

**Figure 7. Predicted and observed landslides; data were compiled by the Geographical Survey Institute of Japan.**

center, slope inclination, azimuth, geology, unit weight, and strength parameters in each grid in the target region. Thirty-two directions are studied to determine the predominant direction of the slope failure. Using the above data file, precise regional landslide susceptibility maps are created with permanent seismic displacement obtained from the Newmark method. To validate the proposed method, the created regional landslide susceptibility map is compared to the landslide inventory map from the 2004 Mid-Niigata Prefecture earthquake.

This method can be used to create regional landslide susceptibility maps for other regions with strong seismic motion, investigate the vertical seismic motion effect, and suggest the installation of methods for determining the permanent seismic displacement considering both the peak and permanent strengths of the geomaterials and the ground water. Finally, it is expected that the proposed method will be adopted in the prediction of future landslide susceptibility.

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## Seismic Settlement of Shallow-Founded Structures on Liquefiable Ground

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### Abstract

Liquefaction near shallow-founded structures has led to excessive residual settlement, tilt, and lateral sliding in past earthquakes. We seek to advance a performance-based design approach to deal with that problem. Such an approach requires a robust set of predictive tools. In this work, we investigate the dynamic response of a soil-foundation-structure system to assess the influence of key parameters on the response of a single building founded above layered, liquefiable soils. The study begins with a comprehensive parametric investigation of the impacts of various soil, building, and ground motion parameters on settlement. These include: the building's fixed-base fundamental period of vibration; height-to-width ratio; foundation bearing pressure; the liquefiable layer's relative density, depth, and thickness; and various ground motion parameters related to intensity and duration. The numerical simulation uses fully-coupled, 3-dimensional, nonlinear dynamic analyses of the soil-foundation-structure system. The methodology has been previously validated against centrifuge experiments. Among all the parameters, those that matter the most are identified as soil relative density and the thickness of the liquefiable layer. Building fundamental period and effective mass matter to a lesser degree, followed by building height and foundation contact pressure. Most of the parameters become more influential with increasing motion intensity, and some become more or less influential based on the relative density of the liquefiable layer. These analyses provide the basis for developing probabilistic predictive models to estimate the settlement of shallow-founded structures on liquefiable ground.

### INTRODUCTION

Observations from previous earthquakes show that buildings, even those designed based on advanced regional regulations, still suffer from the consequences of soil liquefaction. For example, in the 2011 Christchurch (New Zealand) series of earthquakes, excessive settlement, tilt, and lateral sliding, as well as damage to the structural components due to ground shaking were observed in buildings with shallow foundations located atop of liquefiable deposits (Bray et

al 2014). In the 1999 Kocaeli (Turkey) Earthquake, many of the damaged structures were influenced by the liquefaction of thin deposits of silt and silty sand (Sancio et al. 2004; Bray et al. 2000; Bird et al 2004). Building settlement was directly proportional to its number of stories, and the building's height/width (H/B) aspect ratio greatly affected the degree of tilt or in some cases bearing capacity failure (Sancio et al. 2004), showing the importance of a building's dynamic properties. Moreover, previous experimental and numerical studies have revealed that the seismic performance of shallow-founded structures on softened ground is a function of the dynamic characteristics of the underlying soil, structure, and ground motion (Dashti et al. 2010; Karimi and Dashti 2015a,b, 2016a,b).

The state-of-practice procedures for estimating liquefaction-induced settlements (e.g., Tokimatsu and Seed 1987; Ishihara and Yoshimine 1992; Juang et al. 2013) are mainly based on semi-empirical or semi-probabilistic relations with the assumption of free-field conditions, which either completely neglect the existence of the building or bring in the foundation load as an added overburden stress alone. These procedures ignore the influence of structures on static and dynamic stresses induced in the foundation soil, changes in the drainage path, and the impact of soil liquefaction on building performance. These limitations barricade the development of mitigation strategies that improve building performance in terms of foundation settlement and tilt as well as flexural inter-story drift of the structure that is a proxy for building damage.

We seek to advance a performance-based design approach to estimate the settlement of shallow-founded structures on liquefiable ground. Before a performance-based approach to mitigating this settlement can be advanced, robust predictive tools must be developed. This paper presents the results from a numerical sensitivity study to assess the influence of key soil, foundation, and structure parameters on the settlement of a single building on layered liquefiable soils. The most influential parameters were found to be the thickness and relative density of the liquefiable layer. The least influential parameters were found to be the effective structure height and the foundation bearing pressure.

