Sensitivity of predicted liquefaction-induced lateral displacements from the 2010 Darfield and 2011 Christchurch Earthquakes

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ABSTRACT: The 2010 Darfield and 2011 Christchurch Earthquakes triggered extensive liquefaction-induced lateral spreading proximate to streams and rivers in the Christchurch area, causing significant damage to structures and lifelines. A case study in central Christchurch is presented and compares field observations with predicted displacements from the widely adopted empirical model of Youd et al (2002) ("the Youd model"). Cone penetration testing (CPT), with measured soil gradation indices (fines content and mean grain size) on typical fluvial deposits along the Avon River, were used to determine the required geotechnical parameters for the model input. The method presented enables the adoption of the extensive post-quake CPT test records in place of the lower quality and less available Standard Penetration Test (SPT) data required by the original Youd model. The evaluation indicates the Youd model is conservative, with significant over-prediction of the lateral spreading displacement for the studied location. A sensitivity analysis was performed with respect to the uncertainties used as model input, illustrating the models high sensitivity to the input parameters, with mean grain size among the most influential.

1 INTRODUCTION

The Darfield Earthquake of 4 September 2010 (M_w 7.1) and the Christchurch Earthquake of 22 February 2011 (M_w 6.2) triggered extensive liquefaction throughout Christchurch and surrounding suburbs. In particular, liquefaction-induced horizontal ground displacements ('lateral spreading') resulted in severe damage to structures and lifelines in close proximity to streams and rivers (Cubrinovski et al. 2011). There is a clear need to understand and predict the extent of lateral spreading movements, and the consequent hazard to buildings and infrastructure, under future earthquake scenarios. However, the uncertainty in the prediction of lateral spreading is compounded by both the large uncertainty in ground motion estimation and the variability in subsurface conditions at the site.

Case histories of lateral spreading occurrence during historic earthquakes have previously been collated and used to develop simple empirical and semi-empirical models for estimating the magnitudes of lateral displacement (e.g. Zhang et al. 2004, Youd et al. 2002). With uncertainties in spreading displacement estimates on the order of +/-50% (i.e. a factor of two), the predictions can be considered useful to gain an order of magnitude appraisal of expected displacement at a site, suitable for initially scoping the hazard, but not necessarily adequate for detailed design. One commonly adopted method is that of Youd et al. (2002) (the "Youd model").

Youd et al. (2002) employed regression analysis on documented field measurements of lateral spreading following earthquakes in the US and Japan. Regression parameters considered were related to the ground motion (via. earthquake magnitude and distance parameters), topography (i.e. free face or sloping ground cases), and geotechnical properties (potential thickness of liquefied sliding mass and intrinsic soil gradation characteristics). The functional form of the equation developed for free-face conditions is given in Equation (1):

$$logD_H = -16.713 + 1.532M_w - 1.406logR^* - 0.012R + 0.592logW + 0.540logT_{15} + 3.413\log(100 - F_{15}) - 0.795\log(D50_{15} + 0.1\,mm) \quad (1)$$

where D_H is the lateral spreading displacement (m); M_w is the earthquake moment magnitude; R is the horizontal distance to nearest seismic source or fault rupture (km); $R^* = R + R_0$ is the modified source distance, where $R_0 = 10^{(0.89M_w - 5.64)}$; $W = H/L * 100$ is the free-face ratio (where H=height of free-face, L=distance from crest of free-face); T_{15} is the thickness (m) of saturated, cohesionless sediment with SPT $(N_1)_{60} < 15$; F_{15} is the average fines content (%) within T_{15}; and $D50_{15}$ is the mean grain size (mm) within T_{15}. The free-face equation is presented (as opposed to that for sloping ground conditions) as it is more applicable for most areas in Christchurch where slopes are relatively gentle (generally less than ~1-2%) and the river channel serves as the free-face.

