
Chapter 12

EPOLLS Model Summary and Conclusions

12.1. Liquefaction-Induced Lateral Spreading.

In this study, *soil liquefaction* is defined as the significant loss of shear strength in saturated, cohesionless soils resulting from the build-up of pore water pressures and loss of effective stress during an earthquake. In large-magnitude earthquakes, substantial damage often results from ground deformations caused by liquefaction in subsurface soils. If an underlying soil deposit liquefies over a sizable area during an earthquake, large horizontal movements can occur even at sites with a mild surface slope. *Lateral spreading* is defined as the lateral deformation of gently sloping ground (<5%) as a result of pore pressure build-up or liquefaction in a shallow underlying soil deposit during an earthquake. A liquefaction-induced lateral spread is depicted schematically in Figure 1.1. When the underlying deposit liquefies, blocks of intact surficial soil move down the slope or toward a vertical free face, such as a stream bank. Occurring at sites with a nearly level ground surface and shallow, saturated, cohesionless soils, lateral spreads develop most often in alluvial deposits along streams. Note that "lateral spreading", as defined here, does not refer to lateral deformation failures associated with the movement of retaining walls or the slumping of embankments resulting from soil liquefaction.

Horizontal deformations on a lateral spread can range up to several meters with smaller associated vertical displacements. Liquefaction-induced lateral spreads have caused tremendous damage in major historic earthquakes. However, the high cost of earthquake damage associated with lateral spreads typically does not derive from single, devastating lateral spreading events. Rather, costly damages result from the disruption of regional infrastructure caused by numerous lateral spreads over a large geographic area. Regional networks of highways, water supply, and other buried utilities are lifelines that must remain in service to enable emergency response and economic recovery after a major earthquake. Liquefaction and lateral spreading at multiple sites over a metropolitan area are especially destructive to networks of buried pipelines.

Engineers investigating the seismic risks to a lifeline network need to identify areas susceptible to soil liquefaction and, for those sites subject to lateral spreading, predict the magnitude of likely ground deformations. As described in Chapter 4, displacements due to liquefaction-induced lateral spreading have been predicted using empirical, analytical, and

numerical (finite element) methods. These analytical and numerical methods rely on simplified models of liquefiable soils and lateral spreading, and most employ soil parameters that are difficult to measure or accurately estimate. None of these methods have been adequately verified by comparing predicted movements with observed deformations on lateral spreads in the field. Furthermore, in evaluations of liquefaction hazards to regional lifeline networks, models that require more than the most basic soil and site information are often not a practical choice because only a limited amount of site data is available. For these reasons, in engineering studies of liquefaction hazards, empirical methods are usually preferred for estimating surface displacements due to lateral spreading. Prior to this study, the best empirical model for predicting lateral spreading displacements was published by Bartlett and Youd (1995).

In this study, a new empirical model was developed for predicting ground deformations on a liquefaction-induced lateral spread. This new model is referred to with the acronym "EPOLLS", which stands for *Empirical Prediction Of Liquefaction-induced Lateral Spreading*. The model is comprised of eight equations, for estimating the average and standard deviation of horizontal and vertical surface displacements, that rely on different levels of site information. Using multiple linear regression techniques, the model equations were fit to data from published field investigations of lateral spreads. Probability distributions are used in the EPOLLS model to estimate maximum displacements.

12.2. The EPOLLS Database.

The EPOLLS model was developed from data on 78 case studies of lateral spreading that were investigated following past earthquakes. All of the lateral spreads in the EPOLLS database occurred at sites around the Pacific region with most located in Japan, California, and Alaska, and a few additional sites in the Philippines, Central America, and Idaho. The best-documented case studies are located in San Francisco and San Fernando, California, and Niigata and Noshiro, Japan. The EPOLLS database is fully described in Chapter 6 with a complete listing given in Appendix A.

In the EPOLLS database, one "case study" lateral spread is comprised of a soil mass moving in the same general direction. Where liquefaction and lateral ground deformations occurred across a very large area, the limits of individual lateral spreads were delineated based on the site topography, locations of surface fissures, and patterns of the measured displacements. The consideration of the entire slide mass as one lateral spread case study is unique to the EPOLLS database and model. Other empirical models for lateral spreading were developed from data associated with individual displacement vectors or the maximum movement recorded at a site.

