Geotextiles and Geomembranes 46 (2018) 470–485

Contents lists available at ScienceDirect

Geotextiles and Geomembranes

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

A performance-based approach to design reinforced-earth retaining walls

D. Gaudio, L. Masini, S. Rampello*

Department of Structural and Geotechnical Engineering (DISG), Sapienza University of Rome, Via Eudossiana 18, 00184, Rome, Italy

ARTICLE INFO

Keywords:
Geosynthetics
Retaining walls
Reinforced soils
Performance-based design
Earthquakes
Pseudo-static analysis

ABSTRACT

This paper describes a pseudo-static approach developed for geosynthetic-reinforced earth (*GRE*) retaining walls, calibrated against given levels of wall performance defined by specified values of earthquake-induced displacements. The *GRE* walls generally show a good performance under severe seismic loading due to the capability of reinforcements to redistribute the deformations induced by the seismic actions within the reinforced zone. This can be achieved by promoting the activation of internal plastic mechanisms involving the reinforcements strength, providing that they are characterised by adequate extensional ductility. In the proposed procedure, the seismic coefficient k to be used in a pseudo-static calculation is assumed equal to the internal seismic resistance of the wall k_c^{int}, related, through the kinematic theorem of limit analysis, to the maximum strength demand of geosynthetic reinforcements. The seismic coefficient is then calibrated against given levels of seismic wall performance, defined by threshold values of earthquake-induced displacements that result by the temporary activation of plastic mechanisms during severe seismic loading. Permanent displacements induced by earthquake loadings are evaluated through empirical relationships based on a parametric integration of a large number of Italian seismic records and are expressed as a function of the critical and the maximum horizontal accelerations. A procedure is finally proposed to conceive a reinforced-earth retaining wall with an internal seismic resistance lower than the external one, so that a prescribed level of seismic performance and the activation of internal mechanisms are ensured during severe seismic shaking.

1. Introduction

Use of geosynthetic-reinforced earth retaining walls (*GRE* walls) has been significantly expanding in the last thirty years also thanks to a number of field observations showing a generally good performance of *GRE* walls when subjected to severe seismic loading (e.g.: Tatsuoka et al., 1996; Wartman et al., 2006; Shinoda et al., 2007; Tatsuoka, 2008a, b; Koseki et al., 2009). These observations are consistent with those resulting from shaking-table experiments on small-scale (Watanabe et al., 2003; El-Eman and Bathurst, 2004, 2005, 2007; Wang et al., 2015; Komak Panah et al., 2015; Yazdandoust, 2017a, 2017b, 2018), full-scale tests (Ling et al., 1997, 2005, 2009, 2010, 2012 Koseki, 2012; Demir et al., 2013; Santos et al., 2013; Riccio et al., 2014), centrifuge tests (Andersen, 1997; Kramer and Paulsen, 2004) and numerical analysis (Clarke et al., 2013; Chen et al., 2013; Liu et al., 2014; Wang et al., 2011, 2014; Masini et al., 2015).

Earthquake-induced damages on *GRE* walls generally consist of permanent displacements that result from the subsequent, temporary activation of plastic mechanisms that develop within and outside the reinforced soil during the seismic event, with an improved seismic performance compared to conventional retaining walls that can only mobilise the shear strength of the surrounding soil.

Seismic performance of *GRE* walls can be studied via effective stress dynamic analyses, displacement-based sliding block analyses or through force-based pseudo-static methods that are more often adopted in common practice. In a pseudo-static approach, the equivalent seismic coefficient that is introduced in the analysis to represent the seismic action should be calibrated against given levels of wall performance that in turn can be defined by threshold values of earthquake-induced displacements. A calibrated pseudo-static representation of seismic wall stability then needs to relate the safety factor and the equivalent seismic coefficient to the maximum expected permanent displacement.

