Abstract

Physics engines are computer software, which have been developed to make physically plausible scenes in video games, animations and movies. Thus, they are developed for end users who may not be very familiar with concepts of kinematics and dynamics. Such end users demand a software to be fast (capable performing real-time simulations) and stable (not making errors for example due to inconsistency of input parameters). Thanks to the open source community and development momentum, the open source physics engines are developed almost at a same rate as the commercial ones and new features, methods and modules are being added to them. Probably one of the most interesting features of physics engines to engineers is that they are equipped with a highly efficient computation scheme, which makes the analysis significantly faster compared to conventional engineering software.

The principal purpose of my PhD study was to explore the possibilities of using physics engines in civil engineering simulations, especially geotechnical engineering simulations. An initial assessment on the physics engines showed that physics engines are provided in various types in terms of capabilities, methods of computation and purpose. We found it difficult to associate the available features of physics engines with the required characteristics that civil engineering simulations demand. Eventually, we chose **Bullet physics library** (from now referred to as "Bullet") as the base engine to work on due to the interesting features Bullet offers. Additionally, Bullet was the only engine which was associated with engineering usage in the fields of robotics.

In order to investigate the accuracy of the results of the Bullet engine in the first place, we decided to perform pluviation and vibratory densification experiments on poorly graded gravels. Pluviation experiments involve pouring of gravels through a funnel from a certain falling height into a container with a certain shape. As the falling height increases, a denser assembly of gravels is expected in the container. In the vibratory densification experiment, the poured gravels from the pluviation tests were subjected to vibration with a certain amplitude and frequency. It is expected that a denser assembly of gravels forms during the vibration. Such complicated tests were intentionally chosen to emphasize the different simulation capabilities of discrete based methods compared to the continuum methods. Surprisingly, Bullet delivered very accurate results and it paved the way to more confidently with Bullet engine towards granular simulations.

Later we developed an advanced validation experimental scheme using the direct shear box on high precision metal beads arranged in a rhombic pattern. The size and shape of metal beads, as well as the package configuration, can be exactly replicated in the simulations. As a result, the laboratory results will be more consistent and the accuracy of the simulation results could be evaluated in a more detailed approach. We found a close agreement between laboratory and simulation results. The accomplishment of this stage was very important since we managed to answer the big question of my research: "Can physics engines be used for civil engineering simulations?". This question is indeed so comprehensive and a further elaborated answer takes a greater deal of research. However, we have demonstrated that many features offered in advanced discrete element software, can be included in Bullet engine. In order to explore the applicability domain of physics engines in civil engineering simulations, we have decided to model more complex problems, such as the simulation of impact resistance of geotextiles on granular material subjected to dropping of stones. The problem of impact resistance of geotextiles under the impact of dropping stones is very challenging: on one hand, the impact of dropping stones on granular media is associated with highly dynamic granular regimes; on the other hand, the geotextile results in confinement on the granular media underneath. The combination of these two factors results in a highly complex system to solve.

With further investigation of civil and geotechnical engineering problems using Bullet, we noticed that there are engineering features missing in Bullet. Through the simulations, we have developed our own libraries and include them as separate closed source libraries. Later on, our developments were big enough to call it a software: **Geo-Bullet**. The aim is to further develop further Geo-Bullet through prospective studies in order to have a more comprehensive engineering software.

Geo-Bullet, at its current capabilities, is able to simulate a significant number of engineering related problems such as the interaction of dragging anchors and rock berms or seabed cables (or pipelines) protected by rock berms; self-weight penetration of monopiles through scour protection layer; the interaction of scour protection layer with noise mitigation systems (NMS) during off-shore piling; and the interaction of spudcans of jack-up vessels with surficial or buried boulders. Out of the scope of the present doctoral research, simulations have been carried out to investigate such engineering problems. A summary of the results of the interaction of dragging anchors with rock berms is presented in chapter 6 of this dissertation.

One of the most appealing development milestones in the future will be including a fluid module to allow simulations associated with water/mud interactions. Beyond the scope of the current research work, the integration of a fluid module is under development and still in progress at the time of writing this dissertation. Upon the two-way integration (grain-water and water-grain interaction) of the fluid module in Geo-Bullet, new horizons will arrive for the practicality domain of Geo-Bullet in engineering problems, especially off-shore related engineering activities. For example, engineering problems such as the effect of the waves and storms on the jack-up vessels or off-shore platforms; navigability of the vessels in highly sedimented canals; the behavior of granular material in a fall pipe used for pipeline protection; and efficiency of the jack-up vessels in semi-floating conditions can be investigated.

Key words: Bullet physics engine; Geo-Bullet; Simulation; Geotechnics; Rigid body dynamics