Within the boundaries of an EPOLLS case study, the average, standard deviation, and

maximum measured displacements (horizontal and vertical) were recorded in the database. Displacements at specific locations on a lateral spread were measured as: (1) offsets in curbs, fences, drainage channels, etc., as well as compression or extension of bridges and pipelines, (2) cumulative offsets across fissures in the ground surface, (3) movements of reference points, determined from engineering site surveys, and (4) movements of reference points identified in aerial photographs. For the database, the average and standard deviation was computed from all of the measured point displacements within the boundaries of a case study lateral spread. For some case studies, the approximate average or maximum movements were reported by site observers just after the earthquake.

The EPOLLS database contains lateral spreads that experienced fairly limited deformations as well as data from sites subjected to very damaging failures. Using the average horizontal displacement (*Avg_Horz*) as an indication of the severity of the ground failure, the majority of the EPOLLS case studies are lateral spreads that caused small to medium damage. While five case studies have an *Avg_Horz* greater than 4 m, eleven other case studies have an *Avg_Horz* less than 0.2 m. Most of the 78 lateral spreads studied experienced less than 1.6 m of average horizontal displacement.

Various aspects of the mechanics at work in a lateral spread are discussed in Chapter 3, including the behavior of liquefied soil, movement of pore water, and inertial effects. By considering how these factors might affect ultimate deformations, site parameters such as the average surface slope and thickness of liquefied soil were identified as potentially significant in a model for predicting displacements. Fifty-seven variables were defined and compiled in the EPOLLS database. These variables fall into four groups: seismological, geometrical, topographical, and geotechnical parameters. Because of the limited data available from some sites, several of the database parameters could not be defined for all of the EPOLLS lateral spreads. Only the seismological parameters are known for every case study in the database.

12.3. The EPOLLS Model.

The EPOLLS model equations were developed for predicting the average and standard deviation of the horizontal and vertical displacements on a lateral spread. Thus, model predictions represent the variation in displacement magnitudes across the surface of a lateral spread, and not displacements at specific locations on the slide. Eight model equations are organized into four components of the EPOLLS model:

- (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 three components of the EPOLLS model for horizontal displacements are shown in the Figure 12.1 with the vertical displacement component shown in Figure 12.2.

The EPOLLS model for predicting horizontal displacements was organized into the Regional, Site, and Geotechnical components for two reasons. First, the values of several model parameters are unknown for many of the sites in the EPOLLS database. Fitting the model equations in succession allowed for the maximum number of case studies to be used in defining the model coefficients. For example, 68 case studies were used to define the coefficients in the Regional-EPOLLS model for average horizontal displacement, but one or more of the Site-EPOLLS variables were unknown in about ten of these case studies. The R-EPOLLS coefficients were then unchanged when the S-EPOLLS model was fit to 57 case studies. Secondly, the three model components are arranged to allow progressive evaluations that might start with very little site data but are later improved with additional site information. For example, a preliminary estimate of possible displacements might be made with the R-EPOLLS model, which does not require information on the site topography or geology. With the addition of topographic data, the S-EPOLLS model could then be used to get better predictions of horizontal displacements.

The EPOLLS model was developed using statistical regression analyses to fit linear equations to the compiled database. Regression analyses began with selection of regressor variables that would form the "best" model for predicting displacements. The selected model component was then tested for possible high influence observations in the database and for possible problems with linear dependencies among the regressor variables. The regression analyses also included graphical and statistical evaluations of the performance of the fitted model.

A total of eleven site parameters are used in the four components of the EPOLLS model. Listed in Figures 12.1 and 12.2, these variables are:

- M_w = moment magnitude of the earthquake.
- R_f = shortest horizontal distance from the site to the surface projection of the fault rupture.
- A_{max} = peak horizontal acceleration at the ground surface of the site.
- T_d = duration of strong earthquake motions (≥ 0.05 g) at the site.
- L_{slide} = horizontal length from head to toe of the lateral spread.
- S_{top} = average slope across the surface of the lateral spread, exclusive of any free face.
- H_{face} = height of a free face, measured vertically from toe to crest of the free face.
- Z_{liq} = average depth to the top of liquefied soil.
- H_{liq} = thickness of liquefied soil.

Z_{FSmin} = average depth to the minimum factor of safety in potentially liquefiable soil.

ΔZ_{FSmin} = range in depth (maximum minus minimum depth) to the minimum factor of safety in potentially liquefiable soil.

