Chapter 1
Introduction

1.1. Earthquake Damage Caused by Soil Liquefaction and Lateral Spreading.

The liquefaction of loose, saturated soil deposits during earthquakes has been the subject of continuing research over the past thirty years. While soil liquefaction has occurred in nearly all large earthquakes, the phenomenon captured the attention of the geotechnical engineering community after the dramatic and infamous liquefaction failures that resulted from the 1964 earthquakes in Japan and Alaska (Seed 1979; *Liquefaction...* 1985). In Niigata, Japan, soil liquefaction resulted in large sand boils, loss of bearing capacity beneath buildings, differential settlements, and slope movements. Widespread soil liquefaction caused much of the estimated $1 billion in earthquake damage to the Niigata area (*Liquefaction...* 1985). In Alaska, soil liquefaction caused damage over a wide area with huge landslides occurring in Valdez, Seward, and Anchorage (Seed 1968). Seed (1979) recalls:

> *"the distress and amazement which confronted soil engineers when they first observed the enormous damage due to soil liquefaction both in Anchorage, Alaska, and Niigata, Japan. . . . These events, more than anything else, probably did more to stimulate geotechnical engineering studies of earthquake-induced liquefaction than any other single factor."*

When liquefaction results in the down-slope transport of materials over relatively long distances (at least several tens of feet), the slope movement is termed a *flow failure* ("Definition of terms..." 1978). Seed (1968) describes several historical flow failures dating back to the complete destruction of Helice, Greece, in 373 B.C. In the United States, large slope movements occurred along the Mississippi River during the New Madrid earthquake sequence of December, 1811, through February, 1812. The Alaska earthquake of 1964 caused extensive liquefaction and tremendous flow slides in Valdez and Seward; liquefaction of sand lenses beneath the Turnagain Heights area in Anchorage resulted in a large, damaging flow slide. In 1971, an earthquake in California caused a liquefaction flow failure in the upstream slope of the Lower San Fernando Dam that endangered the lives of 80,000 people living downstream (*Liquefaction...* 1985; Seed 1987). Throughout history, soil liquefaction and flow failures have caused loss of life and spectacular damage in earthquakes.

More modest, but no less damaging, displacements on gently sloping ground frequently result from earthquake-induced liquefaction of soils. Termed *lateral spreading,* this type of ground failure damaged over 250 bridges and numerous embankments along the Alaskan Railroad and Highway during the 1964 earthquake (*Liquefaction...* 1985; Bartlett and Youd 1992b). In the San Fernando earthquake of 1971, several buildings collapsed or were damaged by such movements (*Liquefaction...* 1985; Seed 1987). In San Francisco, lateral spreading during the 1906 earthquake caused extensive damage. Notably, ground displacements in one lateral spread broke a water main leading into downtown San Francisco thereby hindering the city's ability to fight catastrophic fires after the earthquake (Youd and Hoose 1976; Bartlett and Youd 1992b). In the 1989 Loma Prieta earthquake, soil liquefaction and lateral spreading again caused significant damage in the San Francisco area (Bardet and Kapuskar 1993; Clough et al. 1994). As occurred in the 1906 disaster, soil liquefaction resulted in numerous water and gas line breaks that contributed to a large, destructive fire in the city (O'Rourke and Pease 1992).

Lateral deformations of less than a few meters due to soil liquefaction may occur at many sites over widespread areas in large earthquakes and cause the disruption of buried utilities, pipelines, and transportation facilities, or differential foundation movements and structural collapse. Hence, while many of the more infamous liquefaction failures involved massive landslides and tremendous movements of the ground surface, smaller displacements due to lateral spreading have caused considerable damage. According to the National Research Council (*Liquefaction...* 1985):

> *"Damage caused by lateral spreads, though seldom catastrophic, is severely disruptive and often pervasive. . . . Cumulatively, more damage has been caused by lateral spreads than by any other form of liquefaction-induced ground failure."*

To some degree, lateral spreads cause a lot of damage because the areas most susceptible to lateral spreading (relatively flat areas along waterfronts) are the same areas most attractive for urban development.

