RIPPABILITY ASSESSMENT IN HILLY TERRAIN OF WEATHERED SEDIMENTARY ROCK MASS

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SCHOOL OF CIVIL ENGINEERING
UNIVERSITI SAINS MALAYSIA
2017

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By

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This dissertation is submitted to

UNIVERSITI SAINS MALAYSIA

As partial fulfilment of requirement for the degree of

BACHELOR OF ENGINEERING (HONS.)
(CIVIL ENGINEERING)

School of Civil Engineering,
Universiti Sains Malaysia

June 2017

UNIVERSITI SAINS MALAYSIA

SCHOOL OF CIVIL ENGINEERING
ACADEMIC SESSION 2014/2015

FINAL YEAR PROJECT EAA492/6
DISSERTATION ENDORSEMENT FORM

Title: RIPPABILITY ASSESSMENT IN HILLY TERRAIN OF WEATHERED SEDIMENTARY ROCK MASS

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ACKNOWLEDGEMENT

Prima facea, I am grateful to the universe for the good health and well-being of myself that were necessary to complete this thesis. I believe everything that happens is controlled by the universe and that Science governs the very fabric of nature and the existence of mankind.

After all hard work in this year, it is necessary to express my gratitude to those people who in one way or another contributed and extended. I wish to express my sincere appreciation to my beloved family especially to my father and mother who have been my backbone and support system in times of difficulty and challenge.

I also wish to express my utmost appreciation to my supervisor Dr Mohd Ashraf Mohamad Ismail for the guidance, support, and continuous help throughout the execution of this project. I'm lucky to have a knowledgeable and passionate lecturer to guide me and push me to perform the best in my pursuit of this project.

I am also grateful to the technical staff at the Geotechnical Engineering laboratory, Mr Ahmad Helmi Ghazali who have been there to guide me in times of doubt and trouble. I am extremely thankful to them for sharing their expertise, valuable guidance and unfailing encouragement.

ABSTRAK

Pembangunan yang pesat di kebanyakkan negara telah menyebabkan struktur pembinaan berada di permukaan batu walaupun mempunyai banyak pertikaian antara pakar geoteknikal untuk menganalisis dan membuat keputusan yang tepat untuk kerja-kerja awal seperti kerja tanah dan reka bentuk. Kemudahan penggalian di dalam batu adalah isu yang rumit kepada pembangunan projek kejuruteraan awam. Penggunaan kaedah kejuruteraan seismik akan menjadi lebih praktikal daripada mejalankan pengerudian dalam kuantiti yang banyak. Pembiasan seismik dan berbilang saluran analisis gelombang permukaan (MASW) sebagai kaedah halaju seismik akan menghasilkan halaju gelombang ricih, V_s dan halaju gelombang '*compressional*', pengedaran V_p. Kebiasaanya dalam bidang geoteknikal, pengunaaan lubang gerudi boleh disepadukan dengan kaedah halaju seismik untuk memberi penilaian yang lebih sesuai pada penggalian batuan enapan. Maklumat '*borehole*' dan model halaju seismik akan memberikan maklumat yang berguna dan panduan dalam reka bentuk kejuruteraan. Korelasi data boleh digunakan untuk mengkategorikan jentera untuk aktiviti penggalian berdasarkan prosedur analisis sistematik yang ada untuk meramalkan kemudahan penggalian batu. Lapisan atas terikat kepada julat halaju boleh digali dan boleh digali sedikit daripada 1.8 km/s kepada 2.4 km/s dan 'non-ripabble' > 2.4 km/s berdasarkan carta penggalian. Jentera merobek yang terdapat adalah D8 R, D9 R, D10 R dan D11 R untuk sistem penggalian berdasarkan carta halaju. Keupayaan jentera penggali Caterpillar yang paling kecil, iaitu D8R dapt menggali batuan berdasarkan halaju seismik.

ABSTRACT

Development in this country have forced structure to be constructed on the rock surface. Rock happened to cause dispute among geotechnical expert to analyse and make the right decision for the preliminary work and design. Rippability or ease of excavation in rock is of great concern in the preliminary work. Assessment can be made to rip the earth material with the use of seismic engineering method will be much more practical as well as low time consuming by spatially covering the site. The study area is at the proposed construction site for development of water reservoir and related infrastructure in Kampus Pauh Putra, Universiti Malaysia Perlis. The study focused on Seismic Refraction and Multichannel Analysis of Surface Wave (MASW) as the seismic velocity method which produce the shear wave velocity, V_s and compressional wave velocity, V_p distribution to provide a unique correlation and subsurface characterization. Conventional geotechnical method of using borehole was integrated with seismic velocity method to provide the appropriate assessment on rippability of the sedimentary rock. Correlated data can be used to categorize the machinery for the excavation activity based on the available systematic analysis procedure to predict the rippability of rock formation. Upper bound of the rippable and marginal velocity ranges from 1.8 km/s to 2.4 km/s and non-ripabble > 2.4 km/s based on the rippability chart. The available ripping machinery is D8 R, D9 R, D10 R, and D11 R for the excavation system based on the velocity chart. Ability of Caterpillar’s smallest ripper, D8R can successfully excavate the earth material based on its seismic velocity.

