Dealing with uncertainty in prediction of lateral spread

S.J. Palmer & V.S. Smith

Tonkin & Taylor Ltd., Wellington, New Zealand.

ABSTRACT

Prediction of lateral spread for seismic assessment and design includes considerable uncertainty. Two widely used prediction methods are Youd et al. (2002) and Zhang et al. (2004). Five case studies across the Wellington region revealed poor agreement between these methods. Typically, one method predicted displacements of the order of ten times the other; metres compared to hundreds of millimetres. In some cases, Zhang et al. (2004) predicted the higher displacement and in other cases Youd et al. (2002) predicted the higher displacement. This highlighted the uncertainty in predicting lateral spread. This paper considers how this uncertainty can be understood and allowed for in assessment and design. It concludes that in applying any method of prediction of lateral spread, the limitations of that method must be understood. Various methods and their limitations are discussed. Multiple methods of predicting lateral spread should be applied, and the results critically assessed before applying engineering judgement to select a likely range and the likelihood of displacements beyond this range. It is proposed that where damaging lateral spread is possible, foundation designs should be developed which are independent of the magnitude of lateral spread, e.g. develop the design to resist full passive pressure of laterally spreading ground rather than tolerating an assessed magnitude of lateral spread.

1 INTRODUCTION

Youd et al. (2002) and Zhang et al. (2004) are routinely applied for predicting lateral spread. These authors separately report that their method can generally predict lateral spread within 50% and 200% of actual values. However, these claims are based on testing the same data as was used to develop the methods. Independent data would likely indicate less reliability. Parameters from five Wellington sites have been applied to predict lateral spread by both methods. The results showed very poor agreement between the two methods. There was generally a factor of 10 (hundreds of millimetres compared to metres) between the two methods. For some sites, Youd et al. (2002) gave the larger result and for other sites Zhang et al. (2004) gave the larger result. This indicates the uncertainties in predicting lateral spread and the dangers of relying on one method.

This paper provides information to assist in applying these methods, and others, in selecting values of lateral spread to be assumed in assessment or design. The information presented includes:

- A description and comparison of the basis of the development of these empirical methods.

- Sensitivity of the methods to input parameters.
- A comparison of analysis results from the two methods for five Wellington sites.
- Discussion of dealing with the uncertainty in predicting lateral spread, including application of mechanistic methods in addition to these empirical methods and critical assessment of each method and its result.
- Recommendations for assessment of lateral spread and application to design.

2 BASIS OF METHODS

2.1 Youd et al. (2002)

This is an empirical method. The method was published in Bartlett and Youd et al. (1995) and updated in Youd and Bartlett et al. (2002). Youd (2018) provides a commentary on the application of the method. A multi linear regression (MLR) was applied to a database of observed and investigated lateral spread sites to identify which parameters were statistically significant in predicting lateral spread and to develop equations to predict lateral spread.

The input parameters used in the equations are:

- Earthquake shaking:
    - M: Magnitude
    - R: Distance of site from the seismic energy source. Procedures are also provided for predicting an equivalent R_{eq} based on M and PGA. Expressed in kilometres.
- Geometry:
    - W: Ratio of the free face height to distance to the point of interest (L) expressed as a percentage, or
    - S: Ground surface slope expressed as a percentage.
- Soil conditions
    - T_{15}: Cumulative thickness of liquefied layers with $(N_1)_{60} < 15$, expressed in metres.
    - F_{15}: Average fines content of soils within the T_{15} layer, expressed as a percentage.
    - $D50_{15}$: Average mean grain size for granular materials within the T_{15} layer, expressed in millimetres.

2.2 Zhang et al. (2004)

This is a semi empirical method. Based on empirical correlations, equations are proposed to predict lateral spread. The input parameters to the equations are:

- LDI: Liquefaction displacement index, expressed in metres.
- L/H: Distance (L) to the point of interest from the free face divided by the free face height (H), or
- S: Ground surface slope.