This paper presents a comparison of lateral spreading field measurements from the Christchurch earthquake with Youd model predictions. Due to limited standard penetration test (SPT) data in proximity to the field measurements, cone penetration tests (CPT) were used to classify the geotechnical input parameters for the model. Abundant CPT and grain size data (fines content, *FC*, and mean grain size, *D50*) along the Avon River were used to develop site-specific correlations for estimating the *F15* and *D50*$_{15}$ parameters. The associated uncertainties with these relationships, as well as with the remaining input values used in the comparison, are addressed in a sensitivity analysis for a specific location.

2 CASE STUDY OF LATERAL SPREADING FIELD MEASUREMENTS

2.1 Site location

The Avon Loop, situated in the north-east of the Central Business District in Christchurch, was subject to significant lateral spreading following the recent seismic events, with lateral ground displacements measured perpendicular to the river ranging from < 10cm to ~1.6m (Robinson et al. 2012, Robinson et al. 2011). The surveyed transects, at which spreading displacements were obtained, and nearby CPT locations are shown in Figure 1. No field data was collected at this location following the Darfield event, and hence the measurements are assumed to be cumulative for both the Darfield and Christchurch earthquakes.

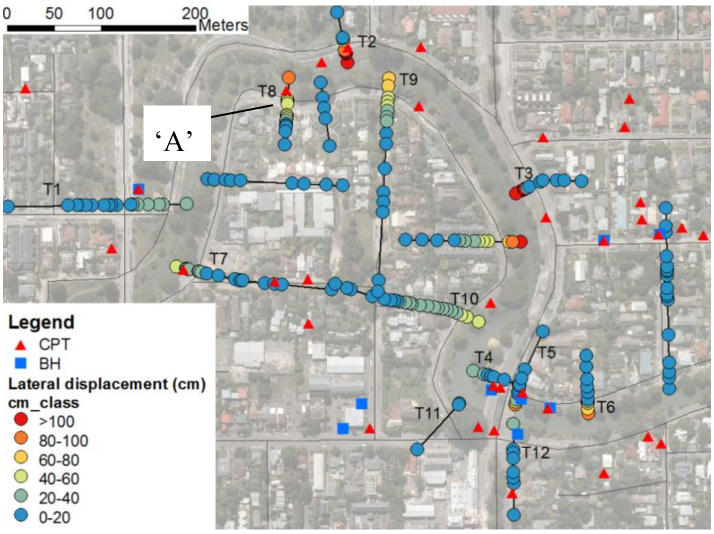

Figure1. Lateral spreading field measurements in the Avon Loop following the 2011 Christchurch earthquake and location of site 'A' used in the subsequently discussed sensitivity analysis

2.2 Collated geotechnical data

Abundant CPT data, and additional borehole and SPT data was collated from sites along the Avon River to develop relationships for estimating the required Youd model parameters, specifically F_{15} and $D50_{15}$ from CPT data. There is relatively limited borehole with SPT data in close proximity (< 50 m) of the majority of surveyed locations (Fig. 1). Of the boreholes shown, many had very little associated *D50* and *FC* data needed for the model input.

For potentially liquefiable soils in Christchurch, an attempt has been made to establish correlations for

FC and *D50* from boreholes with SPT, and the soil behaviour type index (I_c) obtained from CPT test results (Robertson &Wride 1998). Available data on the Canterbury Geotechnical Database (CERA 2012) for sites: (i) between Hagley Park in central Christchurch; (ii) the Estuary in the east of the city; and (iii) situated within 300 m of the Avon River and Bottle Lake suburb (a legacy meander loop of the Avon R.) were considered. The collated data was limited to boreholes with available soil gradation information (enabling *D50* and *FC* indices to be determined) and located within 5 meters of a CPT, which totalled 60 sites (Fig. 2). Some 44 of these boreholes contained soil gradation data. Additionally some tests were carried out only for the determination of *FC* (% passing No. 200 sieve), with no *D50* determination possible. The grain size curves were only for soils with < 50% fines with a few exceptions. Due to the scarcity of available soil gradation data at individual sites where lateral spreading occurred, correlations with CPT data are desirable for estimating the required *FC* and *D50* data.

