
Chapter 5

Design of New Empirical Model for Lateral Spreading

5.1. Nomenclature.

In the remainder of this report, a new empirical model is developed for estimating ground surface displacements due to soil liquefaction and lateral spreading. Reference to this new model is made with the acronym "EPOLLS", which stands for *Empirical Prediction Of Liquefaction-induced Lateral Spreading*. The complete EPOLLS model is comprised of four components given the following names:

- (1) *Regional-EPOLLS* (or *R-EPOLLS*) model component, suitable for predicting horizontal displacements in seismic hazard surveys of geographic regions;
- (2) *Site-EPOLLS* (or *S-EPOLLS*) model component, designed to give improved predictions of horizontal displacements in site-specific studies with minimal data on the subsurface conditions;
- (3) *Geotechnical-EPOLLS* (or *G-EPOLLS*) model component, giving more refined predictions of horizontal displacements when additional data is available from geotechnical soil borings; and
- (4) *Vertical-EPOLLS* (or *V-EPOLLS*) model component, useful to get rough estimates of vertical displacements on a lateral spread.

The design and a general overview of the EPOLLS model is presented in this chapter.

The EPOLLS model is developed from data on lateral spreads that occurred in historical earthquakes. This data set, described in Chapter 6, is called the EPOLLS database. The nomenclature given here and illustrated in Figure 5.1 is used in describing the ground failures in the EPOLLS database:

- *Soil liquefaction*, as defined in Chapter 2, is taken to include all phenomena giving rise to a loss of shearing resistance or the development of excessive strains as a result of transient or repeated disturbance of saturated cohesionless soils.
- *Liquefaction-induced lateral spreading* (or just *lateral spreading*), is defined as the finite, lateral displacement of gently sloping (< 5%) ground as a result of pore pressure build-up or liquefaction in a shallow, underlying soil deposit during an earthquake. As described in Chapter 3, this definition specifically excludes liquefaction-induced failures of earth retaining walls and steeper embankments, which also result in lateral deformations, as

well as flow failures.

- The *head* of a lateral spread is the area in the upper portion, and the *toe* is the area in the lower reaches, of the slide mass. The prevailing direction of movement is from the head toward the toe of a lateral spread.
- The *flanks* of a lateral spread are the margins along the sides of a slide mass.
- A *free face* is a relatively steep, sudden change in the surface topography of a lateral spread. The most common type of free face is a stream bank along the toe of a lateral spread
- The *longitudinal* direction on the surface of a lateral spread is parallel to the prevailing direction of movement. In most lateral spreads the longitudinal direction is roughly perpendicular to a free face or coincident with the direction of maximum surface slope.
- The *transverse* direction on the surface of a lateral spread is perpendicular to the prevailing direction of movement. In most lateral spreads the transverse direction is roughly parallel to a free face or perpendicular to the direction of maximum surface slope.
- The *width* of a lateral spread is the horizontal distance measured across the transverse direction of the slide area between the flanks. The *length* is measured as the horizontal distance from the head to the toe of a lateral spread. Similar definitions were adopted by Youd and Kiehl (1996).

5.2. Selection of Modeling Approach.

In designing the EPOLLS model, the primary objective was to meet the needs of the engineering practitioner faced with predicting the magnitude of displacements in areas susceptible to lateral spreading. The need for these predictions appears to arise most frequently in the evaluation of liquefaction hazards over fairly large geographic areas, especially in assessments of seismic risk to lifeline networks. Hence, the ability to make simplified, low-cost estimates of surface movements at a multitude of sites is probably more useful than the capacity to perform more precise, detailed analyses of individual lateral spreads. To the practitioner, the most useful lateral spreading model must be reliable, yet simple and inexpensive to employ. The method should not use exotic variables that would require specialized testing or site studies.

With the needs of the engineering practitioner in mind, the EPOLLS model for lateral spreading was developed to meet the following criteria:

- The model should be suitable for the rapid analysis of sites previously identified as susceptible to liquefaction and lateral spreading. The ability to predict deformations more precisely in detailed site studies is of lesser importance.
- Rather than making predictions of displacements at specific locations on a lateral spread, the emphasis should be on estimating the pattern of displacements across the slide surface.
- The final model should be compatible with probabilistic methods often used to evaluate liquefaction risks in seismic hazard assessments.

- Only variables that are readily obtained from conventional site investigations should be included.
- The full model should be simple to understand and not require specialized expertise to get meaningful predictions.

Empirical model.

