Chapter 7

Summary, Conclusions and Future Research

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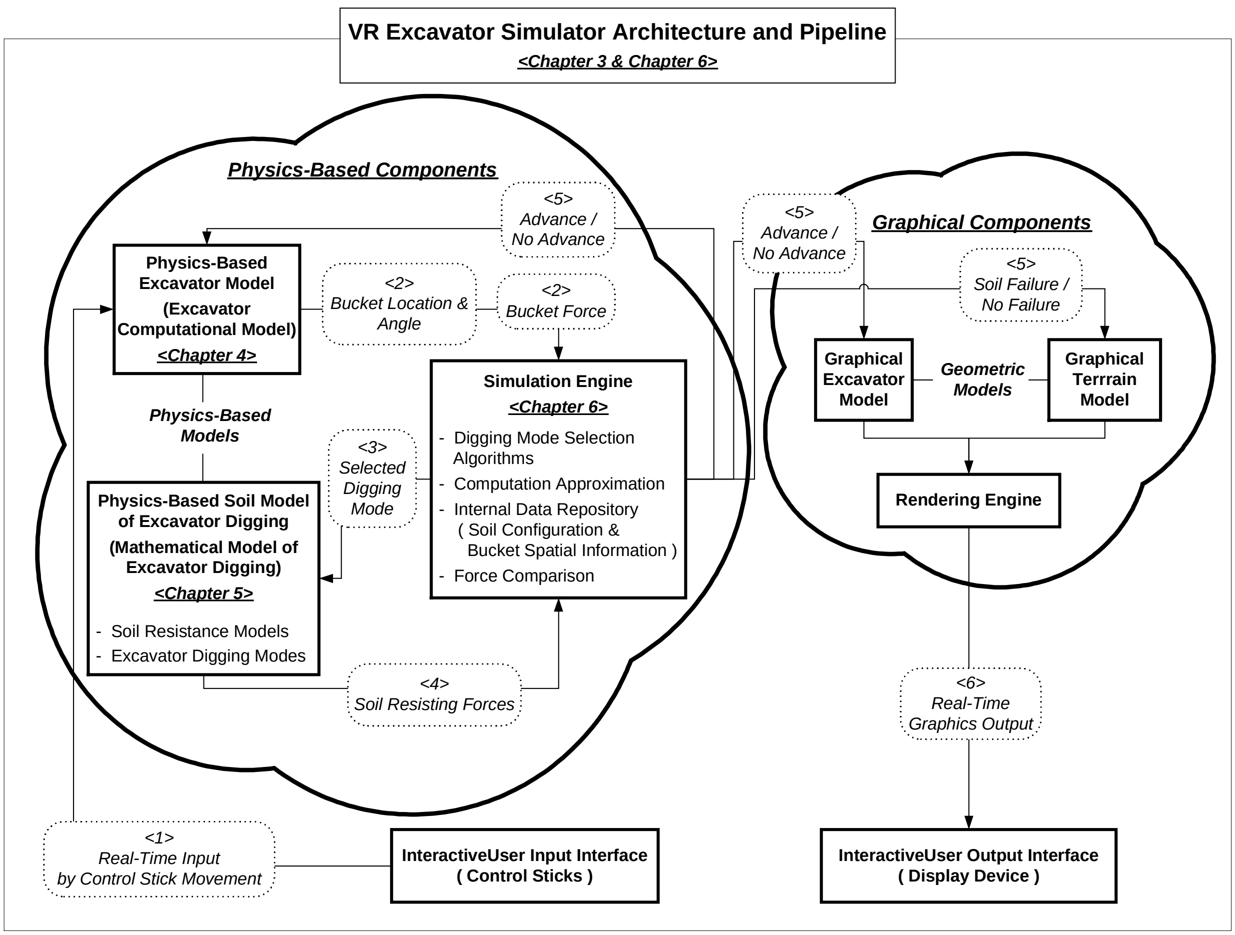

7.1 Summary of Results

The research aims to contribute to the development of a VR construction excavator simulator system by proposing a mathematical model of excavator digging and a calculation methodology.

The mathematical model of excavator digging provides physically meaningful soil-bucket interaction information to a simulator (Chapter 5). The calculation methodology is to provide systematic and efficient computation methods to ensure the seamless integration of the excavator digging model with a VR simulator system as well as adequate system speed (Chapter 6). As a result, the simulator is realized as an engineering process tool equipped with real-time interactivity.

