Engineering Geology 233 (2018) 139–145

Contents lists available at ScienceDirect

Engineering Geology

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

Technical note

Nested Newmark model to calculate the post-earthquake profile of slopes

Ben A. Leshchinsky

Oregon State University, Corvallis, OR 97331, 273 Peavy Hall, USA

A R T I C L E I N F O

Keywords:
Slope stability
Landslides
Earthquake
Displacement
Seismic
Newmark
Limit equilibrium

A B S T R A C T

The Newmark sliding block approach is a common means of evaluating permanent displacements of slopes undergoing seismic loading. However, the conventional Newmark approach omits the presence of multiple shear zones or regions of dispersed shear movement. The occurrence of these shear movements within slopes can often materialize with added vertical and lateral movements above the basal failure surface typically considered in the conventional Newmark approach. This study modifies the conventional Newmark sliding block approach by discretizing a given slope into a series of nested, critical failure wedges, each with an associated yield acceleration, termed a Nested Newmark Model (NNM). Use of the NNM enables assessment of a post-earthquake slope profile within a limit equilibrium framework based on the integration of relative displacements from the toe to the crest. The results demonstrate a different response than conventional Newmark approaches. The model outputs can account for the restriction of toe movements as well as heaving and slumping behavior of the slope face and crest, respectively. Larger seismic excitation resulted in further destabilization of nested wedges near the crest. The presented approach establishes a framework that can be extended to any type of failure geometry or series of failures, including rotational geometry. These results are compared to a numerical model, which exhibit similar behavior. This framework is conceptual, but builds upon the well-accepted Newmark sliding block approach to provide an alternative means of assessing post-earthquake slope movements.

Notation

β	Inclination of nested wedge from the horizontal plane (°)
β_{crit}	Inclination of critical slip surface from the horizontal plane (°)
$F_{\parallel}$	Forces parallel to the shear surface
$F_{\perp}$	Forces perpendicular to the shear surface
ΔH	Height increment
ϕ	Internal angle of friction (°)
σ	Normal stress along internal wedge surface
τ	Shear stress along internal wedge surface
θ	Angle of slope face
c	Cohesion
d_H	Accumulated horizontal displacement of nested wedges at a specific time
d_n	Relative horizontal displacement of a given wedge at a specific time
$d_{n\text{-}V}$	Relative vertical displacement of a given wedge at a specific time
d_{rel}	Relative horizontal displacement of a given wedge at a specific time
d_V	Accumulated vertical displacement of nested wedges at a specific time
E	Modulus of elasticity
FS	Factor of safety
H	Slope height
k_H	Input horizontal acceleration at a given time
$k_{H:rel}$	Difference between input horizontal acceleration and yield acceleration at a given depth
$k_{H:n}$	Horizontal acceleration at a given depth and time
$k_{H:Y}$	Yield acceleration at a given depth
k_y	Yield acceleration
k_V	Input vertical acceleration at a given time
L	Length of internal shear surface for a given wedge
N	Normal force along internal wedge surface
Q	Surcharge load on slope crest
S	Mobilized shear strength along internal wedge surface
T	Shear force along internal wedge surface
t	Time
t_o	Initial time of input motion
Δt	Time elapsed from beginning of input motion
υ	Poisson's Ratio
v_{rel}	Relative velocity of a given wedge at a specific time
W	Weight of a given wedge

E-mail address: ben.leshchinsky@oregonstate.edu.

https://doi.org/10.1016/j.enggeo.2017.12.006
Received 10 August 2017; Received in revised form 5 December 2017; Accepted 7 December 2017
Available online 11 December 2017
0013-7952/

1. Introduction

Permanent slope displacements are a concern after seismic events, often affecting post-earthquake serviceability of infrastructure (Kramer and Smith, 1997, Chigira and Yagi, 2006). One means of evaluating seismic slope stability is the use of pseudostatic limit equilibrium (LE) analysis. However, typical LE approaches ignore post-earthquake displacements. These approaches consider equilibrium based on a sum of forces, moments or both, yielding a factor of safety. This factor represents the relative mobilization of soil shear strength in comparison to driving forces along a slip surface defining the sliding mass (Duncan, 1996). The Newmark approach (Newmark, 1965) determines the permanent displacement of a rigid sliding mass once an input acceleration exceeds the yield acceleration representative of equilibrium conditions. This approach is popular due to its practical nature and simplicity of application (Jibson, 1993; Wartman et al., 2003; Jibson, 2011). The analysis is performed by considering a single sliding rigid mass subject to an acceleration-time history. When this history exceeds its yield value, the shear resistance at the base of the rigid block is overcome and movement occurs. Permanent displacement is then evaluated by twice integrating the acceleration-time history that exceeds the yield acceleration.