As evident from the literature review in Chapter 4, considerable work has been done in developing numerical and analytical models of lateral spreading. However, sophisticated numerical simulations are often too expensive and unsuitable for the routine analysis of lateral spreads. These models generally require considerable input data to define the problem geometry and soil behavior. The effort and expertise required for these numerical models are probably justified only for the occasional analysis of a critical structure impacted by a lateral spread. The simplified, analytical models discussed in Section 4.3, which are easier to implement, have not been sufficiently demonstrated in modeling lateral spreads in the field. Moreover, these numerical and analytical methods all rely on site and soil parameters that are poorly defined, difficult to estimate, or require specialized testing and analysis. Hence, it appears that the available numerical and analytical solutions are not well-suited to the needs of the engineering practitioner.

Empirical models seem to be the most promising approach for satisfying the requirements of a practical method as outlined above. As pointed out in Chapter 4, empirical methods are the state-of-the-practice in estimating deformations on lateral spreads. Even with future improvements in numerical or analytical methods, empirical models can be used to support these calculations as well as provide a means of identifying sites that require more detailed study. However, while empirical methods seem to have many advantages over analytical and numerical models for lateral spreading, comparatively less work has been done to develop good empirical models. The empirical methods available for estimating displacements in a lateral spread (reviewed in Section 4.4) are not completely satisfactory in their present form, and better empirical models should be possible.

Consequently, an empirical approach was chosen for this study. The resulting EPOLLS model satisfies the criteria outlined above. The EPOLLS model consists of a suite of simple algebraic equations and uses variables that can be readily defined for a given site. An empirical approach has the following, additional advantages:

- The complete model can be clearly described and disseminated in the literature. No specialized computer code is required.
- When the model parameters are not well known for a given site, bounding calculations can be used to quickly estimate the possible range of displacements. Such estimates can be used to decide if additional site studies are warranted.

Statistical regression analysis.

Empirical design methods often take the form of design charts that relate system variables

to the corresponding system response. Normalized parameters, which might incorporate one or more factors into a single variable, simplify these models. However, it is difficult to devise such charts that incorporate more than a few parameters. Since a lateral spread is influenced by many soil and site parameters, in a manner that is poorly understood, it would be difficult to develop simple design charts that accurately represent lateral spreading behavior. To consider all of the variables that affect a lateral spread, an analytical technique is needed to define a good empirical model. As discussed here, artificial neural networks were considered, but statistical regression analyses were chosen for the EPOLLS model.

A neural network is a computer algorithm designed to mimic the way a biological brain processes multiple inputs to arrive at a conclusion (Dayhoff 1990). Brains are composed of huge numbers of simple, individual neurons that are interconnected in numerous and complex ways: the power of a brain derives from the tremendous number of connections between individual neurons. In an analogous manner, an artificial neural network simulates a large number of very simple, interconnected processors with special computer software. A neural network model is "trained" by processing several sets of input data to find associations between the input data and output solution. With the advent of powerful computers, neural networks show promise for solving complex engineering problems where relationships between numerous system parameters and a given response are poorly understood.

However, without more case studies for the EPOLLS database, a reliable neural network model for lateral spreading is probably not feasible. The correlation between individual input and output variables (indicated by the weight and bias terms in the trained network) can vary significantly with small changes in successive attempts to train a neural network. A good set of training examples, which reflects the full range of variability in the input parameters, is essential to developing a neural network that can be used to predict future responses (Dayhoff 1990). Given the limited number of lateral spreads in the available database, a neural network would be a poor choice for the EPOLLS model. Moreover, a neural network for the EPOLLS model would be difficult to distribute to other users. For a trained neural network, no simple mathematical expression can be presented showing the relationships between the input and output parameters.

Regression analyses can be used to identify statistical best-fit relationships between variables in a given data set. Multiple linear regression techniques (reviewed in Appendix D) assume that a system response is linearly related to a set of independent variables. Given a database adequately representing the conditions of interest, a regression analysis can yield a reliable model that can be expressed with simple algebraic equations. Based on the stated objective of developing a simple and reliable model, a multiple linear regression analysis was chosen to develop the EPOLLS model. This approach was also used by Bartlett and Youd (1992a; 1992b; 1995) in deriving their empirical model for lateral spreading.

The success of the EPOLLS regression model depends heavily on the database.

Unfortunately, the number of published investigations of lateral spreading is not large. As pointed out by Montgomery and Peck (1992), data sets developed from historical records invariably rely on "happenstance" data:

"Happenstance data are often saturated with defects including outliers, 'wild' points, and inconsistencies resulting from changes in the . . . data collection and information-processing system over time. These data defects can have great impact on the parameter selection process and lead to model misspecification . . . that only the model builder's nonstatistical knowledge of the problem environment may prevent."

Therefore, engineering judgment during development is key to the reliability of the EPOLLS model.