## NUMERICAL SIMULATIONS AND VALIDATIONS

Dashti et al. (2010a,b) performed a series of dynamic centrifuge tests to evaluate the response of different single-degree-of-freedom (SDOF) structures with stiff, shallow mat foundations on layered liquefiable ground. The primary objective was to identify the dominant mechanisms of liquefaction-induced building settlement and to evaluate the influence of different input parameters (IPs) on the response of the SFS system. Three elastic SDOF structures were mounted on 1 m-thick mat foundations with varying contact pressures and height/width (H/B) ratios. Bearing pressure and fixed-base natural frequencies ( $f_n$ ) of structures ranged from 80 to 130 KPa and 2.5 to 3.5 Hz, respectively. The properties of structures and base motions (as recorded) were presented by Dashti et al. (2010a,b) and Karimi and Dashti (2015b,2016a).

Finite element analyses of the centrifuge tests were subsequently performed using the pressure-dependent, multi-yield-surface, plasticity-based soil constitutive model (PDMY02) implemented in OpenSees by Elgamal et al. (2002) and Yang et al. (2003, 2008) to evaluate the capabilities and shortcomings of this numerical tool in capturing soil and structural response. Analyses were performed in 3D to more accurately model the response of the shallow-founded structure and the 3D stress and drainage conditions in the underlying soil. Direct comparisons between experimentally measured and numerically computed responses were made and good agreements were observed in terms of the time and location of liquefaction triggering, softening

followed by re-stiffening, excess pore pressure generation and redistribution, soil and structural accelerations, and settlements near the structure. Numerical model captured the dominant mechanisms of displacement near the foundation soil, and consequently permanent foundation settlement compared well with experimental measurements. More details on the capabilities of the numerical tool in capturing permanent foundation settlement, structure's flexible-based period and its rocking and flexural drift ratios were presented by Karimi and Dashti (2015b, 2016a,b).

## OVERVIEW OF THE NUMERICAL PARAMETRIC STUDY

A numerical parametric study was undertaken using fully-coupled, 3-dimensional, nonlinear dynamic analyses of the SFS system to evaluate and quantify the effects of a wide range of soil, structural, and ground motion IPs on foundation settlement. The models consisted of a single shallow-founded structure on a layered soil column including a layer of liquefiable sand. The embedment depth of the mat foundation was 1m.

Table 1 summarizes the properties of the SFS systems evaluated in the parametric study. 110 cases were investigated with variations in the thickness ( $H_L$ ) of, depth ( $D_L$ ) to, and relative density ( $D_r$ ) of the liquefiable layer as well as the structure's contact pressure ( $q$ ) and fixed-base fundamental period ( $T_{ST0}$ ). Previous studies had shown the influence of a building's dynamic properties on its settlement (Dashti et al. 2010a,b), which is why they were varied in this study. Although some of these parameters are likely to be highly correlated, each parameter was tested individually to isolate its influence on average foundation settlement. For example, foundation pressure was varied by changing the applied pressure on the foundation elements, or effective structure mass was varied by changing the inertial mass contributing to dynamic loading.

**Table 1: Parameters that may influence settlement on liquefiable soils: ranges considered**

Parameter	Abbreviation	Minimum Value	Maximum Value
Relative density of liquefiable layer (%)	$D_r$	30	85
Thickness of liquefiable layer (m)	$H_L$	2	20
Depth to liquefiable layer (m)	$D_L$	1	8
Foundation bearing pressure (kPa)	$q$	30	220
Structure fundamental period (s)	$T_{st}$	0.25	1.0
Effective structure height* (m)	$h_{eff}$	1.7	13.7
Effective structure mass** (kg)	$M$	412,000	2,472,000