These variables are defined more completely in Tables 9.2 and 11.3 and are also discussed in Chapter 6.

The above variables were selected in the statistical regression analysis to produce the "best" model for predicting displacements. However, caution must be exercised in attempting to draw conclusions concerning any single parameter that is or is not included in the final model. The apparent significance of any regressor variable depends on the data considered as well as the other variables present in the model. With additional data from other lateral spreads, the parameters selected for inclusion in the model might be different. Also, some site parameters have roughly the same value in most lateral spreads and, consequently, are not significant predictors of displacement in an empirical model. For example, while the gradation of the liquefied deposit probably influences the deformation of a lateral spread, the mean grain size will not be a significant predictor of displacement if this value is approximately the same for most case studies in the database. Moreover, models using somewhat different combinations of the available regressor variables can be found that fit the data nearly as well. Part of the consideration in selecting the variables to include in the model is the ease or difficulty involved in defining a variable for a given site. Some parameters were dropped from consideration for the EPOLLS model simply because their value was unknown in too many of the available case studies. Hence, soil and site parameters that might affect the ultimate deformation of a lateral spread may not appear in the EPOLLS model. The inclusion or rejection of a specific parameter in the EPOLLS model should not be interpreted as strong evidence for the relative influence of that variable in the behavior of a lateral spread.

In performing the regression analysis, the EPOLLS model equations for the average horizontal displacement (Avg_Horz) were actually fit to the square root of Avg_Horz . This was done to stabilize the variance of the model errors in accordance with a fundamental assumption underlying statistical regression methods. However, when the resulting model is transformed to give predictions of Avg_Horz , a known bias is introduced such that displacements are consistently under-predicted. In the final model equations shown in Figure 12.1, this bias is reduced by the addition of constants (0.149, 0.111, and 0.124) to the three model equations for Avg_Horz . As a result, the theoretical, minimum average displacements that can be predicted (when the squared terms in the model equations are zero) are equal to the bias-reducing constants. Consequently, the Regional-, Site-, and Geotechnical-EPOLLS components will always predict average horizontal displacements that are, respectively, greater than 0.149, 0.111, and 0.124 m. These minimum prediction values are acceptable, from a practical standpoint, because the EPOLLS model is only valid for predicting surface movements where a lateral spread causes surface deformation. Considering the magnitude of surface movements in the case study lateral spreads, a minimum prediction level of 15 cm is reasonable. In fact, predictions of these theoretical,

minimum displacements would involve extrapolation beyond the data used to fit the model.

To represent the variation in displacement magnitudes across the surface area of a lateral spread, statistical distributions are used. Based on data from twenty-nine case studies, the gamma distribution was found to give an effective representation of the horizontal displacements on a lateral spread. Moreover, the 99.5 percentile of the gamma distribution yields a conservative prediction of the maximum horizontal displacement. Similarly, vertical displacements on a lateral spread (mostly settlements, but also including possible uplift) can be represented with the normal distribution. The maximum settlement and uplift can be estimated, respectively, at the 99.5 and 1.0 percentiles of the normal distribution. The specific location on a lateral spread, where the predicted maximum horizontal or vertical displacement will occur, is not indicated by the EPOLLS model. However, the largest displacements usually occur in the vicinity of a free face or similar surface feature, in the central portions of the slide area, and in areas with the thickest liquefied soil.

The EPOLLS model is used to predict potential ground surface displacements on a lateral spread, and not where liquefaction and lateral spreading will develop. The likelihood of soil liquefaction and consequent lateral spreading must be established prior to using the EPOLLS model to forecast deformations. In addition, when using any component of the EPOLLS model, values of the model variables should be checked to ensure that the prediction does not involve extrapolation beyond the limits of the data used to fit the model, as discussed in Sections 9.6 and 11.4. For predictions of the average horizontal displacement, a good way to check for possible extrapolation is to compare the values of D_R , (D_R+D_S) , and $(D_R+D_S+D_G)$ with the minimum and maximum limits given in Table 12.1. An example application of the EPOLLS model, in predicting displacements for a hypothetical lateral spread, is shown in Appendix E.

