Soil Dynamics and Earthquake Engineering 98 (2017) 101–119

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Experimental study on seismic response of soil-nailed walls with permanent facing

Majid Yazdandoust

Department of Civil Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran

ARTICLE INFO

Keywords:
Soil-nailed wall
Damping ratio
Shear stiffness modulus
Seismic earth pressures
Nail axial force

ABSTRACT

A series of 1-g shaking table tests were performed on five reduced-scale soil-nailed wall models to investigate the influence of peak acceleration, loading duration, and nail length on seismic response of the soil-nailed walls in terms of the distribution of shear modulus *(G)* and damping ratio *(D)* in soil-nailed mass, the axial force distribution along the nails and the distribution of dynamic lateral earth pressure behind the surface. It was found that the seismic response of walls highly depends on the length of nails and input motion parameters. By introducing a new non-dimensional parameter (G_{global}) for soil-nailed walls, it was observed that the values of G, G/G_0, and D are strongly dependent of confining pressure, L/H ratio, and shear strain levels, so that the variation trend of these parameters with γ is well expressed as an exponential equation with a high correlation coefficient. Additionally, a proper convergence was found between $T_{max}/H.\gamma_s.S_V.S_H$ and L/H ratio at different levels of acceleration and duration, so that $T_{max}/H.\gamma_s.S_V.S_H$ can be defined as a function of L/H ratio and seismic parameters for different rows of nail. Also, It was discovered that the values of predicated earth pressure by conventional methods in static and seismic conditions are too conservative and these methods predict the location of the resultant lateral earth pressure higher than the actual point.

1. Introduction

Soil nailing is an earth retention technique using grouted tension-resisting steel elements that can be used to retain excavations and stabilize steep cut slopes under static and seismic conditions. Ease of implementation, economic efficiency, and appropriate performance of soil-nailed structures have caused their use rapidly spread universally in temporary and permanent applications in the past decades.

The case histories and post-earthquake investigations show that soil nail walls have performed well during strong ground motions in contrast with the generally poor performance of gravity retaining structures [1,2]. After the 1989 Loma Prieta, 1995 Kobe and 2001 Nisqually earthquakes, it was reported that soil nail walls showed no sign of distress or significant permanent deflection, despite having experienced, in some cases, ground accelerations as high as $0.7g$ [3,4]. These observations indicate that soil nail walls appear to have an inherent satisfactory seismic response. This has been attributed to the intrinsic flexibility of soil nailed systems and possibly to some conservative assumptions in the existing design procedures.

Various research methods have been applied to better understand the static and seismic performance of soil-nailed structures in recent years, including field studies [5–12], experimental studies of full-scale structures [13], experimental studies of reduced-scale models [14–27] and numerical analysis [28–34]. Additionally, analytical models such as the limit analysis [35–37] and the limit equilibrium [38,39] have been developed.

The first field study was performed by Stocker et al. [40] on nearly vertical nailed cuts in cohesion less soil of 18 m height. Felio et al. [41] investigated the performance of nine different soil-nailed excavations in the San Francisco Bay area during the Loma Prieta earthquake. None of excavations showed any signs of movements or similar distress, even thought one of them was located in the vicinity of the earthquake epicenter where there was strong shaking. It was concluded that a combination of conservative design and construction is the primary reason for excellent seismic stability. It was also confirmed that the method developed by seismic codes for calculating the factor of safety is suitable for stability analysis of the soil-nailed excavations in seismic conditions. A study was performed by Jacobsz and Phalanndwa [42] based on three instrumented soil-nails in a wall of 10 m height in Pretoria. The results showed that the maximum axial forces in the top soil nail stabilized at approximately two thirds of the load calculated using a simple failure wedge analysis. Also, it was found that soil nail loads were not mobilized gradually, but in distinct load increments.

So far, few experimental studies on full-scale models of soil-nailed walls have been done. A full-scale model test was performed by Li et al. [43] on the soil-nailed loose fill slope that was constructed with 4.75 m

E-mail address: mj.yazdandoust@srbiau.ac.ir.

http://dx.doi.org/10.1016/j.soildyn.2017.04.009
Received 10 February 2017; Received in revised form 4 April 2017; Accepted 5 April 2017
Available online 14 April 2017
0267-7261/

