Seismic Based Geophysical Engineering Study of Jand Area for Site Characterization

&

Development of a Seismic Engineering Parameters Computation Software

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(2016-2020)

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This dissertation submitted by **SANA KAYANI** D/O **SULTAN SHABIR** is accepted in its present form by the Department of Earth Sciences, Quaid-i-Azam University Islamabad as satisfying the requirement for the award of BS degree in Geophysics.

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<u>Dedications</u>

Dedicated to

My Father for earning an honest living for us and for supporting and encouraging me to believe in myself

My Mother for her sacrifices during my study, a gentle soul who taught me to trust in Allah & believe in hard work,

My Teachers & My Friends.

Acknowledgements

First of all thanks to Almighty Allah**,** the most cordial and sympathy whose great loving care and blessing always enabled us to perceive and pursue most difficult target of life. All respects are for the Holy Prophet Hazrat Mohammad (S.A.W) who is forever a beacon of guidance and knowledge for humanity as a whole and enable us to recognize our creator. He is forever a model of guidance and knowledge for the whole mankind.

This work would not have been possible without the help I received from many people involved with this project. First and foremost among them is my supervisor Dr. Gulraiz Akhter. His guidance throughout this Endeavor was essential to its success from start to finish.

And very special thanks to my advisor Dr. Khalid Amin Khan, Oil & Gas Development Company Ltd, for his continuous guidance and appreciation. His help and direction provided me a framework that aided the progress towards my goal.

I wish to express my deep gratitude for my friends Amber Latif and Usama Bin Younas with whom I spent the best days of my life and which were a continuous source of encouragement and moral support for me.

Sana Kayani.

Abstract

Geophysical Engineering is becoming more and more important due to the demand for construction of large civil infrastructure. The variations in the near surface layers need to be mapped before the construction of any heavy industrial zone or highway. In addition varying thicknesses and velocities of near-surface layers cause serious problems for seismic reflection imaging of the deeper subsurface. Seismic Refraction and Uphole Logging Survey is carried out in Jand area to map the near surface layers and estimate their velocities. This information is used to derive elastic properties, geophysical engineering properties and seismic characterization of the area. These properties give an estimate of the strength of Soil/Rock in the study area are used to identify suitable zones in the area for Civil Engineering works and construction of industrial sites. Contour maps of all important parameters; elastic moduli, soil amplification factor, soil fundamental period, allowable bearing pressure, standard penetration test, average horizontal spectral amplification are used for seismic characterization of the study area. In addition the near surface data is also used to compute Static corrections that can be applied to seismic reflection data for deep imaging of the Earth. The processing and interpretation of the data is performed on a highly interactive software, K-tron SeiRA along with Visual Oil Scripts and Surfer.

As part of thesis work a Geophysical Engineering parameters computation software application has been developed, which efficiently computes all engineering and seismicity parameters from the near surface model and generates contour maps of any parameters on the fly. This application generates quick visualisation of all parameters for efficient interpretation and engineering decisions.

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Chapter 1

Introduction

Geophysics has a significant impact on the welfare of the society and the planet. It uses the methods of Physics to give a picture of interior of Earth. Exploration geophysics has helped us to find the energy sources that have driven much of the social and economic advances over the last century. Now those techniques are being used to safeguard our natural environment.

Geophysical methods on several scales can be applied to wide range of investigations from the entire Earth or other Exploration purposes.

There is a broad division of Geophysical methods which either use natural field of Earth or by the Artificial generated input/energy.

- The Natural field Methods or the Passive Geophysical Methods are those that detect variations within the natural fields, such as; Gravity, Magnetic fields.
- The Active or Artificial field Methods are those which require an artificial energy source; such as seismic and electrical resistivity methods. The seismic method involves the generation of seismic waves and their propagation velocities and transmission paths through the subsurface are mapped to provide information on the distribution of the geological boundaries at depth.

Among these techniques, the most effective and the mostly adopted method for deep imaging of the Earth is the Seismic Technique. Table 1.1 gives a summary of Geophysical methods and their measured properties that can be used as a contrast to delineate different geologic formations (Kearey, 2002).

Seismic technique is the most widely used technique among all the geophysical techniques. *Reflection seismic method* provides fine structural detail at higher depths and *Refraction seismic method* provide precise estimates of near surface layers.

1.1 Seismic Method

The word "Seismic" refers to the vibrations from the Earth. It includes both the earthquakes and the sound waves that penetrate well through the Earth. They have limited utilization due to high cost and difficulty of acquiring seismic data in highly faulted areas. However shallow seismic surveys employ less expensive sources and smaller surveys then are typical of regional surveys.

The seismic method has three principle applications:

Delineation for near-surface geology for engineering studies, coal, and mineral exploration within a depth of up to 1km. The seismic method applied to the near- surface studies is known as *engineering seismology*.

Hydrocarbon exploration and development within a depth of up to 10 Km: The seismic method applied to the exploration and development of oil and gas fields is known as *exploration seismology*.

Investigation of the earth's crustal structure within a depth of up to 100 Km. The seismic method applied to the crustal and earthquake studies is known as *earthquake seismology* (Yilmaz, 2001).

1.2 Seismic Reflection Method

The Reflection seismic method provides deep structural image of the subsurface. It is mainly used to identify structural and stratigraphic petroleum traps. In addition it can also be used for exploration of minerals and coal. Modern seismic reflection techniques also provide details about the lithology, porosity, type of fluids and their saturations.

1.3 Seismic Refraction Method

Seismic Refraction is a near-surface geophysical method that utilizes the refraction of seismic waves, to delineate shallow geology layers and rock units to characterize the subsurface geologic conditions. The method involves a geophysical principal governed by Snell's Law. The seismic Refraction method is based on the measurement of the travel times of refracted waves refracted at the interfaces between subsurface layers of differing velocities (Coffeen, 1986.).

The seismic signal is introduced into the subsurface via a shot point explosives, hammer blow, dropped wave or an elastic wave generator (Igboekwe and Ohaegbuchu,2011).The energy generated either travels directly through the upper layer(direct arrivals), or travel down through the various layers before returning to the surface(refracted arrivals). The energy is then detected on surface at a series of receivers called geophones The signal is recorded at distances much greater than the Depth of Investigation (Igboekwe and Ohaegbuchu,2011).

A seismic refraction recorder usually consists of 24 channels each of which is connected to a geophone. The geophones are placed along a profile with variable geophone intervals. Two shots are taken at both ends of the profile, the first near geophone # 1 is called forward shooting while the second near geophone # 24 is called reverse shooting as shown in Fig 1.1 (Khan,2009). This results in two seismic monitors each with 24 seismograms (traces).

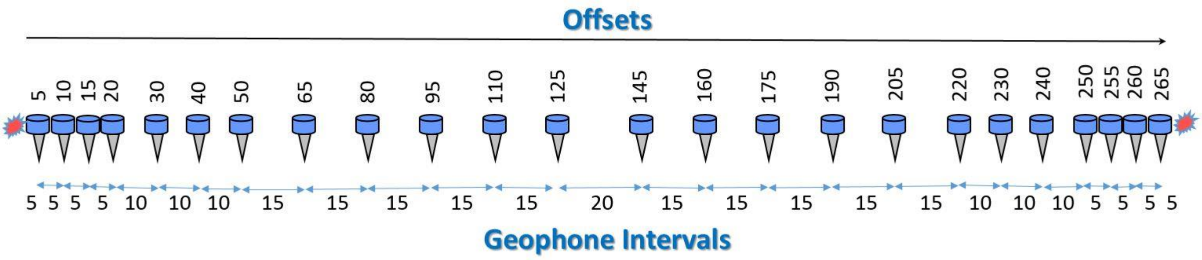


Fig 1.1. Surface Geometry for Forward Reverse Shooting

1.4 Seismic Data Acquisition

Seismic Data Acquisition is the process of generating and recording of seismic data. It involves many different receiver configurations, including laying geophones or seismometers on the surface of the Earth or sea floor, towing hydrophones behind a marine seismic vessel, suspending hydrophones vertically in the sea or placing geophones in a wellbore (as in Vertical Seismic Profiling) to record the seismic signal. A source such as the vibrator unit, dynamite shot, or an airgun generates acoustic or elastic vibrations that travel into Earth, pass through strata with different seismic responses and filtering effects, and return to the surface to be recorded as seismic data. Seismic data can be acquired as 2D,3D or 4D.

2D-Seismic

In 2D, both the source and receiver are moved along a same line. is generally used to obtain a general overview in an area as it is cheap to acquire but has imaging deficiencies.

3D-Seismic

The 3D survey involves the acquisition with In-lines and Cross-lines. It provides a 3D image of subsurface which is much easier to interpret in terms of geology. Thus complex geological structures can more easily be delineated with 3D seismic surveys.

4D-Seismic

3D time-lapse seismic survey is basically a 4D survey. Data is acquired at two or more time intervals to access changes in a producing hydrocarbon reservoir with time. Changes may be observed in fluid movement and saturation, pressure and temperature. It allows geoscientists to optimize static and dynamic models of the complex reservoir.

1.5 Introduction to Study Area

Refraction and uphole logging survey was carried out by Senshe Corporation in Jand area comprising of 100 square kilometres. The survey was carried out in January 2017, to identify sites for construction of industrial zones.

1.6 Location of Study Area

Jand lies in the eastern portion of the study area, which is present in District Attock Punjab Province. It is located at a distance of about 135 km in the south-west of Islamabad. The area comes in Northern Potwar Deformed Zone (Eastern). It is situated in Kohat Road near Jhand and in Western foothills of Himalayas. The area comes in the East of Afghanistan. Along its western side is the river Indus. Geographically it lies in Upper Indus Basin, so it consists of subsurface structures in Extensional Environments along Stratigraphic Traps.

Figure 1.2 shows the Jand study area on Pakistan Map. It has an elevation of 500 Meters AMSL and is bounded between 33.28 to 33.6 N latitudes and 71.75 to 72.1 E longitudes.

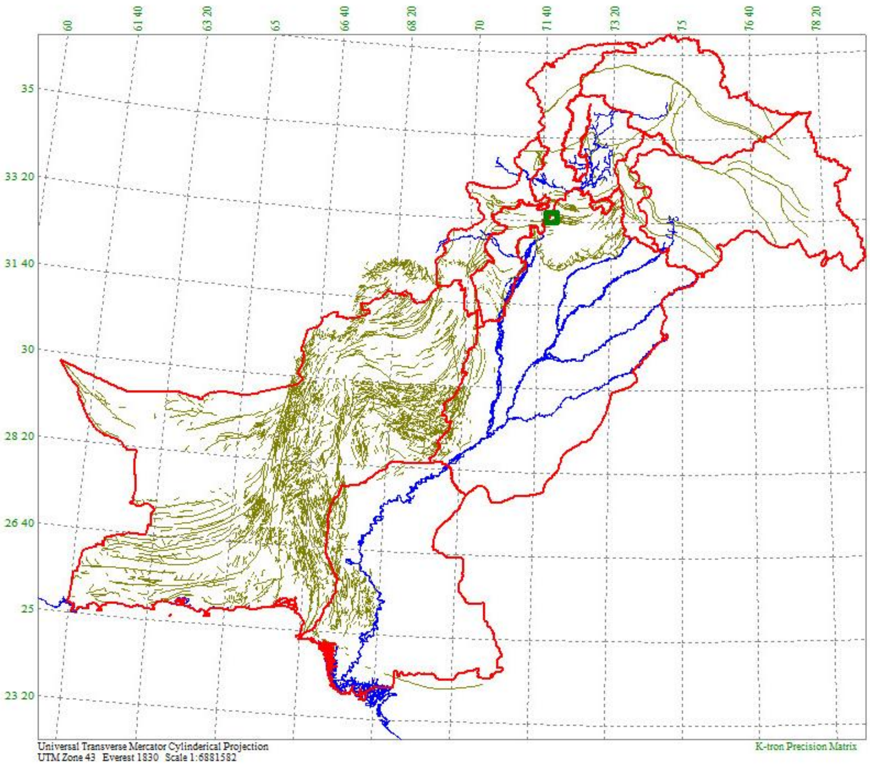


Fig 1.2. Location of study area on Pakistan Map

1.7 Base Map of Jand

A base map comprises of multiple raster and vector layers, such as satellite imagery, cultural information including roads, cities, administrative boundaries, geographic features such as topography and rivers, along with the survey data acquisition points or grid. The base map of the study area is shown in Figure 1.4. It includes satellite imagery as the background overlaid by the seismic refraction or uphole logging survey grid lines. The map has been generated in Universal Transverse Mercator Cylindrical Projection (UTM Zone 43), using Precision Matrix an Integrated Geosystem (Khan,2000).

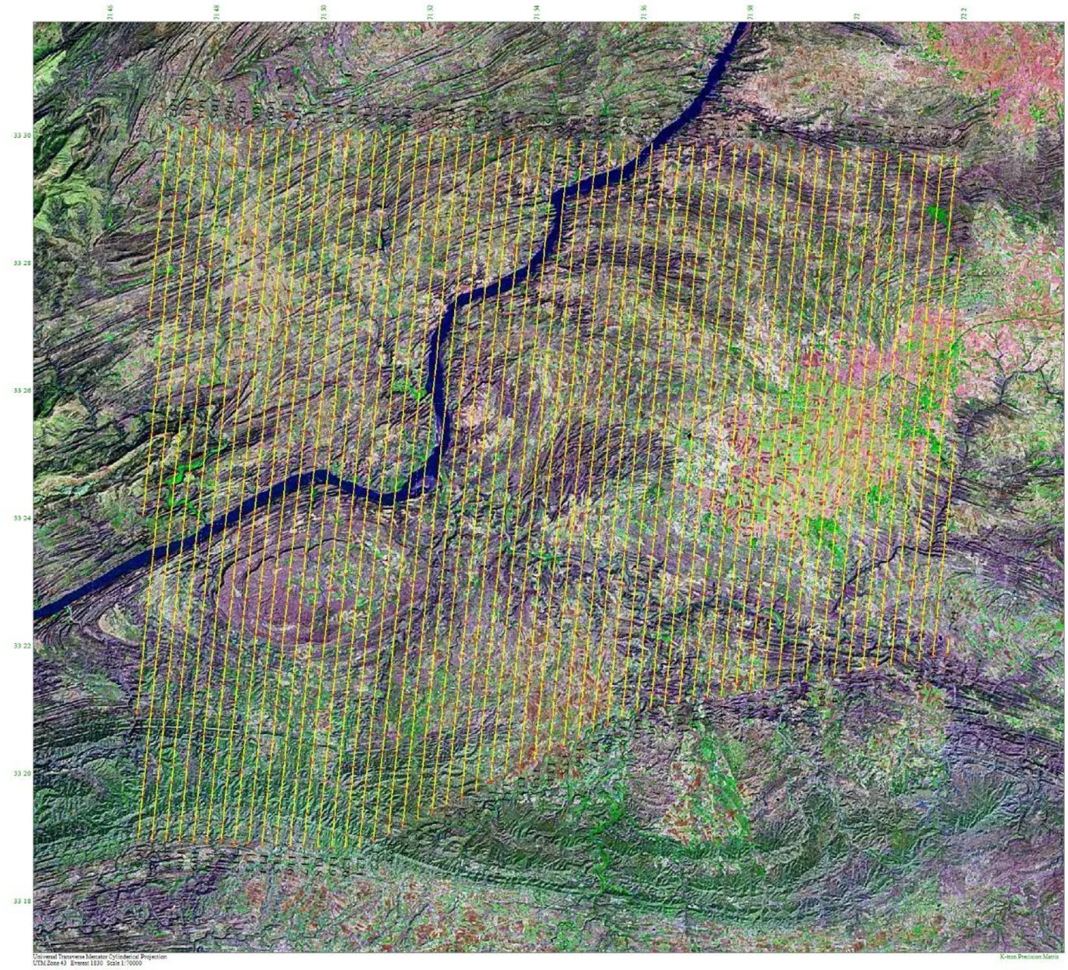


Fig 1.4**.** Base map with Satellite Imagery of the study area showing the survey grid lines.

1.7.1 Digital Elevation Model of Study Area

This is basically a digital representation of geographic information in a raster form and consists of regularly grid of elevation points and is utilized to extract terrain parameters as shown in Figure 1.5 .The Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM) (Farr,2007) and imagery are obtained from a Spatial Data Infrastructure (SDI) for Pakistan (Khan, 2012).

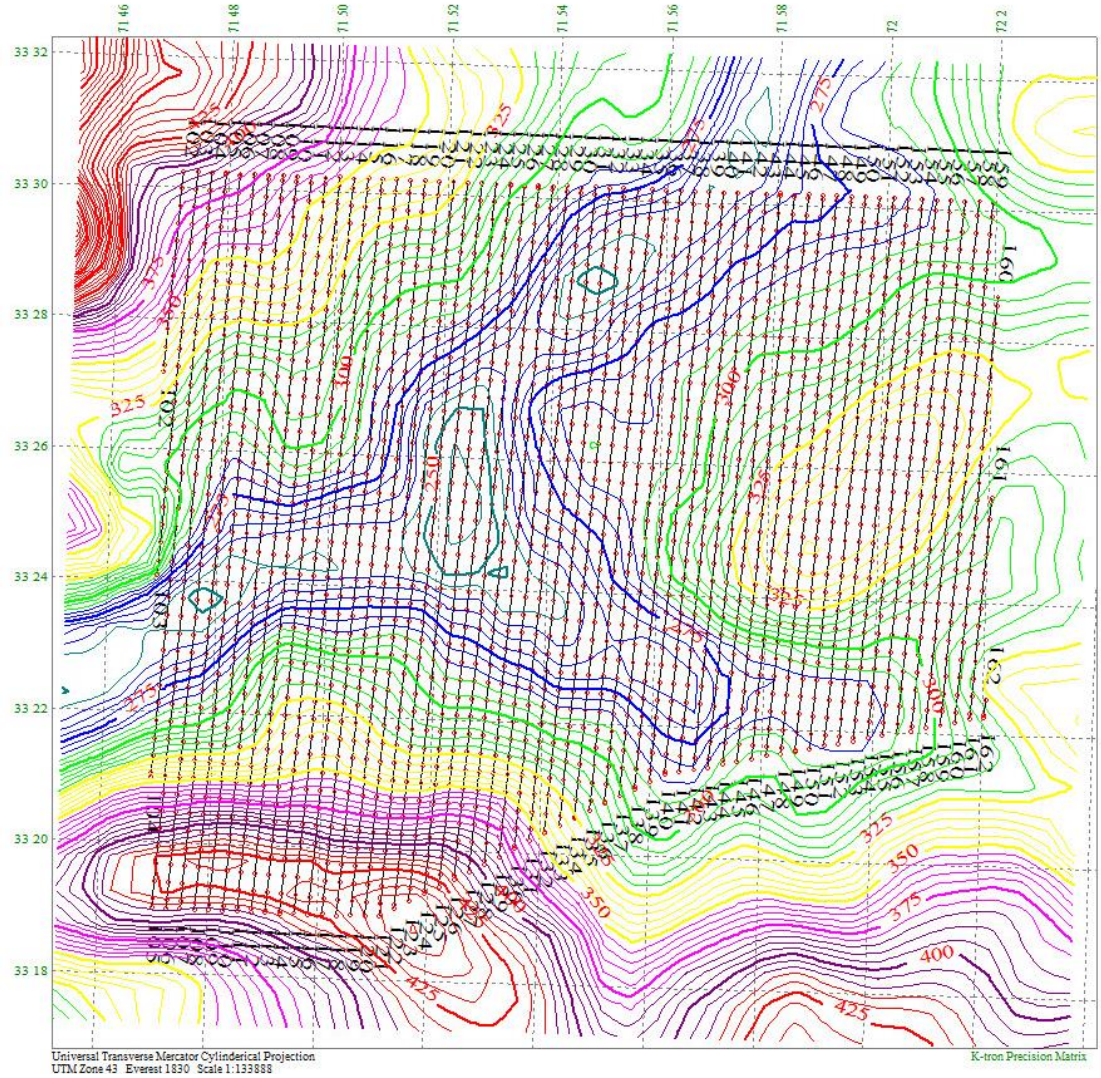


Fig 1.5. Digital Elevation Model of study area along with survey grid lines.

1.8 Survey Data

The survey data is obtained from SENSHE Corporation. It includes Seismic Refraction forward-reverse shooting as well as Uphole Logging datasets.

1.8.1 Uphole Logging

In an area of 100 square kilometres, uphole logging has been carried out at 86 points. The circular uphole geometry for the survey is shown in Figure 1.6. The geophone offsets are 1, 2 and 3 meters and the total hole depth is 70 meters with 20 shots per hole.

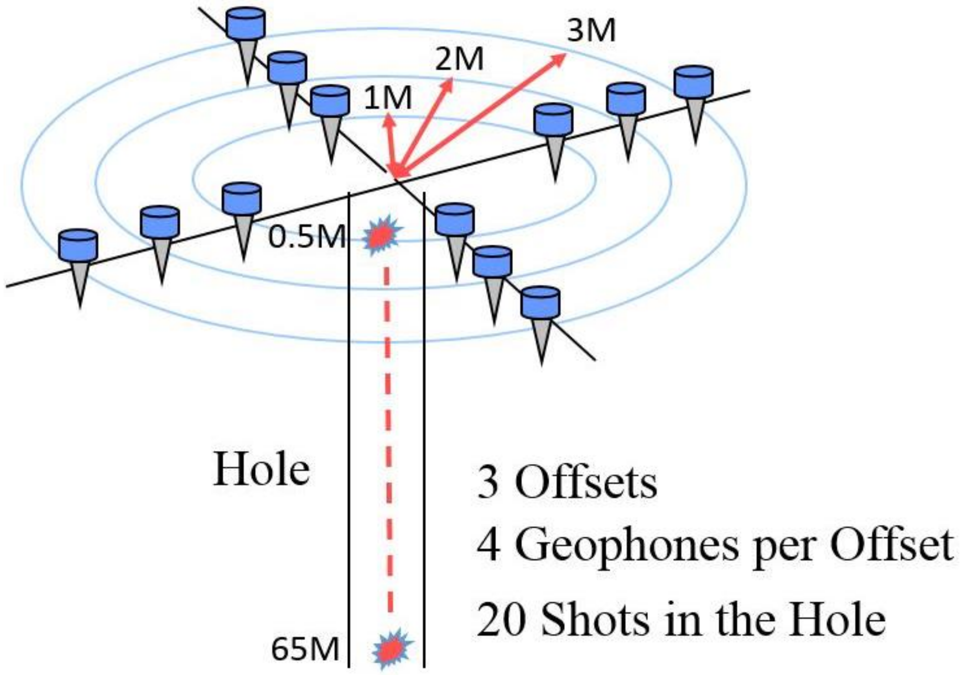


Fig 1.6. Uphole Circular Geometry Layout.

The survey datasets along with their formats are given in Table 1.1 while the uphole parameters are summarized in Table 1.2.

Table 1.1 Data Formats

DATA TYPE	FORMAT
Seismic Refraction Data	SEG-2 Format
Navigation Data	SPS and DBO format
Depth Files	DPT format

Table 1.2 Project Uphole Parameter

Geometry	Circular Shaped
Minimum Offset	1 meter
Maximum Offset	3 meters
Recording Depth	65 meters

Depth of Hole	70 meters
No of Detonators	20
Sample Rate	0.125ms
Record Length	100ms
No of Recorders	12
Source Pickets	86
Geophone	4.5 Hz

1.8.2 Surface Shooting

Surface Shooting was done at 6 Refraction Picket with Forward / Reverse shooting having a spread of 250m and an offset of 12m.

1.9 Software Applications

Once the data is obtained, the next step is to load and process the data with the help of specialized software applications.

The software applications used in the thesis work are listed below:

K-tron Precision Matrix

It is a geodetic transformations and GIS Mapping application and therefore used to generate all types of maps.

K-tron SeiRA (Seismic Refraction Analysis)

It is a software package comprising of three applications which offer many interactive tools and processing modules for first break picking, time-distance graphs and statics computations. It works under the Integrated Geosystems (IGS) environment. Its three applications are briefly discussed below:

AutoPick

It loads the seismic data (SEG-2) and picks first breaks.

Refract

It uses the picked arrival times and performs travel time inversion through the Time-Distance (T-X) graph which gives the weathered layer velocity (Vo), sub-weathered layer velocity (V1) and weathered layer thickness (ho).

StatCalc

It creates the near surface model using gridding and then computes statics.

K-tron Visual OIL

OIL (Output Input Language) is a data formatting language (Khan et al., 2010). It is used to export the Elevation, Velocity & Thickness data from SeiRA to Surfer for gridding and contouring. In addition all engineering and seismicity parameters have been computed using Visual OIL scripts.

Golden Software Surfer

Surfer is the standard gridding and contouring package and therefore it is used to generate contour maps of all parameters computed in the workflow.

Chapter 2

General Geology and Stratigraphy

2.1 Geology and Tectonics of Pakistan

Geology is the science concerned with solid Earth, the rocks of which it is composed, and the processes by which they change over time. Rather than Earth's history, in present times, it is important for mineral and hydrocarbon exploration. It also has a key role in the interpretation of the seismic data as different velocity effects can be generated from same lithological horizons depending on their position and depth in the subsurface. The information about location of faults, their penetration pattern in subsurface and unconformities between rocks of different ages is also very essential for interpretation.

Pakistan is a large country with great variety of environments and complex field logistics. Geoscientific research during the past two decades has established Pakistan as one of the most fascinating parts of the globe. A collision mountain belt comprising the Himalaya, Karakoram and Hindukush Ranges forms its Northern part. Pakistan covers an area of about 803,940 out of which the land area is about 796,096 square kilometres. Pakistan lies on a recognized high seismic belt bordering various active plates, characterized by its seismic instability. It has been source of a number of destructive Earthquakes. Indian plate collision with Eurasian plate which started 30-40 million years ago has produced variety of active fold and thrust wedges in Pakistan. A large part of Pakistan is very active and several neotectonics features have been mapped (Kazmi and Jan, 1997).

2.2 Tectonic Plates of Pakistan

The geological setting of Pakistan in modern concept of plate tectonics, is rare and matchless in the world. Pakistan is unique as it overlaps both with the Indian (Gondwanaland) and Eurasian tectonic plates as shown in Figure 2.1. The south-eastern part of Pakistan belongs to Gondwanian domain and is sustained by the Indo-Pakistan crustal plate. The northern most and western regions of Pakistan fall in Tethyan domain and present a complicated geology and complex crustal structure. In Pakistan, Sindh and Punjab provinces lie on north-western corner of Indian plate while Balochistan and most of Khyber-Pakhtunkhwa lie within the Eurasian plate which mainly comprises the Iranian plate, some part of Middle East and central Asia along the edge of the Indian plate and hence result in violent Earthquakes where the two tectonic plates collide.

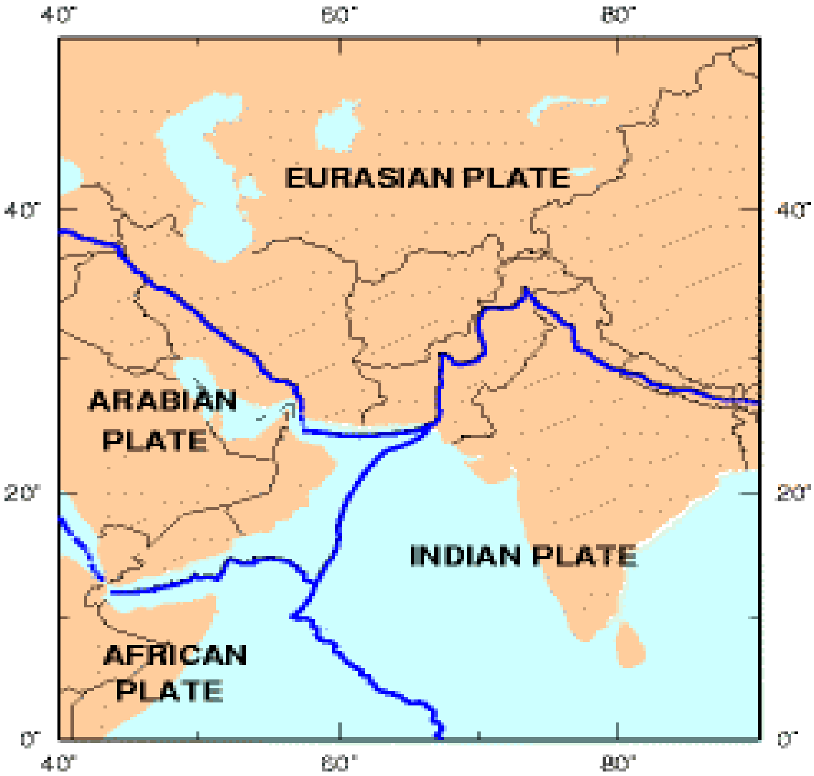


Fig 2.1. Tectonic plates of Pakistan.

2.3 Basins of Pakistan

Basin is an area characterized by regional subsidence in which sediments are preserved for the longer period of time. The main basin in Pakistan is Indus Basin, which is divided into number of regimes i.e., compression regime at foreland margins, basement uplift in Central Indus basin and extensional regime in Lower Indus basin (Kadri ,1995).

The basins and their subdivision includes the following:

1. Indus Basin
    - Upper Indus Basin
        - Kohat Sub-basin
        - Potwar Sub-basin
    - Lower Indus Basin
        - Central Indus Basin
        - Southern Indus Basin
2. Balochistan Basin

3. Kakar Khorasan Basin

In addition to these two major basins, prodder basins are also recognized which are Peshawar basin and Campbellpur basin.

Indus and Balochistan basins are separated by Ornach-Nal transform fault zone. A variety of sub-basins, fold belts and monoclines with variable structural styles resulting from diverse geodynamic conditions have been identified in Balochistan and Indus basin (Kadri ,1995).

Since our project area lies in Indus Basin", so it is customary to discuss it here.

2.4 Indus Basin

This is the largest and thoroughly studied basin of Pakistan. With the trend of NE-SW for 1600 km along its axis and having a considerable width of average 300km, it covers an area of 533,500 km^2.

Indus basin is classified into the following basins:

Upper Indus Basin.

Lower Indus Basin.

2.4.1 Upper Indus Basin

This basin is located in the Northern Pakistan and is separated from the Lower Indus Basin by Sargodha High. The Northern and Eastern boundaries coincide with the Main Boundary Thrust (MBT) eastern most of major Himalayan thrusts. The MBT runs through the Margalla hills, Kala Chitta and Kohat ranges. Western boundary of the basin is marked by an uplift of pre-Eocene sediments and Eastward directed thrusting to the west of Bannu (Kadri ,1995).

