UNMANNED AERIAL VEHICLE BASED VISUALIZATION OF DEEP EXCAVATIONS USING GAME ENGINES

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ABSTRACT

UNMANNED AERIAL VEHICLE BASED VISUALIZATION OF DEEP EXCAVATIONS USING GAME ENGINES

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In the last two decades, the advancements in monitoring tools and growing use of information technologies lead to better visualization of construction sites. The challenge in this field is to develop an extensively capable tool for safety check, progress monitoring and quality control. In this sense, Geotechnical Engineers need a comprehensive understanding of field conditions, which includes topography, soil conditions, effect of nearby structures, etc. In this study, game engines are proposed as visualization tools to interact with the site on a virtual environment formed by the images taken by Unmanned Aerial Vehicles (UAVs). Deep excavations are chosen as test cases where catastrophic failures can be prevented by taking measures according to monitoring activities. In addition, reaching to deep levels in the excavations for quality assurance is always a challenge at the construction site. To overcome such challenges, UAVs with various sensors are used to capture images of the site. In this study, as photographs inherently lack geometric information and does not provide a full imagery, Structure From Motion and Multi View Stereo algorithms are proposed to create a highly dense and colored point cloud. As the cloud may not be interactive enough for inspection, it is further processed through meshing, then imported as a scene into a virtual world via game engines to provide an interactive environment for the engineers. The developed product is successfully tested on two deep excavation sites located in Ankara, Turkey. Promising results show that the game produces sufficient details of construction and topography, which provides engineers a way to investigate the excavation. The study has immense future possibilities such that the developed tool can be employed in educating the engineers, and can be integrated with the current software tools to make them more capable.

Keywords: Game Engine, Unmanned Aerial Vehicle, Deep Excavation, Computer Vision, Photogrammetry.

ÖZ

OYUN MOTORU KULLANILARAK DERİN KAZILARIN İNSANSIZ HAVA ARAÇLARI TABANLI GÖRÜNTÜLENMESİ

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Son yirmi yılda, yapı gözetim gereçlerindeki ilerlemeler ve bilişim teknolojilerindeki yenilikler, inşaat alanlarının daha etkili bir şekilde görüntülenebilmesine olanak sağlamıştır. Bu alandaki zorluk; iş ilerleme takibi, güvenlik denetimi ve kalite kontrol konularının hepsinde uygulanabilecek geniş kapsamlı bir araç geliştirebilmektir. Bu bağlamda, Geoteknik Mühendisleri de sahada, topoğrafya, zemin şartları, çevredeki yapıların etkisi vb. bilgilere erişebilecekleri kapsamlı gereçlere ihtiyaç duymaktadırlar. Bu çalışmada, oyun motorlarının, İnsansız Hava Araçları (İHA) ile çekilen fotoğraflar kullanılarak elde edilen sanal ortamın, etkileşimli bir şekilde görselleştirilmesi amacıyla kullanılması önerilmektedir. Geliştirilen sistemin test edilmesi için derin kazılar seçilmiştir. Derin kazılarda meydana gelebilecek yıkımlar sahalarda yapılan düzenli takip ve denetim çalışmaları ile önlenebilir. Ayrıca, kazılarda derin seviyelerde bizzat gözlem yapılmasının yanı sıra fotoğraf çekmek bile güçlük oluşturmaktadır. Bu çalışmada, bahsi geçen zorluklar, aralarında video kamera da bulunan birçok sensör ile donanmış İHA'lar yardımı ile aşılmış, böylelikle derin kazıların ulaşılması güç bölgelerinde dahi rahatlıkla fotoğraf alınması sağlanmıştır. Bu

çalışmada, fotoğrafların doğası gereği geometrik bilgi içermemesi ve saha hakkında tam bir bilgi verememesi nedeniyle, Hareket Tabanlı Yapısal Algılama ve Çoklu Görünümlü Stereo gibi algoritmaların kullanılması ve böylelikle oldukça yoğun ve renkli nokta bulutlarının oluşturulması önerilmiştir. Elde edilen nokta bulutu, denetleme yapabilmek için yeterince etkileşimli olmaması nedeniyle, daha da işlenerek nokta ağı elde edilmiş ve bu ağ, oyun motorları aracılığı ile, sanal bir ortama katılmıştır. Bu sayede, mühendisler için etkileşimli bir ortam sağlanmıştır. Geliştirilen ürün, Ankara ilinde iki derin kazı sahasında başarı ile test edilmiştir. Elde edilen başarılı sonuçlar, oyunun, inşaat sahasından yeterli ayrıntı ve topoğrafya verisi içerdiğini ortaya koymaktadır ve böylelikle mühendislerin inceleme yapabilmesi amacıyla bir yol oluşturulmuştur. Bu çalışma gelecekte, mühendislerin eğitimi ve hali hazırda kullanılan yazılımlara entegre edilerek yeteneklerinin arttırılması gibi tahmin edilemeyecek bir çok olanağı yaratma potansiyeline sahiptir.

Anahtar Kelimeler: Oyun Motoru, İnsansız Hava Aracı, Derin Kazı, Bilgisayar Görüşü, Fotogrametri.

Dedicated to my beloved family and friends…

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LIST OF ABBREVIATIONS

2D	Two-dimensional
3D	Three-dimensional
4D	Four-dimensional
AI	Artificial Intelligence
ASPRS	American Society for Photogrammetry and Remote Sensing
AR	Augmented Reality
BIM	Building Information Modeling
CAD	Computer Aided Drawing
CMVS	Clustering Views for Multi-View Stereo
CPM	Critical Path Method
DEM	Digital Elevation Model
DOF	Degree of Freedom
DSLR	Digital Single-Lens Reflex
DTM	Digital Terrain Model
MEP	Mechanical – Electrical – Plumbing
GCP	Ground Control Points
GPS	Global Positioning System
GUI	Graphical User Interface
IMU	Inertial Measurement Unit
LIDAR	Light Detection and Ranging
MVS	Multi-View Stereo

OSHA	The U.S. Occupational Safety and Health Administration
RC	Remote Controlled
RGB	Red-Green-Blue
RTK	Real Time Kinematic
SFM	Structure From Motion
SIFT	Scale Invariant Feature Transform
TLS	Terrestrial Laser Scanning
UAV	Unmanned Aerial Vehicle
VR	Virtual Reality

CHAPTER 1

INTRODUCTION

1.1. Overview and Problem Statement

Visualization plays an important role in almost all engineering fields. As a matter of fact, visualizing or seeing something is said to be believing or understanding it. In the field of Civil Engineering, specifically, visualization is the key word in many stages of a project, from the design to construction. In a typical project, the design is performed according to the combination of architectural and technical drawings. In addition to these, there are even mock-up models for some structures, which are built in advance. Before the construction starts, visually, almost everything about the structure to be built is known through its design process. That is the main reason why Building Information Modelling (BIM) gains popularity every day, as these modeling tools bring all design inputs into a single platform for synchronization with the construction stages. Overall, this leads the engineers to visualize ongoing actions in the construction area and learn what to do next accordingly.

Continuous increase of population and its density in urbanized areas and city centers leads to a growing demand for high-rise buildings. Especially in areas where the available space is limited or too expensive, the construction of deep excavations to build the foundations of these structures is inevitable. They are not only necessary to satisfy geotechnical limitations, but also to create spaces for living or infrastructural needs. The construction of deep excavation requires continuous monitoring as when it is constructed or designed poorly, it may lead to instabilities of the nearby structures as well as cause potential danger for the workers inside the construction area. Especially, unforeseen ground conditions may result in catastrophic failures, which can be prevented by taking precautions according to the results of monitoring activities.

Conventionally, planning and drawing software are used as visualization tools. Although many improvements have been added to such tools to visualize the construction sites better, there is still room for further improvements as the technology continuously make progress. In this decade, specifically, three-dimensional (3D) representation of the construction objects using pictures, i.e., obtaining the 3D spatial information derived through processing 2D imagery, is the new challenge of visualization studies. For properly doing this, new techniques for visualization based on images of the construction site are proposed. They are usually developed as a result of technological advancements in the computer vision field, which aims for computers to gather high level information from digital images or videos. Since the most effective and accurate visual inspection of a construction site can only be performed through human eye, i.e., inspection of the site by a supervisor, the techniques developed for construction monitoring need to mimic this action.

In addition to the improvements in digital image processing techniques for construction monitoring, various image collection platforms with the increased quality of cameras have shown up in the market, which also lead to higher efficiency and accuracy for the image interpretations at the site. Among them, emerging unmanned aerial platforms appear as a reliable alternative due to various advantages such as being cheap and easy to operate. Among those platforms, Unmanned Aerial Vehicles (UAVs), also known as drones, are the small, light-weight flying vehicles controlled either by a pilot remotely, or autonomously. Endless advancements in the technologies of UAVs allow them to carry many digital or analog sensors, which include digital or infrared cameras, proximity sensors, inertial measurement units, global positioning system (GPS) units. With these additions, UAVs can be used in many different platforms ranging from natural disaster monitoring and orthomosaic image generation for large populated areas to even live broadcasting of sports games. As a result, the use of UAVs at the construction sites have become almost inevitable nowadays.

Among the visualization tools used for civil engineering projects, finding the good ones that provide the ability to view 3D information in a proper environment and at a low cost is a challenge. Engineers are often required to work with graphic intensive models developed using costly commercial software. A cost free alternative of such software can be game engines, which are the frameworks that optimize the connection between the graphical hardware and the software. They are used to create visually rich and highly interactive virtual environments with the need of lower processing power.

Computer games, since their invention, have been the “enemies”, as parents do not want their children to lose time as kids spend endless hours with games due to their visually rich and intriguing nature. In the old times, this idea might have made sense as parents could find more productive alternatives for the teenagers. However, as games predominate the entertainment market, scientists have begun to understand that the games can be effectively used as a tool for educational purposes since many people love playing them. Through a computer game, knowledge transfers or sharing experiences in a virtual environment is quite possible. In other words, if the game is designed and built realistically, players may get a chance to experience real life scenarios, which allow living in those environments virtually, i.e., without actually “paying the price”. Therefore, implementing real world scenarios into the computer games can be an extremely powerful tool for visualization and learning. In this sense, construction sites implemented in games can be very good education environments for engineers.

Within this overview, 3D models of the deep excavation construction sites obtained using images acquired by UAVs and processed through computer vision techniques can be very helpful. 3D models, when imported into a game engine to make them interactive, are the next generation solutions for visualization of excavation sites to be used for monitoring the constructions.

1.2. Objectives of the Research

In this thesis, the aim is to bring the recently introduced techniques and tools together to create an environment for the visualization of deep excavations and to provide interaction between the user and the environment. While achieving this, the following objectives are also aimed along the way:

- To produce geometrically correct models of deep excavations, which can present the deep excavation site accurately and in sufficient details,
- To offer the engineers an environment where they can visualize the construction site interactively,
- To provide an easy access to areas through UAVs, which are otherwise very hard to reach,
- To provide a virtual environment that can run on various platforms including computers, browsers, mobile phones, etc., which eliminates the dependency of using a commercial software.

1.3. Scope of the Thesis

This study uses many tools for creating a virtual environment to visualize the deep excavation sites. The use of imaging equipment is limited with the employment of low cost commercial UAVs only. Midsize or large size commercial ones are not included in this study, the use of which is very expensive. In addition, other tools such as satellites, regular or professional cameras placed at fixed positions at the construction site, which can also be used for monitoring, are not considered in this study.

Within the framework of creating a virtual environment, many construction sites such as buildings, dams, bridges, etc., can be used as test cases. However, only deep excavations are selected as main focus of this work as they hold a special place in Geotechnical Engineering literature and many deep excavations are currently performed in developing countries such as Turkey.

1.4. Thesis Organization

Considering the objectives of this research and its scope, the rest of thesis is organized as follows: Chapter 2 provides the literature work related to visualization, application of computer vision techniques and the use of UAVs in the fields of construction safety and progress and health monitoring. Chapter 3 introduces the method used in this thesis. Chapter 4 presents the application of the method on two deep excavation case studies. Limitations of the method and the results are also discussed in this chapter. Chapter 5 provides the summary and conclusions together with the future studies related to employed method, monitoring of deep excavations as well as UAVs.

CHAPTER 2

LITERATURE REVIEW

This chapter presents the background work performed in the area of visualization considering engineering applications. The development of a game using images obtained with UAVs for the visualization of deep excavations require good knowledge on (i) Geotechnical Engineering field, (ii) the operation of UAVs, and (iii) Game Engines. Only the combination of expertise from those mentioned fields can produce a good quality work, which can be meaningful for engineers and practitioners at the site. As the unique part of this thesis is the application of UAVs and Game Engines into the field of Geotechnical Engineering, specifically the Deep Excavations, the related literature review is given below.

2.1. Monitoring of Construction Sites

The visualization tools are mostly developed by Computer Scientists using the knowledge obtained mainly from the field of Computer Graphics. The practical applications of such tools can be seen in various disciplines, such as Medicine, Agriculture, etc. The penetration of such technologies, however, has been quite limited in the field of Civil Engineering. In fact, the research and practical studies has started in the area of Construction Engineering and Management in the last decade mostly. The literature part is therefore limited with those presented in this subfield of Civil Engineering. The applicability to the other subfields such as Geotechnical

Engineering, Transportation Engineering, Structural Engineering are now expected to expand with a gigantic acceleration.

It is essential to ensure the safety in a construction site for the workers and the equipment. With this idea in mind, many scientific studies tried to implement new and improved computer vision technologies into the area of construction monitoring including safety related issues (Chi & Caldas 2012; Wang et al. 2015; Ding & Zhou 2013). Among those, Chi & Caldas (2012) developed a system that uses stereo vision camera to detect objects in the construction sites in accordance with the violations stated by The U.S. Occupational Safety and Health Administration (OSHA). They developed this system using image-based object identification and tracking algorithms. In their work they focused on 3 violation types, namely, speed limit violations, dangerous access violations and close proximity violations. Using safety rules stated according to violations, they automated the safety risk identification for loading, hauling and dumping operations. Wang et al. (2015) used Light Detection and Ranging, known as LIDAR, LADAR or laser scanning, and generated point cloud data for identifying safety hazards stated by OSHA regarding cave-ins, falls, contact of workers with equipment or other objects. The developed system was used in a case study where the fall hazards were identified. The detected hazards were used to generate protective systems such as guardrails, soldier piles, etc. in BIM models.

Besides safety monitoring, construction sites should also be monitored for progress and quality control. The workflow of construction monitoring is time consuming, costly and labor intensive (Navon 2007). Recently, researchers used still-images, time-lapse images, videos, laser scanners for this task (Yang et al. 2015; El-Omari & Moselhi 2008; Gordon & Akinci 2005; Memarzadeh et al. 2013). Memarzadeh et al. (2013) used video frames taken from a construction to detect construction equipment and workers in the construction site (Figure 1). Gordon & Akinci (2005) introduced and validated the feasibility of using LIDAR technologies for construction quality control purposes using five case studies conducted on various construction projects. Bosche & Haas (2008), Bosche et al. (2009) and Kim et al. (2013) used laser scanners to detect 3D Computer Aided Design objects in a point cloud in order to monitor the progress of construction. Similarly, Brilakis et al. (2011) used videogrammetry to generate 3D point clouds of the construction site progressively. Golparvar-Fard (2009) used a method that overlays BIM model components on the still-images taken at predetermined locations to determine the parts of the project that are behind schedule, ahead of schedule and on schedule (Figure 2). Zollmann et al. (2014) used a similar superimposing approach using 3-D models instead of still-images. In this work, they generated 3-D models using photos acquired with UAVs instead of laser scanners.

Figure 1 - Detection of Construction Equipment and Workers from Video Frames (Memarzadeh et al. 2013).

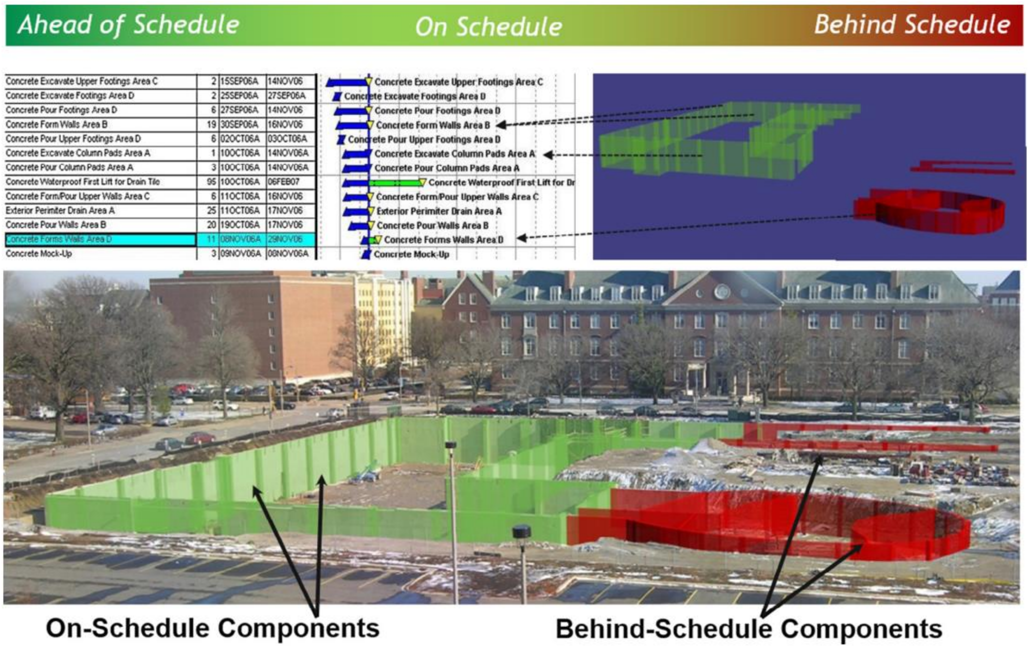


Figure 2 - Method of Superimposing BIM Components on Still Images from Construction Site (Yang et al. 2015).

2.2. Unmanned Aerial Vehicles

A UAV, also called drone, is a flying vehicle that was introduced to eliminate the need for a pilot. UAVs were used for military reconnaissance purposes during 50's. However, they are being used outside of their primarily intended military purpose recently. With the latest developments in UAV systems, they become cheaper and more capable systems and made available for public use. Nowadays, it is easier for anyone to buy a reliable UAV or even build one using open-source tools. Moreover, with the increasing capabilities of the on-board GPS systems, most of the UAVs even support autonomous flight up to some level of freedom. Although it may still be dangerous to fly autonomously at reasonably low altitudes, most of these devices do so with the supervision of a remote controlled (RC) pilot. In dangerous situations, the RC pilot can interrupt the autonomous mission to avoid the collusion.

