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Parametric investigation of lateral spreading of gently sloping liquefied ground

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ABSTRACT

This paper investigates the main parameters affecting the anticipated maximum surface displacements due to earthquake-induced lateral spreading of mildly sloping ground. The main tool used for this purpose is a numerical methodology employing a bounding surface plasticity model implemented in a finite difference code, which has been thoroughly validated against 16 published centrifuge lateral spreading experiments. This study shows that important problem parameters are the mean ground (surface) acceleration, the duration of strong shaking following the onset of liquefaction, the corrected SPT blowcount, the depth to the sliding plane, the inclination of the ground surface and the fines content of the liquefied soil layers. A new approximate multi-variable relation is proposed for the estimation of ground surface displacements due to lateral spreading in gently sloping ground, which includes the foregoing parameters. The form of the relation builds upon sliding block theory, but its final formulation is based on statistical analysis of the input data and the results from 120 parametric analyses performed with the validated numerical methodology. Comparison of the predictions of the proposed relation for ground surface displacement against pertinent field data (from 256 case histories) and centrifuge test measurements shows satisfactory accuracy. Furthermore, the variation of lateral displacements with depth is explored and distinct displacement patterns are proposed for uniform, 2-layer and 4-layer ground profiles.

1. Introduction

"Lateral spreading" is the term used to refer to the development of large horizontal ground displacements due to earthquake-induced liquefaction, in the case of even small free ground surface inclination or small topographic irregularities (e.g. river and lake banks). Recent earthquakes (e.g. Kobe, 1995; Chi-Chi, 1999; Nisqually, 2001) have underlined the fact that this phenomenon is of significant practical importance for civil engineering structures (quay walls, bridge piers, etc.), since it imposes considerable lateral loads and may lead to widespread failures. Fortunately, there exist methods today which can be used for the design of such structures against lateral spreading (e.g. *P*–*y* analysis). However, their accuracy depends greatly on the ability to estimate the anticipated lateral ground displacements and their variation with depth.

The available methodologies for estimating lateral ground displacements are exclusively empirical and can be divided in two main categories, depending upon the type of parameters used to quantify the severity of seismic motion: those that rely on "seismological" parameters of the earthquake motion, like the methodologies of Bardet et al. [1], Rauch and Martin [2], Youd et al. [3], Zhang and Zhao [4], Faris et al. [5] and those that rely on "engineering" parameters, like the methodologies of Hamada et al. [6], Shamoto et al. [7], Hamada [8], Zhang et al. [9], Aydan et al. [10]. Most of these empirical relations are simple and are based on statistical evaluation of data of geotechnical (e.g. corrected blow count) or seismological (e.g. earthquake magnitude) nature. Recently, another approach was proposed [11], where displacements are directly associated with the liquefied (residual) shear strength of the soil, an interesting concept that is adopted in this paper, but in a different manner. In parallel, several researchers ([12–14]) have used the capability of neural networks and genetic programming in order to produce software tools for the estimation of lateral spreading displacement. Despite the scientific merit of the latter approach, this paper focuses on the former approach of developing simple empirical relations in order to facilitate its use by practitioners.

Regardless of the parameters used, most empirical methodologies are based on databases of case histories, such as the one proposed by Youd et al. [3], thus having the advantage of fitting data directly from actual events. However, the uncertainties that are inherent in the documentation of any case history do not allow the scatter of the predictions to be minimized. In addition, due to the uniqueness of each case history, it is almost impossible

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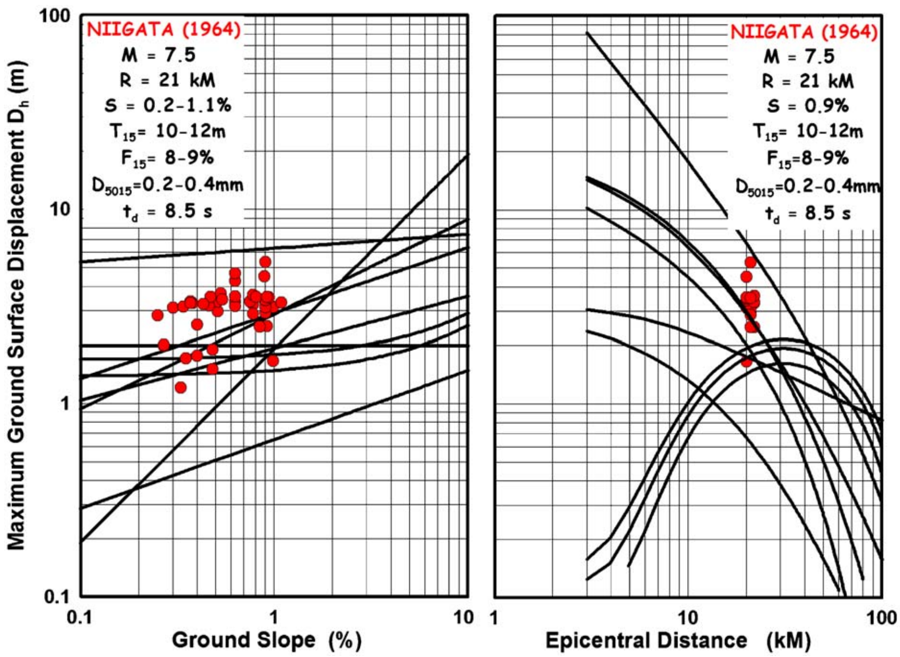