This basin is further classified into

- Potwar sub-basin in the East.
- Kohat sub-basin in the West.
-

2.4.1.1 Potwar Sub-basin

Potwar sub-basin preserves the sediments from Precambrian to Quaternary age in the subsurface and all of these areas exposed in the Salt Range a southern most thrust. The Trans Indus Ranges in the South of Kohat sub-basin exposed sediments from Cambrian to Pliocene age. Regardless of the small size of the Kohat and Potwar sub-basin, they depict facies variation (Khan et al., 1986).

Here mostly the productive reservoirs are Eocene and Palaeocene carbonates albeit recent targets are some deeper in Permian formation zones.

The Potwar is surrounded by Kalachitta ranges and Margalla hills, The Indus river and Kohat plateau to the west, and the Jhelum river and the Hazara Kashmir syntaxes to the East. Both Kohat and Potwar sub-basin are characterized by an unconformity between Cambrian and Permian. Mesozoic sediments are also exposed around the basin rim. However, this presence is governed by pre-Palaeocene erosion which progressively cut into older sequence from the Trans Indus ranges in the West to East Potwar to Salt Range.

2.4.1.1.1 Structural style and tectonics of Potwar basin

Potwar plateau is covered by Siwalik sequence in large scale, although at some places upper Eocene shales and Limestone occurs locally in folded outliers. The Soan syncline divides the Potwar Basin into two major zones as Northern Potwar Deformed Zone (NPDZ) and Southern Potwar Platform Zone (Khawar, et al , 2012). NPDZ is more intensely deformed. It is characterized by East-West tight and complex folds, overturned to the South and sheared by steep angle faults (Kazmi & Jan, 1997).

The structural style of the central, eastern and western parts of Potwar plateau shows a marked difference. In the central western parts of Potwar plateau, the deformation appears to have occurred by south-verging thrusting. While in eastern part, deformation is in NE-SW direction with tight and overturned anticlines apart by synclines. The difference may be due to less thickness of salt in Infra-Cambrian in the Eastern areas and very low dip of basement compared to Central Potwar where mainly faults are bounded by thrusts and back thrusts.

Based on the seismic interpretation, the structures in the Potwar area may be divided into following;

- Triangle zone
- Salt cored anticlines
- Snake head anticlines
- Pop-up anticlines

Structural style of Potwar Plateau is shown in Figure 2.2.

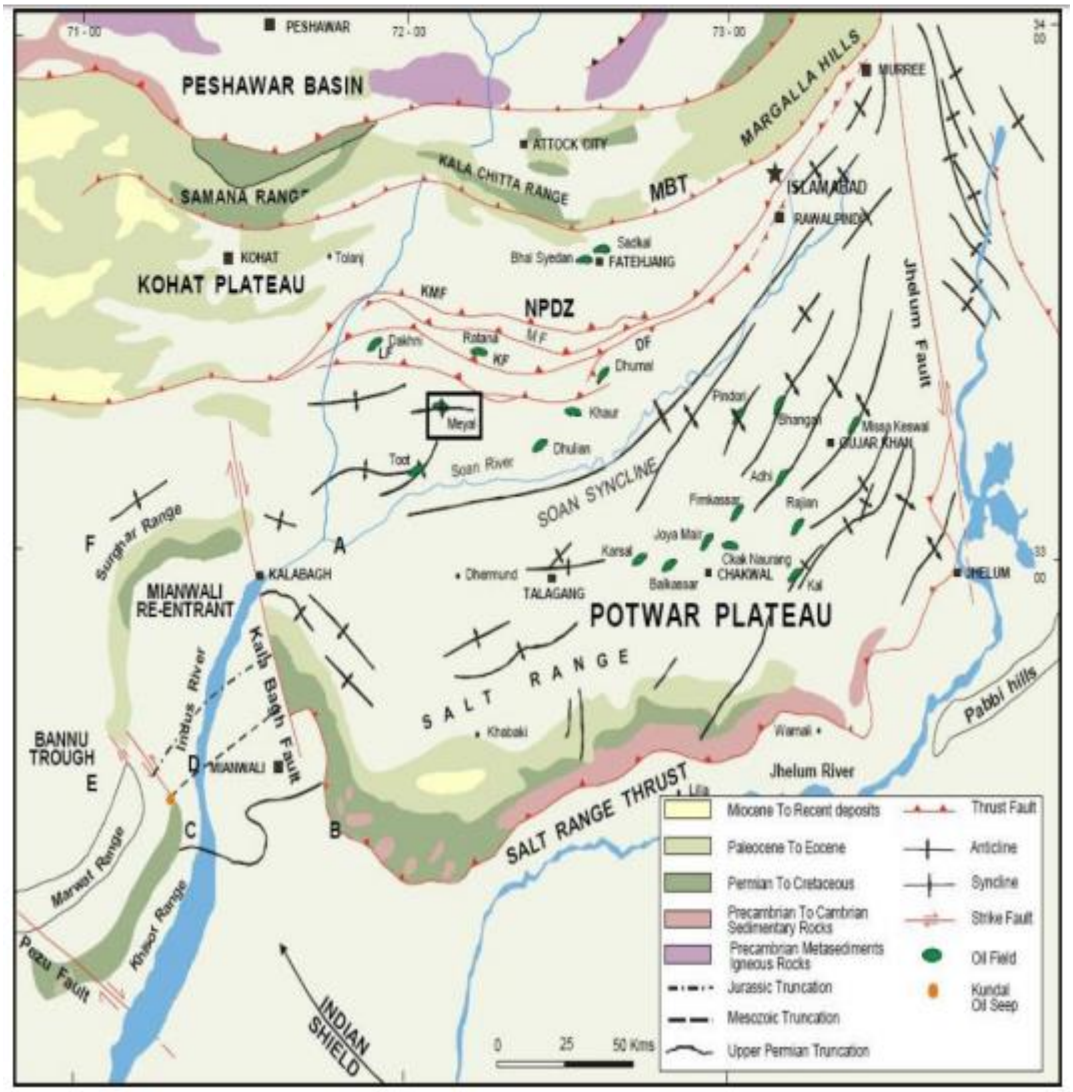


Fig 2.2. Geological and Structural map of Potwar Plateau (Ahmed et al, 2011)

2.4.1.1.2 Major Faults in Potwar Basin

It is highly deformed area and represents southern margin of Himalayan collisional zone, therefore a variety of faults and folds can be seen in the area. Some of the faults in the area are:

Khair-i-Murat Fault

Khair-i-Murat fault is a north dipping major emergent thrust in the NPDZ, along which high velocity Eocene carbonates are thrusted southward over low velocity molasses (Jadoon et al., 1995).

Kanet Fault

Kanet fault is a north dipping emergent thrust in the western part of NPDZ, developed in the direction of tectonic transport, and in the eastern part of the NPDZ. It is underthrusted beneath the DBT. KF bound the Kanet syncline from the North (Jaswal et al., 1997).

Sakhwal Fault

It is a north northeast trending backthrust which merges into the south merging Ahmadal fault in the south of the Nauthian and dies out in the Chinji formation in the north of Sakhwal, is an overstep, passive step thrust, developed in the roof sequence of Dhurnal backthrust. It cuts the surface just north of Dhurnal.

Mianwali Fault

Mianwali Fault is a high angle intraformational thrust at the surface that can be traced only in streams where good water exposure is present, on the basis of shear zones, fault breccia and secondary calcite. The rocks having steep dips are present in the area between MF and KMF and represent northern most exposure of Siwaliks (Jaswal et al., 1997).

Riwat Fault

Riwat Fault is a passive roof thrust in the south of Soan syncline in the eastern Potwar plateau, and is hinterland dipping fault rather than foreland. At its southward terminus, it dies along the southern flank of Chakbeli khan anticline and to the northeast it dies to the Soan syncline axis (Pennock et al., 1989).

2.4.1.1.3 Major Folds in Potwar Basin

Soan Syncline

Soan syncline is a broad,wide and asymmetrical that divides the Potwar Plateau into Northern Potwar deformed zone (NPDZ) and Southern Potwar deformed zone(SDPZ). Soan river marks its axis. Soan syncline developed at 2.1 to 1.8 Ma (Shaami and Baig, 2002).

Chak Naurang Anticline

Chak Naurang has two dipping limbs. These limbs are namely, southern limb which is dipping steeply while northern limb dipping moderately. Anticline is an example a fault-propagated fold. A strong northward-dipping basement reflector is there which is overlain by thick evaporite strata (Mari et al., 1999).

Mahesian Anticline

Mahesian anticline exposes Chinji Formation in its core. The fold is cut by two small faults, neither of which shows surface displacement of more than a few meters. The southern end of the fold has an overturned limb (600-750) and a moderately dipping western limb (30°-40°) (Pennock et al., 1989).

Adhi-Gungril Anticline

Adhi-Gungril Anticlines are relatively symmetrical structures. Their crustal region dips gentle. Seismic reflection data indicates the Adhi-Gungril structure is a popup bounded by reverse faults to the northwest and southeast. Adhi-5 well confirms the presence of the salt in the core of the fold at relatively shallower depth of 1516 m. (Pennock et al., 1989).

Joya Mair Anticline

Joya-Mir Anticline is a doubly plunging anticline and plunges at 10osouthwest and 4° northeast. The fold axis of anticline trends northeast-southwest and is cross-folded to form northeastsouthwest trending Joya Mair antiformal syncline. The geologic, structural, seismic and borehole data shows that the Joya Mair structure is a triangle zone in the subsurface. The Joya Mair triangle zone lies in the Southern Potwar Platform zone and is segmented along left-lateral Vairo and Dhab Kalan Faults (Shami and Baig, 2002).

Dhurnal Anticline

Dhurnal Anticline is a thrust formed anticline in a triangle zone hidden under an adjacent, foreland synclineAt Eocene level the Dhurnal structure is an east-northeast-trending popup structure bounded by forward and backward thrusts on the southeast and northwest respectively. This is also the largest producing oil field in Pakistan **(Jaswal, et al., 1997).**

2.5 Structure and Tectonics of the Study Area

The Jand study area also includes the Dakhni Oil Field. The dominant direction of stress is towards the North, with the Pre-Cambrian salt acting as a Decollment surface. Thrusting has dominated and controlled the formation of the Dakhni structure and influenced the development of the Carbonate and Sandstone reservoirs in the field. The Dakhni structure is steeply dipping anticline to the Northeast and shallow dipping anticline to the Southwest. A series of high angle Faults which have strike slip component cut across the back thrust. According to geological/geophysical data, the structure of Dakhni makes a closure of 200ms

TWT between the Time contours of 2300 and 2500 ms which means Amplitude of 350m at depth of 4025m. Approximate aerial extent is of the magnitude of 62 km^2.

The area exhibits complex tectonics. Topography represents typical bad land terrain comprising of barren cliffs as high as 100m from the plateau. Indus river follows its course from NE-SW through area. Faulting trends are in East West direction. Two synclines and an anticline has been mapped topographically. Siwaliks are exposed on the surface throughout the area expect in the Northwestern extremes where some older formations like Kuldana and Jatta Gypsum are mapped. The geological map of Dakhni area is shown in Figure 2.3

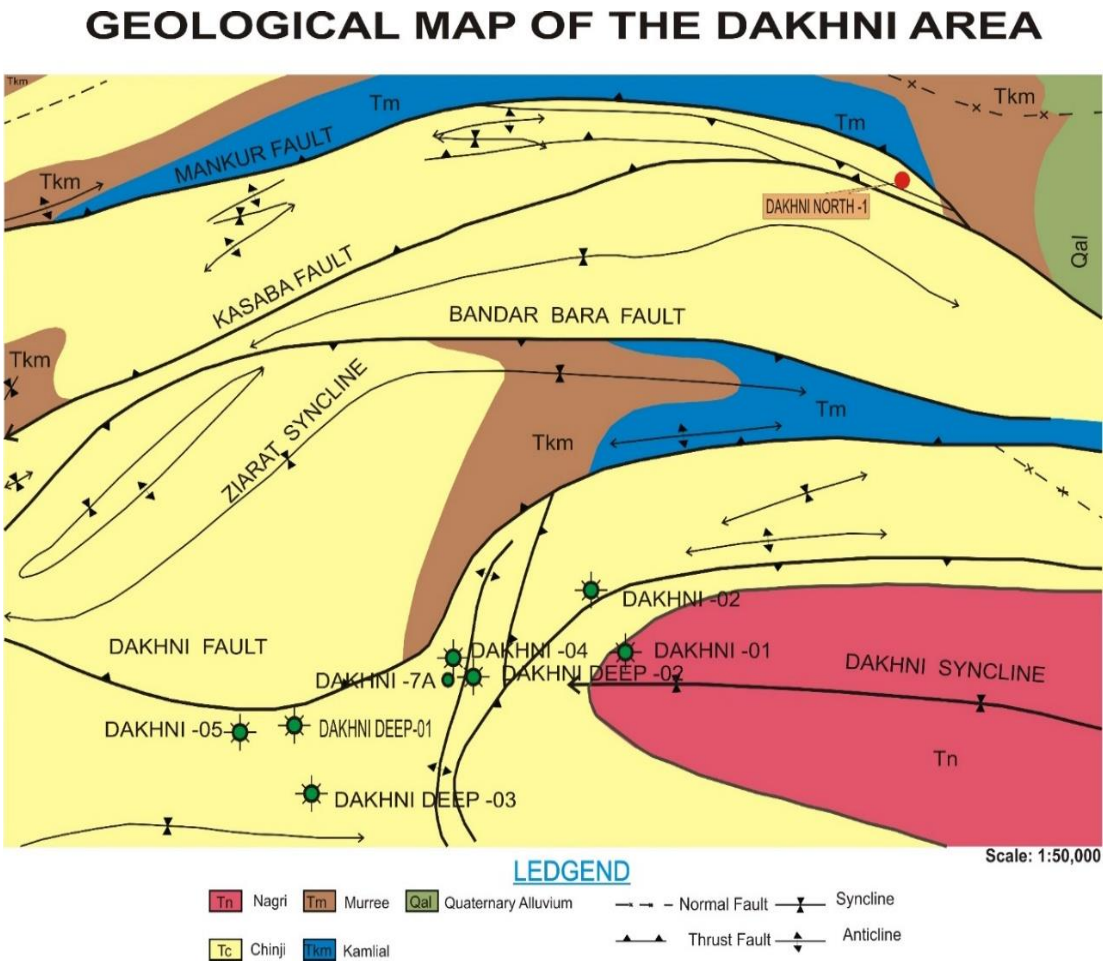


Fig 2.3. Generalized stratigraphy of Potwar sub-basin (Moghal et al., 2007).

2.6 Stratigraphy

The structural and stratigraphic study includes the outcrop of formations at different places and the oil and water wells drilled in the area. The oldest Formation of the cover sequence known to lie at the top of basement is the Eocambrian Salt Range Formation which is available as outcrop and at many places. It is also confirmed in the subsurface from the well log data. (Khawar et al., 2012) The rocks of Miocene-Pliocene age are known as Nagri Formation and Chinji Formations are exposed in the core of the structure. Here thrust tectonics plays important role (Kazmi et al., 1982).

The general stratigraphy of Potwar sub-basin is shown in Figure 2.4, while Stratigraphic column of the Potwar Basin is shown in Figure 2.5.

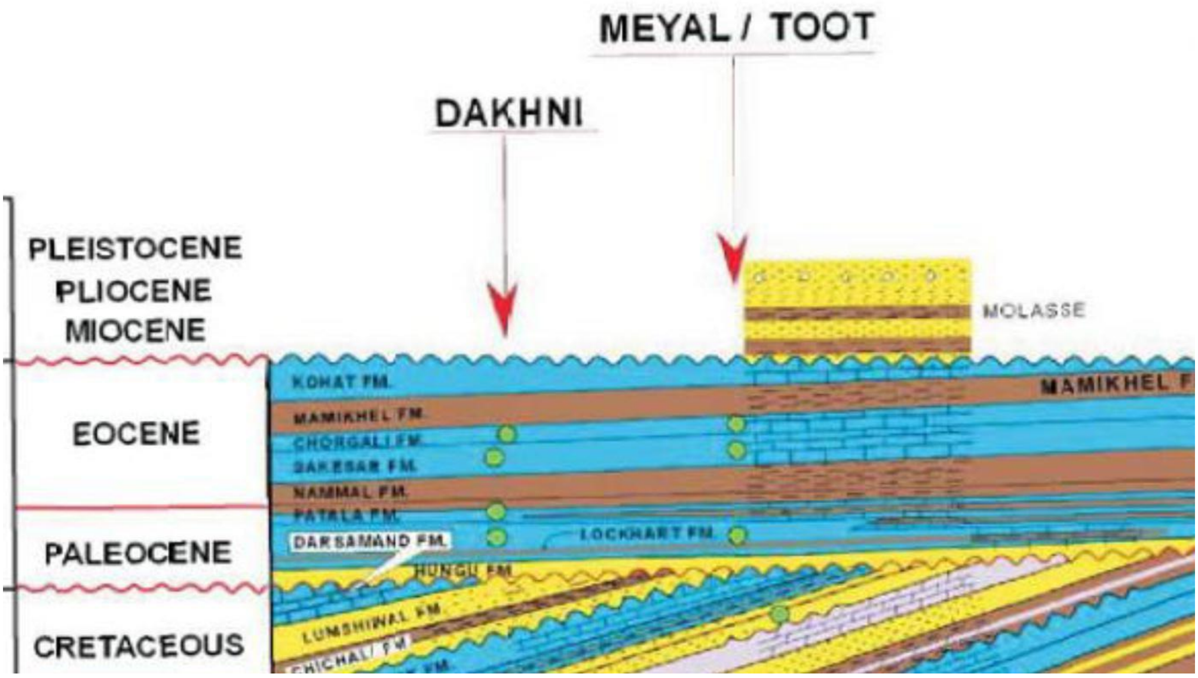


Fig 2.4. Generalized Stratigraphy of Potwar Sub-Basin (Moghal, et al., 2007)

The lithological formations are lying uncomfortably over Paleozoic formation, and the whole Mesozoic section is absent in and around the area which is the sign of unconformity. The Sakesar limestone and Chorgali Formations of Eocene age are the primary reservoirs, while Permian and Cambrian sandstones are secondary targets. The Eocene, Paleocene and Permian shales are supposed to be the potential source of oil and gas and cap rocks (Khawar et al., 2012).

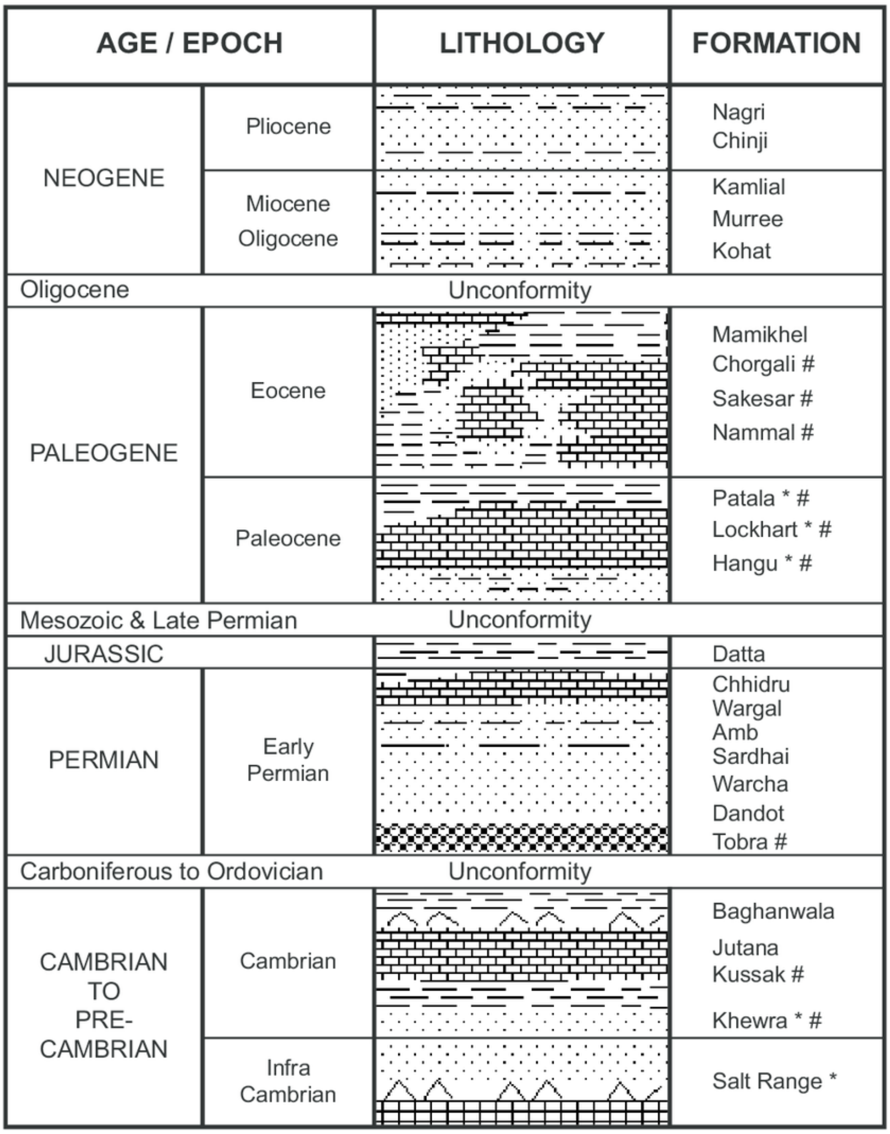


Fig 2.5. Stratigraphic column for the Potwar Basin (Wandrey et al., 2004)

2.7 Petroleum Play of Potwar and Study Area

Potwar marine facies has great potential of hydrocarbon. Previous drilling was restricted up to Eocene carbonate. Recent discoveries in Potwar result in delineation of deep subsurface crest. (Kadri, 1995). Potwar region which is traditional oil producing area of Pakistan has the average geo-thermal gradient of the order of 2ºC/100m. Hence the oil window lies between 2750-5200 meters (Kadri, 1995).

Initially, Dakhni field was producing commercial quantity of Condensates and sour gas from the Chorgali and Sakesar formations. Then Condensate and sweet gas was discovered from the Lockhart formation in Dakhni Well No 8. Later on Condensate and sweet gas were discovered from deeper horizons i.e, Datta and SamanaSuk and Shinawari formation in Dakhni deep Well No. 1, 2 , and Well No. 11 respectively.

2.8 Source and Reservoir Rocks of Potwar

The Pre Cambrian Salt range formation shales encountered non-commercial oil in wells drilled in Dhariala, Kallarkahar. Marine shales of Kussak, Jutana and Khisor formation of Cambrian has source potential for Hydrocarbons.

In Permian, Shale of Dondot and Sardhai and Limestone and Black shale of Zaluch group has source potential of oil. Triassic unit of Potwar having Khatkiara Member of Tredian Formation have good reservoir characteristic. In Jurassic the black clay and organic content of Datta and some part of Shinawri Formation are good source. Similarly Samana Suk Formation has also good reservoir characteristic. In Cretaceous Chichali Formation has good source potential due to abundant of organic material while Lumshiwal Formation is good reservoir having gas discovered in some area of Punjab Platform. In Paleocene Patala shale is major source in this region while the Paleocene reservoir is productive in all part of the Indus Basin like in Dhulian, Toot, Meyal and Missakeswal. Early Eocene carbonate are good source and reservoir rock. Sakesar and Chorgali with fractured Limestone have hydrocarbon potential in Adhi (PPL), Dhurnal (OXY), Dakhni (OGDCL), Missakeswal (OGDCL) etc. In Dhulian the Permian and Paleocene succession is quite thin. Carbonates of Chorgali and Sakesar Formations are major oil producing units in this area. Moreover the sandstone of Murree Formation also has good potential. Clay and shale of Murree Formation provides good vertical and lateral seal to these Eocene carbonates. (Geomodelling of Hydrocarbon of Potwar) (Shami & Baig, 1998).

2.9 Source Rocks

The potential source rock has the tendency to generate sufficient quantity of hydrocarbon which later can migrate to a reservoir rock (Law, 1999). As source rock is the primary element of a petroleum play therefore the determination of Kerogen type, its thermal maturity are of key importance in evaluating the hydrocarbon potential of an area (Peters and Cassa, 1994; Rodriguez and Philp, 2010). The gray shales of the Mianwali (Triassic age), Datta (Jurassaic age) and Patala Formations (Paleocene age) are potential source rocks in Salt Range Potwar-Foreland Basin (SRPFB) (Khan et al, 1986). The oil shales of the Eocambrian Salt Range Formation include 27% to 36% total organic content (TOC) in isolated pockets of shales, and are considered as the source rock in SRPFB (Shami and Baig, 2003).

2.10 Reservoir Rocks

Rocks from Infra Cambrian to Miocene in Kohat Potwar foldbelt are proved to be Petroleum play reservoirs. Clastics and carbonates of Infra and Lower Cambrian, Clastics of Permian, lower to middle Jurassic, lower Cretaceous, carbonates of Upper Paleocene and Lower Eocene and clastics of Miocene are the prey reservoirs (Government of Pakistan, 2010).

On Kohat-Potwar plateau oil and gas has been produced from the following formations (Khan et al., 1986):

- Cambrian
- Khewra Sandstone
- Kussak
- Jutana
- Permian
- Tobra
- Amb
- Wargal
- Jurassic
- Datta
- Cretaceous
- Lumshiwal
- Paleocene:
- Khairabad
- Lockhart
- Patala
- Nammal
- Eocene
- Bhadrar
- Chorgali
- Margalla hill limestone
- Miocene
- Murree Formation

Sandstone porosities range from less than 5% to 30% and in average from 12% to 16%. Permeability ranges from less than 1millidarcy (mD) to greater than 3000 mD, with an average ranging from 4 to 17 mD (Khan, et al., 1986)

2.11 Traps and Seals

Evaporite and shale have good sealing potential for Infra-Cambrian reservoir. Interbedded shale, mudstone and siltstone provide seal to Cambrian reservoirs. Limetones and intraformational shales are the potential seals for the Cenozoic and Mesozoic reservoirs. Paleocene shales (Patala Formation) and Miocene shale are the regional seals in the area (Government of Pakistan, 2010). Most of the fields discovered in Kohat-Potwar geological province to date are either due to overturned faulted anticlines, popup structures or fault-block traps. The latest trap-forming thrust event began at approximately 2 to 5 Ma (Jaswal et al., 1997). Seals include fault truncations and interbedded shales and the thick shales and clays of the Miocene and Pliocene Siwalik group (Wandrey et al., 2004).

Chapter 3

Seismic Refraction Data Processing and Interpretation

In seismic refraction surveying method the first arrivals of seismic energy are picked at different offsets which are due to direct or refracted waves. Similarly, in Uphole logging surveys the first arrivals are picked as a function of depth. These arrival times against their offsets, for both forward and reverse shooting are plotted on a time-distance graph, which in turn are used for travel time inversion to get information about velocity and depth of near surface layers.

The near surface information is used to compute engineering and seismicity parameters for characterization of zones for Civil works. In addition Statics corrections are also computed from this near surface data and then applied to seismic reflection data to remove the effect of weathered layers and elevation. These corrections are applied by reducing the data with respect to a Datum Plane.

3.1 Inroduction

After the seismic data acquisition, geophysical data processing is the most important step to derive useful subsurface information. The main purpose of seismic data processing is the analysis of recorded seismic signals to eliminate unwanted components (noise) and create an image of the subsurface to enable geological interpretation, and eventually to get an estimation of the distribution of material properties in the subsurface. In other words it removes all other effects that degrade the accuracy that is increasing signal to noise ratio, balancing amplitude of refracted waves to obtain desired results. In data, an event of interest is called signal while rest is called noise. A noise is a term used for unwanted data and it should be removed or suppressed in order to make better interpretation. Noise always results in misleading during interpretation of seismic data. Signal and noise are relative terms, in refraction methods we are interested only in first breaks while the rest of the events are of no interest, on the other hand in reflection method we are interested in reflected events from deeper horizons.

Data processing is done using the following software applications:

- K-tron SeiRA (Seismic Refraction Analysis) version 4.30
- K-tron Visual OIL (Output and Input Language)
- K-tron Precision Matrix version 4.10
- Golden Software Surfer 8 & 11

3.2 Seismic Refraction Data Processing

All Base maps have been generated using Precision Matrix, while SeiRA is the main software used for processing the seismic refraction and uphole data. A number of Visual OIL scripts are used to compute engineering and seismicity parameters from near surface information derived by SeiRA and Surfer is used to generate contour maps of all parameters. Processing flow of the above mentioned applications is shown in Figure 3.1.

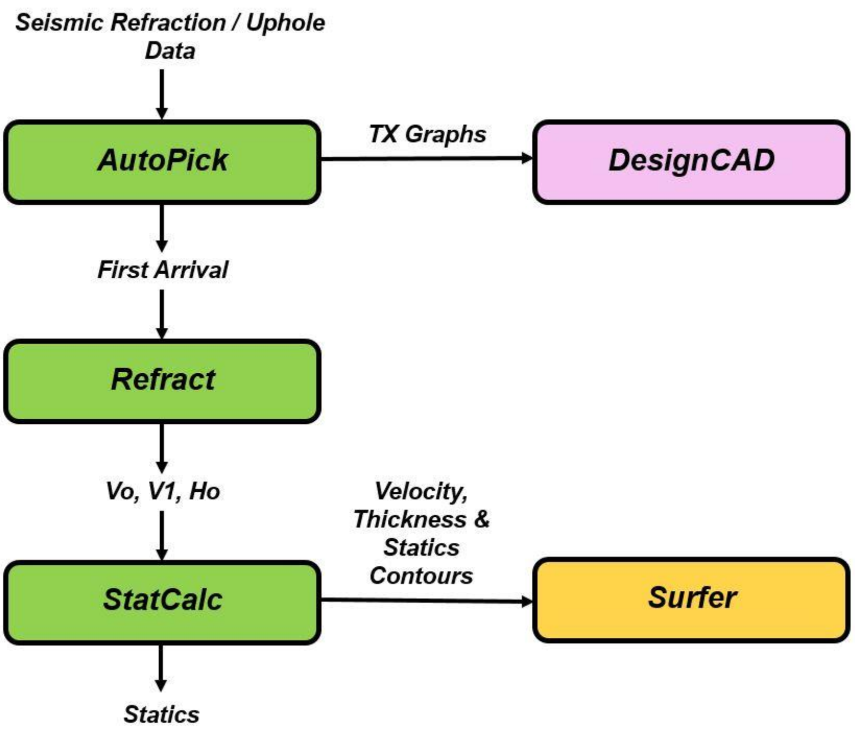


Fig 3.1. Refraction Data Processing Workflow.