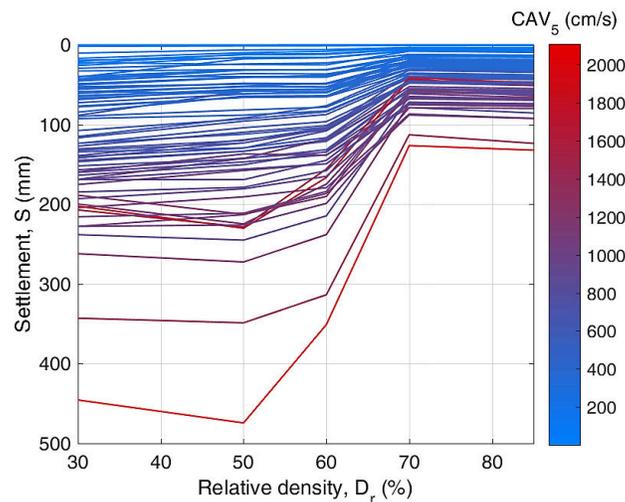
\*Height of an equivalent single-degree-of-freedom oscillator

\*\*Inertial mass of an equivalent single-degree-of-freedom oscillator

A suite of 75 ground motions, with earthquake moment magnitudes ranging from 4.92 to 7.28, site-to-source distance from 0.07 to 47.2 km covering a wide range of intensity, duration, and frequency characteristics were selected. Ground motions were all recorded on rock or stiff soil to be applied to the rigid base in the numerical models, which replicated the conditions in the centrifuge experiments.

## SENSITIVITY OF FOUNDATION SETTLEMENT TO MODEL CHARACTERISTICS

The sensitivity of average foundation settlement to the relative density ( $D_r$ ) of the liquefiable layer is shown in Figure 1 as a function of intensity as measured by cumulative absolute velocity with  $5 \text{ cm/s}^2$  of acceleration threshold ( $CAV_5$ ) introduced by Kramer and Mitchell (2006).  $CAV_5$  was selected as the intensity measure (IM) for this study because it has been shown to be an efficient and sufficient predictor of foundation settlement due to liquefaction (Karimi and Dashti 2016b, 2017; Dashti and Karimi 2017) as well as an efficient and sufficient predictor of liquefaction triggering (Kramer and Mitchell 2006). An efficient IM is the one that minimizes the uncertainty in predicting a certain response (here foundation permanent settlement), given that IM. A sufficient IM is the one that minimizes the dependence of predictions on source parameters such as magnitude and distance. For low intensities, the foundation settlement does not vary with  $D_r$ . However, the sensitivity of settlement to  $D_r$  increases with intensity. Settlement is similar for sands up to 50%  $D_r$  at all intensity levels, but there is a sharp decrease in settlement for relative densities in the range between 50% and 70%. Settlement is nearly constant for densities above 70%, and is not necessarily negligible.

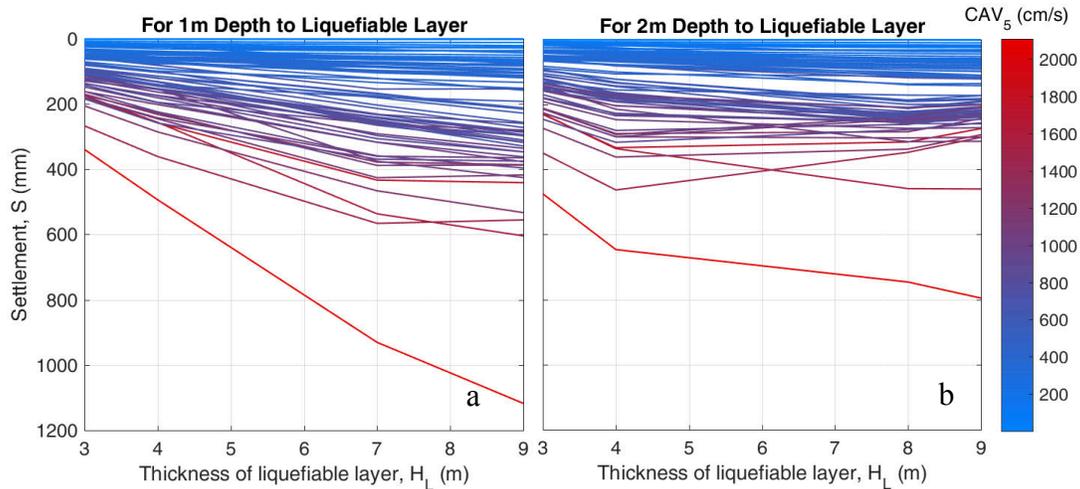


**Figure 1: Sensitivity of foundation settlement to relative density of liquefiable sand ( $D_r$ ), as a function of intensity level ( $CAV_5$ ). Each line shows results for a different ground motion.**