2.2.1. Physical Characteristics and Sensors

In most general sense, small UAVs can be classified as either fixed wing, or rotary wing UAVs (Eisenbeiß et al. 2009). The fixed wing UAVs can easily be distinguished by their plane like single or multiple fixed wing structure. On the other hand, rotary wing UAVs, as their name suggest, consist of single, double or multiple rotors. The main advantage of fixed wing UAVs over rotary wing UAVs is their range and cruising speed, since they can naturally glide with their wings and require smaller rotor with less power consumption whereas rotary wing systems require bigger and in most cases multiple rotors that consume power faster. However, this feature gives rotary wing UAVs higher maneuverability and increased payload capability. A comparison chart between these systems is given in Table 1.

Table 1 - Rotary Wing and Fixed Wing UAV Comparison Table (SenseFly 2015)

	Fixed Wing UAVs	**Rotary Wing UAVs**
Projects	Mapping	Small area mapping & inspection
Applications	Rural land surveying, agriculture, GIS, mining, environmental, construction	Inspection, cinematography, real estate, urban surveying, construction, emergency response, law enforcement
Cruising Speed	High	Low
Coverage	Large	Small
Object Resolution	cm per pixel	mm per pixel
Take-off/landing area	Large	Small
Flight	High	Low

UAVs are equipped with various sensors, including, gyroscope, magnetometer and accelerometer to detect 3D orientation (the combination is also called Inertial Measurement Unit) and a GPS sensor for navigation. In addition to the on-board sensors, some UAVs also include vision-positioning system, which makes use of a low-resolution camera directed to the ground to detect small movements at low altitudes, and a sonar system to detect altitude in areas where GPS-measurements are inaccurate. With that UAVs are even capable of automatically avoiding collusions in either autonomous or pilot-controlled flights. Moreover, they can be equipped with different payloads such as First-Person-View camera systems, Digital Single-Lens Reflex (DSLR) cameras, Infrared sensors and Laser Scanners. Depending on the size and weight of the UAV, the range of these payloads can change. For example, most of the mid-end commercial UAVs can be equipped with digital cameras with an image capture resolution capacity with a range changing from 720p to 4k. However, for the high-end models, mostly DSLR cameras are used.

2.2.2. UAV Based Applications

Using sophisticated sensors in UAVs led to increased number of research studies recently (Siebert & Teizer 2014). These works include archeological studies (Sanders 2015), agricultural applications (Grenzdörffer et al. 2008; Rokhmana 2015), coastal surveillance (Turner et al. 2016; Gonçalves & Henriques 2015), structural health monitoring with crack detection (Pekcan et al. 2016; Sankarasrinivasan et al. 2015), landslide monitoring (Niethammer et al. 2012) and disaster scene reconstruction (Herman 2014).

To provide some examples from these studies, Grenzdörffer et al. (2008) outlines the possible use of UAVs in agriculture as; field trials and research, biomass, crop growth and food quality inspection, precision farming, fungicide reduction, senescence monitoring of cereals and logistic optimization. Sanders (2015) points out the possible uses of UAVs in virtual heritage creation regarding archeological sites. Turner et al. (2016) emphasizes the use of UAVs in post-storm coastal surveying via integrating this technology into their regular coastal monitoring program in Australia.

All the above studies conducted using UAVs also have something in common, called photogrammetry. American Society for Photogrammetry and Remote Sensing (ASPRS) defines photogrammetry as, “the art, science, and technology of obtaining reliable information about physical objects and the environment, through processes of recording, measuring, and interpreting images and patterns of electromagnetic radiant energy and other phenomena” (ASPRS 2015). In this sense, UAV photogrammetry can be defined as, the use of an autonomous/remotely controlled measurement platform that includes some form of photogrammetric measurement system such as a camera to gather spatial information of the environment (Eisenbeiß et al. 2009). The spatial information generated with UAV photogrammetry can be Digital Elevation Model (DEM), Digital Terrain Model (DTM), high resolution orthomosaic image or point cloud.

The first successful use of autonomous UAVs in generation of DTM was accomplished in Eisenbeiß and his colleguage's work (Eisenbeiß et al. 2005). Then in Niethammer et al. (2010) and Niethammer et al. (2012) the accuracy of UAV photogrammetry was tested with Super-Sauze landslide in France (Figure 3). In these works, a rotary wing UAV with 4 rotors, also called a quadcopter, with an on board digital camera was remotely controlled to acquire 1486 airborne photographs. Orthomosaic photographs and DTMs were generated for whole sliding area (850 x 250 m), with 199 georeferenced Ground Control Points (GCPs), were generated using photogrammetry tools. For orthomosaic generation, a plane image rectification approach was used and final processing was done on OrthoVista software. The ortomosaic image was used to detect the movements in the landslide for a period from May 2007 to October 2008. For DTM generation, a tool called Vision Measurement System (VMS) and an image matching algorithm called GOTCHA was used. The accuracy of the generated DTM was tested against a DTM of the same region generated using Terrestrial Laser Scanner (TLS). The quality of georeferencing assessed around the GCPs were reported around 0.5 m. The accuracy of photogrammetric DTM was tested by comparing the elevation difference between the DLM and TLS DTM. The root mean square of elevation difference was reported as 0.31 m although most of the error was due to the vegetation.

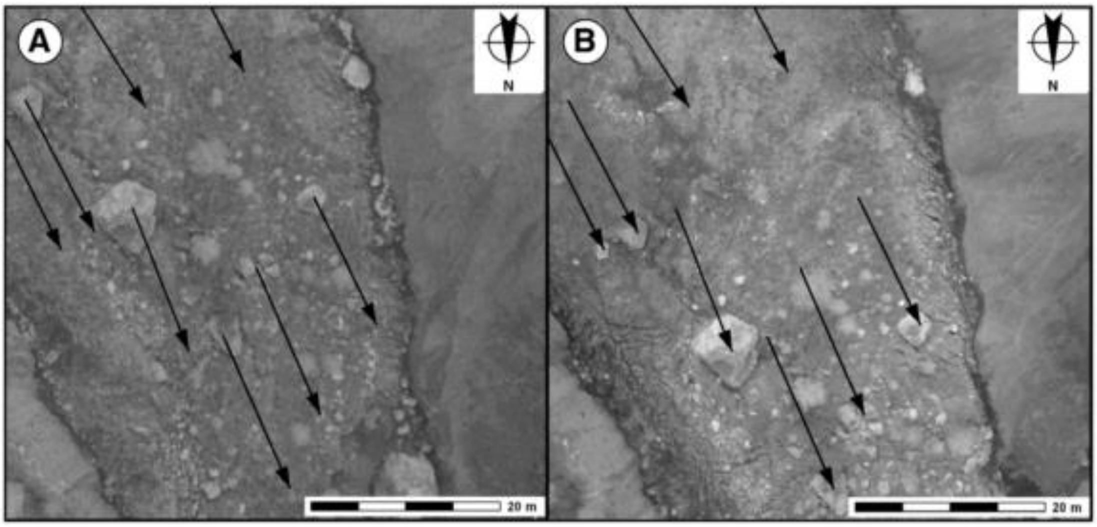


Figure 3 - Displacement Analysis on The Toe Region of Super-Sauze Landslide Between May 2007 (Left) and October 2008 (Right) (Niethammer et al. 2012)

In recent years, several studies were conducted on the accuracy of the DEMs generated using UAV photogrammetry (Krš et al. 2016; Uysal et al. 2015; Al-Fugara et al. 2016; Siebert & Teizer 2014). Among these, Krš et al. (2016) uses a UAV called Phantom 2 Vision+ by DJI (which is also used in this study) to generate 3D model of a surface mine site in Slovakia. Then they tested the accuracy of 3D model by comparing it with the traditional tachymetry data.

2.2.3. UAV Based Photogrammetry

In Siebert & Teizer (2014), a UAV photogrammetry workflow that includes the planning of the autonomous flight path called Mikrokopter Flight Planning Tool was developed. Using this workflow, data were acquired from a parking lot as test bed and several other field studies. Acquired data were processed using a commercial photogrammetry software Photoscan by Agisoft. The results from the test bed showed that the data generated from UAV deviates from the traditional tachymetry data with a mean of 0.6 cm and 1.1 cm, in position and height, respectively. Then the feasibility of the system was tested on real world civil engineering problems. First problem was the surveying of a toxic landfill. In this test the economic advantage of the UAV photogrammetry was emphasized. With the use of this system, the survey was completed in nearly 1/3 of the time of a Real Time Kinematic (RTK) GPS surveying with a significantly increased data size with 0.03 points/m^2 vs. 92 points/m^2. Next, two test scenarios were the earth moving operations of a road and high-speed rail construction projects. In these projects, the errors found in earth volume calculation compared to RTK GPS were in between 8% and 16%. With the significant increase in data size, the earth volumes calculated with photogrammetry can assumed to be the more accurate ones. In short, estimating the volumes beforehand and in a fast manner provides the engineers with an important information regarding the scheduling of the work.

There are several free or commercial photogrammetry software solutions in the market (Gómez-Gutiérrez et al. 2014). However, all these software follow the same fundamental Structure From Motion (SFM) (Ullman 1979) steps. The first step is to detect matching features in images by first, detecting features with a feature detection algorithm such as SIFT (Lowe 2004), SURF (Bay et al. 2008), and FAST (Rosten & Drummond 2005), etc. and then matching them across all images. Using these matched features, the camera model parameters and the position and orientation of the cameras are calculated with Bundle Adjustment (Snavely et al. 2006). After the camera parameters are estimated, the point cloud generation is just a simple projection. The points on a 2D plane with known orientation (features on images) are projected onto the 3D world. The final calculated point cloud with SFM is generally not georeferenced and not dense enough. Therefore, at these points, most software tools use Multi View Stereo (Seitz et al. 2006) algorithms to generate a dense point cloud. Finally, the point cloud is georeferenced either manually using GCP or automatically if the images have GPS data embedded.

2.3. Game Engines

Game engines are the software frameworks developed specifically for the creation of video games. They achieve this functionality by incorporating some components such as a rendering engine, an audio engine, a physics engine and artificial intelligence (AI). Rendering engine calculate the graphics seen by the player for each frame of the game. A rendering engine makes use of the 3D coordinate data in the game as well as lighting and shadows cast by the objects in the environment. Audio engines conduct the audio specific works in the game. They need to assign specific sounds to objects and how the sound disperses in the game environment. Physics engines responsible for incorporating the natural physical phenomenon such as gravity, friction, etc. into the virtually created game world. And lastly, AI part of a game is responsible how the entities with the movement capabilities other than the player itself behave in the game environment. Game engines optimize these specific components to make use of certain hardware in the computer, for example, a rendering engine optimize the use of display hardware while displaying the 3D (or 2D) game environment.

Various game engines are present in the market either commercially or as a freeware. The list of these engines and their comparison are provided in Table 2. Most of these engines provide user with sufficient tools to develop an elegant virtual world. Although their characteristics are slightly different and these differences can affect the final choice, familiarity of the developer is still the most important factor when making decisions about which game engine to use. After all, none of these features cause a significant change on the results since an engine is merely the platform to simulate the collected data (Li et al. 2015).

Table 2 - Feature Comparison for Few of The Most Used Commercial/Free Game Engines (Li et al. 2013)

	Unreal Engine	**CryEngine**	**Gamebryo**	**Unity3D**
Texturing	Basic, Multi-Texturing, Bump mapping, Procedural	Basic, Multi-Texturing, Bump mapping	Basic, Multi-Texturing, Bump mapping	Basic, Multi-texturing
Lighting	Per-vertex, Per-pixel, Gloss/Specular Mapping, Lightmapping	Per-vertex, Per-pixel, Lightmapping, Gloss mapping, Anisotropic	Per-vertex, Per-pixel, Lightmapping, Radiosity, Gloss maps	Per-vertex, Per-Pixel
Shadows	Shadow Mapping, Projected, Shadow Volume	Shadow Volume	Shadow Mapping	Project planar
Special Effects	Environmental Mapping, Particle Systems, Bill Boarding, Lens Flares	Environmental Mapping, Particle Systems, Bill Boarding, Lens Flares	Environmental Mapping, Particle Systems, Bill Boarding, Lens Flares	Environmental Mapping, Particle Systems, Bill Boarding, Lens Flares
Animation	Forward Kinematics, Keyframe Animation, Skeletal Animations, Morphing, Animation Blending	Forward Kinematics, Keyframe Animation, Skeletal Animations, Morphing, Animation Blending	Forward Kinematics, Skeletal Animation, Morphing, Facial Animation, Animation Blending	Forward Kinematics, Keyframe Animation, Skeletal Animations, Morphing, Animation Blending

Recently, the terms gamification and serious games are being used in the digital media. "Together with serious games, gamification uses games for other purposes than their normal expected use for entertainment" (Deterding 2011). In this sense, these concepts are being used in the globally well-known companies such as Google, Microsoft, etc. to support their main business by using these engines in areas such as management, administration, marketing (Uskov & Sekar 2014). Moreover, there are many research studies on the use of game engines in different fields such as education and training (Bosché et al. 2008; Pilegard & Mayer 2016; Nikolic et al. 2011), virtual heritage (Sanders 2015), construction resource planning (Li et al. 2015), disaster modeling and preparedness (Herman 2014; Ondercin 2016).

Among the above studies really interesting works exist. For example, in archeology, it is often difficult to visualize the past forms from the ruins found in the archeological sites. Scaled models are usually used to give perspective to the people as to what happened in that particular site. However, with the developing computer technologies, it is possible to provide people with an immersive experience of traveling into the past and see what those ruins really were through the screen of a computer of a Virtual Reality (VR) goggles. For example, Rua & Alvito (2011) created 3D models of a historical site "The villa of Casal de Freiria". The models created different architectural theory or hypothesis to test and analyze these theories or hypotheses for historical scenarios. The models created were laid on the GIS data of the terrain. The compound model created at the end was imported into a map editor called The Elder Scrolls Construction Set (Bethesda Softworks 2016) of a game built on top of Gamebryo (Gamebase 2016) game engine. The choice of the game integration environment was affected by the system's ability to easily integrate the model as a map, its high quality graphics engine, physics engine, AI, ease of adding vegetation. The AI package of the system made it easy to add easily modified avatars into the environment, e.g., a guard that defends the villa in the presence of enemies, a slave that wakes up, works and returns home in the evening, etc. The environment developed in this study makes it easy for researchers to test any theory that surfaces during their studies in a visually rich environment. Sanders (2015) reviews the advancements of the Virtual Heritage research area over the years. From this research it can be seen that with the additions of the recent developments in the areas such as UAVs and photogrammetry, virtual gaming environments prove their usefulness in the use of archeological fieldwork.

Another interesting work with games engines is in the area of Construction Engineering. Traditionally, construction resource planning is done using Critical Path

Method (CPM). Although CPM is well proven, it is difficult to detect the design errors and mismatches without properly visualizing the construction environment (Li et al. 2008). With the recent developments in the BIM technologies, software in this field can provide necessary tools to use 4D modeling in construction resource planning. Li et al. (2015) developed a 4D simulation environment to be used in construction project planning. In this research, a game engine called 3DVIA Virtools was used due to the researcher's familiarity with the engine. The produced system gets site layout and construction sequence as two inputs then simulates the construction process. By changing these inputs, user can determine the best sequence and layout via simulation. The system then was tested in a case study in the construction of extension to a viaduct in Hong Kong. The simulation was applied to determine the most suitable temporary steel platform in the construction of the foundations.

Game engines also become popular in education. In this field, it is important to provide the learner with the enough visual content in order for them to understand the subject properly. In this sense, a game environment not only provides students with a sufficient visualization, it also provides an opportunity for them to learn by their mistakes, which was recognized as an effective and memorable experience by students (Li et al. 2015). Therefore, game engines are continuously being used for education and training purposes (Uskov & Sekar 2014). Wang (2007) developed a game engine based construction planning framework called Virtual Construction Simulator (VCS) to help construction engineering students understand the 4D model implementation workflow. This allows students to visualize the construction schedule in the 3D model before creating the CPM schedule. In this study, a discontinued game engine called Deep Creator, was used. Unlike regular 4D model workflow, where a 3D model and CPM schedule was used together to create a 4D simulation, CPM schedule was created linking activities and objects in the 3D model (Figure 4). This study shows, seeing the actual construction schedule happening in the virtual world before applying CPM helps students understand how changes in the real schedule actually affects the final CPM charts.

Similar to education, training also greatly benefits from enriched visual tools. Bosché et al. (2008) developed a Mixed Reality system that uses virtual reality goggles and 6-

degree-of-freedom (DOF) pose tracking device to train construction trade workers for challenging site conditions, such as heights, using a game environment created with the commonly used Unity3D (Unity 2016) game engine. The combination of virtual reality goggles and 6-DOF tracking system makes the training an immense experience for the trainees by passing real world movements to the virtual world. New construction technologies such as BIM promise many advantages for the construction companies, however, the real implementers of this technologies are the construction workers. Therefore, training of the construction workers according to the new technologies is also required. That's why this study provides promising improvements in this area.

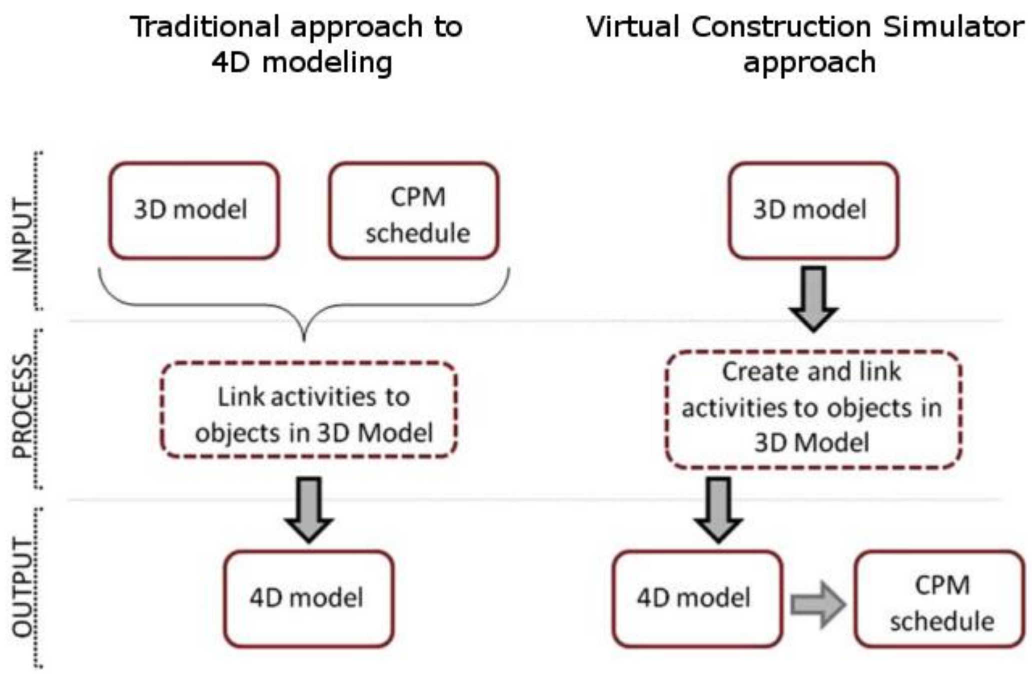


Figure 4 - Traditional 4D approach vs VCS approach. (Nikolic et al. 2011)

Game engines are also used for disaster modeling and simulation. Herman (2014) developed a disaster scene reconstruction system. This system provides first responders with valuable knowledge and visual cues around the rubble of collapsed building by accurate 3D models and simulations. In this work, 3D models of a simulated urban disaster environment called OPP Reference Rubble Pile in Bolton, Ontario were created. The point cloud of the environment was obtained using a RGB-Depth sensor mounted on a UAV. The RGB-Depth sensor is basically a camera system with an infrared depth sensor that depicts a depth image and combines it with RGB image. The game engine used in the study was Unity3D engine. The final product allowed users to use a lighter to further illuminate the environment, make measurements between selected points, place shoring into the rubble site, and add a point of interest for further inspection and sharing.