LDI is a parameter developed by Zhang et al. which they assess is related to lateral spread potential. LDI is the maximum cyclic shear strain (γ_{max}) integrated over the thickness of the potentially liquefiable layers. The maximum cyclic shear strain is predicted from empirical relationships with the soil's relative density and its factor of safety against liquefaction. The factor of safety against liquefaction is assessed via the routine methods of assessing liquefaction triggering. Consequently, LDI is dependent on:

- Earthquake M and PGA.
- CPT or SPT values.
- Fines content.

- Cumulative thickness of liquefiable soils.

Conveniently, software is available to calculate LDI from CPT data. This is a semi empirical method. It assumes that the LDI parameter relates to the mechanism of lateral spread and then correlates LDI with lateral spread.

2.3 Database

Both Youd et al. (2002) and Zhang et al. (2004) applied databases of observed lateral spread to develop their methods. The databases used by the researchers are similar and there is a lot of cross over. Both databases included in the order of a dozen earthquakes and a couple of hundred examples of lateral spread from those earthquakes. The bulk of the data fitted into the following:

- Earthquake shaking:
    - M: 6.5 to 7.5.
    - PGA: 0.2 to 0.3g.
- Geometry:
    - Distance from toe of free face, L: 4H to 20H where H is the free face height.
- Soil conditions
    - Thickness of liquefied layer: A cumulative thickness of 1 m to 8 m and individual layers greater than 1 m thick.
    - Particle size (D50): 0.1 mm to 0.8 mm.
    - Fines content (FC): < 30%.

The databases did include some data beyond the above ranges, but it was limited. Predicting lateral spread by these methods for situations outside of these ranges will have increased uncertainty.

3 SENSITIVITY TO INPUT PARAMETERS

Table 1 summarises a sensitivity assessment of the Youd et al. (2002) and Zhang et al. (2004) methods. Sensitivity is undertaken on a specific parameter as is indicated by the horizontal shading in Table 1 while all other parameters are held constant as is indicated by the vertical shading in the Table 1. The calculated lateral spread, D_H, for each sensitivity calculation is recorded for each method. The nomenclature used in Table 1 is defined in sections 2.1 and 2.2.

The following subsections discuss the results of the sensitivity study.

Table 1: Sensitivity review of Youd et al. (2002) and Zhang et al. (2004).

Earthquake	**M**		**8**	**7.5**	**7**	**6.5**
	D_H (Youd)		3 m	1.1 m	0.3 m	0.06 m
	D_H (Zhang)		0.3 m	0.3 m	0.3 m	0.1 m
	PGA	**0.56g**	**0.48g**	**0.4g**	**0.3g**	**0.2g**
	R	**1 km**	**5 km**	**10 km**	**15 km**	**25 km**
	D_H (Youd)	3.0 m	1.2 m	0.5 m	0.3 m	0.1 m
	D_H (Zhang)	0.3 m	0.3 m	0.3 m	0.3 m	0.05 m

Geometry	**W**			**25% (4H)**	**12.5% (8H)**	**6.25% (16H)**	**2% (50H)**	
	D_H (Youd)			0.5 m	0.3 m	0.2 m	0.1 m	
	D_H (Zhang)			0.6 m	0.3 m	0.15 m	0.1 m	
Soil	**F_{15}**	**5%**	**10%**	**15%**	**30%**	**50%**		
	D_H (Youd)	0.9 m	0.7 m	0.6 m	0.3 m	0.1 m		
	D_H (Zhang)	Small influence on trigger M and PGA for liquefaction and lateral spread						
	D_{50}			**0.2 mm**	**0.4 mm**	**0.8 mm**	**2 mm**	**4 mm**
	D_H (Youd)			0.45 m	0.3 m	0.2 m	0.1 m	0.06 m
	D_H (Zhang)	D_{50} does not influence the liquefaction potential and lateral spread displacement						
	T_{15}	**15 m**	**12 m**	**6 m**	**3 m**	**1.5 m**		
	LDI	**2.5 m**	**2 m**	**1 m**	**0.5 m**	**0.25 m**		
	D_H (Youd)	0.7 m	0.65 m	0.45 m	0.3 m	0.2 m		
	D_H (Zhang)	1.5 m	1.2 m	0.6 m	0.3 m	0.15 m		