7.1.1 Mathematical Model of Excavator Digging

Digging of construction excavators is complex in terms of their interaction with soil media (Chapter 2). It is because excavator digging relies on different excavating mechanisms (penetration, separation and secondary separation), and these digging mechanisms are constantly changing and oftentimes coupled together during an excavation process.

In order to manage the complexity of excavator digging process, the framework is proposed as an analytical basis, by which even the most complex soil-tool interaction between an excavator bucket and soil is analyzed effectively (Section 3.2). The main idea of the framework is that any digging process of an excavator can be segmented into pieces and each segmental piece represents a snapshot of a digging action at that point in time. Depending upon the number of segments, there could be numerous corresponding digging actions. However, these digging actions can be classified into a few common groups, each of which represents an unique bucket-induced soil resistance calculation scheme. Thus no matter how many digging action segments exist in a digging process, the segments belong to particular digging action groups. Therefore identified digging action groups are used as building blocks to form a certain digging process. These digging action groups are called excavator digging modes.

The purpose of digging modes is to provide means for any particular digging action to be classified into a certain digging situation (digging mode) so that its underlying digging mechanisms (penetration, separation, and secondary separation) specified in each digging mode are identified (Section 5.5). Once the types of mechanisms are known, a corresponding soil resistance model is applied to predict the soil resistance for each mechanism (Section 5.3 and Section 5.4).

A resistance model for an excavator separation mechanism is developed by adapting the Perumpral's model in a way that the unique situation of an excavator digging is properly handled in the model (Section 5.3). Specifically, an inclined terrain condition and the unique shape of an excavator bucket are included in the model formulation. Another resistance model for an excavator penetration mechanism is proposed by providing solutions to the inherent problems of the cavity expansion theory when the theory is used in an excavator digging case (Section 5.4). The penetration process of an excavator bucket is also suggested so that the application of the proposed penetration resistance model in a penetration process is realized.

The procedure in Figure 7.1 shows how the suggested mathematical model of excavator digging is applied to predict a series of soil resistance forces (penetration resistance + separation resistance) in an excavator digging process.

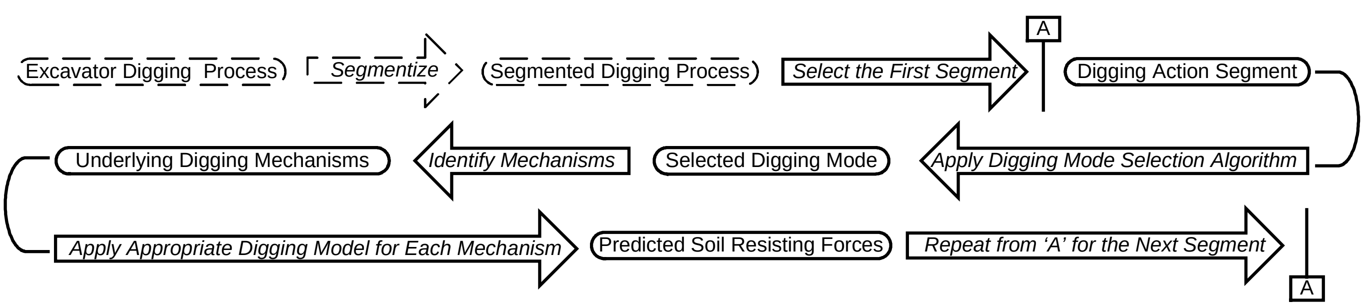

Figure 7.1 Proposed Procedure for Soil Resistance Calculation in an Excavator Digging Process

7.1.2 Calculation Methodology

As a starting point for providing systematic and effective calculation scheme for the development of a VR excavator simulator, a VR excavator architecture and pipeline is proposed (Section 3.3). It describes what the essential components are in a VR excavator simulator; what actions need to be taken in each component; and how and what calculation information are transferred from one component to another. The proposed mathematical model of excavator digging along with excavator computational model (or physics-based excavator model, Chapter 4) are the essential components in the system in that they account for the soil-bucket interaction in an excavator digging process for the simulator.