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LIST OF ABBREVIATIONS

MASW	**M**ultichanel **A**nalysis of **S**urface **W**ave
SRT	**S**eismic **R**efrection **T**omography
SPT	**S**tandard **P**enetration **T**est
RQD	**R**ock **Q**uality **D**esignation
EC8	**E**urocode 8
UCS	**U**niaxial **C**ompresive **S**trength
1-D	**O**ne **D**imensional
2-D	**T**wo **D**imensional
P-wave	**C**ompressional **W**ave
S-wave	**S**hear **W**ave
NHERP	**N**ational **E**arthquake **H**azards **R**eduction **P**rogram

CHAPTER 1

INTRODUCTION

1.1 Background of the study

Construction on weathered rock areas has increased in recent years because of the growth progress occurring throughout the world. Potential construction projects on rock areas to be developed causes many disputes among the practitioner. Prime concern in such areas will be the preliminary work and design before start of the substructure. Preliminary work such as excavation work, platform design and foundation design is happened to cause problems and tend to increase the cost of project and delays. Predicting the ease of excavation of rock and rock masses is very significant in earthworks for construction and other civil engineering works and foundation (Tsiambaos & Saroglou, 2010). Ease of excavation or rippability is a critical decision making parameter in the selection of both the overburden removal and the required equipment (Dindarloo 2016).

Rocks can be classified into three types which is igneous, sedimentary, and metamorphic. Sedimentary rocks consist of material derived from the destruction of pre-existing rocks (Caterpillar, 2001). Sedimentary rocks are generally the most rippable material among others. The geology of sedimentary rock masses, which are mostly composites and interbedded, consisting of tectonically disturbed sequences of alternating layers of two or more lithological units (mainly sandstone, shale or siltstone), proved to be highly variable and challenging as compared to other types of rock masses such as igneous rock, which is more homogeneous (Liang et al. 2015). In sedimentary rock areas, in addition to geological mapping, at least three boreholes per major hill should be carried out to determine the stratigraphically formation, presence of defective or unstable geological structural discontinuities and its strength properties as an intact rock.

Seismic survey may have to be carried out for major projects on hilly areas involving massive and deep excavation. This is to ensure that more geological information is made available for slope stability assessment and the quantity of rock excavation can be estimated with reasonable accuracy (JKR, 1998). Various non-invasive geophysical methods have been developed to investigate and characterize subsurface condition. Previous researchers have found that velocity method could become a fundamental property in evaluating rock parameters. In minimal disturbance, in situ geophysical methods have considerable advantages and accuracies over determining the seismic velocity (Ariffin et al., 2016). Surface wave and seismic refraction tests are non-invasive seismic techniques and have been used to determine the velocity profile. The methods provide a simplified characterization of subsurface in two-dimensional 2-D which is the distance and depth profiles (Adegbola et al., 2013)

Civil engineering projects have greatly benefited from the mechanical excavation of hard rock technology (Gillani & Butt, 2009). Determining whether a rock formation can be ripped is not a simple process, but today's technology and experience can help develop a reasonable prediction. Obviously, the ideal test for determining rippability is to put a ripping tractor on the job and see if it can rip the material and usually carried out by trial. But this may not be practical due to the time and expense involved. Therefore, to determine if ripping is feasible, a basic knowledge of geology and rock characteristics affecting ripping is necessary (Caterpillar, 2001). Ripability is often classified in 3 categories qualitatively. It may be rippable, marginal and non-rippable (Parkland, 2015). Surface excavation works in rock have often been reported to be challenging and often cause dispute among engineers and clients in engineering works such as construction of highways and foundation. These uncertainties include selection of the excavation method, the types of machineries, and rate of excavatability. These decisions are significantly important as they affect and determine the cost and time required for the entire project. Wrong estimations or decisions made during the preliminary design could lead to unnecessary cost and serious project delays which reflects in the bill of quantity, tender and sometimes claims (Liang et al., 2015).

1.2 Problem Statement

The problem of rippability or ease of excavation in rock is of great concern to the development of civil engineering project at the area consist of weathered sedimentary rock. The fact that weathered sedimentary rock are widespread in the northern region of Malaysia, so the construction projects on the rock surface is avoidable. Excavation works is the preliminary work before start of construction work. Excavation in rock is very challenging due to the heterogeneity and undulating rock layers which may presence in sedimentary weathered rock formation. Excavation work should be planned carefully to avoid problems during the works. Planning should be including the excavation method and equipment to excavate the rock material for desired platform level and foundation work. Identification of rock parameters is very important to make reliable judgement on the method and machinery.

Identification of geotechnical parameters of rock using conventional method having limitation due to the test which was localized to the point at which the test is conducted. Therefore, an adequate number of tests must be carried out at distributed points throughout the site to make a fair assessment. This makes it more time consuming and costly to cover an extensive site. Besides that, rock subsurface profile can be anisotropic and heterogenous which require spatial assessment on the subsurface condition. Thus, the use of seismic engineering method will be much more practical as well as low time consuming by spatially covering the site and to predict the suitable machinery for excavation work.

Present day geophysical surveys are being carried out in logistically difficult and hostile terrain conditions. During the seismic data acquisition, the infield data quality is the prime concern of field geophysicist. It is well known fact that ensuring equal geophone spacing is the most fundamental and important requirement for acquiring good quality seismic data. Data acquisition in hilly terrain tend to force the geophysicist to avoid placing geophones in steep slope which can leads to poor seismic data acquisition.

1.3 Objectives

The objectives in this study are:

1. To characterize the subsurface condition using compressional wave velocity, V_p from seismic refraction method.

2. To determine site classification of the study area using shear wave velocity, V_s from multichannel analysis of surface wave (MASW) method.

3. To analyse the rippability of the earth material at the study area from the correlation between V_p, and the borehole data.

1.4 Scope of work

The scope of work performed in this study consists of:

- **Surface mapping**

Mapping of the surface using drone imagery to extract the Digital elevation model of the study area.

- **Field study and data collection**

Subsurface investigation using seismic refraction and MASW at the study area followed by borehole drilling

- **Subsurface profiling**

Establish two-dimensional (2-D) profile of compressional wave velocity, V_p and one-dimensional (1-D) profile of shear wave velocity at 30m investigation depth using SeisImager software.