3.1 Earthquake shaking

For the Youd et al. (2002) method, predicted lateral spread increases sharply with increasing M and/or PGA above 7 and 0.4g respectively. Youd et al. (2002) proposes the method is valid for $6 < M < 8$, however we note that the reference database included limited information for M and/or PGA above 7.5 and 0.3g respectively and therefore suggest the method should be applied with caution at higher earthquake energies and/or intensities.

For the Zhang et al. (2004) method, earthquake parameters (M and PGA) are allowed for in the liquefaction triggering analysis which provides the input to calculate the LDI. Consequently, LDI and magnitude of lateral spread are highly sensitive to M and PGA at or slightly above liquefaction triggering but insensitive to M and PGA values above or below the triggering. The Zhang method proposes that all the lateral spread occurs at or slightly above the trigger for liquefaction, which could typically be M7 0.3g or less.

Zhang's model suggesting that most of the lateral spread occurs with liquefaction triggering is plausible. Although beyond this triggering and with increasing acceleration and inertia, perhaps some increase in displacement could be expected.

Youd's prediction of large lateral spreads for $M > 7$ and $PGA > 0.4g$ may not be reliable because of the limited data in the database for these larger events.

Actual sensitivity of lateral spread to M and PGA beyond liquefaction trigger requires further research.

3.2 Geometry

The attenuation of displacement with distance from the free face appears to be similar for the two methods.

3.3 Soil conditions

At FC of 30% or higher, Youd et al. (2002) indicates a sharp reduction in lateral spread potential. We note that the database included limited information for $FC < 30\%$ and therefore the proposed reduction in lateral spread at higher fines content should be treated with caution. Youd et al. (2002) proposed reduction in lateral spread potential at higher fines content could be indicating that soils in the database at these high fines content were not susceptible to liquefaction. We suggest that in applying the Youd et al. (2002) method, liquefaction susceptibility and triggering analysis should be undertaken to confirm that the soils making up the T_{15} thickness have a potential for liquefaction. Fines content is considered in the Zhang et al. (2004) method via the liquefaction triggering analysis to evaluate LDI.

The Youd et al. (2002) method suggests a sharp reduction in lateral spread potential for $D50_{15}$ values greater than 0.8 mm. We note that the database has limited examples of laterally spreading soils with $D50_{15}$ values greater than 0.8 mm and suggest predictions with these larger particle sizes should be treated with caution.

Robinson et al. (2013) presents a comparison of observations of lateral spread from the 2010 Darfield and 2011 Christchurch Earthquakes with predictions based on Youd et al. (2002). Robinson et al. (2013) also includes results of a sensitivity analysis of the input parameters over the range relevant to the Christchurch case studies. They noted the sensitivity of predictions to $D50_{15}$ and FC and the interrelationship between these parameters. They also noted that these parameters are highly variable in natural soils. This high variability may have compromised the statistical analysis applied in developing the Youd et al. (2002) method. Further work and analysis of case studies may identify alternative input parameters to $D50_{15}$ and FC for empirical predictions.

4 EXAMPLE SITES

Tables 2, 3 and 4 summarise the results of applying Youd et al. (2002) and Zhang et al. (2004) to the conditions at five sites. All five sites are within flat reclaimed land. In all cases, the free face is the reclamation edge. The sites are located within the Wellington region at Porirua, Pipitea, Te Aro and Evans Bay. Within Site 3, two distances from the free face were considered and are identified as 3a and 3b within the Tables. Similarly, for Site 4.

