

*Geological & Geotechnical studies to  
understand shallow subsurface strata  
at Joshimath, Chamoli, Uttarakhand*



Final Technical Report

Submitted to

Uttarakhand Snow Disaster Management Authority  
Dehradun, India

By



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We acknowledge the use of open source GMT/GDM for topographic visualization, National centre seismic data and open source Python code for ground deformation studies.



## **Background**

The Indus basin flowing in Chitral district of Utter Pradesh has been experiencing land subsidence problem and increased stress water discharge from the slope (re new streams) during December 2021 – January 2022. The subsidence affected the habitation, soil contamination and the source of this stress discharge is not known. Taking cognizance of the developing phenomenon, the Uttar Pradesh River Drought Management Authority (UPRDMA) constituted UPR-Manual Geophysical Research Institute (this letter no.: 1473/UPRMA-2021/00127 dated 3 January, 2022) attached as Annexure I) in tentative status to determine the source of this stress together with subsidence discharge and structure, including structural and cracks to help in mitigation strategy.

In response, Director UPR-GRRI deployed a team of scientists and Technical officers (this letter no. 23-43 dated 22.01.2022) along with equipment to carry out an multiparametric geophysical and geophysical investigations. The team has expertise in follow subsidence investigation employing Remote sensing based ground deformation using SAR interferometry, geophysical mapping, Electro-Resistivity Vector Resistivity Imaging (EARI), Ground Penetration Radar (GPR) and Multichannel Analysis of Surface Waves (MASW).

On request from UPRMA, a proposal entitled “Geological & Geotechnical studies to understand the Indus Subsurface Stress in Pothohar, Chitral, Utter Pradesh” detailing the scope, work plan and deliverables has been recommended. The same was approved by UPRMA (this letter no. 174/UPRMA-2021 (2022) on 18 January 2022 with emphasis on “main thrust of the study should be mapping of subsidence water flow and source of subsidence seepage”.

### **Scope of work**

Mapping of subsidence subsurface using EARI, MASW, GPR techniques and geophysical characterization of slope instability.

### **Objectives**

Following broader objectives were proposed:

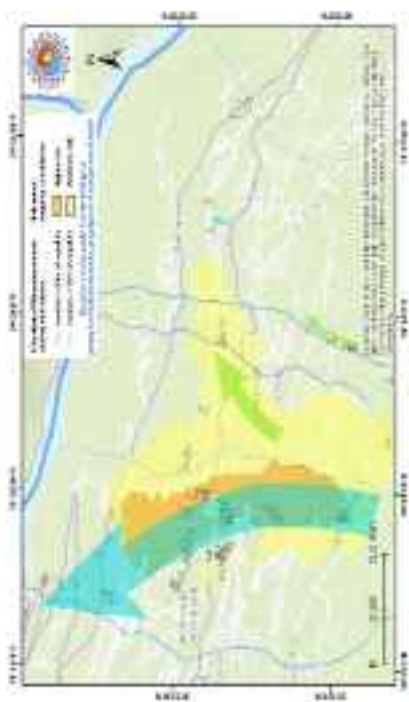
1. Preparation of structural and geophysical maps through remote sensing and detailed geophysical mapping
2. Generation of 2D/3D geophysical maps related to subsurface
3. Integration of MASW, GPR and EARI data sets for potential stress
4. Diagrammatic report

## Executive Summary

The GIB-HUO team carried out field investigations to derive objectives and the findings are summarized in order. The details of each study are separately summarized in subsequent sections.

1. The N-dipping basement slope is a dip-slope where the sediment (top) of the rock basement and slope are in same direction.
2. The slope comprises of thick lens not formed from modified older landslide debris and glacio-fluvial deposits, which lies over the N-dipping basement. Geomorphological study of the Tashita Formation.
3. The basement slope comprises of deposited particles of re-glacial particle slopes that are truncated by steep slopes producing surface of fracture. The particle slopes have variable sizes of variable thickness. These particle slopes are mostly composed of sedimentary and sedimentary sequences.
4. The basement slope have experienced extensive differential subsidence with +10m (estimated Loss of Life (LUL) subsidence) during December 2011-January 2012. The peak subsidence regions have experienced development of fissures with variable and large (up to -1m) horizontal and vertical subsidence. The subsidence caused extensive damage to houses and properties including infrastructure.
5. The ground surface pattern suggest a current subsidence zone corresponding to the zone identified as LULM, zone.
6. The Electric Vector Sonar (EVS) survey covering different part of the basement slope reveals the current lenses of high thickness with variable thickness, which often exceeds >70 m thickness in the stream or parallel to the slope. The high sonar survey basement reveals the lens across zones of fracture where the ground water is channelled, especially towards the sea region.
7. The subsidence and zone of flow mass (MMSF) profile covering subsidence zone suggests the high thickness zone and higher velocity (indicating stiffness of layer) conditions with variable lens thickness. The top 1-1.5 m zone velocity layer is light-soft and with Velocity < 100 m/s, followed by 10-20 m thick light-soft and with a thin underlying light-soft and layer over the basement of Combedana/Nor Ave Formation with a velocity of > 1000 m/s.
8. The basement low velocity layer (<100 m/s) is identified derived from old landslide debris material is more prominent in lateral, Wadingshik, Jela and Kapa Uby area.

- The distribution of the low velocity layer should be considered for safety reasons, though the bathymetry is not precise in this location.
8. The UPR survey confirms the stratification with the 1<sup>st</sup> higher density layer, which governs the soil response, whereas the low velocity sediments are defined as sediment. The deep, artificial features are extremely developed and extend to a depth >50m. The features become gentler and disappear in the sediment layer at the toe of the berm, where the sparsely sedimented discharge was observed during subsidence.
9. The subsidence caused disappearance of water surface discharge (pulses) in the former lateral areas. The surface runoff direction (NNE) doesn't match the subsurface flow direction discharge in the sea area (NNE direction).
10. The hydrodynamics of dense water velocity (TV) distribution, defined by extrapolation and measuring of observed MOFF profiles, suggest the <10 m thick sediment column at the upper slope region, such as Maderia Bay, show NE flow accumulation like the surface runoff direction. Therefore, the area >40m depth shows subsurface flow accumulation in NE direction as observed in the field when the disappearance of tracers and sparsely sedimented discharge over the lower TV zone.
11. The highwater act as sediment in the subsurface flow and lag in dissipation in sedimentation, which is observed in the sparsely sedimented discharge during subsidence.
12. On the basis of density analysis of different sediment layers, we defined two risk areas for the present / future subsidence. We considered the boundary defined by bathymetry subsidence and the field observation as limits of the risk areas. The former distribution are comparing well with the peak subsidence area where deep-seated subsurface flow was channelizing the surface runoff and decreasing of the soil column at a depth >20-30 m in the regolith thickness. It is defined as High risk areas (marked as orange color marked with high error). The other area located in gentle, unconsolidated medium subsidence without deep-seated development of fissures or ground subsidence covering >10 m of regolith cover with similar subsurface flow and surface runoff is defined as Moderate risk area.



The land use distribution and infrastructure are presented in subsequent sections.



## INTRODUCTION

The Chesapeake has been threatened by shoreline instability, erosion, cliff-falls, floods, & earthquakes and the ground subsidence. Some notable events of mass wasting during past century are: (i) the 1881 Galesville landslide and the 1894 & 1979 Solom's Cliff along the Potomac Gorge near the Akimaka (ii) the 1975 Klondike Gulch (Dorham) landslide blockage of the Elizabeth (iii) the 1948 Oldbrook landslide in the McPetershollows Gorge (iv) the 1963 Mathews cliff-fall and flood (v) West Hill mudfall down glacial-front taluge along North Branch prior to the January 1922 subsidence in the Jackson.

