Soil Dynamics and Earthquake Engineering 65 (2014) 11–29

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Predictive model of Arias intensity and Newmark displacement for regional scale evaluation of earthquake-induced landslide hazard in Greece

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ARTICLE INFO

Article history:
Received 8 November 2013
Received in revised form
18 May 2014
Accepted 25 May 2014

Keywords:
Newmark displacement
Arias intensity
Attenuation relation
Earthquake-induced landslides
Greece

ABSTRACT

Defining the possible scenario of earthquake-induced landslides, Arias intensity is frequently used as a shaking parameter, being considered the most suitable for characterising earthquake impact, while Newmark's sliding-block model is widely used to predict the performance of natural slopes during earthquake shaking. In the present study we aim at providing tools for the assessment of the hazard related to earthquake-induced landslides at regional scale, by means of new empirical equations for the prediction of Arias intensity along with an empirical estimator of coseismic landslide displacements based on Newmark's model. The regression data, consisting of 205 strong motion recordings relative to 98 earthquakes, were subdivided into a training dataset, used to calculate equation parameters, and a validation dataset, used to compare the prediction performance among different possible functional forms and with equations derived from previous studies carried out for other regions using global and/or regional datasets. Equations predicting Arias intensities expected in Greece at known distances from seismic sources of defined magnitude proved to provide more accurate estimates if site condition and focal mechanism influence can be taken into account. Concerning the empirical estimator of Newmark displacements, we conducted rigorous Newmark analysis on 267 one-component records yielding a dataset containing 507 Newmark displacements, with the aim of developing a regression equation that is more suitable and effective for the seismotectonic environment of Greece and could be used for regional-scale seismic landslide hazard mapping. The regression analysis showed a noticeable higher goodness of fit of the proposed relations compared to formulas derived from worldwide data, suggesting a significant improvement of the empirical relation effectiveness from the use of a regionally-specific strong-motion dataset.

1. Introduction

Greece is characterised by high seismicity, which is attributed to its location, on top of the convergence boundary of two lithospheric plates, i.e. the European plate, which is being overthrusted and moves to the southwest, and the African plate which is being subducted and moves towards an approximately north direction. Additionally, as effect of topographic and geological characteristics of its relief, the Greek area is subject to diffuse phenomena of slope instability, which are exacerbated by the high seismic activity. These reasons have resulted in the fact that earthquake-induced landslides have appeared almost everywhere within the Greek territory, with the exception of the north Greek mainland [47]. This makes the estimation of where and in what shaking conditions earthquakes are likely to trigger landslides a key element in hazard assessment. Such estimation comprises an important information which can be used in conjunction with other commonly used factors (e.g. [59,5,6,48,60]) in order to optimise land-use planning and decision-making procedure.

An earthquake can cause a slope to become unstable by the inertial loading it imposes or by causing a loss of strength in the slope materials. One of the shaking parameters that proved to be more representative of the earthquake impact on slope stability is the Arias intensity [4], which is proportional to the total energy transmitted by seismic waves to soil during an earthquake. Thus the estimation of the Arias intensity expected on landslide prone slopes as effect of an earthquake of defined characteristics is useful for a preliminary delimitation of area potentially subject

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http://dx.doi.org/10.1016/j.soildyn.2014.05.009
0267-7261/

to seismically induced mass movements, where a successive more advanced hazard analysis can be worthwhile to be carried out.

A possible successive level of hazard analysis refinement can benefit from simplified models of slope stability analysis under dynamic conditions, which are applicable to regional scale evaluation. Among slope stability models, the permanent-displacement analysis developed by Newmark [46] is often used to derive estimates of coseismic landslide displacements for a given recorded or synthetic accelerogram. Newmark's analysis models the part of the slope which is under stress as a uniform block sliding over an inclined surface. For a known critical acceleration, it calculates the cumulative permanent displacement of the block relative to its base under a given shaking by means of a double integration of its acceleration-time history. Thus, a conventional Newmark analysis requires the selection of an appropriate earthquake record and the determination of the critical acceleration of the investigated slope. This approach has been successfully applied in many cases to evaluate, predict and map earthquake-induced slope displacements (e.g. [70,69,23,49]). However, because strong-motion records at specific sites are not always available, several relations between seismic ground-motion parameters and computed landslide displacements have been developed, avoiding the computational complexity and the difficulties of selecting appropriate earthquake time-histories associated with the conventional Newmark analysis.