5.3. Definition of a Lateral Spread Case Study.

In fitting an empirical model for making predictions, a fundamental assumption is that all of the observations in the data set are independent of one another. At best, each observation in the data set should represent some unique combination of conditions. If large portions of the data set used in fitting a model represent similar site conditions, a biased, unreliable model may be obtained. For example, using data on lateral spreads entirely from one small geographical area may yield a fitted empirical model that gives misleading predictions for other areas. Hence, a critical consideration in developing the EPOLLS model is the independence of the observations in the database. As Liao and Whitman (1986) point out, this problem can be thought of in terms of how a single "case study data point" is defined in the database.

In the EPOLLS database, a "case study" is defined as a single lateral spread consisting of a contiguous mass of soil moving in the same general direction. Lateral spreading may occur in many places across an area, but separate case studies can be distinguished by the resulting, consistent pattern of horizontal displacements and surface fissures. This is illustrated in Figure 5.2 where four lateral spreads are delineated on a map of observed ground surface displacements. Although somewhat subjective, the boundaries defining a lateral spread case study can usually be located by changes in the topography or the direction of movement.

An alternate approach, where each measured displacement vector is one case study, was used by Bartlett and Youd (1992a; 1992b; 1995) in compiling their database of lateral spreads. For many lateral spreads described in the literature, less than a dozen horizontal displacements were measured. Many more displacement vectors were recorded at some sites. As a result, nearly three-quarters of the case studies (individual displacement vectors) used by Bartlett and Youd come from lateral spreads in just two cities in Japan. As pointed out in Section 4.4, the resulting model is biased toward the conditions found in these areas.

Defining EPOLLS case studies as separate ground failures ensures a reasonable degree of independence within the database. However, since multiple lateral spreads often develop within an area during an earthquake, many of the EPOLLS case studies share common seismic and geologic settings. Hence, the key to constructing a reliable EPOLLS model is the assembly of a sufficiently large and diverse database. Lateral spreads from any single region or earthquake should not represent a large portion of the data set. In the EPOLLS database, case studies are needed that represent a good dispersion of site conditions.

5.4. Overview of the EPOLLS Model.

The EPOLLS model is applicable to lateral spreads resulting from soil liquefaction in earthquakes. Lateral spreading, as defined earlier, is taken to mean the movement of intact soil blocks over a liquefied soil layer with less than a 5% surface slope at sites that may encompass a vertical free face. The scope of the EPOLLS model does not include lateral spreads supported by structures such as walls, large pipelines, and tunnels. In addition, the EPOLLS model is not applicable to liquefaction failures related to the outward movement of earth retaining walls or slumping failures of steeper slopes and embankments. An overview of the complete EPOLLS model is given in Figures 5.3 and 5.4.

The EPOLLS model is designed only for estimating the magnitude of displacements that can occur if the underlying soil liquefies and a lateral spread develops. Potential lateral spreads can be identified, for a given earthquake, based on the topography and geology of a site. As indicated in Figure 5.3, the earthquake hazard, liquefaction potential, and possible development of a lateral spread must be assessed independently prior to using the EPOLLS model. First, the potential for soil liquefaction must be evaluated for the design seismic event based on knowledge of the subsurface soil conditions. If liquefaction is expected over a sufficiently large area, and the surface topography is conducive to lateral spreading, the EPOLLS model can then be used to forecast the likely magnitude of displacements. The EPOLLS model is not intended to predict where a lateral spread might develop, but only the potential deformations where lateral spreading is expected.

As discussed below, probability density functions are used to estimate maximum likely displacements in the EPOLLS model. However, probabilities associated with occurrence of an earthquake and subsequent liquefaction at a given site are not explicitly considered in the EPOLLS model. The model is suitable for quantifying likely displacements in a larger probabilistic evaluation of liquefaction risks.

Average and distribution of displacements.

Individual displacement vectors vary in magnitude across the surface of a lateral spread. In general, smaller displacements tend to occur along the edges of the slide mass while larger

displacements are usually observed in the center of the slide area or in the vicinity of a free face. Displacements also vary with local changes in topography and subsurface geology. The actual pattern of displacements across a lateral spread, involving the movement of intact soil blocks over the liquefied sublayer, is erratic. Furthermore, while an infinite number of displacement vectors exists on the surface of a lateral spread, only a relatively small number of displacements can be measured in a field investigation.

Upon initial examination, it might seem that a good model of lateral spreading should be capable of predicting displacements at specific locations. However, since displacements vary with position on a lateral spread, an empirical model would have to incorporate some measure of relative location on the slide surface. Devising a system to establish this relative position is handicapped by the need to define the edges of a ground failure. With the exception of a possible free face, locating the boundary of a potential lateral spread is a difficult task. In addition, parameters would be needed that could represent the changing topography and geology at specific points on a lateral spread. Since the amount of available site data is usually limited, especially with respect to subsurface data, an empirical model for predicting displacements at specific locations would require parameters that are not readily available.