- **Integration and correlation of borehole data and both V_p and V_s data**

- **Rippability assessment**

Determine and comparing the suitable ripping machine for the excavation work using the correlation of velocity distribution at the study area

1.5 Dissertation Outline

The thesis has been categorized into specific chapters for better viewing and understanding of the study. This dissertation consists of five chapters.

Chapter 1: Introduction – this chapter gives an overview of the thesis, followed by the problem statement to identify, and understand why this research was carried out and its relevance to current times followed by the objectives of this research in order to set the desired target of work and finally the justification of this research.

Chapter 2: Literature review – this chapter provides important theoretical and conceptual understanding on the research title, rippability, geophysical methods and terrain mapping.

Chapter 3: Methodology – this chapter give detailed description on the methods, tests conducted and details on study area. The flow will be viewed in detail to facilitate understanding on the execution of this project.

Chapter 4: Results and Discussion – this chapter encompasses the results and discussion of this project to ensure the objectives stated have been accomplished and have produced substantial results to suggest the best available ripping machine.

Chapter 5: Conclusion – this chapter briefly summarize and conclude the findings in this research including the suggestion and recommendation for improvement of future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter review the rippability assessment in hilly terrain of sedimentary rock to choose the best ripping machine. The importance of the assessment for rock excavation will also be discussed in this chapter. The assessment is made based on the correlation between seismic method and in situ borehole data. Besides that, the use of surface mapping to identify the suitable survey line is also discussed in this chapter.

2.2 Sedimentary Rock

Mibei (2014) stated that the sedimentary rocks are formed through the deposition of material at the Earth's surface and within bodies of water. Sedimentation is the collective name for processes that cause mineral and organic particles to settle and accumulate or minerals to precipitate from a solution. Sediments can be detrital, chemical, and organic sediments. Detrital sediments are mechanically eroded from pre-existing rocks. Chemical sediments on the other hand are fluid precipitates or evaporates deposited in various environments. Sedimentary rock masses typically behave anisotropic due to bedding planes, which act as planes of weakness along which slip may occur.

From previous studies by Liang et al (2015) geology of sedimentary rock masses, which are mostly composites and interbedded, consisting of tectonically disturbed sequences of alternating layers of two or more lithological units (mainly sandstone, shale or siltstone), proved to be highly variable and challenging as compared to other types of rock masses such as igneous rock, which is more homogeneous. The different lithological units exhibit a structure of alternating layers of competent and incompetent rocks with varying thickness. The engineering characterization of heterogeneous and complex geological sedimentary rock mass formations for estimating their rock mass strength and deformability characteristics constitutes a challenge to geologists and engineers dealing with the design and construction of slopes and tunnels, as well as excavation works since it constitutes the greatest variation in strength and behaviour.

They are built up by successive layers of material differing in type, texture, colour, thickness or these properties. Individual layers which are uniform in texture. colour and composition may be found within a stratum. These are called beds and may vary in thickness from paper thin to several hundred metres. Sandstone, dolomite, tillite, shale, calcrete and ferricrete are among the most common sedimentary rocks. These generally are the most easily ripped. (Weaver, 1975)

2.3 Rippability of Rock

From the previous studies, Tsiambaos & Saroglou (2010) state that to describe the excavation of rocks, different terms have been used, related to the principle of excavation and the mechanics of fracture. These include cuttability, rippability, excavatability, diggability and drillability. In the present work, the term excavatability is used as a broad term that refers to the ease of excavation of rock and rock masses and includes the methods of (a) digging, when easy/very easy excavation conditions exist, (b) ripping, for moderate to difficult excavation conditions, and (c) blasting for very difficult excavation conditions. The knowledge of the physical and mechanical characteristics as well as the behaviour of the geo-materials to be excavated is vital for the selection of the most effective method of excavation.

Ripping is one of the primary methods used for mechanical breaking or losing the rock layers to a level enough for platform level and construction to be carried out. Moustafa (2015) state that, over the year's techniques for preparing construction programmers and estimating the costs of excavation have also amended. It is significant in preparing these estimates to know the type of equipment required to excavate a site. In most cases ripping with a bulldozer is cheaper than boring and blasting. However, as the ripping becomes harder, the wear and tear on the bulldozer increases and the productivity decreases.

Due to its mode of excavation, ripping is suitable for shallow excavation (surface stripping) of a large area, particularly in obtaining a required finished level (e.g. preparation of project site and road alignment). In earthwork, ripping is commonly used to excavate rocks that are relatively weak to be blast but, too strong to be removed by normal excavator. Despite of being a common excavation method, no proper classification is currently available to be used as basis in evaluating the degree of difficult to undertake the actual ripping work on site. At present, the rippability of rocks is often based on contractors' experience and trial ripping on site. With increasing number and size of earthwork and variation of rock types encountered on site, such a subjective approach is easily exposed to elements of dispute and exploitation, which may lead to lengthy industrial arbitration and expensive variation orders. (Mohd Amin and Chan Sook Huei, 2006)

Rippability and diggability are effective engineering properties. Both properties depend on rock's intrinsic properties (e.g., density, modulus, and strength) and fabric (e.g., strike, dip, joints and fractures, foliation, and Rock Quality Designation (RQD). Rippability is the response of rock to steel tines (teeth, claws) penetrating and ripping (pulling) through rock. Rippability is highly dependent on the size of the excavator, bucket, and ripping claw in use and the penetration and ripping process. (Murphy III et al., 2011)

2.3.1 Rippability Assessment

Rippability assessment needs evaluation of several rock mass parameters from core borings and geophysical work. The physical principle used for the determination of rippability is that seismic waves move faster through rock having a higher mass density than through the rock less consolidated. There are many geological factors that influences wave velocity such as rock hardness, stratification, degree of fracturing, and amount of decomposition or weathering which directly influence the rippability of the earth. (Moustafa, 2015) Caterpillar found that a comparison of the wave velocities recorded with those obtained in a similar material from previous experience gives a good indication of ripper performance. Caterpillar have published charts showing ripper performance as related to seismic wave velocities for their equipment which enables the industry practitioner to choose the correct equipment. Rippability may be qualitative which is rippable, marginal, and non-rippable. Caterpillar (2000) rating charts as shown in figure 2.1 is to assess the rippability of investigated rocks based of seismic wave velocity values.