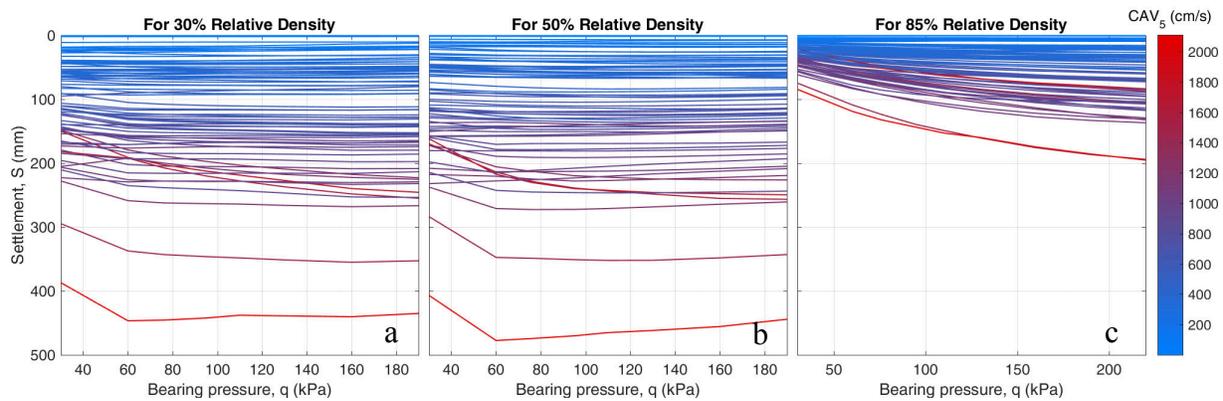
Figure 2 illustrates the sensitivity of settlement to the thickness of the liquefiable layer ( $H_L$ ), when the liquefiable layer is at two different depths, as a function of base motion  $CAV_5$ . Settlement is more sensitive to  $H_L$  when liquefiable layer is at shallower depth (e.g. Figure 2a), showing generally increasing foundation permanent settlement with increasing  $H_L$ . In other words, settlement is more sensitive to  $H_L$  when the layer is 1 m deep than when it is 2 m deep. The sensitivity of settlement to  $H_L$  also increases with intensity. Except at high intensities, settlement plateaus above a layer thickness of approximately 7 m when 1 m deep or a thickness of 4 m when 2 m deep.

The sensitivity of settlement to foundation bearing pressure ( $q$ ) for three relative densities as a function of intensity is shown in Figure 3. Like most of the other parameters, the effect of  $q$  on foundation settlement increases with intensity. For the same intensity, the foundation settlement is also much larger for loose to medium liquefiable sand. For loose and medium sand with

relative densities between 30% and 50%, settlement increases with  $q$  up to 60 kPa, but the effect then saturates. However, for dense sand with a relative density of 85%, this “saturation” is not reached even at a bearing pressure of 220 kPa.