Furthermore, using the measured displacement of specific points in the derivation of an empirical model would make the model more sensitive to the errors associated with these measurements. In the EPOLLS case studies, the accuracy of the displacement vectors measured is often no better than ± 0.5 m. However, one can assume that these errors are random. Given enough measurements, the mean of the measured displacements should give a good indication of the average displacement across the slide mass. Therefore, greater confidence can be placed in the average and variance of the measured deformations than in the magnitude of any single displacement vector. Even less confidence can be placed in the maximum recorded displacements, because the actual maximum movement may have occurred in an area of a slide lacking reference points, and it is quite possible that the true maximum deformation of a given case study was simply not measured.

Instead of trying to predict displacements at specific locations, the EPOLLS model was designed to estimate the average and standard deviation of the displacements across a lateral spread. The pattern or variation in displacement magnitudes across the surface of a slide is represented with statistical distributions (more correctly, "probability density functions"). As discussed in Chapter 8, the gamma distribution was found to give the best representation of horizontal displacements while the normal distribution was chosen for the vertical displacements. To then estimate maximum displacements, the EPOLLS user selects an appropriate percentile value of the distribution defined by the predicted average and standard deviation. For both the maximum settlement and horizontal displacement, the 99.5 percentile of the normal and gamma distributions, respectively, are suggested by the analysis in Chapter 8. This design of the EPOLLS model is indicated in the flowchart of Figure 5.3.

Using the EPOLLS model to estimate the average and distribution of displacements in this way is better matched to the needs of the engineering practitioner. Engineering evaluations of lateral spreading hazards are often driven by the average or maximum displacements that might occur, as opposed to the displacement expected at a specific location. Most structures will be severely damaged by even moderate displacements in a lateral spread; a prudent evaluation will usually call for mitigation efforts to either prevent liquefaction or isolate the structure from ground deformations. On the other hand, the EPOLLS methodology is well suited for assessing the impact of lateral spreading on regional networks of lifeline systems. In this application, predictions of average and maximum likely displacements are more useful than displacements predicted for specific locations on a lateral spread.

Organization of four model components.

The full EPOLLS model is comprised of a suite of eight complementary equations for predicting ground surface displacements on a lateral spread. Specific model equations, utilizing three different classes of site information, can be used to predict the average or standard deviation of both horizontal and vertical displacements. When little site data are available, but liquefaction and lateral spreading are expected, approximate estimates of the horizontal displacements can be made. As additional site data are obtained, better predictions of displacement can be obtained from the appropriate component of the EPOLLS model. Vertical displacements can be predicted only when subsurface soil data are available. The EPOLLS method is thus useful in phased liquefaction risk studies: starting with regional risk assessments and minimal site information, more precise predictions of displacements can be made with the addition of detailed, site-specific data.

The four components of the EPOLLS model, with the associated classes of input parameters, are indicated in Figure 5.4. Each component of the model has two equations, one for the average displacement (*Avg_Horz* and *Avg_Vert*) and the other for the standard deviation of displacements (*StD_Horz* and *StD_Vert*). Three components of the EPOLLS model yield predictions of horizontal movements, while the fourth is for vertical displacements:

- (1) The *Regional-EPOLLS* (or *R-EPOLLS*) component is suitable for predicting horizontal displacements in seismic hazard surveys of geographic regions. Only parameters for the seismic source and local severity of shaking are used in this component, consistent with the general level of information available in regional hazard assessments.
- (2) The *Site-EPOLLS* (or *S-EPOLLS*) component is designed to give improved predictions of horizontal displacements in site-specific studies. Here, additional data on the surface topography and dimensions of the anticipated area of sliding are used. However, predictions are possible with this model component in the absence of detailed data on the subsurface soil conditions.
- (3) The *Geotechnical-EPOLLS* (or *G-EPOLLS*) component is designed to give more refined predictions of horizontal displacements in site-specific studies when additional data from soil borings are available.

- (4) The *Vertical-EPOLLS* (or *V-EPOLLS*) component can be used to get rough estimates of vertical displacements on a lateral spread, and requires data on the subsurface soil conditions.

Taken together, the Regional-, Site-, and Geotechnical-EPOLLS model equations give reasonably good predictions of horizontal movements. However, the Vertical-EPOLLS model is much less reliable and should only be used for rough, first-order estimates of vertical deformations that might occur on a lateral spread.

