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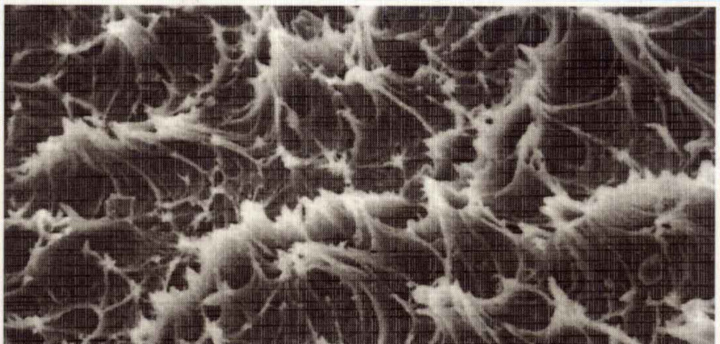

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A collection of papers from the journals

Soil Dynamics and Earthquake Engineering
Computers and Geotechnics
International Journal of Rock Mechanics and Mining Sciences
Tunnelling and Underground Space Technology
Geotextiles and Geomembranes
Journal of Terramechanics

2000

2002
AMSTERDAM – BOSTON – LONDON – NEW YORK – OXFORD – PARIS
SAN DIEGO – SAN FRANCISCO – SINGAPORE – SYDNEY – TOKYO

ELSEVIER SCIENCE Ltd
The Boulevard, Langford Lane
Kidlington, Oxford OX5 1GB, UK

First edition 2002

Library of Congress Cataloging in Publication Data
A catalog record from the Library of Congress has been applied for.

British Library Cataloguing in Publication Data
A catalogue record from the British Library has been applied for.

ISBN: 0-08-044095-9

∞ The paper used in this publication meets the requirements of ANSI/NISO Z39.48-1992 (Permanence of Paper).
Printed in The Netherlands.

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PREFACE

This compendium is made up of a selection of the best and most representative papers from a group of Elsevier's geotechnology journals. Selections were made by the journals' Editorial teams.

The papers all appeared during 2000 and we hope they will provide a useful snapshot of the field for researchers, students and practitioners.

The journals from which papers have been selected and their Editors are:

Soil Dynamics and Earthquake Engineering *L. Finn, M. Erdik*
Computers and Geotechnics, *G. Pande, S. Pietruszczak*
International Journal of Rock Mechanics and Mining Sciences *J. Hudson*
Tunnelling and Underground Space Technology *R. Sterling, E. Broch, J. Zhao*
Geotextiles and Geomembranes *R. K. Rowe*
Journal of Terramechanics *G. Blaisdell, S. A. Shoop, P. W. Richmond*

Each paper appears in the same format as it was published in the journal; citations should be made using the original journal publication details.

It is intended that this compendium will be the first in a series of such collections. A compendium has also been published in the area of structural engineering-
(ISBN: 0-08-044038-X)

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Geotechnology Compendium I

Energy dissipating restrainers for highway bridges

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Accepted 25 September 1999

Communicated by A. Cakmak

Abstract

Recent destructive earthquakes have demonstrated the vulnerability of highway bridges to collapse due to excessive movement beyond the available seat widths at expansion joints. This paper investigates the efficacy of using energy dissipating restrainers at expansion joints for preventing collapse of highway bridges in the event of a severe earthquake. The restrainer consists of a nonlinear viscous damper and an elastic spring connected in parallel or in series. Two-dimensional finite element analysis using bilinear hysteretic models for bridge substructure joints and nonlinear gap elements for expansion joints is performed on example bridges with one or two expansion joints. The analytical study demonstrates that the energy dissipating restrainers are effective in reducing the relative opening displacements and impact forces due to pounding at the expansion joints, without significantly increasing ductility demands in the bridge substructures. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Bridge; Expansion joint; Energy dissipating; Restrainer; Earthquake

1. Introduction

Following the 1971 San Fernando earthquake, the California Department of Transportation (Caltrans) identified 1250 bridges as having vulnerable expansion joint hinges susceptible to collapse due to seismic response beyond the available seat widths [1,2]. To prevent unseating, these bridges have been retrofitted with restrainers made of steel rods or cables under Caltrans' phase I retrofit program. These restrainers are typically designed to work statically, rather than dissipate energy dynamically [3]. Post-earthquake evaluations from recent earthquakes have shown several cases where the restrainers failed. The partial collapse of the Gavin Canyon Undercrossing during the 1994 Northridge earthquake is one of the examples [4,5].