12.4. Performance of the EPOLLS Model.

The coefficients of multiple determination (R^2 and the adjusted \bar{R}^2), which vary between 0 and 1, give an indication of the quality of the fit between the EPOLLS model and the available case study data. A model that explains more of the variation in the observed displacements will yield a higher value of R^2 and \bar{R}^2 . Summarized in Table 12.2 are the R^2 and \bar{R}^2 values for all components of the EPOLLS model. For the average horizontal displacement, better predictions are obtained as one goes from the Regional-EPOLLS ($\bar{R}^2=0.509$) to the Geotechnical-EPOLLS ($\bar{R}^2=0.688$) model components. The additional improvement gained by going from the R-EPOLLS to the Site-EPOLLS model ($\bar{R}^2=0.670$) is greater than that gained by going from the S-EPOLLS to the G-EPOLLS model. The additional improvement in the predictions of the average horizontal displacement is probably not sufficient to warrant a site characterization program to define the required soil parameters. On the other hand, the additional G-EPOLLS parameters can be obtained from the analysis of subsurface explorations performed to assess the

liquefaction potential.

Again referring to Table 12.2, the quality of the fit for the three model components for the standard deviation of horizontal displacements is less than for the average displacement models. In part, this is because the standard deviation of the displacements is known in fewer case studies. Because the three model equations for the standard deviation of the horizontal displacements are simple linear functions of the predicted average horizontal displacement, no additional site parameters are required and the values of R^2 are appropriate for judging the quality of these models. From Table 12.2, the G-EPOLLS model yields an $R^2=0.608$ in predicting the standard deviation of the horizontal displacements.

The quality of the Vertical-EPOLLS model, as indicated by the values of R^2 and \bar{R}^2 in the bottom of Table 12.2, is much lower than for the other components of the EPOLLS model. Specifically, $R^2=0.245$ for the 25 case studies used to fit the V-EPOLLS model for the average vertical displacement. In general, there appears to be an insufficient amount of data to develop a good model for predicting vertical displacements on a lateral spread. EPOLLS model predictions of vertical displacements are much less reliable than predictions of horizontal displacements. Therefore, Vertical-EPOLLS model predictions should be viewed only as rough indications of potential vertical movements on a lateral spread. Other empirical methods for estimating liquefaction-induced settlements are reviewed in Section 4.5.

The least accurate predictions from the EPOLLS model are for the maximum horizontal and vertical displacements. These predictions are less reliable because they are derived from a combination of three model predictions: average displacement, standard deviation of displacement, and a percentile of the gamma or normal distributions. The uncertainty associated with each part of the EPOLLS model is combined in predicting the maximum displacements.

An empirical model for predicting displacements on a lateral spread, comparable to the EPOLLS model, was developed by Bartlett and Youd (1992a; 1992b, 1995). Because Bartlett and Youd's model predicts horizontal displacements at specific locations, while the EPOLLS model predicts the average and variation in displacements across a slide mass, these two models are difficult to compare directly. As discussed in Section 9.5, a comparison between predictions from the EPOLLS model and Bartlett and Youd's model was inconclusive. However, the EPOLLS model is believed to represent an improvement over Bartlett and Youd's model with respect to the following:

- The EPOLLS model is less biased toward the large-deformation lateral spreads in Niigata and Noshiro, Japan. While case studies in these two cities represent 24% of the EPOLLS database, 72% of the data used by Bartlett and Youd were measured in these areas. Moreover, lateral spreads associated with sixteen earthquakes were compiled in the EPOLLS database, while Bartlett and Youd had data from only eight earthquakes.
- In the EPOLLS model, the mass of moving soil in a lateral spread is treated as one event,

as opposed to treating each displacement vector as an "independent" observation. By introducing a statistical distribution to represent the variation in displacement magnitudes, this approach allows for the maximum displacement on a lateral spread to be predicted in terms of a probability.

- A more thorough statistical analysis was performed for the EPOLLS model including the examination for possible high influence data and linear dependencies among the model variables.
- With the EPOLLS model, displacements can be estimated without extensive site data. Better predictions can be obtained with the addition of topographic and subsurface information. This aspect should be attractive to engineers doing seismic hazard mapping or preliminary site studies where detailed information is lacking.