The EPOLLS model is perhaps most useful for inexpensively assessing the impact of lateral spreading on existing facilities at a variety of locations. As discussed by Honegger (1992), regional assessments of earthquake risks to lifeline systems typically rely on very simple analyses to forecast the magnitude of damage and prepare for emergency repairs. These analyses are usually not refined enough to make specific recommendations for remedial work. Rather, regional risk assessments focus additional investigations at selected sites to ensure survivability of the system. Because successive predictions can be made at relatively low cost, the EPOLLS model is particularly well suited for assessments of risk to lifelines that require progressive studies of individual sites across large geographic regions.

5.5. General Limitations of the EPOLLS Model.

Being empirical, the EPOLLS model is valid only over the range of conditions represented in the database used to fit the model equations. The limitations associated with the input parameters are addressed in the discussion of each model component in Chapters 9, 10, and 11. In addition, the model explicitly represents only the geologic settings of the case studies in the EPOLLS database. Most of the EPOLLS case studies are lateral spreads in Japan and the western United States, including Alaska. Therefore, the EPOLLS model best represents plate margin earthquakes along the west coast of North America and the eastern islands of Asia. The reliability of the EPOLLS model outside these regions, where seismic attenuation characteristics may significantly differ, is unknown.

The fit of the EPOLLS model equations to the available data set is not perfect; hence, for a given set of site parameters, predictions of displacements are approximate to some degree. The level of uncertainty arising from the imperfect fit of the model equations can be expressed statistically using confidence levels on the EPOLLS predictions. For example, an upper-bound estimate can be computed for a 90% likelihood that the actual average displacement will be less than the predicted value. However, since the available database of lateral spreads does not represent all possible site conditions, some additional uncertainty is present when using the EPOLLS model. This is an unavoidable limitation of any empirical procedure and can be overcome only with the addition of more case histories to the database.

Finally, it must be recognized that the EPOLLS model may yield conservatively high predictions of deformation magnitudes because of an inherent bias in the database. That is, the natural tendency in a post-earthquake investigation is to focus on larger, more damaging ground failures. Smaller, less damaging events are more likely to be overlooked. Consequently, most published investigations of lateral spreads probably tend to reflect more severe conditions that result in larger surface deformations. In the EPOLLS database, lateral spreads of smaller dimensions or insignificant deformation may be under-represented with respect to their relative occurrence in a large earthquake. Because this problem arises from limitations in the published data, it is difficult to quantify this suspected bias in the EPOLLS model. Figure 6.9 in the next chapter shows histograms of the average displacements compiled in the EPOLLS database. Fortunately, these plots indicate that a large number of small-deformation events, with average horizontal displacements less than two meters, are present in the EPOLLS data set. Based on this evidence, the fitted EPOLLS model is not thought to be overly biased toward the more damaging lateral spreads.