3.3 Visual OIL (Output Input Language)

K-tron Visual Oil is basically a scripting language under Integrated Geo Systems base environment (IGS). It is basically a format engine used to convert data from one format into another. Basically it works as a bridge between different software applications to covert data in their required formats. Visual OIL scripts are also used for Velocity inversion to compute Engineering and Seismicity parameters. Visual OIL has a number of data type classes. For velocity inversion the "weathered layer data" class is used as shown in Figure 3.2.

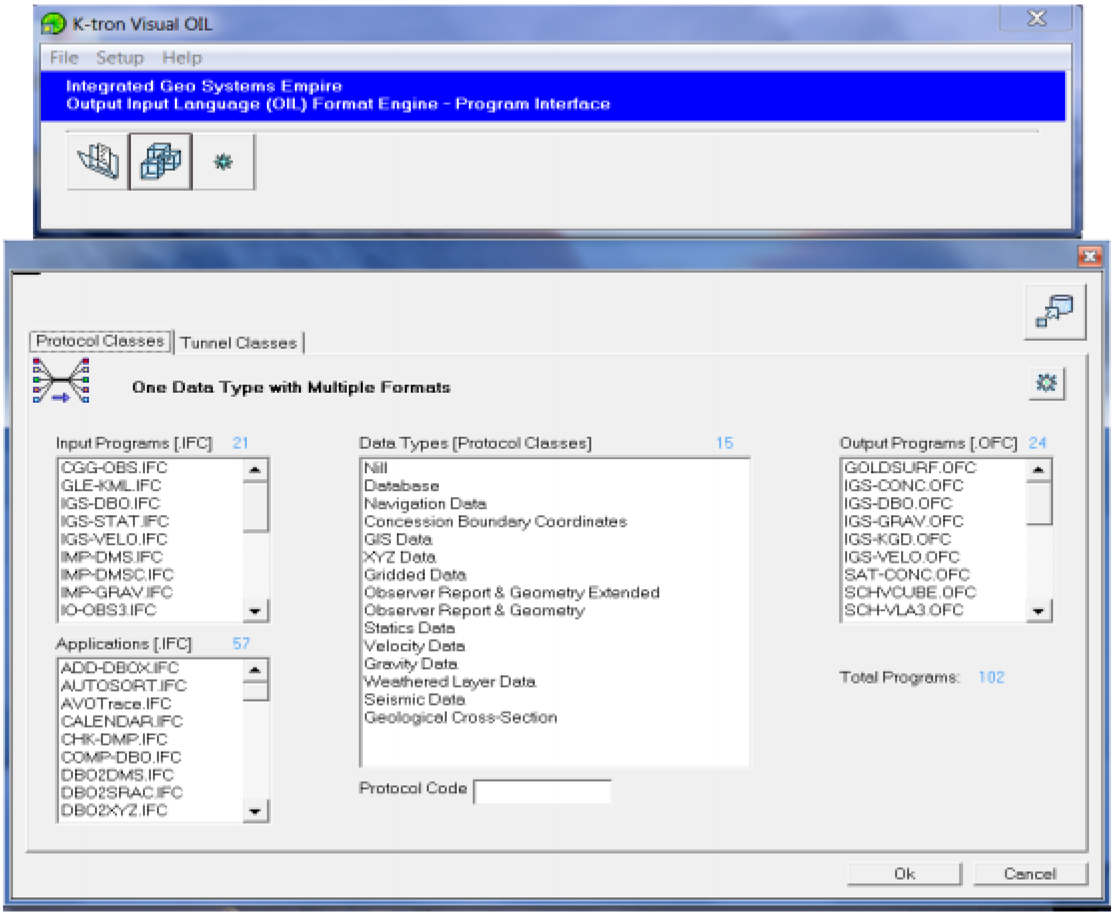


Fig 3.2. Visual OIL Data Type Classes and associated programs.

3.4 Seismic Refraction Software

SeiRA is a PC based highly integrated 2D and 3D seismic refraction and statics computation software, running under MS Windows. It is based on the latest state of the art technology, providing interactive facilities to display and edit traces, pick and QC first breaks, model refractor parameters, compute and display refraction statics and finally output the statics corrections for application to seismic reflection data. It helps in first break picking, balancing amplitude, smoothing of statics and integrated LVL and uphole project facilities . The software works under the Integrated Geo Systems (IGS) environment and is integrated with other geoscientific software applications for data connectivity. It also uses IGS E&P Workflow Data

Formatting Engine-Output Input Language (OIL) interpreter for data connectivity with any third-party software.

SeiRA has three processing applications.

- SeiRA Autopick.
- SeiRA Refract.
- SeiRA Statcalc.

3.5 First Breaks Picking

AutoPick is the very first processing tool of SeiRA which uses artificial intelligence based automated first break picking and quality control. The accuracy of static corrections largely depends on the quality of first break pick times (Khan, 2007).

It reads seismic data in industry standard SEG formats, picks arrival times automatically as well as interactively and saves them in SeiRA data files [.SRA]. The seismic data can be viewed on the screen and a number of interactive QC and manual picking tools can be applied. Several processing modules, including gains and auto-picking algorithms can be applied to the loaded data. AutoPick also has a Job Engine which allows multiple processing steps to be written in a script file and then applied to the seismic data in a single step.

After the project has been saved in AutoPick, it can also be loaded in Refract for processing the arrival times using TX graphs and finally in StatCalc for gridding and statics computation.

The software requires the following types data:

• Navigation Data (DBO format)

• Depth files (DPT format)

• Offsets files (OFS format)

• Seismic Data (SG2 format)

3.5.1 Project Manager

As the navigation data is loaded in AutoPick, a small GIS map appears in Project Manager. The Project Manager is specially designed to manage and process statics for large 2D/3D seismic surveys. A Project Manager is a system that registers all datasets involved in the project; all setup parameters and jobs used in the processing of data. It keeps track of the current processing status of the project and stores all this information in a project database [.KPM]. Loading a KPM file would provide access to all datasets involved in the project. The Project Manager with Project GIS interface displays a project map, all seismic lines, in the project, are displayed along with the refraction survey pickets (Refraction Points).

Figure 3.3 shows that Project Manager along with GIS and Data Explorer. The Project Explorer lists all the data resources; navigation, depths/offsets, seismic and arrival times. The GIS and Data Explorer provide direct access to the data. We click on GIS or on any picket in Data Explorer and the related data will be displayed.

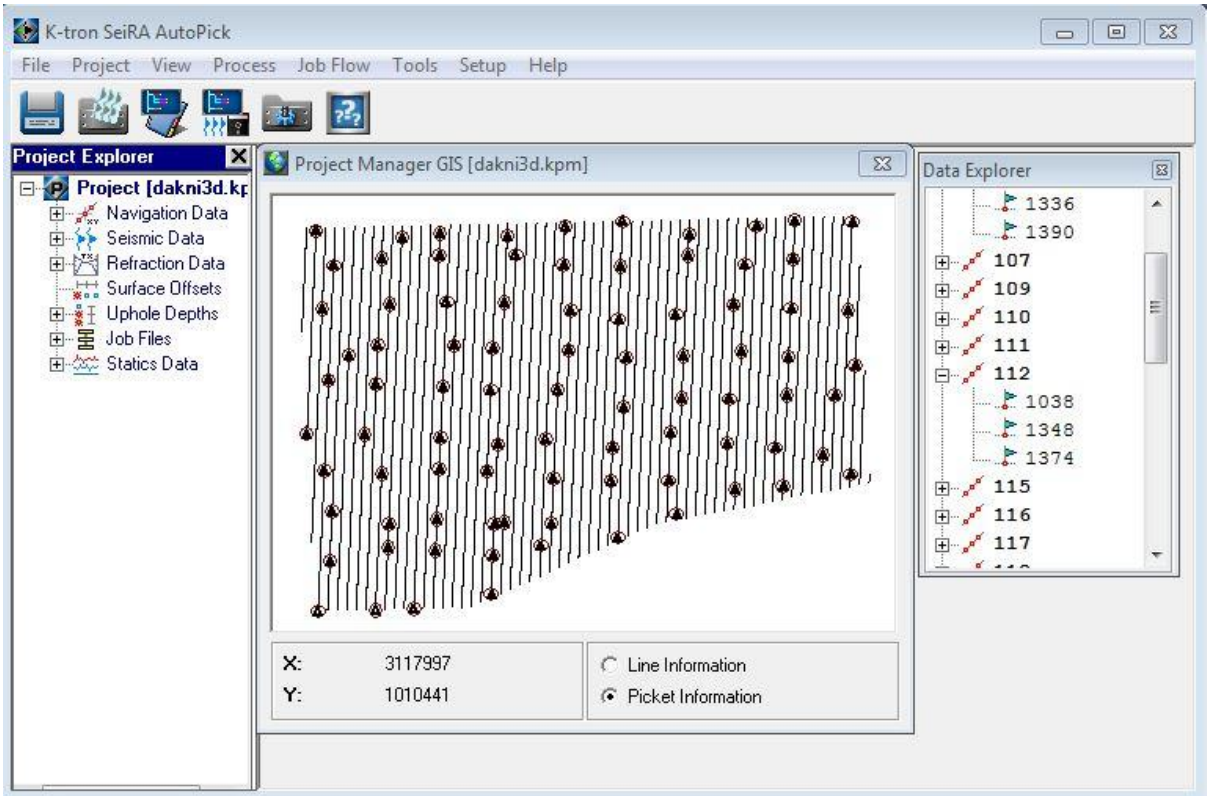


Fig 3.3. Project Manager along with Project GIS displays a project map along with Data Explorer

Seismic refraction and uphole data is loaded by consulting observer report for each refraction and uphole data point. The data for contains 86 uphole logging points each with 20 shots is loaded. The AutoPick seismic data loading and trace selection interface is shown in Figure 3.4, where the first offset with traces 1 to 4 is selected.

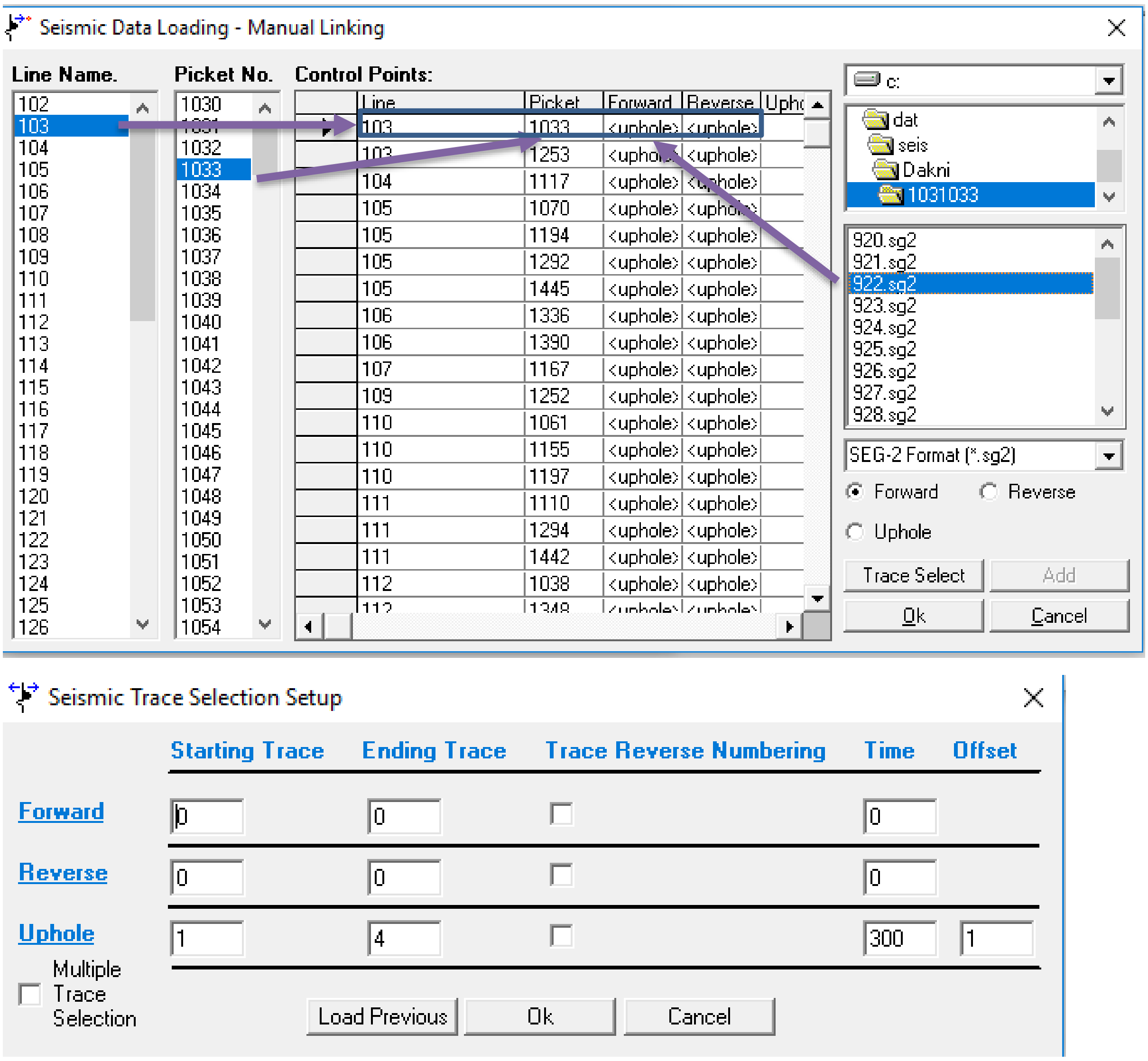


Fig 3.4. AutoPick Seismic Data Loading and Trace Selection Interface.

3.5.2 Job Based Seismic Processing

AutoPick has a Job Engine, which provides the facility to write Job scripts where multiple processing modules along with their parameters can be specified. The Job Engine executes all the processing steps in one go, providing the user and easy and efficient processing environment. A sample Job Script file contains processing steps is shown in Figure 3.5. The processing steps include; Polarity Reversal, Scale to Maximum Gain, Automated Picking and again Polarity Reversal. Figures 3.6 and 3.7 respectively show the interfaces of ScaleMax and AutoPick-Square Wave processing modules.

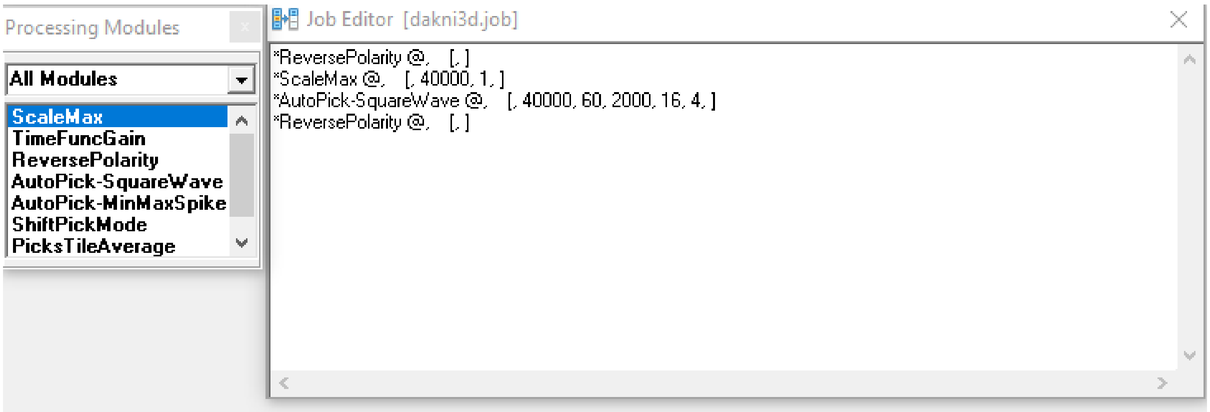


Fig 3.5. Job Script with Four Processing Modules in Job Editor.

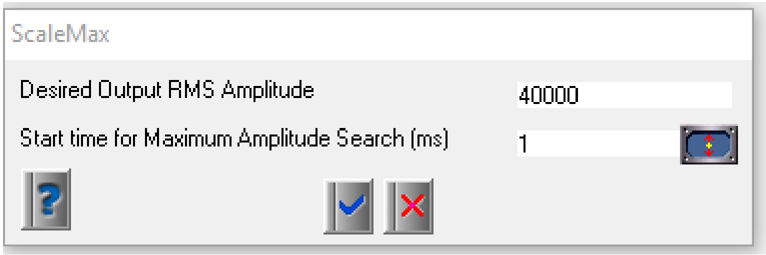


Fig 3.6. ScaleMax Setup Parameters

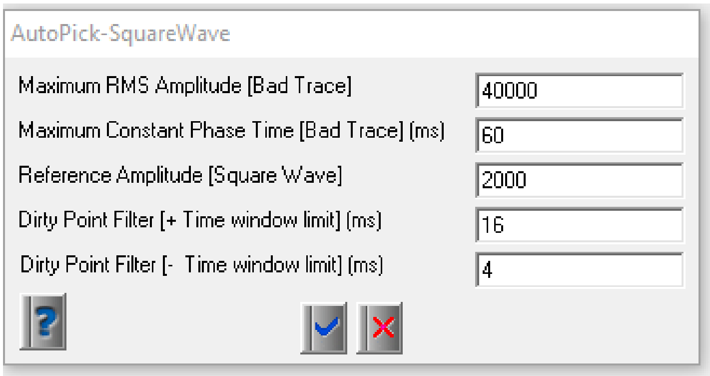


Fig 3.7. AutoPick-SquareWave Setup Parameters.

The software has built in neural network based Automated First breaks picking as well as Interactive Manual picking tools. If the neural network is not able to pick first breaks correctly then the user has full range of Interactive tools through which the first breaks can be interactively modified using auto-trackers. A seismic shot with automatically picked first breaks is shown in Figure 3.8 along with Interactive Tools toolbar.

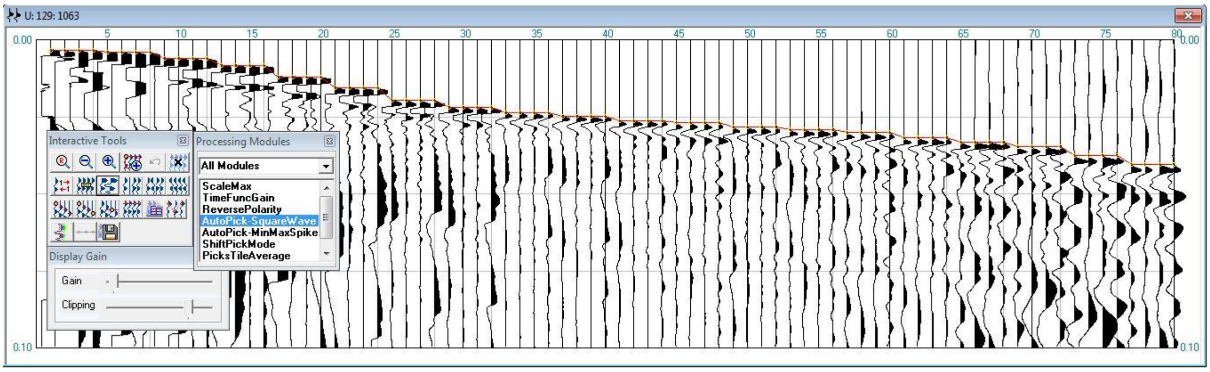


Fig 3.8. Seismic Shot Record with Automatically Picked First Breaks and Interactive Tools.

3.5.2.1 Scale Max

In order to apply the Auto Picking module we must balance the amplitudes from near to far offset traces. Usually the near offset traces have very high amplitudes as compared to far offset traces. The ScaleMax Gain will balance the amplitudes of all near to far offset traces at the desired RMS level as shown in Figure 3.9.

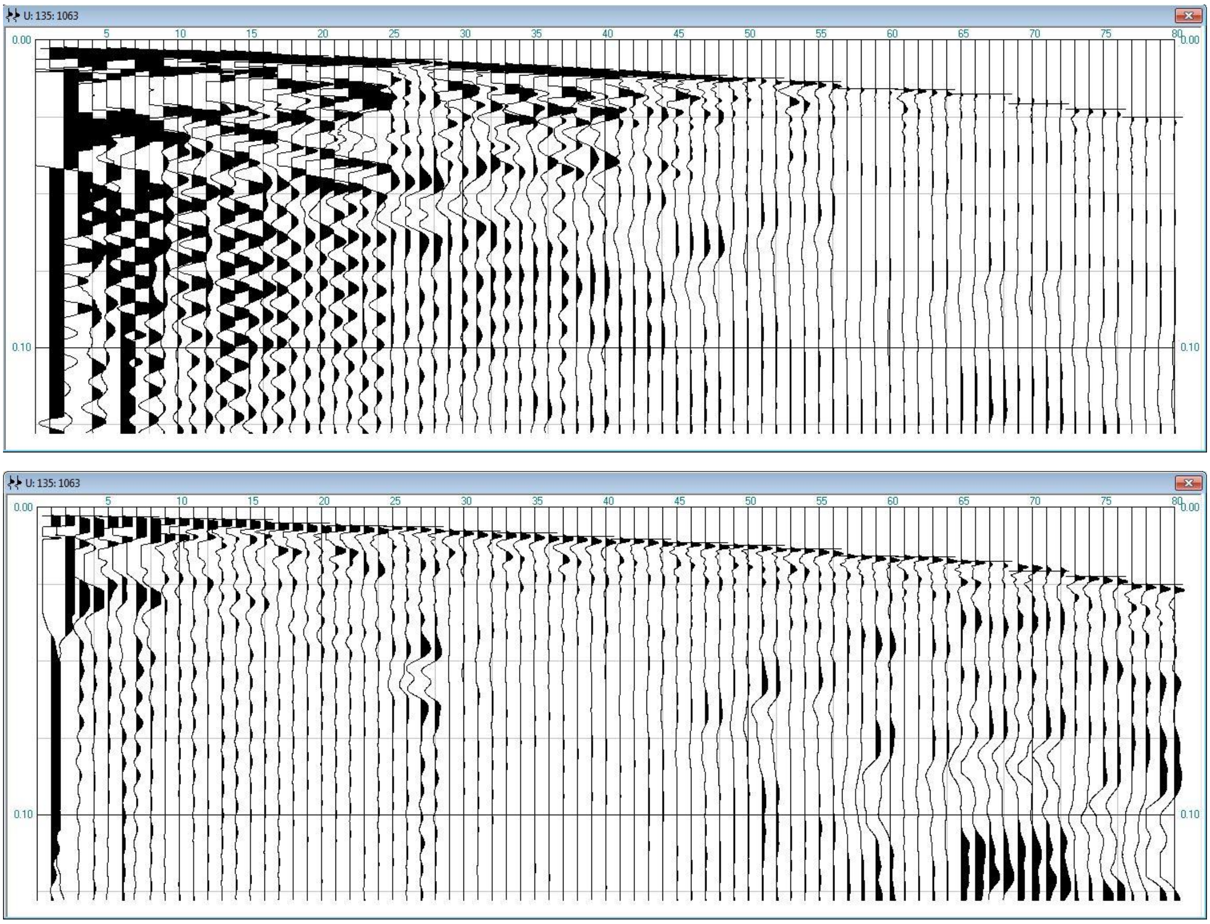


Fig 3.9. Amplitude decay with Offset (before ScaleMax)**;** Trace balancing after applying ScalemMax.

3.5.2.2 AutoPick Square Wave

This is the processing module which automatically picks the 1st breaks in seismic traces. It is completely automated two step first break picking method. The first step picks the first breaks, while the second step acts as a quality control stage to validate the picked times and refine them if necessary (Khan 2007). The complete Auto Picking algorithm is shown in Figure 3.10.

Steps involved in Auto picking are:

- A time invariant gain is applied to the input seismic traces by scaling their maximum amplitudes to the desired RMS amplitude Arms. Each trace is scanned to get its maximum amplitude Amax.

  Ascale = 1.414Arms (Ai/Amax)

  For reflection records an optional time variant exponential gain, sandwiched between the above mentioned scaling gains, is also applied.

- After this initial preprocessing of traces, the data is input to the main step for automatic first break picking. Internally this step consists of several stages as summarized below:

➢ Each trace is scanned to get the time of its maximum amplitude sample. A linear regression trend through these times helps in identification of the near offset. The Near offset trace is used as pilot trace for starting the first break picking.

➢ Bad traces are identified by analysing all the input traces.

➢ Trace to trace tracking is carried out after automated picking on the near offset trace.

- If the picked first breaks contain mispicks they are refined through the automated quality control step. This step also has several internal stages as given below:

➢ Spike search window is created for each trace around its first break.

➢ Trace is scanned to get maximum and minimum samples in each cycle.

➢ To get relative change in spike amplitude from its preceding spikes, the ratio of spike amplitude Ai to the average of all preceding spikes Ak of the same polarity is computed:

$$AR_i = \frac{A_i}{\sum_{k=1}^{i-1} A_k \,/(i-1)}$$

➢ Similarly the spike amplitude ratio is also computed for all negative spikes. To further differentiate the first break from preceding noise the energy of its side lobes is also included by adding the absolute *Ari* of the preceding and following negative spikes to twice the *Ari* of the positive spike as given by

$$AE_i = |-AR_{i-1}| + 2AR_i + |-AR_{i+1}|$$

- These enhanced spike amplitudes *Aei* are sorted according to their magnitude and the largest four are selected.

- Once the final first breaks have been picked they are shifted to one of the desired pick modes; crest, trough, zero crossing positive slope or zero-crossing negative slope.

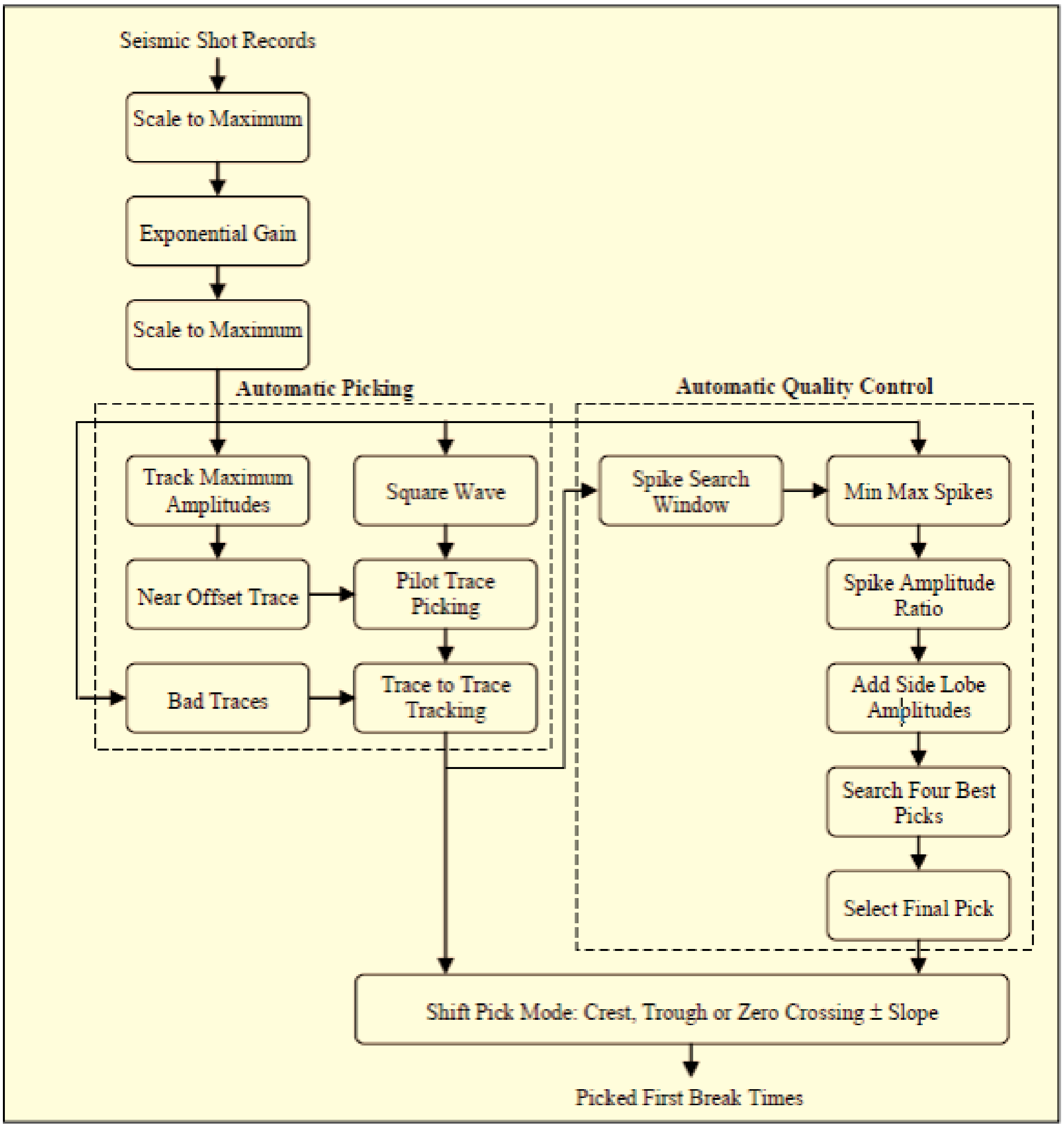


Fig 3.10. Processing Flowchart of the Automated First Break Picking and Quality Control Method. (Khan, 2007)

3.6 Full Project Data Processing

AutoPick can do the complete processing of the project data with a single command. It offers the following two options as shown in Figure 3.11.

- Job based Background Processing
- Job based Automatic and Interactive Processing.

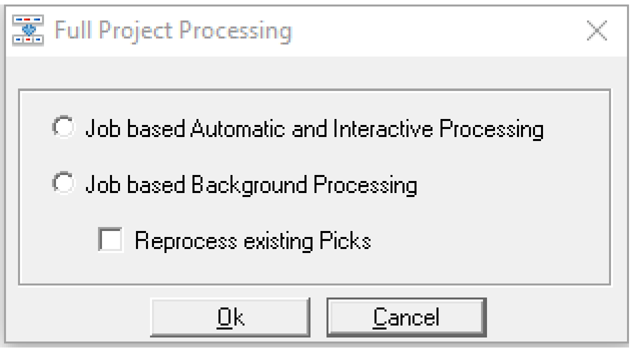


Fig 3.11. Full Project Processing Modes.

3.6.1 Job based Background Processing

Job based background processing is completely automatic as first breaks for the whole project are picked in the background. Usually the background processing is not preferred as the software as later the user has to review these picks for quality control.