Lastly, there are very few studies related to use of Game Engines in Geotechnical Engineering. Cicekci et al. (2014) developed a soil profile tool, called Profiler 3D, using a Game Engine (Figure 5). In this study, a case study was performed to produce a 3D appearance of a deep excavation site. Ondercin (2016) used a game engine generated system to model and simulate rockfalls along a railway corridor in British Columbia, Canada. The author mainly focused on simulating the failure behavior of rock falls and rock slide. The study makes use of previously acquired coarse national coverage DEMs mostly generated with satellite imagery, point clouds generated using either stationary data collections, i.e., using Terrestrial Laser Scanning, or aerial laser scanning, or helicopter mounted camera based photogrammetric methods. The final 3D model was a compound that was imported into the Unity3D engine. Then several rockfall scenarios were simulated in the virtual models of the real environments by dropping rock-like shaped objects in the environment and tracking their movements along the slope (Figure 6). Finally, the results of the work were compared with traditional rockfall modeling tools that are used in the industry.

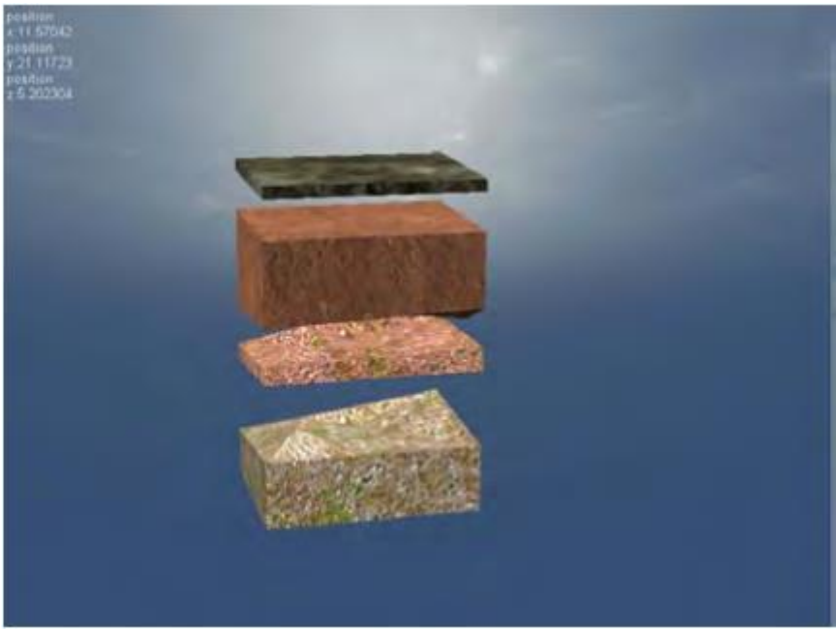


Figure 5 - Visualization of Deep Excavation Area in a Game Engine (Cicekci et al. 2014)

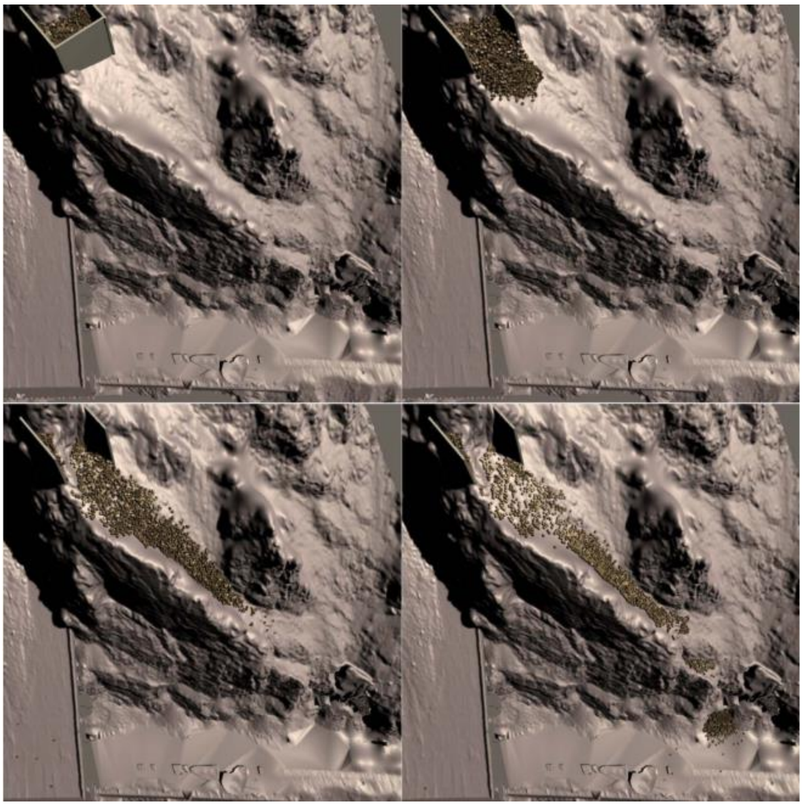


Figure 6 - Simulation of Debris Flow on The Slope in The Game Environment (Ondercin 2016)

CHAPTER 3

DEEP EXCAVATION GAME USING UNMANNED AERIAL VEHICLES

In this chapter, the steps to create a virtual environment for visualization of deep excavation to comprehend the details of design and construction using the pictures obtained from the UAVs are provided. The generation of a 3D computer game using the 2D pictures obtained from UAVs generally requires the application of following consecutive steps; (i) flight planning, (ii) image acquisition, (iii) point cloud generation, (iv) production of textured mesh and (v) game engine integration. Within this frame, first, the planning of UAV flights and its details are provided in this chapter. Then algorithmic aspects of creating an accurate geometric model of the deep excavation site are discussed here in detail. Later, the technical details for the integration of the model within the game engine are given. The options for fine tuning, i.e., the post processing of the data are provided. Finally, different options for building the game are given in the end. In the following sections, these steps are explained along with their applications to deep excavations.

3.1. Flight Plan

Due to its practical advantages such as being cheap and easy to use, UAVs have found a place for themselves in various fields. The recently introduced literature work is given in Chapter 2 of this thesis. Although, UAVs are available for everyone's use now, the more sophisticated ones may require sound knowledge about the use of the radio controlled aircrafts as well as some electronic circuitry experience. Together with the recent advancements in the computer architecture, these devices now even have on-board computers making them smarter. These smart on-board add-ons make the vehicle user friendly for the operator by assisting them during flight. They are capable of being controlled with nothing but a smartphone. Moreover, some models even support pre-planned flights so that autonomous flights can be carried out without the interference of a human pilot.

As the name implies, construction of deep excavations generally requires reaching to very deep levels. Some of these excavations also extend to long distances horizontally. Although in recently developed UAVs, including the ones used in this study, it is possible to plan a flight and fly autonomously, in a deep excavation environment this may not be possible. Because reaching to certain points in an excavation may sometimes be dangerous considering construction safety or it may totally be impossible due to topography. Specifically, for deep excavations, there may be critical obstacles such as available struts, piles, or other construction elements below the ground surface level, which prevent capturing the details. In addition, the availability of GPS signals may be extremely limited as the UAV goes deeper, which makes a GPS assisted autonomous flight impossible. For properly overpassing such difficulties, the flight plan for UAVs may need to be carried out very carefully.

A representative flight for UAVs to model the excavation area should be planned accordingly. While planning the flight, it is important to keep in mind that, images taken should have at least 60 % overlap with each other, which guarantees obtaining a better processing result. The velocity of UAV should be adjusted accordingly. Generally, the flight paths are chosen as direct ones which should be parallel to the borders of deep excavation area. When corners are present, the direction of flight changes rapidly, the control points should be defined there. The accuracy of these points is dependent on UAVs GPS signal. In addition, the flight should cover the whole area at an altitude such that UAV should be able to capture 360-degree view if the excavation area has a closed geometry. A representative plan for a typical flight is given on Figure 7. In this figure, the dotted points are the control points, which a UAV should definitely pass through. Along these points, usually, a fixed height flight over the deep excavation is executed with camera looking directly downwards.

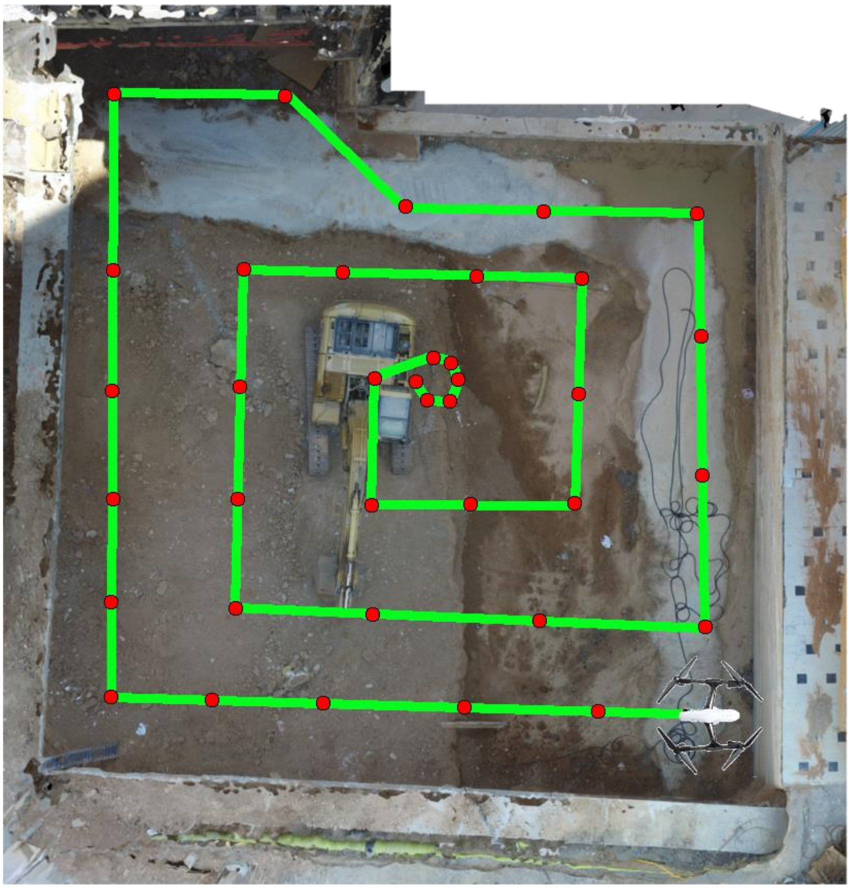


Figure 7 - An Example Flight Plan for Image Acquisition

3.2. Image Acquisition Through UAVs

In digital image processing, image acquisition is generally referred to as obtaining an image from a digital source, usually a hardware component designed for taking pictures. Hardware sources range from a camera designed for daily use to more sophisticated devices such as action cameras, infrared cameras, and satellites, etc. Within this context, nowadays, the recent technological advancements have led UAVs to be more robust especially due to their gimbals, i.e. special devices designed to stabilize the camera, and as a result, they have started to be used as reliable sources for capturing images.

UAV's are often equipped with many sensors including a conventional digital camera (Table 3). With these cameras, several images can be acquired in a small amount of time. In most photogrammetric studies, the image acquisition is done from a predetermined pattern and altitude. However, as the construction scene needs to be imported into a virtual game environment, a closer look to the site is essential to be able to capture more details. For this reason, entering into the field of deep excavation is inevitable.

In this study, the images were acquired using two different commercial UAV systems called Phantom 2 Vision+ and Inspire 1 by DJI (DJI 2016). Figure 8 provides the outlook of these UAVs. The first device, Phantom 2 Vision+, an older model developed by the company DJI, is a quadcopter fitted with a 14 MP digital camera. The second model is also a quadcopter, however, it has significantly improved features such as, better camera, stiffer carbon-fiber chassis, retractable legs to provide better view for the camera and many more. Table 3 gives technical specifications of these UAVs.

(a) DJI Phantom 2 Vision + **(b) DJI Inspire 1**

Figure 8 - UAVs Used in This Study

Table 3 - Technical Specifications of UAVs Used in This Study

	DJI Phantom 2 Vision+	**DJI Inspire 1**
Supported Battery	DJI 5200mAh LiPo Battery	LiPo 6S High voltage battery
Weight (Battery & Propellers Included)	1242g	2935 g
Max Flight Time	Approximately 25 minutes	Approximately 18 minutes
Max Flight Speed	15m/s	22 m/s
Indoor Hovering	None	Enabled by default
Diagonal Length	350mm	559 to 581 mm
3-axis Camera Stabilization Gimbal	Yes	Yes
Gimbal Controllable Range	Pitch : -90°—0°	Pitch: -90° to +30°, Pan: ±320°
Camera Effective Pixels	14 Megapixels	12.4Megapixels
Camera Resolution	4384×3288	4000x3000
HD Recording	1080p30 & 720p	4096x2160p24/25, 3840x2160p24/25/30
Camera Recording FOV	110° / 85°	94°
Communication Distance (Open Area)	500-700m	2 km

In many cases, especially when the excavation is too deep, a flight pattern can easily miss topographic irregularities. In such situations, to cover the area of deep excavation as much as possible, flight pattern needs to be executed in control of a pilot manually. As described in the flight plan, first a fixed height flight over the flight path is performed with camera looking directly downwards. This kind of flight pattern used commonly in mapping purposes, and it provides reliable results. Then, UAV is flown into the deep excavation site to get closer images of the side walls of the construction with camera directed at a certain angle to the sides to get a better texture, which in turn increase the visual quality of the model once it gets imported into the game environment. Figure 9 shows an example of pictures taken on the flight path in the excavation area.

Figure 9 - Pictures Taken on the Flight Path in the Excavation Area

3.3. Point Cloud Generation

3.3.1. General Workflow

Detecting the scene information from multiple images has been a challenge for decades. Gathering the scene geometry and camera motion using multiple images is called Structure from Motion (SFM) problem. Ullman (1979) proposed a solution to this problem and stated that some form of unique scene information can be obtained from at least three non-coplanar views. Later, many other research studies have further improved or refined this solution (Crandall et al. 2013; Tomasi & Kanade 1993; Wu 2013). The general workflow of such solutions to SFM problem is given in Figure 4. Each step in this figure to obtain the point cloud is explained in the following sections.

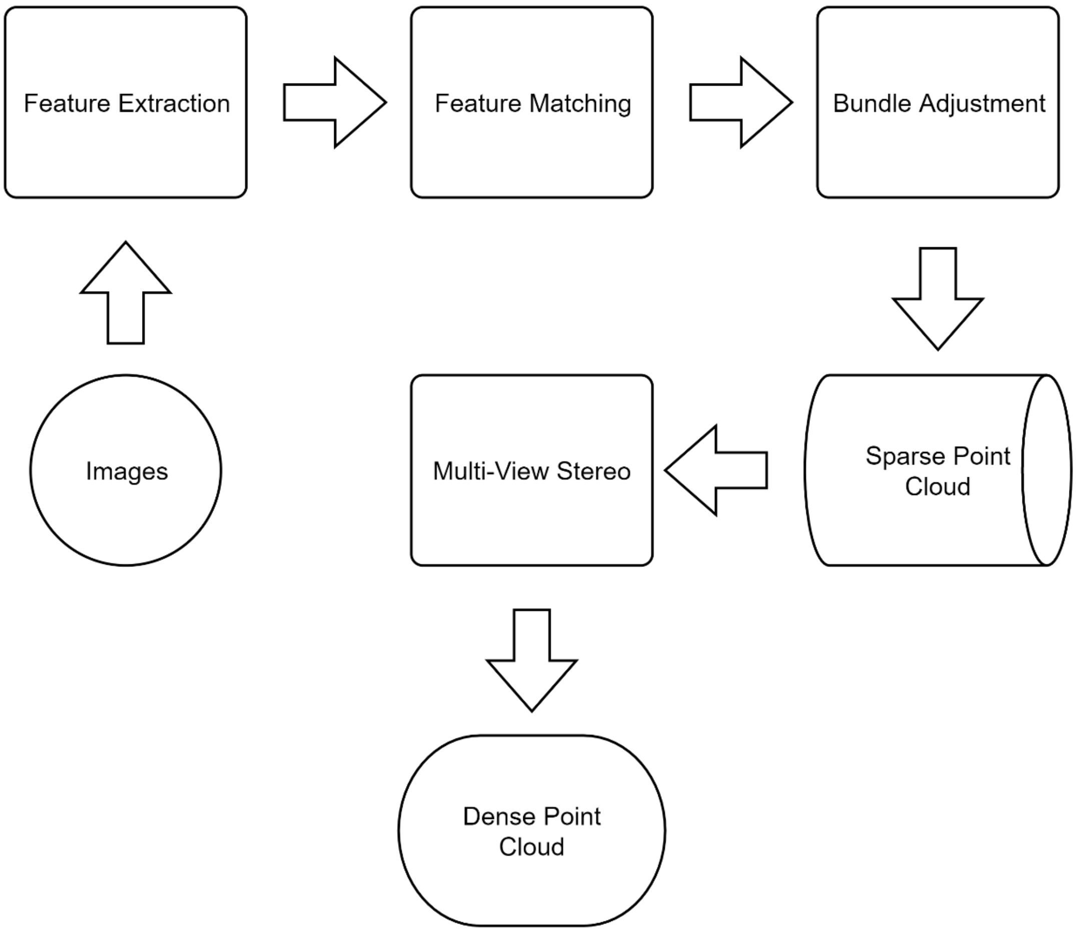


Figure 10 - SFM Workflow

In SFM, depth information can be gathered through specific points, called features, matched in the views of multiple images. Detection of these common features, i.e., edges, corners, etc., is another challenge when solving the SFM problem. Scientists have developed many feature detection algorithms detecting those distinctive points in an image and describe them accordingly, which are called descriptor or key-points. Among those algorithms, Scale Invariant Feature Transform (SIFT) is the most commonly used one (Lowe 2004). Figure 11 provides an example of detected and matched features over two images.