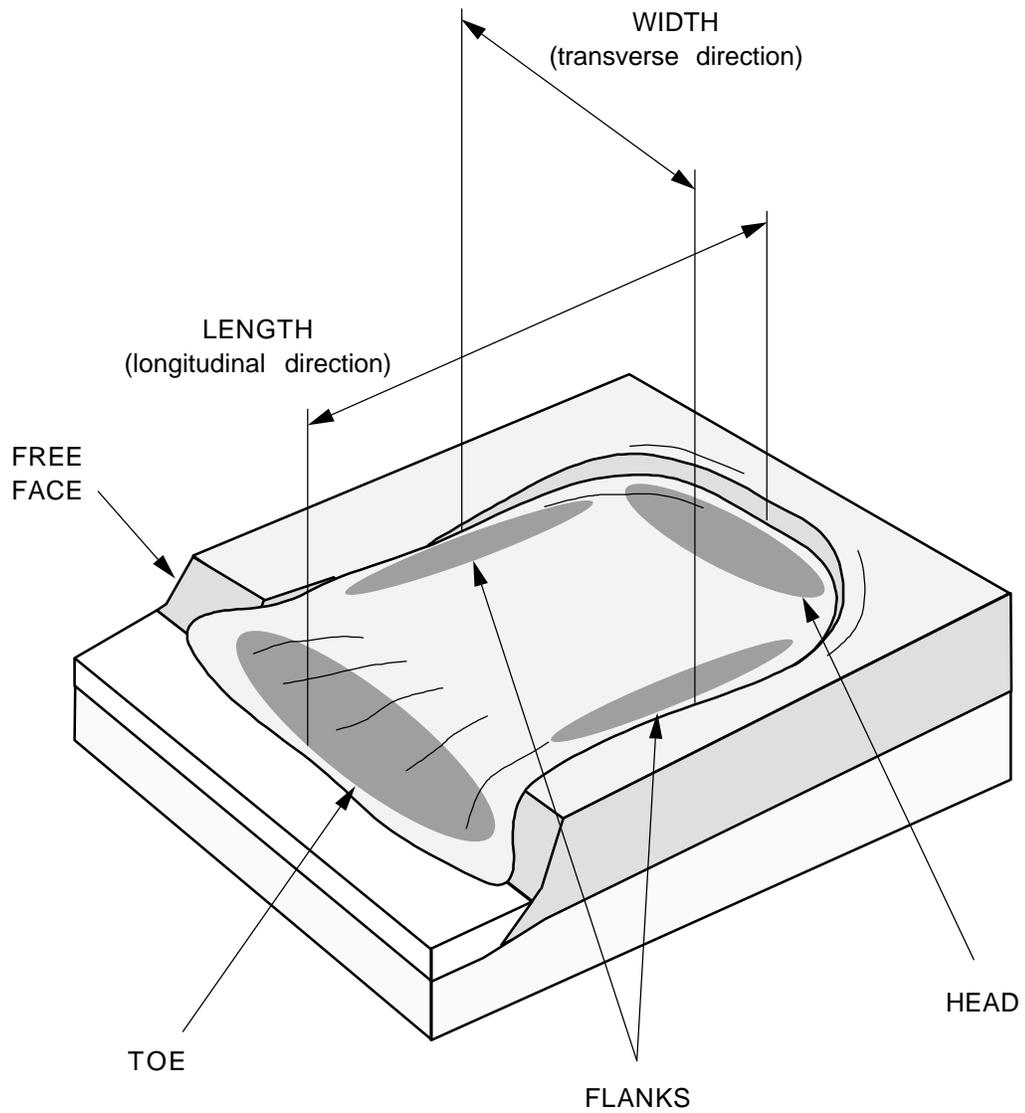


Figure 5.1. Nomenclature associated with a liquefaction-induced lateral spread.