3.6.2 Job based Automatic and Interactive Processing

Thus Automatic and Interactive Processing is preferred, where the software will automatically pick a shot record and display it for the user for review, if required the user can interactively use manual picking tools to correct the mispicks.

Some selected shots of Uphole Logging as well as Surface Forward Reverse Shooting are shown in Figures 3.12 to 3.14.

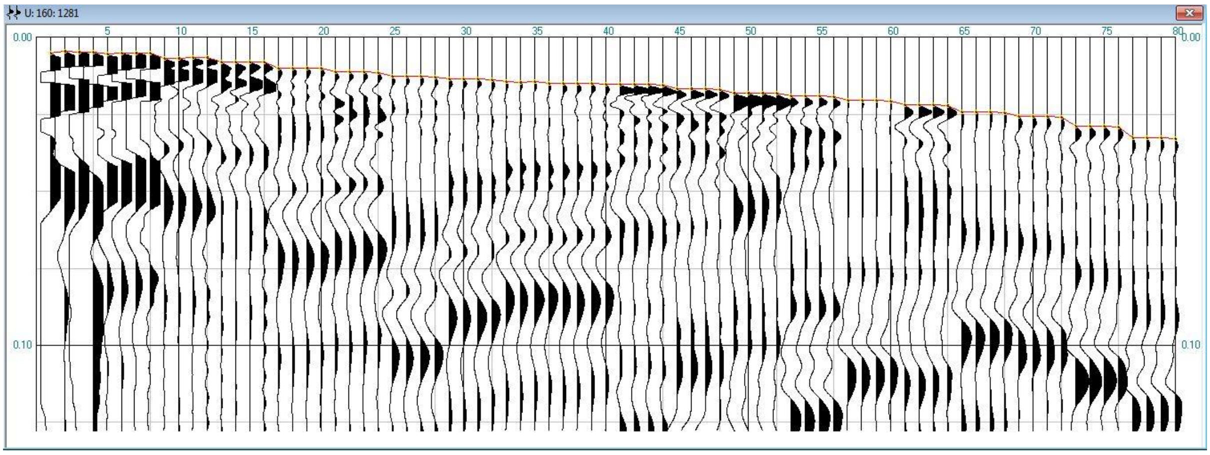


Fig 3.12. First Breaks picked on Seismic Uphole Record at Picket 1281 of Line .

Figure 3.13 and 3.14 show the Seismic Uphole and Surface Shooting records with colored amplitude attribute.

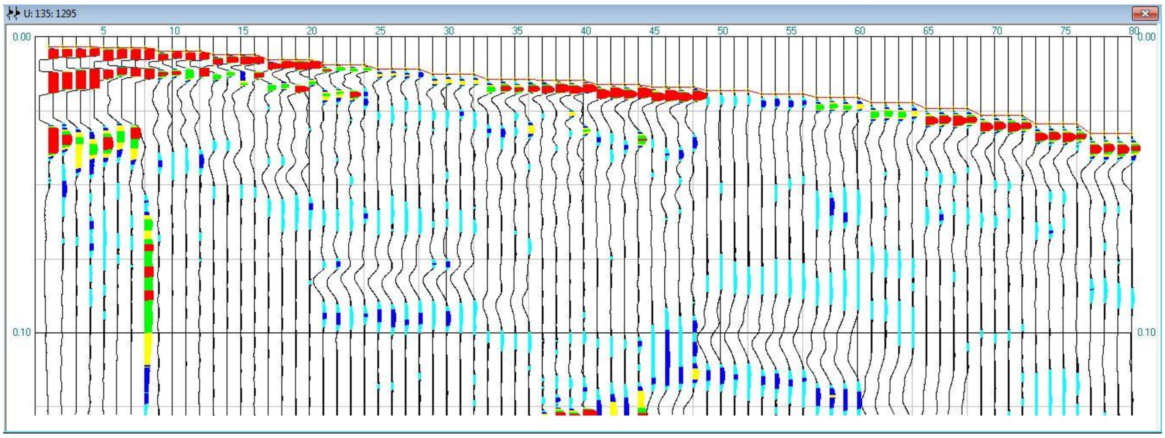


Fig 3.13. First Breaks picked on Seismic Uphole Record at Picket 1295 of Line 135.

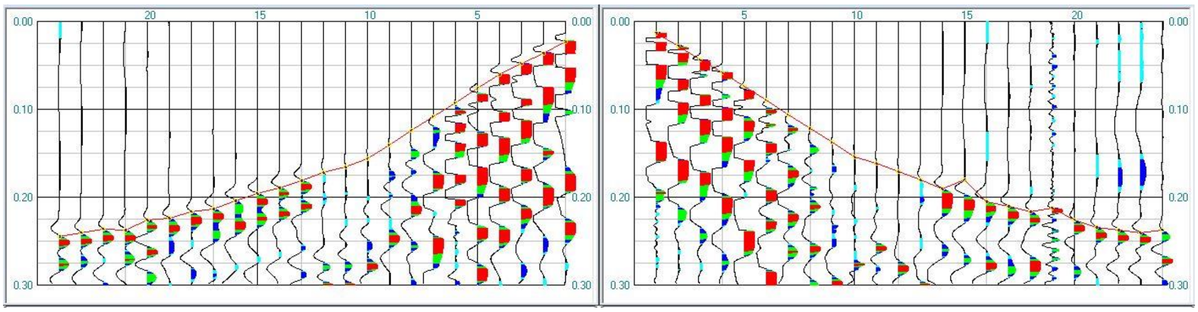


Fig 3.14. First Breaks Picked on Forward Reverse Surface Seismic Shots displayed with colored applitude attribute.

3.7 Reference Amplitude Visualisation

Interactive tools have a variety of applications that are useful for visualization of the data. A reference amplitude based coloring tool highlights samples greater than a reference amplitude. This helps in selection of a reference amplitude for AutoPick as shown in Figure 3.15.

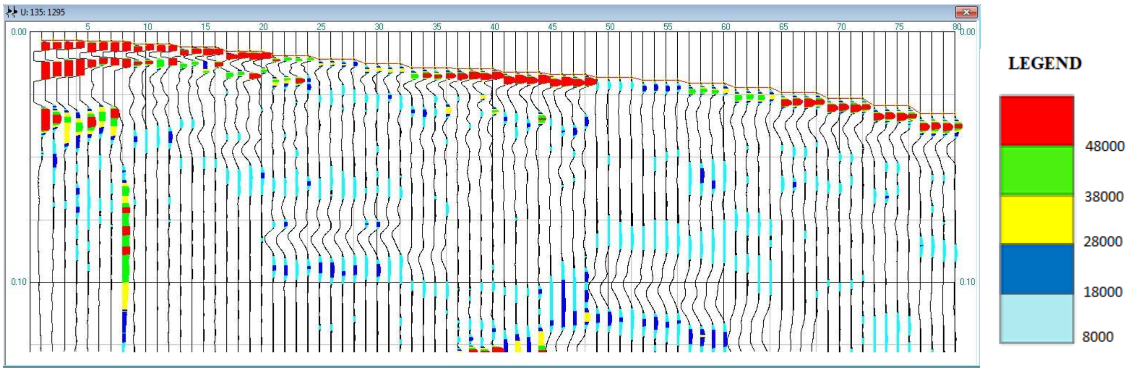


Fig 3.15. Trace Visualisation with Reference Amplitude

In addition Visual OIL script can export the seismic data to a grid format which can be used to generate a 3D view of seismic record with first break amplitudes prominently shown (Figure 3.16).

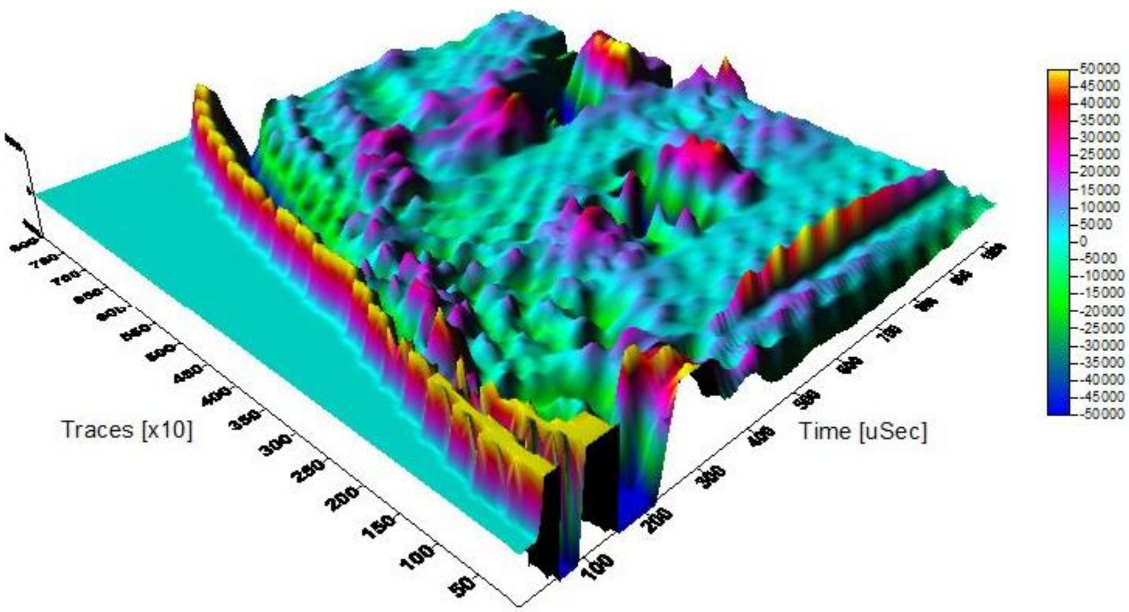


Fig 3.16. 3D Display of Seismic Shot Record with prominent continuity of First Breaks.

3.8 Travel Time Inversion

Refract is the next SeiRA application which reads the arrival times picked by AutoPick from SeiRA data files [.SRA] and performs travel time inversion. It generates time-distance TX graphs of arrival times, using neural networks automatically layers the data and then passes best fit lines for each segment of data. The slopes of these lines are used to calculate apparent velocities of weathered and sub-weathered layers. The travel time inversion algorithms including plus-minus method, delay time methods, generalized reciprocal method and travel time tomography are used to compute true velocity and thickness of the weathered layer. The processed results are saved back to the SeiRA data files.

TX graphs are cross plots between first arrivals times and corresponding offset distances. This module also has the Full Project Processing option which automatically processes the TX graphs for each point and display it for quality control. The TX graphs for Uphole logging and surface shooting are shown in Figures 3.16 and Fig 3.17.

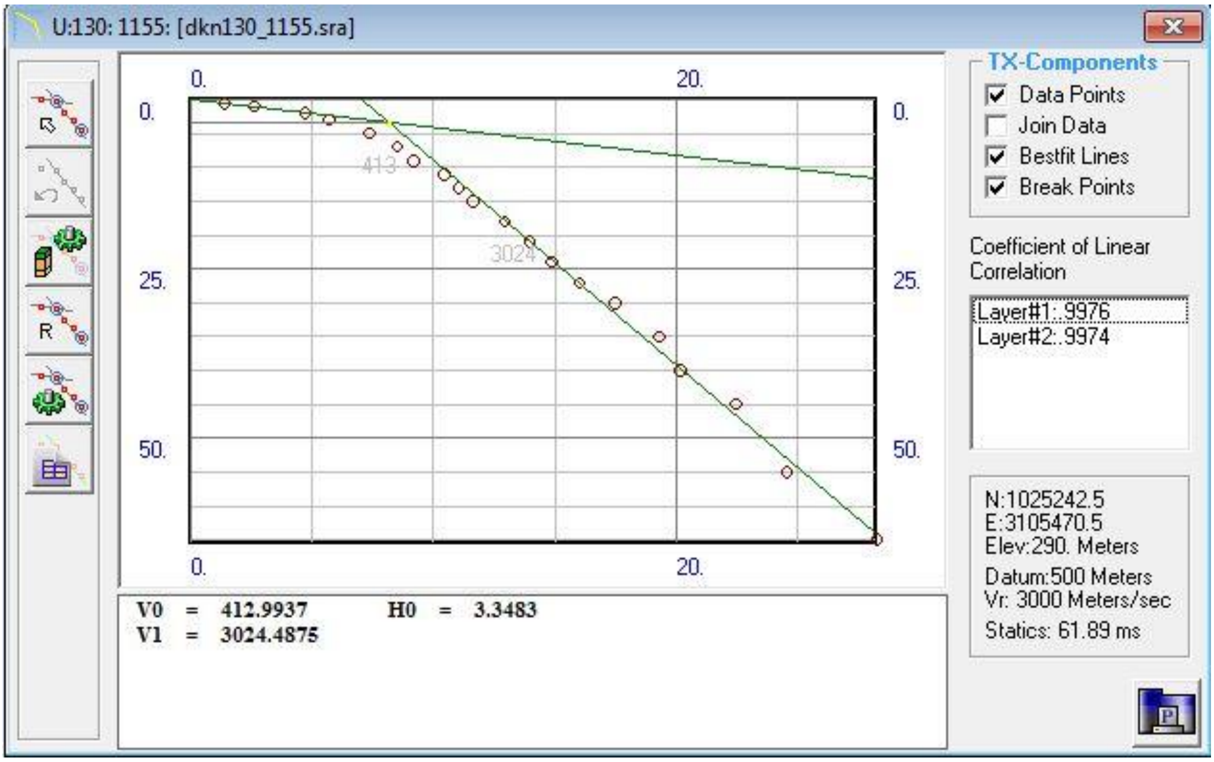


Fig 3.16. Uphole Data TX Graph of Picket 1155 at Line 130 along with Auto-Layering.

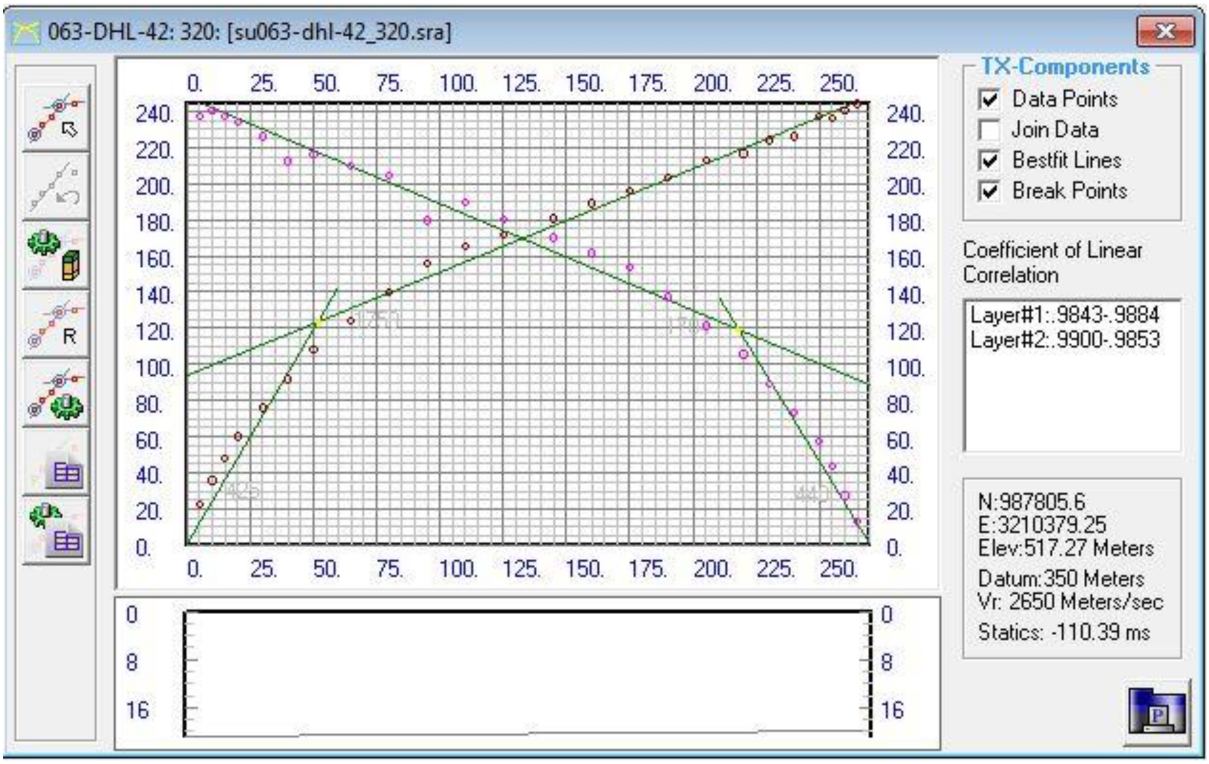


Fig 3.17. Surface Forward-Reverse Shooting TX Graph of Picket 320 at Line 42 along with Auto-Layering.

The TX-graphs along with all processed parameters can be exported to DesignCAD. Selected Uphole and Surface Shooting TX Graph plots are shown in Figures 3.18 to 3.20.

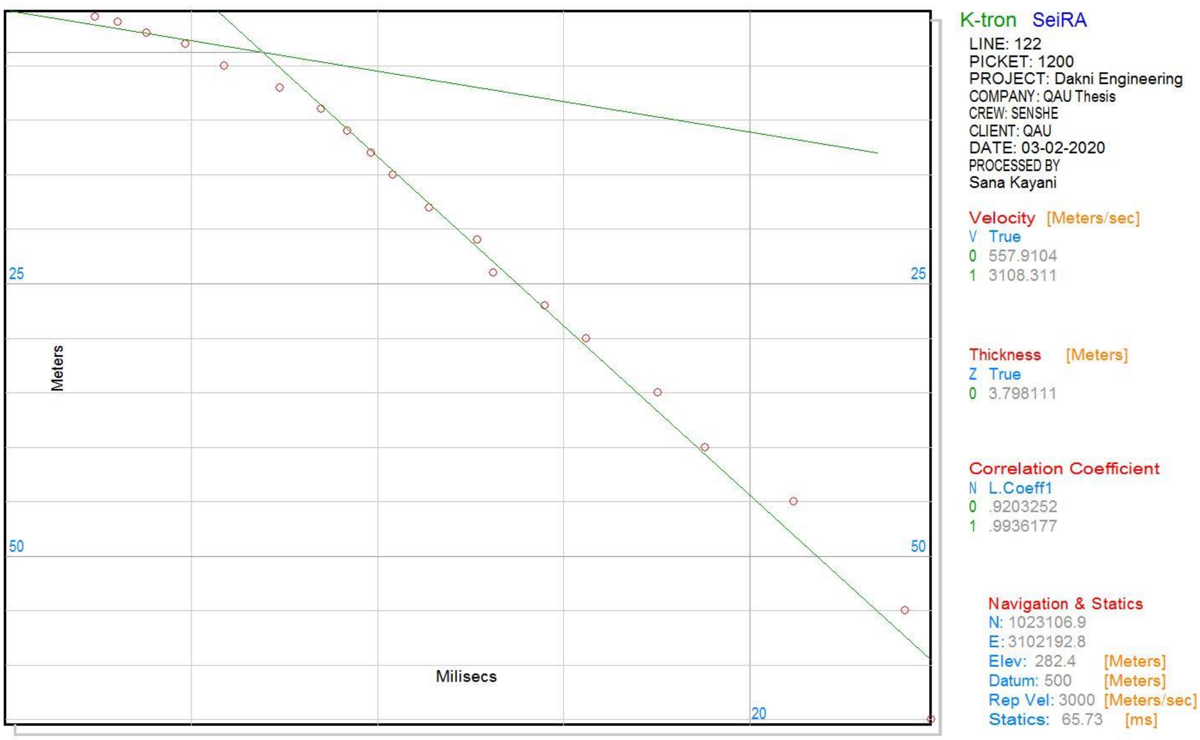


Fig 3.18. DesignCAD Plot: Uphole Picket 1200 at Line 122.

Fig 3.19. DesignCAD Plot: Uphole Picket 1057 at Line 148.

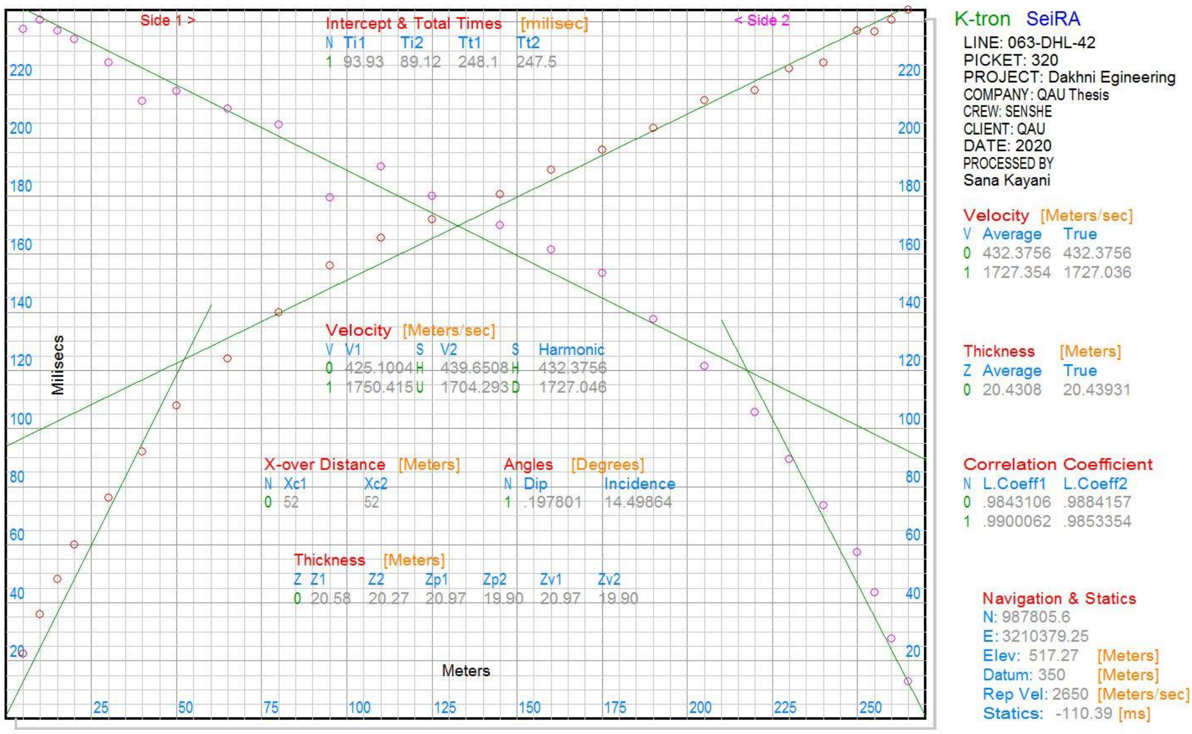


Fig 3.20. DesignCAD Plot: Surface Shooting Picket 320 at Line 142.

It can be observed from these TX graphs that these are mostly two layers case, thus the computed parameters are Weathered Layer velocity (V0) and Thickness H0 and Sub-Weathered Layer Velocity (V1).

3.9 StatCalc

After all the time distance TX graphs in the project are processed and near surface layers velocities and thicknesses are computed, this information is input into the StatcCalc module which creates 3D near surface model using gridding, based on Inverse Distance Weighted (IDW) interpolation. This near surface model is used to compute statics that can be applied to the seismic reflection data. The computation of statics requires selection of a datum plane as well as replacement velocity as shown in Figure 3.21.

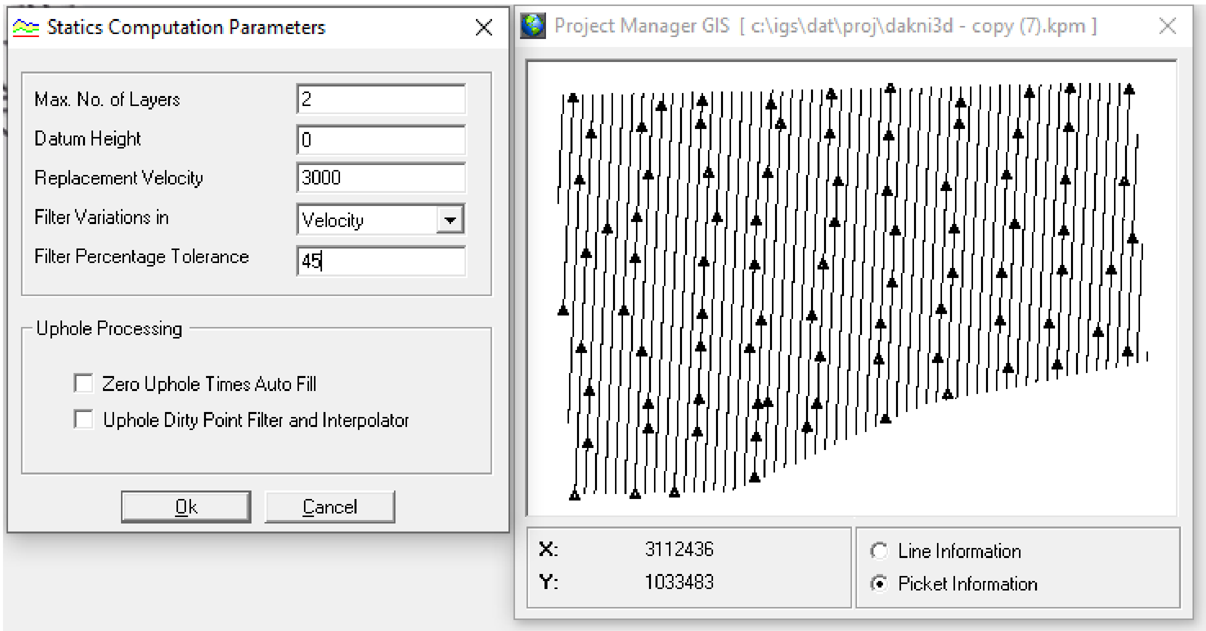


Fig 3.21. StatCalc: Setup Parameters for computation of Statics.

For the current project the processing parameters are as follows:

- Replacement velocity 3000 m/s.
- Datum is taken M.S.L (50m).
- Filter percentage tolerance 50 %.

3.9.1 Attributes Map

Attribute Maps are the Color Maps of Elevation and Statics generated by StatCalc . After statics are computed, a colour spectrum is loaded to generate colour map for Elevation and statistics. Attribute map for elevation of the area is shown in Figure 3.22, while the statics map is shown in Fig 3.23. Prominent variation can be seen in map due to variation s in the velocity and thickness of the weathered layer.

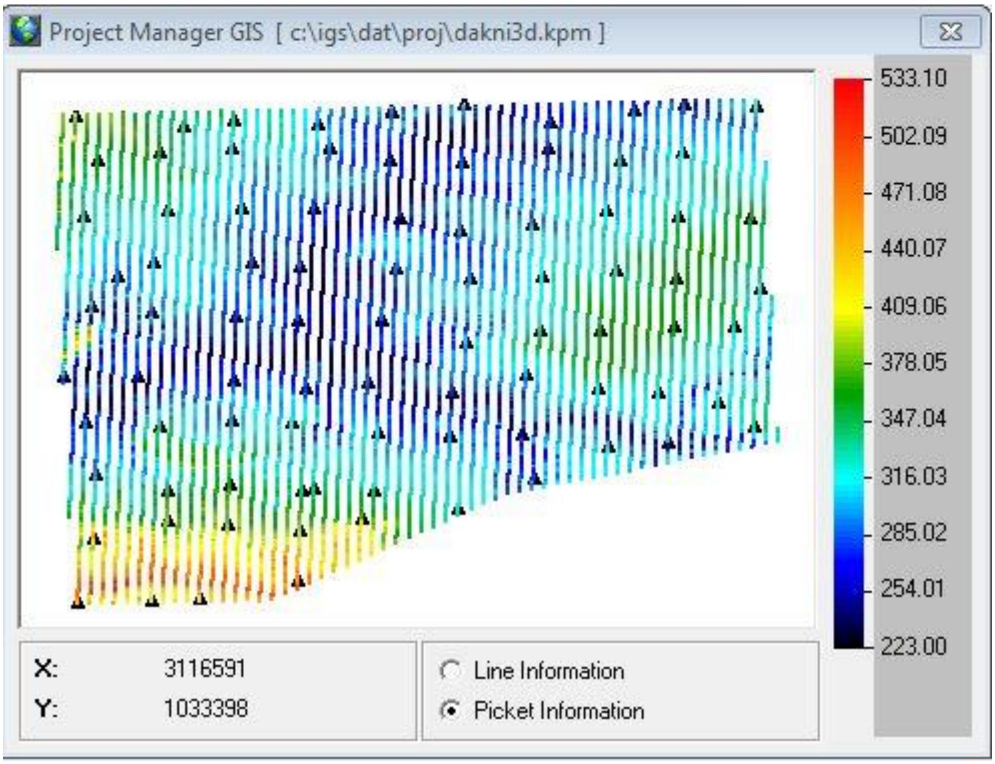


Fig 3.22. Elevation Attribute Map on Project GIS.

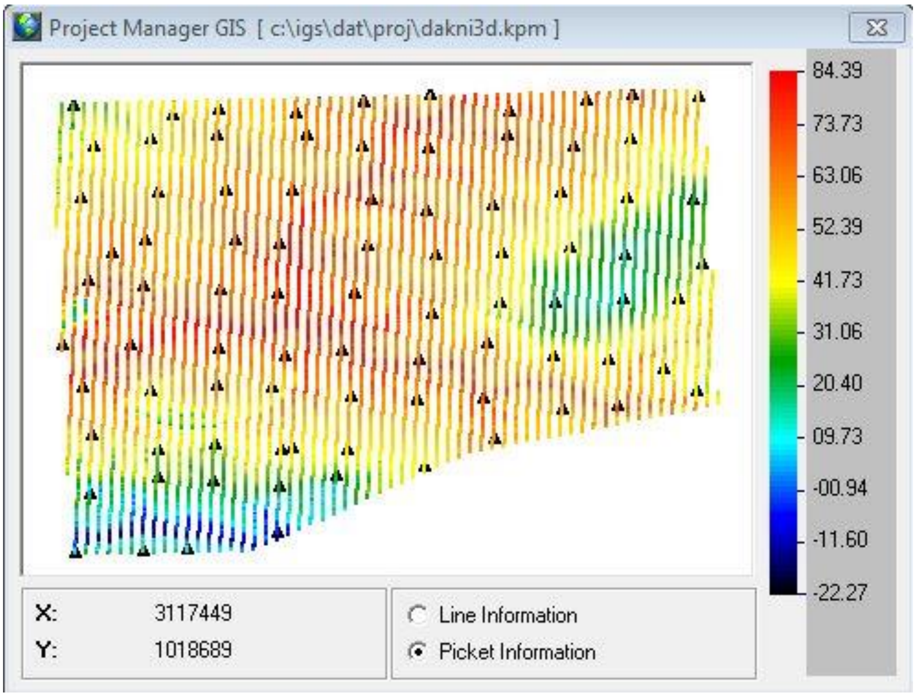


Fig 3.23. Statics Attributes Map on Project GIS.