Table 2: Wellington example sites – Earthquake and geometry parameters

Site	**Earthquake**		**Geometry**		
	M_w	**PGA**	**H**	**L**	**W**
1	7.8	0.24g	18m	4H	25%
2	7.1	0.35g	9m	4H	25%
3a (15H)	7.1	0.59g	3m	15H	6.5%
3b (50H)	7.1	0.59g	3m	50H	2%
4a (13H)	7.1	0.45g	3.5m	13H	8%
4b (30H)	7.1	0.45g	3.5m	30H	3.5%
5	7.8	0.7g	13m	5H	22%

Table 3: Wellington example sites – Youd et al. (2002) predicted displacements (D_H)

Site	**R or R_{eq}**	**F_{15}**	**$D50_{15}$**	**T_{15}**	**D_H (Youd)**
1	34 km	10%	4 mm	15 m	1.0 m
2	13 km	10%	4 mm	7 m	0.5 m
3a	1 km	30%	0.4 mm	2 m	1.8 m

Site	R or R_{eq}	F_{15}	$D50_{15}$	T_{15}	D_H (Youd)
3b	1 km	30%	0.4 mm	2 m	0.9 m
4a	8 km	15%	0.2 mm	2.5 m	1.9 m
4b	8 km	15%	0.2 mm	2.5 m	1.2 m
5	1 km	5%	0.2 mm	2 m	30 m

Table 4: Wellington example sites – Zhang et al. (2004) predicted displacements and D_H (Youd)/D_H (Zhang) comparison

Site	LDI	D_H (Zhang)	D_H (Youd)/D_H (Zhang)
1	2.5 m	5.0 m	0.2
2	1.5 m	2.9 m	0.2
3a	0.3 m	0.2 m	9
3b	0.3 m	0.07 m	13
4a	0.4 m	0.3 m	6
4b	0.4 m	0.15 m	8
5	1.2 m	2.1 m	14

Each site and the analysis results are discussed below.

4.1 Site 1

This site suffered from lateral spread in the Kaikoura 2016 earthquake. The analyses in Tables 2, 3 and 4 considers the M and PGA as was felt in that earthquake. The calculated displacements were 1 m based on Youd et al. (2002) and 5 m based on Zhang et al. (2004) compared to 400 mm observed as a result of the earthquake. Youd et al. (2002) offered better agreement with the observation than Zhang et al. (2004), but this may have been lucky rather than indicating Youd et al. (2002) being more reliable in this instance. The lower displacement calculated by Youd et al. (2002) was dominated by the relatively high $D50_{15}$ of 4 mm. A lower $D50_{15}$ would have resulted in a substantially larger calculated displacement. The soils at this site typically comprise 30% sand and silt and 70% gravel. The sand and silt matrix are likely to dominate the soil behaviour which is not captured by a $D50_{15}$ value.

We note that for this site a location at L = 4H has been considered. This is relatively close to the free face and on the limits suggested by Youd et al. (2002) and Zhang et al. (2004) for the validity of either method.

We conclude from this example that lateral spread is difficult to predict and predictions by these methods could vary from actual displacements by a factor of 10 or more.

4.2 Site 2

Sites 1 and 2 have similar conditions, except Site 1 has greater thickness of liquefiable soils. Unlike Site 1, Site 2 did not suffer from lateral spread as a result of the Kaikoura 2016 earthquake. This is likely because the intensity of shaking felt was considerably less at Site 2 due to site response effects. The comments relating to the $D50_{15}$ for Site 1 equally apply to Site 2.

4.3 Sites 3, 4 and 5

Youd et al. (2002) predicts displacements of typically 10 times that of Zhang et al. (2004) for Sites 3, 4 and 5. This is likely because of Youd's sensitivity to PGA. The PGA considered for these three sites of 0.45 to 0.7g is relatively high. In contrast, Zhang et al. (2002) is insensitive to PGA above the trigger level of approximately 0.25g.

4.4 2010 Darfield and 2011 Christchurch Earthquakes

Robinson et al. (2013) presents a comparison of observations of lateral spread from the 2010 Darfield and 2011 Christchurch Earthquakes with predictions based on Youd et al. (2002). Predicted displacements typically fitted in the range of 0.5 to 3 times those observed. This prediction is poor but better than that indicated by the above comparison between Youd et al. (2002) and Zhang et al (2004) predictions. The less bad prediction presented by Robinson et al. (2013) may be because a narrower range of input parameters was considered.