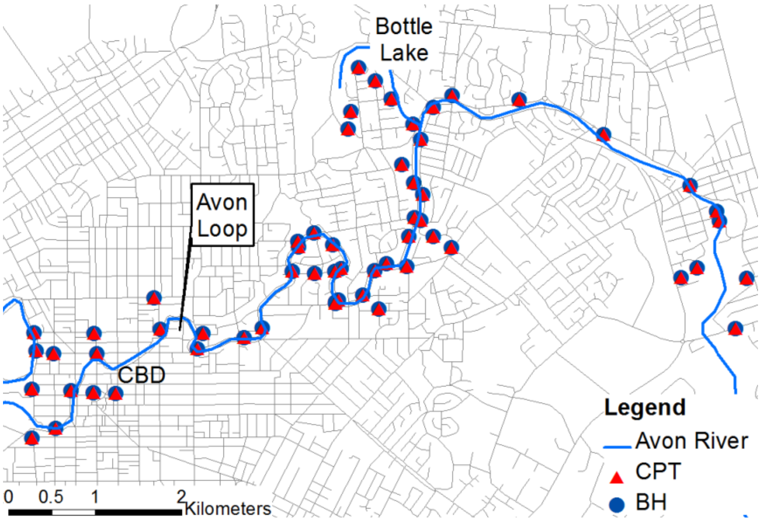

Figure 2.Location plan of SPT boreholes (BH) and CPT tests used in grain size correlations

In addition to the explorations, ground surface elevation data from LiDAR surveys (CERA 2012) following the Darfield event was used to determine the channel heights, i.e. height of the free-face, *H*, at the surveyed locations in the Avon Loop. Typical channel heights in this area range from about 1 - 3.5 m.

2.3 Development of Youd et al. (2002) geotechnical parameters, *F15* and $D50_{15}$

2.3.1 *Estimation of fines content, FC, from CPT data*

A relationship between soil behaviour type index, I_c (after Youd et al. 2001), and *FC* specific to the soils subject to lateral spreading along the Avon River was developed from available CPT and nearby boreholes with soil gradation data. Using changes in tip resistance,q_c, andI_c,a simplified interpretation of soil strata was developed to obtain average $I_c$values for the corresponding depths to soil gradation data in adjacent boreholes. The interpreted strata were compared to the borehole logs to ensure consistency in the selected $I_c$layer and the soil description for the sample. The final $I_c$value was selected to correspond to the layer of the grain size sample in the borehole. The relationship between I_c and *FC* developed is specific to the soils subject to lateral spreading along the Avon River, and is shown in Figure 3.The I_c within an interpreted soil layer, typically varies on the order of +/-0.1-0.2, which is presented as horizontal error bars in the plot.