Table 1. Degree of knowledge about the world in Lithuania

| Year | Items of the inspection                            | Comments                                                                                              |
|------|----------------------------------------------------|-------------------------------------------------------------------------------------------------------|
| 1970 | Biogeochem. standards                              |                                                                                                       |
| 1971 | Microbiology standards for first day               | CCOE - American by standard                                                                           |
| 1972 | Chlorophyll <i>a</i> & <i>b</i>                    | 7-plate Daniel                                                                                        |
| 1973 | Fluorescing in Biogeochem.                         | Storage Agreement                                                                                     |
| 1974 | Transfer standards                                 |                                                                                                       |
| 1975 | Boyle Charge Checked over Station                  | Over emergency facilities and functions of Station T-1                                                |
| 1976 | Daniel receipt of Station Lake                     | Storage arranged, level of Charge close to 1 m at Station, Storage used obtained with site for 12 hrs |
| 1977 | Boyle Charge checked                               | LCOE                                                                                                  |
| 1978 | Boyle Charge returned                              | LCOE                                                                                                  |
| 1979 | Boyle Charge returned                              | 20 lbs to the rock storage                                                                            |
| 1980 | Work with system delivery of Boyle Charge          | 7-plate, 1-plate over long                                                                            |
| 1981 | Biogeochem. checked by laboratory                  | LCOE                                                                                                  |
| 1982 | Station T-1 received, Chlorophyll level            | LCOE - American - American - American - 1982                                                          |
| 1983 | First Charge checked                               | LCOE                                                                                                  |
| 1984 | Station T-1 received, Biogeochem. checked          | LCOE                                                                                                  |
| 1985 | Biogeochem. checked between Station and Laboratory | LCOE                                                                                                  |
| 1986 | Station T-1                                        | More than 100 lbs. received from of preparation and                                                   |
| 1987 | Boyle Charge                                       | More than 100 lbs. 10" high of Measurement per night on                                               |
| 1988 | Transfer of facilities to Station                  |                                                                                                       |
| 1989 | Microbiology facilities                            |                                                                                                       |
| 1990 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 1991 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 1992 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 1993 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 1994 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 1995 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 1996 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 1997 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 1998 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 1999 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 2000 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 2001 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 2002 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 2003 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
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| 2005 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 2006 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 2007 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 2008 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 2009 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 2010 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 2011 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 2012 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 2013 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 2014 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 2015 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 2016 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 2017 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 2018 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 2019 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 2020 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 2021 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 2022 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 2023 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 2024 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |
| 2025 | Station T-1                                        | More than 100 lbs. 10" high and receive storage in                                                    |

The region surrounding Tschudi's equipment (antennas) includes triggered glacier-bed deluge on 7 February 2011 and intense precipitation of 400 mm during 17–18 October 2000 on the Tschudi slope. Through the natural subsidence and displacement of rocks in the geological structure, no being reported for over a year (since November 2011) in that way) is without pain. For a large part of the Tschudi becoming started, resulting in the first week of January 1973 and subsidence has not since (Fig. 1). The subsidence is accompanied by disappearance of surface discharge in circles and going of electric powered discharge to the G. Shvartsk, was around the equipment, but none of the Tschudi area.



The report aimed at determining cause of subsidence phenomenon by characterizing the cause effects relationship, the settlement pattern, surface characteristics of soil and geometry of the fissures in parts of Jolameth, which has increased under subsidence besides sea. The Ministry conducted a detailed report in year 1978 considered the place suitable material in the region as a major cause of slope instability (Dr. JAGJIT SINGH dated 26 April 1978). Since the Jolameth is an important water resource belonging to District, District, East and Valley of Kharay and formed pool along Ganga-Johar border in the west of the country, its stability is important.

Jolameth, in the Chamoli district of Uttarakhand, lies at an elevation between 2000-3000 m above sea level (Fig. 1) on the left bank of the Alaknanda river. The tectonostructural development of present Kharay protected under is 4000 years until 24 Jan. 2000 has created conditions and natural water among subsidence.



Fig. 1. The topography of Jolameth region.

## GEOLOGY OF THE REGION

Jolameth broadly is situated in the Higher Himalayas where the crystalline rocks of Udhkot Group lie tectonically over the Lesser Himalayas crystalline of Munson Group rocks along the Vindhyas Thrust (Vaidya, 1981; Fig. 2). The hillsides of Jolameth is made up of medium to high grade metamorphic rocks of the Greater Crystalline comprising of variety and basalt gneiss and schist, intrusions exposed at the base of the Jolameth zone, adjacent to the north. The northern top ridge of the Jolameth, where the northern dipping crystalline rocks of the

Yakima River are covered with the thick glacial till. The deposit near which the Yakima River mouth has grown. The tillite is composed mainly of non-sorted sandy gravel and large blocks and boulders of granite.



Fig. 3  
Geology of the  
Yakima River  
mouth area. 1:100,000  
scale.

#### GROUND DEFORMATION (SATELLITE-BASED SAR INTERFEROMETRY)

It is important to understand the type and spatial extent of the ground deformation in order to better understand the spatial mapping of ground failure and geophysical characterization of shallow sub-surface faults. We carried out the Synthetic Aperture Radar (SAR) interferometry for the spatial and temporal characterization of ground subsidence using Sentinel-1A data, which has an open access data with frequently repeat interval.

##### Data and method

The Sentinel-1A SAR data set of L1 and L2 products (S1A and S1B) was downloaded in 10° January 2020 pertaining to the pre and post-fault subsidence event of Yakima. The data were downloaded in interferometric wide-swath (IW) TOPX mode in Level-1 Single-Looking Complex (SLC) format (Kenna, 2015) using the precise orbit for the same time (Altimetry file, 2015). The SAR processing is done by SNAP software, starting with selecting of an appropriate mask (VV-ONLY) and limits to limit the processing stream pertaining to the study region. The precise Sentinel-1 orbit was applied to the data that provides an accurate position of SAR images and the option of the original acquisition of SAR product. Co-registration

includes band-passing, which is reprojecting the raw LID profiles of same site stack using cubic B-splines and IIRF. The advanced spatial filtering process was done to estimate a constant smooth shift between each image, which minimizes the phase discontinuity across the frame. After compensating the smooth effect, interference was generated. Subsequent processing is done to merge number of frames in the smooth inverse or frame sensitive image. The topographic phase components in the raw interferometric phase were removed using the geometry of the InSAR and IIRF to compensate the topographic effect. The residual phase includes phase signature related to deformation.

The干涉ograms were filtered using Goldstein phase nonlinear adaptive filtering (Goldstein and Werner, 1993) followed by multi-looking (4-1), which improves the wrapped phase accuracy. Wrapped interferometric phase is unwrapped using wrapped tool (SNAP2, 2012). The unwrapped differential phase value (radian) is converted to the displacement value (in mm) along the line of sight (LOS) of the sensor. The geometric correction was done using the range Doppler matrix correction (quarter geocentrically correct SAR data and provide the ground displacement map (Fig. 4). Data fusion techniques were used to derive the vertical velocity by combining LOS measurements from two independent InSAR viewing geometries (i.e. Ascending and Descending). The vertical velocity is derived by using ascending and descending LOS measurements using Forman et al. (2009) on a pixel by pixel basis.



Fig. 4. InSAR data geometry's local ground deformation in the Line of Rize (LOS) of the satellite using two-looks repeat observation.