12.5. Application of the EPOLLS Model.

The EPOLLS model, comprised of four components, is a new empirical method for predicting ground surface displacements due to soil liquefaction and lateral spreading in earthquakes. While designed primarily for predicting horizontal movements, one model component was developed to give rough estimates of the vertical displacements. The EPOLLS model was conceived for forecasting the severity of deformations due to lateral spreading at a given site, as opposed to predicting displacements at specific locations on a lateral spread. Treating the mass of moving soil in a lateral spread as one event, the EPOLLS model attempts to predict the distribution of horizontal and vertical displacement magnitudes across the surface of a lateral spread. Model equations are used to estimate the average and standard deviation of displacements within the boundaries of a lateral spread. Then, using probability distributions, the maximum likely displacement at the site can be estimated. However, the location of the maximum displacement is not explicitly predicted.

Using statistical regression techniques, the EPOLLS model was developed from a database of 78 lateral spreads. Reliability of the model is unknown outside the range of conditions represented in the database. Hence, application of the EPOLLS model should include a check to see if the predictions require extrapolation beyond the data used to fit the model. In addition, all of the EPOLLS case study sites are located around the Pacific rim (western North America, Alaska, Central America, Japan, and the Philippines). The reliability of EPOLLS model predictions in other regions of the world is unknown. Finally, because post-earthquake investigations tend to focus on the most severe ground failures, the EPOLLS database and model may be inherently biased toward larger and more damaging lateral spreads; however, the severity of this possible bias is probably not serious.

As with all empirical models, the reliability of the EPOLLS model can be verified only when data on additional lateral spreads become available. Based on the available data used to fit

the model equations, the EPOLLS model is believed to produce a reasonably accurate prediction of the average horizontal displacements. On the other hand, the precision of these predictions is much less; that is, any single prediction of the average horizontal displacement is likely to be in error by as much as a meter, but the model should be reliable in correctly indicating the severity of lateral spreading deformations. The accuracy of predicted maximum horizontal displacements, as well as vertical displacements, is much less.

Being fairly simple and inexpensive to use, the new EPOLLS model is a good tool for predicting ground deformations due to liquefaction-induced lateral spreading. The model should be especially valuable for progressive studies of liquefaction hazards: starting with minimal information, displacements can be estimated while better predictions are possible with the addition of more detailed site data. In a regional seismic hazard evaluation, where the incidence of liquefaction and lateral spreading can be forecast based on geologic maps, the Regional-EPOLLS model can be used to estimate horizontal deformations without detailed site information. After identifying sites that warrant further study, better predictions of horizontal movements can be obtained with data on the site topography and the Site-EPOLLS model. With additional data from soil borings at a site, better predictions of the horizontal deformations, as well as estimates of the vertical displacements, can be obtained with the Geotechnical- and Vertical-EPOLLS model components. As noted previously, the improvement garnered from the Geotechnical-EPOLLS model is not sufficient to justify an extensive soil boring program.

While the EPOLLS model predictions are not highly precise, even approximate predictions of displacements are useful as the first step in an engineering site analysis. In this sense, the EPOLLS model is well-suited for preliminary hazard studies in which sites subject to liquefaction and lateral spreading are ranked according to the potential for large deformations. The EPOLLS model is also well-suited for assessments of potential liquefaction damage to lifeline networks. In this application, numerous sites over a large geographic area can be studied with minimal site information. In general, the EPOLLS model is intended to be used more in regional studies of liquefaction hazards than in detailed site studies.

In evaluating the impact of lateral spreading on a single, critical structure, the EPOLLS model should be used in conjunction with other methods for predicting potential ground deformations. Additionally, the EPOLLS model will not be very useful for evaluating the effectiveness of site improvement measures undertaken to limit potential deformations due to lateral spreading. For example, the effect of a soil buttress or retaining wall can not be considered in the current form of the model. Also, the EPOLLS model assumes liquefaction of the underlying soils and is incapable of predicting deformations, associated with soil softening during an earthquake, when soil improvements at the site prevent complete liquefaction.

Table 12.1. Range of model parameters corresponding to the limits of the field data used to fit the EPOLLS model components for average horizontal displacement.

Model Component	Factor	Minimum Value	Maximum Value
Regional-EPOLLS	D_R	2.57	3.88
Site-EPOLLS	$D_R + D_S$	2.81	4.35
Geotechnical-EPOLLS	$D_R + D_S + D_G$	2.82	4.53

Table 12.2. Summary of statistics indicating the quality of fit for the EPOLLS model.