Fig. 1. Range of the estimations of the "seismological" relations [1–5] for the maximum ground surface displacement D_h of 18 case histories from the Niigata 1964 earthquake.

to isolate the effect of any individual parameter and to study it independently.

An example of the repercussions of these objective limitations is given in Fig. 1, where the range of the predictions of five "seismological" relations (e.g. [1–5]) is being compared with the actually measured ground displacements for 18 case histories from the Niigata 1964 earthquake. In each of the two subplots in Fig. 1, the case histories were selected from the database of [3] as a set of events having approximately similar values for all parameters, except for the parameter plotted in the abscissa, i.e. earthquake magnitude M=7.5, epicentral distance $R \cong 21$ km, thickness of layers with SPT blowcount less than 15 T_{15}=10–12 m, fines content (in the foregoing layers) F_{15}=8–9%, mean grain size (in the foregoing layers) D_{5015}=0.2–0.4 mm and duration of seismic motion t_d=8.5 s. In particular, in Fig. 1a, the ground slope varied from S=0.2–1.1%, while in Fig. 1b the slope was fixed to S=0.9%. The scatter in the predictions, as compared to the field data, in Fig. 1 implies that in order to improve accuracy of predicting tools one could potentially supplement data from case histories with physical and numerical geotechnical modeling. This approach was followed here, employing recent advances in numerical geotechnical modeling ([15–17]), which promises remarkable qualitative and quantitative reliability in the simulation of seismic liquefaction related problems. Hence, in order to study the phenomenon and to derive reliable approximate relations for the evaluation of ground surface displacements due to liquefaction-induced lateral spreading, the following steps were followed in this study:

(a) Thorough verification (and calibration) of the numerical methodology against cyclic liquefaction (element) tests and model (centrifuge) tests.
(b) Identification of the basic problem parameters and their inter-relation, through the use of a theoretical model, namely a rigid block sliding on a plane under harmonic seismic shaking.
(c) Extensive parametric analysis of the problem using the foregoing verified numerical methodology.
(d) Identification of all problem parameters and independent evaluation of their effect, based on the results of the performed parametric analyses.
(e) Statistical analysis of all numerical predictions and derivation of optimized multi-variable relations for the prediction of lateral spreading displacements and their variation with depth for uniform and multi-layered ground profiles.
(f) Evaluation of reliability of the proposed relations against centrifuge test results, as well as field measurements from the literature.

2. Numerical methodology

The employed numerical methodology has been developed at N.T.U.A. over the years ([16–19]) and has been extensively validated against centrifuge experiments related to a number of different seismic liquefaction related problems: lateral spreading and pile response ([20]), shallow foundation settlement ([19]), seismic response of level and sloping ground ([17]) and use of drains for liquefaction mitigation ([21]).

More specifically, the numerical methodology employs a constitutive model that incorporates the framework of Critical State Soil Mechanics, while it relies upon bounding surface plasticity with a vanished elastic region (a concept first proposed by Dafalias [22] and Dafalias and Popov [23]) to simulate the non-linear soil response ([17,16]). This model is based on the original two-surface model of Papadimitriou et al. [15] and Papadimitriou and Bouckovalas [24], which in turn was based on the work of Manzari and Dafalias [25]. In their papers, the authors demonstrated the capability of the original model to simulate the cyclic behavior of non-cohesive soils (sands and silts), under small, medium and large cyclic strain amplitudes and various initial stress and density conditions, using a single, soil-specific set of model constants, at the element level.

In particular, the original model inherited the four (open cone) surface formulations (yield, critical state, bounding, dilatancy) and the dependency of the last three surfaces on the state