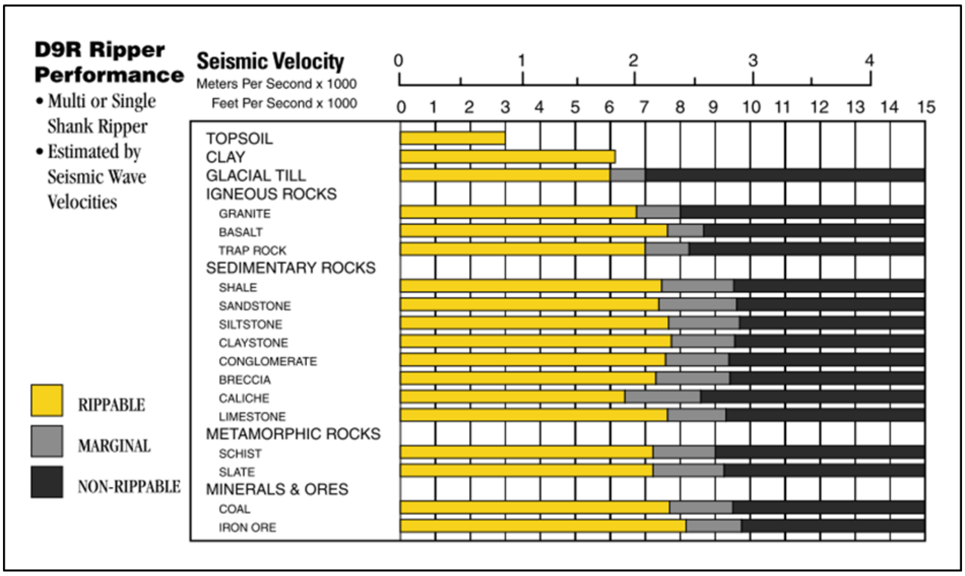

Figure 2.1: Rippability classification of different rock masses according to their P wave seismic velocity values (Caterpillar, 2001)

The physical principal used for the determination of excavatability is that seismic waves travel faster through denser material as compared to less consolidated material. In general, a lower velocity indicates material that is soft and a higher velocity indicates more difficult to be excavated. However, a few researchers have noted that seismic velocity method alone does not correlate well with the excavatability of the material. In this study, a seismic velocity method was used in Nusajaya, Johor to assess the accuracy of this seismic velocity method with excavatability of the weathered sedimentary rock mass. A direct ripping run by monitoring the actual production of ripping has been employed at later stage and compared to the ripper manufacturer’s recommendation. During the direct ripping test, it shows that the layers were unripped by Caterpillar D9. The material consists of highly weathered (grade IV) sandstone which can be broken by strong hand pressure. Discontinuity spacing measurements were made with scanline technique. In this line, discontinuity measurements revealed that there are 4-6 discontinuities per metre square with average spacing of 0.25 m. Material has to be broken by drill and blast method. At least 46% of this area that supposed can be ripped by manufacturer's recommendation, could not be ripped. The seismic velocity charts of Caterpillar Performance Handbook only provide guidelines to certain extent. There are 2 cases shown that the handbook suggested chart could not correlate well to the actual rippability performance if solely based on a single parameter, i.e. seismic velocity. (Tonnizam et al., 2011)

Borehole data alone is not an adequate measure of subsurface condition in karstic terrain. Geophysical investigations are best utilized to plan borehole locations and/or correlate geology between borehole locations. A geophysical survey was conducted along a portion of the southbound retaining wall of Missouri Highway 152 in Kansas City, Missouri. The purpose of the geophysical survey was to map bedrock geology, structure, and engineering properties of the shallow (upper 50 ft) subsurface. Geophysical methods used during this investigation included the seismic refraction and 2-D resistivity imaging techniques.

Geophysical techniques are not without fault. Seismic data at this site was affected by high ambient noise levels and steep topographic terrain prohibited the placement of far-offend shots, limiting depth of penetration. Interpretation.(Shawver & Dalrymple, 2006). P.B.Choudry (2009) states that shear wave velocity profiles was used to characterize the sub-surface ground and assess its rippability. Seismic profiling tests were conducted using multichannel analysis of surface wave, at two different locations in a limestone mine. The ability of seismic profiling using MASW for ground characterization of the subsurface strata by providing plots (1-D or 2-D) of variation of in-situ shear and compressional wave velocities with depth. The knowledge regarding the type of rock existing in the subsurface stratum helps in proper planning, execution method selection and equipment selection. The quality of rock existing below ground can be very well judged by rock existing below ground can be very well judged by rock quality designation RQD. The information of shear wave velocities is also required to match the specification of machinery or equipment like rippers, dozers, and tractor which can be employed to ripping the strata.