3.10 Precision Matrix

Precision Matrix is a specialized GIS software for 2D/3D Seismic surveys. It can download data directly from electronic theodolyte and GPS instruments. An open architecture allows designing of user-defined plug-ins for reading the data from any instrument specific format. A built in GIS Mapping capability allows interactive editing of field data, designing and modeling of 2D seismic profiles and generation of multi-layer base maps incorporating seismic lines, concessions, wells, contours and cultural information. This software is used for geodetic projection transformations and generation of all types of base maps. The software is backed by an array of database from which it can extract satellite imagery and Digital Elevation Model data.

3.11 Surfer

Surfer 8 is a full-function geostatistical gridding, visualization, contouring and 3D surface generation application. The velocities and thickness XYZ files are exported from SeiRA using Visual OIL scripts. These files are gridded and finally rendered into contour maps and 3D surfaces. In addition all engineering and seismicity parameters computed by Visual OIL scripts are also gridded and contoured by Surfer.

3.12 Contour Maps

Surfer provides full control over all map parameters. 3D surfaces of topographic Elevation and Weathered Layer thickness are generated while contour maps of the velocity of Weathered and Sub-weathered layers are generated. The four components (two surfaces and two maps) are integrated to generate a 3D Visualisation of Elevation, Thickness of weathered layer and Velocity of weathered layer and sub-weathered layer as shown in Figure 3.24.

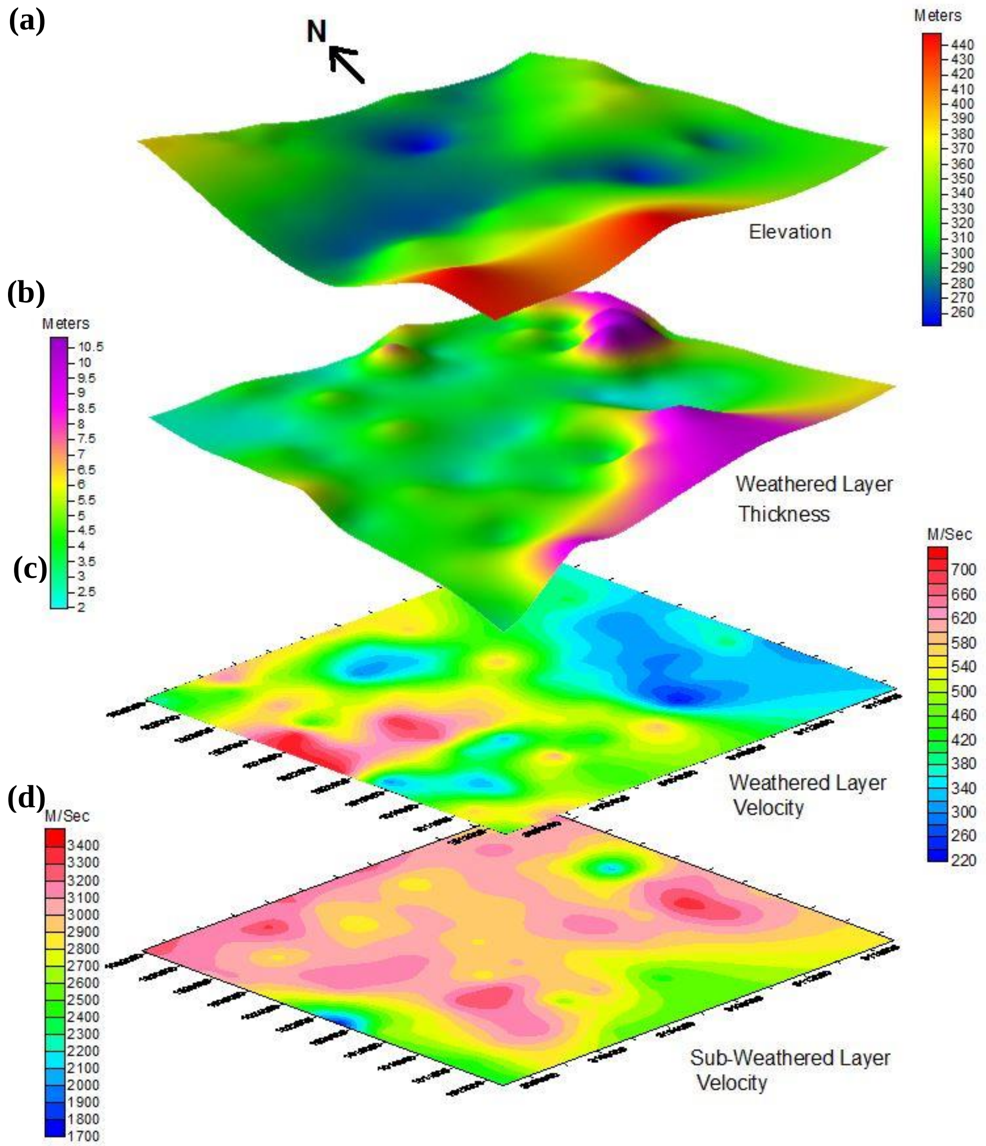


Fig 3.24. 3D-visualization of (a) elevation (b) thickness of weathered layer (c) velocity of weathered (d) velocity of sub weathered layer.

From the figure it can be seen that:

a) In Elevation surface there is a low-lying channel from North-East towards Western side. This is due to flowing river through that area. Similarly, from the middle area towards South-West region is again low elevated area with an elevation of 260 meters. In South-Western part, the area is highly elevated with an elevation of 440 meters. While the Eastern side is elevated to about 340 meters. In the same manner the North-Western region, the elevation increases and reaches around 370 meters.

b) From the weathered layer surface it can be seen that the weathered layer thickness is higher around 10 meters throughout the Southern portion and likewise in North-Eastern region. Throughout the region, the weathered layer thickness is around 5 meters while moving towards North in the middle portion there are few localised regions where the weathered layer thickness slightly increases to about 7 meters.

c) Weathered layer contour map shows that Weathered layer velocity is lowest in the Eastern part of the region about 300 M/Sec. Moving towards the West it increases and in the middle region it increases to about 450 M/Sec and while moving further towards middle Western portion it considerably increase above 700 M/Sec.

d) The Sub-Weathered layer contour map indicates that the velocity is low in the Southern region as well as in the South-Western region around 2500 Meters/Sec. The velocity increases to 3500 metres as we move towards Northern part. However in the Eastern part we have localised regions where the velocity drops to 2500 Meters/Sec as well as the localised regions where the velocity becomes much higher above 3400 Meters/Sec.

Based on the variations in the topography, the weathered layer thickness and its velocity, the static contour map is shown in Figure 3.25.

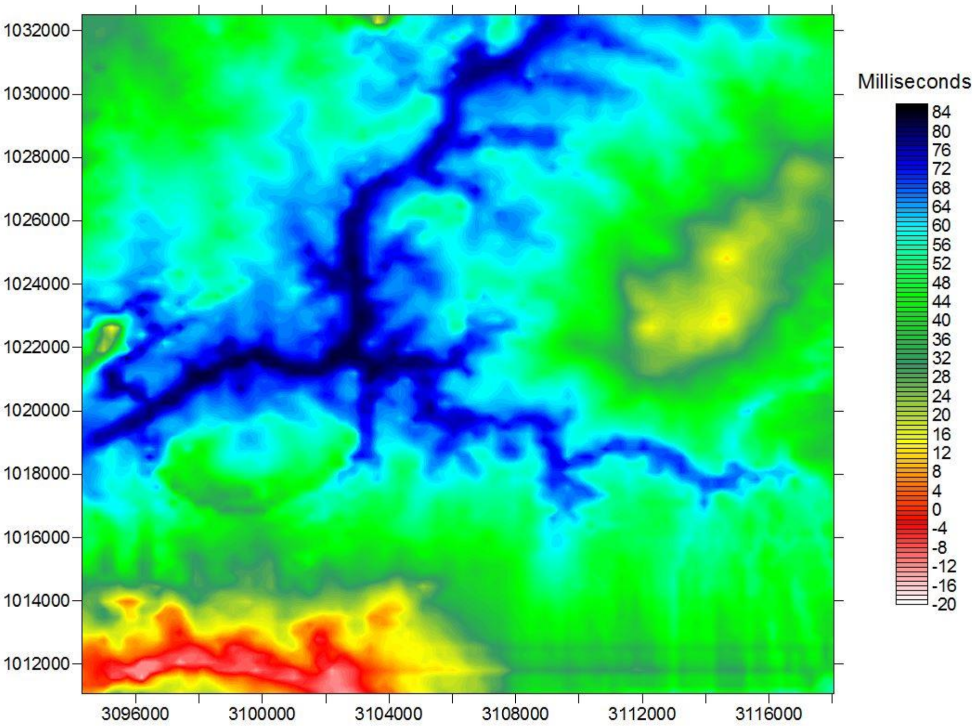


Fig 3.25. Statics contour map of the study area.

The topography of the area varies from 250 meters to a maximum of 510 meters. The maximum topography lies in the South-Western region of the area. Since the datum has been selected at 500 meters/sec therefore except the South-Eastern portion, all the area is below the datum plane therefore the elevation correction would be positive. From the static contour map, it can be seen that the water channel which was flowing through the area from the middle of North to the middle of West is clearly visible by the blue color indicating maximum positive statics. Similarly, as seen in the topographic map, there is also a channel from the middle of North to middle of West and moving towards the South-Eastern side where the topography is low. Due to this, the statics are positive as highlighted with the Blue and Black colour in the Statics contour map. It can also be seen that for the rest of the area, the statics fluctuates between 10 to 35 milliseconds.

Chapter 4

Geophysical Engineering Properties and Site Characterization

4.1 Introduction

Geophysical engineering techniques are becoming common day by day due to their wide applications to site selection for high-rise buildings, dams, stable sites for industries as well as nuclear plants. Most of these techniques are dependent on seismic method where seismic velocities are measured and these velocities are further used to compute elastic, engineering and seismicity parameters. The term rock physics contains the range of techniques that relate the geological properties (e.g. porosity, lithology, saturation) of a rock at certain physical conditions (e.g. pressure, temperature) with the corresponding elastic and seismic properties (e.g. elastic modulus, velocity, impedance) (Dewar and Pickford, 2001).

Most of these near surface geophysical techniques such as Seismic Refraction method, where the thickness and velocities of the near surface earth layers are measured and then these velocities are used to compute the shear velocities, density and other elastic parameters which in turn are used to compute various engineering parameters that are very useful and site selection for civil engineering works. These parameters are also used to derive out seismicity of an area that is helpful in seismic based site characterization or site classification. Thus seismic method has evolved into a cost-beneficial tool for rapidly determining depth to bedrock in engineering and construction projects.

4.2 Geomechanics

Geomechanics is the geologic study of the behaviour or mechanical response of geological material. Many aspects of geomechanics overlap with parts of Geotechnical engineering, engineering geology, and Geological engineering. Modern developments relate to seismology, Continuum mechanics, Discontinuum mechanics, and transport phenomena. In the petroleum engineering industry, Geomechanics is used to predict important parameters, such as in-situ rock stresses, modulus of elasticity, leak-off coefficient and Poisson's ratio. Reservoir parameters that include: formation porosity, permeability and bottom hole pressure can be derived from Geomechanical evaluation. Generally, geomechanics is divided into two main disciplines:

- Soil Mechanics
- Rock Mechanics

4.2.1 Soil Mechanics

It deals with the behaviour of soil from a small scale to a landslide scale while rock mechanics deals with issues in geosciences related to rock mass characterization and rock mass mechanics, such as applied to petroleum industry or high depths, tunnel design, rock breakage, and rock drilling.

4.2.2 Rock Mechanics

Rock mechanics is a theoretical and applied science of the mechanical behaviour of rock and rock masses; compared to geology, it is that branch of mechanics concerned with the response of rock and rock masses to the force fields of their physical environment. Rock mechanics is concerned with the application of the principles of engineering mechanics to the design of structures built in or of rock. The structure could include but not limited to a drill hole, a mining shaft, a tunnel, a reservoir dam, a repository component, or a building.

The velocities of the near surface layers are used to compute the elastic, engineering and seismicity parameters of the soil that are helpful in characterizing a site for civil engineering works. (Khan, 2010)

It is important to have knowledge about the bearing capacity, soil amplification factor and other engineering properties of the top soil before construction of any heavy structures such as buildings and highways. During Engineering planning, design and construction of works, there are many rock mechanics issues such as (Redpath, 1973):

- Evaluation of geological hazards
- Selection and preparation of rock materials
- Analysis of rock deformations
- Analysis of rock stability
- Bearing Strength of rock
- Seismicity

4.3 Workflow for Geophysical Engineering Properties

The processing of Seismic Refraction data provides weathered and sub-weathered layer velocities and thickness, which along with Elevation and topographic information are used for the computation of engineering properties. The workflow adopted for the computation of geophysical and seismicity parameters is given in Figure 4.1.

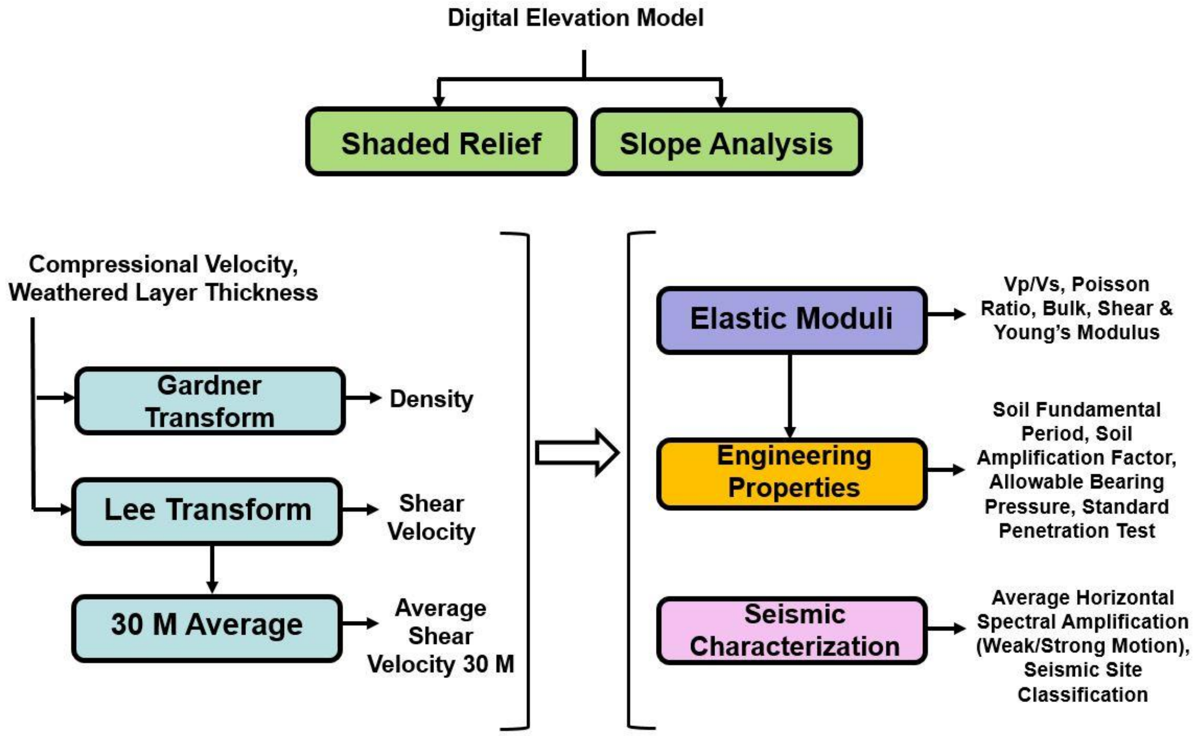


Fig 4.1. Workflow for computation of Geophysical Engineering and Seismicity properties.

The Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission Model **(Farr,** T. G et al., 2007) is obtained for the study area expanded 50km in all directions. This larger scaled DEM is used to generate a Shaded Relief Map of the area as shown in Figure 4.2. The derivative of the DEM data is also computed for slope analysis.

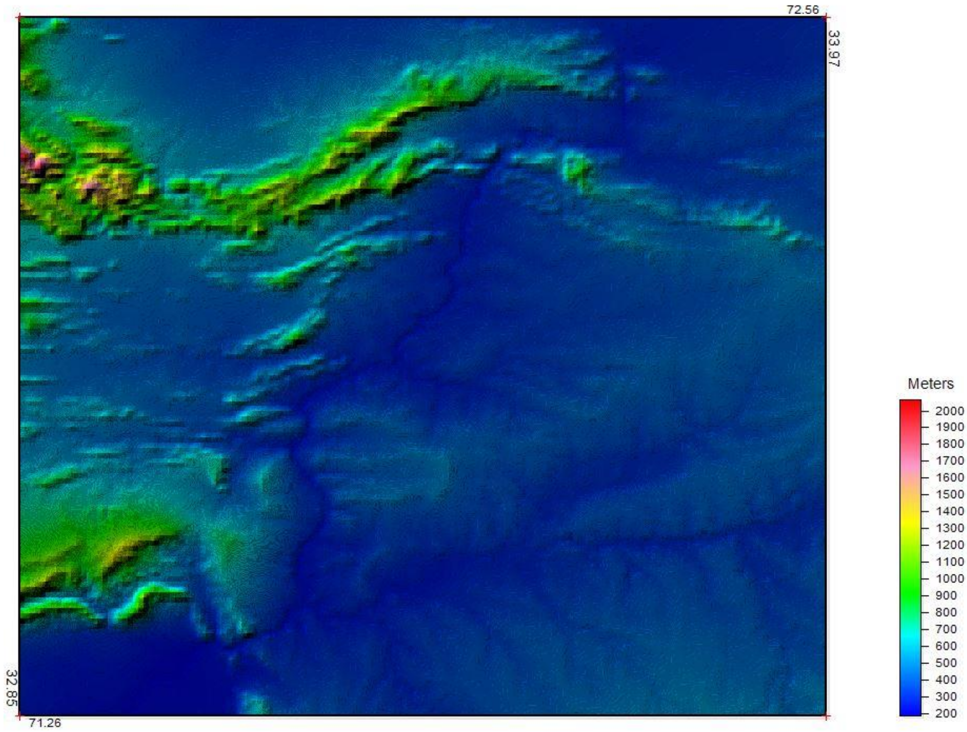


Fig 4.2. Shaded Relief Map of the Area.

The basic concept behind Shaded Relief Map is that face of the topographic features facing the light source appear brighter, hill sides on the other side appear darker giving a shadow effect. The angle between the light source (Sun) and the topographic surface is used to compute the brightness or darkness at a given point. Direct light will give the highest brightness but as the angle increases and become oblique, the brightness reduces and ultimately changes to darkness.

Thus, from the shaded relief map shown above, the site area lies in the centre. In the North and Western sides, the map is showing topographically elevated areas having elevation of 1000 to 2000 meters whereas the site area which lies in the middle of the figure is a low lying area. Thus the study area is topographically stable without any considerable topographic variations.

The DEM is also used to compute Slope or Dip Map by computing the derivatives from the DEM Grid. The Dip Map is shown in Figure 4.3. This slope map indicates the rate of change of elevation.

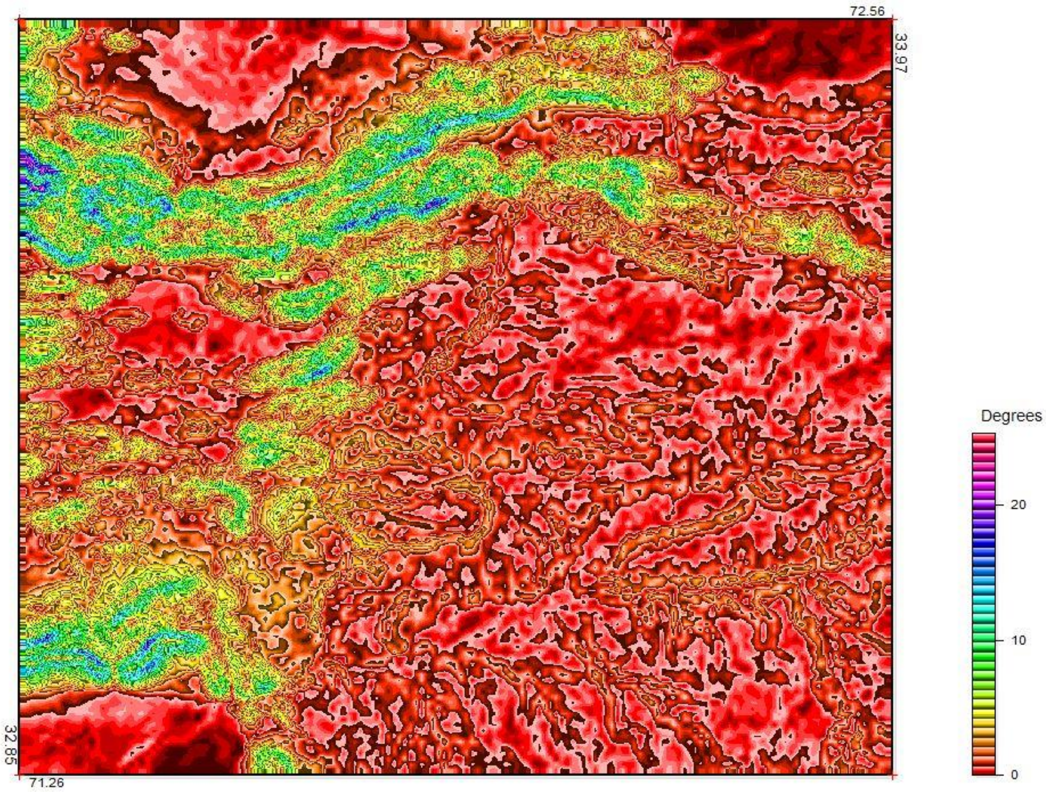


Fig 4.3. Slope Analysis Map of site area

Slope Analysis is also an important component for analysing stability, land sliding and is an important parameter for site selection. As slope is a measure of the rate of change in elevation thus it is a crucial parameter in several well-known predictive models used for environmental management. A thematic slope layer is composed of slope interval categories derived from a slope layer.

In the figure, the site area which is in the middle of the region has very gentle slope from 0 to 5 degrees. The red portion is showing stable areas having 0 degree or a little above slope, while yellow indicates 5 degrees, green indicates 10 degress , blue indicates 15 degrees and purple indicates 20 degrees slope.

4.4 Elastic Moduli Computation

An elastic modulus, or modulus of elasticity is the mathematical description of an object or substance's tendency to be deformed elastically (i.e. non-permanently) when a force is applied to it. An elastic modulus (E) can be determined for any solid material and represents a constant ratio of stress and strain (a stiffness):

$$E = \frac{stress}{strain}$$

A material is elastic if it is able to return to its original shape or size immediately after being stretched or squeezed. Almost all materials are elastic to some degree as long as the applied load does not cause it to deform permanently. Thus, the "flexibility" of any object or structure depends on its elastic modulus and geometric shape.

Figure 4.4 shows the equations used to calculate the elastic properties of rocks.

$$K = \rho(V_p^2 - \tfrac{4}{3}V_s^2)$$

$$\rho = 0.31 * V_p^{.25}$$

$$M = K + \frac{4\mu}{3}$$

$$E = \frac{9K\mu}{3K + \mu}$$

$$A = V_p * \rho$$

$$\mu = \rho V_s^2$$

$$\lambda = K - \frac{2\mu}{3}$$

$$\sigma = 0.5(V_p^2 - 2V_s^2)/(V_p^2 - V_s^2)$$

$$\phi = (2.68 - \rho)/(2.68 - 1)$$

$$VpVs_{Ratio} = \sqrt{\frac{K}{\mu} + \frac{4}{3}}$$

$$V_p = \sqrt{\frac{K + \frac{4\mu}{3}}{\rho}}$$

$$V_s = \sqrt{\frac{\mu}{\rho}}$$

Fig 4.4. Equations for Computation of Rock Physical and Engineering Properties. (Khan, 2009).

In the previous chapter we computed thicknesses and velocities of weathered and sub-weathered layer from seismic refraction data . This data would be used to compute all the elastic moduli of both the weathered and sub-weathered layers using the standard equations. These parameters can be further used to compute various engineering, and seismicity parameters.

Initially the Gardner Equation is used to compute the Density of weathered and sub-weathered layer (Gardner, 1974). Similarly, the Shear velocities of unconsolidated rocks are computed using Lee Equation (Lee,2010). Using these Compressional velocity, Shear velocity and Density, Elastic moduli are computed for the weathered and sub weathered layers. The computed parameters are then used to compute Geophysical Engineering parameters such as

Soil Fundamental Period, Soil Amplification Factor, Allowable Bearing Pressure, and Standard Penetration Test.

Moreover, the Seismic characterization parameters or Seismic zoning parameters are computed such as Average Horizontal Spectral Amplification (Weak and Strong Motion) and Seismic site Classification.

4.4.1 Density and Porosity

It is a mineralogical constituent parameter. The density of the material directly affects the P-Wave velocities passing through it. The variation in the density of the sub-surface material can be studied by analysing the velocities

$$\rho = 0.31 * Vp^{.25}$$

Above formula is used to calculate the density for the rock present in study area.

While, Porosity is defined as the ratio of the volume of void spaces to the total volume of the rock. Velocities have an inverse relation with the porosity, high velocity value indicates low porosity value.

Following mathematical relationship is used to calculate porosity value.

$$1/V_{bulk} = \Phi/V_{fluid} + (1- \Phi)/V_{matrix}$$

It is a very important property of rock it decides whether the rock under study is a good reservoir or not. As the study is carried out for near surface rocks so the porosity value will decrease moving downwards showing more compactness.

The density computed from Gardner equation is subsequently used to obtain the porosity of weather and sub-weathered layer. The density and porosity have an inverse relationship. Figure 4.5 shows the contour maps of densities and the porosities of the weathered and sub-weathered layers.

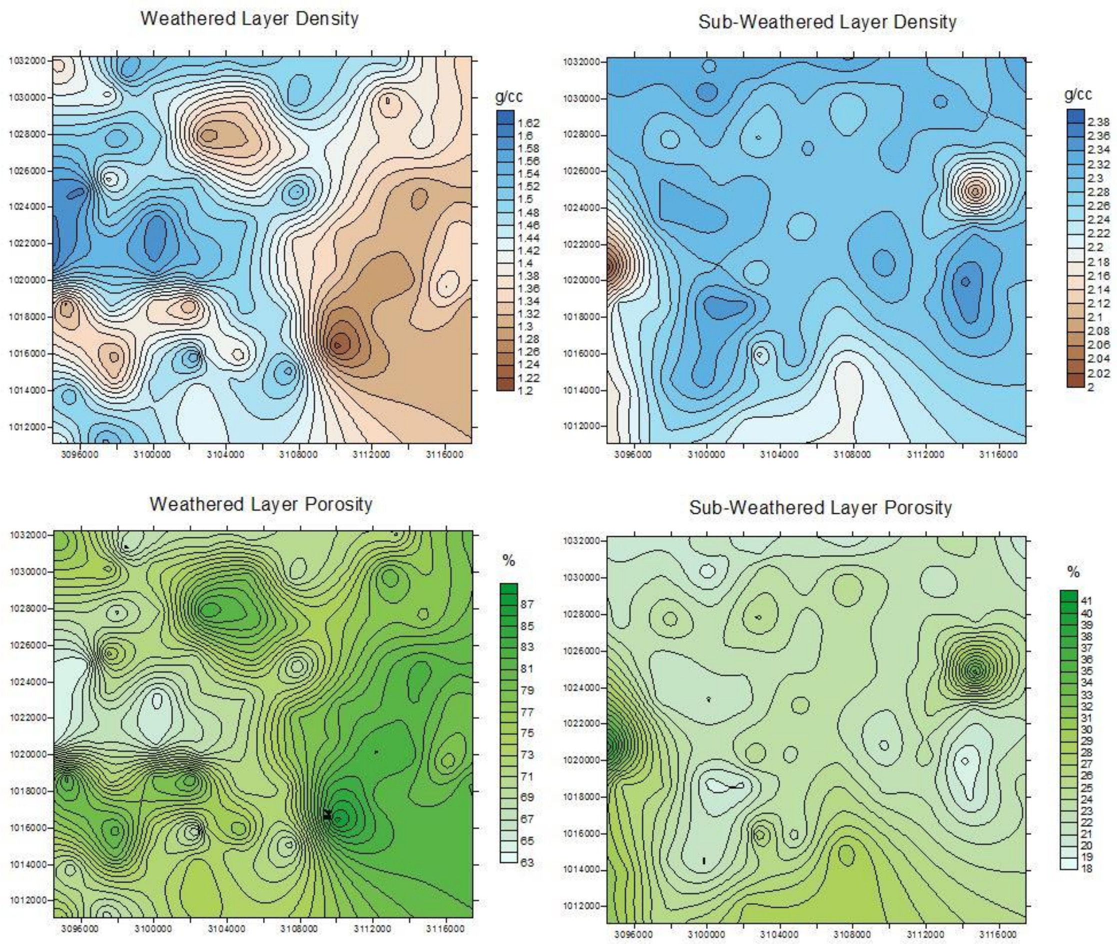


Fig 4.5. Variations in the Densities and Porosities of Weathered and Sub-weathered layers, over the study area.

The above figure clearly shows that the weathered layer has a very low density varying from 1.2 to 1.8 g/cc and its Eastern region has further lower density. Similarly, as the weathered layer represents a loose sand the porosity ranges from 63 to 87%.

The Sub-weathered layer has a relatively higher density ranging from 2.0 to 2.38 g/cc. Most of the region is blue having a density of 2.3g/cc. On the Western most side, the density decreases to 2. Similarly, the porosity is ranging from 18 to 41% while most of the region has lower porosities from 18 to 24%.

Seismic Refraction method provides compressional wave velocities of subsurface materials. The Elastic properties of the material can only be computed when both compressional (Vp) and sear velocities (Vs) are known. Shear wave velocities can also be measured using specialized surveys. However, shear velocities are computed from compressional velocities the most common Castagna’s equation**.** (1985)

The equations is valid for Siliciclastic rocks.

$$Vs = \frac{(Vp-1.36)}{1.16}$$

The velocity of near surface layer is much lower as compared to deeper layers due to presence of unconsolidated material. Thus, when Vp < 1.36 (km/s) the above equation is not valid as it provides negative values of Vs. Thus the above equation does not hold true for near surface unconsolidated rocks.