Component of the EPOLLS model	Number of case studies with no missing parameters	R^2	\bar{R}^2
<i>For average horizontal displacement</i>			
Regional-EPOLLS	71	0.537	0.509
Site-EPOLLS	58	0.710	0.670
Geotechnical-EPOLLS	45	0.752	0.688
<i>For standard deviation of horizontal displacement</i>			
Regional-EPOLLS	40	0.477	0.400
Site-EPOLLS	39	0.590	0.481
Geotechnical-EPOLLS	30	0.608	0.402
<i>For average vertical displacement</i>			
Vertical-EPOLLS	25	0.245	0.176
<i>For standard deviation of vertical displacement</i>			
Vertical-EPOLLS	17	0.512	0.480

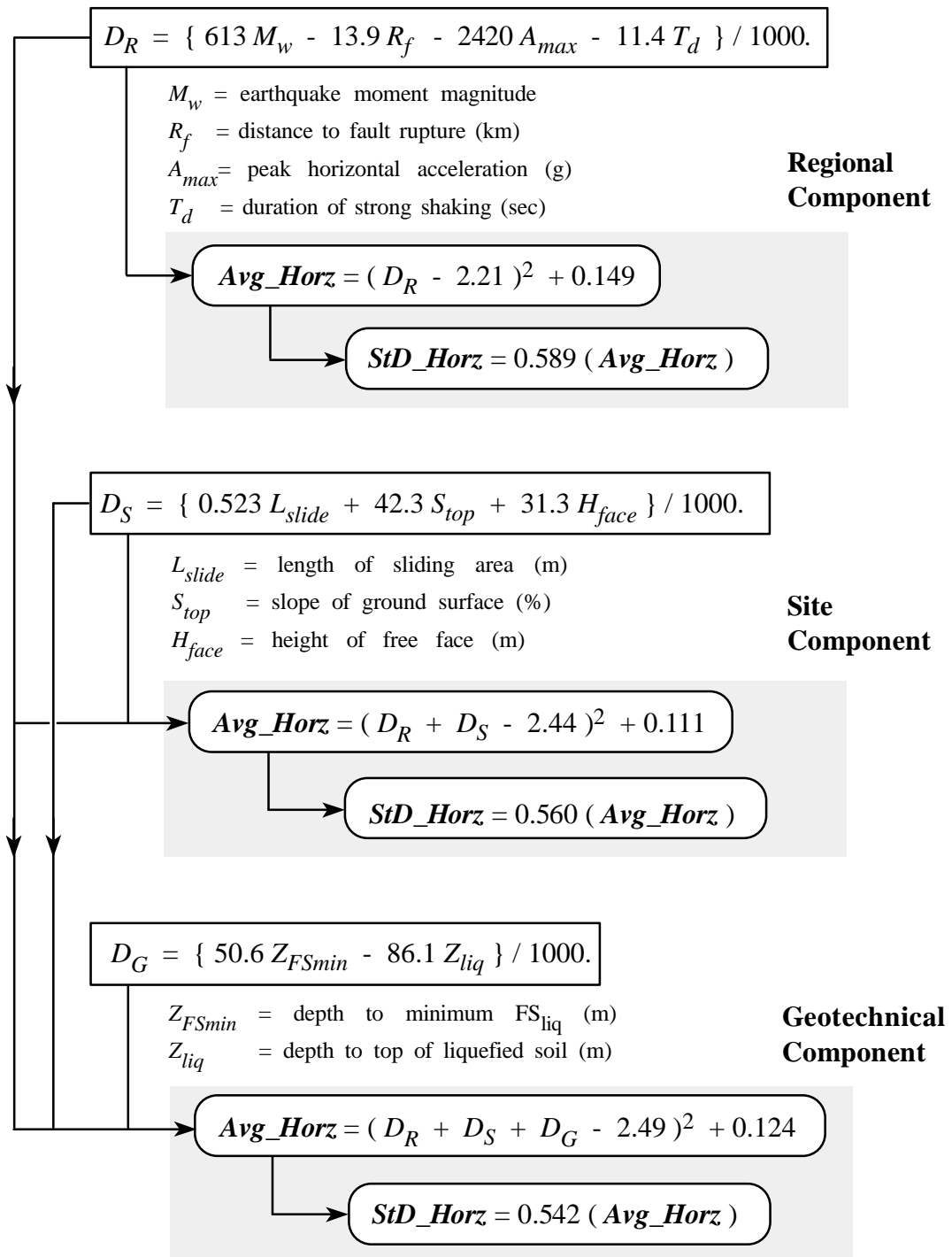


Figure 12.1. Overview of EPOLLS model for predicting the average and standard deviation of horizontal displacements (Avg_Horz and StD_Horz) in meters.