One of the basic principles for assessing rippability of earth and rock materials are that seismic waves travel through different materials at different velocities. Using a refraction seismograph, the seismic wave velocity through various layers of material is measured from which the degree of consolidation, including such factors as rock hardness, stratification, degree of fracturing and degree of weathering can be determined. From this information, an indication of the equipment necessary and method of excavation is obtained. Seismic wave velocity alone does not provide the answer and results obtained must be tempered by cognisance of geological factors for correct analysis of rippability. (Weaver, 1975)

2.4 Morphology influence in rippability assessment

For such studies the availability of a topographic dataset is fundamental in particular for those systems characterized by a complex morphology. (Mancini et al., 2013). Bedrock deposits are differentiated according to the physical properties that control ground response; maps of these properties are prepared by analyzing existing geologic maps, the geomorphology of surficial units, and geotechnical data obtained from boreholes and seismic testing. (Kockar, 2006) Geological terrain mapping is carried out based on the evaluation of four attributes, namely, slope gradient attribute, terrain or morphology attribute, activity attribute and the erosion and instability attribute. To prepare the various derivative maps, a GIS system (using Arc Info or Arc View software) is used to analyse data from the four attributes. (Zakaria, 2003)

2.4.1 Terrain Mapping Method

There are many method of terrain mapping, for example contouring, vertical profiling, hill shading, and perspective view. In the process of planning for a developing an area, the planner would require basic information such as the geology, topography and landform of the area, as well as other relevant information. Such information will assist engineers in preparing the layout plans, designing the foundation system and deciding on the most appropriate type and method of construction. Rational evaluation of the overall terrain should be conducted and the data should be presented in the form of various types of thematic maps for an easy assessment and utilisation of the information required, whereby the planners and engineers may utilise them. Many quantitative and qualitative studies in geoscience research are based on digital elevation models (DEMs) and 3D surfaces to aid understanding of natural and anthropogenically-influenced topography. As well as their quantitative uses, the visual representation of DEMs can add valuable information for identifying and interpreting topographic features.(Bonaventura et al., 2017)

Among other techniques, aerial and terrestrial photogrammetry have long been used to control the displacements of landslides and glaciers as well as for the detection of terrain morphological changes. Unmanned Aerial Systems (UAS) are today an efficient tool to perform data acquisition in rough or difficult terrain, both safely and quickly, avoiding hazards and risks for the operators while at the same time containing the survey costs. Vasić et al (2014) stated that the terrain mapping can be done using an unmanned aerial vehicle. With the use of UAV, we can obtain orthorectified frames and the possibility of generating a precise digital terrain model. The advantages of using terrain mapping are its practicality and a rapid and efficient mapping of rather large areas for terrains usually unavailable to conventional mapping methods. It has found application in various kinds of designing, as well as in engineering geodesy.

Aerial photography provides a basis for gathering spatial data. Before geological information can be extracted from these data in a way that is useful for mapping and further analysis, the aerial images must be georeferenced in an absolute manner. This process, which aims at placing each image pixel on its true location on the Earth's surface, should also try to take care of all geometric transformations that occur during the imaging process. As a result, this method largely accounts for most relevant kinds of geometrical degradations and is capable of generating 3D models and ortho-photos that are perfectly suited for geological purposes.(Verhoeven et al., 2012)

As UAVs can be considered as a low- cost alternative to the classical manned aerial photogrammetry. Following a typical photogrammetric workflow, 3D results like Digital Surface or Terrain Models (DTM/DSM), contours, textured 3D models, vector information, etc. can be produced, even on large areas. A typical image-based aerial surveying with an UAV platform requires a flight or mission planning and GCPs (Ground Control Points) measurement (if not already available) for geo-referencing purposes. (Nex and Remondino, 2013)

After the acquisitions, images can be used for stitching and mosaicking purposes (Neitzel & Klonowski 2012), or they can be the input of the photogrammetric process. In this case, camera calibration and image triangulation are initially performed, to generate successively a Digital Surface Model (DSM) or Digital Terrain Model (DTM). These products can be finally used to produce ortho-images, 3D modelling applications or for the extraction of further metric information. In Figure 2.2, the general workflow is shown: the input parameters are in green, while the single workflow steps are in yellow and they are discussed more in detail in the following sections.

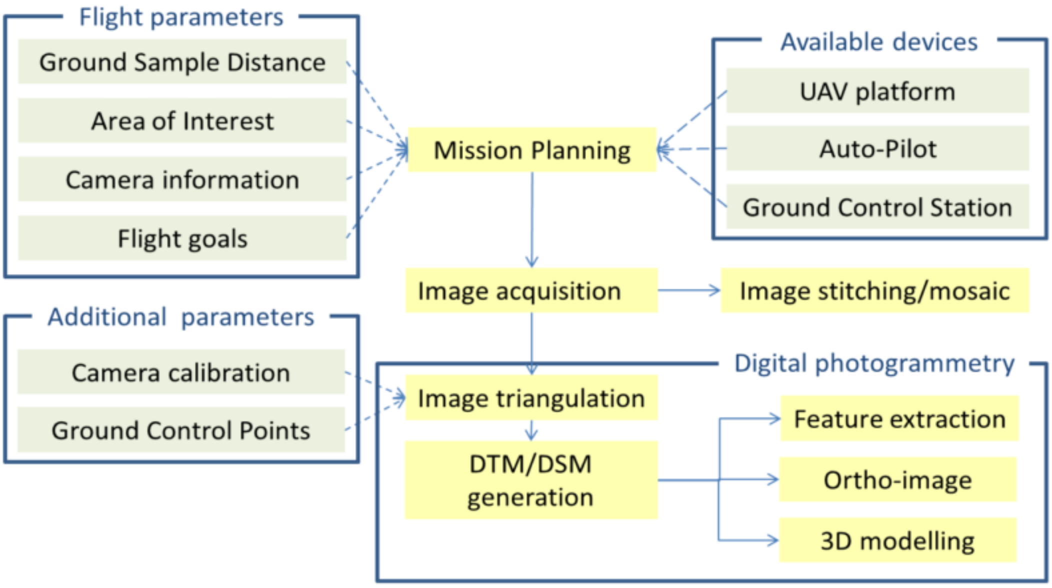

Figure 2.2: Typical acquisition and processing pipeline for UAV images. (Nex and Remondino, 2013)