## Results

The local deformation map using Sentinel-1A data for the period of 17<sup>th</sup> December 2022 to 17<sup>th</sup> January 2023 (Fig. 4) supports the volcano's phenomenon started during onset of December 2022 and continued during January 2023. The negative values indicate the LOS contraction,

in velocity during early flow the season, during the period of persistent inundation. The subsidence values are 2–4 dm between the 15–17 December 2002 reduced to 2–4 dm by 12<sup>th</sup> January 2003. There was no subsidence observed at the end of January 2003. The subsidence was observed in the middle and western side of the floodwater zone, although isolated subsidence observed throughout the floodwater zone. The subsidence prominent towards the eastern slope with the peak subsidence is 10.75–12.22 cm along narrow area.

The land-cover analysis of satellite data reveals the percentage of built-up footprint increased from 1.22 sq.km to 1.3 sq.km between 2000–2005 divided in two decade (2002 to 2003), which is 100% increase per decade. It is obvious to expect that the rapid growth of built-up area would permeate water pressure zone subsidence to demand and supply chain of water potential, large scale building of irrigation pvt. and would interrupted the steady water balance situation.

# GROUND FURTHER MAPPING

We carried out a detailed mapping of the flow in the floodwater zone (Fig. 3). The flow is stopped in the barren agriculture fields, along the road and the forest of buildings etc. The flow is distributed from the upper slopes at ~1200m in flood region in the floodwater zone in the case of the floodwater slope at ~1400m with the map pattern (Fig. 3) show a clear localization along the identified subsidence zone (Fig. 4). The vertical displacement varies from centimetre to inch and flow spacing up to 10 cm risk are observed.



Fig. 3. The ground flow distribution in the floodwater zone

Based on the field observations, the mapped area has been divided into 5 (Fig. 6) blocks namely, a) Youth, b) Momin Bagh, c) Bapkhin, d) Momin, and e) Mardang Khadin.

d) **land west**, situated on the northern upslope of Jomashin along the Jom road, has been experiencing landsliding and houses disappearance for over 30 year with the confirmed representation to district administration was submitted in November 2011. The improvement of housing is considered as the necessary structure in the form of building of retaining walls, transferring of the concrete structure supports to the slope. The several houses have appeared in January 2011 with the ground movement including rupture extending into houses in order due to unequal settlement of houses etc. (Fig. 4). The houses are mostly created a E-Walter over houses perpendicular to the slope was observed, digging without. Land West is a part of land west, situated adjacent to land. Moving further westward, the orientation of the surface rupture lines is N-S direction perpendicular to the direction of the slope. Indication of surface movement in the surface towards these structures.



Fig. 6. Field observations of cracks and bulging in land west

e) **Momin Bagh**, situated on the National Highway-7 connects the main Jomashin township, which is severely affected with development of extensive ground fissures affecting buildings. The fissure show S-SE on vertical displacement and upto 30 cm horizontal displacement (Fig. 7). The general trend of fissures are E-W direction parallel to the slope with transverse N-S trending fissures, perpendicular to the slope direction towards the eastern margin ground fissures.



Fig. 3. Structural damage of Muzum high rise in the basement forming with extensive damages to the structure

- c) Significant vertical cracks in the support of ground beams ranging from 10 cm to 1 m vertical and horizontal displacements (Fig. 3). The observed beams are oriented at 2-3° direction parallel to the slope.
- d) Likewise, at JV culvert, situated at the southern side towards the Akkanand river, region is affected with the ground beams developed parallel to the slope (Fig. 3). Towards the base of the slope, a large area with the dense shrub vegetation cover slope creeping, as marked by tilting of the trees. The cross measured major displacement of ~1m, which had impacted the structure in the vicinity. The two region experienced pushing of structural mass of retaining walls with the peak discharge in high as 4000 lps (Fig. 4), which gradually decreased in a week. The discharge picked up again on 20-02 January 2011 after the back water fell and river and subsided around two days to almost nil flow with a few trees like perennials.
- e) Harding Meander section shows major development of more ground beams with extensive displacement and minor cracks at the buildings and retaining walls. The minor fissures, in comparison to the rest of the region, indicate unstable slope but should not be neglected. Further, the slope below lower slopes adjacent to the Akkanand bank, slope may not fully secure.





Fig. 8  
Larger  
frames and  
ground  
deformations  
are observed  
adjacent to  
the bridge  
region, where  
there is the  
trapping of  
sediments.  
The  
area on the  
right is  
located at  
23 miles  
upstream  
from  
sediments.



Fig. 9. The  
frames and  
ground  
deformations  
observed  
adjacent to  
the bridge  
region at  
23 miles.



# Figure 10

We analyzed the displacement (height and width) along the fissures in order to understand the area most prone of the surface subsidence of foldmark steps (Fig. 11). The maximum horizontal displacement along the fissures are observed in part of Basil, Khachatur and Haghar with displacement as high as 41 cm (Fig. 11a), whereas the vertical displacement as high as 135-140 cm are observed in Haghar and Akhmet-37 square (Fig. 11b).

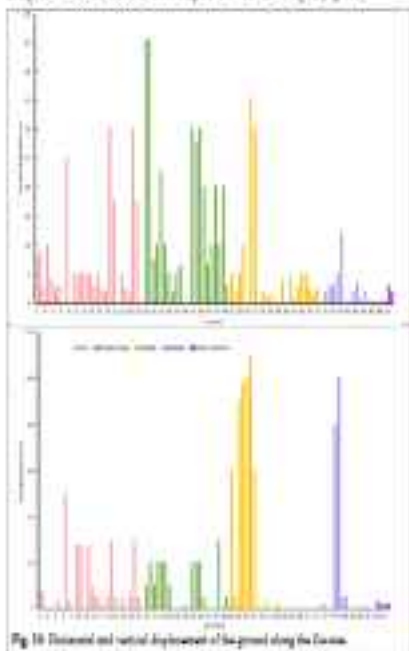


Fig. 10 Horizontal and vertical displacement of the ground along the fissures.

### *Fluvial landform as geomorphic landform*

It was observed that the large displacement along the fluvial are confined to the upper half of the channel cut as it converges into the landward area. To understand the fluvial landform, we analysed the geomorphology evidence of the landward slope. We used open source DEM3D Data Explorer Model (DEM) of 10m spatial resolution. We also used 15m spatial resolution ALN Data DEM, but results were similar. We generated slope and aspect maps of the landward slope (Fig. 11) and treated them with the drainage flow distribution and the build up area.

Three prominent flowing streams and their lower order tributaries drain the landward slope. The slope is dissected with a series of gentle slope regions (marked in green) extending in E-W direction are separated by high slope slope. The gentle sloping segment in the Kharak bag (B) and Dugdhar (C) area are highly infilled with the fluvial. The fluvial distribution is across and the transverse fluvial adjacent to the N-NW trending Dugdhar defines the prominent slope break and margin of the fluvial distribution (Fig. 11) during present subsidence. The lower gentle slope around Marwah (B), further NW ward, has experienced development of terrace with large displacement (Fig. 10).

The Dugdhar appears to be an important geomorphic discontinuity as observed in the slope aspect map. It is important to note that the surface channel is originates from Dugdhar whereas the other channels terminate and vent are originating from the And slope (Fig. 11).

### **Summary**

- The ground deformation with development of faults and subsidence is observed
- The fluvial are mostly confined to the gentle sloping during areas
- The fluvial segments have several displacement associated with the fault subsidence were observed in the field data analysis.
- The fluvial show characteristic displacement on the vertical displacement is prominent in post 1991 era, whereas the horizontal displacement is prominent in the upper and mid reaches of the subsidence zone.
- The main subsidence zone is controlled by the N-NW trending Dugdhar, which also control the surface runoff as observed in the drainage.