Use of energy dissipation devices as restrainers for expansion joints was proposed by one of the authors immediately following the1994 Northridge earthquake. In the previous studies performed by her and her associates, effort was made to demonstrate that linear viscous dampers are in principle effective in reducing the displacement at expansion joints [6–9]. They focused on the Gavin Canon Undercrossing and pounding effects at the expansion joints were not considered in the analysis. In this study, nonlinear viscous dampers combined with elastic springs in parallel or in series are examined. Two general models representing typical Caltrans bridges built with expansion joints were considered for nonlinear response analysis [10]. The nonlinearities include yielding of columns, pounding of adjacent bridge frames at expansion joints, and nonlinear characteristics of the energy dissipating restrainers. The SAP2000/Nonlinear finite element computer code was used for the two-dimensional (longitudinal and vertical directions) seismic response analysis of the bridges involving nonlinearities [11].

2. Analytical models of bridges and energy dissipating restrainers

It is typical of California highway bridges with more than four spans to have expansion joints located nearly at inflection points (i.e. 1/4 to 1/5th of spans) to allow for thermal expansion. The bridge superstructures consist of reinforced or prestressed concrete box girders. Two typical Caltrans bridges with expansion joints are chosen in this study.

* Corresponding author.

Reprinted from *Soil Dynamics and Earthquake Engineering* **19 (1)**, 65-69 (2000)

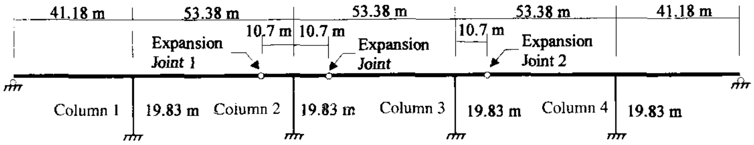


Fig. 1. Elevation of example bridges.

1. Model TY1H: five span bridge with one expansion joint.
2. Model TY2H: five span bridge with two expansion joints.

The geometry and boundary conditions of bridge models are shown in Fig. 1. The material and cross-sectional properties of the models are as follows: Young's modulus = 27.79 GPa, mass density = 2.40 mg/m^3, cross-section area and moment of inertia of the box girders are, respectively 6.936 m^2 and 4.787 m^4, and 4.670 m^2 and 1.735 m^4 for columns. These bridges have dominant horizontal vibration modes with periods of 0.5–1.0 s in each isolated frame separated by expansion joints.

The bridges are modeled with the SAP2000/Nonlinear finite element computer program. The nonlinearities involved in the bridge analytical model are depicted in Fig. 2(a). The plastic hinge formed in the bridge column is modeled as a hysteretic model. The expansion joint is constrained in the relative vertical movement, while allowing horizontal opening movement and rotation. The closure at the joint, however, is resisted by a linear impact spring with stiffness of 100 MN/m once the movement exceeds the initial gap width of 2.54 cm.

The energy dissipating restrainers examined in this study are nonlinear viscous dampers with the damping exponent of 0.5 combined with elastic springs in parallel or in series. The nonlinear viscous damper, whose force–velocity and force–displacement relationships are given in Fig. 2(b), is considered since it can prevent itself from generating excessively large force at large velocity and also dissipate larger energy at small velocity, compared with a linear viscous damper. The restrainers are installed at expansion joints between two adjacent bridge frames.