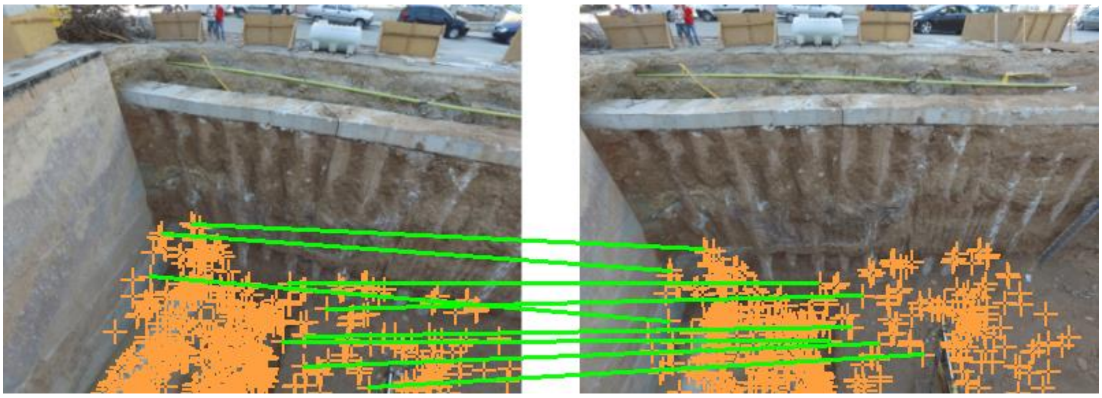


Figure 11 - Feature Matching Among Pictures Taken from Different Views

Having the features matched over multiple images, the location of these key-points in 3-D space along with the location and orientation of the camera views are obtained. Then the locations of the detected features are corrected iteratively using camera parameters (Wu 2013), which is called Bundle Adjustment. At the end of this step, a sparse point cloud is generated as shown in Figure 12.

Sometimes, the 3D point cloud generated using SFM is not dense enough to be further used. To expand the initial matches and further densify this mesh, scientists developed Multi-View Stereo (MVS) algorithms (Furukawa & Ponce 2008). Among those MVS algorithms, a special one called Clustering Views for Multi-view Stereo (CMVS) (Furukawa et al. 2010) can be used effectively, where points from the sparse cloud are expanded to nearby positions iteratively to get a denser point cloud. Figure 13 provides an example of such a dense point cloud. Created point cloud is then used to construct 3D image of the deep excavation region.

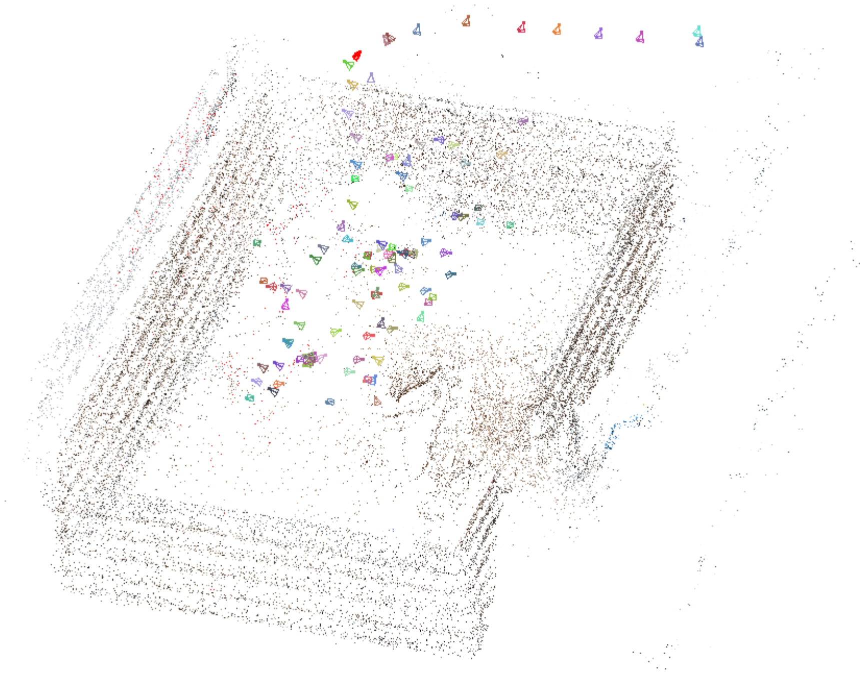


Figure 12 - Sparse Point Cloud

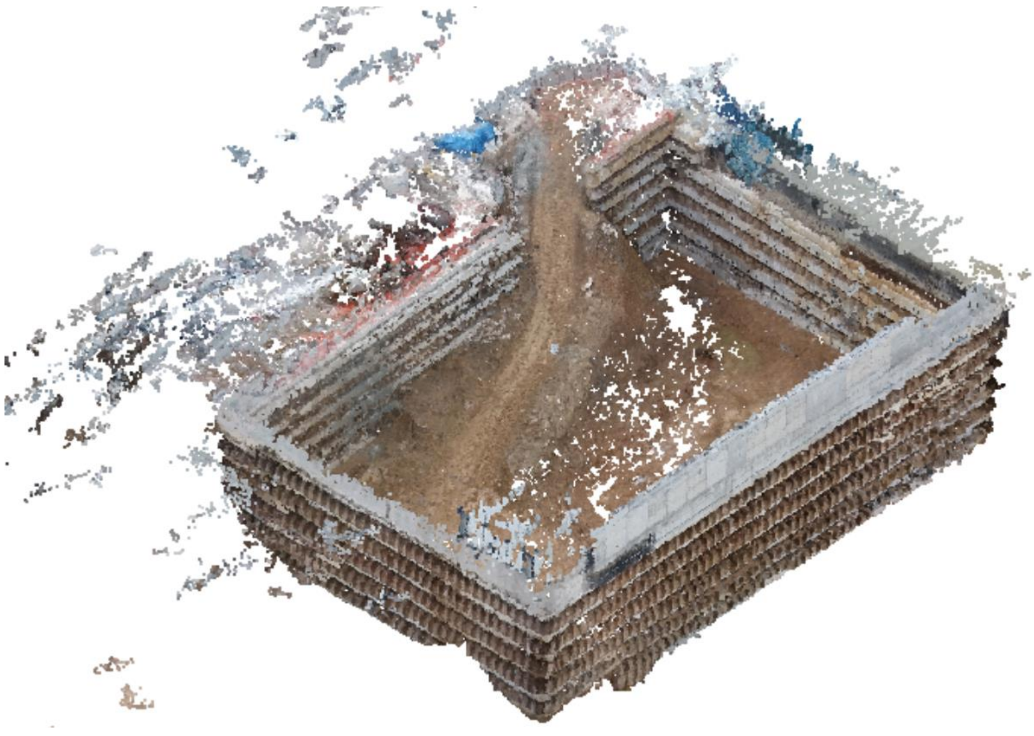


Figure 13 - Dense Point Cloud Created with Multi-View Stereo

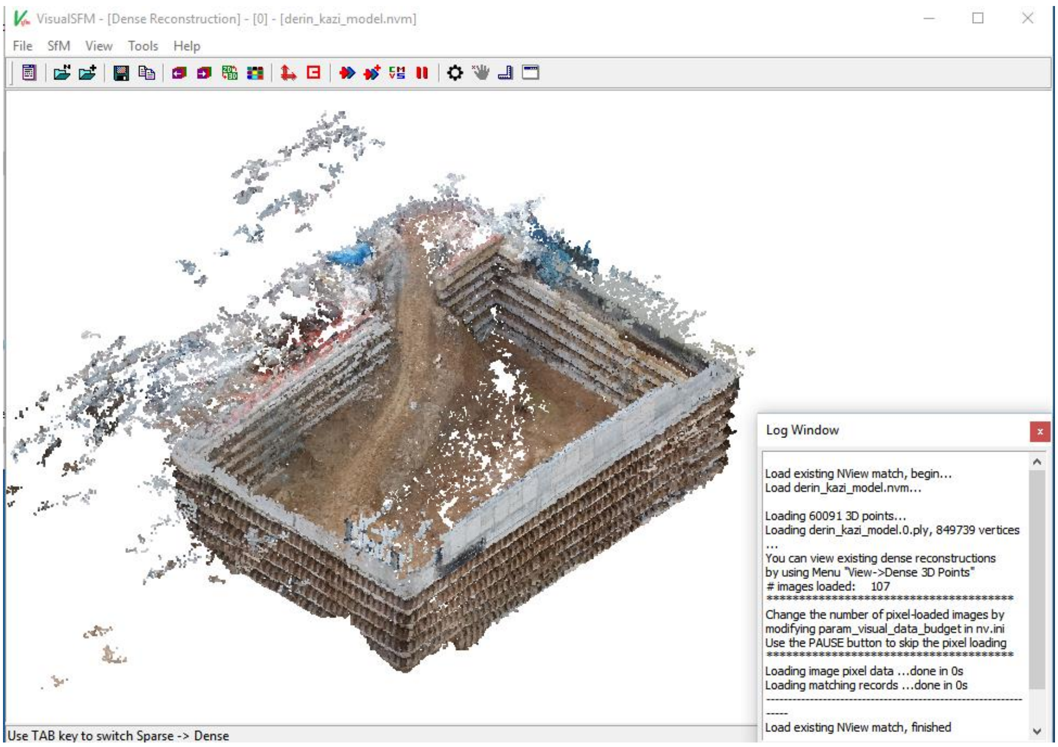
3.3.2. Software Implementations for Photogrammetry

Since the above process involves complex computations which might require excessive time and computing power, the above workflow needs to be implemented efficiently for automation purposes. In recent years, many software packages have been developed for efficiently detecting the features, match them and produce a 3D point cloud using set of images. Among these software, most of them are commercial and provide many options that can be used before or after the generation of the point cloud, such as re-generating the cloud with corrected matches, doing length, area and volume measurements on the cloud, and many more. In addition to those, there are free software packages with more or less the same functionality but with less capabilities, which are, however, generally less flexible for implementation.

In this study, two photogrammetry software packages called VisualSFM (Wu 2013) and Pix4D Mapper (Pix4D 2016) are used. Graphical User Interfaces (GUI) for both software are given on Figure 14. The free software VisualSFM ultimately provides a point cloud file (*.PLY) of the excavation site from the provided images. However, a point cloud itself is not suitable to be directly used with the game engine. Therefore, additional steps are taken to generate a 3D textured mesh file (*.OBJ) from the densified point cloud. Unlike the free software, the commercial software Pix4D provides several types of outputs including an *.OBJ file. Moreover, Pix4D provides re-optimization methods for creating the final model such as scale and orientation constraints. In this software, a scale constraint can be applied such that, when the user inputs the distance already known for calculated feature points in the model, then software can automatically scale the whole model accordingly. In addition, in Pix4D, an orientation constraint can be applied by the user, choosing a predetermined coordinate axis as the primary direction of the construction members. For example, “z” axis can be chosen as the direction of piles. When both constraints are provided, the final generated model is eligible for measurements, i.e., the users can measure the distances between selected points in the model. All software packages, at the end, provide a densified point cloud to be further processed for visualizing the deep excavation model.

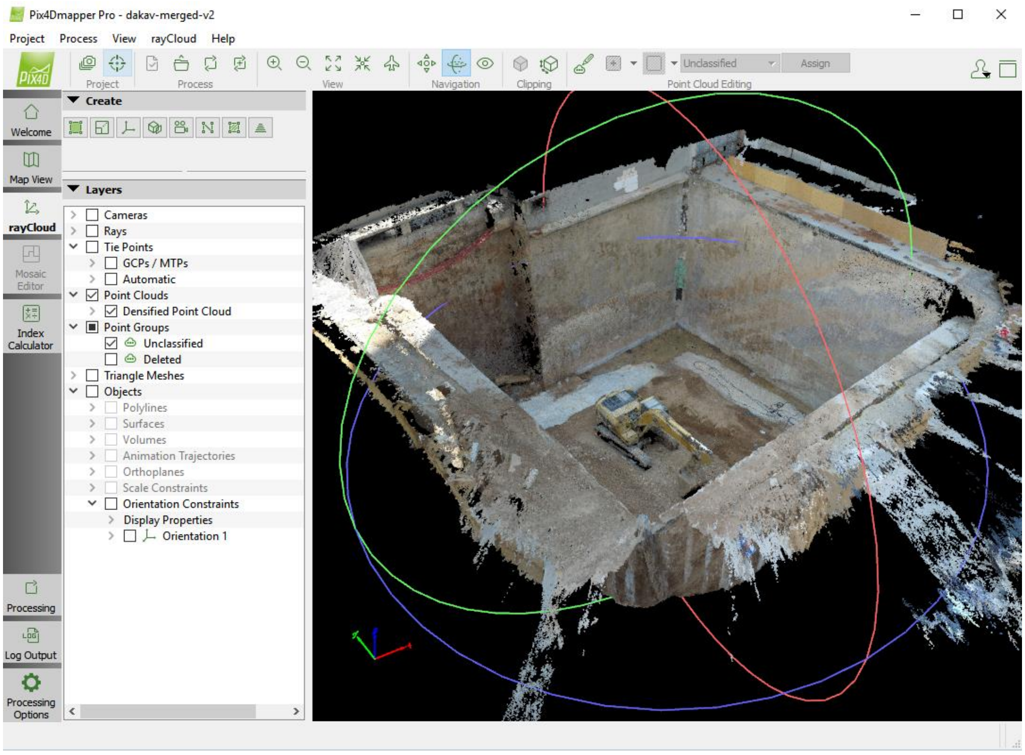
3.4. Production of Textured Mesh

In addition to the point cloud generation, some of photogrammetry software can also produce a textured mesh as an output. However, this is often an oversimplified version of the mesh to decrease the processing time and output size. In such cases, instead of using sparse textured mesh output, a detailed one is re-generated from the dense point cloud. For this purpose, a 3D processing software called Meshlab (MeshLab 2005), an open source, portable and extensible system for processing and editing of unstructured 3D triangular meshes, is utilized. The GUI for the Meshlab is shown in Figure 15.



(a) VisualSFM

Figure 14 - The GUI for Photogrammetry Software



(b) Pix4D

Figure 14 – Continued

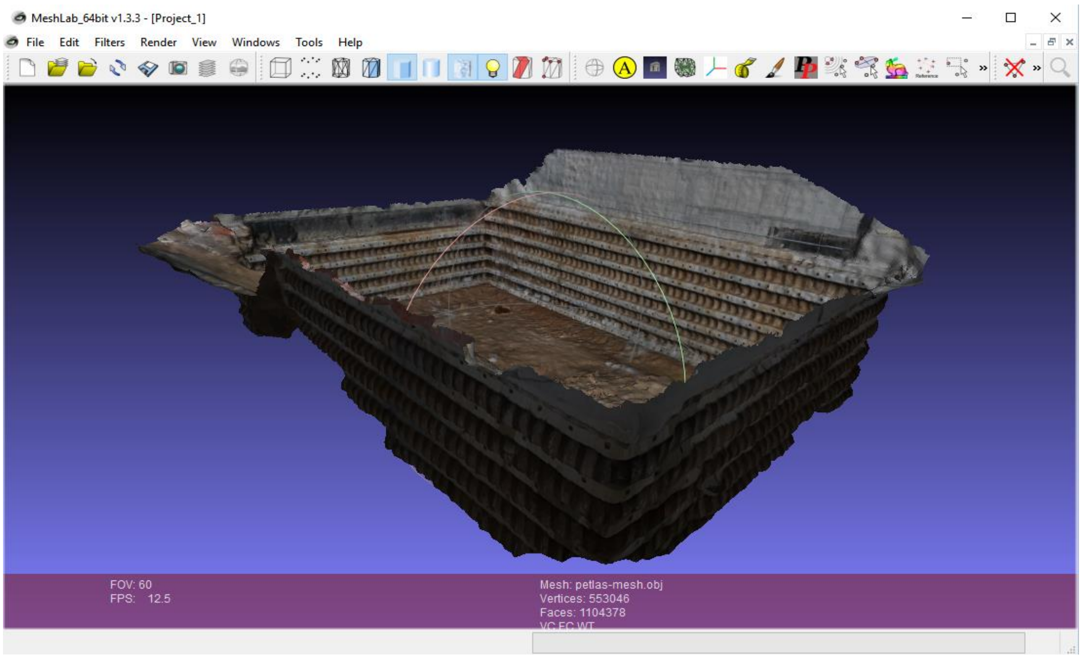


Figure 15 - The GUI for Meshlab Software

The procedure for re-generating the textured mesh starts with trimming the outside regions of deep excavation from dense point cloud, called noise elimination. Generally, as the photos are taken at reasonably high altitudes, they mostly consist of regions outside the excavation site, as shown in Figure 16. Although they provide spatial information about the features and their relevant portions help the system putting other points together, this results in having lots of noise in the final point cloud. The resultant point cloud for outside regions is very sparse and needs to be clipped manually. Figure 17 shows the noise in the point cloud around the deep excavation area. Getting rid of these parts provide us a dense and fairly uniform point cloud as shown in Figure 18.

