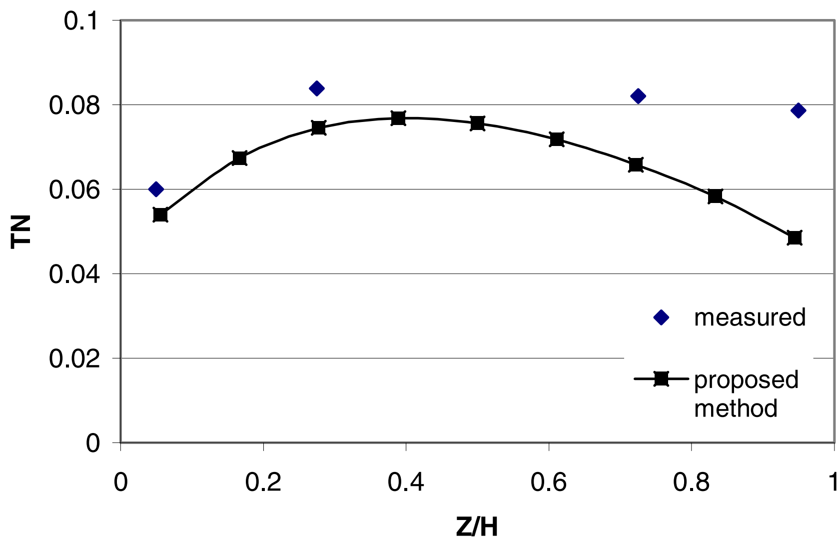

Fig. 4 Comparison of measured and computed forces in nails versus depth

PARAMETRIC STUDIES

Effect of loading angular frequency

The influence of earthquake loading frequency has been investigated and shown in Figs. 5 to 8 for upper, middle, and bottom flexible nails, respectively. In this study $\beta=15^o$, c=5 kPa, $\phi=35^o$, $\gamma=18$ kN/m^3, $k_v=0$, $k_h=0.1$, V_s (soil shear modulus) = 90 m/s, $S_v=S_h=1.5$ m.