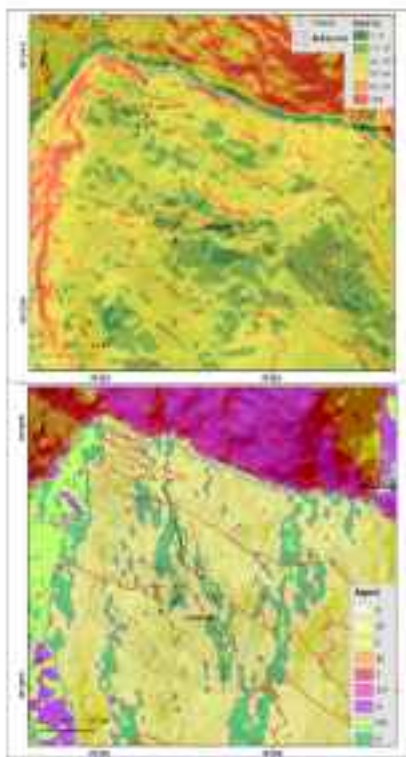


Figure 11: Slope and slope aspect map of the Inuvik region (generated from 30TM DEM at 30 m spatial resolution) in

## MULTISPECTROSCOPICAL CHARACTERIZATION OF SHALLOW SUBSURFACE SUBSTRATE

The surface runoff of a karst river channels has disappeared during bedrock subduction and the surface geobiosphere-subsurface linkages have been cut in Karst area. A key to the location and signal in the subsurface structure maps and flow of the surface river (Fig. 11). The paper focuses the possibility of the visualization of *S* during surface river towards *MS* direction through subsurface flow. Further, the assertion of a localized perched water table in the area and trigger of subsidence in bedrock are commonly discussed among the speleological policy makes with frequent karst collapses. To evaluate the hypothesis, this paper aims to map the subsurface *S* subsurface configuration of the karst river relative to the bedrock slope, which is defining and classifying the subsurface flow?

In case of high relative relief and strongly sloping rugged areas of bedrock, we planned and used Ground-penetrating radar survey (GPR), Multichannel Analysis of Surface Waves (MASW) and Ground Penetration Radar (GPR) techniques for shallow subsurface exploration with specific objectives. The GPR survey along a line long profile with 100m depth coverage could help in finding depth and geometry of subsurface signals with the basement across the subsidence affected area. The MASW profile could help in constraining the subsurface characteristics of soil and distribution in other regions within the subsidence area. The GPR is employed to map subsurface geometry and extent of fissures and local structure pattern of the soil column up to a depth of ~10-15m. The understanding from these methods will be integrated with the geological observation to constrain subsidence features and subsurface flow pattern in the bedrock slopes.

### A. Electrical survey over bedrock region

The electrical survey is conducted for the bedrock area with an electrical resistivity of 1400-2000  $\Omega$  (Figure 12). The resistivity profile runs parallel to the stream with an electrode spacing of ~12 m. These profiles are almost parallel to the stream system following the stream E-W trending trend. An obvious difference between these results are very high with no continuity in the N-S (steeply sloping direction) > 50-70 deg, constraining our surveys along the road. In total, 12 long-profile lines have been planned for each profile. The multiple current injection were done in the profile direction to cover the area with substantial resolution. The accepted voltage and current with helped us in data acquisition for such extremely challenging subsurface areas. Finally, measurement were adjusted up to order of mass kilo-ohm ( $\sim 2k\Omega$ ). Such high resistivity values are observed soil resistance with the exposed hard rocks in the region. Also, we tried to inject a substantial amount of

currents > 1000 mA at using both TMT and TMM potential measurements for both  $\pm 1$  MT and 1000 V) for greater depth of investigation (penetration to maximum of  $\sim 100$ –500 m depth) and good data quality. At each node, two potential figures were measured along the profile direction with a dipole length of  $\sim 25$  m. Finally, the potential voltage (in order of some millivolt to several of millivolt) and current waveform are processed to provide the apparent resistivity data.



Figure 12. A 3D terrain-based false color map for the Jindan area. Shaded area shows the electrode positions along the four 2 VV profiles according pairs of four fixed electrode dipoles. Through identification of the electrode areas and ground lines show the locations of previously suggested lateral displacements. The resistivity models are generated along the four 2 VV profiles (Figs. 13–16) after inserting the original data provided with reasonable error floor of  $\sim 1\%$  and at electrode voltage error of  $\sim 0.1$  mV. The mesh with millions of subdivided cells was used in the model space with  $\sim 100$  the background resistivity as starting model. The background resistivity is the average of the acquired resistivity data. In horizontal direction, it has better cells are defined in the model, and in vertical direction, the model cell size was kept  $\sim 1$  m. The topography was also included precisely in the model based on the acquired DEM data spatial resolution 10 m of the Jindan area. The original resistivity models have marked some prominent features and structures sensitive patterns.

Three major domains were recognized from the resistivity distribution, i.e.,

- (i) highly resistive area and the coal field (25–50 Ohm),
- (ii) the lateral unconformable conductive calderas (20–100 Ohm),

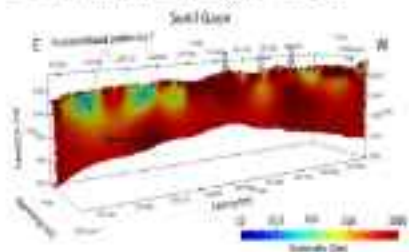
- (b) uniformly resistive basement granitic rocks (100-150 Ohm), and
- (c) resistive regional rocks and basins underneath ( $> 100$  Ohm).

The results suggest the unconformable sedimentary (productive sediment) mostly confined to a depth  $< 150$  m. Some shallow resistive anomalies possibly show the existence of the situated hydrocarbons. At places, shallow resistive anomalies occur and represent the big basins distribution in the region. There are regional bed rocks visible at the surface also consistent to the observed seismicity results. The possible distribution of the structures between the basement and unconformable soil sediments are clearly marked in the models. Some shallow resistive and conductive anomalies are consistent with the observed lateral displacement in the field.

The resistivity signature of all the three profiles in South Giza, Minshia Elgiza, Elmagara and IF & Elmarout villages are discussed below in further details.

### 1. South Giza area

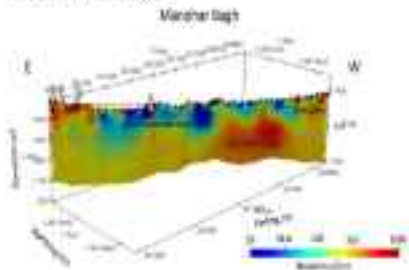
In South Giza area, it shows a thick area (dark pile of unconformable sediments non-lithified) (Fig. 11). The general geometry of this resistive area extending for almost two sections of well channel affecting the marginal area with weathering and degradation of asphalt. The basement side of the section (near the ITRF range) is mostly hard rocks with some minor sand zones. It shows weak zones are consistent with mapped location of the basin.



**Figure 11:** Resistivity model obtained along the ITRF profile at South Giza area with the well location (grey shaded vertical section) in the same area as in Figure 12.

## II. Upper Mississippian High area along the hell road

There is indication of a thin-out/boundary interval unconformable sediment and basement rock in the Mississippian High profile (Fig. 14). These sediments are at least as about 70-80 meters thickness in the central portion. It becomes relatively thin in the western side as basement gets up very and occasionally resistant topologies are also seen. The location of the orogenic activity pattern in the eastern side of this profile. It is also (normal) near closely to the highly deformed area by tectonic process.



**Figure 14** Density contrast contrast along the E-W profile in Mississippian High area, with the orogenic activity (grey shaded vertical) pattern in the same area as in figure 17. Red shaded roughly shows the location of the dense cluster of basement with effect of  $\sim 100$  m.