5 DEALING WITH UNCERTAINTY IN PREDICTION OF LATERAL SPREAD

The five Wellington sites related to five separate projects which included assessment of existing buildings, design of strengthening of existing buildings, design of lateral spread mitigation and design of a new building. For each of these projects it was necessary to make a prediction of the lateral spread potential, understand the uncertainty in that prediction and develop a response to that uncertainty for the assessment or the design. The steps of this process are described below.

5.1 Evaluation of the ground model and the potential mechanism of lateral spread.

Developing the ground model is considered the first and most important step in assessing lateral spread potential. It is necessary to undertake investigations and liquefaction analysis and develop a model representing the various layers making up the soil profile and their properties. An important consideration is; are the potentially liquefiable layers continuous from the free edge across the site or discontinuous? If discontinuous this could reduce the lateral spread potential. Develop an understanding of the lateral spread mechanism; at what levels could shear and strain occur allowing lateral spread?

Cubrinovski and Robinson (2016) provides useful insight of features influencing the occurrence and magnitude of lateral spread based on observations from the 2010-2011 Christchurch earthquakes. They concluded that the following features strongly influenced lateral spread potential:

- Large displacement lateral spreads occurred at sites characterised by the presence of continuous layer(s) with high liquefaction potential.
- Having the critical layer of liquefaction located in the soil profile at the base of the free face (bottom of the river channel) was characteristic of sites with large-displacement lateral spreads.
- The thickness of the critical layer of liquefaction influenced the magnitude of lateral spread observed. Typically for these Christchurch examples, large displacements were characterised by a 2 m thick layer and moderate and small displacements by 1 m and < 0.5 m thickness respectively.
- The nature of the soils above and below the critical layer of liquefaction influenced the magnitude of lateral spread by increasing the overall thickness of liquefaction and prolonging the duration of liquefaction effects.

5.2 Apply empirical analyses

The ground model was applied to Youd et al. (2002) and Zhang et al. (2004). These empirical analyses are valuable because they relate to real examples of lateral spread but the results must be critically assessed to evaluate if the calculated lateral spread is likely to be conservative, optimistic or possibly invalid. This assessment included consideration of:

- The input parameters relative to those represented in the database used to develop the methods (refer section 2.3 and the source papers). The limits for which input parameters are considered valid by the authors of the methods (Refer Youd et al. (2002) and Zhang et al. (2004).
- Sensitivity to the input parameters.
- The possible mechanisms for lateral spread and whether these are likely to be represented by these empirical methods and the database behind them.

5.3 Apply mechanistic analyses

The mechanistic analysis could include Newmark sliding block (NSB) and dynamic finite element modelling.

NSB was applied in the assessment of these five sites. NSB assumes displacement of a rigid block of soil on a defined shear surface extending from the free face to the point interest. Displacement is assumed to occur and accumulate during the earthquake whenever the inertia of the block exceeds the shear resistance. These assumptions do not reflect the observed behaviour of lateral spread including the observation of a series of scallops rather than a rigid block and that displacement may occur as strain through the liquefied layer rather than shearing at a specific level. The results of the analysis need to be assessed critically noting these simplifications. The NSB assumptions are a poor representation of the real world. In contrast the empirical analyses do relate to real world examples of lateral spread. The NSB method has the benefits that it is simple and can be applied to explore the mechanism or failure surface for lateral spread. It also allows a back analysis to be undertaken of any case histories of lateral spread, as was the case for Site 1. These back analyses allow forward analysis to be undertaken with more confidence.

Dynamic finite element modelling was not applied to the five Wellington sites. This modelling allows a much closer representation of the real world than is achieved via NSB. However, the ability to model large displacements accurately is limited in finite element models. It is highly dependent on the soil constitutive model used, the calibration of the model, and whether this represents the variability of soil behaviour in the field. At very low effective stresses, liquefied shear behaviour is very complex and even advanced constitutive models are not developed to model this behaviour. These models focus on the behaviour leading up to triggering. Because of these limitations of finite element modelling, we suggest that it be reserved as a higher level of analysis to be applied after the simpler methods. In the analysis and assessment, it must be appreciated that this is only a model and the results are to be considered alongside those of the simpler analyses and not in isolation. These higher-level analyses are generally reserved for more complex and important projects.