3. Results of nonlinear analysis

3.1. Input ground motions and restrainer parameter values

Four seismic ground motion, each with two components, are used as inputs for the two-dimensional simulation analysis. They are recorded during the El Centro earthquake (NS-component, UD-component, 1940), the Taft earthquake (N21E-component, UD-component, Lincoln School Tunnel, 1952), the Loma Prieta (EW-component, UD-component, Dumbarton Bridge, 1989) and the Northridge earthquake (NS-component, UD-component, Newhall, 1994). The horizontal components of the original accelerations were linearly scaled so that their PGAs are 0.70 g in accordance with the maximum PGA in the seismic design spectra used by Caltrans. The vertical components of these ground motions are scaled accordingly. These selected motions represent a variety of earthquakes with different durations and frequency components.

Twenty-one different values of spring constant k as well as damping coefficient c are chosen. For the restrainers with the damper and the spring connected in parallel, the parameter values are in the ranges $0 \le k \le 3.5 \times 10^4$ kN/m and $0 \le c \le 3.5 \times 10^4$ kN s/m, while those connected in series are, $0 \le k \le 10.0 \times 10^5$ kN/m and $0 \le c \le 3.5 \times 10^4$kN s/m. Totally, 441 cases were analyzed for each model bridge and each earthquake input.

3.2. Relative displacements at expansion joints

Table 1 lists peak opening displacement at expansion

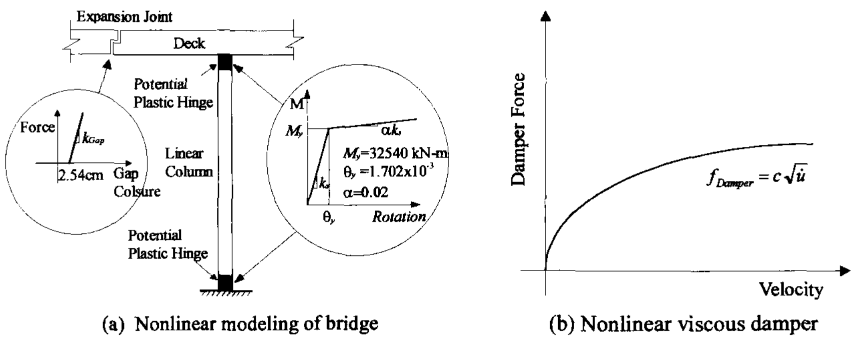


Fig. 2. Nonlinear models. (a) Nonlinear modeling of bridge; (b) Nonlinear viscous damper.