## III. Paraglynnic member

The profile shows near the Linggitee rock in the east and western towards the Paraglynnic member in the west (Fig. 15). At the west, unconformable sediments become thinner or eroded in central portion, where it reaches up to 70-80 meters. At places, resistant land units are exposed to the surface. In some deeper rock zones are identified in the western end close to the Linggitee rock.



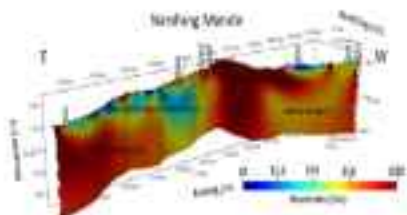


Figure 15: Accuracy error contour along the JF02 profile in Nanhai Island area with the calibration error (grey shaded vertical arrow) in the same case as in figure 12.

#### IV. JP and Marwan area

In JP area close to Marwan village, mostly highly sensitive land mines are seen (Fig. 16). Some weak mines are found to be associated with cracks location as represented by the relatively continuous anomalies. These weak mines are highly localized and exhibiting a maximum of  $\sim 4\text{ dB}$  at usually. These weak mines are the hosts of disulphide, which usually occur along the cracks line. The presence of some weak mines near JP mine field (along which the profile is obtained) and increased presence of land rock outcrops clearly suggest the section represent the basement horizon at the toe of the diapir zone.

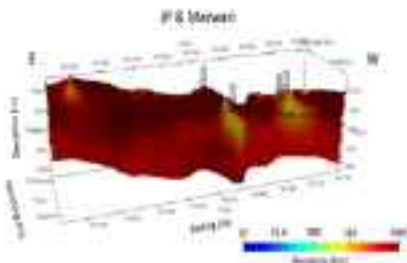


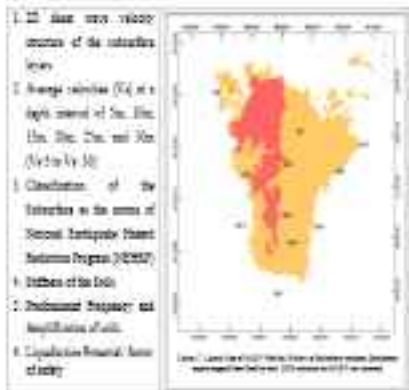
Figure 16: Accuracy error contour along the JF03 profile in JP & Marwan area with the calibration error (grey shaded vertical arrow) in the same case as in figure 12.

## Summary

- The regolith cover is not uniform across the island.
- The weathering cover in the form of cement dunes with the maximum thickness is observed around main streams.
- The regolith cover is 3.17 m around Kumbhakar and Naranka Dargah areas and laterally extends for > 100m.
- The streams are mostly situated at the areas with thin regolith cover. Therefore, the major cause for water pollution is industrial effluent.
- At 3P area, the basement is exposed near the surface with minor degree extent of weathered rock and soil. This signifies the emergence of industrial effluents from an exposed large discharge during collection.

## 2. Multisensor Analysis of Trench & Wave (MAW) results

It is important to determine the subsurface soil characteristics in landslide regions to understand the site condition and the response of soil stratification during present subsidence and future events. The MAW is a well-established geophysical method to determine shear wave velocity distribution of the shallow subsurface geological layer and it provides input parameters to the civil soil structural equations for safety aspect of the civil structures. The acquired MAW data along trench profiles in soil around substation area identified from satellite images and field identification of damaged (Fig. 17). The physical length of each profile is 100 m, which varies depending on the availability of the space to lay the equipment. The shear wave velocity ( $V_s$ ) was stopped up to a depth of 30 m to 40 m from the surface. The following subsurface soil parameters are estimated from MAW survey:



## Methodology:

In most seismic seismic surveys, the methods of test: seismic energy generated using a compressed air source is required and Rayleigh waves (Kohler, et al., 1973), which is the prompt component of ground soil. Although ground soil is considered as mass or body wave surveys (i.e., reflection or refraction profiling), its dispersive properties can be utilized to

into wave surface elastic properties (Kanas, et al., 1981; Jelinek, et al., 1984; Bell, et al., 1984). Assuming constant velocity variation, each frequency component of a surface wave has a different propagation velocity (called phase velocity,  $C_p$ ) at each unique frequency component ( $f$ ), which results in different wavelengths. Further, a series of the high terms of different frequencies will have the same velocity. These different phase velocities of frequency terms for a given frequency are termed as modes. The lowest velocity for any given frequency is called the fundamental mode velocity. The next higher velocity above the fundamental mode phase velocity is called second mode velocity and so on. The fundamental phase velocities when calculated with high accuracy will generally provide reliable shear wave velocities (Park, et al., 1999 and Xia, et al., 2000). Construction of a shear ( $V_s$ -wave) velocity ( $V_s$ ) profile through the analysis of phase-wave, fundamental-mode Rayleigh waves is one of the most common way to use the dispersive properties of surface waves (Jelinek, 1985). This analysis provides key parameter commonly used to evaluate soil-surface stiffness, which is a critical property for geotechnical studies (Jelinek, et al., 1984).

The shear wave velocity ( $V_s$ ) of a soil/rock is a function of the elastic properties and is directly related to the stiffness of the materials (Table 30). The  $V_s$  are used to compute harmonic mean shear wave velocity, stiffness, predominant frequency, amplification and liquefaction potential for the study area, which is important parameter to assess the quality of the rock for civil engineering construction and estimation of liquefaction hazard potential is extremely active region. Harmonic shear wave velocity over the top 30 m is referred to as  $V_{sh}$ . Both the National Earthquake Hazard Reduction Programme (NEHRP) provisions and the Uniform Building Code (UBC) modification (of 1997) uses  $V_{sh}$  to classify sites according to type of soil for earthquake engineering design (Table E2, Dwyer, et al., 2000; Rinaldi, et al., 2000).

Table E1. Average Velocities for different rock types

| Rock Type                  | Formations                                                                            | P-wave Velocity<br>( $V_p$ ), m/s | S-wave Velocity<br>( $V_s$ ), m/s |
|----------------------------|---------------------------------------------------------------------------------------|-----------------------------------|-----------------------------------|
| Very hard rock             | Granite gneiss, Basalt, Gneiss and<br>Jasperite                                       | >3000                             | >1200                             |
| Hard                       | Trachyte/andes, And, Basalt, Lava<br>stone, Diabls and Pyrite ls and                  | 2000 to 3000                      | 700 to 1200                       |
| Very hard<br>and soft rock | Lava, Metasediment gneiss, Basalt,<br>Sediment, Slate and Clay<br>stone Pyrite ls and | 2000 to 3000                      | 200 to 700                        |
| Soft rock                  | Crystalline Metasediment, Shale,<br>Soft Sub Fresh Limestone                          | 1000 to 2000                      | 350 to 650                        |
| Soft Soil                  | Lava, Sediment, And, Clay,<br>Fillstone                                               | <1000                             | <350                              |

Table B1: Soil profile type classification for seismic amplification (NRC, 2015)

| SoilType<br>NEHRP | Formulas                                | Average Shear Wave Velocity<br>in ft/sec (ft/s, m/s) |
|-------------------|-----------------------------------------|------------------------------------------------------|
| A                 | Stiff Soil                              | $v > 1500$                                           |
| B                 | Soil                                    | $750 < v \leq 1500$                                  |
| C                 | Very Loose Soil and Soft Rock           | $500 < v \leq 750$                                   |
| D                 | Soft Soil                               | $100 \leq v \leq 500$                                |
| E                 | Soft Soil                               | $v \leq 100$                                         |
| F                 | Soil requiring site specific evaluation |                                                      |

Liquefaction is defined as the transformation of a granular material from solid to a liquid state because of increased pore water pressure that reduces effective stress. The occurrence of liquefaction depends upon the amplitude and duration of the ground shaking and the depth of the water table. In general, older soils have a lower liquefaction potential. Soils at depths of more than 10m generally do not liquefy due to the high effective confining pressure.