In view of providing, relatively to the Greece region, tools for different level of evaluations of the landslide seismo-induction hazard, in the present study we developed empirical relationships to predict expected values both of Arias intensity on landslide-prone slopes and of coseismic landslide displacements according to Newmark's model, as effect of earthquakes of prefixed characteristics. We used a dataset of strong-motion records that incorporates the most recent information available spanning up to mid 2013. For the development of both equations, we separated a subset of records used to obtain the regression coefficients, from a second data sample that we used to compare the effectiveness of different relations in order to select the optimum model. We tried to make both samples as homogeneously distributed as possible over the independent variables adopted in each regression model.

The most general functional form of the new predictive equation for Arias intensity incorporates moment magnitude, epicentral distance, fault plane solution mechanism, and site category. The coefficients of the explanatory variables were calculated by employing a two-step procedure separating the determination of parameters representative of the energy release at source from those accounting for propagation effects. With regard to the empirical estimator of Newmark displacement suitable for the geological and seismotectonic setting of Greece, a rigorous Newmark analysis was conducted on a selected up-to-date dataset of strong ground-motion records. We tested formulas of different forms whose coefficients were computed through multivariate regression analyses. The derived properly calibrated regional relation is expected to considerably improve the effectiveness of the empirical estimator for the Greek area in comparison to equations that have been developed using global datasets. The derived formula allows the estimation of landslide displacement as a function of shaking intensity, quantified by Arias intensity, and critical acceleration for regional earthquake-induced

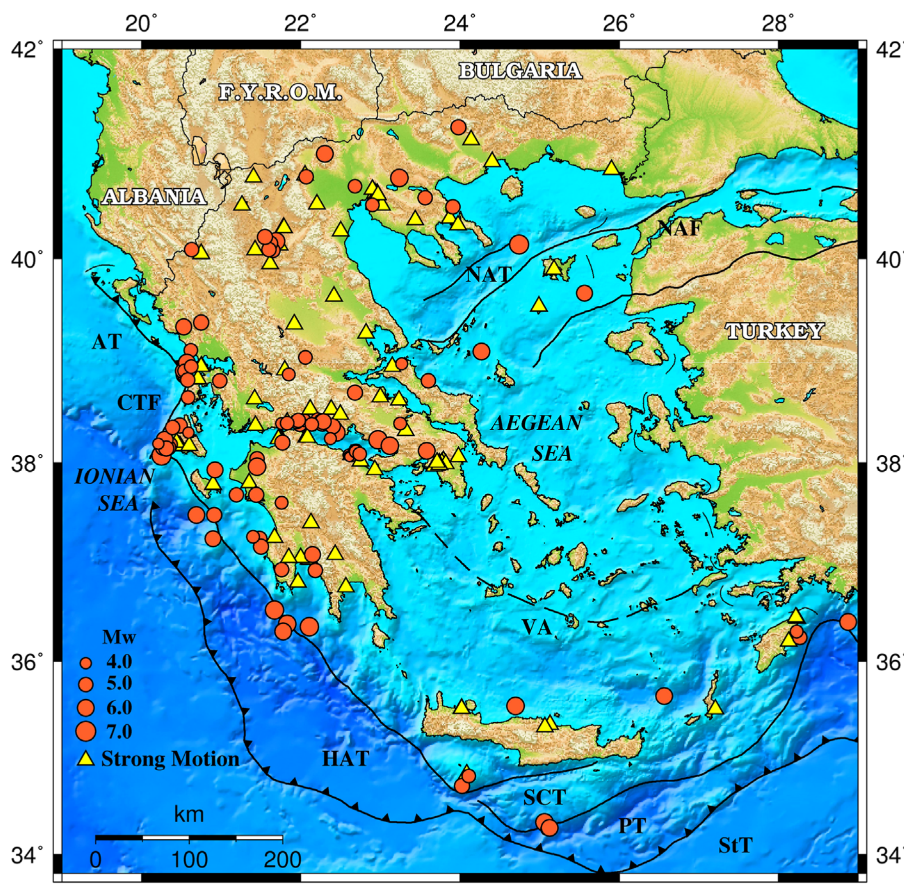

Fig. 1. Epicentre distribution of the earthquakes used in the analyses along with spatial distribution of the Greek strong-motion stations used in the present study. Black lines show the traces of the Hellenic Arc-Trench System (HAT), the Cephalonia Transform Fault (CTF), the Apulian Thrust (AT), the Volcanic Arc (VA) and the North Anatolian Fault (NAF). Also shown the North Aegean Trough (NAT), the South Cretan Trough (SCT), the Pliny Trench (PT) and the Strabo Trench (StT).