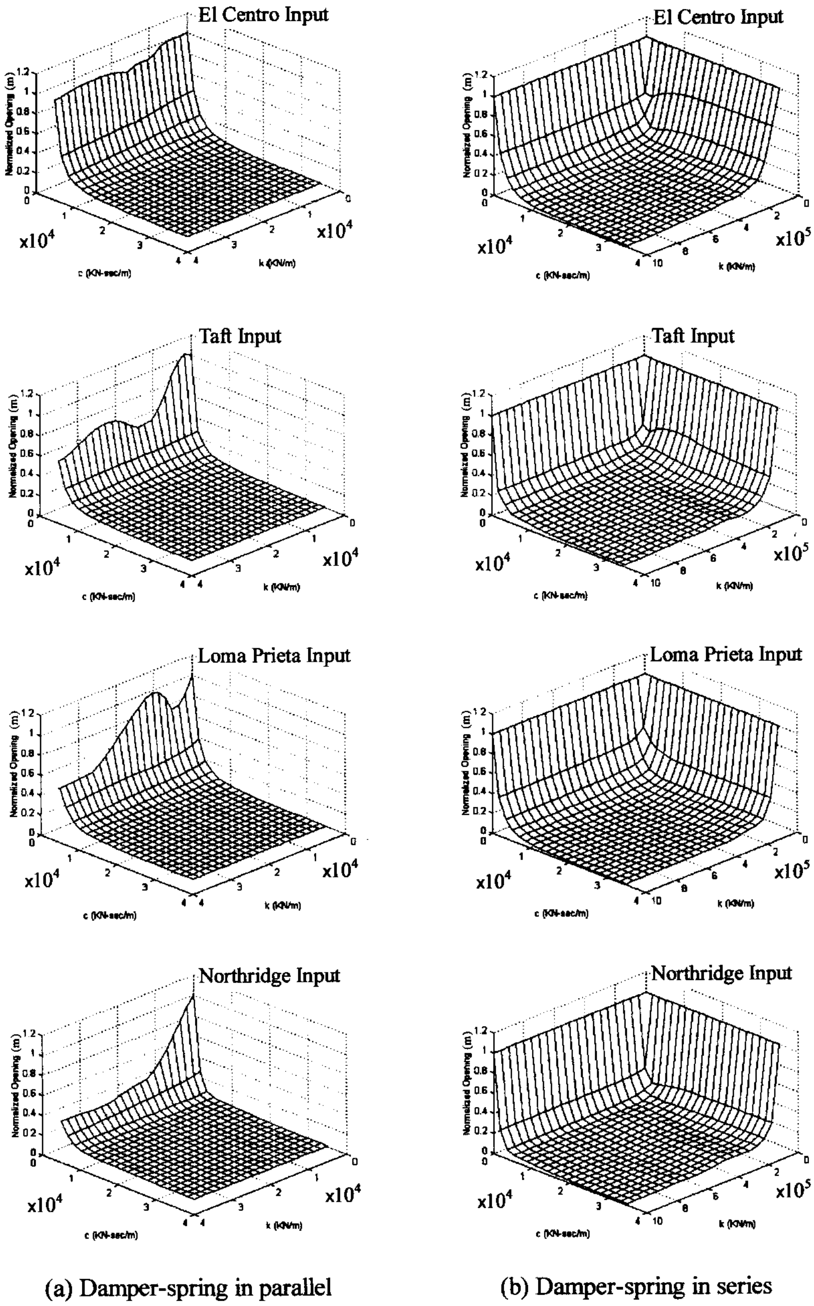


Fig. 3. Normalized peak opening displacements for bridge TY1H: (a) damper–spring in parallel; (b) damper–spring in series.

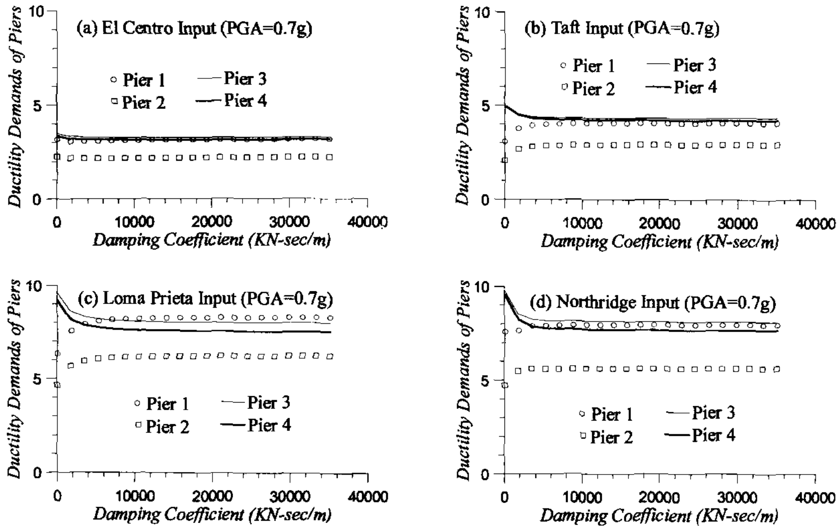


Fig. 4. Ductility demands in columns of bridge TY1H.

joints of the bridges without the energy dissipating restrainers installed under different earthquake ground motions. Normalized peak opening displacements at the expansion joints protected by the restrainers are plotted in Fig. 3 for bridge TY1H. The displacement values are normalized with respect to the peak openings without the restrainers.