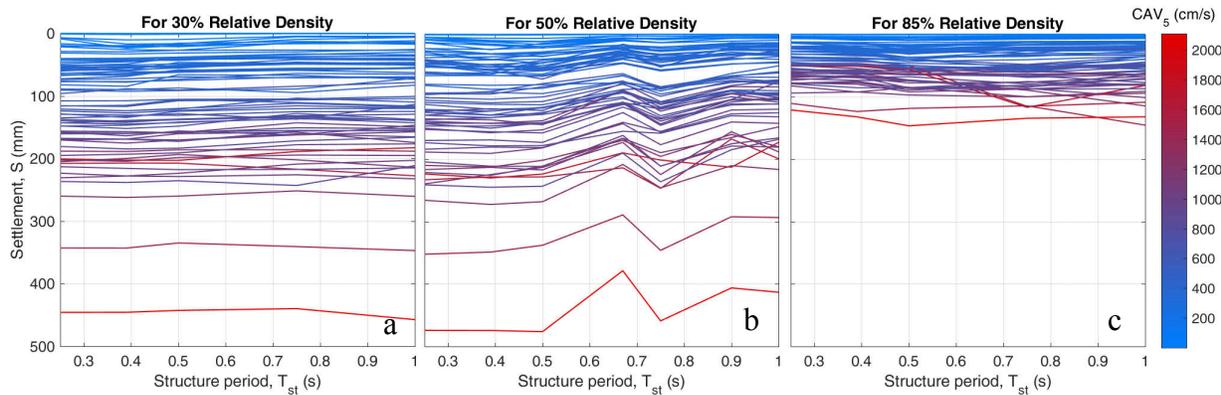


**Figure 2: Sensitivity of foundation settlement to liquefiable layer thickness for two depths to liquefiable layer, as a function of intensity level ( $CAV_5$ ). Relative density of the liquefiable layer was 50%.**



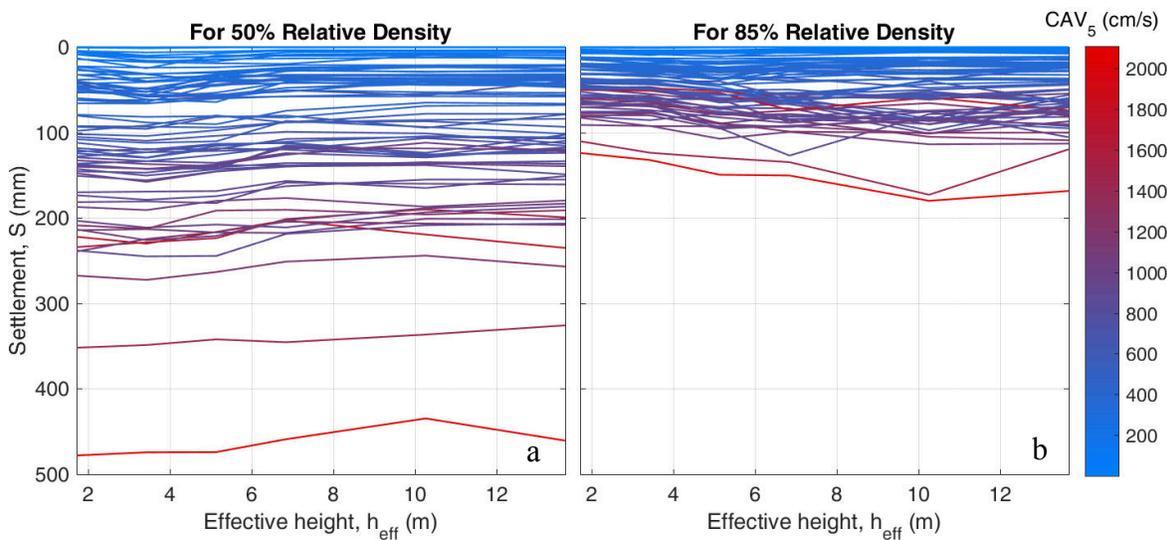
**Figure 3: Sensitivity of settlement to foundation bearing pressure for three relative densities of liquefiable sand, as a function of intensity level ( $CAV_5$ )**

Figure 4 shows the sensitivity of settlement to the fundamental period of the structure for three relative densities as a function of ground motion intensity. For loose and dense sand, this parameter has very little influence. However, for medium dense sand, it is more significant, although still not as influential as relative density or liquefiable layer thickness. The effects of this parameter are particularly difficult to characterize because it interacts with the period of the soil column and the frequency content of the ground motion in ways that the other considered parameters do not. Unlike most of the other parameters, the influence of structure period is not related directly to intensity as measured by  $CAV_5$ .

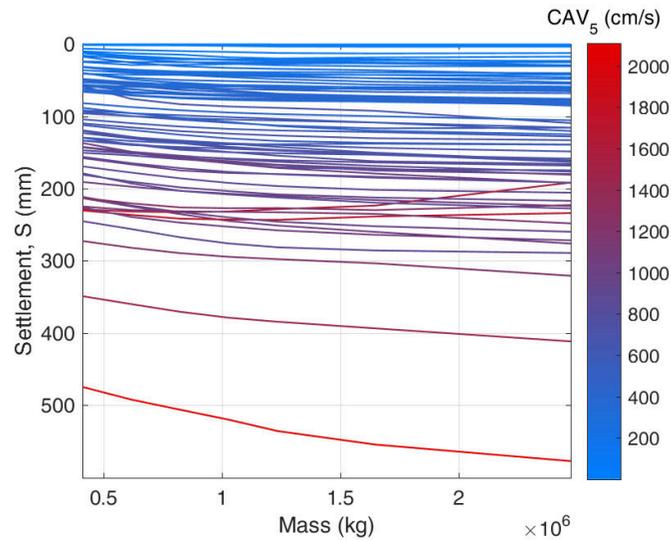


**Figure 4: Sensitivity of foundation settlement to structure fundamental period for three relative densities of liquefiable sand, as a function of intensity level ( $CAV_5$ )**