Figure 16 - Images Taken That Contains Regions Causing Noise in Final Model

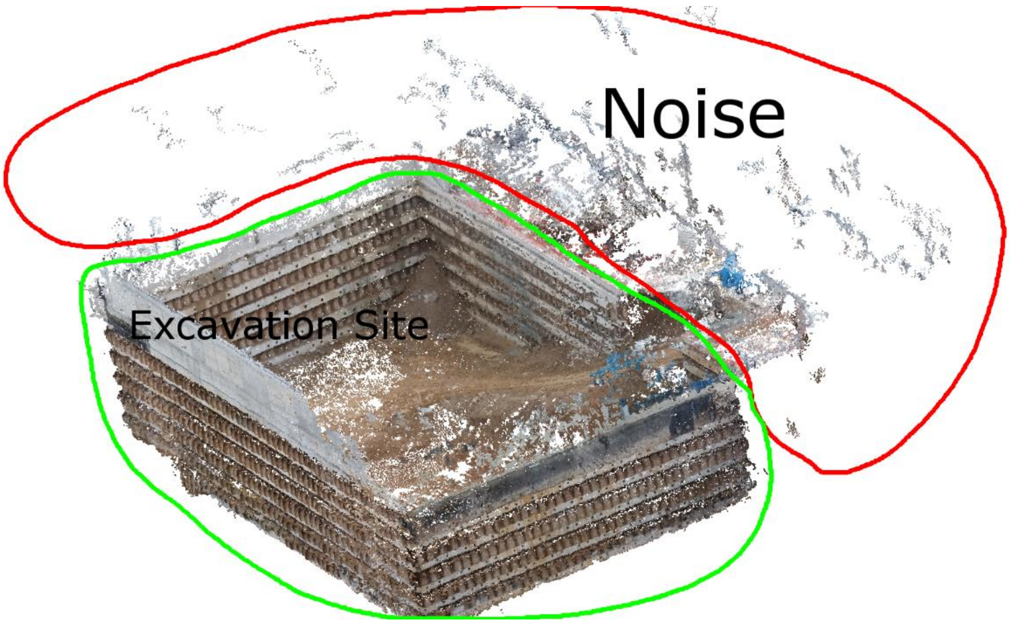


Figure 17 - Noisy Point Cloud

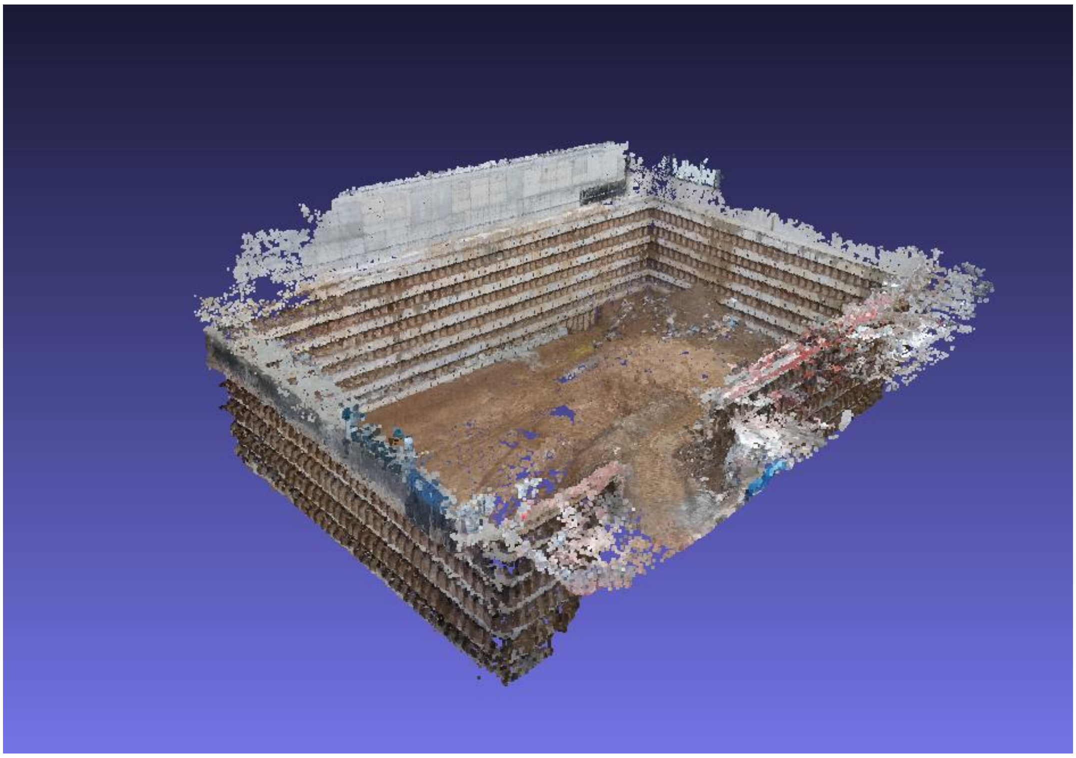


Figure 18 - Cleaned Dense Point Cloud in MeshLab

Having successfully cleaned the noise, the point cloud is then re-sampled. Re-sampling is a process used to reduce the point density in a cloud to have more uniform distribution of points without losing significant information about the geometry. This step is crucial to increase the computational efficiency as point cloud provided by the photogrammetry software is so dense that it is almost impossible to work with using a regular computer. After re-sampling, the next step is to find the vertex normals for the point cloud, which are used to determine the front face of the mesh. Since the points in the cloud do not have any information about vertex normals, surface construction is not possible. Fortunately, Meshlab has the ability to estimate these normals for the point cloud given a viewpoint.

The next processing step is to generate a surface to connect the points using planes, i.e. faces. Once the vertex normals are estimated, a procedure called Poisson Surface Reconstruction (Kazhdan et al. 2006) is applied to the point cloud to generate the surface (Figure 19). This procedure uses orientation of the vertex normals in the point cloud. During surface construction, some problems may arise. For example, as a side-effect, the surface loses its color information. Some anomalies such as holes may appear, which look like visual glitches in the game unless they are fixed in the mesh after the surface generation. In addition, the surface may have too many faces and vertices, which can be simplified using a procedure called “mesh decimation”. When all such issues are handled, to provide visual aid in the game engine environment, textures are re-generated over the surface using the original colors of the vertices, which were retrieved from the unprocessed point cloud. The final product, which is a smooth 3D surface representing the deep excavation site is shown in Figure 20.

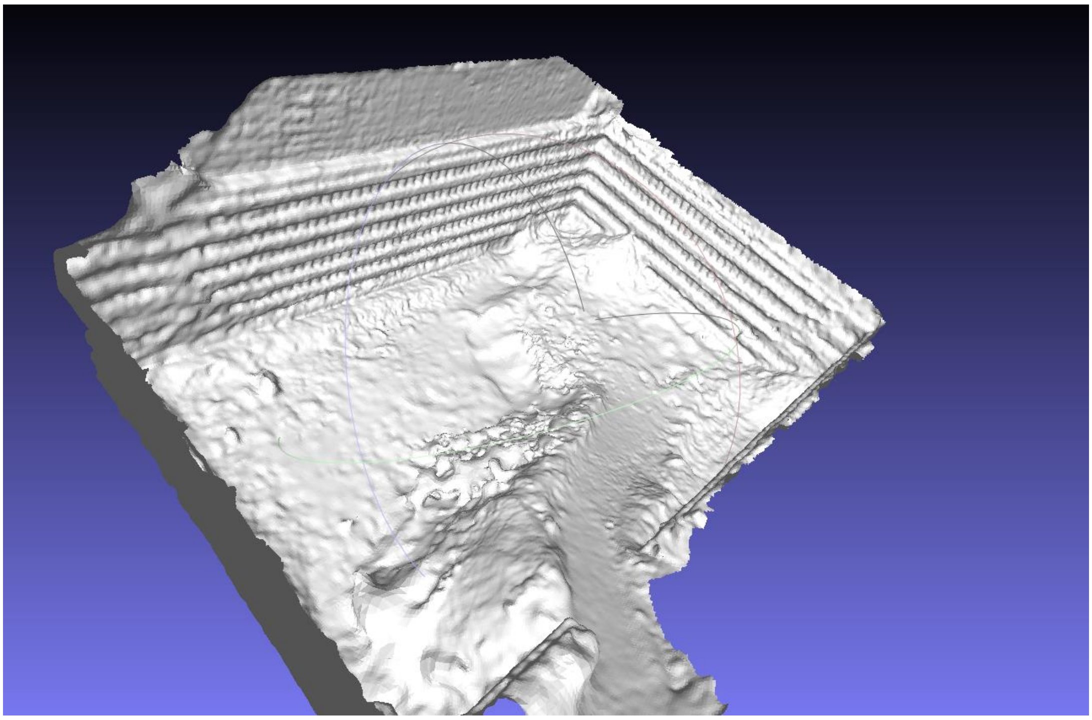


Figure 19 - Model after Poisson Surface Reconstruction

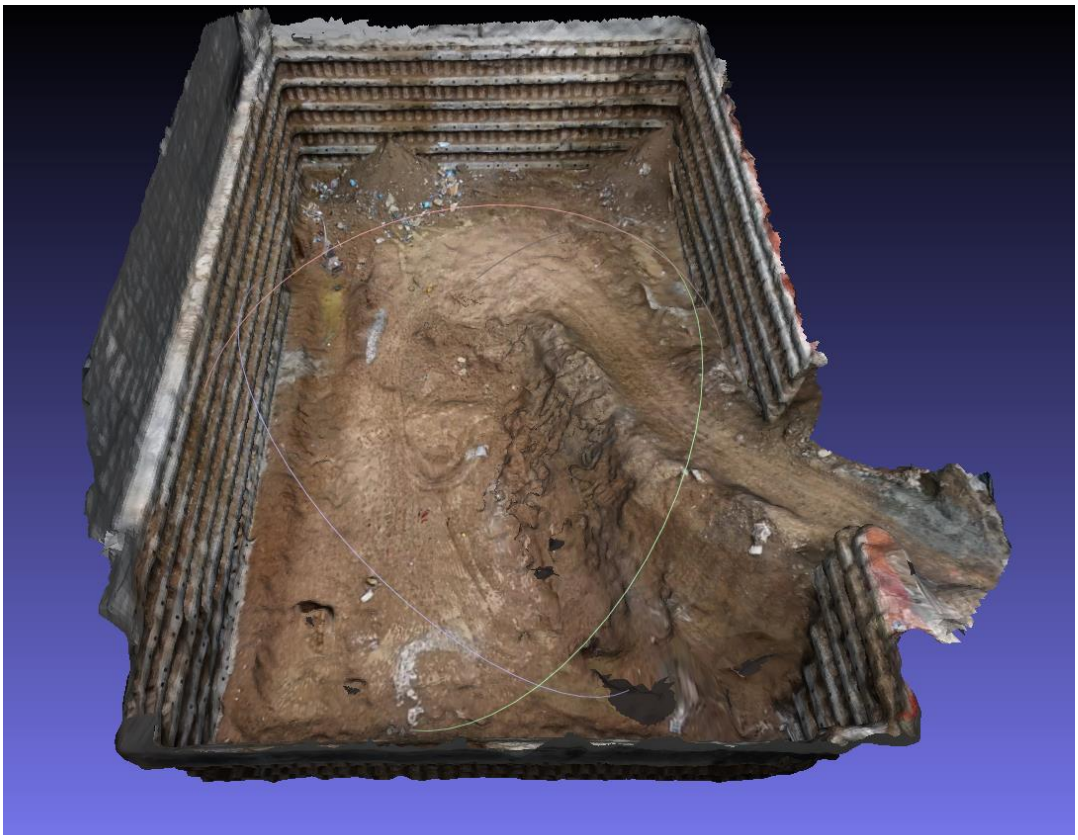


Figure 20 - Textured Surface

3.5. Game Engine Integration

Game engines, as special software for rendering 3D environments, provide users with the ability to visualize and interact with the environment virtually. They can execute graphically heavy tasks easily. Everything in this environment should have physical properties. Most game engines provide users with vast number of tools that help developing visually appealing, dynamic and accurate simulations. They provide a virtual world with its own physical phenomenon like gravity, winds, collusions, etc.

3.5.1. Unity Game Engine

In this study, Unity Game Engine is utilized mainly because it is free to use and it provides a multiplatform support including virtual reality through scripting languages C# and Javascript. Currently, Unity is one of the most commonly used game engines in the market. It provides user with capability of storing game objects as assets and an ability to reach the asset store composed of commonly used game objects created by the game designer community.

In Unity, a game is a combination of scenes, each of which correspond to different levels. GUI is shown in Figure 21. In this figure, the area marked with (1) shows the assets that are in the current scene of the game. Each scene has its own objects created by the programmer or imported from the store. Area (2) shows the visual representation of the scene, where assets shown in area (1) can be visualized here. In addition, the actual simulation can be displayed dynamically. Area (3) is reserved for viewing and editing the properties of the assets. Area (4) shows all the available assets in the current project. Importing the 3D model is generally performed first in this area and then complete mesh is transferred to the scene in Area (1). Certain components such as mesh collider can be added to the game using the properties window shown in Area (3). Area (5) simply consists of the menu items, including the simple file operations, user preferences and a User Manual, etc.

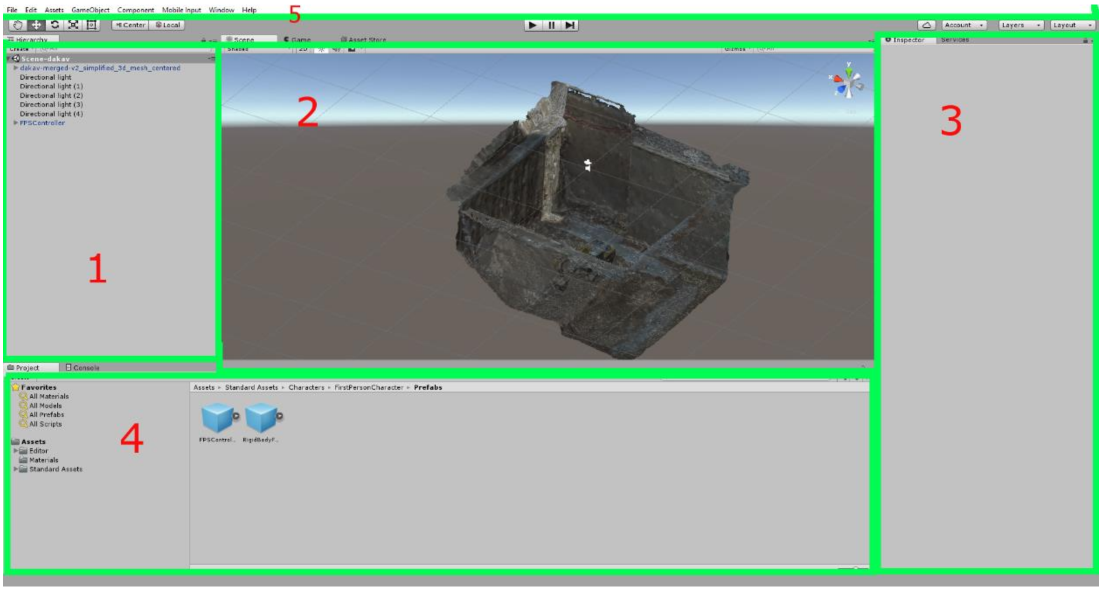


Figure 21 - Unity Game Engine GUI Components

3.5.2. Creating the Game

In this study, a game with a single scene is created since the idea of leveling is not mandatory in the final product. After importing the generated surface into the game engine as described in the above section, the first thing to do is to assign a mesh collider to the surface. A mesh collider is then added to the game, which satisfies the collision constraints of objects. Mesh collider is crucial as it provides the player a solid surface to walk on.

The next step in creating the game is to put a person into the virtual world to represent the game player for visualizing the environment and interacting with it. For this purpose, Unity provides a character to represent the game player, which resembles a human. With the addition of the first person character asset, the player gains built-in walking, running, jumping functions as well as a camera attached to its head level. This lets the user feel as if it was walking through the deep excavation and seeing the field through various control movements, i.e., turning right, left, going forward and backward, and jumping. This provides game player or site engineers an ability to visually inspect the excavation site.

Then the following step is to add lighting. Similar to the real world, in virtual world in order for an object to be seen, there has to be a light source to illuminate it. In addition, a light source is needed to see the details of surfaces in the model. At this step, a sky and a light source is added to the environment using Unity. It should be placed at a high altitude and directed towards the ground as if the light was coming from the sun.

3.5.3. Building the Game

As the final step, the game needs to be built for the desired target platform such as Windows Operating System or Mac Operating System, which are available as either 32 bit or 64 bit. Moreover, the Unity provides compact versions for mobile operating systems such as Android and IOS, and even internet browsers. In this study, all versions are used to provide versatility to the users. Then the game is ready for playing in the deep excavation for visualization.

CHAPTER 4

CASE STUDIES

In this chapter, the proposed workflow was used to model two deep excavation projects using the images captured through UAVs, in the city center of Ankara, Turkey. Within this scope, the general information about the project and the details of excavation construction, including the soil profile, dimensions of construction elements such as length and diameter of piles are given. Then the implementation details of workflow such as the UAVs used in the study, model generation parameters, the specifics of modelling software and game engine are provided. Next, results are given using the game screenshots and the chapter ends with the discussion about the quality of game simulation, success in modelling, effects of various parameters such as illumination. At the end, the game engines and the use of UAVs are assessed using observed advantages and disadvantages for the creation of a game.

4.1. Petlas Building

4.1.1. General Information

The deep excavation site is located in Çankaya region of Ankara, Turkey. It is along northern side of Eskisehir Road, where, to supply the demand due to the increase in population density, various high-rise structures are built in close vicinity of the excavation place. Figure 22 shows the exact location of construction site on the map. The topography is seemingly flat, only the two sides of the excavation are occupied by the high-rise buildings and the other sides are surrounded by local roads. The building to be constructed here is a high-rise office building, which consist of 5 basement levels, 1 ground level and 25 additional levels. The foundation of the building is planned to be mat foundation with dimensions 34.80 m x 57.37 m. The depth of the excavation from the ground surface is 16.50 m. In addition, area of the excavation is about 1996 m^2. The layout and cross sectional views of the building are given in Figures 24 and 23, respectively.