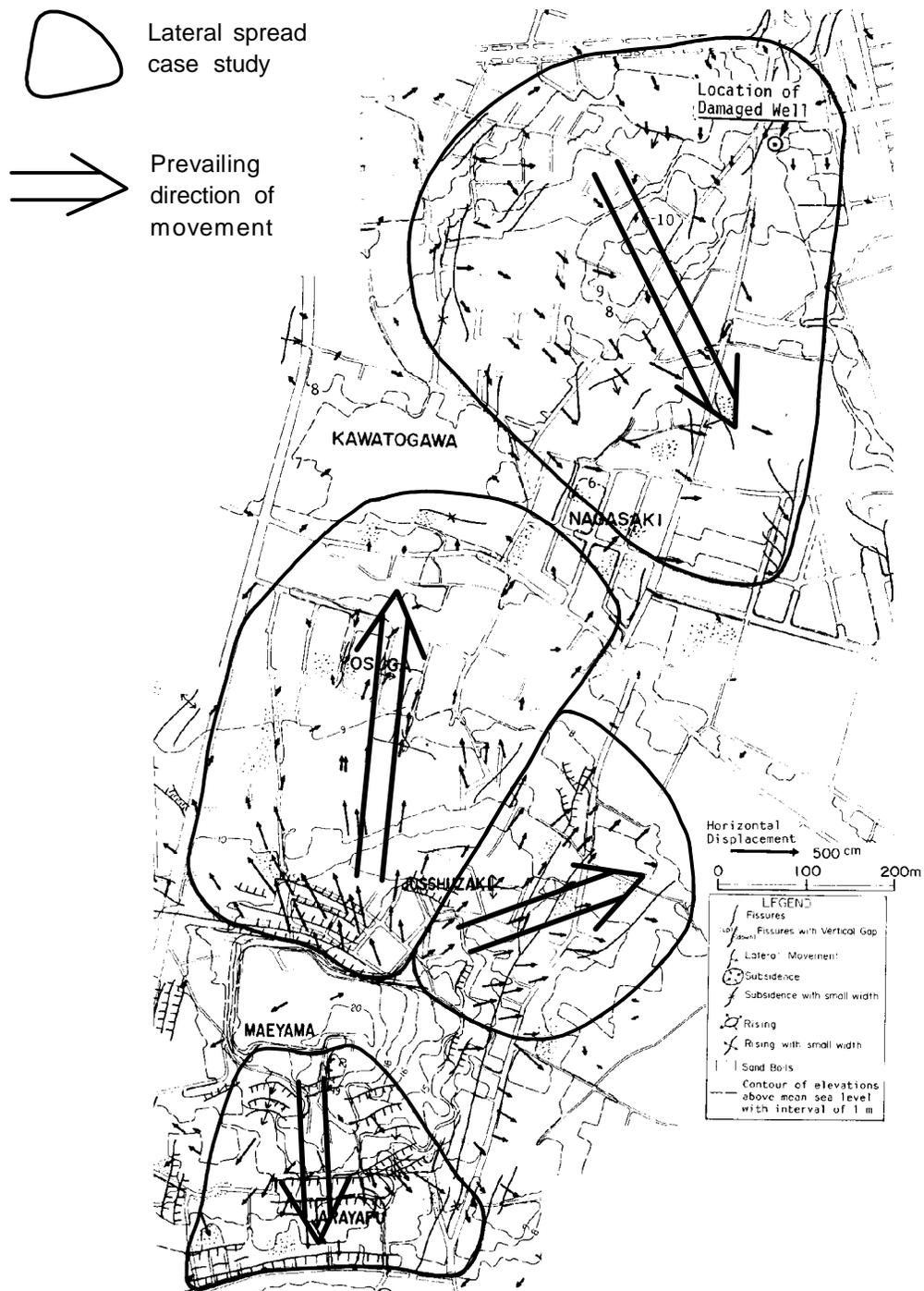


Figure 5.2. Delineation of four lateral spreads in Noshiro, Japan, for the EPOLLS database (base map from Hamada 1992b).

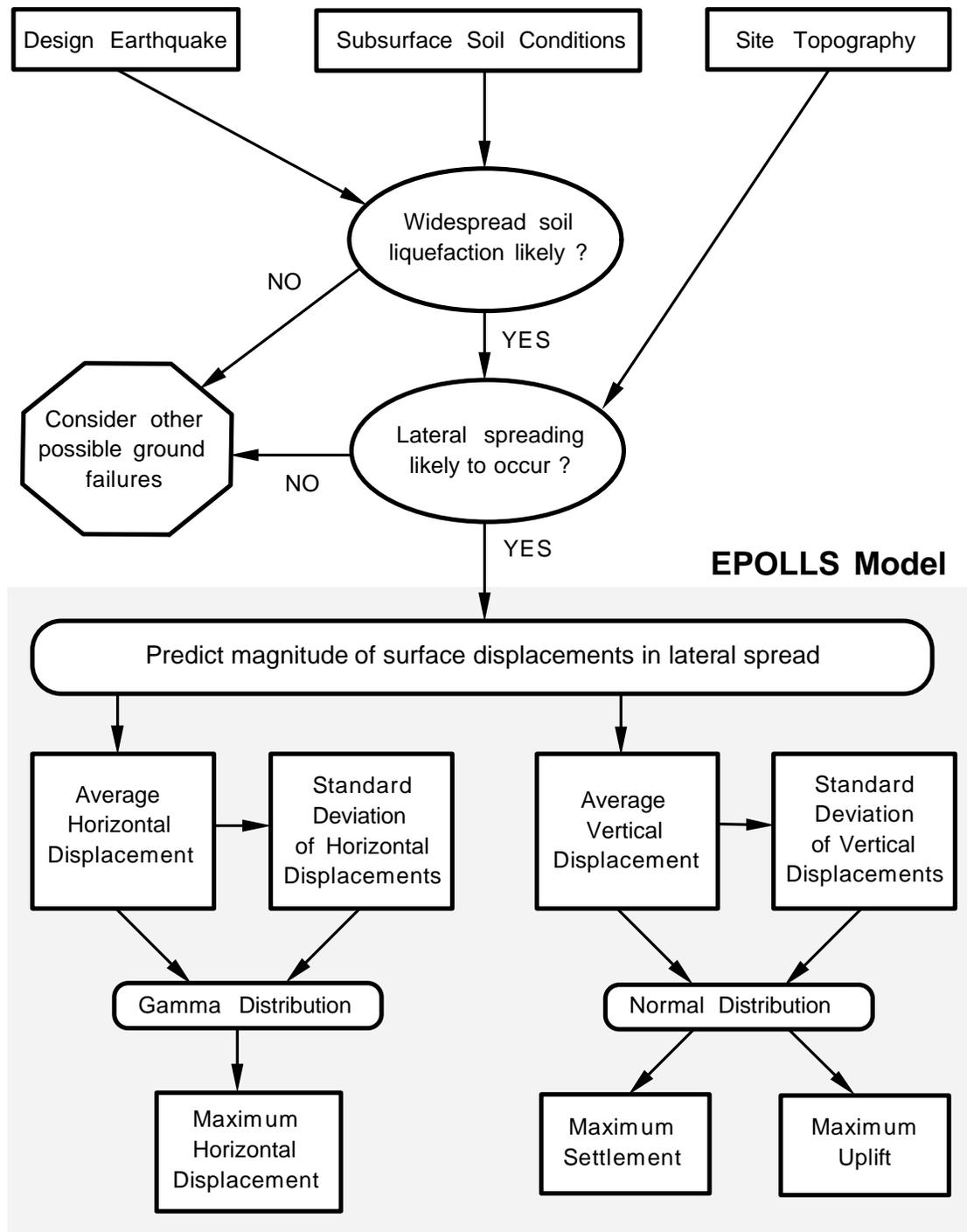


Figure 5.3. Flowchart showing application of the EPOLLS model in the evaluation of soil liquefaction and lateral spreading.