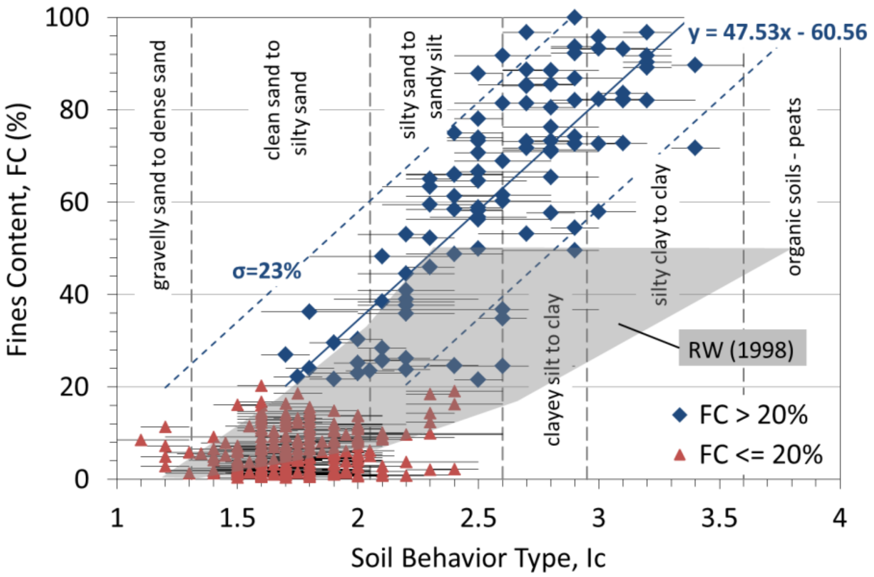

Figure 3.Correlation between FC and I_c for Christchurch soils in comparison to the general relationship of Robertson and Wride (1998)

To develop a parametric relationship between I_c and FC two distinct zones of data were considered, as delineated by *FC*=20%. There exists a large degree of scatter associated with the*FC*<20% data for which no apparent trend exists, illustrating a decreasing sensitivity of I_c to soils with low fines content. The *FC*-I_c relationship for *FC*>20%has a more distinct trend, and is compared to the general empirical correlation proposed by Robertson and Wride (1998). The Christchurch data (*FC*>20%) generally fits with the lower bound presented in Robertson and Wride for low-plasticity soils (*PI*<5%), as expected given the non-plastic nature of the fluvial silty sands prevalent in Christchurch. The relationship provided in Figure 3 may be used in order to approximate *FC* from CPT-derived I_c (for *FC*>20%). Due to the lack of a trend for soils with FC<20%, an average fines content of 10% has been adopted in subsequent analyses with the Youd Model, when the computed *FC* is less than 20%.

2.3.2 *Estimation of mean grain size, D50*

2.3.3 To estimate $D50$ values used in the Youd model, using the same data discussed in the last section, trends between $D50$, I_c and FC were examined. Figure 4(a) illustrates the correlation between *D50* and I_c, which is seen to be very weak. However, as illustrated in Figure 4(b), the data does show stronger correlation between *FC* and D50, particularly for soils with FC > 20%. The relationship provided in Figure 4(b) for *FC* > 20% may be used for estimating *D50* for a given *FC*. In general, for soils with *FC* < 20%, *D50* typically ranges between approximately0.1-0.25mm.

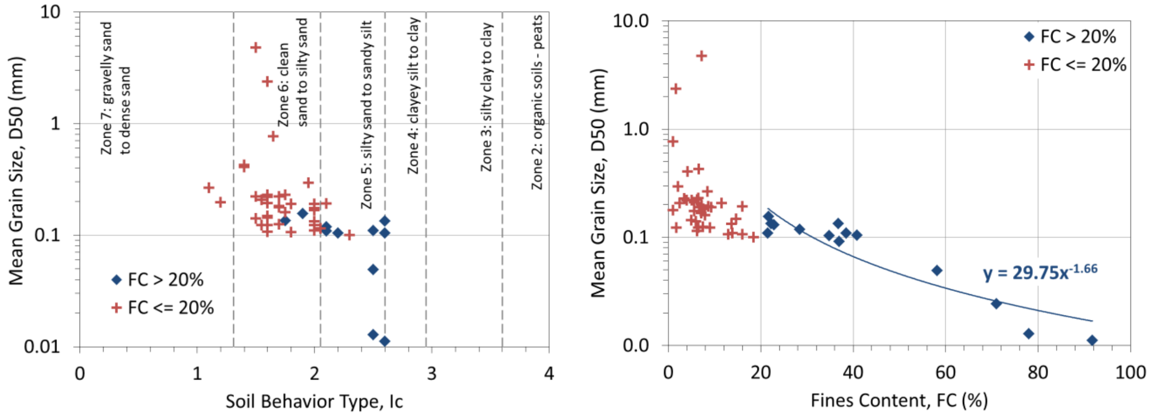

Figure 4.Relationship for Christchurch soils between mean grain size, *D50*, and (a) Soil behaviour type, *Ic* and (b) Fines content, *FC*

3 COMPARISON OF FIELD OBSERVATIONS AND YOUD MODEL PREDICTIONS

In this section transects along the Avon Loop located within 50 m of a CPT are considered to compare observed spreading displacements with predictions. This included 12 of the 15 surveyed transects shown in Figure 1 as'T1'-'T12'.