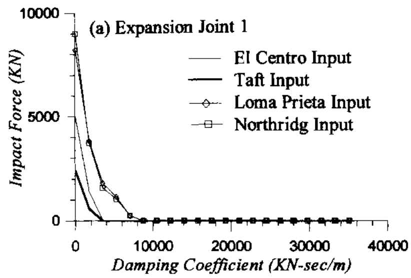
For all the earthquake ground motions, the trends of the relative opening displacements at the expansion joints are quite similar for each type of restrainers. For the first type of restrainer, where the nonlinear damper and elastic spring are connected in parallel (with results shown in Fig. 3(a)), the effect of spring stiffness k on the peak relative displacement is not as pronounced as the effect of damping coefficient c. Particularly, when c is large the effect of elastic spring on the relative displacement is almost diminished. This suggests that the nonlinear viscous dampers are far more effective than the elastic springs (which are, in fact, the current steel cable/rod restrainers used in seismic retrofit of California bridges) in reducing the relative displacement at the expansion joint. Also, the nonlinear viscous damper alone can serve the purpose of the restrainer. For the second type of restrainer where the damper and the spring are connected in series (with results shown in Fig. 3(b)), the larger the damping coefficient c and the spring stiffness k, the more effective the restrainer becomes.

3.3. Ductility demands in bridge substructures and impact forces

The effect of energy dissipating restrainers at the expansion joints on the bridge substructure performance is also examined. The ductility demands in the four columns of bridges TY1H are calculated and plotted in Fig. 4 as functions of the damping coefficient c under the four earthquakes. In this case, the elastic spring in the restrainer is eliminated, as it does not significantly contribute to the control of the opening displacement at the expansion joints as shown in Fig. 3(a). The ductility demand is defined as the ratio of plastic hinge rotation (θ) at the bottom of column to the yield rotation of the nonlinear spring (θ_y). Although the restrainer increases the ductility demand in columns 1 and 2 of bridge TY1H, it actually decreases the ductility demand in the rest of the columns. The ductility demands in all the columns approach a constant regardless of an increase of the damping coefficient, since the viscous dampers work to equalize the absolute horizontal displacement of the superstructures. More importantly, the maximum ductility

Table 1
Peak opening displacements at expansion joints without restrainers(the peak ground acceleration of scaled motion for the inputs is 0.70 g)

Bridges		El Centro Input (cm)	Taft Input (cm)	Loma Prieta Input (cm)	Northridge Input (cm)
TY1H		7.6	14.0	17.9	18.4
TY2H	Joint 1	29.0	21.8	40.4	49.4
	Joint 2	32.0	19.7	42.6	30.2



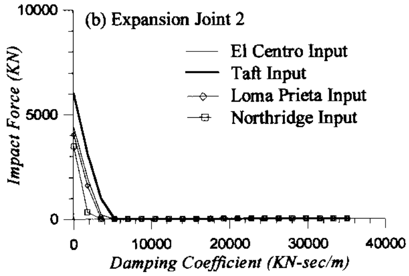


Fig. 5. Impact forces at expansion joints of bridge TY2H.

demand, among all the four columns, is associated with column 3 under the Loma Prieta earthquake when there is no restrainer installed ($c = 0$). Therefore, for this bridge with an identical cross-section for all the columns, the energy dissipating restrainer does not increase the maximum ductility demand in the columns. Similar observations can be made for bridge TY2H.

Fig. 5 plots the impact forces at the expansion joints 1 and 2 due to pounding of adjacent bridge frames of bridge TY2H under different earthquake ground motions, as functions of damping coefficient c and spring constant k. Again, elastic springs are not used for the restrainers in this analysis. The impact forces decrease substantially with increase of the damping in the restrainers. The same observations can be made for bridge TY1H. Therefore, the energy dissipating restrainers can significantly reduce the impact forces due to pounding, thus protecting the expansion joints from damage during severe earthquakes.