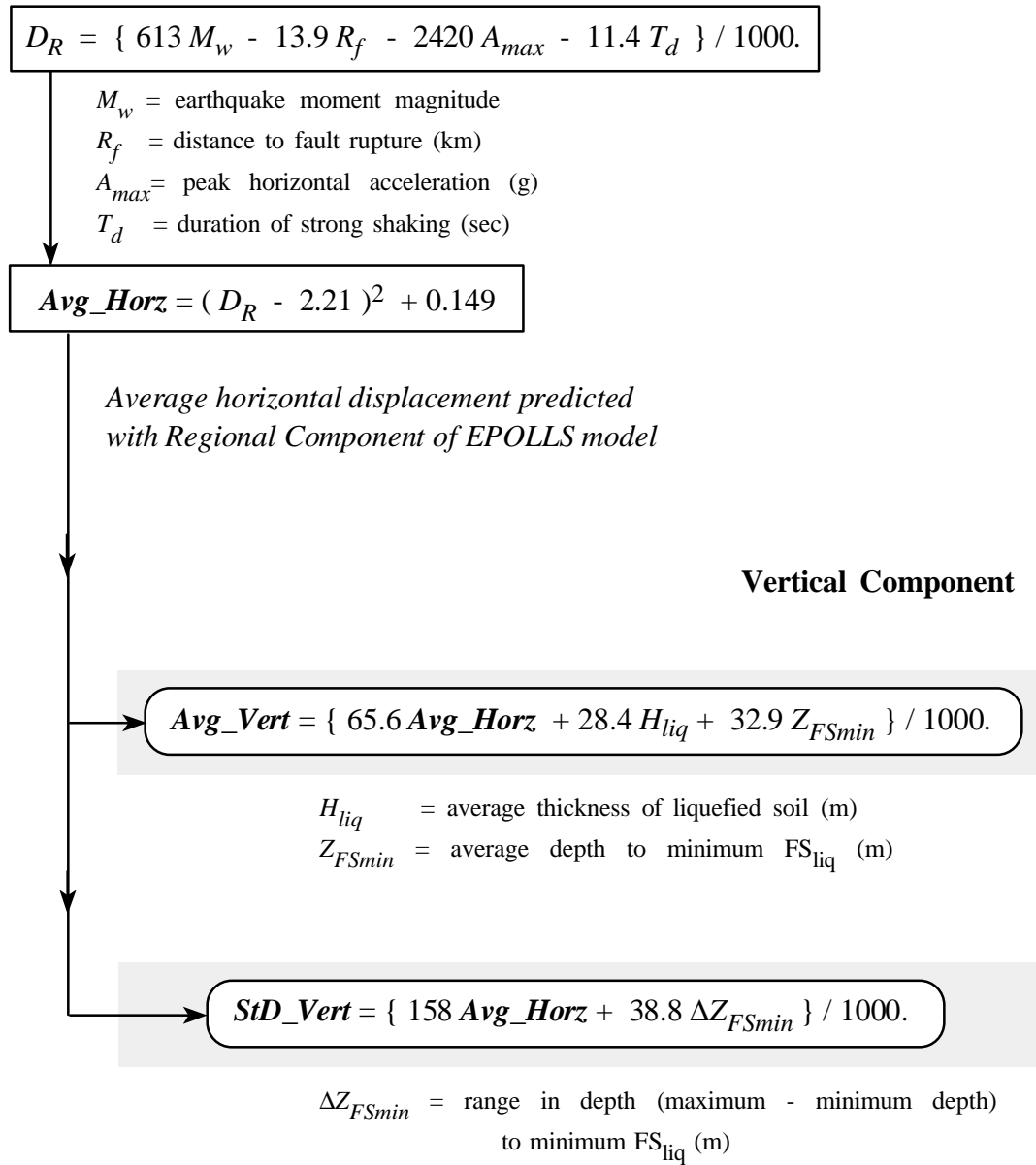


Figure 12.2. Overview of EPOLLS model for predicting the average and standard deviation of vertical displacements (Avg_Vert and StD_Vert) in meters.