3.1 Determination of input parameters

The parameter T_{15} is defined by Youd et al. (2002) as saturated, cohesionless material with corrected, normalised SPT $(N_1)_{60}$<15. In order to compute T_{15} using CPT data, an equivalent threshold of normalized tip resistance, q_{c1} = 8MPa was used. This was based on q_c-N relationships provided by Jeffries and Davies (1993). To satisfy the "saturated, cohesionless" conditions, material with an $I_c > 2.6$ (indicative of plastic fine grained soil response, typically of low susceptibility to liquefaction), or above the groundwater table, were not considered to contribute to T_{15}. This interpretation of T_{15} is consistent with previous comparisons of the Youd et al. (2002) model using CPT data; e.g. Chu et al.(2006).

Using the grain-size relationships developed in the previous section, the *F15* and $D50_{15}$ parameters were estimated using the following approach: The equation presented in Figure 3 was used to compute *FC* for each *Ic*-value within T_{15} (if the computed *FC*<20% then it was set to *FC* = 10%). These values were then averaged to yield *F15*. The relationship provided in Figure 4(b) was used to determine an appropriate $D50_{15}$ based on *F15*. For *F15*<20%, an average value (for the range of *FC*<20%), $D50_{15}$=0.18mm was used. Again, the uncertainties associated with these relationships are recognised and discussed further subsequently in the sensitivity analysis.

Groundwater depths at the time of the February earthquake were estimated at the CPT locations using the groundwater model provided by Tonkin and Taylor (CERA 2012). The free-face ratio, *W*, was computed using channel heights (H), estimated at each location from LiDAR elevation data taken after the September 2010 event (CERA 2012), and the distance, *L*, taken as the distance from the CPT to the waterway. The analysis was limited to 20%>*W*>1%, per the Youd et al. (2002) model specifications.

Site-to-source distance, *R*, and peak ground acceleration, PGA, values at the site were obtained from Bradley & Hughes (2012). The latter was used in an alternative analysis that considered an equivalent *R*-value, R_{eq}, back calculated from the estimated PGA, at the site with the earthquake magnitude, using a suggested relation in Youd et al. (2002). *R*-values of 17 km and 4 km were used for the September 2010, M_w7.1 and February 22nd M_w6.2 events, respectively, with the computed values of R_{eq} being 15.5 km and 1 km, respectively.

3.2 Results

The predicted spreading displacement results from the two earthquake events were summed to compare this cumulative displacement with the field measurement for a given distance from the free-face, *L,* on an individual transect, and are presented in Figure 5 for both the R (PGA unknown) and R_{eq} (PGA known) cases. These comparisons considered field displacements within 10 m of the measurement at *L* to account for variability of measured crack locations over a relatively short distance in the field, represented by the horizontal error bars in the plot.