4. Conclusion

The efficacy of using energy dissipating devices consisting of nonlinear viscous dampers and elastic springs as restrainers for expansion joints of highway bridges is examined in this study through finite-element seismic response analysis. The nonlinearities of viscous dampers, plastic hinges of bridge substructures and pounding at the expansion joints are considered in the analysis. The results indicate that the nonlinear viscous dampers are significantly effective both in limiting the relative opening displacements and in reducing pounding forces at the expansion joints, without significantly increasing ductility demands in bridge substructures. The elastic springs, which are basically the current restrainers used in seismic retrofit of older bridges in California and elsewhere, are far less effective than the nonlinear viscous damper. Therefore, use of nonlinear viscous dampers at expansion joints is recommended. For older bridges with insufficient seat widths the dampers can be installed as restrainers for seismic retrofit purposes, while for newer bridges the dampers can be used to improve seismic performance including reducing the negative effects of pounding at the expansion joints.

Acknowledgements

This study is supported by the National Center for Earthquake Research under the auspices of Federal Highway Administration (Contract No. DTFH61-92-C-00106) and the National Science Foundation (Grant No. CMS-9501796)

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Seismic stability analysis of reinforced slopes

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Accepted 27 January 2000

Abstract

In this paper, the seismic stability of slopes reinforced with geosynthetics is analysed within the framework of the pseudo-static approach. Calculations are conducted by applying the kinematic theorem of limit analysis. Different failure modes are considered, and for each analytical expressions are derived that enable one to readily calculate the reinforcement force required to prevent failure and the yield acceleration of slopes subjected to earthquake loading. Several results are presented in order to illustrate the influence of seismic forces on slope stability. Moreover, a suitable procedure based on the assessment of earthquake-induced permanent displacement is proposed for the design of reinforced slopes in seismically active areas. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Seismic stability; Reinforced slope; Yield acceleration; Permanent displacement

1. Introduction

Construction of earth structures reinforced with geosynthetics has expanded extensively in the last twenty years, also in seismically active areas. Although severe damage was not observed during recent strong earthquakes [1–3], the performance of these structures under seismic loading is not fully known. This is due mainly to the almost absolute lack of well-documented case histories with specific regard to the properties of soil and reinforcement, earthquake characteristics and measurement of deformations earth structures undergo. Several studies have been, on the contrary, conducted on reduced-scale models using shaking table tests [4,5]. However, due to modelling limitations the results found are not often very meaningful when seeking to deduce the seismic performance of full-scale prototype structures from that of reduced-scale physical models.

To date, the theoretical approach is the most widely used to analyse seismic stability of reinforced earth structures. In the last few years, several analytical methods have been formulated and many parametric studies have been carried out to show the importance of the main design parameters [6–8]. The finite element method is certainly the most comprehensive approach to analyse the performance of soil structures subjected to seismic loading. However, its use usually requires high numerical costs and accurate measurements of the properties of the component materials, which are often difficult to achieve. In addition, further difficulties arise with modelling failure in frictional materials [9]. This makes use of the finite element method not very attractive for current applications. Finite difference techniques have also been employed for seismic analysis of reinforced structures [6,10].

The majority of the methods used by practitioners are based on the pseudo-static approach where the effect of earthquake on a potential failure soil mass is represented in an approximate manner by a static force acting in the horizontal direction. The stability of the soil structure under this force is expressed by a safety factor that is usually defined as the ratio of the resisting force to the destabilising force. Failure occurs when the safety factor drops below one. The most common technique used for design is the limit equilibrium method. Many studies were conducted using this method, where the failure surface was assumed to have differing geometry [7,11–13]. In order to solve a limit state problem, limit analysis is also an effective methodology. Michalowski [8] has recently applied the kinematic theorem of limit analysis to calculate the reinforcement strength and length necessary to prevent collapse of earth structures, under the assumption that the reinforcement strength is uniformly distributed through the slope height or linearly increasing with depth. The solution proposed by Michalowski [8] should be used when a large number of reinforcement layers is installed. In the above studies, design charts have been presented to determine the reinforcement requirements for simple slopes.