Figure 5 and 6 provide similar sensitivity analyses for the effective structure height and effective structure mass, respectively. It must be noted that increasing the effective mass only related to the mass of the oscillator in these simulations, while the contact pressure on the foundation was kept constant to evaluate the impact of structural inertia separately. Two relative densities of the liquefiable layer were considered for structure height, but only medium dense sand was considered for structure mass. The influence of these two parameters is small relative to other parameters, especially at low to median intensity levels.



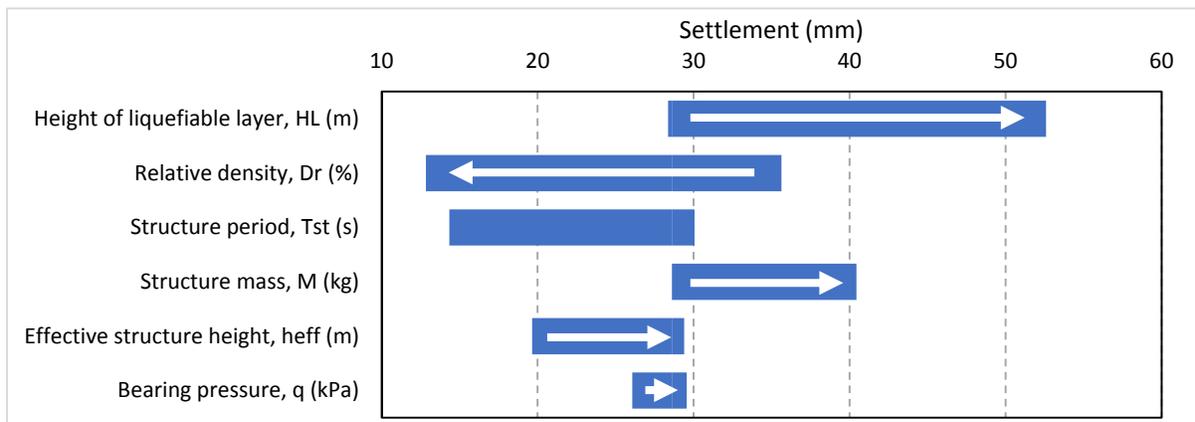
**Figure 5: Sensitivity of foundation settlement to effective structure height for two relative densities of liquefiable sand, as a function of intensity level ( $CAV_5$ )**



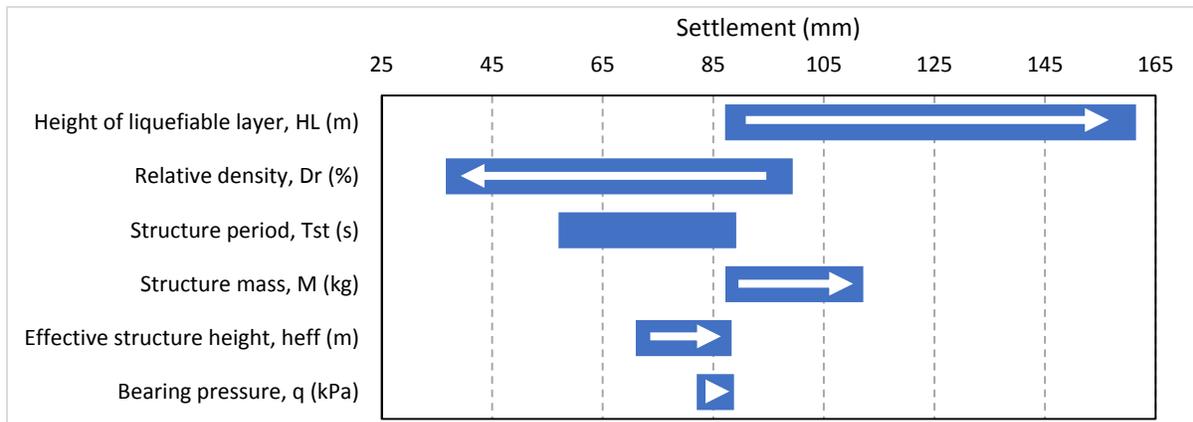
**Figure 6: Sensitivity of foundation settlement to effective structure mass, as a function of intensity level ( $CAV_5$ )**