#### Field Data Acquisition and Processing

The MATH field data was acquired along the fault profile, i.e. Profile NMM-1 to NMM-4 (Fig. 17, Table B1). The input pulse rate generated through the cable interface is a square wave. The vertical geophones used as sensors and multi-purpose sensors (weather vane, 37 channels Barco (barometer, barometer, wind) to record the signals (Fig. 18). During acquisition varying interval and record length were taken as 0.25 to 0.5 sec and 0.5 to 1 sec and noise filter applied to avoid the scattering of electrical signals from any unknown misinterpreted sites. Its cut off is fixed by suppression filter to allow all types of frequencies received from the different locations.

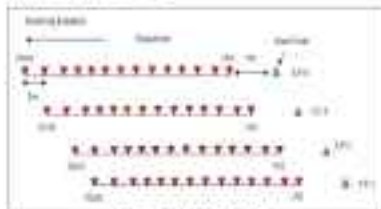


Figure 18: MATH Field layout

| Table B1. NALF Japanese Annotations |                           |                     |                      |                    |                 |
|-------------------------------------|---------------------------|---------------------|----------------------|--------------------|-----------------|
| File No.                            | Symbol Length (approx. m) | Symbol Interval (m) | Symbol Interval (km) | Symbol Length (km) | Symbol duration |
| 2021-1                              | 100                       | 1                   | 0.12                 | 1                  | Time-Base       |
| 2021-2                              | 100                       | 1                   | 0.12                 | 1                  | Time-Base       |
| 2021-3                              | 100                       | 1                   | 0.12                 | 1                  | Time-Base       |
| 2021-4                              | 125                       | 2                   | 0.12                 | 1                  | Time-Base       |
| 2021-5                              | 100                       | 1                   | 0.12                 | 1                  | Time-Base       |
| 2021-6                              | 100                       | 1                   | 0.12                 | 1                  | Time-Base       |
| 2021-7                              | 100                       | 1                   | 0.12                 | 1                  | Time-Base       |
| 2021-8                              | 125                       | 2                   | 0.12                 | 1                  | Time-Base       |
| 2021-9                              | 100                       | 1                   | 0.12                 | 1                  | Time-Base       |
| 2021-10                             | 100                       | 1                   | 0.12                 | 1                  | Time-Base       |
| 2021-11                             | 125                       | 2                   | 0.12                 | 1                  | Time-Base       |
| 2021-12                             | 125                       | 2                   | 0.12                 | 1                  | Time-Base       |
| 2021-13                             | 100                       | 1                   | 0.12                 | 1                  | Time-Base       |

The raw seismic data, preprocessed, Japanese annotations and waveform images are presented (Fig. 1 to Appendix E2). The same procedures reported for acquiring all data sets. The original seismic data are processed using “vertical coherence” (VCH) method. The seismic data processing involves conversion of BEP-2 data to VCH format, assignment of polarity (in this study either: 1 is/for and group interval, 1.1 to 2.1 m has been chosen), timing of polarity assigned data (by 6 factors mode to modify the first interval and multiples respectively), generation of dispersion curve, estimation of dispersion curve, integration of dispersion energy to get the 1D shear wave velocity image of each record and generation of 2D shear wave velocity image by combining all the 1D shear wave velocity images. Accurate generation of dispersion curve is one of the critical factors in the estimation of shear wave velocity profile.

#### Results

The data from individual profiles (11 nos.) are presented following three periods and the profile images with related observations along them are presented in the Appendix E2. The general property along the profiles are summarized in Table B2 and Fig. B3.

#### Average Shear Wave Velocity ( $V_s$ ) and associated Overburden parameters:

The  $V_s$  is varying from 100 to 750 m/s throughout the region from 30 to 150m. The observed average shear wave velocity from 1 m to 15m depth in each one (2021-1 to 2021-14) are summarized by using statistical numerical techniques. The average shear wave velocity ( $V_s$ ) images and corresponding  $V_s/V_{max}$  and classification from 30 to 150m depth in the study domain region are plotted (Fig. B5). According to classification of shear based on  $V_s$ - $V_{max}$  in T<sub>0</sub>-30 is given by Tokimachi (Empirical) (Tokimachi, 1997) and Modified Building

Coda (JBO-0002, 1997). The Fudianchi region is composed of "Shui" soils (Class-D) and Yanyang soils (class C). Shui soils are observed up to the depth of 1m followed by a dense soil up to the depth of 60 m. A very hard rock is observed below the 50 m. The average shear wave velocity distribution from 1m to 50 m is also presented.

The stiffness of the soils is varying from 100 kPa to 400 kPa. The proportionality is observed in stiffness of the soils with shear wave velocity. Proportionate frequency and Amplitudes of the soils varies from 1.0 Hz to 1.5 Hz and 0.7 to 0.9 throughout the subsurface area. The maximum Amplitudes from 0.5 to 4.0 Hz Amplitudes up to 30m with reference to maximum earthquake of 6.4 Mw (Chen's earthquake) with PGA of 0.11g (Table B-6).

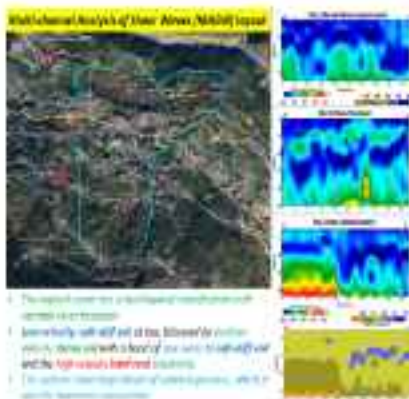
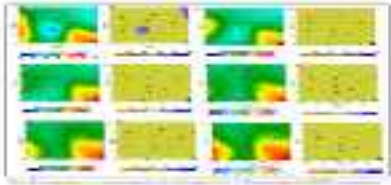


Fig. 19. Average profile of MASW analysis and output summary. The details of each profile are given in Appendix E.







### Conclusions of MATH studies:

The shear wave velocity of 12 profiles in and around basement sediments was revealed:

- The regular multi-layered stratification is observed in the crustal section, especially near the top of the sediment zone. The layering are not regular and show local variation.
- The shear wave velocity ( $V_s$ ) of the sed layers ranges from  $<150$  to  $<170$  m/s up to a depth of 25 m.
- The top 5-10m low velocity layer is  $145\text{--}150\text{ m/s}$  and with  $V_s < 150\text{ m/s}$ , followed by 10-20m thick  $145\text{--}150\text{ m/s}$  and with a thin underlying  $145\text{--}150\text{ m/s}$  layer, over the basement at Coochbeard-Bard Area basement with a velocity of  $>1600\text{ m/s}$ .
- The deeper low velocity layer  $<150\text{ m/s}$  (which is also previously reported at Kambalda area) is present. This low velocity is more prominent at Merredin, Norrington, Kambalda and Koppa Vee area in Shear zone top.
- The sediments have large blocks (often  $>10\text{m}$  in diameter) of bedrock present today, which have  $V_s$  similar to the basement below.
- The distribution of this low velocity layer in depth should be consider for seismic research.

#### C. Ground Penetrating Radar (GPR) (Mapping former geometry and topography)

The Ground Penetrating Radar (GPR) survey has been employed to understand subsurface characteristics of the top soil and former geometry in the evaluation area. The GPR survey was conducted along adjacent to the DTM and MATH profiles (Fig. 11) for any correlation



Figure 11. Aerial view of GPR Profiles (G1 to G12) overlaid on the Google image.