Lee (2010) has proposed equations for unconsolidated rocks as given below:

$$V_s = (V_P/2.286)^{1/0.672} \quad ; Vs > 1 Km/sec \quad Eq-1$$
$$V_s = (V_P/2.042)^{1/0.103} \quad ; Vs < 0.6 Km/sec \quad Eq-2$$

Figure 4.6 shows the relation between P and S wave velocities for unconsolidated rocks, from various sources.

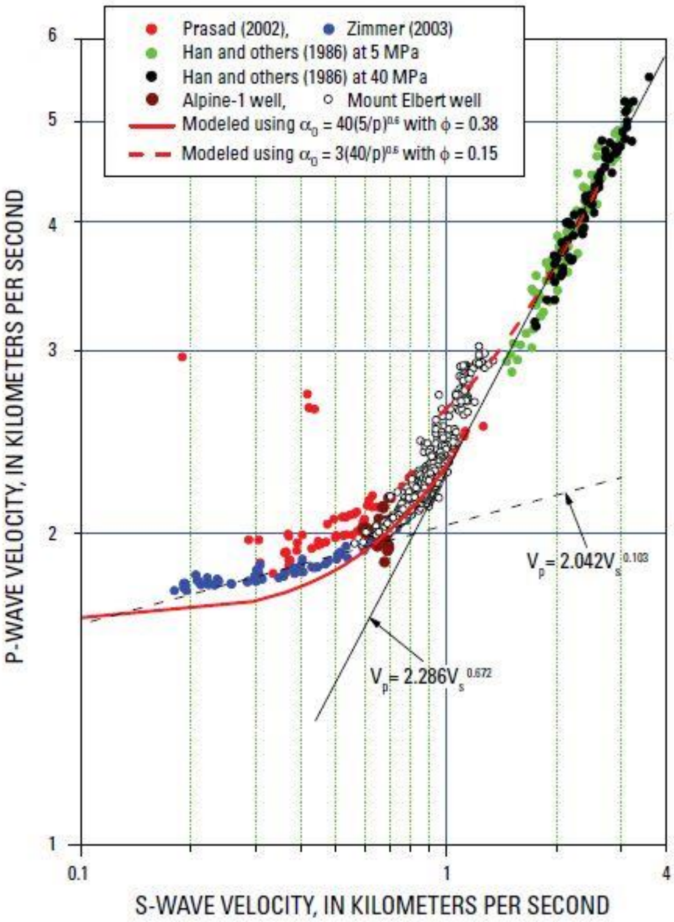


Fig 4.6. Graph of and samples used by Lee (2010) to derive relation between P-wave and S-wave velocities for unconsolidated rocks.

4.4.2 Shear Wave Velocity at 30 meters

Estimation of subsurface mechanical properties by using surface waves was proposed by seismologists for the investigation of the earth crust and upper mantle. Derived S-wave velocity information can be useful in foundation dynamics, pavement analysis, soil improvement and static correction of S-wave reflection data.

In geophysical engineering applications, instead of weathered and sub-weathered layers; an average shear wave velocity for first 30 meters of the Earth is required. Thus using the weathered and sub-weathered layers velocities, average shear wave velocity for 30 meters is computed.

The contour maps of Shear wave velocities for weathered, sub-weathered layers and 30 m average are shown in Figure 4.7.

It can be seen in the figure that the weathered layer shear velocity is lower on the Eastern part shown by blue colour ranging from 30 to 70 M/Sec and it goes on increasing on the Western side up to 180 M/Sec.

The Sub-weathered layer shear wave velocity is low at the Southern portion ranging from 1000 to 1400 M/Sec as well as in Western portion it is lowest from 650 to 950 M/Sec but it increases towards the Northern side from 1600 to 1800 M/Sec.

Similarly; in the 3rd contour map, Shear wave velocity of 30 meters Average is lower in the South-Eastern portion around 150-200 M/Sec and it gradually increases to around 800 M/Sec as we move towards North-Western side.

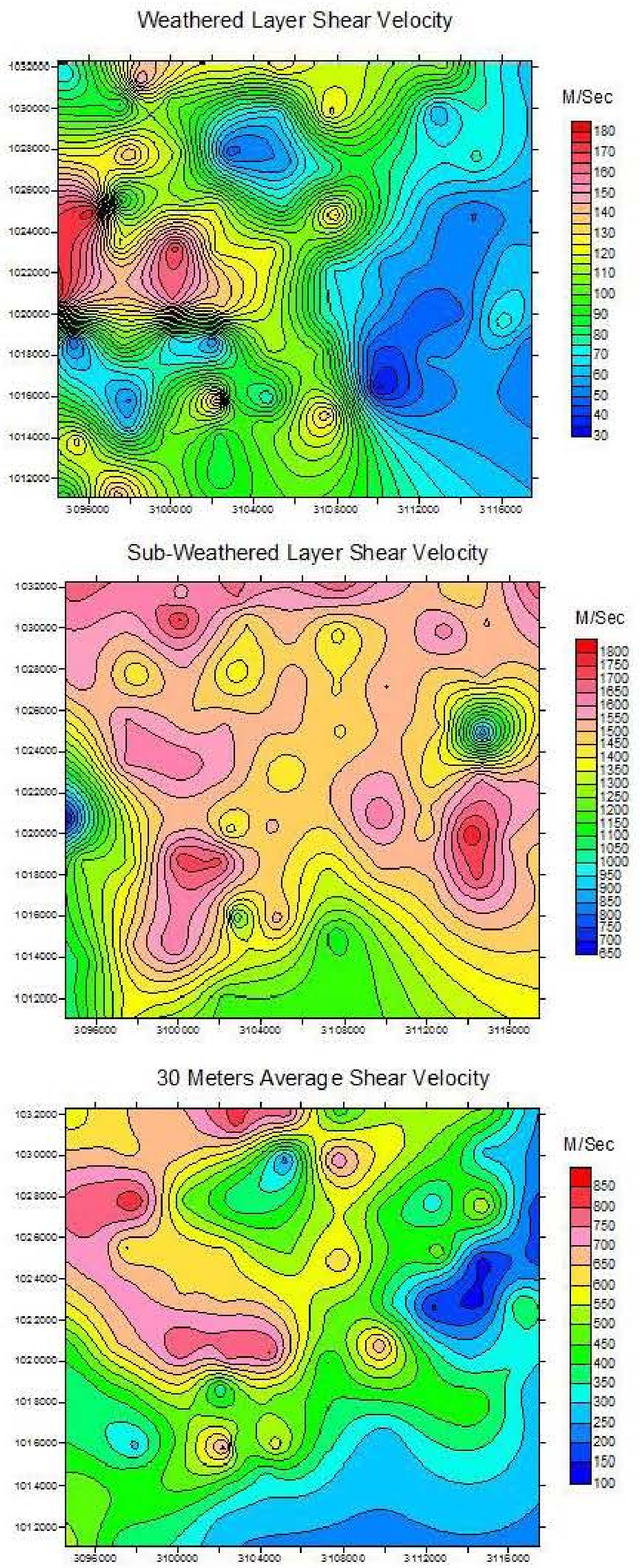


Fig 4.7. Contour maps of Shear wave velocities for weathered, sub-weathered layer and 30m average

4.4.3 Bulk Modulus, Shear Modulus and Young's Modulus

- Buk Modulus is the measure of capacity of a substance to be compressed and shows changes in volume and density are proportional to the change in pressure. The constant of proportionality is represented by k (Robinson, 1988).
- Shear Modulus is ratio of shear stress to the shear strain (angle of deformation).
- Young's modulus is a measure of the ability of a material to withstand changes in length when under lengthwise tension or compression. Sometimes referred to as the modulus of elasticity, Young's modulus is equal to the longitudinal stress divided by the strain.

Figure 4.8 shows the contour maps of Bulk Modulus, Shear Modulus and Young's Modulus for the weathered and sub-weathered layers. The Bulk Modulus for Weathered layer is highest in the most Western side around 0.8 GPa and it goes on decreasing in the most Eastern side upto 0.1 GPa and the South-Eastern part shows a high fall in Bulk modulus up to 0.05 GPa. The Shear modulus shows a similar trend with highest values on Western side ranging from 0.004 to 0.008 GPa and lowest values in the Eastern and South-Eastern parts ranging 0.008 Gpa and decaying further to 0. Likewise the Young's Modulus trend is same with highest values in West from 0.15 to 0.13 GPa and falling to 0.02 in Eastern quadrant.

Now for the sub-weathered layers, the Bulk modulus is high in the North-Eastern portion ranging from 15-18 GPa, while it starts decreasing towards Southern side. The lowest values occur in the most Western side ranging from 5-9 GPa. The Shear modulus gives a smeared trend with highest values in North and Eastern portions from 6.5 to 8.5 GPa and gradually lowers in the South portion while extreme lowest values are obtained in Western part from 0.5 upto 3 GPa. The Young's modulus is highest in the North, South-Eastern and South-Western portions with values typically lying between 15 to 21 GPa. The middle portion has moderate values from 11-15 GPa while it is lowest in Western part from 2 to 8 GPa.

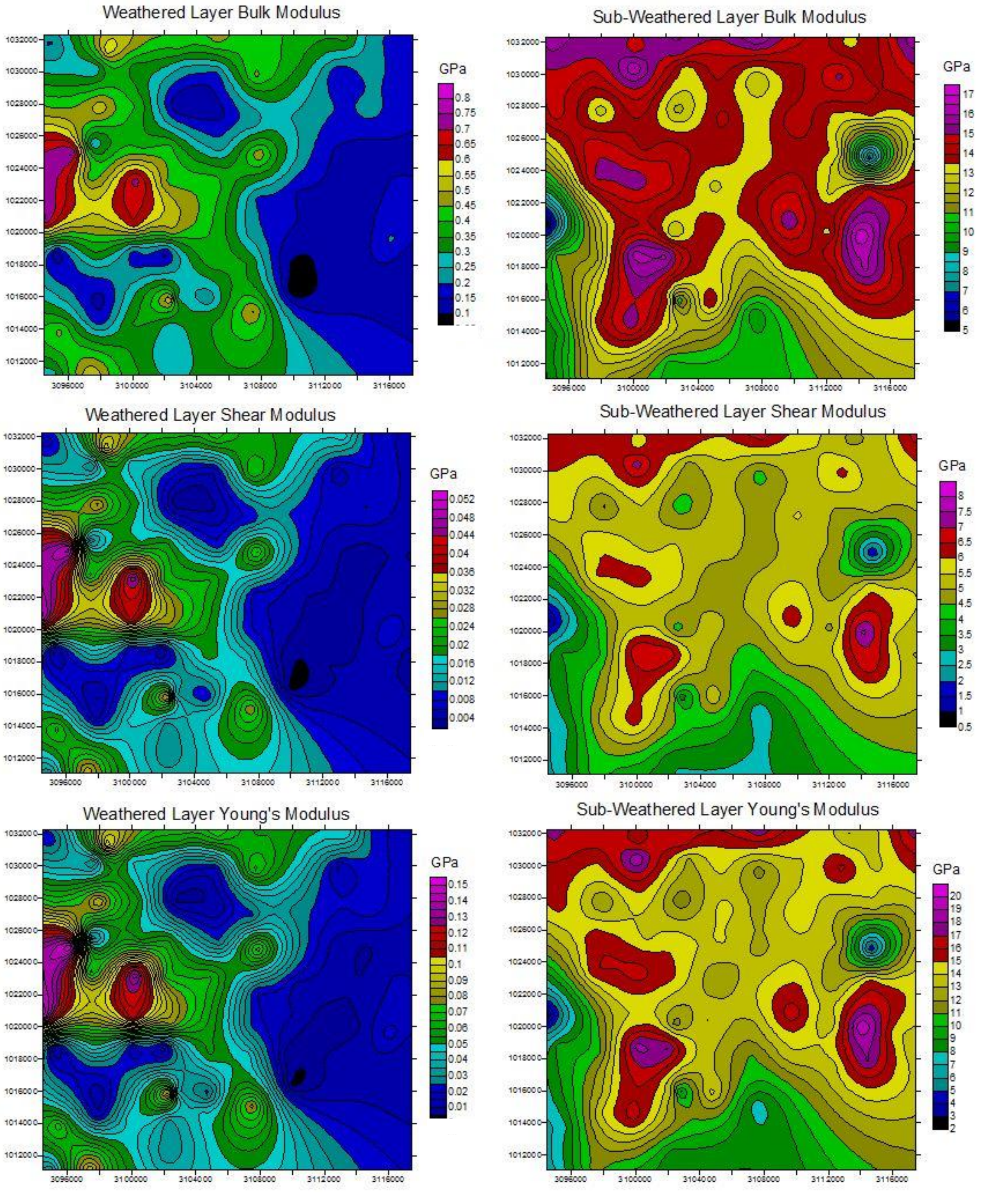


Fig 4.8. Contour maps of Bulk Modulus, Shear Modulus and Young Modulus of weathered and sub-weathered layers.

4.4.4 Vp-Vs Ratio and Poisson Ratio

- Vp/Vs ratio is an important rock diagnostic parameter, which can be directly determined by seismology. It is a ratio between two same types of quantities thus it has no units.
- Similarly, Poisson Ratio is the ratio between transverse strain to the longitudinal strain and therefor it is unit less.

The contour maps for Vp/Vs ratio and Poisson ratio of weathered and sub-weathered layers are shown in Figure 4.9. Vp/Vs ratio for weathered layer is low in the North and Eastern portion ranging from 4 to 5. As we move further towards Eastern side, it tends to increase from 5 up to 5.8 and moving further it ranges from 5.8 and touching its peak value of 7 in the South-Eastern portion. For sub-weathered layer, the Vp/Vs ratio is very low from 1.85 to 2.05 in major portion. But it tends to increase as we move Southern and Eastern side. The highest values typically lying in the Western portion ranges from 2.45 to 2.65 respectively.

The figure also shows that the Poisson ratio for weathered layer has the highest values in the South-Eastern side ranging from 0.487 to 0.49 and thereby decreasing as we move further Eastern side. Low values are encountered as we move towards West and becomes lowest in the most Western portion ranging from 0.467 to 0.471. For the sub-weathered layer, the Poisson ratio is highest up to 0.4 at local regions in the East and West portion. The South and Eastern sides are also showing moderate values from 0.345 to 0.375. While the major portion is giving low values ranging from 0.305 to 0.34.

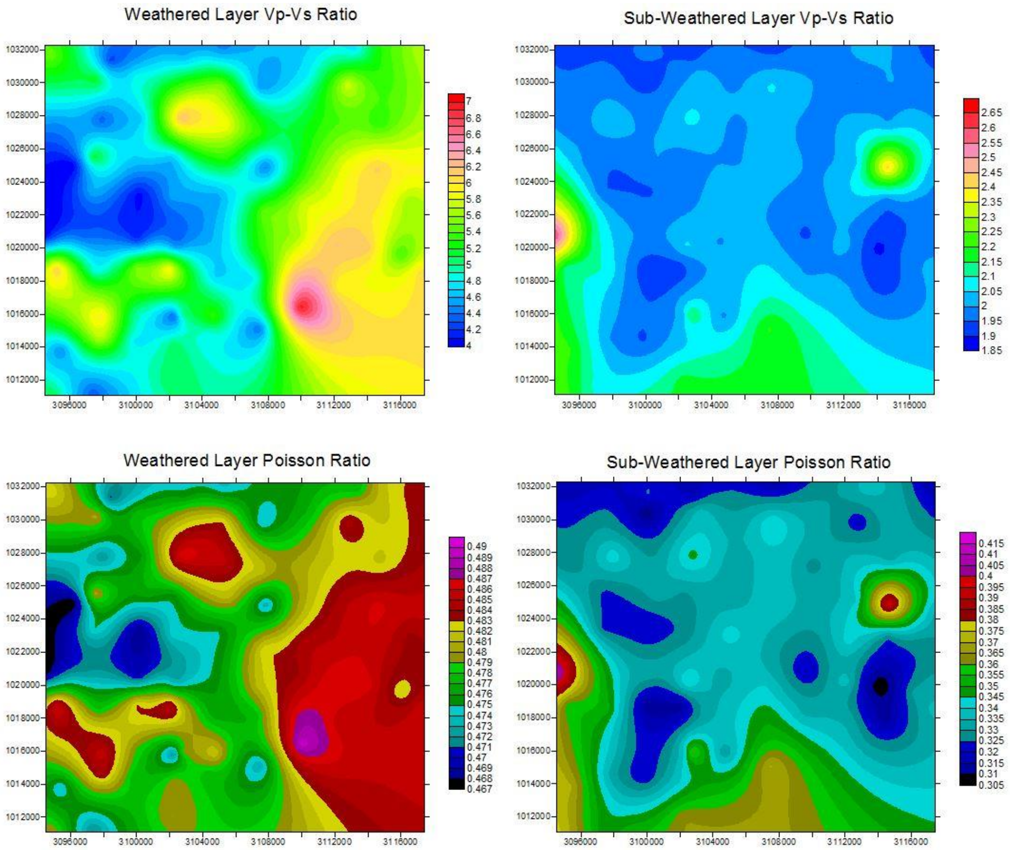


Fig 4.9. Vp-Vs Ratio and Poisson Ratio of weathered and sub-weathered layers.

All these computed parameters are further used in the computation of engineering properties as well as seismic characterisation properties which are discussed in the subsequent sections.

4.5 Geophysical Engineering Properties

In this section, we will discuss various engineering properties that are useful for site selection for any high-rise building or sensitive engineering plant. These engineering parameters are discussed below.

4.5.1 Soil Amplification Factor and Soil Fundamental Period

Soil amplification is a phenomenon observed in many earthquakes where the strength of the shaking increases abnormally in areas where the seismic-wave velocity of shallow geologic layers is low. As a result, earthquake shaking is felt more strongly than in surrounding areas without similar geologic conditions.

In softer soil, the soil amplification phenomenon is well known for soil amplified earthquake vibrations.

Peak ground acceleration is considered most important in structural seismic design. Since many variables such as soil characteristics and attenuation relations are probabilistic parameters, the peak ground acceleration cannot be determined using deterministic approaches, as conducted on Yerba Buena Island (E-W) and Treasure Island (E-W) (Bouckovalas, 2010)..

Table 4.1 identifies the soil types on the basis of shear wave velocities.

When earthquake waves propagate through soil media, their amplification or attenuation is mainly dependent on fundamental natural period of the soil, which is referred as the Soil Fundamental period. This fundamental period of soil is dependent on its thickness, low strain stiffness and density. So it is essential to estimate this parameter for site selection of roads and heavy industrial construction.

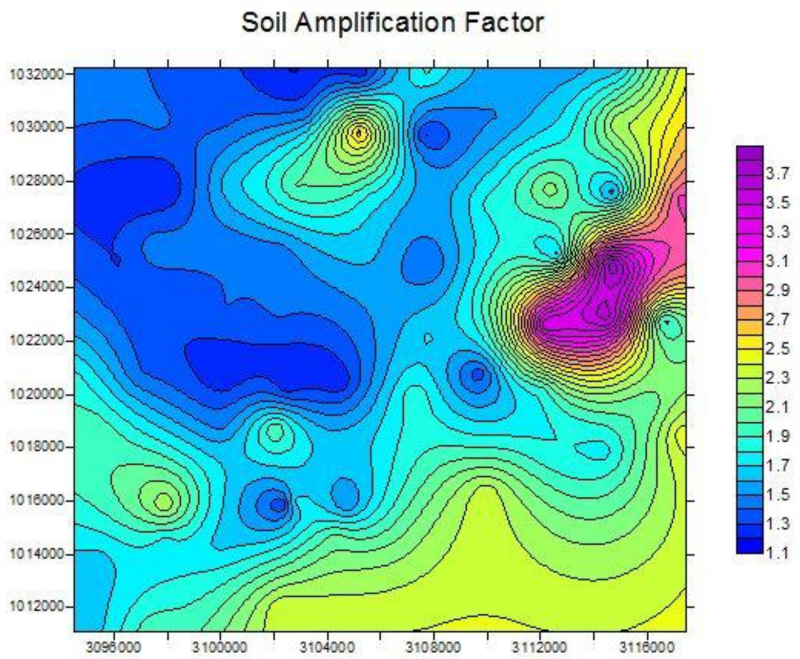
Mathematical models are used for computation of Soil Amplification Factor (Midorikawa, 1987) and Soil Fundamental Period (Kanai, 1983) from Seismic data. The contour maps for Soil Amplification factor and Soil Fundamental Period are shown in Figure 4.10.

From the figure, it is clear that the Soil Amplification Factor is high in the Eastern portion from 2.8 to 3.9. The values are moderate in Southern and South-Eastern portion ranging from 1.9 to 2.5. While the values are lower in the North, Eastern and South-Eastern sides ranging from 1.1 to 2.1.

Similarly, the Soil Fundamental Period values are high in the Eastern portion from 0.8 to 1.15 Sec. The values gradually decreases as we move towards South from 0.65 to 044 Sec and becomes lowest in West and North-Western side ranging 0.15 to 0.35 Sec.

Table 4.1. Shear wave velocity based Soil Types Identification

Soil Types Amplification		
Soil Type A	Vs> 1500 m/sec	Includes unweathered intrusive igneous rock. Occurs infrequently in the bay area. We consider it with type B (both A and B are represented by the color blue on the map). Soil types A and B do not contribute greatly to shaking amplification.
Soil Type B	1500 m/sec >Vs.> 750 m/sec	Includes volcanics, most Mesozoic bedrock, and some Franciscan bedrock. (Mesozoic rocks are between 245 and 64 million years old. The Franciscan Complex is a Mesozoic unit that is common in the Bay Area.)
Soil Type C	750 m/sec >Vs.> 350 m/sec	Includes some Quaternary (less than 1.8 million years old) sands, sandstones and mudstones, some Upper Tertiary (1.8 to 24 million years old) sandstones, mudstones and limestone, some Lower Tertiary (24 to 64 million years old) mudstones and sandstones, and Franciscan melange and serpentinite.
Soil Type D	350 m/sec >Vs.> 200 m/sec	Includes some Quaternary muds, sands, gravels, silts and mud. Significant amplification of shaking by these soils is generally expected.
Soil Type E	200 m/sec >Vs.	Includes water-saturated mud and artificial fill. The strongest amplification of shaking due is expected for this soil type.



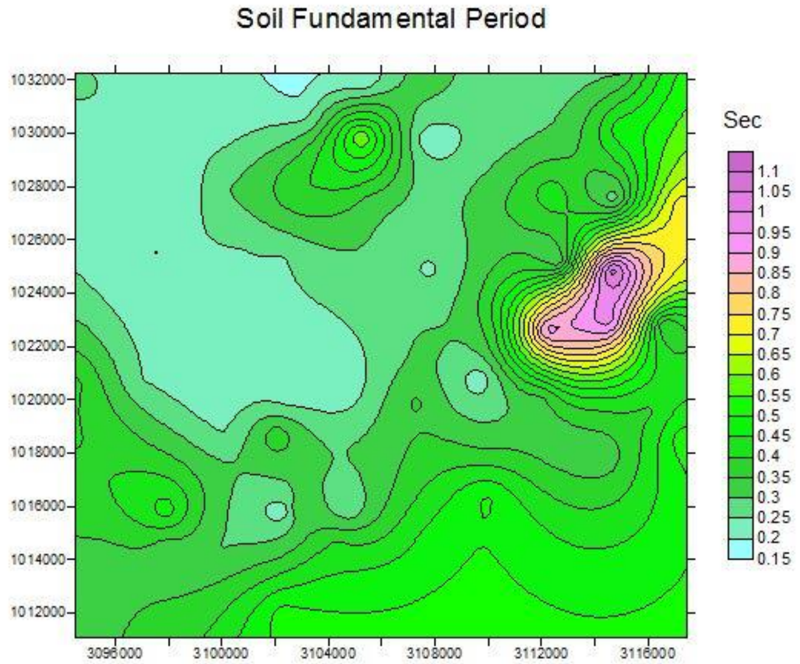


Fig 4.10. Soil Amplification Factor and Soil Fundamental Period.

4.5.2 Allowable Bearing Pressure

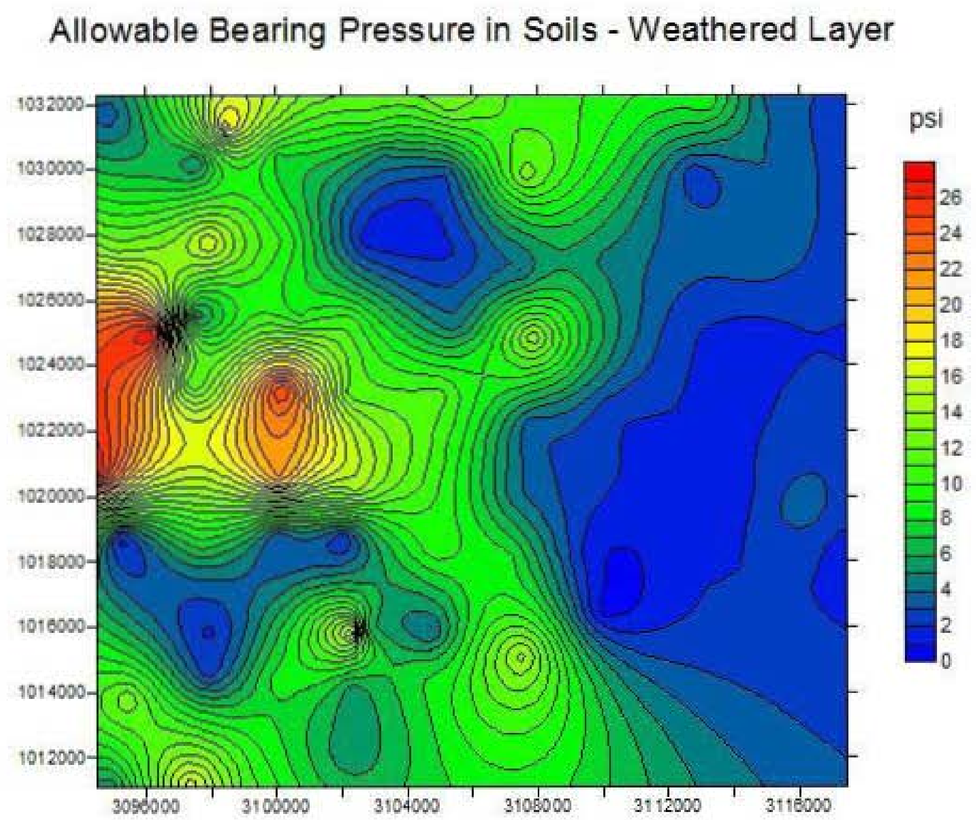
Allowable Bearing Pressure is another parameter to check the bearing capacity of soil if it can withstand the load of high rise buildings and highways with heavy loads of traffic. This parameter defines the limit of pressure to withstand from heavy duty vehicles.

(Uchiyama et al., 1984) have developed a method to compute the Allowable Bearing Pressure in soils using Shear wave velocities of the ground. Using this method, the Allowable Bearing Pressure of weathered and sub-weathered layers is computed as shown in Figure 4.11.

The contour map for Allowable Bearing Pressure for weathered layer shows that the Average Bearing Pressures in soils is increasing in the Western portion from 20 to 28 psi. The middle portion from North-Eastern to South-Eastern shows moderate to average values ranging from 8 to 16 psi, while it decreases to minimum in the North-Eastern and South-Eastern portions from 6 psi.

The Allowable Bearing Pressures contour map for sub-weathered layergives a different trend with the highest values lying in the Northern, some Eastern and in the middle of the site area with values ranging from 4000 to 5200 psi. While the values lying in the middle are neither low nor high (giving medium range) from 1800 to 3600 psi. The values are lowest in the Western portion from 400 to 1200 psi.

Thus from construction point of view, the Weathered layer has a much lower Average Bearing Pressure and is not suitable for Engineering construction and needs to be bulldozed.



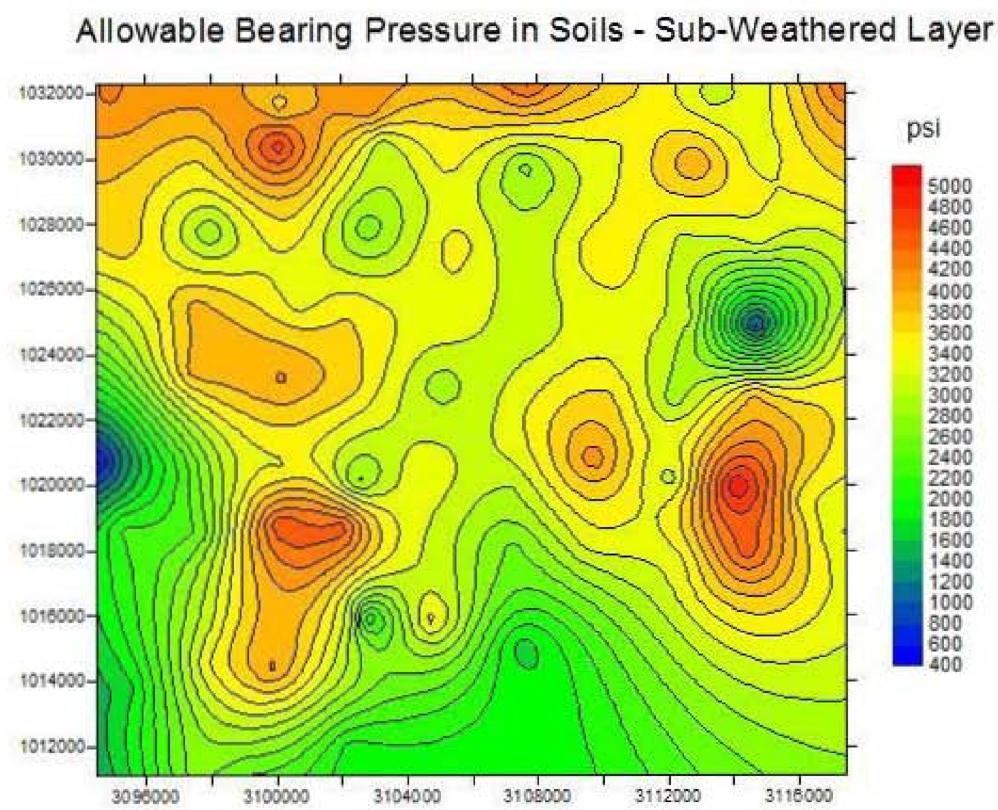


Fig 4.11. Allowable Bearing Pressures in soil for weathered and sub-weathered layers.