A liquefaction-induced lateral spread is depicted schematically in a three-dimensional perspective in Figure 1.1. A more detailed description of lateral spreading is given in Chapter 3. Throughout this report, the term *lateral spreading* is restricted to the type of failure shown in Figure 1.1 and excludes other types of liquefaction failures that are sometimes described as "lateral spreading". For example, slumping failures of roadway embankments (resulting from liquefaction of the underlying deposits) and outward rotation of retaining walls (related to the higher active earth pressures from a liquefied backfill) produce lateral deformations that are commonly identified as "lateral spreading" in post-earthquake damage surveys. Both of these types of liquefaction failure are specifically excluded from the definition of lateral spreading used in this study.

1.2. Need for New Procedures to Predict Lateral Spreading Displacements.

Since 1964, research has focused on developing reliable methods to evaluate the likelihood of liquefaction in a given soil deposit. As Seed (1987) points out, our ability to predict the onset of liquefaction is relatively good. However, this addresses only part of the problem in a liquefaction assessment where the geotechnical engineer must answer two questions: (1) given a likely seismic event, is the soil prone to liquefy, and (2) if liquefaction occurs, what consequences can be expected, in terms of ground movements (Seed 1987; Bartlett and Youd 1992b). Hence, as our ability to predict the onset of liquefaction has improved, attention has turned to developing methods of engineering analysis which can forecast the consequences of liquefaction. In a review of the state of knowledge on soil liquefaction, the National Research Council (1985) identified the need for research to develop *"methods for evaluating the permanent soil deformations that can be induced by prescribed earthquake shaking."*

For critical structures such as dams and nuclear power plants, Seed (1987) argues that engineering design should endeavor to prevent soil liquefaction. For less critical structures, an alternative design approach is to anticipate liquefaction, predict the severity of the ensuing ground displacements, and, if the forecasted displacements are relatively small, design the facility to accommodate the movement without failing. While few structures can survive large, flow-type landslides, many structures can survive differential displacements of several centimeters with only minor damage (Youd and Perkins 1987). Hence, predictions of modest deformations due to lateral spreading are useful in the evaluation of many non-critical structures. Nevertheless, when a proposed site for new construction is subject to possible liquefaction, mitigation or relocation to another site is often the preferred, prudent course of action. For existing facilities, relocation or mitigation may be expensive alternatives; then, reliable predictions of ground displacements are needed to define the liquefaction risks.

The ability to forecast liquefaction-induced ground movements probably finds widest application in assessing seismic risks for lifeline networks (Glaser 1993; 1994). O'Rourke (1994) identifies *lifelines* as water, sewage, transportation, electric power, gas and liquid fuel delivery, and telecommunications systems which are essential for maintaining public safety, health, and commerce. Since individual ground failures can interrupt service at numerous locations in a regional network, liquefaction and lateral spreading can be severely disruptive to lifeline systems. To ensure the continued operation of important systems after major earthquakes, engineers must evaluate the seismic risks to large lifeline networks. Many existing facilities can survive fairly significant displacements, so risk assessments rely on estimates of liquefaction-induced ground deformations to identify vulnerable system components. Given that mitigation efforts at all potential liquefaction sites in a regional network may be prohibitively expensive, risk assessments can be used to prepare contingency plans or to prioritize system improvements to prevent or accommodate damages from lateral spreading. For new lifeline routes where liquefiable soils are unavoidable, the designer needs estimates of the deformation magnitudes that the new facility must withstand to survive a major earthquake (Glaser 1993).

Reliable methods are needed to quantitatively predict ground movements due to liquefaction and lateral spreading in earthquakes. For buried pipelines:

> *"Lateral spreading has long been recognized as a potentially severe seismic hazard but evaluation of potential impacts [has been] limited primarily by the lack of a means to estimate the location, magnitude and distribution of ground movements. . . . Accounting for the effects of lateral spreading in the design of a buried pipeline at a specific location requires that some estimate be made of the expected pattern of ground deformation [including] the size of the lateral spread (length and width), the depth of the spreading soils and the distribution of soil movements within the spread"* (Honegger 1992).

