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Research Paper

Seismic stability of geosynthetic-reinforced walls with variable excitation and soil properties: A discretization-based kinematic analysis

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ABSTRACT

Seismic stability of vertical slopes is investigated using the discretization-based kinematic analysis, aiming at determining the geosynthetic reinforcement force required for preventing slope failure. The earthquake effect is characterized by spatial and time varying seismic inputs in sinusoidal functions. Two modes of seismic inputs are proposed for describing the 2D rather than 1D spatial effect. Further, the change in cyclic amplitude of the acceleration time-history is incorporated into kinematic analysis. The reinforcement force is formulated from the work rate-based balance equation. The pseudo-static/dynamic solutions are sought and compared. Comparisons are highlighted between the numerical results from three different seismic inputs.

1. Introduction

Vertical cut slopes are common in cut and fill construction particularly in urban settings, where land is scarce. However, these slopes are vulnerable to failure since the stability cannot be resisted on its own without propping in many scenarios. In order to improve slope stability, reinforced structures such as piles and/or geotextiles are installed so as to provide additional resistance. In severe conditions, for instance, earthquake or rainfall, even more resistance is necessitated to balance the driving forces. In this paper, geosynthetics are considered to maintain the stability of vertical soil walls.

The kinematic analysis provides prediction of actual failure load no larger than that calculated from the equilibrium of internal and external rates of work [3]. The efficacy of such an analysis in resolving stability problems is attributed to no stresses involved when considering a linear strength envelope. In order to ensure the kinematical admissibility condition, a log-spiral failure mechanism was proposed and widely applied to slope stability analyses [15,21,22,25,28]. It is noted that this mechanism is a prior assumption with a sound approximation to the actual failure, and only suited to consider a constant friction angle of the soil, thereby unable to account for the variations of friction angle and unit weight in the conventional kinematic analysis. Such a shortcoming was overcome with the use of discretization technique which enables one to generate a kinematically admissible failure mechanism with considerations to non-uniformity of soil parameters. Also, the discretized mechanism facilitates the analyses of slope stability under complex scenarios which cannot be readily dealt with in the conventional limit analysis. This technique was initially applied to generate a two-dimensional (2D) and/or three-dimensional (3D) failure mechanism for active and passive failure of a pressurized tunnel [16,17]. Then, it was further extended to investigate the 3D tunnel face stability in multi-layered soil strata considering varying soil properties [9] and in anisotropic and nonhomogeneous soils [20].

In the presence of an earthquake, a crucial factor is to characterize the seismic input in terms of displacement, velocity or most commonly used acceleration. The actual acceleration time-history is suitable for numerical analyses, but with considerable computational effort consumed in a specific analysis. For the ease of theoretical derivation, a constant acceleration over the entire problem domain is generally assumed in a pseudo-static analysis. Although such an approach has been widely used in slope stability analysis, it is unable to characterize the dynamic earthquake effect and yields overly conservative solutions. A good compromise between computational effort and accuracy is to adopt a pseudo-dynamic approach considering the spatial and time effect. A pseudo-dynamic earth pressure theory was proposed by Steedman and Zeng [27] to account for the influence of phase difference over the height of a vertical retaining wall. This approach recognizes that a base acceleration input will propagate up through the retained soils at a speed that corresponds to the shear velocity of the soil. As presented in publications [2,4,5,18], the sinusoidal functions were used to depict the horizontal and vertical accelerations without accounting for the initial phase difference. The pseudo-dynamic solutions were derived with the limit equilibrium method for investigating the internal and/or external stability of a retaining wall with or without geosynthetics. However, there exist two main drawbacks: (1) the spatial effect is only considered in the vertical direction rather than a 2D case;