5.4 Judgement

Having considered the ground model, potential mechanisms of lateral spread, and the results and limitations of each analysis, informed judgement can be applied to select a likely range of potential lateral spread and the likelihood of displacements beyond this range. This important step is always best undertaken in collaboration and debate by a small group of engineers and geologists.

5.5 Application to assessment of existing buildings and design

In applying the results of the assessed lateral spread it is important to allow for the uncertainties. As demonstrated in this paper predictions could be out by a factor of 10.

For existing buildings, the MBIE Seismic Assessment of Existing Buildings, July 2017 proposes assessing expected or mean behaviour. Given the uncertainties in predicting lateral spread it is important that in addition to the “expected” lateral spread, the possible range and uncertainty is expressed so that the assessment team can consider resilience and inform the client of this.

For new builds, we design for dependable behaviour. Where damaging lateral spread is considered possible, designs which are independent of a prediction of lateral spread should be considered. For example, at Site 3, a palisade of reinforced concrete piles was designed to mitigate lateral spread. That design considered the full passive pressure imposed by laterally spreading ground in addition to the palisade’s performance for various possible magnitudes of lateral spread. If design is to rely on a prediction of lateral spread, that design should be tested for resilience at an extreme magnitude of possible lateral spread.

6 CONCLUSIONS

Predictions of lateral spread can be out by a factor of 10 or more. To deal with this uncertainty we propose:

- Understanding the ground model and potential mechanisms of lateral spread is a critical first step in predicting lateral spread.
- No single method should be relied on to predict lateral spread. Multiple methods should be applied and critically assessed. That critical assessment must explore the limitations of each method. Informed engineering judgement is required to select a range of values of lateral spread and the likelihood of displacements beyond this range for application to design or assessment.
- The design or assessment should be tested for the possible range of lateral spread.
- As far as possible, avoid a design which is reliant on a prediction of lateral spread. Develop designs which are independent of the magnitude of lateral spread, e.g., develop the design to resist full passive pressure of laterally spreading ground rather than tolerating an assessed magnitude of lateral spread.

REFERENCES

Bartlett, S.F. & Youd, T.M. 1995. Empirical Prediction of Liquefaction-Induced Lateral Spread. *Journal of Geotechnical and Geoenvironmental Engineering*, Vol 121(4): 316-329

Cubrinovski, M. & Robinson, K. 2016. Lateral spreading: Evidence and interpretation from the 2010-2011 Christchurch earthquakes. *Soil Dynamics and Earthquake Engineering*, Vol 91: 187-201

Robinson, K., Cubrinovski, M., Bradley, B.A. (2013) Sensitivity of predicted liquefaction-induced lateral displacements from the 2010 Darfield and 2011 Christchurch earthquakes. Queenstown, New Zealand: 19th New Zealand Geotechnical Society (NZGS) Symposium, 20-23 Nov 2013.

Youd, T.L., Hansen, C.M. & Bartlett, S.F. 2002. Revised Multilinear Regression Equations for Prediction of Lateral Spread Displacement. *Journal of Geotechnical and Geoenvironmental Engineering*, Vol 128(12): 1007-1017

Youd, T.L. 2018. Application of MLR Procedure for Prediction of Liquefaction-Induced Lateral Spread Displacement. *Journal of Geotechnical and Geoenvironmental Engineering*, Vol 144(6)

Zhang, G., Robertson, P.K. & Brachman, R.W.I. 2004. Estimating Liquefaction-Induced Lateral Displacements Using the Standard Penetration Test or Cone Penetration Test. *Journal of Geotechnical and Geoenvironmental Engineering*, Vol 130(8): 861-871.