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Seismic displacement of gently-sloping coastal and marine sediment under multidirectional earthquake loading

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ABSTRACT

Gentle sediment-laden slopes are typical of the onshore coastal zone and offshore continental shelf and slope. Coastal sediment are commonly young weakly consolidated materials that are well stratified, have low strength, and can mobilize shear displacements at low levels of stress. Seismically-driven plastic displacements of these sediment pose a hazard to coastal cities, buried onshore utilities, and offshore infrastructure like harbor protection and outfalls. One-dimensional rigid downslope-directed Newmark sliding block analyses have been used to predict earthquake deformations generally on steeper slopes that are modeled as frictional materials. This study probes the effect of multidirectional earthquake motions on inertial displacements of gently sloping ground of the coastal and offshore condition where soft-compliant soil is expected. Toward that objective, this investigation seeks to understand the effect on Newmark-type displacements of [1] multidirectional earthquake shaking and [2] soil compliance. In order to model multidirectional effects, the earthquake motions are rotated into the local slope strike- and dip-components. On gently sloping ground, including the strike component of motion always results in a larger and more accurate shear stress vector. Strike motions are found to contribute to downslope deformations on any declivity. Compliant response of the soil mass also influences the plastic displacements. The magnitude of seismic displacements can be estimated with a simplified model using only the estimated soil yield-acceleration (k_y) and the peak ground velocity (V_{max}) of the earthquake motions. Compliance effects can be effectively mapped using the concept of Plastic Displacement Response Spectra (PDRS).

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1. Introduction

Broad regions of the world's coastal zone are composed of gently sloping deposits of Holocene and Pleistocene sediment and sedimentary terrace deposits. Onshore, and on the continental shelf, the slopes are exceedingly flat ranging from level ground to at most a few degrees. Globally, the width of the continental shelf is 70 km from shoreline-to-shelf break whose depth averages 135 m. That is, these environments are nearly level. Seismic displacements on the continental shelf occur on nearly level surfaces. Worldwide, the continental slope averages 4°. A study of the entire known-catalog of Atlantic coast seafloor mass movements by Booth et al. (1993) found that 70% of the failures occurred on slopes of 6° or less. One-half of the known Atlantic seafloor mass movements involve displacement of relatively thin bodies of sediment, no more than tens of meters in thickness, that cover areas of five-square kilometers, or less. The dominant mechanism of failure of these mass movements is infrequent earthquakes (Booth et al., 1993; Lee et al. 1993). The abundance of thin seafloor mass movements in weakly consolidated sediment on low angle slopes is counter to the experience of geologists on land who might ascribe the term 'landslide' to a steeper feature. Nevertheless, these gentle slopes of sediment are the dominant environment for earthquake-driven mass movements in the offshore and coastal zone.

Onshore, permanent seismic displacements of the ground have resulted in considerable damage to underground pipeline networks buried in soft young deposits. Pipeline breaks in non-liquefied ground have damaged urban buried infrastructure, for example during the Northridge earthquake (Trifunac and Todorovska, 1997; O'Rourke, 1998) and the Hyogo-Nambu Earthquake (e.g. Loukidis et al., 2001).

Over one-hundred years ago, the American geologist Grove Karl Gilbert, reported on the geologic aspects of the 1906 M7.8 San Francisco, California earthquake (Lawson, 1908) and described nearly 10 m of seismic displacement in Tomales Bay sediment at Point Reyes, north of San Francisco. The noteworthy aspect of his observation was the upslope movement on a gentle slope.

> 'It is a notable feature of this displacement that the disturbed material moved up the slope instead of down, so that the transfer was not only independent of gravity but opposed to it. The phenomenon, therefore, does not fall in the same category with landslides, and if properly interpreted it may throw light on the mechanics of the earthquake pulses.'
>
> [–G.K. Gilbert (Lawson, 1908)]