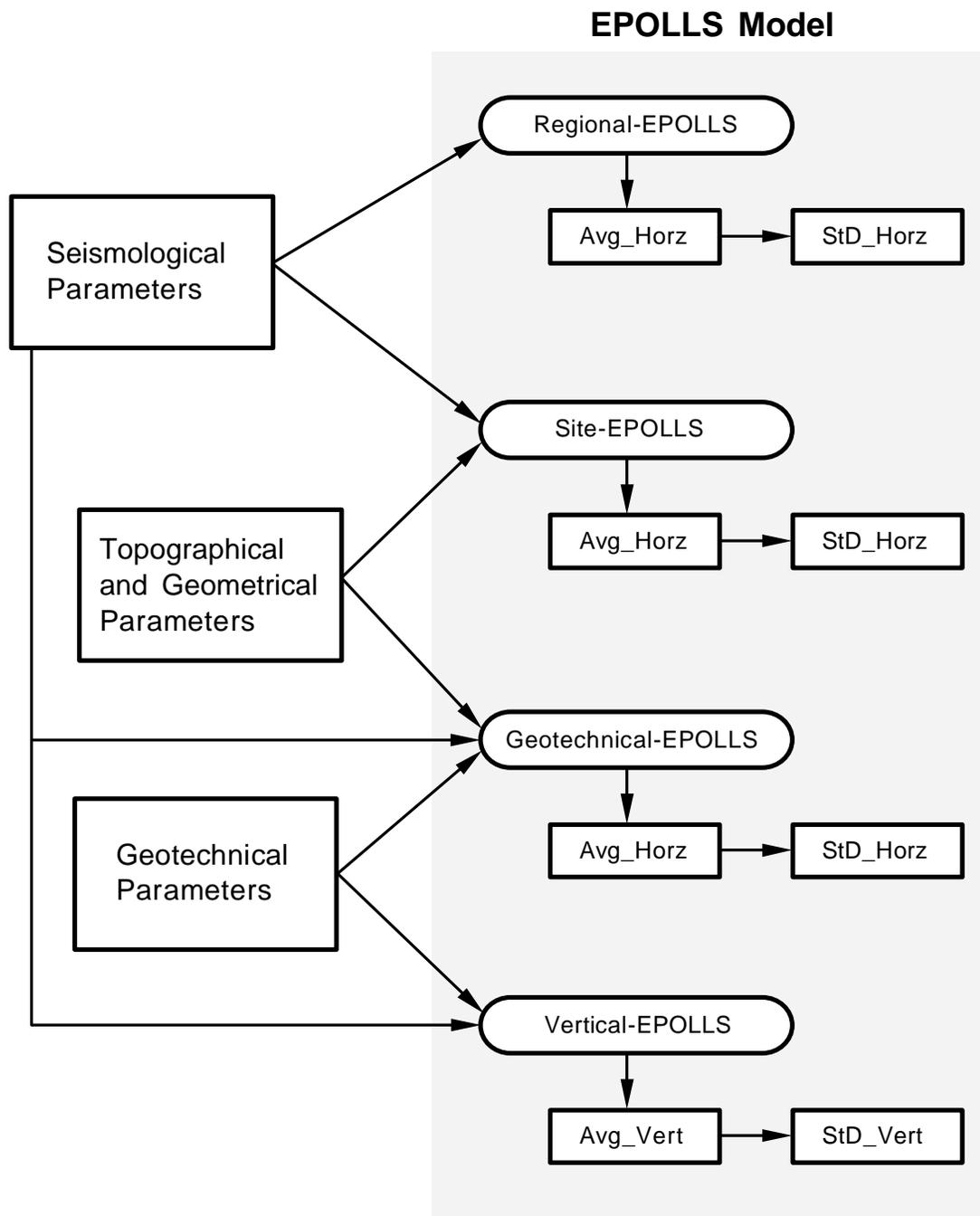


Figure 5.4. Flowchart for input data used in the four components of the EPOLLS model.