Owing to the utility of the Newmark approach, researchers have modified it to mitigate some of the dynamic and geometric constraints associated with a single, rigid sliding block. Slopes may deform internally under seismic shaking, exhibiting flexible behavior that affects acceleration-time histories within a sliding mass (Jibson, 2011; Del Gaudio and Wasowski, 2011; Leshchinsky et al., 2017). In order to better capture this flexible behavior and its effects on realized acceleration-histories and displacements, decoupled and coupled sliding block analyses were developed to capture a refined dynamic site response (Makdisi and Seed, 1977; Lin and Whitman, 1983; Kramer and Smith, 1997; Rathje and Bray, 1999, 2000). However, these approaches are often limited to a singular, predefined failure surface (e.g. a geomembrane in a landfill). Alternative failure geometry has been applied to evaluate permanent displacements using the Newmark sliding block concept for given acceleration-time histories. Ling and Leshchinsky (1995) evaluated rotational displacements of log-spiral surfaces subject to seismic excitation. Ling (2001) supplemented this approach to evaluate translational displacements of two-part wedges. Bandini et al. (2015) evaluated seismic displacements for generalized slip surface geometry. The aforementioned approaches have expanded on the utility of the Newmark sliding block concept to evaluate seismic displacements of slopes that displace as a single coherent mass. However, co-seismic landslides may exhibit multiple failure surfaces or regions of internal shear movements observed in the field (Stewart et al., 2001), in experimental studies (Kutter and James, 1989, Wartman et al., 2005, Fig. 1), and in numerical simulations (Wakai and Ugai, 2004). This observed behavior of seismic displacement was also described, albeit briefly, in the seminal Newmark (1965) study. This study described two general mechanisms of slope displacement, the first being along a well-defined plane of weakness, and the other occurring when no single plane of sliding is easily identifiable (Fig. 1). The study describes that displaced slope profiles without a well-defined plane of weakness may be common in cohesive materials, limiting application of a single sliding block. Thereafter, Newmark's study proceeded to focus on only coseismic displacements where a plane of weakness was easily identifiable. Analytical solutions that can incorporate and evaluate the dispersed slope deformations stated in Newmark's study are limited.

This Technical Note builds conceptually on Newmark's method providing a framework to assess the effects of multiple slip surfaces or dispersed regions of internal shear movement. For simplicity, it uses the sliding block concept to establish an infinite series of sliding blocks that enable determination of a relative movement profile throughout the slope. The geometry of the nested failure surfaces enables evaluation of a vertical and horizontal permanent slope displacement profile. By evaluating displacements of multiple sliding blocks, the nested approach yields different results than those determined in the traditional Newmark approach, which evaluates a single sliding mass. Similar to Newmark's original study, such an approach could account for planar or rotational mechanisms, but also generalized failure geometry. Hence, the objective of this study is to provide a rational framework for extending the basic concept of Newmark's sliding block model to evaluate the post-earthquake displacement profiles of slopes that possibly exhibit more than one slip surface or regions of distributed shear.

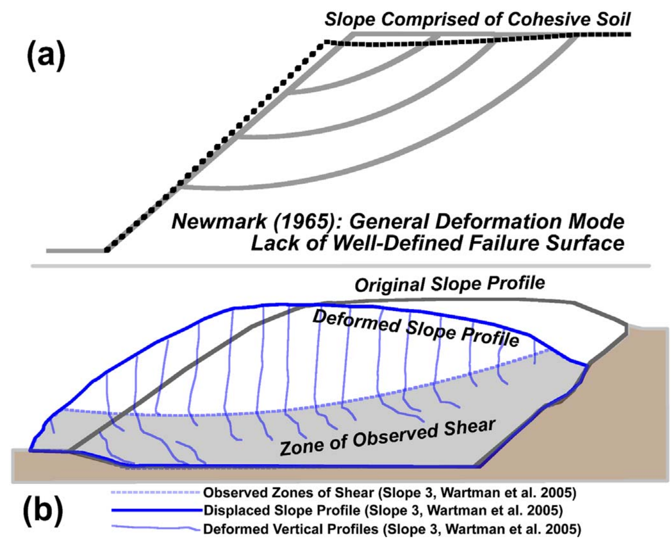

Fig. 1. (a) Top, Example of general deformation mode briefly discussed, but not analyzed, in Newmark's (1965) study, often occurring in cohesive soils where shear is dispersed (after Newmark 1965). (b) Bottom, Small-scale tests from Wartman et al. (2005), where cohesive slopes demonstrated regions of shear deformation (after Wartman et al., 2005).

2. Methodology

The methodology, termed the Nested Newmark Method (NNM), builds upon the traditional Newmark analysis by discretizing a slope stability problem into a series of nested failures selected by a user (Fig. 2). Then, the relative displacement of each body is evaluated and integrated from the toe to develop a post-earthquake displacement profile (Fig. 3) for a given slope. Each surface is limited in translational displacement by the discrete geometry of the ground in front of the toe (Fig. 2b), presenting a rational means of capturing the post-earthquake subsidence and heave of slopes with multiple potential zones of shear (Fig. 3c). For brevity, the derivation of the proposed approach is limited to translational failures considering a simple homogeneous slope with nested failures emerging at the face. However, extension to consider layered soils or complex slopes considering general shaped failure geometries may be implemented using the same process presented herein. An example using curved geometry is presented later in this study.

The NNM procedure begins by considering a slope of angle θ and height H, discretized into an n wedges, each exiting at a location on the face infinitesimally more upslope than the previous point (Fig. 2b). For each wedge static force equilibrium is evaluated for a geometry defined by angle of failure β. It considers external loading (surcharge, Q), body force (wedge weight, W), inertial loading (k_H, k_V) and resultant normal (N) and shear (T) forces acting on failure plane (Fig. 2a). Equilibrium perpendicular and parallel to the failure plane can be defined as:

$$\sum F_{\parallel} = 0 = W\sin\beta + Q\sin\beta + k_H W\cos\beta - k_V W\sin\beta - T \tag{1}$$

$$\sum F_{\perp} = 0 = N - W\cos\beta - Q\cos\beta + k_H W\sin\beta + k_V W\cos\beta \tag{2}$$