4.5.3 Standard Penetration Test

The Standard Penetration Test (SPT) is an in-situ dynamic penetration test designed to provide information on the geotechnical engineering properties of soil**.** This test can provide useful information in very specific types of soil conditions. This test involves a sample tube, which is thick walled to endure the test environment, is placed at the bottom of a borehole. A heavy slide hammer (140 lbs) is dropped repeatedly 30 inches onto the top of the sample tube, driving it into the soil being tested. The operation entails the operator counting the number of hammer strikes it takes to drive the sample tube 6 inches at a time. Each test drives the sample tube up to 18 inches deep. It is then extracted and if desired a sample of the soil is pulled from the tube. The borehole is drilled deeper and the test is repeated. In cases where 50 blows are insufficient to advance it through a 150 mm (6 in) interval the penetration after 50 blows is recorded. The blow count provides an indication of the density of the ground, and it is used in many empirical geotechnical engineering formulae. SPT unit is the blow counts. Schematic assembly of SPT is shown in Figure 4.12.

The main purpose of the test is to provide an indication of the relative density of granular deposits, such as sands and gravels from which it is virtually impossible to obtain undisturbed samples.

The usefulness of SPT results depends on the soil type, with fine-grained sands giving the most useful results, with coarser sands and silty sands giving reasonably useful results, and clays and gravelly soils yielding results which may be very poorly representative of the true soil conditions. Soils in arid areas, such as the Western United States, may exhibit natural cementation. This condition will often increase the standard penetration value.

One of the most commonly used empirical approaches is based on the measured SPT resistance of the soil. A number of studies have been carried out to identify empirical relationships between SPT and shear wave velocity for different areas.

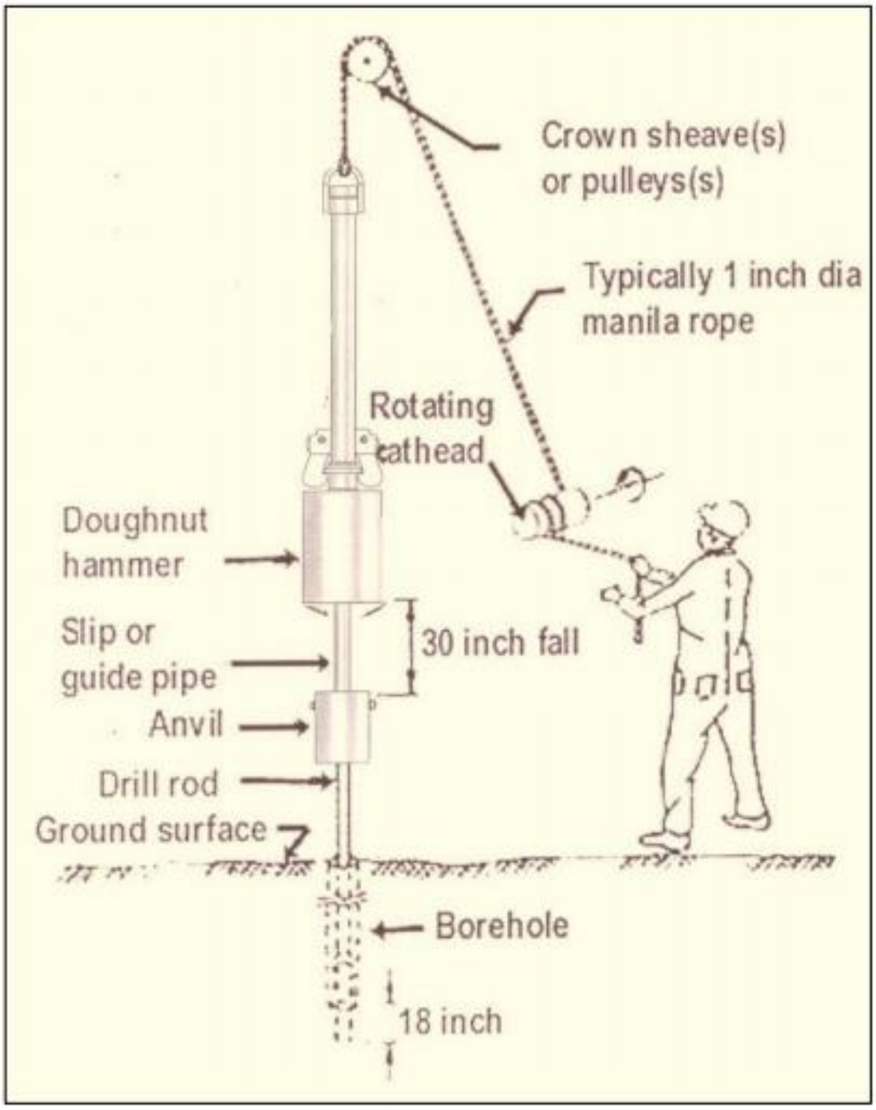


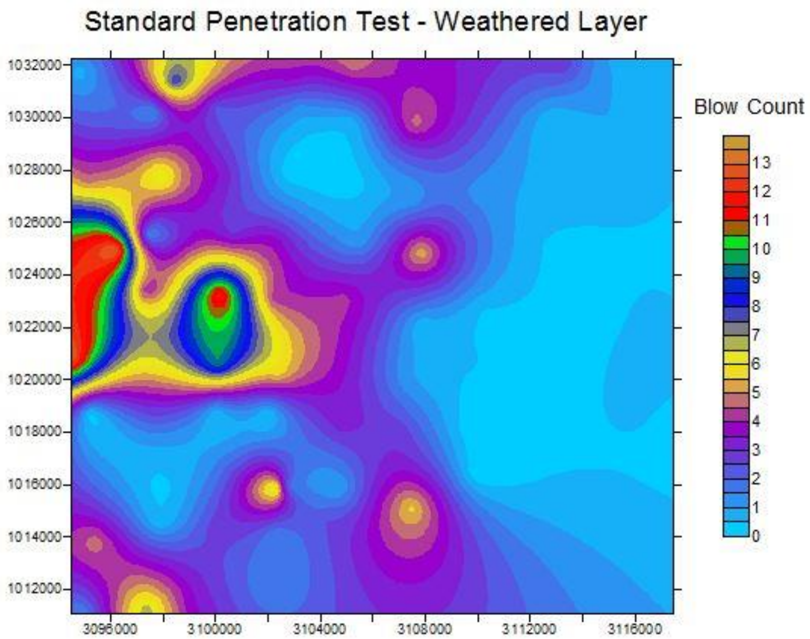
Fig 4.12. Schematic Assembly of SPT

In 1970, Imai and Yoshimura correlated the Standard Penetration Test with the seismic elastic wave properties and formulated a model. Using this Model, SPT is computed and contour maps for weathered and sub-weathered layers are shown in Figure 4.13.

It must be noted that the minimum allowable Standard Penetration SPT value should be 50 for any site construction, thus the top layer soil needs to be compacted thereby survey needs to be re conducted.

Looking at the map given for the Standard Penetration for the Weathered layer, it is indicating that the Western portion has the highest values near 13 Blow Counts which is much lower as compared to the acceptable values. While the rest of the map is shows much lower values for the Blow counts. Thus from this map, it is clear that the weathered layer is not suitable for Engineering construction works and therefore needs to be bulldozed.

The sub-weathered layer SPT contour map shows that in most of the region the SPT is 3500 Blow Count or above. Thus the Standard Penetration Test minimum value is 3500 and goes as high as above 13000 Blow counts. This shows that sub-weathered layer is best for engineering construction.



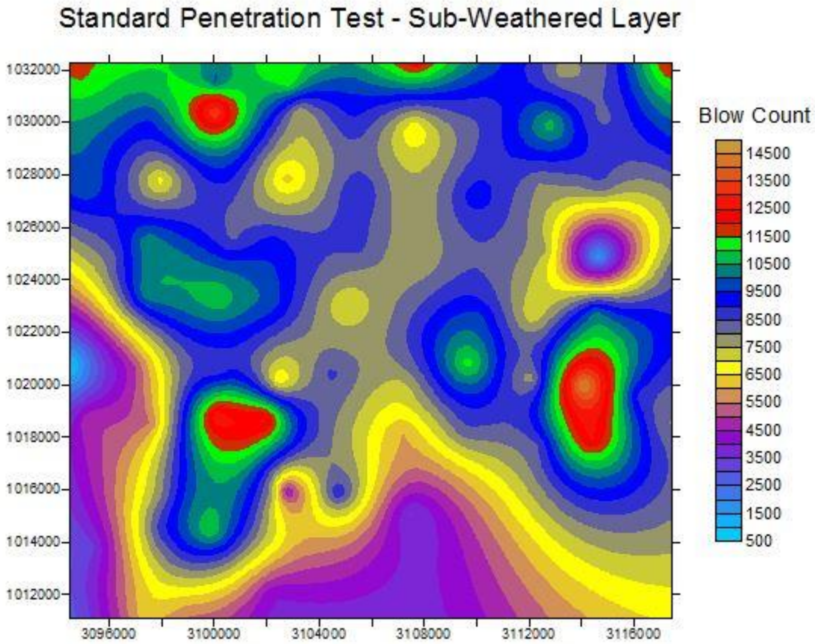


Fig 4.13. Standard Penetration Test in weathered and sub-weathered layers

4.6 Seismic Site Characterisation

Seismicity characterisation is defined as zoning of a site based on the seismicity of the area which is usually based on Horizontal Spectral Amplification of weak and strong motions and then developing various site characterisation standards.

The earthquake hazard of a particular area can be accessed using geophysical and geotechnical site investigations. In the present study, seismic site characterization was carried out to evaluate earthquake risk.

4.6.1 Average Horizontal Spectral Amplification (Weak and Strong Motion)

This technical term is associated with earthquake engineering, incorporated with site response investigation in every micro zonation study. Different approaches in site effect evaluation are used but to enhance the signal to noise ratio and to acquire real data, the most valueable and widely approach is called Horizontal to Vertical Spectral Ratio (H/V) first introduced by Nakamura in 1989, assuming that the vertical component is not amplified by surface layers required the single station recording and uses the vertical component.

Now Average of Spectral ratios over specified period bands provide estimate of ground response useful for summarizing variation on regional scale and variations pertinent for different types of structures. Ratios for period 0.4 to 2.0 sec provide a useful parameter to summarize variations in ground response on a regional scale. These ratios are computed with respect to local Rock sites and results confirms that in general the largest influence of local deposits occurs for horizontal motion at sites underlain by alluvium and mud so maximum average spectral amplification observed at those sites ranges 1.4 to 6.6.

The analysis of aftershock and mainshock data indicates that the spectral shape and amplification is quite different during the main-shock and the aftershock. This, in turn, implies that the use of weak motion/aftershock records may lead to erroneous conclusions regarding the expected ground motion during a strong earthquake. It is a relative parameter and has no units.

Average Horizontal Spectral Amplification (AHSA) for strong motion shows the major Earthquakes motion while the Average Horizontal Spectral Amplification for weak motion shows the amplification motion due to weak energy aftershocks.

The Average Horizontal Spectral Amplification for weak and strong motion have been computed and their spatial distribution is shown in Figure 4.14.

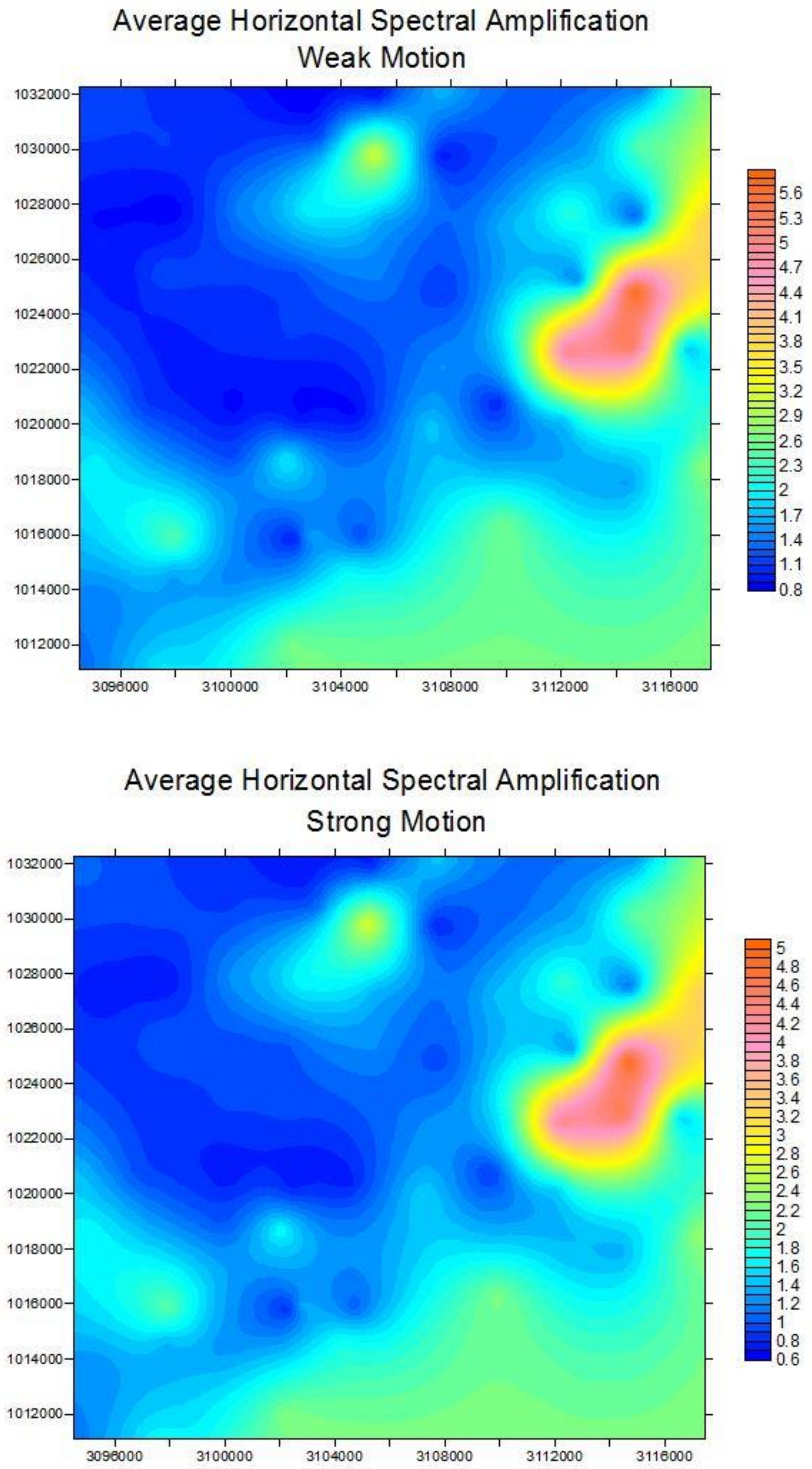


Fig 4.14. Average Horizontal Spectral Amplification (Weak and Strong Motion)

Average Horizontal Spectral Amplification for weak motion generally shows that the major site has low values from 0.8 to 2.7 thereby increasing gradually in the Southern and South-Eastern portion from 2.0 to 2.9. The values become highest in the Eastern portion with values ranging from 3.8 to 5.6.

The strong motion has a similar effect as weak motion. However, its values are slightly lower than the weak motion.

From the maps interpretations, it is clear that the blue shaded regions are safer zones from seismicity point of view and therefore can be used for civil engineering works.

4.6.2 Site Characterisation

National Earthquake Hazard Reduction Program (NEHRP) has developed a site characterisation based on the weak and strong motions. These standards are prepared by Building Seismic Safety Council (BSSC) (2001).

The site characterisation map based on NEHRP has been generated as shown in Figure 4.15.

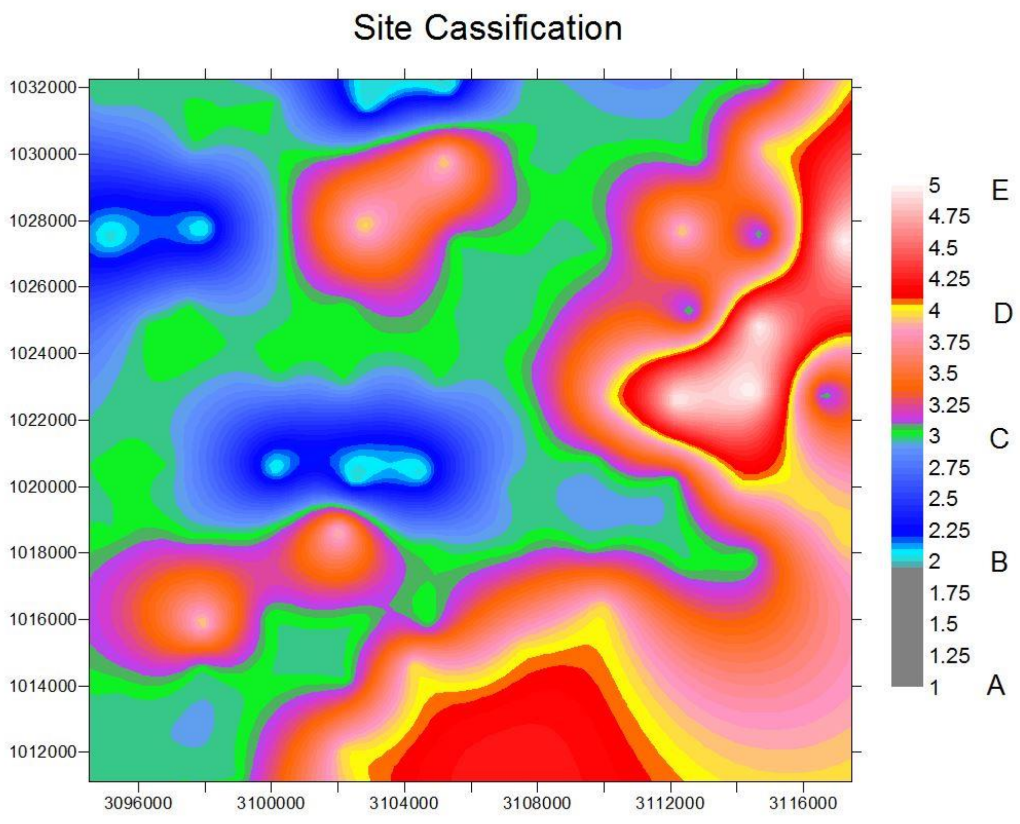


Fig 4.15. Site Characterisation Map of the Study Area.

In the previous figure, A is the most stable zone having value less than 3. According to this map, all the blues are the safer sides while all the red and orange sites are not safe as they all lie in the category D and E which are seismically more hazardous zones. Thus most of the North-Western region and the middle blue region are the safer and stable sites having values almost 2.25. This map also shows the same trend as shown by the AHSA maps.

Chapter 5

Development of a software for generating Seismic based Engineering Parameters

5.1 Introduction

Seismic Refraction method is generally used for mapping weathered layer and other shallow engineering problems. The standard workflow as shown in the previous chapter shows that Seismic Refraction and Uphole logging surveys are carried out to measure the velocities and thicknesses of near surface layers.

Using the Seismic Refraction method, we record the seismic data, pick First Breaks, develop TX Graphs and then finally with the inversion of the Arrival times we compute the velocities and thicknesses of near surface layers. To compute the engineering properties, we need to convert these compressional wave velocities into shear wave velocities, densities and then computes various Elastic parameters which are then finally used in computation of Engineering parameters as well as Seismicity parameters for the characterization of a zone.

As discussed in the previous chapters, a number of scripts were being executed in Visual OIL to compute shear wave velocities, densities, elastic parameters, Engineering Parameters as well as Seismic Parameters. The data points are then exported to Surfer **xyz** files where they are gridded. The Grid files are generated and finally contour maps are generated. The whole procedure was very lengthy and thus takes a lot of time. In addition, if the input velocity is refined, the whole process needs to be repeated.

In this chapter the development of software is discussed which can perform all the above tasks efficiently and accurately on the fly. The main motivation for the development of this program is to develop a single Interactive software which computes all the parameters from the seismic data, internally generates the grids of these parameters and then finally generates a contour map. In this way the software is able to generate map of any parameter on the fly with just a single click.

5.2 System Analysis and Design

The problem domain consists of three steps.

1. Computation of Engineering parameters at each observation location. This is basically x, y and multi z (multiparameters) data.
2. Geostatistical gridding using the Kriging method to generate a grid.
3. Generation of a Contour map.

In System Analysis and Design, we have two approaches for the system.

Approach 1 is illustrated in Figure 5.1

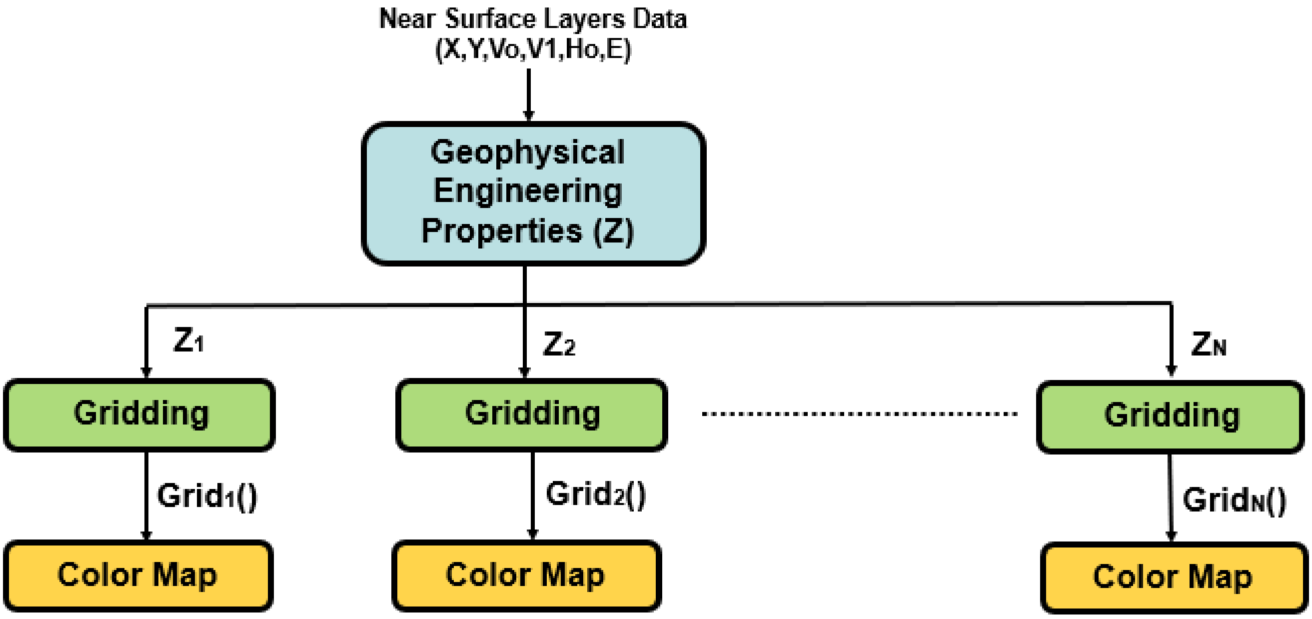


Fig 5.1. Flow Chart for implementing Approach 1

According to this approach, the weathered layer information along with coordinates is input and various Elastic, Engineering and Seismic parameters are computed and stored in arrays. These values are computed at the recorded stations thus they represent the **xyz** data. In the next stage each of these parameters is initially gridded and a separate grid for each of these parameters is computed. The respective grids are then input to the Color Mapping routines to generate Colour Maps.

The major drawbacks of the system are:

- It requires a very large memory because for each parameter, a separate grid array is implemented.
- Once the input file is loaded, the Kriging algorithm for gridding of each of the parameters would take a much longer time. Usually, for an average data set of about 200 to 300 points, it takes 2 to 3 sec, but if there are 25 parameters to be gridded, it would take 50 sec or 1 min. Thus, the user has to wait a much longer time after loading the input file.

The only positive thing about the system is:

- Since all the grids have been pre-computed, later on, when the user selects any parameter on the corresponding contour map would be instantly displayed.

The Second Approach is shown in Figure 5.2.

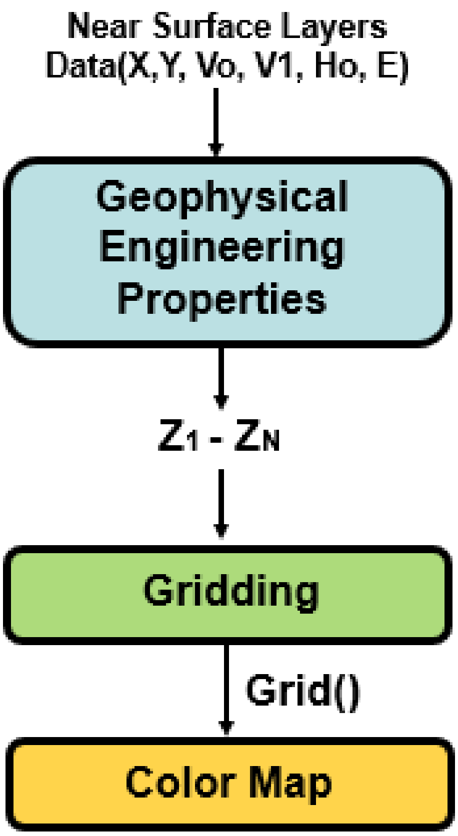


Fig 5.2. Flow Chart for implementing Approach 2

In this approach, the input data of weathered layer velocities is used to compute various Elastic, Engineering and Seismic parameters. As can be seen, instead of having separate grids for each of the parameters; a single grid array is maintained and when the user selects any parameter the geostatistical Kriging algorithm is run and the grid is generated. This grid is then input to Colour Mapping routines to generate Contour map. Practically this system initially computes only the Elastic, Engineering and Seismicity parameters and does not grid these parameters. Gridding is performed only on the selected parameter before generating the Color Map.

The major advantages with this approach are:

- Once the input file is loaded, the software generates a single grid of weathered layer velocity which takes just a second to display a Colour map.
- It uses a much smaller memory whereas 25 memory arrays were maintained for previous Approach.

The only drawback with this approach is:

- On user's selection, it performs the geostatistical gridding which takes a longer time. However, the back-end computational libraries are very fast, therefore the gridding process is computed within a second and the user instantly gets the Color Map display.

After System and Analysis and Design, this 2nd Approach is selected for the development of the system.

5.3 Seismic Engineering Engine (SEE)

The software that has been developed to compute these Engineering parameters and is titled as Seismic Engineering Engine. The source code of the program is listed in Annexure A. The block diagram of the system is shown in the Figure 5.3.

It can be seen from the figure that the weathered layer information in the form of Northing/ Easting Coordinates, Velocities of weathered and sub-weathered layers, their Thickness as well as Elevation is used as input.

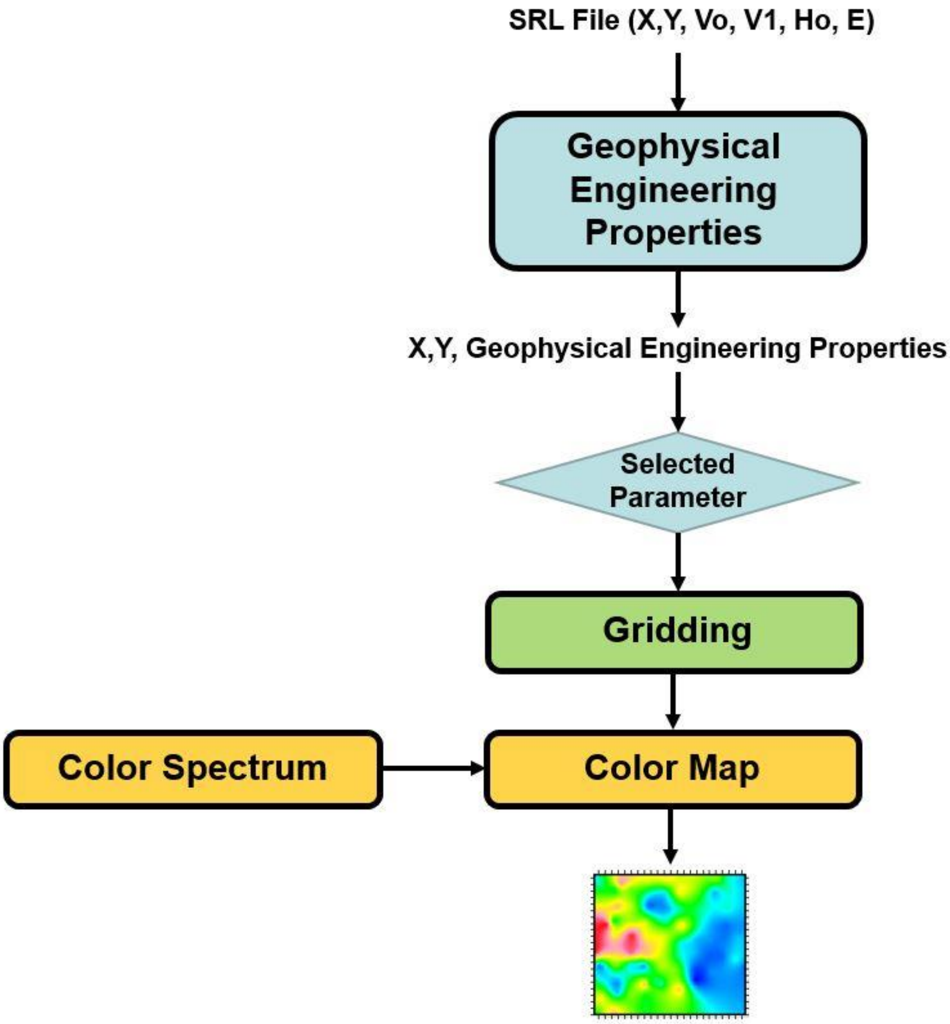


Fig 5.3. Seismic Engineering Engine Work Flow.

From the above figure it can be seen that in the first stage, all the Geophysical Engineering parameters which include Shear-wave velocities, Densities, Elastic parameters, different Engineering as well as Seismicity parameters are computed. The selected parameter is gridded and the grid is input to the Colour Mapping system. Color spectrums for each parameter have been pre-defined and are used to generate color maps.

5.3.1 Working of Seismic Engineering Engine

The interface of the Software is shown in Figure 5.4. From the figure it can be seen that the interface has a single button which is used to select the input Weathered Layer data file. Once the data file is loaded, the software computes all the Engineering parameters at the input locations. A tree listing all the parameters is displayed on the left side. Clicking any parameter on the tree results in generating its Color Map. In this way the software provides a highly efficient facility for computation and visualization of these parameters.