Therefore, methods are needed to estimate the areal extent of lateral spreading and displacement direction, patterns, and magnitude, including mean and maximum values (Ballantyne 1994; Honegger 1994; "Reports..." 1994). As Rinne (1987) points out:

> *"Analytical techniques for estimating the amount of lateral spread deformation are virtually nonexistent to both the researcher and practising engineer. Development of semiempirical methods to at least bracket the range of lateral movements expected would greatly assist the practising engineer.*"

While deformations vary with a wide range of site-specific variables, a simple design model for lateral spreading, which can be employed by a geotechnical engineer without special expertise, is desired. Methods suitable for studies of seismic hazards over broad regional areas and at specific sites are needed. Prediction models should require a minimum number of input parameters and permit approximate estimates when soil conditions are poorly understood (Ballantyne 1994; Honegger 1994; "Reports..." 1994). Hence, research is needed to develop and improve simple methods of predicting ground movements due to liquefaction-induced lateral spreading. This effort is all the more critical considering the damage that lateral spreads have historically inflicted on lifelines.

1.3. Overview of Report and New EPOLLS Model.

This report details the development of an empirical model for predicting ground surface displacements resulting from liquefaction-induced lateral spreading in earthquakes. This new model is referred to as the EPOLLS model (for *Empirical Prediction Of Liquefaction-induced Lateral Spreading)*.

In the next three chapters of this report, a review of the published research on liquefaction and lateral spreading is given. In Chapter 2, the behavior of saturated soils in cyclic shear and soil liquefaction is reviewed. Lateral spreading, a particular type of ground failure resulting from soil liquefaction, is described in Chapter 3. In Chapter 4, available methods for predicting ground displacements due to lateral spreading are discussed. An overview of the new EPOLLS method is given in Chapter 5. Development of the model is based on a database of lateral spreads observed and studied following historical earthquakes. The EPOLLS database is described in Chapter 6 and listed in Appendix A. The source materials used in compiling the EPOLLS database are cataloged in Appendix B. The methods used to analyze soil borings from the case study sites are described in Chapter 7 and the corresponding computer code, written to speed analysis of the soil boring data, is documented in Appendix C. In Chapter 8, the distribution of horizontal and vertical displacements observed in lateral spreads are studied. Fitting of the EPOLLS models to the database, using multiple linear regression analyses, is presented in Chapters 9, 10, and 11. A general review of regression techniques is given in Appendix D. The final EPOLLS methodology is summarized, with other conclusions, in Chapter 12. An example application of the full model, for a hypothetical site, is presented in Appendix E.

Designed to match the needs of the engineer who must sometimes work with very little data for a given site, the complete EPOLLS model is comprised of four components:

(1) *Regional-EPOLLS* model for predicting horizontal displacements based on the seismic source and local severity of shaking, intended for use in regional risk assessments where very little site-specific information is available.
(2) *Site-EPOLLS* model for improved predictions of horizontal displacements when more site-specific data, such as surface topography, are available.
(3) *Geotechnical-EPOLLS* model for even better predictions of horizontal displacements using additional data from soil borings at the site.
(4) *Vertical-EPOLLS* model for rough predictions of vertical displacements and requiring data from site soil borings.

In each component of the EPOLLS model, equations are presented for predicting the average and standard deviation of displacements. Maximum displacements can then be estimated using probabilities and the gamma distribution for horizontal displacements or, for vertical displacements, the normal distribution. For a given site, however, the user must independently determine that liquefaction and lateral spreading will occur: the EPOLLS model is only useful for estimating the resulting ground surface deformations.

