Summary

Pile tunnel interaction is a relatively new problem, most commonly found in urban areas. Deep foundations are used to support buildings and other elements of the urban infrastructure, while tunnels offer an alternative pathway for the flow of people and resources in and out of cities, without interfering with the densely constructed urban surface. These two structures have co-existed for decades. Most piles were installed along ground layers far from the deep-level bored tunnels, scarcely placed through the city. However, technological innovations have changed this: piles are now installed in deeper layers to support the ever rising buildings and shallower tunnels, much more widespread through the cities, can be built. This thesis analyses how the construction of a new tunnel might affect an existing pile foundation, explains the mechanism through which this happens and recommends a methodology to calculate the consequences for design.

The first step was to examine the current state of knowledge on **pile tunnel interaction** through an extensive literature review. Quantitative measurements collected from case studies, full-scale tests and scaled models. The results were set-up in a framework where they could be compared and contrasted, revealing patterns that were not distinguishable in individual studies. Most reported structures were not affected by a tunnel construction, but under certain conditions, interventions were necessary. Two mechanisms are described, one at the pile toe and one along the pile shaft. (1) The tunnel degrades the toe capacity, which mobilizes the shaft resistance for equilibrium. (2) Negative friction is induced along the pile shaft, which increases the loading at the pile toe. In both cases, once the shaft is fully mobilized, significant settlements occur to re-mobilize the pile toe.

The quantitative data reveals that the measured pile settlements are always inversely proportional to its lateral distance from the tunnel alignment. In loaded-piles, the average axial force along the pile reduces when the piles are right above the tunnel, but increases when the piles were farther away ($Ld > Rt$). The mathematical models used to compute the consequences of pile tunnel interaction have also been studied. A pilot methodology is proposed and the promising results set the course for the developments in this project. At that stage the model imposed the pile settlements and calculated the resultant axial forces. It did not consider the possibility of pile failure, or a constant load boundary condition.

For the analysis of **piles**, a new and accessible framework was created, where it is possible to calculate the pile settlements and load transfer for any loading condition, and to consider the effects of ground displacements. This last point connects the pile response with the tunnel excavation, and it was achieved by linking the load mobilization with the relative movements between the pile and the soil. The framework is based on an adapted version of the load transfer method, and implemented within a regular spreadsheet.

The functions defining the reactions from the shaft and toe have, for the most part, only been calibrated for pile loading. However, there are important mechanisms taking place during the unloading stage. These unloading functions are also very important to model the effects of ground displacements. While normally understood as the consequence of a load reduction, unloading can also be the consequence of ground settlements. The related literature and the details of the methodology were discussed. The results were then validated for an instrumented pile load test. The method is able to reproduce the field measurements of the load-settlement curve and axial loads along the pile body.

For the analysis of **tunnels**, specifically on the matter of predicting the induced ground movements, a new take on the problem has been proposed with a focus on pressurized tunnel boring machines (TBMs). The study tried to answer the following question: What are the forces acting on the excavation perimeter of a tunnel? This led to a general review of the processes around a TBM, the physical mechanisms involved, and the numerical techniques used to model them. The literature review shows how the mathematical models used to simulate a TBM tunnel have evolved from a basic stress release to direct accounts of the boundary pressures connected to different elements of a TBM.

An intrinsic feature of mechanized tunnelling is that every step of the excavation cycle is performed through mechanical or hydraulic systems. The interaction mechanisms between the TBM and the surrounding ground result from the operation of these systems to excavate and support the ground around the tunnel. It is self-evident that for each of these actions there will be a reaction from the ground to achieve equilibrium. However, these mechanisms are often interpreted within idealized frameworks that do not account for important features of the ground reaction that have been observed in the field. Therefore, these frameworks need to be adapted to better represent the interaction between the TBM and the ground. Two methodologies were proposed to evaluate the stages of grout injection and grout consolidation around the tunnel lining at the back of a TBM. The methodology was then validated for an instrumented case study of a tunnel in The Netherlands. The model was able to reproduce the grout pressures around the excavation perimeter, and estimate the surface settlements better than the traditional stress-release method.

Finally, these two separate studies are combined into a design tool to compute the consequences of **pile tunnel interaction**. The pilot methodology is enhanced with more realistic models for the pile reaction. At this point, the load mobilization functions can account for pile failure and have distinct paths for loading and unloading. The pile settlements can be directly obtained through a root search for equilibrium, and don't have to be imposed anymore. Unfortunately, there are no instrumented field tests to this day where the pile settlements and axial forces were recorded concurrently to the grout pressures around a tunnel boring machine. However, the methodology can simulate the fundamental mechanisms of pile tunnel interaction identified in the literature review.