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Notations

A_{i1}, A_{i2}	area of ith infinitesimal element
A, B, C	three quantities for a quadratic equation
a_h, a_v	horizontal and vertical seismic acceleration within soil medium
c	average soil cohesion
c_0	soil cohesion at slope toe
c_h	soil cohesion at slope crest
$c(y_i)$	soil cohesion at y_i
f_h, f_v, f	soil amplification factor
f_t	average tensile strength of geosynthetics
f_{ti}	tensile stress distribution of geosynthetics
F_r	reinforcement force of geosynthetics
g	gravity acceleration
h_i	vertical depth from slope toe above
H	slope height
k_h, k_v	horizontal and vertical seismic coefficient
L	distance from starting surface (where $a_h = k_h g$) to the vertical sloping surface for the shear wave propagation
$\overrightarrow{n_i}$ (n_{xi}, n_{Yi})	unit normal vector at point P_i
$\overrightarrow{OP_{i+1}}$	vector from point O to point P_{i+1}
PV	peak amplitude in the acceleration time-history
$\overrightarrow{P_iO}$	vector from point P_i to point O
$\overrightarrow{P_iP_{i+1}}$	vector from point P_i to point P_{i+1}
r_0	initial radius
T_s, T_p	period of shear and primary velocity
t_0	initial phase difference between horizontal and vertical seismic waves
$\overrightarrow{v_i}$ (v_{xi}, v_{yi})	velocity vector at point P_i
$\dot{W}_{D1}$	work rate of internal energy dissipation
$\dot{W}_{D2}$	work rate of geosynthetic reinforcement
$\dot{W}_G$	work rate of soil weight
$\dot{W}_{Gh}$, $\dot{W}_{Gv}$	work rate of seismic forces from soil weight
x_i, y_i	coordinates of point P_i
x_{i+1}, y_{i+1}	coordinates of point P_{i+1}
x_{oi}, y_{oi}	coordinates of gravidity point for trapezoidal element $P_iQ_iQ_{i+1}P_{i+1}$
α, β, ζ	parameters for seismic acceleration input
δ	incremental angle for generation of a potential collapse mechanism
φ	average soil friction angle
φ_0	friction angle at slope toe
φ_h	friction angle at slope crest
φ_i or $\varphi(y_i)$	friction angle at y_i
γ	average soil unit weight
λ_{i+1}	module of vector $\overrightarrow{OP_{i+1}}$
λ_s, λ_p	wave length of shear and primary wave
η_i	angle of inclination of the reinforcement layer to the failure surface
θ_{gi1}, θ_{gi2}	angle between vector $\overrightarrow{OC_i}$ and the ground surface
θ_i, θ_{i+1}	angle between the ground surface and $\overrightarrow{OP_i}$ or $\overrightarrow{OP_{i+1}}$
θ_0	initial angle
μ_v	ratio of vertical acceleration to k_h within soil medium
ω	angular velocity of potential sliding block at failure

and (2) the change in cyclic amplitude of idealized acceleration cannot be simulated for the seismic excitation. A new expression for the horizontal acceleration input is proposed in this study to resolve the first problem. It is well understood that an actual earthquake wave undergoes change in cyclic amplitude. Based on this line of thought, an idealized acceleration time-history was used to simulate the variable-amplitude seismic excitation [8,29]. Combined with the newly proposed horizontal acceleration input, the pseudo-dynamic analysis will be revisited to overcome the above mentioned drawbacks for seismic slope stability analysis.

In the analysis of geosynthetic reinforced soils, its reinforced effect can be investigated with different approaches. Under different layouts of geosynthetics, different failure modes may be induced, such as internal and external mechanisms. Michalowski [13,14] derived a rigorous upper bound on the reinforcement strength and limit loads for reinforced soil structures. The pseudo-static solution of a geosynthetic-reinforced slope was sought considering a rotational and sliding failure mechanism, for the sake of evaluating the earthquake-induced permanent displacement [1]. Further, the pseudo-dynamic approach was applied to investigate the internal stability or for tieback analysis of a reinforced soil wall, aiming at determination of the required tensile strength and length of geosynthetics [19]. Seismic stability of reinforced slopes was investigated in pseudo-dynamic analysis considering the non-associative flow rule and the planar failure surface only [6]. In geotechnical engineering, the reliability of solutions is highly associated with uncertainties in parameters. The combined effects of uncertainties on the structure performance were assessed by the reliability-based approach in a slope stability analysis, according to EC7 partial factor design method [7]. Considering three different failure mechanisms, a deterministic failure analysis was presented to establish the relationship between the factor of safety and reinforcement length and strength. Monte Carlo simulation was adopted to perform probabilistic stability analyses of reinforced slopes under different slope angles and geomaterials [10].

The purpose of this paper is to evaluate the reinforcement force required for seismic slope stability within the framework of plasticity theory, considering variations in soil properties and earthquake loading. The solutions will be obtained from different inputs of seismic excitation.

2. Earthquake input

A crucial work in seismic slope stability is the approach to account for the earthquake input which has a direct and substantial effect on solutions. For earthquake signal in time domain, apart from (peak) displacement and velocity, the more commonly used parameter is (peak) acceleration. A constant acceleration is mainly used in the pseudo-static analysis which has been widely employed in theoretical derivation due to its simplicity. Notice that, however, such an analysis cannot reflect the dynamic response of earthquake effect and yields overly conservative solutions. The other extreme is to adopt the complete acceleration time-history which enables one to obtain more reliable solutions in the stability analysis but is generally limited to numerical simulation rather than closed-form solutions.

Faced with the shortcomings of the pseudo-static approach and actual acceleration time-history, the pseudo-dynamic approach provides a good avenue to the analysis of seismic slope stability. In the literature [2,4], the earthquake signal, horizontal and vertical accelerations, is expressed in the form of sinusoidal functions. This is logical since the irregular wave pattern is the weighted sum of sine and cosine functions. Such a sinusoidal expression is capable of accounting for the cyclic effect with time and hence able to depict the dynamic characteristics of ground shaking. For simplification, the horizontal and vertical accelerations were assumed to act at the slope base at the same time without initial phase shift between these two inputs. Moreover, the spatial effect in the vertical direction was discussed with a soil amplification factor f, indicating an increase in amplitudes of horizontal and vertical accelerations from the slope toe to the ground surface.

Pseudo-dynamic approach considers finite shear and primary wave velocities propagating within slopes with the former being expressed by

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