The GPR data sets was acquired along the 12 profiles (Fig. 11), i.e. Profiles from G1 to G12 in and around the infrastructure region covering the Marathi, Bait road, Kurl area, Khoshkar Bag, Raje wry, Through Marathi, Khoshkar Road and B road. The location and length of each profile is listed in Table-C1.

The acquired GPR data has been processed using "Reflex" software following the protocol presented in the Annexure-VI. The results of the 1-D observations are visualized in the form of 1-D profiles (Fig. 12), which are presented in Annexure-VI. From related observations, the conventional order:

- a) Topsoil up to a depth of 1m is poorly saturated.

- A partially cemented saprolite with calcification is usually observed between 1-15.0 m depth. The soil becomes increasingly calcareous with the higher values decrease of NAPP.
- The lower section around the trunks are having good soil structure.
- Highly cemented areas are observed Marwell, Singaper, Marwell Singh, Badi, but it is occasionally along the surface - calcification near the (cracks) region.
- However, the dry soil are filled soil column (cracks or large voids - yellow color) are common in the surface of the forest.
- Samples of subsurface zone and upper section are showing various size of depth as follows are listed in the saprolite layer.

Table C1: Details of GPS profile

| PNo    | Village name    | Latitude | Longitude | Profile  |           |
|--------|-----------------|----------|-----------|----------|-----------|
|        |                 |          |           | Latitude | Longitude |
| P0-1   | Marwell         | 10.3321  | 79.1341   | 10.3321  | 79.1339   |
| P0-2   | Marwell         | 10.3321  | 79.1334   | 10.3321  | 79.1344   |
| P0-3   | Marwell         | 10.3321  | 79.1344   | 10.3340  | 79.1340   |
| P0-4   | Singaper Soot   | 10.3319  | 79.1341   | 10.3318  | 79.1340   |
| P0-5   | Singaper Soot   | 10.3319  | 79.1341   | 10.3320  | 79.1339   |
| P0-6   | Singaper Soot   | 10.3321  | 79.1339   | 10.3321  | 79.1339   |
| P0-7   | Singaper Soot   | 10.3321  | 79.1340   | 10.3319  | 79.1339   |
| P0-8   | Marwell Marwell | 10.3321  | 79.1341   | 10.3340  | 79.1340   |
| P0-9   | Marwell Marwell | 10.3320  | 79.1341   | 10.3320  | 79.1339   |
| P0-10  | Marwell Marwell | 10.3321  | 79.1340   | 10.3340  | 79.1339   |
| P0-11  | Marwell Marwell | 10.3321  | 79.1340   | 10.3340  | 79.1339   |
| P0-12  | Marwell Marwell | 10.3340  | 79.1340   | 10.3340  | 79.1339   |
| P0-13  | Marwell Marwell | 10.3340  | 79.1340   | 10.3340  | 79.1339   |
| P0-14  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-15  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-16  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-17  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-18  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-19  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-20  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-21  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-22  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-23  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-24  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-25  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-26  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-27  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-28  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-29  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-30  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-31  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-32  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-33  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-34  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-35  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-36  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-37  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-38  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-39  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-40  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-41  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-42  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-43  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-44  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-45  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-46  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-47  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-48  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-49  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-50  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-51  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-52  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-53  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-54  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-55  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-56  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-57  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-58  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-59  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-60  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-61  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-62  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-63  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-64  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-65  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-66  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-67  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-68  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-69  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-70  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-71  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-72  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-73  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-74  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-75  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-76  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-77  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-78  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-79  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-80  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-81  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-82  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-83  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-84  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-85  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-86  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-87  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-88  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-89  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-90  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-91  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-92  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-93  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-94  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-95  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-96  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-97  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-98  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-99  | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |
| P0-100 | Marwell Marwell | 10.3320  | 79.1339   | 10.3320  | 79.1339   |

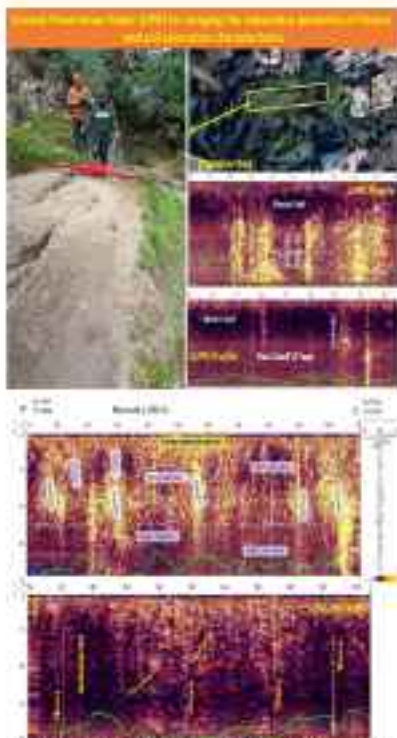


Fig. 22: SFR profiles along different transects in the central region of Kodumathi. The soil resistivity contour in the region shows variation in degree of saturation and variable geometry of burrows. The lateral movement compression in burrows IV.

- Most to some flowers are larger and/or tubular in partially protected soils. The distribution of flowers and fruits are independent to individual regions.
- Smaller, so called, vertical flowers are frequently observed in the higher reaches.
- The flowers are as deep as ~11 m, though depth and geometry of flowers varies in the central soil zone (marked in black and purple colors) and become shallower and somewhat  $\approx$  15-20 m depth towards lower reaches.

## INTERPRETATION AND DISCUSSION

It is important to separate the outcrop-scale observations from the remote sensing, geological and geophysical techniques to understand the ground subsidence phenomena in the Foldbelt. It is important to summarize the critical observations and inferences from the profiles and look for the relevant source.

The surface observations from the present study can be summarized as:

- The Foldbelt is north-facing dip slope, where the basement is composed of north-dipping gentle folds of Tertiary Formation (Fig. 3).
- The dips is represented with series of regular gentle slopes are separated by steep slopes forming digitated across basins.
- The EMI measurements made for the December 2011 and January 2012 in this region a well-defined subsidence zone with higher subsidence towards the western flank (Fig. 4) where the ground fissures and building damage are observed (Fig. 2-4, Annexure 2).
- The deep fissures are frequent with large horizontal displacement in the gentle slope area in front, Mainline Bag and High Dhar area (Fig. 10). The larger vertical displacement is common in High Dhar and Mirzanagar JP area (Fig. 10).
- The north facing dip slope of Foldbelt is represented with variable regular core thickness as observed in EMI study (Fig. 13-16). The gentle sloping area (Fig. 11) exposed erosion here regular thickness of ~50m, forming concave profile due to independent steep area associated to slope aspect and are separated by the shallow basement rock (Fig. 13-16).
- The regularity has 5-4 brands of horizontal fractures spaced out and close-off with of variable thickness as observed over the local, unroofed basement rock (Fig. 11, 13, Annexure 3).
- A large set of fissures later developed in the overburden regularity. The fissures extend ~10 m length with variable geometry. The fissures are often as filled in the upper middle slope and are having a shallow later (convex/concave) geometry towards the toe slope around Mirzanagar and JP (Fig. 12, Annexure 4). The soft dense middle soil layer is MMTV (Fig. 18) is able to hold soil masses (Fig. 12) for an interval of sometime in upper middle slope.

However, the following observed features and surficial change needs explanation considering shallow sub-surface observation of the present study.

- The piling of debris came from the terrace and at the slope at Maricao-IP and has occurred simultaneously with the bedrock subsidence during initial days of subsidence.
- Several small craters with minor surface runoff happened during the bedrock subsidence.
- The snow and precipitation on 10-11 January 2011 produced the subsided snow discharge at the terrace near IP, which happened in next couple of days.
- This suggests the dissipation of disappeared surface runoff as subsidence line. However, there is no direct representing surface runoff before the snow January.