The EPOLLS model is valuable in progressive liquefaction risk studies: starting with regional risk assessments and minimal site information, more accurate predictions of displacements can be made with the addition of more detailed site data. Moreover, the variables used in the EPOLLS equations can be readily estimated by an engineer performing a site study and the model itself is composed of a suite of uncomplicated, algebraic equations. Being fairly simple and inexpensive to use, the new model is a good tool for predicting ground deformations due to liquefaction-induced lateral spreading. While this empirical model can be expected to yield accurate, but not highly precise predictions of displacement, even approximate estimates are useful for deciding if more detailed and expensive engineering site studies are warranted.

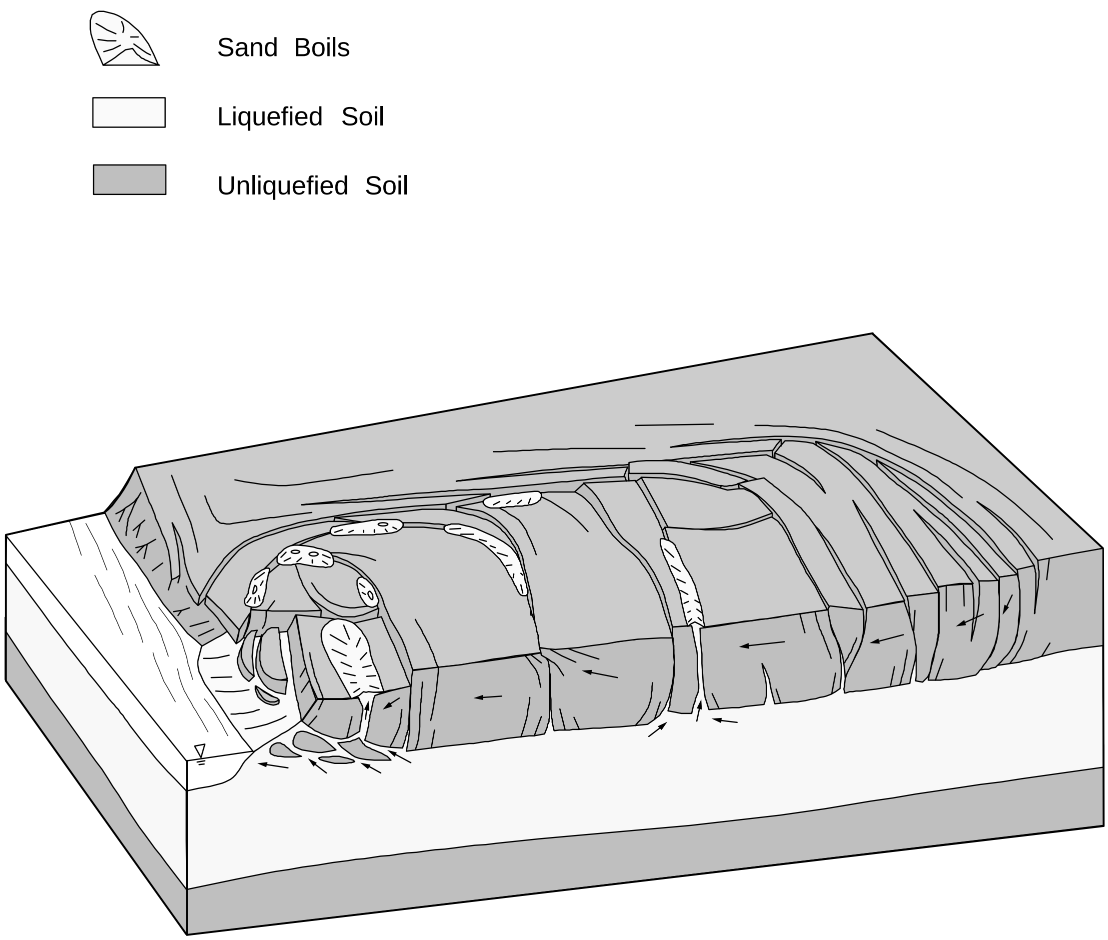

Figure 1.1. Schematic depiction of a lateral spread resulting from soil liquefaction in an earthquake (after Varnes 1978).