Permanent displacements can be evaluated using Newmark-type displacement analysis (Newmark, 1965) which requires the evaluation of the critical acceleration a_c ($= k_c \cdot g$) that activates the plastic mechanisms and is based on the integration of the relative motion; in this procedure, the seismic motion must be described through acceleration time-histories. However, empirical relationships do exist, based on parametric integration of earthquake records, which relate the maximum expected displacements to selected ground motion parameters and to the critical acceleration: these relationships permit to express the equivalent seismic coefficient as a function of upper-bound

* Corresponding author.
E-mail addresses: domenico.gaudio@uniroma1.it (D. Gaudio), luca.masini@uniroma1.it (L. Masini), sebastiano.rampello@uniroma1.it (S. Rampello).

https://doi.org/10.1016/j.geotexmem.2018.04.003
Received 8 November 2017; Received in revised form 20 March 2018; Accepted 3 April 2018
0266-1144/

displacements induced by earthquake loading.

For a geosynthetic-reinforced structure, limit analysis and limit equilibrium methodologies can be extended to pseudo-static conditions and used iteratively to evaluate the lower, that is the critical acceleration and the associate plastic mechanism among all possible mechanisms that can be activated.

The satisfactory behaviour of *GRE* walls can be ascribed to the overall ductile behaviour deriving from the large deformation that can be accommodated by the soil-reinforcement system, provided that the reinforcements are characterised by a large extensional ductility (Masini et al., 2015). Therefore, according to a performance-based approach, the wall design should promote the activation of internal mechanisms to guarantee the redistribution of plastic deformations within the reinforced zone. In a pseudo-static analysis, this task can be achieved imposing that the critical seismic coefficient associated to internal mechanisms is lower than that associated to external mechanisms, $k_c^{int} < k_c^{ext}$.

In this work, a parametric study is first presented in which the maximum reinforcement strength demand is evaluated as a function of k_c^{int}. The computations are presented in a non-dimensional form to study the role of the different parameters and to generalise the results. The seismic coefficient $k = k_c$ to be used in a pseudo-static calculation for the design of *GRE* walls is then calibrated against prescribed levels of seismic performance using a parametric integration of a set of Italian acceleration time histories. A design approach based on the proposed procedure is finally applied to a reference case to illustrate how a pseudo-static calculation can be calibrated against specified levels of wall performance ($k = k_c^{int}$), and a reinforced-earth retaining wall be conceived with $k_c^{int} < k_c^{ext}$ to promote the activation of internal plastic mechanisms during a severe seismic loading.

2. Problem definition

Fig. 1 shows the problem layout. A fill of height H is retained by an earth structure with a slope β, reinforced with a number n of geogrid layers with constant length L, uniform spacing s, and tensile strength T_T. The fill is made of dry coarse-grained soil with an angle of shearing resistance φ′ and unit weight γ. The resistance at the soil-reinforcement contact is purely frictional with a friction angle $\varphi'_{s/GSY} = \tan^{-1}(f_{s/GSY} \cdot \tan\varphi')$, where $f_{s/GSY}$ is the interface friction factor. The reinforcements provide forces acting in the horizontal direction that result by their tensile or pull-out resistance. Resistance to shear, bending and compression is ignored as typically assumed for geosynthetics. External forces acting on the retaining structure are: the self-weight W, the active pseudo-static earth thrust S_{aE} and the inertial force $k{\cdot}W$ applied at the centre of gravity of the wall. Only the seismic forces induced by a horizontal seismic coefficient k are considered in the following, in that preliminary analyses have shown the vertical seismic coefficient k_v to have a negligible influence on the permanent displacements evaluated by a Newmark-type displacement analysis, as also pointed out by Garini et al. (2011).

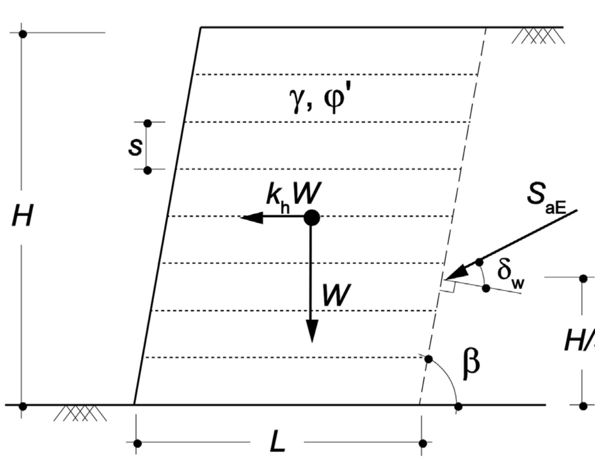

Fig. 1. Schematic layout of the problem.