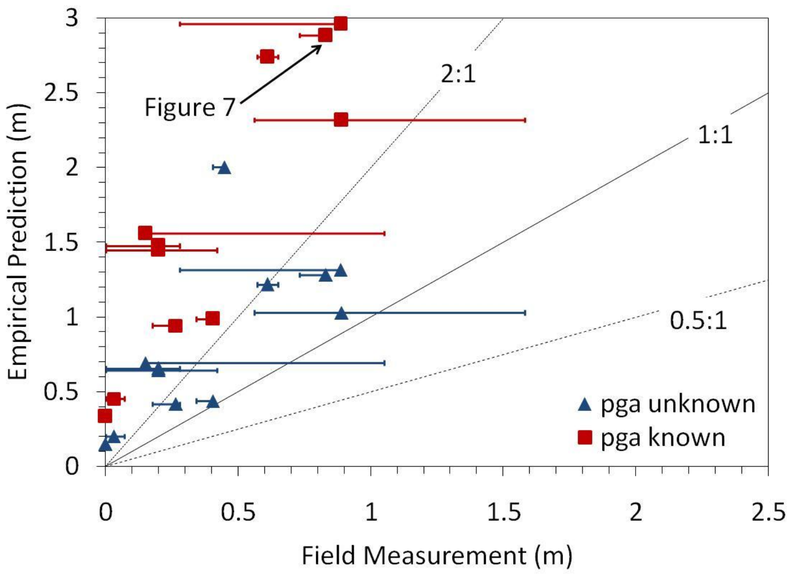

Figure 5.Comparison of field measurements of lateral displacements in the Avon Loop area with empirical predictions from the Youd et al. (2002) model

3.3 Uncertainties in Model Application

The empirical predictions for both calculations (using R and R_{eq}) clearly over-predict the field observations at all locations, with the majority of predictions more than two times that observed in the field. There are several sources of uncertainty that may attribute to the variation between predicted values and field measurements which, in order of decreasing inferred significance are:

- Variability in site conditions from the point of exploration (the analysis considered CPTs are up to 50m away from transects where spreading displacements were measured);
- Scatter in the empirical relationships between FC-I_c and *D50-FC*used to convert CPT data;
- Near source effects in using R_{eq}=1km for the February event;
- Uncertainties in groundwater levels that may affect the value of T_{15};
- Limitations in field measurements of spreading, such as cracks repaired before the time of the investigation, lateral extension of the ground not propagating as measurable cracking, and obstacles in the field hindering continuation of the transect.

4 SENSITIVITY ANALYSIS

On account of the bias in the model towards over-prediction of lateral spreading displacements at the site, a sensitivity analysis was performed in order to assess whether this bias can be attributed to uncertainties in the model input. A specific measurement from transect T8 was selected for the analysis (location 'A' in Figure 1). The field measurement of lateral displacement at this location was ~ 0.8 m, with a model prediction of 2.9 m (using R_{eq} i.e. PGA known). The input parameters and associated uncertainties were quantified as follows:

Table 1. Summary of input parameters for sensitivity analysis

Parameter	Input value	Range	Notes regarding uncertainty
R(M_w6.2/M_w7.1)	1km/15.5km	4km/17km	alternative (PGA unknown)
W	9%	7-20%	variability in channel height across the site (and model limitations of 20%)
T_{15}	5.3m	4-6m	changes in groundwater levels ~ +/-1m
F15	22	20-40	~ +/-6 from *FC-Ic* relationship (Figure 3)
$D50_{15}$	0.18	0.06-0.25	*D50* range corresponding to *F15* range from *D50-FC* relationship (Figure 4(b))

The sensitivity of lateral displacements were computed for the parameter ranges presented in Table 1, by varying a single parameter over is range of values, while holding the remaining parameters constant (at the ‘input’ value). The parameters $D50_{15}$ and *F15* were analysed together based on the clear correlation seen between these two parameters in Figure 4(b), i.e. the upper bound of *F15* was used in conjunction with the lower bound of *D50* and vice versa. The results of the sensitivity analysis are provided in Figure 6 with respect to the predicted and observed displacements. The Youd model exhibits a high sensitivity to all parameters for the parameter uncertainty ranges considered, with T_{15} causing the least sensitivity. This is likely due to the relatively small uncertainty associated with its determination. As $D50_{15}$ is increased to 0.25, one would expect to see a decrease in displacement; however, the correlation with a lower *FC* value dominates the computed displacement, yielding a higher prediction. A relatively small increase in channel height (from ~1.1m to 2.6m) created a relatively large increase in *W*, and consequently a notable resulting prediction variation. Using *R* as the site-to-source distance (PGA unknown) also resulted in a much closer prediction to the observed.