**DISCUSSION OF THE RELATIVE INFLUENCE OF MODEL CHARACTERISTICS**

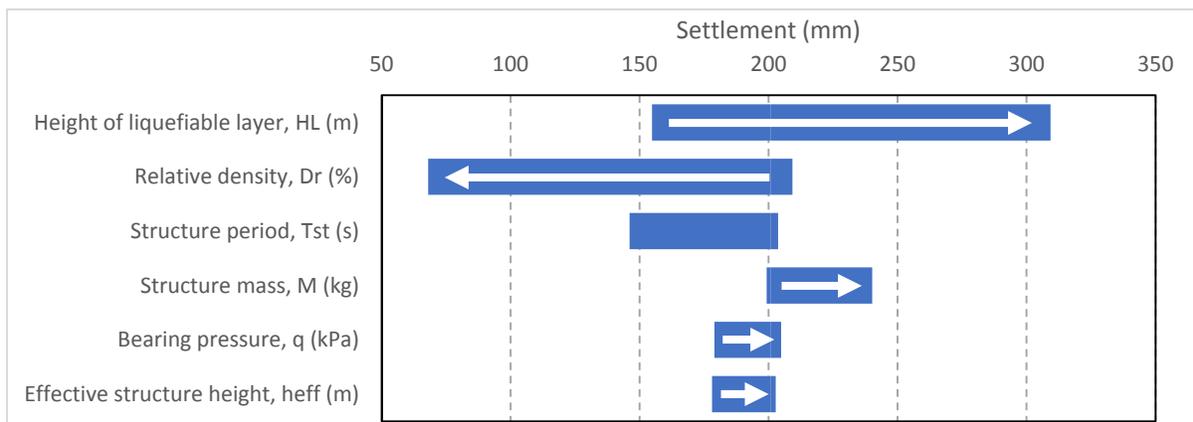
Figures 7 through 9 provide tornado diagrams showing the relative sensitivity of settlement to different input parameters for three intensity levels. The intensity levels are represented by the bottom, middle, and top thirds of the ground motion set ordered by  $CAV_5$ . The settlement values used are the mean for a given model across all of the ground motions in the respective third. In all cases, the two parameters with less influence on foundation settlement are the foundation bearing pressure and the effective mass of the structure. The relative density of the liquefiable sand and the thickness of the liquefiable layer are very influential on settlement at all intensity levels. These two parameters become comparatively more significant at higher intensity levels. The structure period and effective structure height have much more influence on settlement at low intensity levels, which makes them comparatively less significant at higher intensities.



**Figure 7: Tornado diagram for low intensity (bottom third  $CAV_5$ ); the directions of the arrows denote larger parameter values**



**Figure 8: Tornado diagram for median intensity (middle third CAV<sub>5</sub>); the directions of the arrows denote larger parameter values**



**Figure 9: Tornado diagram for high intensity (top third CAV<sub>5</sub>); the directions of the arrows denote larger parameter values**

## CONCLUSION

This numerical sensitivity analysis indicates that the most significant parameters affecting foundation settlement due to seismic liquefaction are the relative density and the thickness of the liquefiable layer. The period and effective height of the structure are also significant, but they are only comparatively as significant as these other key parameters at low intensity levels. Effective structure mass and foundation bearing pressure are less influential, but their influence increases at stronger levels of shaking.

Foundation settlement is more sensitive to changes in most of the parameters at high intensities of ground shaking, when ground shaking intensity is measured in terms of the CAV<sub>5</sub> parameter. The amplification of sensitivity at higher intensity levels is particularly significant for the relative density of the liquefiable sand and the thickness of the liquefiable layer. It is less pronounced but still evident for the foundation bearing pressure for the profile with dense sand,