2.4.2 Digital Elevation Model

Digital Elevation Models (DEM) allow to provide multiple views and generate reports that eventually are useful for practitioners. (Siebert and Teizer, 2014). Digital elevation models obtained from methods such as airborne and terrestrial laser scanning, photogrammetry, and satellite imaging, are used ubiquitously within the geosciences, facilitating studies of natural and man-made phenomena across a wide range of scales. Commonly, elevation data, comprising height measurements linked by a grid or triangulation structure, are supplemented with digital image texture as the basis for qualitative and quantitative interpretation. Visualizing and communicating terrain model data, with or without image texture, is important to fully exploit the benefits of geospatial data in geoscience applications. However, until now, user support for obtaining representative viewpoints and guiding the extraction of salient information about the terrain's shape has been minimal.(Bonaventura et al., 2017)

The availability of Digital Surface Models (DSM) at high spatial resolution and vertical accuracy is of increasing importance for all sciences interested in the three-dimensional reconstruction of the environment. For such studies the availability of a topographic dataset is fundamental for those systems characterized by a complex morphology. Successively, for further investigations on the absolute accuracy of 3D surface from the point cloud, a linear interpolator was used to produce a DSM. The meshed DSM shows a fine representation of the elevation dataset over the study area. The resulting DSM is represented in Figure 2.3 below. (Mancini et al., 2013)

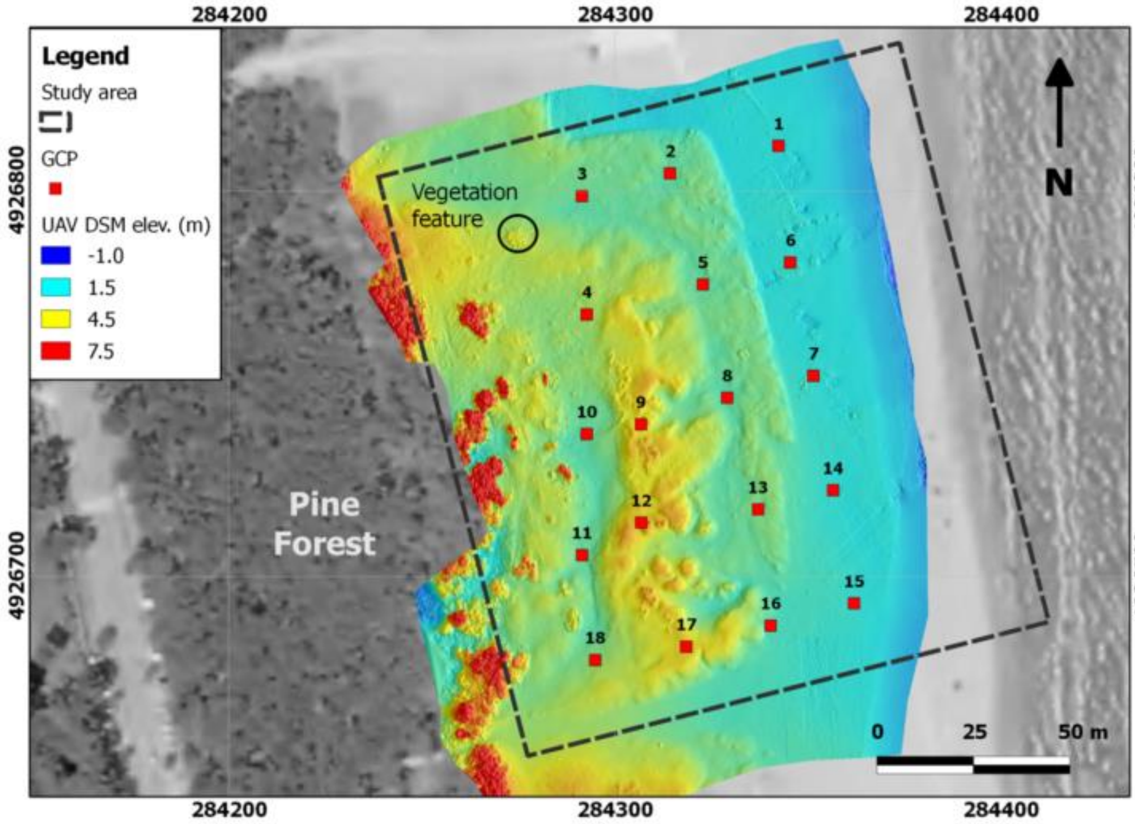

Figure 2.3: Hill shaded DSM from UAV survey with elevations above sea level (m) and locations of available GCPs. (Mancini et al., 2013)

2.5 Influence of seismic waves to earth material properties

Seismic waves are low frequency waves that travel through the earth and generally caused by an earthquake. It is like a mechanical disturbance or energy packet that can propagate from point to point in the earth. Basically, seismic waves are elastic waves. Earth material must behave elastically to transmit them, the degree of elasticity determines how well they are transmitted. By the pressure expanding from an earthquake shear rupture, the surrounding Earth material is subjected to stress (compression, tension, and shearing).

Upon striking a boundary between differing material properties, wave energy is transmitted, reflected, and converted. The properties of the two media and the angle at which the incident ray path strikes will determine the amount of energy reflected off the surface, refracted into the adjoining material, lost as heat, and changed to other wave types.(US Army Corps of Engineers, 1995)

A wave generated at the surface will spread in all downward directions, but also along the surface; called the direct wave. As a wave crosses an interface to a layer with a higher velocity, it refracts away from the normal according to Snell`s law, Figure 2.4. A more oblique angle to the interface might finally result in a critical angle where the refracted angle is exactly 90 degrees making the refracted wave travel along the interface.