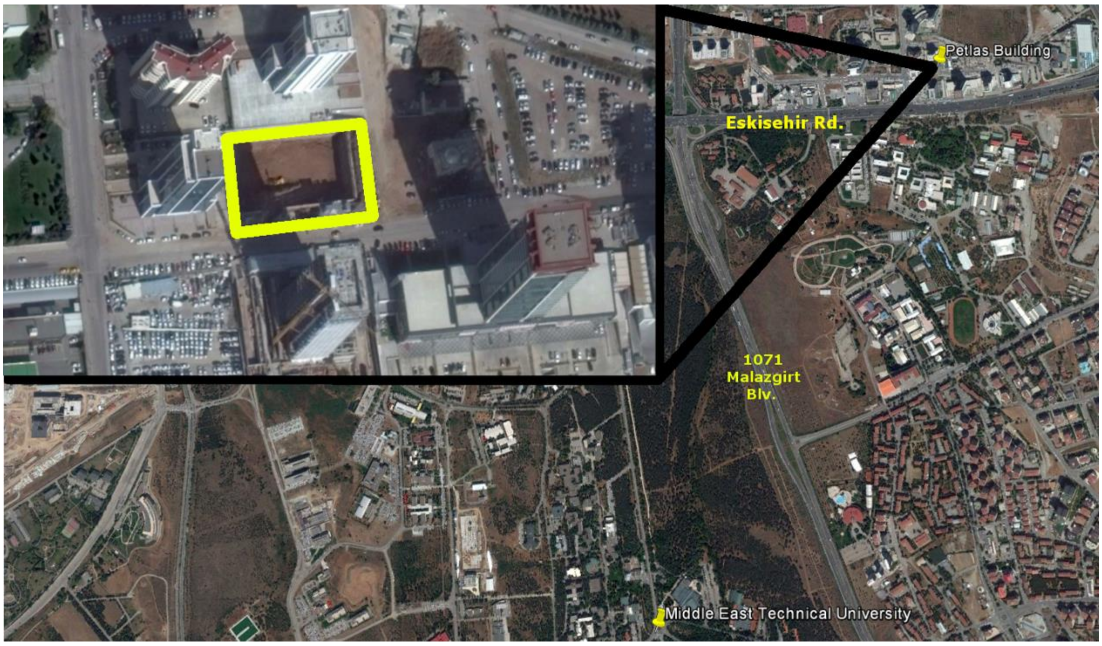


Figure 22 - Location of Petlas Building in Ankara

Figure 23 - Cross-sectional Views of Petlas Building

4.1.2. Geotechnical Information

Around the construction site, total of five boreholes were drilled, as shown in Figure 24. The boreholes SK-1, 2, 3 and 4 were located on the corners of the excavation area almost symmetrically, whereas the last one, SK-5, was centered in the middle. The borehole data showed that fill material with about 0.5 m thickness exists for boreholes SK-1, 2, and 5. On the other hand, the thickness of the fill increases to about 3.50 m for boreholes SK-3 and 4. Underneath the fill material, a brownish stiff to very stiff clay layer was found, which also includes thin layers of sand and gravel bands. The clay was reported to be highly plastic. The classification for the clay layer is as follows;

- Classification : CH – SC - CL
- Liquid Limit (%) : 67
- Plastic Limit (%) : 22
- Plasticity Index (%) : 40
- Bulk Unit Weight (kN/m^3) : 18
- Water Content (%) : 22.7

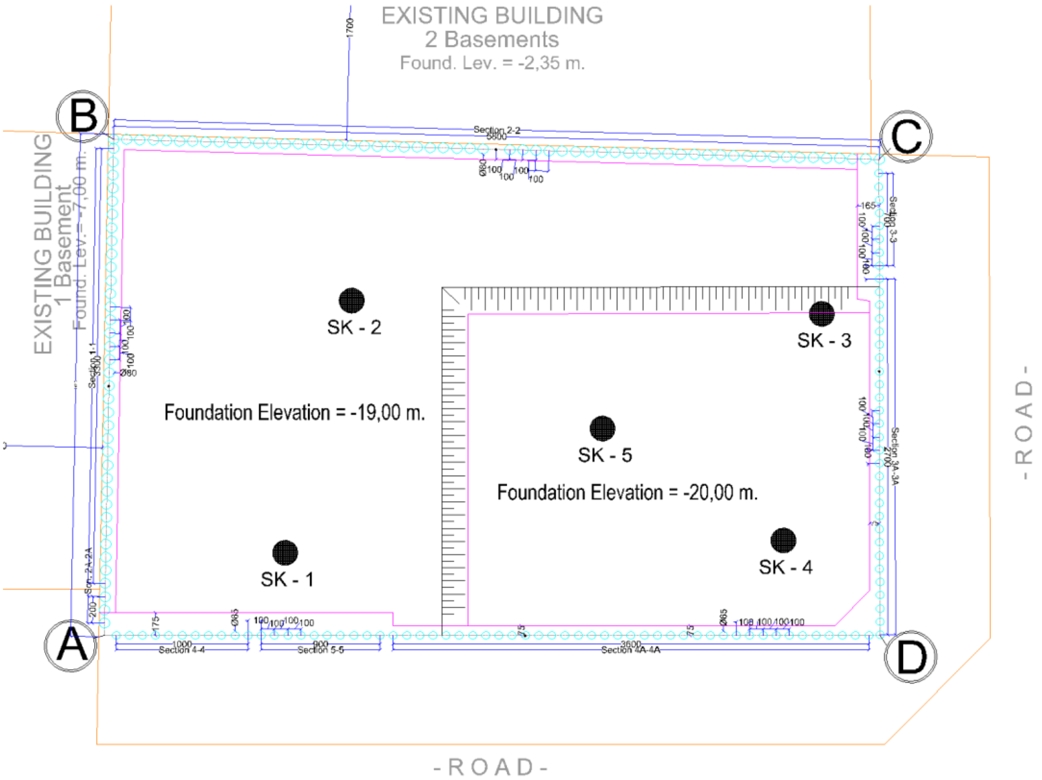


Figure 24 - Layout and Borehole Locations of Petlas Building

A geologic cross-section taken through boreholes SK-1, 5, and 3, section A – A’, is given in Figure 25. Considering the geotechnical and structural aspects of design, piles with varying length between 26.7 m and 33.2 m were designed. The piles are 65 cm and 80 cm in diameter and constructed at every 1.0 m.

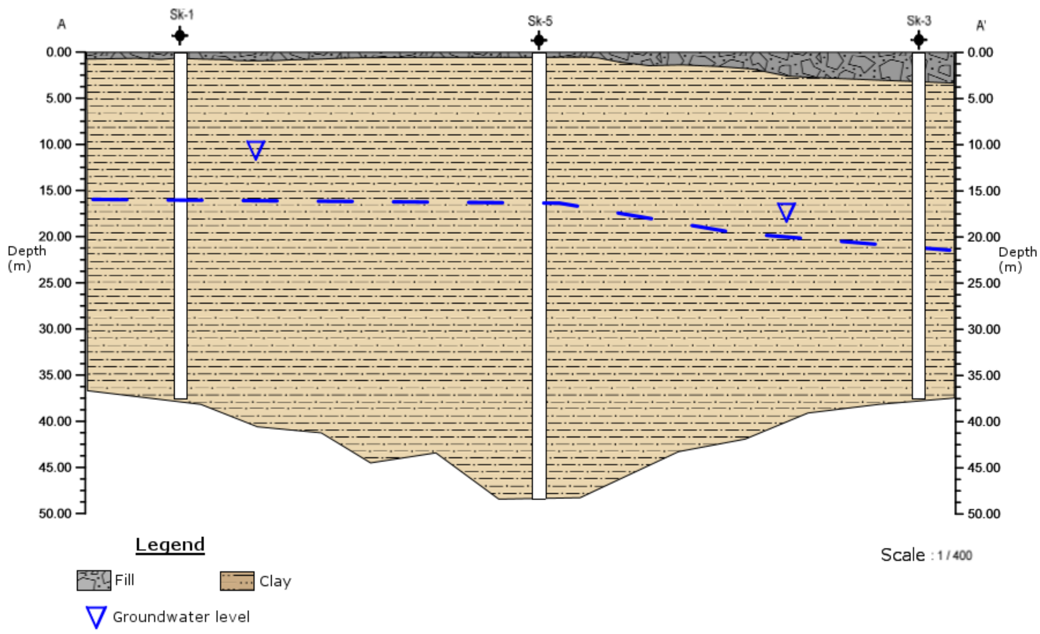
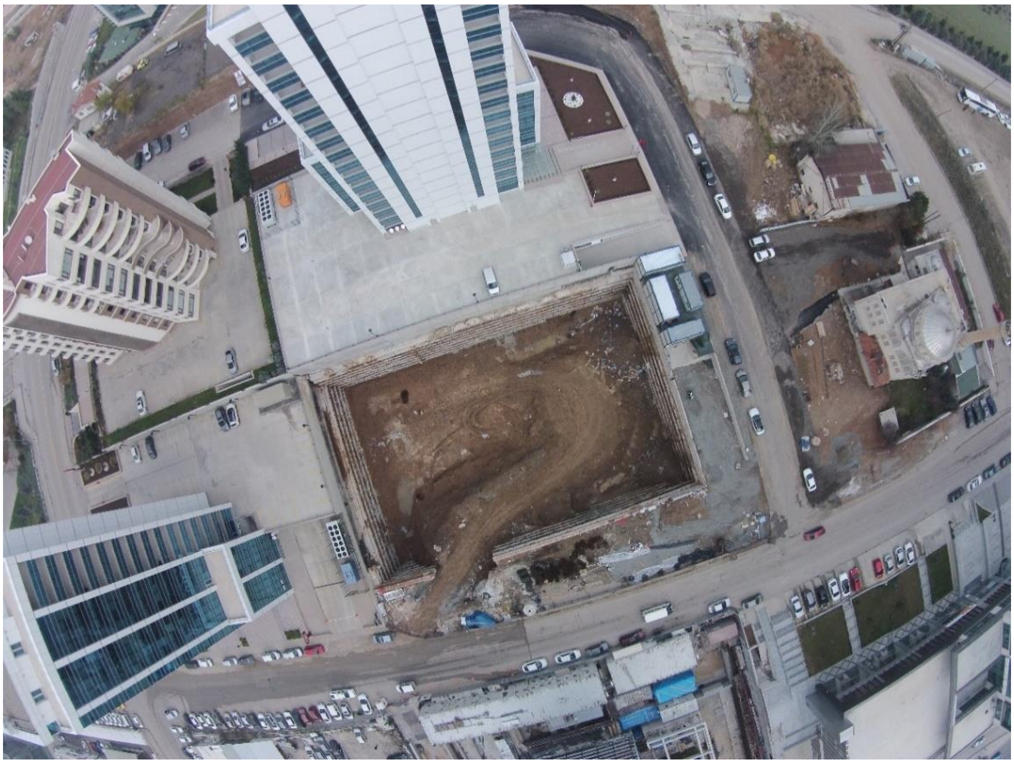


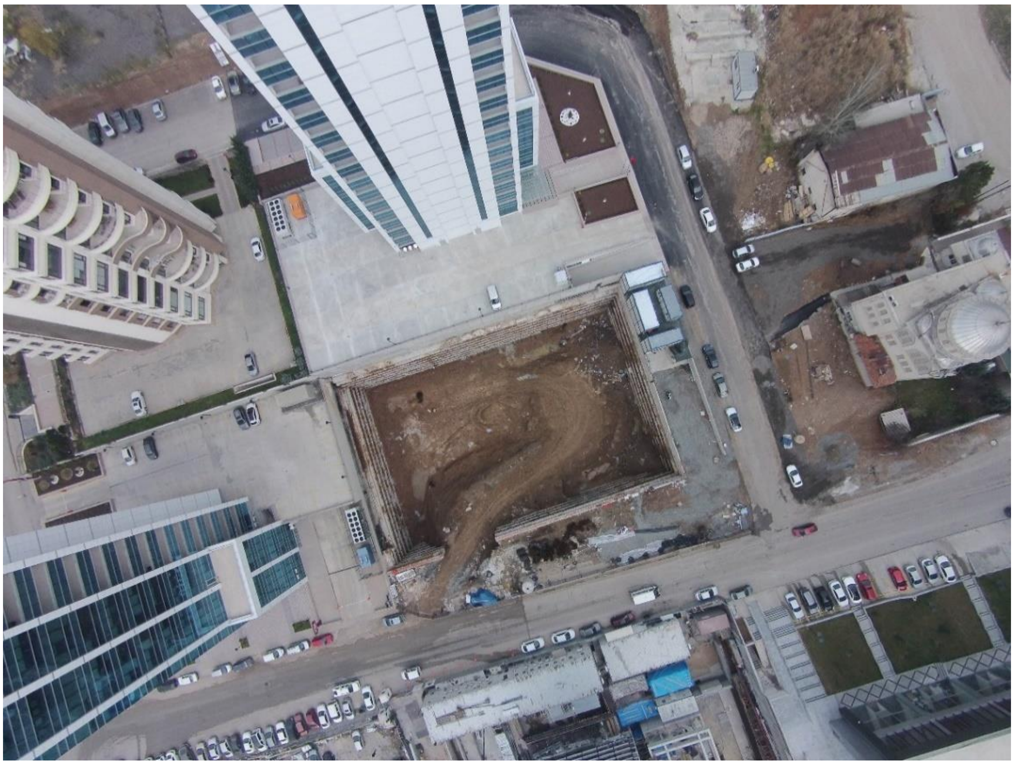
Figure 25 - Geologic Cross-section Through Boreholes SK-1, 5, and 3

4.1.3. Model Generation

For the modelling of Petlas Building, DJI Phantom 2 Vision+ was used, as it was almost the best technology at the time of construction. For the acquisition of images, a video was recorded with this UAV and total of 107 frames were extracted from the video to cover the area as much as possible. The camera of this UAV has a fisheye lens that produces ultra-wide field of view, however, with a cost of producing strong visual distortion. Using a distorted image in point cloud generation decreases the quality of the final model as the lines closer to the edge of the canvas seem more like curves in distorted images, which unfortunately eliminates the features detected at the edges of the images. Therefore, fisheye lens correction should be applied to these images before actually using them for point cloud generation. Fortunately, camera manufacturers provide the required lens profile for the application of this correction to eliminate the distortion. A comparison between an original image and the corrected version is shown in Figure 26.



(a) Original Image



(b) Corrected Image

Figure 26 - Fisheye Lens Correction Example

In this study, the images were processed in VisualSFM software. Since it is a free software, its capabilities are limited. VisualSFM takes a series of images as input and gives a sparse point cloud as output as described in Chapter 3. Some of the images used as input are shown in Figure 27. Although VisualSFM has an option to generate the dense point cloud, it does not work out of the box and requires an extra effort. Instead, a special form of the MVS algorithm called Clustering Views for Multi View Stereo (CMVS), as explained in Chapter 3, was utilized to generate the point cloud. Importing the CMVS binaries to VisualSFM enables generation of the dense point cloud. Then, the final dense point cloud was further processed in MeshLab since VisualSFM does not provide a mesh as output (see Chapter 3). Finally, using Poisson Surface Reconstruction, a textured mesh was generated to be used in the game engine.

Figure 27 - Sample Images Used in Generation of Petlas Building Model

4.1.4. Results

The sparse and dense point clouds generated in this case study are shown in Figure 28 and Figure 29 from different view angles. In Figure 30, the mesh generated using the dense point cloud is shown. As the model was created using video frames, no georeferencing was possible after the model creation, which results in the fact that the final model was not scaled. The point cloud is then imported into the game engine to obtain the final look of the computer game. In this game, with the keyboard shortcuts ("w" for forward, "a" for left, "s" for backward, and "d" for right) the player can be moved in the excavation site. Moreover, using space key, it is possible to jump while moving. Screenshots from the final game are shown in Figures 31, 32 and 33.