The stability of the reinforced-earth retaining structure depicted in Fig. 1 is analysed using different kinematic approaches based on limit analysis, assuming no surcharge load applied to the boundaries. Following Ausilio et al. (2000) and Michalowski and You (2000), for a *GRE* wall attaining the limit condition $k_h = k_c$ the kinematic theorem of limit analysis can be written as:

$$\dot{D}(k_t) = \dot{W}_\gamma + \dot{W}_s(k_c) \tag{1}$$

where $\dot{D}(k_t)$ is the rate of internal energy dissipated in the reinforcement layers intersecting a sliding surface; $k_t = \frac{n \cdot T_T}{H}$ is the average strength of the reinforcements; $\dot{W}_\gamma$ is the rate of work done by the soil weight; and $\dot{W}_s(k_h = k_c)$ is the rate of work done by the equivalent inertial force.

Equation (1) can be used to calculate the upper bound to the critical seismic coefficient k_c for a given reinforcement strength k_t, or the lower bound to the reinforcement strength demand k_t for a given k_c. Hence, if the strength capacity of the reinforcements is chosen to be equal to the strength demand, then it is $k_h = k_c$.

Fig. 2 shows the plastic mechanisms considered in this study: mechanisms 2(a) to 2(c) have been already studied in the past (e.g.: Michalowski, 1998; Ausilio et al., 2000; Michalowski and You, 2000), while mechanism 2(d) is introduced in this paper as suggested by results of dynamic analyses obtained in Masini et al. (2015). Fig. 2(a) describes a rotational mechanism in which a portion of the reinforced soil slides along a log-spiral sliding surface that passes through the toe of the structure and either includes only the reinforced zone or extends out of it, to the upper portion of the backfill; in Fig. 2(b) a simple translational mechanism is analysed in which the soil mass slides along a planar surface with slope α to the horizontal; Fig. 2(c) depicts a two-block mechanism, usually referred to as direct sliding, in which one block slides over the lowest reinforcement layer and the inter-block sliding surface BD intersects the reinforced soil; Fig. 2(d) also shows a two-block mechanism, in which the first block is triangular and

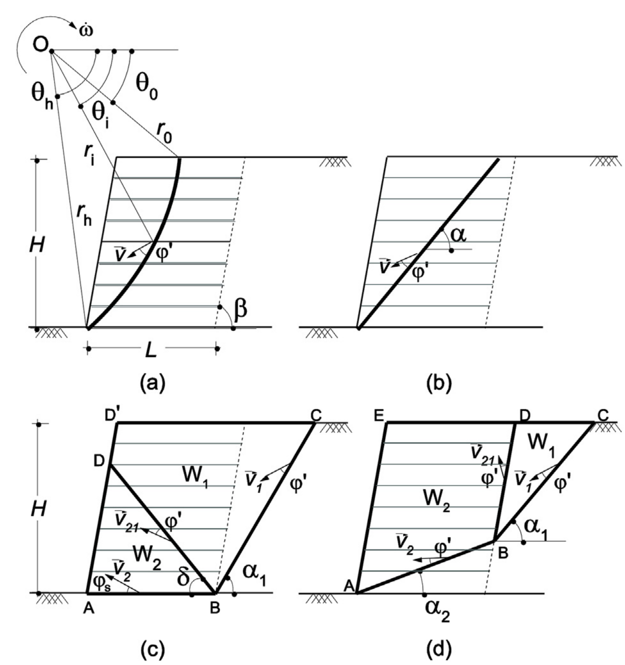

Fig. 2. Plastic mechanisms analysed with the kinematic theorem of limit analysis: (a) log-spiral, (b) planar surface, (c) direct sliding, and (d) two-block mechanism.