Nomenclature

a_i	acceleration within ith horizontal slice
A_i	shear plane area of ith slice
C_c	coefficient of curvature
C_u	coefficient of uniformity
D	damping ratio
D_r	relative density
D_{cyci}	cyclic component of horizontal displacement of ith slice
f_f	fundamental frequency
G	shear stiffness modulus
G_0	initial shear stiffness modulus
G_{global}	global shear stiffness modulus of soil-nailed wall
G_s	specific gravity
h_i	thickness of ith slice
H	wall height
i	index showing number of slice
K_{AE}	total (i.e. dynamic and static) earth pressure coefficient
L	reinforcement length
m_i	mass of ith slice
N	scale factor between prototype and physical model
R	location of the resultant lateral force
S_H	horizontal spacing between reinforcement
S_V	vertical spacing between reinforcement
T_{max}	maximum mobilized tensile force
T_0	nail head force
V_S	shear velocity of soil
W	maximum stored elastic energy per cycle
γ	shear strain
γ_d	dry unit weight of soil
γ_i	average shear strain of ith slice
γ_s	unit weight of soil
$\gamma_{wet.}$	moist unit weight of soil
Δx	lateral displacement of facing
ΔK_{AE}	incremental dynamic earth pressure coefficient
ΔW	energy loss per cycle
$\Delta\sigma_{AE}$	incremental dynamic earth pressure
λ	governing parameter
σ_v	confining pressure
σ_{AE}	total (i.e. dynamic and static) earth pressure
τ_i	average shear stress along base of ith slice
φ_{max}	maximum internal friction angle
$\varphi_{ult.}$	ultimate internal friction angle
ψ	dilation angle
ω	moisture content

high, 9 m wide, and 33° to the horizontal. Performance of the nailed slope was monitored with various instruments for about six months until the slope was tested to fail by surcharging and wetting. The overall results showed that soil nailing with a surface grillage is a potentially effective way to enhance the stability of old fill slopes.

Among the geotechnical laboratory techniques, centrifuge modeling has been effectively used to explore the deformation and failure behavior of soil-nailed structures under various loading conditions through producing an equivalent gravity-induced stress field between the model and prototype. One of the first centrifuge model studies was performed by Shen et al. [44] on the soil-nailed walls in sand. The information obtained from this research indicated that centrifuge model testing is a useful tool for investigating the stability of earth structures particularly in the absence of prototype failure records. Tufenkjian and Vucetic [45] used dynamic centrifuge model tests to investigate failure mechanism of soil-nailed excavations. They found that longer nails provide improved stability against seismic loading and models with the ratio of length to height (*L/H*) higher than 0.6 show favorable performance under cyclic loading. Wang et al. [46] performed a series of dynamic centrifuge model tests to compare the seismic response of nail-reinforced and unreinforced slopes under earthquake conditions. The nails were discovered to not only significantly decrease the deformation with more uniform distribution within the slopes, but also to arrest the possible failure that would occur in unreinforced slopes. Jacobsz [47] pointed out that the measured nail forces in the centrifuge are conservative due to the mobilization of a portion of the shear strength of the model soil during the acceleration of the centrifuge, leaving less un-mobilized shear strength available to resist loads resulting from the excavation. Rotte and Viswanadham [48] studied the effect of facing type on the stability and deformation behavior of soil-nailed slopes by centrifuge model tests. It was observed that the slope facing prevents the local failure of the soil between the nails. Moreover, soil-nailed slopes without facing were found to experience face failure due to bearing failure of the soil beneath soil-nail heads.

Nowadays a significant amount of research on soil-nailed structures using shaking tables can be found in the literatures. A series of reduced-scale 1-g shaking table tests were performed on five model slopes with different nail angles and nail lengths under different frequency of excitation by Hong et al. [49]. Experimental results showed that nails markedly improve the seismic resistance of all steep model slopes, in the sense that the nailed slopes exhibit characteristics of ductility under strong excitation. Additionally, it was observed that the failure surface of the soil mass is approximately a bilinear surface and the pullout the lower rows of nails causes total slope failure. On the other hand, they pointed out that the angle of the nails influences the deformation of the slope but only slightly affects seismic resistance. Giri and Sengupta [50] and Sengupta and Giri [51] used shaking table tests on small scale nailed embankment slopes to study the effect of slope angle, slope height and nail inclination on their behavior under dynamic conditions. The results indicated that the failure surfaces are shallow and rotational type, so that the mass movement and size of possible failure wedges decrease with a decrease in loading cycles. Other results of these tests showed that the nail forces and amplification of motion increase with increasing in slope steepness and slope height. They also suggested that the nails oriented in the horizontal direction to be more efficient. To examine the seismic stability of existing bridges which have been reinforced by nailing, a series of shaking table tests were performed in 1-g by Tatsuoka et al. [52]. The results indicated that the seismic stability of existing conventional-type bridges increases substantially by nailing the intact and the supporting ground with large-diameter nails connected to the top and the bottom of the abutments.

In this study, the duration and peak acceleration of excitation and the nail length were varied to examine their effects on the seismic response of the soil-nailed walls using a series of reduced-scale uni-axial shaking table tests. For this purpose, first, in order to select appropriate materials for use in foundation and intact zone of models, a series of direct shear and triaxial tests were performed. Also, to select the best superseded element to be used instead of traditional nails and surface in reduced-scale models, some pullout and flexural tests were conducted. Then, the five soil-nailed wall models were constructed with different nail lengths and were loaded to failure using a variable-amplitude harmonic excitation with different durations and peak accelerations. The quantitative and qualitative responses of the walls to base shaking in terms of the distribution of shear modulus *(G)* and damping ratio *(D)* in soil-nailed mass, the axial force distribution along the nails and the distribution of dynamic lateral earth pressure behind the surface are identified and presented.