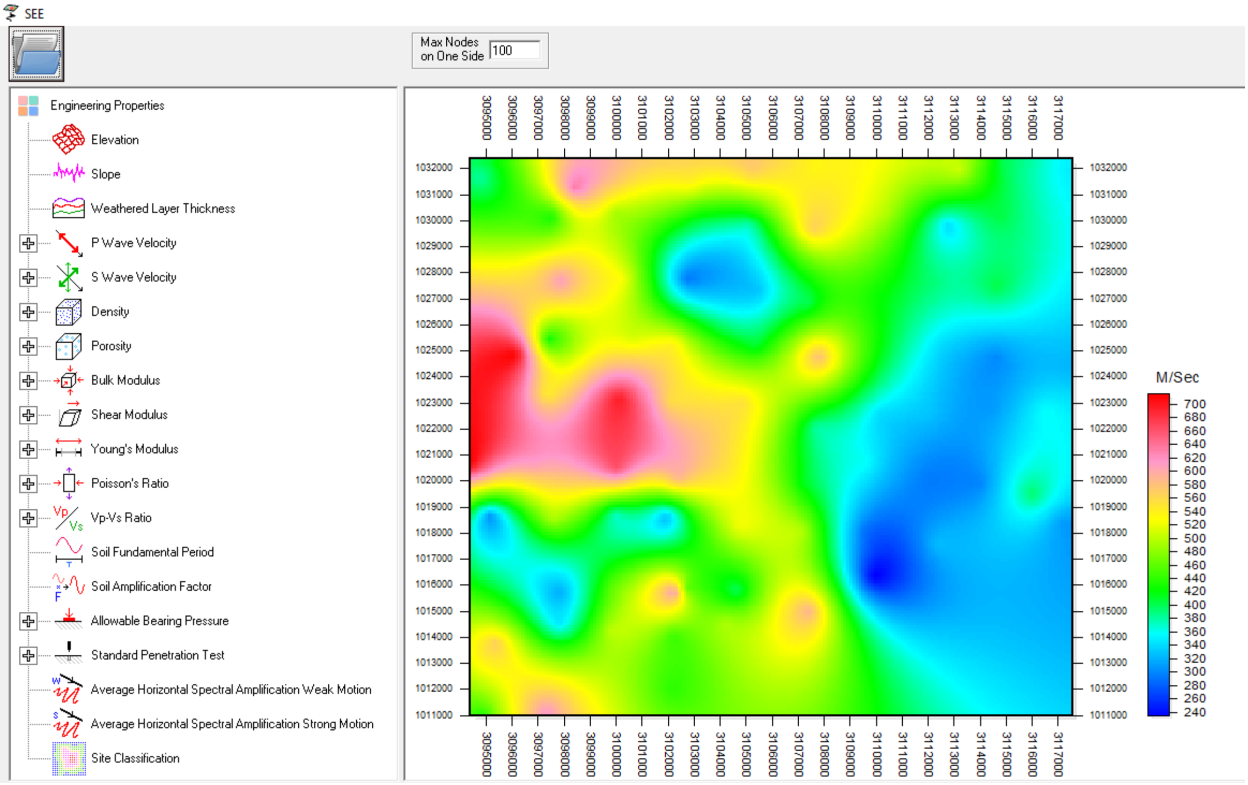


Fig 5.4. Seismic Engineering Engine Interface

Figure 5.5 shows some selected colour maps generated by the software. It can be seen from the tree shown on the left side; whatever the parameter is selected, that parameter is gridded and the Contour maps are instantly generated.

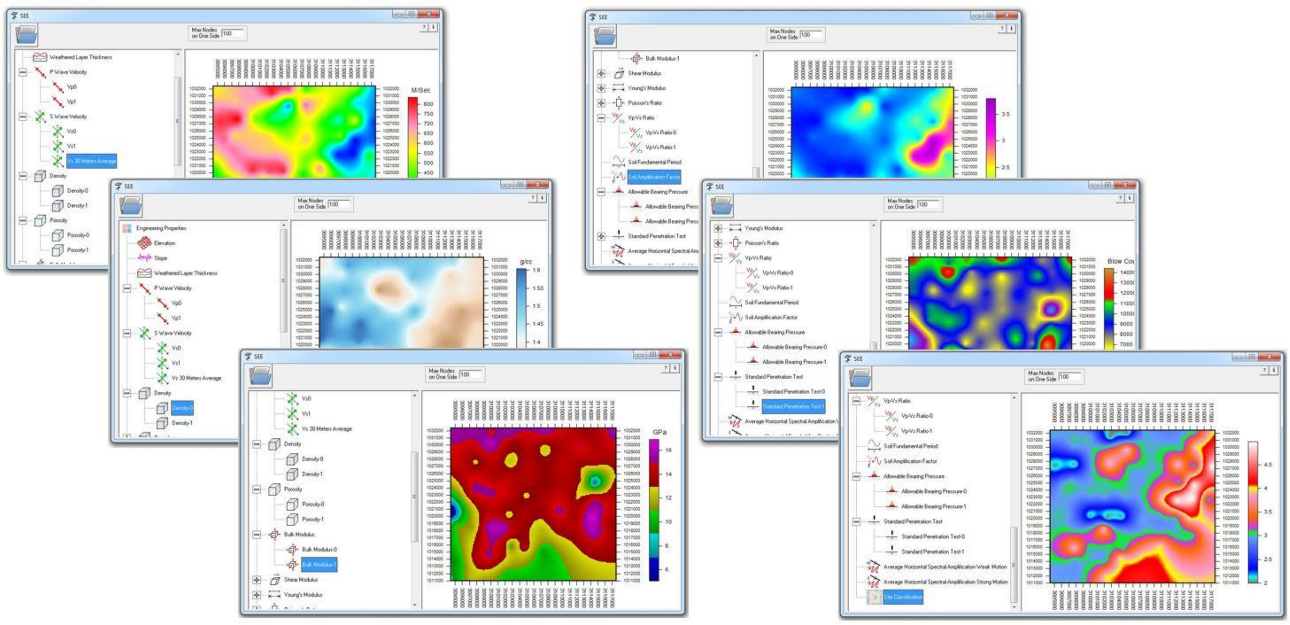


Fig 5.5. Selected Colour maps generated by the software

5.3.2 Development of Seismic Engineering Engine

The software has been written in Microsoft Visual Studio along with Component Object Model (COM)/.NET framework.

The software has been developed using the following GeoStudio Libraries.

- General Library - general computation.
- GeoStat Library - Kriging based grid file generation.
- GridPro Library - Reading and Writing grids and Computation of Slopes.
- GeopEngg Library – Computation of Geopyhsical Engineering parameters.
- Grid Map Library - Generating Colour Maps.
- ColourSpectrum Library – Using Colour Spectrums in Colour Maps.

For computation of Engineering properties, a Geophysical Engineering Class has been created which is able to compute the following parameters.

- Shear Wave Velocity (Lee, 2010).
- Slope/ Dip.
- Density (Gardner, 1974).
- Porosity.
- Bulk Modulus.
- Shear Modulus.
- Young's Modulus.
- Poisson's Ratio.
- Vp/Vs Ratio.
- Soil Fundamental Period (Kanai, 1983).
- Soil Amplification Factor (Midorikawa, 1987).
- Allowable Bearing Pressure (Uchiyama, 1984).
- Standard Penetration Test (Imai, 1970).
- Average Horizontal Spectral Amplification-Weak Motion (Borcherdt et al., 1991).
- Average Horizontal Spectral Amplification-Strong Motion (Borcherdt et al., 1991).
- Site Classification (BSSC, 2001).

5.3.3 Conclusions

The software is useful for engineering works as it instantly provides the spatial variation of any parameter. This is quite help for quick interpretation and decision making.

Conclusions and Recommendations

Conclusions

- Near surface Seismic Refraction and Uphole Logging survey of Jand area was carried out to monitor and characterise the Engineering properties of the area for the construction of Industrial zones.
- The area has a thin weathered layer ranging from 2 to 10 meters with a velocity ranging from 250 to 750 meters, while the sub-weathered layer velocity ranges from 2000 to 3400 meters. The area has a stable topographic variation and the general maximum dip in the area based on slope analysis is below 5. Thus, from topographic point of view, this area is easily accessible for an Industrial site.
- Various Engineering parameters computed from Seismic Refraction velocities data such as Soil Amplification Factor, Allowable Bearing Pressure, Standard Penetration Test indicates that the Eastern portion of the area is not suitable for construction of any Industrial site.
- The computed Seismicity parameters such as Average Horizontal Spectral Amplification also confirms the previous Engineering properties and indicates that the Eastern area is not suitable.
- Based on National Earthquake Hazard Reduction Program (NEHRP), the site has been characterised. Accordingly, South-Eastern portion of the region lies in the Zone 5 of the characterisation which is highly unstable zone and not suitable for construction. While rest of the area except small patches between Zone 2 to Zone 3 are acceptable.

Recommendations

- Standard Penetration Test indicates the Eastern portion has lowest values of less than 10 Blow counts. The whole area has SPT value below 20 whereas the minimum acceptable value is 50 Blow counts. Since the weathered layer thickness is just 2 to 10 meters so therefore, it is recommended that the weathered layer should be bulldozed before any construction for an Industrial site.
- In addition to this geophysical engineering study, an interactive and highly efficient Engineering and Seismic parameters computation software has been created which can compute and generate Contour maps of all Engineering and Seismicity parameters on the fly. It is recommended that this software should be used for quick visualisation and interpretation of all the parameters for efficient Engineering decisions.

Annexure A

Module: frmMain.frm

```
Dim DatLoad As Boolean
Dim mKey$

Private Sub Form_Load()
'Parent(Relative):Key, Relationship(Child),Own Name:Key, Text Description, Image:Key from ImageList
tvwEP.Nodes.Add , , "EP", "Engineering Properties", "EP"
 tvwEP.Nodes.Add "EP", tvwChild, "E", "Elevation", "E"
 tvwEP.Nodes.Add "EP", tvwChild, "DEG", "Slope", "DEG"
 tvwEP.Nodes.Add "EP", tvwChild, "H0", "Weathered Layer Thickness", "H0"
 tvwEP.Nodes.Add "EP", tvwChild, "VP", "P Wave Velocity", "VP"
  tvwEP.Nodes.Add "VP", tvwChild, "VP0", "Vp0", "VP"
  tvwEP.Nodes.Add "VP", tvwChild, "VP1", "Vp1", "VP"
 tvwEP.Nodes.Add "EP", tvwChild, "VS", "S Wave Velocity", "VS"
  tvwEP.Nodes.Add "VS", tvwChild, "VS0", "Vs0", "VS"
  tvwEP.Nodes.Add "VS", tvwChild, "VS1", "Vs1", "VS"
  tvwEP.Nodes.Add "VS", tvwChild, "VS30", "Vs 30 Meters Average", "VS"
 tvwEP.Nodes.Add "EP", tvwChild, "D", "Density", "D"
  tvwEP.Nodes.Add "D", tvwChild, "D0", "Density-0", "D"
  tvwEP.Nodes.Add "D", tvwChild, "D1", "Density-1", "D"
 tvwEP.Nodes.Add "EP", tvwChild, "POR", "Porosity", "POR"
  tvwEP.Nodes.Add "POR", tvwChild, "POR0", "Porosity-0", "POR"
  tvwEP.Nodes.Add "POR", tvwChild, "POR1", "Porosity-1", "POR"
 tvwEP.Nodes.Add "EP", tvwChild, "BM", "Bulk Modulus", "BM"
  tvwEP.Nodes.Add "BM", tvwChild, "BM0", "Bulk Modulus-0", "BM"
  tvwEP.Nodes.Add "BM", tvwChild, "BM1", "Bulk Modulus-1", "BM"
 tvwEP.Nodes.Add "EP", tvwChild, "SM", "Shear Modulus", "SM"
  tvwEP.Nodes.Add "SM", tvwChild, "SM0", "Shear Modulus-0", "SM"
  tvwEP.Nodes.Add "SM", tvwChild, "SM1", "Shear Modulus-1", "SM"
 tvwEP.Nodes.Add "EP", tvwChild, "YM", "Young's Modulus", "YM"
  tvwEP.Nodes.Add "YM", tvwChild, "YM0", "Young's Modulus-0", "YM"
  tvwEP.Nodes.Add "YM", tvwChild, "YM1", "Young's Modulus-1", "YM"
 tvwEP.Nodes.Add "EP", tvwChild, "PR", "Poisson's Ratio", "PR"
  tvwEP.Nodes.Add "PR", tvwChild, "PR0", "Poisson's Ratio-0", "PR"
  tvwEP.Nodes.Add "PR", tvwChild, "PR1", "Poisson's Ratio-1", "PR"
 tvwEP.Nodes.Add "EP", tvwChild, "VPS", "Vp-Vs Ratio", "VPS"
  tvwEP.Nodes.Add "VPS", tvwChild, "VPS0", "Vp-Vs Ratio-0", "VPS"
  tvwEP.Nodes.Add "VPS", tvwChild, "VPS1", "Vp-Vs Ratio-1", "VPS"
 tvwEP.Nodes.Add "EP", tvwChild, "SFP", "Soil Fundamental Period", "SFP"
 tvwEP.Nodes.Add "EP", tvwChild, "SAF", "Soil Amplification Factor", "SAF"
 tvwEP.Nodes.Add "EP", tvwChild, "ABP", "Allowable Bearing Pressure", "ABP"
  tvwEP.Nodes.Add "ABP", tvwChild, "ABP0", "Allowable Bearing Pressure-0", "ABP"
  tvwEP.Nodes.Add "ABP", tvwChild, "ABP1", "Allowable Bearing Pressure-1", "ABP"
 tvwEP.Nodes.Add "EP", tvwChild, "SPT", "Standard Penetration Test", "SPT"
  tvwEP.Nodes.Add "SPT", tvwChild, "SPT0", "Standard Penetration Test-0", "SPT"
  tvwEP.Nodes.Add "SPT", tvwChild, "SPT1", "Standard Penetration Test-1", "SPT"
 tvwEP.Nodes.Add "EP", tvwChild, "AHSAw", "Average Horizontal Spectral Amplification Weak Motion", "AHSAw"
 tvwEP.Nodes.Add "EP", tvwChild, "AHSAs", "Average Horizontal Spectral Amplification Strong Motion", "AHSAs"
 tvwEP.Nodes.Add "EP", tvwChild, "SC", "Site Classification", "SC"

End Sub

Private Sub Form_Resize()
On Error Resume Next

fmW& = frmMain.Width
fmH& = frmMain.Height
picMain.Width = fmW - picMain.Left - 255
picMain.Height = fmH - picMain.Top - 600
tvwEP.Height = picMain.Height
cmdHelp.Left = frmMain.Width - 885
cmdInfo.Left = frmMain.Width - 585

RefreshGraphics mKey
End Sub

Private Sub cmdOpen_Click()
DatLoad = True
```

```
Dim File$, ft%
CommonDialog frmMain.CommonDialog1, "SeiRA List File(.srl)|*.srl", "c:\igs\dat\sra", "sra", "Load Weathered Layer Data", "o", File$, ft%
If File = "" Then Exit Sub            'If no file selected then returns back
ReadSRL App.Path & "\dat\dkn3d.srl"     'Read SRL File
AllocMemory                           'Acclocate Arrays
ComputeGeopEnggProp                   'Compute Geophysical Engineering Parameters
Gridding VP0()
Mapping frmMain.picMain, App.Path & "\dat\Color-V.clr", "M/Sec"
mKey = "VP0"
End Sub

Private Sub cmdHelp_Click()
ShellExecute Me.hWnd, vbNullString, App.Path & "\SEE.pdf", vbNullString, vbNullString, vbNormalFocus
End Sub

Private Sub cmdInfo_Click()
frmInfo.Show 1
End Sub

Private Sub tvwEP_NodeClick(ByVal Node As MSComctlLib.Node)
'Call Grrding with selected Parameter Data Array

If DatLoad = False Then Exit Sub

mKey$ = Node.Key

If mKey = "E" Then
 Gridding Elev()
ElseIf mKey = "DEG" Then
 Gridding Elev()
 SlopeAnalysis
ElseIf mKey = "H0" Then
 Gridding H0()
ElseIf mKey = "VP0" Then
 Gridding VP0()
ElseIf mKey = "VP1" Then
 Gridding VP1()
ElseIf mKey = "VS0" Then
 Gridding VS0()
ElseIf mKey = "VS1" Then
 Gridding VS1()
ElseIf mKey = "VS30" Then
 Gridding VS30()
ElseIf mKey = "D0" Then
 Gridding D0()
ElseIf mKey = "D1" Then
 Gridding D1()
ElseIf mKey = "POR0" Then
 Gridding POR0()
ElseIf mKey = "POR1" Then
 Gridding POR1()
ElseIf mKey = "BM0" Then
 Gridding BM0()
ElseIf mKey = "BM1" Then
 Gridding BM1()
ElseIf mKey = "SM0" Then
 Gridding SM0()
ElseIf mKey = "SM1" Then
 Gridding SM1()
ElseIf mKey = "YM0" Then
 Gridding YM0()
ElseIf mKey = "YM1" Then
 Gridding YM1()
ElseIf mKey = "PR0" Then
 Gridding PR0()
ElseIf mKey = "PR1" Then
 Gridding PR1()
ElseIf mKey = "VPS0" Then
 Gridding VPS0()
ElseIf mKey = "VPS1" Then
 Gridding VPS1()
ElseIf mKey = "SFP" Then
```

```
  Gridding SFP()
ElseIf mKey = "SAF" Then
  Gridding SAF()
ElseIf mKey = "ABP0" Then
  Gridding ABP0()
ElseIf mKey = "ABP1" Then
  Gridding ABP1()
ElseIf mKey = "SPT0" Then
  Gridding SPT0()
ElseIf mKey = "SPT1" Then
  Gridding SPT1()
ElseIf mKey = "AHSAw" Then
  Gridding AHSAw()
ElseIf mKey = "AHSAs" Then
  Gridding AHSAs()
ElseIf mKey = "SC" Then
  Gridding SC()
End If
RefreshGraphics mKey
End Sub

Private Sub RefreshGraphics(Key$)
'Generate Color Map for the Selected Parameter by using the appropriate Color Spectrum & Units

If Key = "E" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-E.clr", "Meters"
ElseIf Key = "DEG" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-DEG.pal", "º"
ElseIf Key = "H0" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-H0.clr", "Meters"
ElseIf Key = "VP0" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-V.clr", "M/Sec"
ElseIf Key = "VP1" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-V.clr", "M/Sec"
ElseIf Key = "VS0" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-V.clr", "M/Sec"
ElseIf Key = "VS1" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-V.clr", "M/Sec"
ElseIf Key = "VS30" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-V.clr", "M/Sec"
ElseIf Key = "D0" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-D.clr", "g/cc"
ElseIf Key = "D1" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-D.clr", "g/cc"
ElseIf Key = "POR0" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-POR.clr", "%"
ElseIf Key = "POR1" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-POR.clr", "%"
ElseIf Key = "BM0" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-PR.clr", "GPa"
ElseIf Key = "BM1" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-PR.clr", "GPa"
ElseIf Key = "SM0" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-PR.clr", "GPa"
ElseIf Key = "SM1" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-PR.clr", "GPa"
ElseIf Key = "YM0" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-PR.clr", "GPa"
ElseIf Key = "YM1" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-PR.clr", "GPa"
ElseIf Key = "PR0" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-PR.clr", ""
ElseIf Key = "PR1" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-PR.clr", ""
ElseIf Key = "VPS0" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-V.clr", ""
ElseIf Key = "VPS1" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-V.clr", ""
ElseIf Key = "SFP" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-SFP.clr", "Sec"
ElseIf Key = "SAF" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-SAF.clr", ""
```

```
ElseIf Key = "ABP0" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-ABP.clr", "psi"
ElseIf Key = "ABP1" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-ABP.clr", "psi"
ElseIf Key = "SPT0" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-SPT.clr", "Blow Count"
ElseIf Key = "SPT1" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-SPT.clr", "Blow Count"
ElseIf Key = "AHSAw" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-AHSA.clr", ""
ElseIf Key = "AHSAs" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-AHSA.clr", ""
ElseIf Key = "SC" Then
  Mapping frmMain.picMain, App.Path & "\dat\Color-SC.clr", ""
End If
End Sub
```

Module:DataProcess.Bas

```
Dim ge As New GeopEngg          'Create an Instance of Geophysical Engineering Class
Dim gn As New General           'Create an Instance of General Library
Dim gp As New GridPro           'Create an Instance of GridPro Library
Dim gs As New GeoStat           'Create an Instance of GeoStat Library
Dim gm As New GridMaps          'Create an Instance of GridMaps Library
Dim cs As New ColorSpectrum     'Create an Instance of ColorSpectrum Library


                'Data Memory Arrays for Input SRL File: [X,Y,E,Ho,Vo,V1] (X,Y,Muti-Z)
Dim LName$(), PktNo&(), Xe#(), Yn#()
Global Elev#(), H0#(), VP0#(), VP1#(), n&

                'Data Memory Arrays for Computed Geophysical Properties] (Muti-Z)
Global D0#(), D1#(), VS0#(), VS1#(), VS30#()
Global POR0#(), POR1#(), BM0#(), BM1#(), YM0#(), YM1#(), SM0#(), SM1#(), PR0#(), PR1#(), VPS0#(), VPS1#()
Global SFP#(), SAF#(), ABP0#(), ABP1#(), SPT0#(), SPT1#()
Global AHSAw#(), AHSAs#(), SC#()

Dim Grid#()          'Grid Data Array
Dim Xmin#, Xmax#, Ymin#, Ymax#, Zmin#, Zmax#
Dim GridXN&, GridYN&
Dim gridstepX#, gridstepY#

                'Color Spectrum Nodes Array
Dim NodeCol&(1024), NodePos#(1024), csM%
Dim ColSpec&(256), csN%     'Color Spectrum Array & Variables

Public Sub ReadSRL(File As String)
'Read SeiRA List (SRL) File
'File = File Name

Dim fn%, hdr$, i&       'temp variables

n = GetDataCount(File)      'Get Dataset Records Count & Allocate the Arrays Size
ReDim LName$(n), PktNo&(n), Xe#(n), Yn#(n), Elev#(n), H0#(n), VP0#(n), VP1#(n)

fn = FreeFile          'Open File
Open File For Input As #fn

Input #fn, hdr, hdr       'Read Header
For i = 1 To 4
  Line Input #fn, hdr
Next

i = 0            'Read Data
Do
  i = i + 1
  Input #fn, LName$(i), PktNo&(i), Xe#(i), Yn#(i), Elev#(i), hdr$, VP0#(i), H0#(i), VP1#(i)
Loop Until EOF(fn)

Close #fn           'Close File
End Sub
Private Function GetDataCount(File As String) As Long
```

```
'Return the Number of Records in the Dataset
'File = File Name

Dim fn%, i&, dat$            'temp variables

fn = FreeFile
Open File For Input As #fn
i = 0
Do
  i = i + 1
  Line Input #fn, dat$
Loop Until EOF(fn)
Close #fn
GetDataCount = i - 5
End Function

Public Sub AllocMemory()
'Allocate the Size of the Output Multi-Z Arrays (Geophysical Engineering Properties)

ReDim D0#(n), D1#(n), VS0#(n), VS1#(n), VS30#(n)
ReDim POR0#(n), POR1#(n), BM0#(n), BM1#(n), YM0#(n), YM1#(n), SM0#(n), SM1#(n), PR0#(n), PR1#(n), VPS0#(n), VPS1#(n)
ReDim SFP#(n), SAF#(n), ABP0#(n), ABP1#(n), SPT0#(n), SPT1#(n)
ReDim AHSAw#(n), AHSAs#(n), SC#(n)
End Sub

Public Sub ComputeGeopEnggProp()
'Compute Geophysical Engineering Properties Multi-Z Arrays

Dim i&                   'temp variable

With ge
  For i = 1 To n
    VS0(i) = .SWaveVelocity(VP0(i))
    VS1(i) = .SWaveVelocity(VP1(i))
    VS30(i) = .SVel30MAve(VS0(i), VS1(i), H0(i))
    D0#(i) = .Density(VP0(i))
    D1#(i) = .Density(VP1(i))

    POR0#(i) = .Porosity(D0#(i))
    POR1#(i) = .Porosity(D1#(i))
    BM0#(i) = .BulkModulus(VP0(i), VS0(i), D0#(i))
    BM1#(i) = .BulkModulus(VP1(i), VS1(i), D1#(i))
    SM0#(i) = .ShearModulus(VS0(i), D0#(i))
    SM1#(i) = .ShearModulus(VS1(i), D1#(i))
    YM0#(i) = .YoungsModulus(BM0(i), SM0#(i))
    YM1#(i) = .YoungsModulus(BM1(i), SM1#(i))
    PR0#(i) = .PoissonsRatio(VP0(i), VS0(i))
    PR1#(i) = .PoissonsRatio(VP1(i), VS1(i))
    VPS0#(i) = .PSVelocityRatio(BM0(i), SM0#(i))
    VPS1#(i) = .PSVelocityRatio(BM1(i), SM1#(i))

    SFP#(i) = .SoilFundamentalPeriod(VS0(i), VS1(i), H0(i))
    SAF#(i) = .SoilAmplification(VS30(i))
    ABP0#(i) = .ABP(VS0(i))
    ABP1#(i) = .ABP(VS1(i))
    SPT0#(i) = .SPT(VS0(i))
    SPT1#(i) = .SPT(VS1(i))

    AHSAw#(i) = .AHSAWeak(VS30(i))
    AHSAs#(i) = .AHSAStrong(VS30(i))
    SC(i) = .NEHPRSiteClass(VS30(i))
  Next
End With
End Sub

Public Sub Gridding(Z#())
'Grid the Input Z data

frmMain.MousePointer = vbHourglass

                  'Read XYZ Data
'gs.ReadXYZData App.Path & "\Dat\DKN-VS0.dat", X(), Y(), Z(), N
```

```
Dim mn%                     'Temp Variable


                        'Geostatistical Gridding
                              'Compute Min Max of Input XYZ Data
gs.GridMinMax Xe(), Yn(), Z(), n, Xmin#, Xmax#, Ymin#, Ymax#, Zmin#, Zmax#

mn = Val(frmMain.txtMaxNodes)         'Set Number of Grid Nodes in X & Y Direction with Maximum 100 Nodes along the longest side
If mn <= 2 Then
  MsgBox "Minimum Grid Resolution is 3 Nodes.", vbCritical
  mn = 3
  frmMain.txtMaxNodes = 3
End If
If mn > 300 Then
  MsgBox "Maximum Grid Resolution is 300 Nodes.", vbCritical
  mn = 300
  frmMain.txtMaxNodes = 300
  DoEvents
End If
gs.GridNodes Xmin#, Xmax#, Ymin#, Ymax#, mn, GridXN&, GridYN&
gs.SetSearch 0                   'Kriging: No Search, use all samples for interpolation
gs.SetVariogram 0, 1000, 4000, 100     'Kriging: Set Linear Variogram
                              'Geostatistical Grid Nodes Interpolation using Kriging
gs.GridKriging Xe(), Yn(), Z(), n, Xmin#, Xmax#, Ymin#, Ymax#, Zmin#, Zmax#, Grid(), GridXN, GridYN

                        'Write the computed Grid Data in Surfer Format
gp.WriteSurferGrid App.Path & "\Dat\tmp.grd", Grid(), GridXN, GridYN, Xmin#, Ymin#, Xmax#, Ymax#, Zmin#, Zmax
                        'Read the Grid Data from Surfer Format
gp.ReadSurferGrid App.Path & "\Dat\tmp.grd", Grid(), GridXN, GridYN, Xmin#, Ymin#, Xmax#, Ymax#, Zmin#, Zmax, gridstepX, gridstepY

frmMain.MousePointer = vbDefault
End Sub

Public Sub SlopeAnalysis()
'Compute Dips from Elevation (DEM) Data

Dim GridBuf#()             'Create a Temporary Grid Buffer
                        'Copy the Elevation (DEM) Grid Data to the Temporary Grid Buffer
gp.CopyGrid Grid(), GridBuf(), GridXN, GridYN
                        'Input the Input Temporary Grid with Elevations, compute Dips and output them to the main Grid Array
gp.Slope_2FD GridBuf(), GridXN, GridYN, gridstepX, gridstepY, Grid()
                        'COmpute Min Max of the Dips
gp.GridMinMax Grid(), GridXN, GridYN, Zmin#, Zmax#
End Sub


Public Sub Mapping(obj As Object, CSFile$, Units$)
'nerate Smoothed Color Maps

                        'Temp Variables
Dim XDMin#, YDMin#, XDMax#, YDMax#

                        'Read Color Spectrum
If LCase(Right(CSFile, 3)) = "clr" Then
  cs.ReadSurferCLR CSFile, NodeCol(), NodePos(), csM
  cs.GenerateColorSpectrum NodeCol(), NodePos(), csM, ColSpec(), csN, 256
Else
  cs.ReadAllPAL CSFile, ColSpec(), csN
End If

                        'Map Color Spectrum to Data Min-Max Range
gm.SetColorSpectrum ColSpec(), csN, Zmin, Zmax

gm.SetOrigin 60, 60          'Set Map Origin
                        'Set Map View Area
gm.SetView obj.ScaleWidth - 195, obj.ScaleHeight - 125

                        'Set Data XY Min-Max Range & Grid Increments
gm.SetDataMinMax Xmin, Ymin, Xmax, Ymax, gridstepX, gridstepY
gm.SetScale obj, , 1         'Set Color Maps Scale/Zoom
```

```
obj.Cls                    'Clear DIsplay Area

                           'Draw Color Spectrum Legend
gm.GetDataMinMax XDMin#, YDMin#, XDMax#, YDMax#
intvc! = gn.GetInterval(Zmin, Zmax)
cs.DrawVLegend obj, gm.gx(XDMax) + 70, gm.gy(YDMin), 20, 300, ColSpec(), csN, Zmin, Zmax, intvc, , , Units$, , 1

                           'Display Color Map
gm.ColorMap obj, Grid#(), GridXN&, GridYN&
gm.ColorSmoothedMap obj, Grid(), GridXN, GridYN

                           'Display Map Boundary
gm.MapBoundary obj, QBColor(0), 2, 1

                           'Display Map Annotations
intvx# = gn.GetInterval(Xmin, Xmax)
gm.GridAxisAnnotation obj, intvx, , , , 3, 3

frmMain.MousePointer = vbDefault

End Sub
```

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December 8, 2019

Near Surface Seismic Data for Engineering Studies.

Ms. Sana Kayani, BS Geophysics student, Quaid-i-Azam University, Islamabad, has been provided Seismic Refraction and Uphole Logging data of Jand Area to carry out engineering studies of the site as part of her thesis research work.

The student is required to submit the outcome of the research work to Xian Senshe Electronic Technology Corporation (Pvt) Ltd.

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