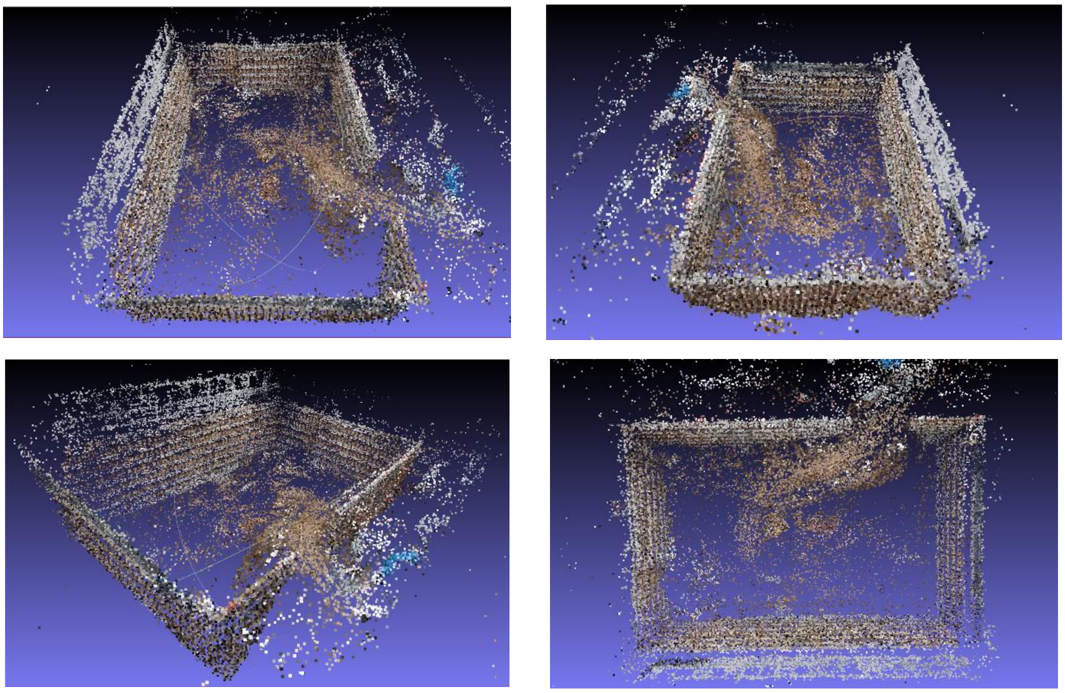


Figure 28 - VisualSFM Sparse Point Cloud Output

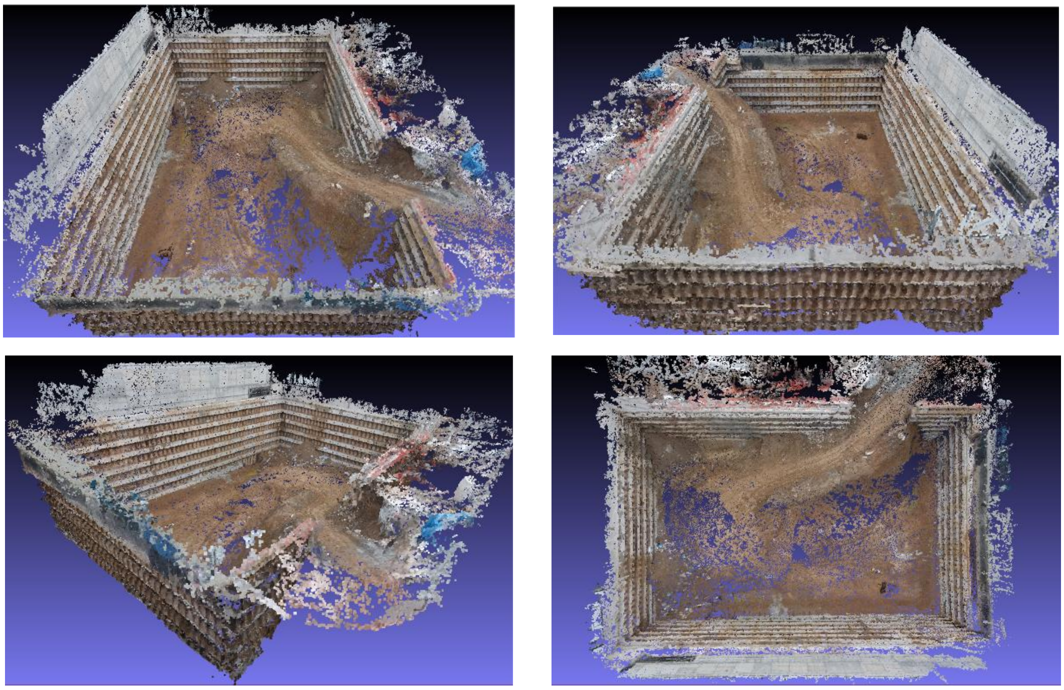


Figure 29 - VisualSFM Dense Point Cloud Output

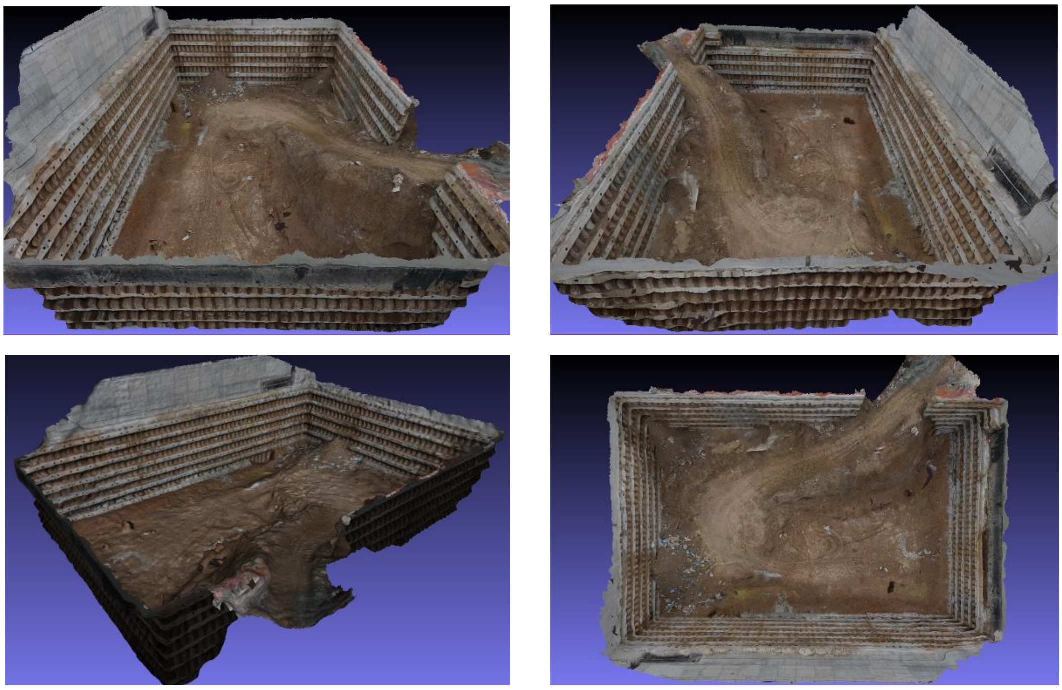
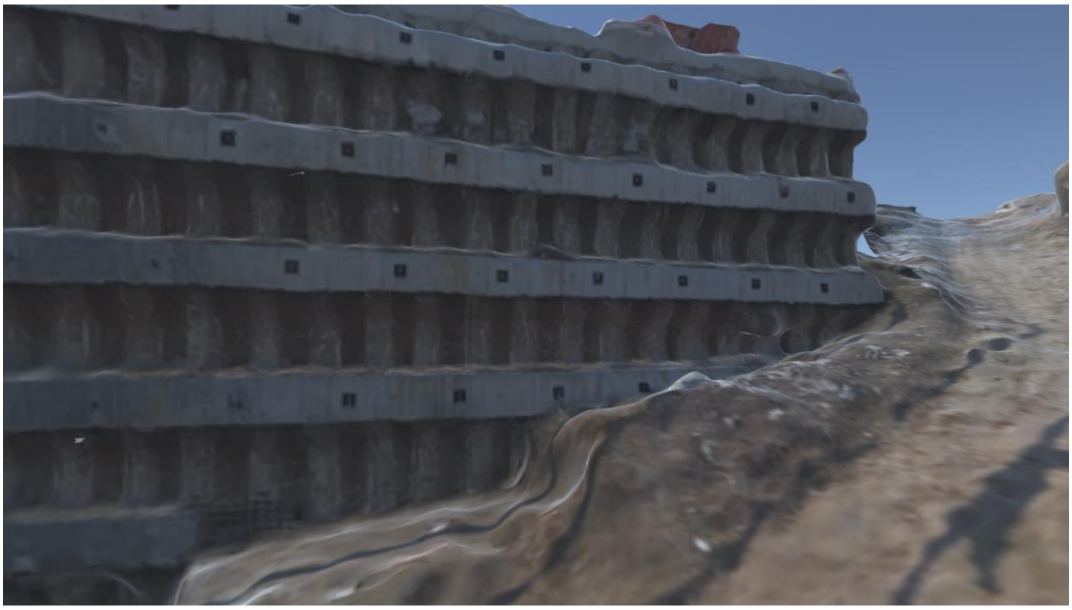


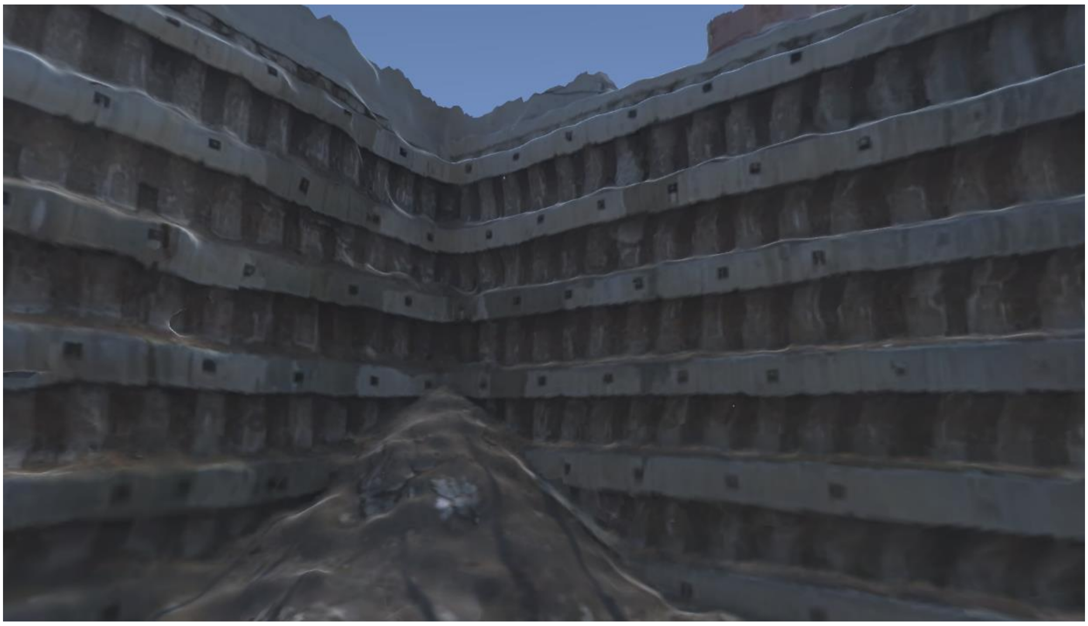
Figure 30 - Mesh Generated from The Point Cloud



(a) Screenshot from the Game

(b) Photograph from the Site

Figure 31 - Comparison of Visualization vs Reality for Petlas Building (View 1)



(a) Screenshot from the Game

(b) Photograph from the Site

Figure 32 - Comparison of Visualization vs Reality for Petlas Building (View 2)

(a) Screenshot from the Game

(b) Photograph from the Site

Figure 33 - Comparison of Visualization vs Reality for Petlas Building (View 3)

4.2. Dakav Building

4.2.1. General Information

The second deep excavation site is also located in Çankaya region of Ankara, Turkey. The building to be constructed here is a campus building for an educational institute. It is along western side of Konya Road, where high-rise structures are currently built in the neighborhood of the excavation place. Figure 34 shows the exact location of construction site on the map. The topography is flat, where the two sides of the excavation site are currently occupied by a dormitory building and the other two parts are roadways. The foundation level was -13.00 m from the ground. The building is designed to have 3 basement levels, 1 ground level and 10 stories. The architectural cross sectional drawing of the planned building is shown on Figure 35. Since the basement of neighboring building is at -18.50 m and the selected elevation for the building is -13.00 m, piles were already installed for only the two faces of the excavation that neighbors the roadway. These two faces are 23.95 m and 22.40 m long. With that, the total area for the excavation is 445 m^2. The layout and cross sectional views of the building are given in Figure 36 and 35, respectively.

Figure 34 - Location of DAKAV Building in Ankara

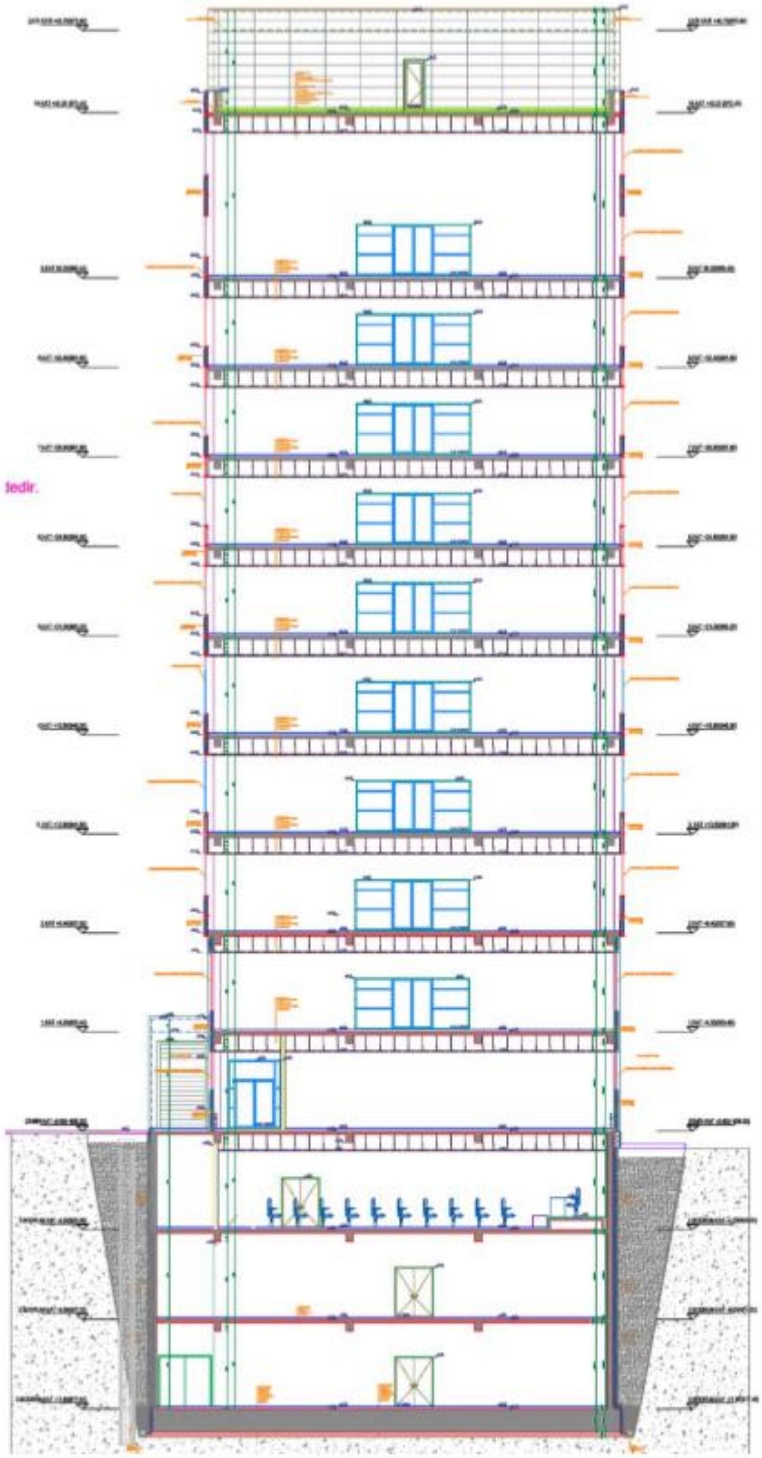


Figure 35 - Architectural Cross-Section for The Dakav Building

4.2.2. Geotechnical Information

Around the construction site, 3 boreholes were drilled, namely SK-1, 2, and 3. The general layout of the borehole locations are shown in Figure 36. The depth of the boreholes SK-1 and 2 are 25.45 m, and that of SK-3 is 30 m. The borehole logs show there are two different soil layers underneath the ground. The first one is the excavated fill material. The thickness of this layer is about 8 m throughout the site. The next soil layer is brownish reddish Ankara clay layer partly including some sand and gravel, which is stiff to very stiff. The ground water level observed at the site is at around 15.00 – 19.80 m depth. The soil profile of the site is given in Figure 37. According to the borehole data, there is no laboratory data for the fill layer. The classification for the Ankara clay layers is as follows;

- Classification : MH-CH-CL
- Liquid Limit (%) : 52
- Plastic Limit (%) : 30
- Plasticity Index (%) : 22
- Bulk Unit Weight (kN/m^3) : 19
- Water Content (%) : 22.1

Along the roadway sides of the deep excavation, 120 cm diameter bored piles having 21.60 m depth were placed at every 1.50 m. The whole length of the piles is 18.00 m whereas their socketing length is 8.60 m.

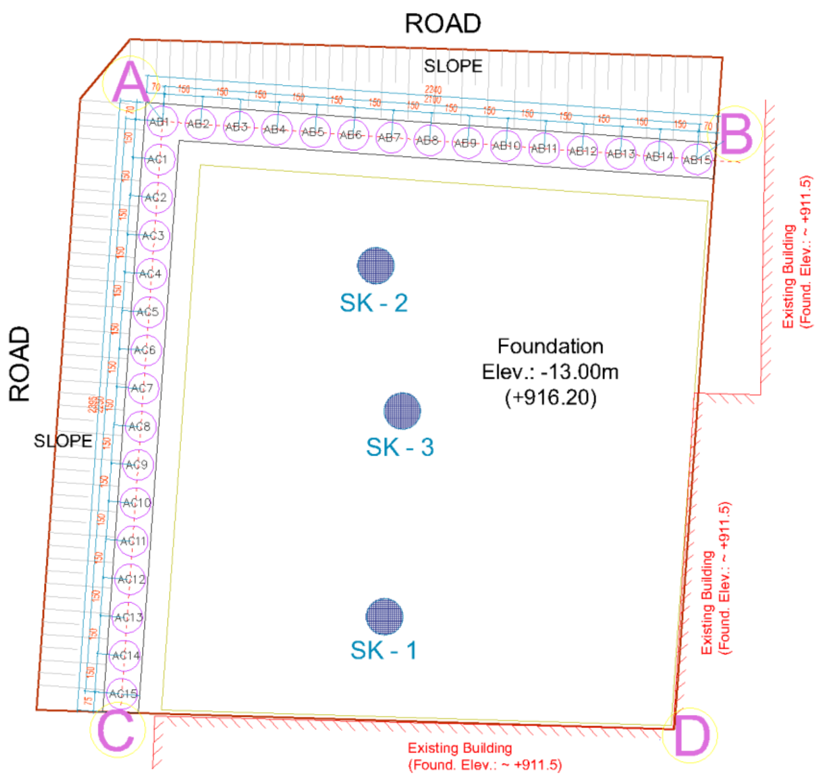


Figure 36 - Layout and Borehole Locations for Dakav Building

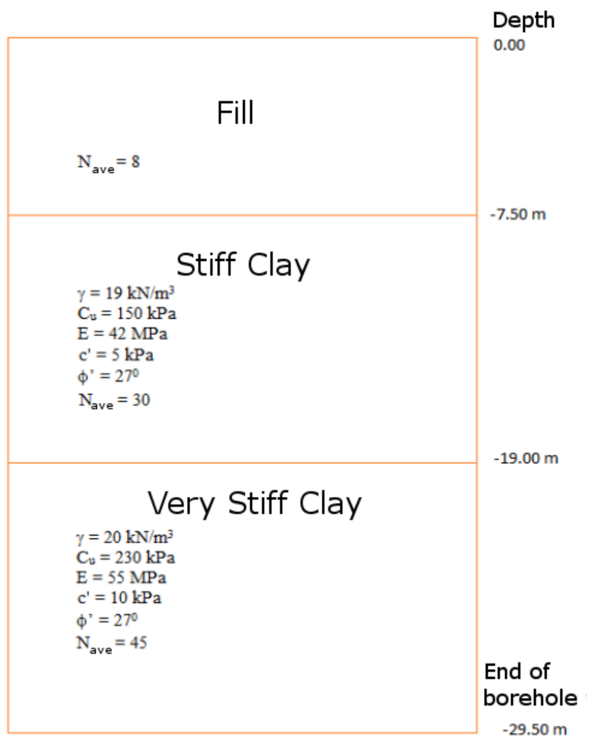


Figure 37 - Soil Profile for The Site

4.2.3. Model Generation

In this case study, a more advanced UAV, DJI Inspire 1, was used. For the image acquisition, images were taken across a predetermined flight path. This flight path included views pointing directly downwards or directly towards the excavation walls. Along the path, total of 64 photos were taken. Unlike the UAV used in the previous study, this UAV has a camera with rectilinear lens instead of fisheye lens. A rectilinear lens has no barrel distortion; therefore, the acquired images can directly be used with the model generation software.

Another difference of this study is that, instead of VisualSFM, a commercial photogrammetry software Pix4D was used. Compared to the former, the latter provides richer interface with more functionality and more options during the processing stage (see Chapter 3). Moreover, this software also provides orthomosaic images as output, thus making it a valuable tool especially for mapping purposes.

4.2.4. Results

The sparse and dense point clouds generated for this case study from different angles are shown on Figure 38 and Figure 39. Pix4D also generated the textured mesh as output, which is shown in Figure 40. In this case study, high resolution images with geolocation information were used. Therefore, the final model generated is scaled. However, accuracy of the GPS in this case study was very low because of surrounding high rise buildings and UAV flying under the ground level during shooting. This inaccuracy caused some orientation problems in the final model. To solve this, the tool called orientation constraint that is provided by Pix4D was used. This way, a face of the construction was marked as “z” axis and the model was translated and rotated accordingly by Pix4D in an automated manner.

The final model created was then imported into the game engine. In the game, piles, walls and the capping beam can be clearly seen. Moreover, this construction site also had an excavator inside, which can also be clearly seen in the game. With keyboard shortcuts, the player can be moved along the excavation site including jumping while moving. Screenshots from the final game are shown in Figures 41, 42 and 43.