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Nomenclature

a_c	critical yield acceleration of Wilson and Keefer (1985)
A_c	correction of isotropically-consolidated shear test results to represent anisotropic field conditions
a_n	dimensionless stiffness and geometry parameter for a wedge embankment (Ambraseys, 1960).
A_r	measured of the degradation of strength due to repeated cyclic loading, determined through cyclic triaxial shear testing degradation during cyclic loading
a	acceleration from an earthquake time history
F_D	total dynamic load on the sliding plane
F_{eq}	Earthquake inertial force
F_α	slope gravitational force
F_c	damping force
F_k	stiffness force
g	acceleration due to gravity, 9.81 m/s
h_w	depth of the water table
H	total sliding mass thickness
I_h	two-component horizontal Arias intensity of either the relative motion of the sliding mass or the earthquake base motion
I_n	ratio of the relative Arias intensity of the 2-component sliding mass normalized by the 2-component Arias intensity of the earthquake base motion
k	partitioned mass shear-stiffness element
k_y	yield acceleration
k_{max}	peak ground acceleration
M_r	mass ratio, m_1/M_T
m_1	upper mass of partitioned block
m_0	lower mass of partitioned block
M_T	total mass of block
NSP	Normalized Strength Parameter approach of Ladd and Foott (1974), based on the assumption that strength parameters normalized by their consolidation stress are constant for a given sediment with a given OCR
OCR	overconsolidation ratio ($\sigma'_{vm}/\sigma'_{vo}$) measured through consolidation testing
p	the average normal effective stress acting on a mass
q	shear stress acting on a mass
S	effective stress normalized-normally consolidated shear strength adjusted for dynamic loading and anisotropy factors
S_u	undrained shear strength
S_n	ratio of the static undrained shear strength of a normally consolidated sediment to its consolidation stress
Δt	earthquake recording time step increment
T	fundamental mode period of slope or truncated wedge
u_{max}	Maximum sliding displacement
$\ddot{u}_b$	Acceleration beneath the failure plane
$\ddot{u}_o$	Relative acceleration of the lower mass above the failure plane
$\dot{u}_1$	Relative velocity of the upper mass
u_1	Relative displacement of the upper mass
V_{max}	peak ground velocity (PGV) of earthquake motion
V_s	Shear wave velocity
α	slope angle (degrees)
γ	bulk density of a sediment
γ_w	density of fresh water (1.00 g/cm^3), or seawater (1.025 g/cm^3)
Λ_0	overconsolidation power function
η	log of the ratio of k_y and V_{max},
ϕ	Mohr-Coulomb angle of effective shear resistance
σ_{vo}	in-place vertical total stress exerted by the weight of overburden material
σ'_{vo}	in-place vertical effective stress exerted by the weight of overburden material
σ'_{vm}	maximum past vertical effective stress exerted on a soil material.
τ_d	driving stress vector
τ_y	yield stress
τ_{dip}	total shear stress in the dip direction
τ_{strike}	total shear stress in the strike direction
$\tau_{eq,d}$	earthquake inertial stress in the dip direction
$\tau_{c,d}$,	mobilized viscous damping stress in the dip direction
$\tau_{k,d}$	mobilized stiffness stress in the dip direction
$\tau_{eq,s}$	strike motion inertial stress
$\tau_{c,s}$	strike-mobilized viscous damping stress
$\tau_{k,s}$	strike-mobilized stiffness stress
θ	azimuth of the total stress vector

Gilbert recognized that the displacement in soil was driven upslope by earthquake motion, counter to the gravitational direction of normal slope mass movements. The observation that earthquake motions could drive displacements upslope in a gently sloping environment was an important contribution, though in Gilbert's time no practical method was available to evaluate the interaction of gentle soil slopes and earthquake motions.

Nathan Newmark (1965) presented a computational method for assessing the seismic displacement potential of slopes. The method assumes rigid-plastic behavior of sloping ground subjected to loading by an acceleration time history. Block displacement begins when the yield acceleration, k_y, of the sliding mass is exceeded by the earthquake acceleration.

This paper explores the effects of multidirectional ground motion and soil compliance in order to understand how soil slides develop on gentle slopes typical of the coastal plain and offshore shelf and slope. Including multidirectional seismic shaking leads to the computation of complex trajectories of plastic seismic-displacements. A fundamental aspect of the approach is the analysis of the local-slope strike and dip motions, that are rotated from the two orthogonal ground motions typically recorded in the east-west and north-south directions. The strike and dip motions are used compute shear stress on the soil mass in both the strike and dip directions. Plastic deformation occurs when the combined loads exceed the capacity of the soil mass to resist yielding.

The original Newmark (1965) formulation analyzed downslope dip-directed motion and assumes a rigid-plastic behavior of the sliding ground. Typically, when applying Newmark analyses, practitioners use the component of motion that contains the peak ground acceleration and neglect the effect of the orthogonal component of motion. A modern implementation of the rigid 1-D Newmark approach with a strain softening element can be found in Jibson et al. (2013). Work by Goodman and Seed (1966), Seed and Martin (1966), Ambraseys and Sarma (1967) and Makdisi and Seed (1978) extended Newmark's original method, incorporated soil compliance, and provided practitioners with simplified procedures for estimating seismic displacements of slopes. Two alternate approaches have been used to address the dynamic response of soft ground. A decoupled procedure developed by Seed et al. (1973), and Seed (1979), involved computation of the elastic response of a compliant soil mass along a potential failure plane, assuming no displacement. The computed averaged motion at the depth of the potential failure plane, termed the Horizontal Equivalent Acceleration, is used to compute permanent displacements in a separate rigid-plastic Newmark analysis. This approach decouples the compliant response of