This component-based description of the calculation flow in a VR excavator simulation system is refined in detail by presenting the data-and-function-based description of the computation flow in a particular time segment of digging operation (Section 6.2). This information is critical for a simulator development, especially in a program implementation stage.

A digging mode selection algorithm is proposed to provide systematically organized instructions in a finite and unambiguous format in order to identify a digging mode for a particular digging action segment (Section 6.3.2).

Another algorithm, the imaginary joint calculation algorithm of multi-joint circular trajectory, is proposed to accurately and swiftly (from a computation perspective) construct a circular trajectory for a multi-joint-based digging action segment (Section 6.3.3).

The repetitive calculation requirement of the proposed separation resistance model (Section 5.3) is a major bottleneck in the whole calculation process of a VR excavator simulator. Through a series of sensitivity analysis, an approximation formula that determines soil failure angle is proposed to enhance the calculation speed (Section 6.4).

7.2 Recommendations for Future Research

7.2.1 Recommendations on the Mathematical Model of Excavator Digging

- <u>Tolerance on the Separation Blade Angle Conditions</u>

The first criterion in the digging mode selection algorithm is the separation blade angle with respect to the tangent line at bucket tip on a circular trajectory. The conditions are 'tangential', 'normal', or 'angled'. It is, however, not clear how much of angle of tolerance needs to be given to each condition for those conditions to be practically correct. For example, 10 degree of angle of blade with respect to the tangent line at bucket tip could be considered to be a 'tangential' case instead of 'angled' case. Therefore, more explanation on this aspect can be beneficial for the digging mode selection algorithm to be more practically correct. As a result, unnecessary calculation for soil resistance can be eliminated.

- <u>Degree of Coupling Effect</u>

The basic assumptions of the research framework on the resistance calculation of mixed-mechanism digging modes such as Mode III, IV, and V is that each mechanism contributes to the final resistance amount without affecting the other mechanism's contribution to the total. However, in order to be a more accurate model, the further investigation can be pursued in this aspect to suggest the degree of each mechanism to another so that more accurate resistance can be predicted.

- <u>Adaptation of the Mathematical Model of Excavator Digging to Provide Close-to-Reality Resistance to an Excavator Bucket in a Loose Soil Environment</u>

The way the proposed mathematical model of excavator digging works is that the excavator bucket gets the resistance force when the soil gets failed after being pushed to a certain degree. However, if the soil is not dense enough, or if the digging action segment is very small, the truth is that the bucket is getting the resistance constantly from the soil even before it gets failed. A research on this issue will be useful to provide users with the better feeling of excavation operation.

7.2.2 Recommendations on the Excavator Computational Model

- Machine Interaction with Soil at the Track

The interaction of an excavator bucket with the soil environment affects the degree of the interaction of an excavator body at the track, and vice versa. A further research on this relationship can be used to have more accurate bucket forces or to provide more credible machine spatial information, for example, to give users the credible feeling on the machine movements.

- Dynamic Effect of Moving Bucket

The dynamic effect of a moving bucket can be a factor in a digging process, especially in the initial phase of digging. Shallow excavation or excavation in small resistance soil can be another cases where the dynamic effect is not negligible.

7.3.3 Recommendations on the Soil Medium Representation

- Effective Way of Representing Soil Medium

Current practice of representing soil medium is that it is an assembly of numerous small cubes or dots placed in 3-dimensional space. These are the data stored in the database and accessed by other components in a VR simulator system. If a VR excavator system requires more accuracy, it means that the database needs to have more elements, which conversely, means that the system needs to sacrifice the speed. If there are not enough of points or cubes, the quality or the accuracy of the calculation will deteriorate even though a certain level of speed requirement can be met.

7.3.4 Recommendations on User Perception Improvement

- Level of Detail

The relationship between the *level of detail in model representation*, the *degree of a system speed* and the *degree of user perception*, should be identified for a VR simulator to be efficient. Therefore, depending on the requirement from a user, the requirement of a VR system could be determined. This is true not only for the graphical components of a VR system but also for the physics-based components.

- User Interfaces

The user interfaces could be big factors to affect the degree of success of a VR simulator system. For example, use of CAVE™ as an output device, force-feed back control-sticks, a motion platform, or sound or smell effect could increase the level of perception of VR operators. A research effort could be extended in this aspect to justify the money and time expense for better system performance.