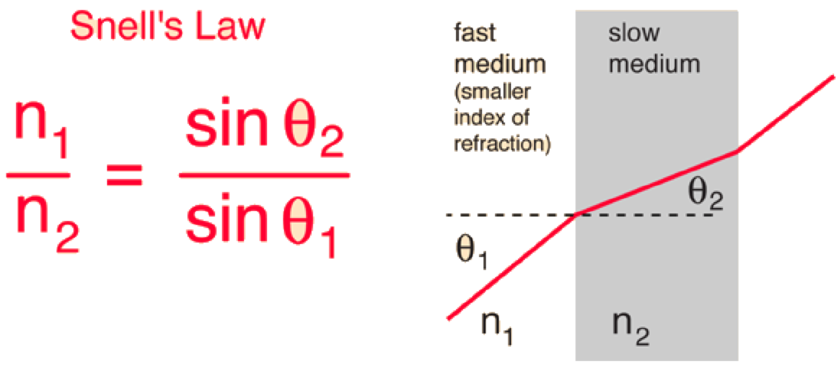

Figure 2.4: Snell`s law.

Where: n_1 = velocity of layer 1

n_2 = velocity of layer 2

θ_1= angle of incidence

θ_2= angle of refraction

At the surface, the seismic energy will be registered by receivers (geophones) and there are three ways for the energy to reach the receivers; direct waves, refracted waves, and reflection waves. These three waves reach the receivers at different times where direct waves in most cases reach the receivers first due to shortest travel distance. The direct wave reaches the receivers after a time that equals the distance divided by the velocity. The time for a refracted wave to reach the receivers is the time spent below the interfaces, the time it takes to go from the ground down to the interface and back up again. Using a time-distance diagram it is possible to calculate the different velocities of the layers, where changes in the slope of the line indicate a new velocity and thus layer.

Layer`s composition is determined by the velocity of waves. By calculating the velocity of the refracted wave, it is possible to determine the composition of the layer, mainly by comparing the calculated seismic velocities for the P- and S- wave to known P- and S-wave velocities in different geological materials. This is the basic theory of seismic refraction. This method can also be used in more complex situations with several interfaces, tilted interfaces and undulating interfaces. (Telford et al., 1990)

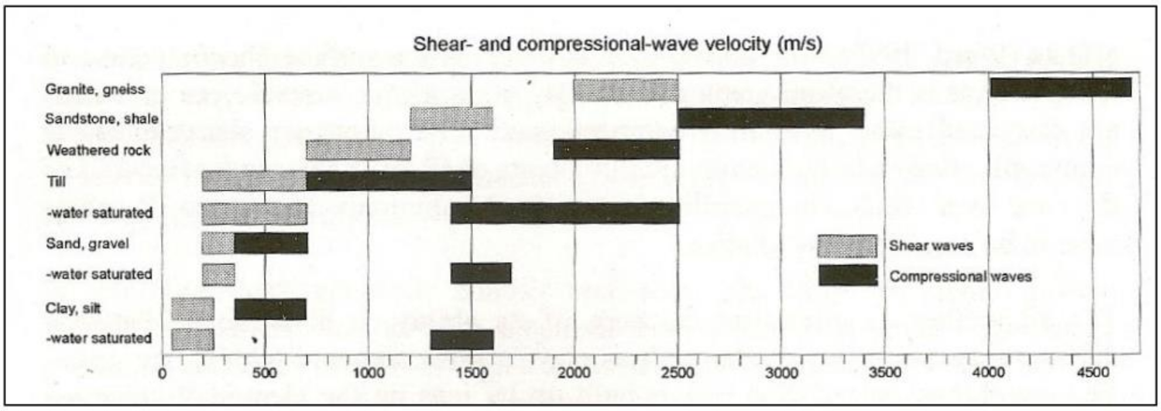

Figure 2.5: Typical seismic velocities for P-wave and S-wave in different geological material. (Telford et al., 1990)

There are several different kinds of seismic waves, and they all move in different ways. Specially, the two type of seismic waves are body wave and surface wave. Body waves propagate through the volume of the earth, but surface waves can only move along the surface of the earth. Typically, earthquake radiate seismic energy both body and surface waves. The velocities of the P-wave depend on different material parameters such as density, porosity, the elastic module, water content, rock type and how weathered the rock. For example, seismic waves propagate with a higher velocity in a more consolidated soil compared to a light soil due to the higher density in the consolidated soil. The seismic velocity also varies in the same rock due to, for example, the variability of quality of the mass of the rock (Mussett et al., 2000). The S-wave velocity also varies depending on the soil type, the effective strain level, and the pore number. The propagation velocities of seismic waves through different types of geological media are given in Table 2.1. The seismic wave propagation velocity varies from 100 m/s on the horizontal humus terrain to 6800 m/s in the marble.

Table 2.1: Typical propagation velocities of seismic wave through different types of geological media. (Gurvich, 1972)

MEDIUM	Velocity (m/s) min	Velocity (m/s) max
Air depending on temperature	310	360
Weather soil horizon	100	500
Gravel, dray sand	100	600
Loam	300	900
Wet sand	200	1800
Clay	1200	2500
Water depending on temperature	1430	1590
Sandstone friable	1500	2500
Sandstone dense	1800	4000
Chalk	1800	3500
Limestone	2500	6000
Marl	2000	3500
Gypsum	4500	3500
Ice	3100	4200
Granite	4000	5700
Metamorphosed rock	4500	6800

The velocity of the P-wave can be described as a function of

$$V_p = \sqrt{((\lambda + 2\mu)/\rho)} \quad (2.1)$$

The velocity of the S-wave can be described as

$$V_s = \sqrt{(\mu / \rho)} \quad (2.2)$$

Where λ = wavelength

μ = rigidity constant for the material where the wave spreads

ρ = the density of the material

As mentioned earlier, the S-wave can only move in solid material, as liquids and non- solid materials has a rigidity constant close to or zero, and with zero in the velocity formula the S-wave velocity becomes zero. The velocity of the P-wave is, unlike S-wave, also dependent of the wavelength and can therefore travel through any material (Dahlin et al., 2001).