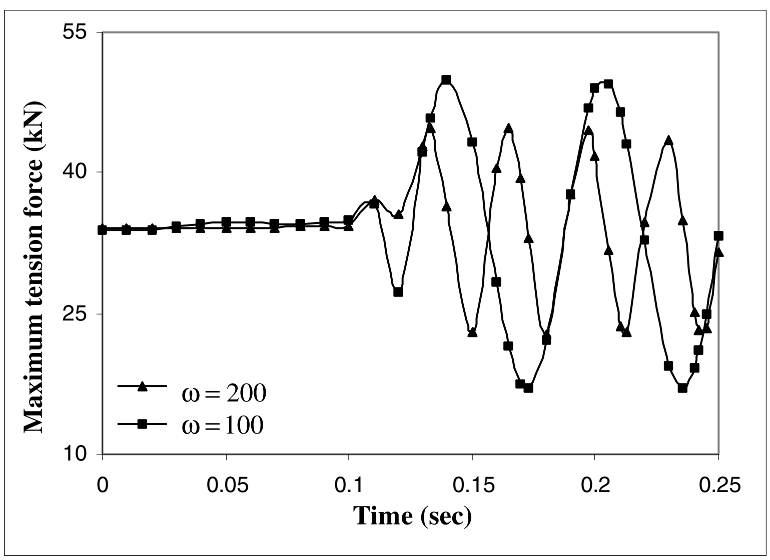

Fig. 5 Effect of loading frequency on maximum tension force in upper nail

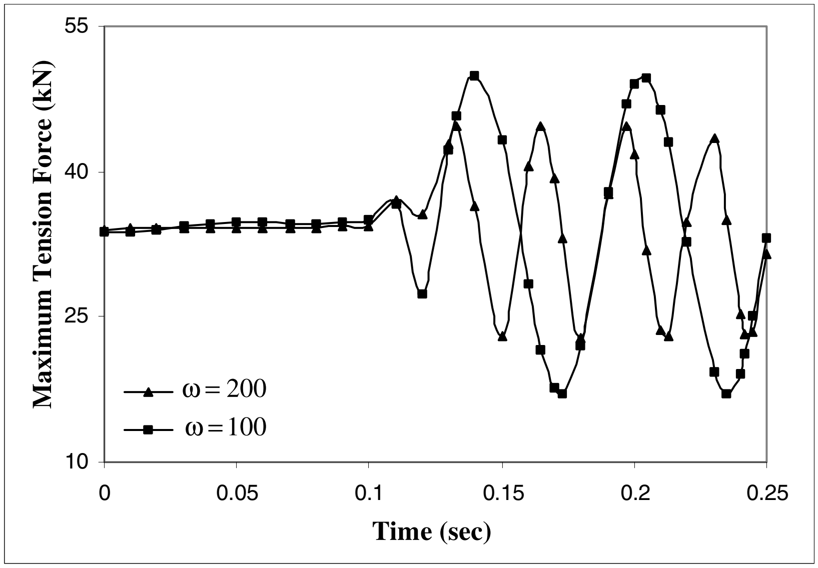

Fig. 6 Effect of loading frequency on maximum tension force in middle nail

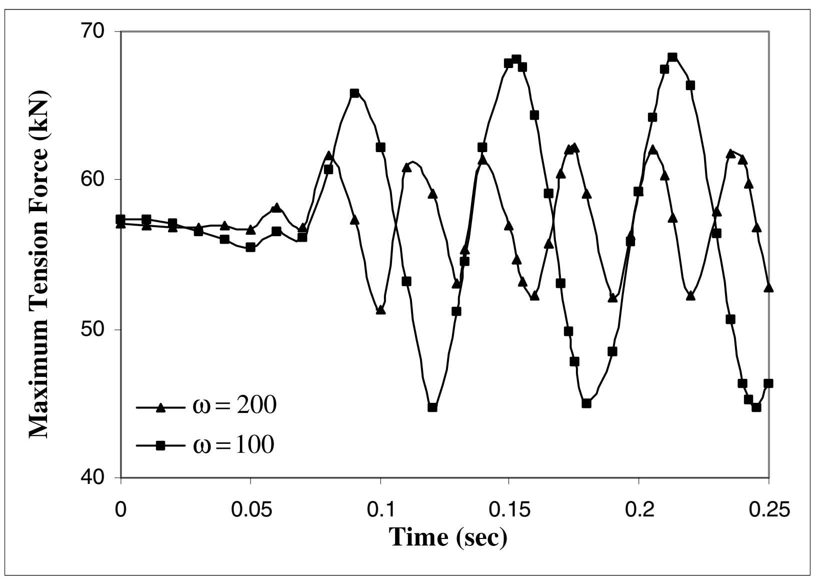

Fig. 7 Effect of loading frequency on maximum tension force in lower nail

As seen, in Figs. 5 to 7, as the frequency increases, the maximum tension force in each nail decreases as expected. The nails have no enough time to respond a quick loading. Thus smaller forces are induced into the nails.

The effect of horizontal acceleration coefficient on maximum tension force in the middle nail is illustrated in Fig. 8. As seen, with increasing k_h, the maximum tension force in the middle nail increases as expected.

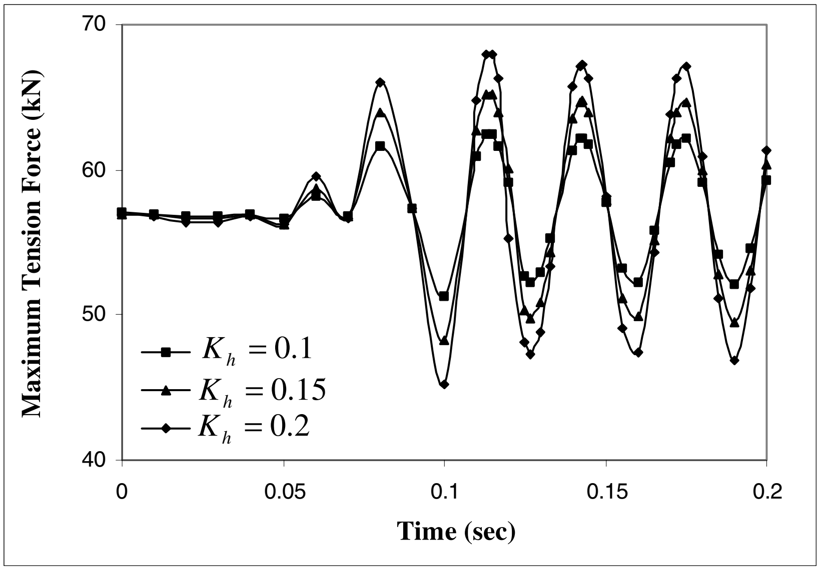

Fig. 8 Effect of horizontal acceleration coefficient on maximum tension force in middle nail

CONCLUSIONS

A working-stress pseudo-dynamic design method for stability of nailed slopes has been presented in this paper. The work is the extension of an available static analysis of mass. Log-spiral shape has been assumed for the failure surface. The slope has been divided into some slices in which a nail exists. Kotter's equation is used to compure the normal soil stress along the failure surface. The mobilized nail forces arec determined by satisfying the horizontal equilibrium of forces acting on each nailed slice. Two invo;ved kinematical parameters namely inclination angles of the failure surface at the top and the bottom of the reinfoced soil mass are determined by satisfying the moment equilibrium condition. The analysis method was verified using available experimental data in static conditions. Parameteric studies show that with increasing loading frequency and horizontal acceleration coefficient, the maximum tension force in nails increase.

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