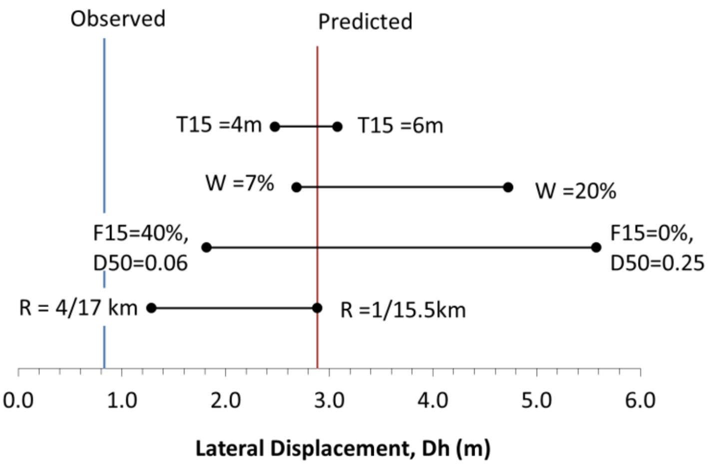

Figure 6. Sensitivity analysis of parameter uncertainties at location ‘A’

Figure 6 illustrated that the model is very sensitive to the input parameters, especially *F15* and $D50_{15}$, based on the range of parameters investigated. A second analysis was performed to determine whether this prediction variation is due to the actual model sensitivity or due to the uncertainty associated in determining the parameters themselves. Each input parameter was individually varied by +/-10% and the resulting displacement is shown in Figure 7. Figure 7 shows that in general, a 10% change in input parameters results in a less than 10% change in predicted displacement. Thus, if the input parameters can be accurately defined within 10% there is likely to be little difference in predicted displacement. However, for the purpose of the analyses considered in this paper, as well as many cases where grain size data from soil samples is not abundant, there will likely be more than 10% error associated in the approximation of these geotechnical parameters (*D50* and *FC*) and the sensitivity of these input parameter values on the corresponding uncertainty in predicting spreading displacements clearly creates difficulty in producing accurate and precise model predictions.

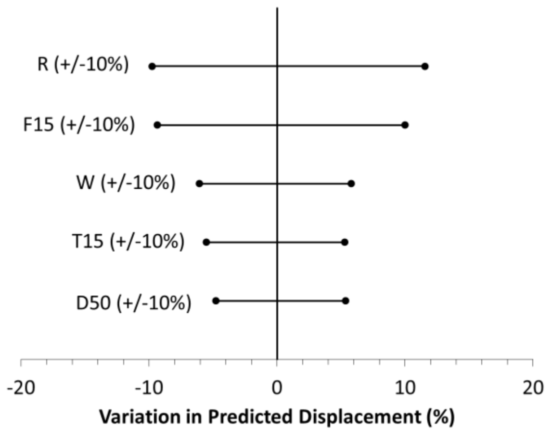

Figure 7. Sensitivity of Youd model relative to 10% change in input parameters

5 CONCLUSIONS

Lateral spreading displacement measurements from the Christchurch earthquakes were compared to the empirical model of Youd et al. (2002). Due to the limited availability of borehole and SPT data in proximity to the surveyed locations, an attempt was made to derive the geotechnical parameters required by the model from CPT data, specifically for parameters derived from soil gradation indices, *F15* and $D50_{15}$. The results of the comparison between the Youd et al. model and the observed field data in Christchurch show the model over-predicts lateral spreading displacements generally by more than a factor of two, indicating a high degree of conservatism. A sensitivity analysis was performed for a specific location and found the model to be highly sensitive to all input parameters, with *T15* being the least influential on the displacement prediction. The strong influences of *F15* and $D50_{15}$ on the predictions indicate that the uncertainties associated with the derived correlations may be too significant for accurate application of the model. Future work on additional comparisons with the Youd model and others is on-going with an aim to achieve a more accurate method of lateral spreading predictions in Christchurch.

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