Also, the vertical resolution is dependent on the different wave types, concluded in (Barton, 2007) under all conditions, shear-waves penetrated with less attenuation than compression-waves, also being unaffected by water saturation". The explanation for the better vertical resolution offered by shear-waves compared to compression-waves, especially in shallow unconsolidated sediments, are that shear-waves velocities in such case only are about half of the P-waves velocities. In this case, there is a very small wavelength, even though the dominant frequency of S-wave data generally is lower than the P-wave data. Therefore, to achieve the same resolution with P-waves, a very high frequency pulse should be generated, which inconveniently will make the lower seismic layers more attenuated.

2.5.1 Body Wave

Body wave travel from the focus of the earth and travel underground. These waves are of a higher frequency than surface waves. Body waves are transmitted through the interior of the earth, the medium of the wave, and consist of compressional waves (P waves) and shear waves (S waves) as shown in figure 2.6 and 2.7. The particle motion of compressional waves is parallel to the motion of the wave itself, causing dilatation and compression of elementary volume particles. The fastest traveling of all seismic waves is the compressional or pressure or primary wave (P-wave). The particle motion of P-waves is extension (dilation) and compression along the propagating direction. P-waves travel through all media that support seismic waves; air waves or noise in gasses, including the atmosphere, are P-waves. Compressional waves in fluids, e.g. water and air, are commonly referred to as acoustic waves. (US Army Corps of Engineers, 1995)

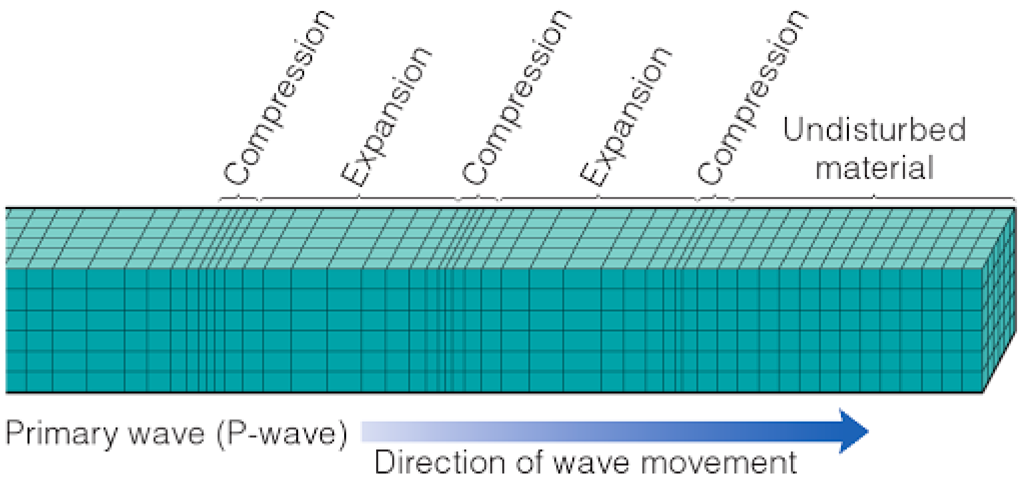

Figure 2.6 : Particle motion associated with compressional waves. (James, 2014)

The particle motion associated with shear waves is perpendicular to the direction of wave propagation and has therefore both a vertical (S_V) and a horizontal (S_H) component. The transverse particle motion causes shear deformations of volume elements within the medium (Aki Keiiti, 1980).

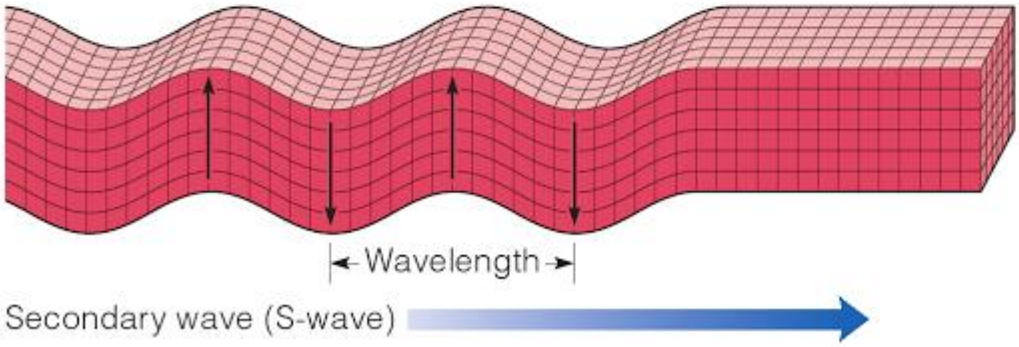

Figure 2.7: Particle motion associated with shear waves. (James, 2014)

2.5.2 Surface wave

Surface waves propagate along the interface between two different media, such as along the surface of the earth. There are two types of surface waves of main interest for engineering purposes; Rayleigh waves and Love waves. (L.Kramer 1996). Rayleigh waves result from the interaction of P waves and SV waves with the surface of the earth (Aki Keiiti. 1980). The particle motion of Rayleigh waves has both a vertical and a horizontal component and is reminiscent of rolling ocean waves, as shown in Figure 2.8. The wave motion is retrograde (anticlockwise) closest to the surface, but becomes prograde (clockwise) at greater depths.