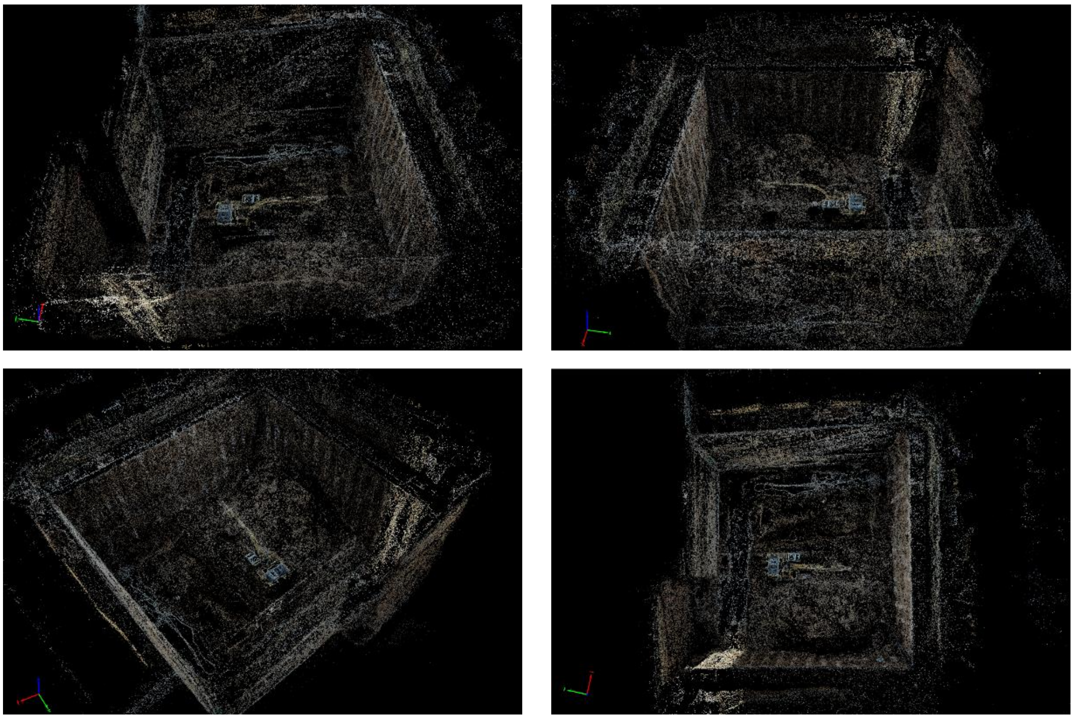


Figure 38 - Pix4D Sparse Point Cloud Output

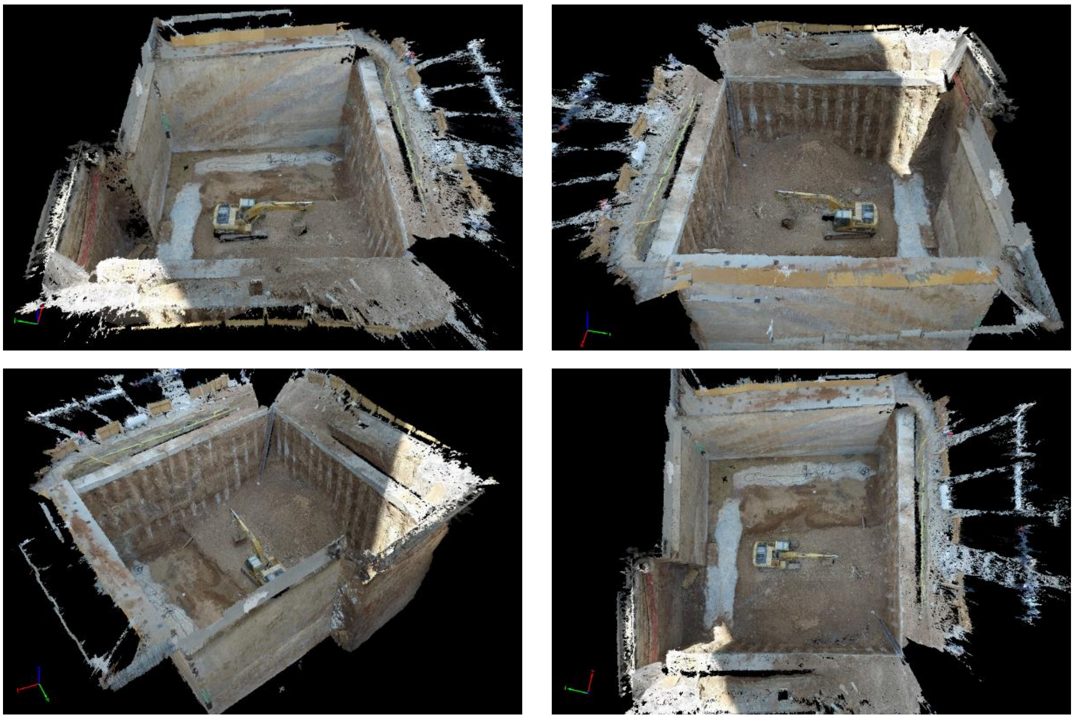


Figure 39 - Pix4D Dense Point Cloud Output

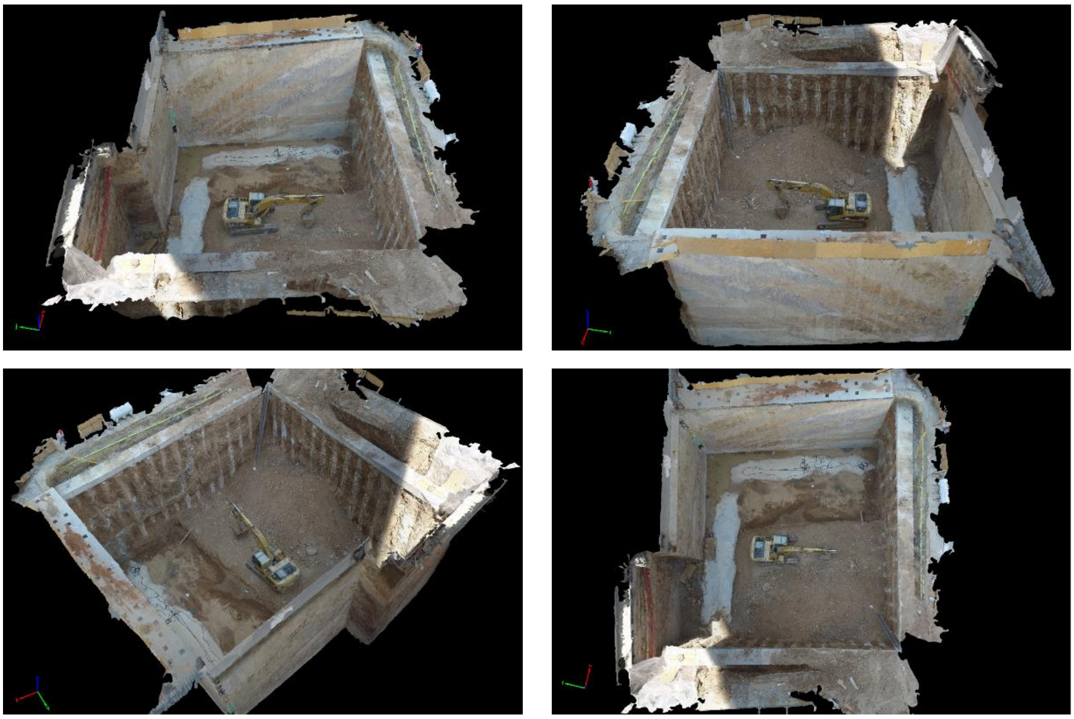


Figure 40 - Mesh generated by Pix4D

(a) Screenshot from the Game

(b) Photograph from the Site

Figure 41 - Comparison of Visualization vs Reality for Dakav Building (View 1)

(a) Screenshot from the Game

(b) Photograph from the Site

Figure 42 - Comparison of Visualization vs Reality for Dakav Building (View 2)

(a) Screenshot from the Game

(b) Photograph from the Site

Figure 43 - Comparison of Visualization vs. Reality for Dakav Building (View 3)

4.3. Discussion of Results

In this section, the outcomes of the visualization work through game engines are discussed considering the following aspects: (1) Simulating the Reality, (2) Quality of the Model, (3) Texture Excellence, (4) Illumination, (5) Coverage, and (6) Accessibility aspects. At the end, the advantages and disadvantages of using UAVs and utilization of game engines for deep excavation visualization are discussed.

4.3.1. Simulating the Reality

As shown in the figures above, the deep excavation environment and its structural or geotechnical objects such as piles, anchorages, beams, etc., can be clearly seen in the game. Within this perspective, the results show that this study achieves its main purpose by giving the user, mostly engineers for the time being, the feeling of being in an actual deep excavation site. This provides the engineers with a chance of inspecting the construction site visually without the need of actually being there. This result mainly stems from the geometric accuracy of the 3D models generated using the UAV imagery.

Specifically, in the second game, the construction equipment can also be included in the 3D model. This implies that when modeled separately, several construction equipment/objects can also be imported into the game such as cranes, lightings, warning signs for more realistic viewing experience.

4.3.2. Quality of the Model

The details of the generated model usually depend on the overlap percentage of the images taken by UAVs. Increasing this percentage value leads to more images required for visualization, which results in the need for greater computing power. On the contrary, considering the need for increasing the overlap percentage, if images are acquired too close to the surface of the excavation, they may possibly contain many similar features. In the case of deep excavations, the faces of the excavation site have continuous arrays of recurring piles, anchorages and beams, which may lead to incorrect matches among the features detected.

The detailing of the model also depends on the computing capabilities of the computer using which the game is developed, as increasing density of points requires greater computing power.

4.3.3. Texture Excellence

Achieving sufficient details for the texture requires using higher resolution images. In our study, commercial UAVs with cinematography/hobby purposes were used because of their significantly lower price. However, it is also possible to use more professional hexacopter/octocopter UAVs mounted with significantly higher quality cameras. Since, they have more rotors, they are also more stable in harsher environments with low GPS coverage, such as an excavation site in an urban area with high rise buildings around. They also have redundancy, i.e., in the event of one of the rotors failing, they can adapt themselves flying with remaining working rotors.

4.3.4. Illumination

The selection of time of the day when the image acquisition is made is very important in this type of work. As differential illumination throughout the acquired images would cause the model generated to be in separate parts. This is because the features having supposedly the same shape and color are actually very different in color in the case of differential illumination. For example, in the second case study, it can be seen that there is a bright area on the one face of the deep excavation model (see Figure 44). This is because sunshine was illuminating that part directly during the image acquisition. Therefore, first, the illumination generated by the sunlight should be as uniform as possible when the images are acquired. Second, the images acquired should all be taken at the same time of day, which is quite the case for observing narrow the deep excavations.

Figure 44 - Sunlight on The Face of the Model

4.3.5. Coverage

The model generated can have only the parts of the excavation site that are visible in the captured images. If any place in the excavation site is not properly photographed, the software used in this study completes the missing part by interpolation. However, even if the interpolation can be performed correctly, the texture generated for the missing part will not be precise, as there is no photograph containing the missing information. For example, since there is a limit for how deep the UAVs can go down in the excavation site, e.g. especially when reaching to lower level beams in the first case study, there is some distortion in the model and texture as the photos acquired did not cover the lower faces of these beams (Figure 45).

Figure 45 - Shape Distortion on The Beams

4.3.6. Accessibility

This workflow provided access to the parts of the construction site that were otherwise inaccessible. For example, in the second study, the only access to the deep excavation site was through a ladder, including a potential danger considering the construction safety (see Figure 46). Using the game generated from the images acquired with the UAV, players can freely roam the deep excavation site without taking such risks.

Figure 46 - A Ladder Used to Access the Excavation Site

4.3.7. Advantages and Disadvantages

In this study, images taken by UAVs are exploited for creation of deep excavation game, the creation of which requires the use of various software in addition to the game engine. This approach has several advantages when compared with the conventional ones, which are given as the followings:

- As the technology of UAVs increase, they become cheaper every day. Compared to other monitoring technologies, these devices have the potential for visualization of such constructions.
- The employed workflow requires the use of free software to generate 3D models, which are capable enough to create detailed models.

- Use of games means high quality visual information can be viewed with less powerful computers. Therefore, a detailed inspection through deep excavations may become a daily practice in the future.
- With the help of game engines, users can freely roam in the virtual environment. This provides flexibility to discover new features when the site is visualized offline.

On the other hand, the disadvantages of using the suggested workflows are given below:

- GPS modules on UAVs may not work efficiently in deep excavation environments, therefore, flying the UAV in such construction sites requires a significantly experienced UAV pilot.
- Although free software can be used to generate the models, they are not as powerful as the commercial ones.
- Since deep excavations consist of repeating structures like piles, the determination of optimum flight distance during image acquisition requires know-how.
- Legal restrictions on the use of UAVs are continuously increasing due to increasing number of UAVs. Many governments now put strict restrictions on the use of UAVs in the urban areas currently, which needs to be handled in advance before the modelling studies start.

CHAPTER 5

SUMMARY, CONCLUSIONS AND FUTURE WORK

5.1. Summary

In this study, a game engine was utilized as a framework where the 2D images captured through a recently introduced technological tools called unmanned aerial vehicles (UAVs) were transformed into 3D rendered objects for the precise and interactive visualization of construction sites. Specifically, deep excavation sites were chosen as the main targets of this study. The reason behind this choice is that deep excavations keep a unique place in the field of Geotechnical Engineering: During the design stages of the deep excavation project or even more importantly through its construction stages, visualizing and therefore understanding of field conditions plays an important role for continuous monitoring to keep the construction site and nearby structures safe and inspect the quality of the excavation work, as not doing so can lead to tragic results.

Creation of this UAV based tool required several steps to be taken. These steps are (i) flight planning, (ii) image acquisition, (iii) point cloud generation, (iv) production of textured mesh, and (v) game engine integration. Within this algorithmic framework, first the flight path for the UAV was determined. Because the GPS modules are not reliable during a flight under the ground level or in high density urban areas, the autonomous flight along the predetermined path was not possible in a deep excavation scenario. Then images were acquired while piloting the UAV according to the flight plan. All scenes were photographed, i.e., the whole area was covered in detail. Extra images were also taken for the objects in the excavation site such as construction equipment to prevent distorted shapes in the final model. In the next step, the point cloud was generated using a photogrammetry software. It has several sub-steps to be applied, namely, “Structure From Motion” (SFM) and “Multi View Stereo” (MVS). Application of SFM step resulted in the generation of a sparse point cloud. However, this point cloud was not dense enough to generate a useful mesh for the game engine integration. Therefore, MVS step was applied to generate a dense point cloud of the scene.

Having successfully created the dense point cloud using a special purpose point cloud software, the point cloud was re-sampled, in order to have a more uniform point cloud with less points. This software also estimated the surface normals of the point cloud for a given viewpoint. Then a surface is generated over the point cloud using the Poisson Surface Reconstruction. The negative aspects of this tool such as losing the color information and the final surface having too many faces were eliminated using “mesh decimation”. After the decimation step, the texture was generated over the mesh using the original colors of the vertices again.

The final textured mesh was imported into the game engine called Unity. Using Unity, a mesh collider was added for satisfying the collision constraints of objects. With the addition of the user to the game, a first person character asset provided by Unity, the player gained built-in walking, running, jumping functions as well as a camera attached to its head level. Then the next step was to add lighting to see the excavation surfaces clearly. Finally, the game was built for the target operating system.

5.2. Conclusions

The engineering interpretation of the deep excavation environment created through the game engine leads to drawing the following conclusions in this study:

- Even though it is through a computer environment, the created game stimulates the feeling of being inside a deep excavation site. Through this tool, the users can move around to see the details of construction, which helps them inspect the deep excavation site virtually, i.e., without the need of actually being there. All in all, the game created in this study provides an interactive experience.

- The construction elements frequently used in a deep excavation site such as piles, beams, anchorages were modelled and implemented successfully in the game. Especially in the second study out of the two case studies, even the construction equipment were clearly visible in the game environment.
- The overall accuracies of the models created using photogrammetry tools are reasonably acceptable although there is no universal criterion to measure the success of modelling.
- Successful accurate model creation achieved by both free and commercial photogrammetry software showed that the proposed workflow method does not depend on a single software.
- In this study, UAVs were used for surveillance purposes. In both case studies, the UAVs used were hobby or cinematography purposed air vehicles, which provided access to the parts of the excavation site that were otherwise inaccessible.
- UAVs provided ease of access in the excavation site. They also provided a quicker imaging solution compared to taking many photos with a hand held camera. The capabilities of the UAVs allow them to be used to take over 100 images in an excavation site in 10 minutes.
- The game engines have been used to create realistic video games for years. In this study, they were used to smooth out the interaction between the generated 3D model and the visualization hardware of the computers. With the increase in the computational power of the personal computers, creating such realistic virtual world using the imagery from the real world is now much easier than ever.
- The main target users of the game can be engineers, engineering students, or instructors all of which can use this tool for varying purposes including understanding field conditions or teaching the fundamentals of deep excavations.

5.3. Future Work

This thesis mainly dealt with creating a virtual environment for the visualization of deep excavations using a game engine. Although the objective and scope of this study was limited, the implications are immense as this game as a play tool is the first one created to feel the heart of construction sites. The following list of future work are mentioned below, however, it should be kept in mind that the borderlines of such studies may not only be limited with these.

- The data obtained from the boreholes may be added to the game to visualize the soil layers and provide flexibility with the mesh formed to create the game. Adding such a tool is intended to increase the level of understanding and to model the details of deep excavation construction.
- The method developed in this study, when applied continuously with certain intervals in a construction site, could effectively be used for construction monitoring purposes. Moreover, since every model created can be kept as a specific level of a game, then it becomes a virtual archive for the construction process. This archive then can be used to backtrack the problems that may have occurred during the construction progress.
- There are more stable UAVs in the market especially with more rotors such as hexacopters or octocopters. These UAVs may help acquiring images even deeper into the construction site without losing the control of the aircraft completely. This leads to getting more detailed photographs in deeper areas of the excavation site, which means more details at the bottom of the excavation.
- Depending on the intended use of the game, the details of the created model can further be increased if a UAV mounted with a better camera is used. With the increasing technologies such as increasing quality of the devices providing more stability to UAVs, not only its camera, but also the UAV itself can be upgraded to create a better graphical models with higher resolutions and number of details in a deep excavation environment.

- In order to increase the quality of the end product, further studies are necessary for manipulation of mesh and point cloud generation. Among those, point cloud filtering, estimation of surface normals, surface reconstruction and mesh decimation can be counted.
- When capturing the details of deep excavations at a desired level is not satisfactory, there may be other solutions added to the currently developed system, such as laser based measurement systems that especially increase the resolution of the point cloud.
- Adding non-built objects into the virtual environment such as cranes, excavators, etc., is possible, through which the interactivity level can be increased.
- Integration with the sophisticated technological devices which can make the visualization tools interactive and more enjoyable with virtual and augmented reality concepts, such as Oculus Rift (Oculus VR 2016) or HoloLens (Microsoft 2016) is possible in the future.
- This study has a huge potential for quality construction and assurance in various of fields of Civil Engineering. For example, the same system can be implemented for the inspection of bridges, pavements and high rise buildings.
- This study has also potential to be used in engineering education. In order to test the use of proposed system for the education of civil engineering students, several different scenarios may be provided to the students and their learning performance may be measured with the use of questionnaires.

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