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Reprinted from *Soil Dynamics and Earthquake Engineering* **19 (3)**, 159-172 (2000)

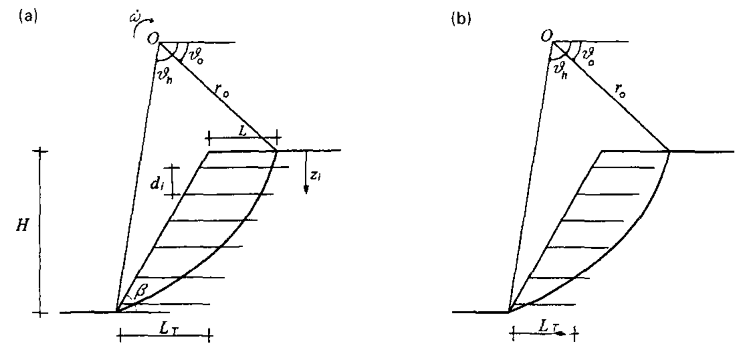

Fig. 1. Rotational slope failure mechanism: (a) log-spiral failure surface involving the reinforced zone; and (b) log-spiral failure surface extending within and beyond the reinforced zone.

As known, design based on pseudo-static analysis is generally considered conservative, since even when the safety factor drops below one the soil structure could experience only a finite displacement rather than a complete failure. A design procedure based on a tolerable displacement against sliding was proposed by Ling et al. [7]. They employed Newmark's sliding block method to evaluate permanent displacement of reinforced slopes during earthquakes. More recently, the same approach has been extended by Ling and Leshchinsky [14] to include the vertical component of ground acceleration.

In the present study, the kinematic theorem of limit analysis is applied to calculate both the forces required to ensure the stability and the yield acceleration for slopes reinforced with a discrete number of geosynthetic layers. Different possible failure mechanisms are considered, and for each of them analytical expressions that allow the above design parameters to be determined are derived. Comparisons of results obtained in this study to those existing in literature are shown, and the most significant differences are indicated. Results are also presented in order to illustrate the effect of seismic force on stability of reinforced earth structures. Finally, a suitable procedure based on the assessment of earthquake-induced permanent displacement is proposed for the design of reinforced slopes subjected to earthquakes.

2. Method of analysis

The kinematic theorem of limit analysis is applied here to analyse the stability of reinforced slopes under seismic loading. This theorem state that a slope will collapse if the rate of work done by external loads and body forces exceeds the energy dissipation rate for any assumed kinematically admissible failure mechanism. Applicability of the theorem requires that soil will be deformed plastically according to the normality rule associated with the Coulomb yield condition.

Following the pseudo-static approach, the effect of earthquake on a potential failure soil mass is represented by a force acting horizontally at the centre of gravity, which is calculated as the product of a *seismic intensity coefficient* and the weight of the potential sliding mass. An appropriate value of the seismic coefficient should be selected to account for possible acceleration amplification that is not implicitly considered in the analysis. The effects of pore pressure build-up and change of soil strength due to earthquake shaking are ignored. The analysis concerns slopes of homogeneous cohesionless soils, where the reinforcement layers are finite in number and have the same length. The reinforcement provides forces acting in the horizontal direction that are given by the tensile strength or pull-out resistance of the layers. As is usually assumed in the case of geosynthetics, resistance to shear, bending and compression is ignored. Under these assumptions, the rate of external work is due to soil weight and inertia force induced by earthquake and the only contribution to energy dissipation is that provided by the reinforcement.

The possible failure modes considered in this work are illustrated in Figs. 1–3. Specifically, Fig. 1 shows a rotational mechanism involving a log-spiral failure surface passing through the toe of the slope which may extend within (Fig. 1a) and also beyond (Fig. 1b) the reinforced zone. Moreover, the simple failure mechanism of Fig. 2 is also analysed, where the soil mass translates as a rigid body along a planar surface. Finally, in the mechanism schematised in Fig. 3, the reinforced soil mass slides over the

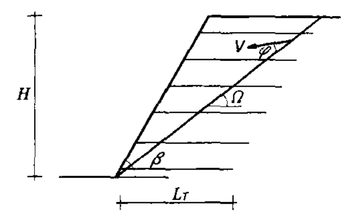

Fig. 2. Translational slope failure mechanism.