Chapter 5

CONCLUSIONS AND FUTURE OUTLOOK

This thesis presented some key developments regarding the micro and macro mechanics of soil liquefaction. These developments should facilitate a more physical assessment of liquefaction susceptibility at the field-scale.

The simplest manifestation of liquefaction occurs when a soil specimen is subjected to monotonic or static loading under undrained conditions in a triaxial compression test. By analyzing the mechanics underlying the onset of flow liquefaction in such a setting, we developed a fundamental understanding of the phenomenon. Specifically, we defined a flow liquefaction potential $\mathcal{L}$ that helped understand soil behavior under conditions of 'partial drainage'. Flow liquefaction potential $\mathcal{L}$ provides an elegant framework to visualize how a soil can liquefy despite volume changes prevalent under partial drainage; this can happen during seismic shaking in the field, or under static loading when there is differential pore pressure generation between adjacent soil layers with different densities. Unequal pore pressure generation can lead to pore water being injected into certain layers and being extracted from other layers, causing volume changes. In addition, by analyzing the evolution of stresses in a triaxial compression test, we were also able to identify a necessary precursor for the onset of flow liquefaction instability. The concept of a necessary precursor can help in identifying at-risk slopes in hydraulic fill dams, spoil tips, and tailings – slopes that are formed of loose deposits and are susceptible to flow liquefaction under undrained loading.

A numerical investigation into the mechanics of liquefaction charts revealed that the lower end of these charts may correspond to sites that are susceptible to flow liquefaction, as opposed to cyclic mobility. This could arm an engineer with some predictive power regarding the effects of liquefaction. For instance, it could be useful in augmenting the procedure for calculating the 'Liquefaction Potential Index' (LPI), as defined by Iwasaki et al [38]. LPI is used in estimating the severity of liquefaction manifestation at the ground surface. A modification could be foreseen where a higher weight could be used while calculating LPI, if the site in question is susceptible to flow liquefaction. This would result in a higher value of LPI, which would imply a greater severity of liquefaction manifestation at the ground surface.

A grain-scale numerical investigation enabled us to investigate the micro-mechanics of shear wave velocity in a granular assembly. Specifically, we observed how the anisotropy of fabric, or grain-arrangement, affects the shear wave anisotropy. The differences in fabric are also accompanied by a difference in liquefaction resistance of a granular assembly. This suggests that while assessing liquefaction potential in the field, shear velocity may serve as a suitable proxy to estimate not just the prevailing stress state and relative density – as is the case presently, but also for estimating the prevailing soil fabric. Our results suggest the existence of a correlation between shear wave anisotropy and fabric anisotropy, suggesting that knowledge of shear wave anisotropy could provide insight regarding the micro-mechanical structure of in-situ soils. Such knowledge could help in translating laboratory test results onto field conditions, with greater certainty, and consequently refine the field-assessment of liquefaction susceptibility.

5.1 Future Outlook

Some future research directions are immediately apparent from this thesis. For instance, we identified a necessary precursor prior to the onset of flow liquefaction in a triaxial compression test. This provides motivation to look for a necessary precursor at the field-scale. Knowledge of a precursor could be useful if slopes are fitted with instruments monitoring their deformation, or if slopes are monitored via remote sensing satellites. Once at-risk slopes are identified, steps could be taken to mitigate the effects of the liquefaction risk.

We also suggested a modification in the calculation of LPI wherein sites susceptible to flow liquefaction could be assigned a higher weight. Presently, when LPI is calculated at a site, all liquefaction occurrences are treated the same, with no distinction between flow liquefaction and cyclic mobility. Empirical limits based on existing liquefaction case histories are used to determine whether an LPI value corresponds to significant liquefaction hazard at the surface. However, these empirical limits have been found to vary depending on the location of the hazard [55]. Is it possible for the LPI values to have more uniformity across regions, if we incorporate for the different effects of flow liquefaction and cyclic mobility? Chapter 3 of this thesis gives us motivation to explore this question.

The results in Chapter 4 suggest a correlation between shear wave anisotropy and fabric anisotropy. This motivates a detailed micro-mechanical study to explore such a correlation, so that knowledge of shear wave anisotropy in the laboratory or the field can be used to reliably quantify the soil fabric. A numerical study via the discrete element method seems the most plausible path, since numerical simulations permit investigation of grain-scale properties and can be used to develop an appropriate fabric quantification. Any correlation proposed via numerical studies must be subsequently validated via laboratory investigations before it can be tested in the field.

5.2 Closing Remarks

A more fundamental understanding of the physics of soil liquefaction can aid in the development of liquefaction hazard maps, which map entire regions and help identify areas where liquefaction is likely to occur. Development of such maps is a necessary endeavor to make cities and economies resilient to the effects of liquefaction. By investigating the micro and macro mechanics, this thesis helps in a more physical assessment of liquefaction susceptibility and its accompanying hazards, at the field-scale and the regional scale.