It raises a question, whether subsidence cause (groundwater) flow is different from surface runoff, and how?

To deal with the above question, it is important to understand that series of the bedrock steps, which is composed of horizontal original gentle slope horizontal by steep slope forming series of benches (Fig. 11). The subsidence affected slope (A, B, C, D areas) are degraded small settlements have formed from pattern are broken by the landslide (Fig. 12), which seems to control dissipation of the surface runoff along the terrace and gradually subsidence line as well. The slope and aspect map of the region clearly suggests that the landslide type is in its direction to the N-NNE directed surface runoff.



Fig. 12: Google maps of the bedrock steps overlaid with the small enclosure. The LIDAR DEM (was generated by other agency) could give a better resolution.



To visualize the flow accumulation pattern of the Tachikawa slope using HETM DEM of 10m spatial resolution (Fig. 10), which itself suggest the dominant surface flow is in NE-N direction, which is observed by the NW-trend flow pattern of topographic. The SAR-based subsidence (Fig. 4) and levee pattern (Fig. 5) also suggest the northwesterly subsidence bordered by the Suga Dam. The estimated transient flow at Maruyama observed during 20-21 January 2011 (Fig. 6) and progression of Tachikawa slope. The discrepancies of NE-N flowing direction in the upper slope, practical estimated transient flowings at Maruyama during subsidence suggest a northwesterly subsidence flow (Fig. 10, 16).

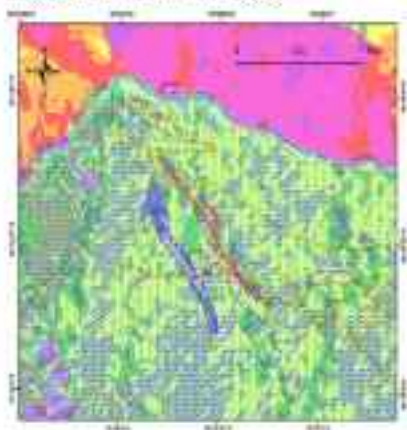


Fig. 11. Flow accumulation pattern (derived from HETM DEM spatial resolution) of the Tachikawa slope representing the direction of surface runoff. Please note the direction of subsidence and the subsidence mouth is observed at Maruyama towards SW direction. The Suga Dam with NW flow direction acts as barrier to the SE-N directed surface flow of the slope.

To understand the subsidence flow behavior, we compared the depth slices of  $V_s$  derived from SAR interferometry with an assumption that the  $V_s$  contours at 1, 10, 15, 20, 25 and 30m depths could help in constructing a broad picture of subsidence geometry of the subsidence area with

similar property (Fig. 22). The correspondence lines of TI contours will locally point towards flow accumulation at that depth. It is interesting to note that the TI contour correspondence pointing a flow path, which changes from NE direction up to 13m depth and to NW direction at deeper levels.

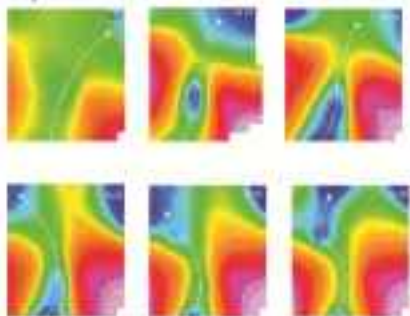


Fig. 22. Evolving MAFF profile (white) at different depth distribution of flow from Talukoti (TL). Please note the contour correspondence possible a varying flow path whereby the subsurface accumulation would be in NE direction up to 13m depth and it changes to NW direction at deeper levels.

It appears interesting to learn if  $\sim 10$  m depth Trenches in the upper slope region of Lockhead (Fig. 17, Appendix-77) would characterise disappearing profile result to the NW directed subsurface flow, as observed during subsidence.

Further, the transient discharge at IP-Midwest slope has progressively decreased from  $\sim 100$  gms to  $\sim 1$  gms (highlighted within a bracket) and presence of air-filled fractures at  $\sim 10$ – $20$  m depth point towards extreme denudation of the regolith (or structure) due to enhanced base flow along the basement-erosion interface. The transient revival of enhanced discharge after a short spell of rain-event on 26-27 January 2008 also suggests that the subsidence and associated subsurface discharge is not over yet.

It would encourage a qualified person to examine the Lockhead subsidence as denudation phenomenon, which is rendering Trenchy the interior of the slope subsidence and

discharge during the forthcoming monsoon season (November) could reveal the climatic stage of present sublimic phenomenon.

### Field Visit

We continued all the above observations to demonstrate the affected area with various degree of risk with various soil erosion features (Fig. 2b) with the understanding that the risk and vulnerability will be higher in higher vulnerable soil erosion. We define very poor zone with boundary defined by land use, vulnerability and the field observation. The flood-prone locations are coupling well with the peak vulnerable zone and therefore we define it as High-risk area, affected by a deeper subsurface descending flow involving >10m of saprolite thickness. The other area represented surface subsidence without widespread development of flood or ground subsidence is defined as Moderate risk area where the subsurface flow is limited to the surface runoff and it affects <10 m of saprolite cover.



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Abstract

*Geological & Geotechnical studies to  
understand shallow subsurface strata  
at Joshimath, Chamoli, Uttarakhand*



Drab Report Number:

Submitted to:

Uttarakhand State Disaster Management Authority  
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By:

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Uppal Road, Hyderabad 500071



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#### Investment Risk Factors (Table 4)

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10. *Staphylococcus aureus*

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**Abstract**

From:

**Secretary**  
District Management and Administration  
Govt. of Karnataka

To:

**Director**  
CDM - NDR  
Hyderabad

Urgency:

Reference No: /A. Dated: 2021

Subject:

Approval of proposed project extension to Andhakh Town.

Dear Sir,

There is a reference to the letter from No. 16413/2020, dated 01/01/2021 dated 01/01/2021, subsequent to which your office has submitted the report titled "Technical and Financial studies to extend the Urban Suburban Area to Andhakh". In this regard it is informed that the proposed has been accepted as per the following terms:

1. The extension area to be submitted within a week, however, it is required that more focus of the study should be mapping of unimproved area for identification of suburban project.
2. The stated extension of report is preferable after conducting the preliminary survey of the area.
3. In case any important clarifications will require to submit of the area are cleared if they are required to be reported immediately.
4. The Institute is required to submit the budgetary report based on required extension immediately.

As the matter is highly important, need that it is required to be submitted the work immediately.

Sincerely,



Dr. Rajesh Kumar Gade

Secretary

Copy is following for information and necessary action:

1. Secretary to Public CD/Visiting Township
2. Member Secretary, National Disaster Management Authority (NDMA), New Delhi
3. Joint Secretary, Ministry of Home, Govt. of India
4. Divisional Commissioner, CDM-6
5. Additional Joint Secretary (Urban Affairs), Municipal Area Office Management Authority
6. District Magistrate, Channarayana

  
Dr. Rajesh Kumar Gade

Secretary



Appendix II: Details of optimal surface

| Loc. | ID. | Z       | Y       | Excavation |       |          | Consumption |           |       |
|------|-----|---------|---------|------------|-------|----------|-------------|-----------|-------|
|      |     |         |         | Dig Area   | Tools | Exp. fee | Water cost  | Wage cost |       |
| A    | 1   | 7.14993 | 0.04437 | 20         | 122   | 101      | 10          | 4         | 1     |
|      | 2   | 7.07601 | 0.07427 | 20         | 150   | 111      | 10          | 4         | 7     |
|      | 3   | 7.07754 | 0.07407 | 20         | 150   | 104      | 10          | 3         | 3     |
|      | 4   | 7.07773 | 0.07373 | 20         | 147   | 117      | 103         | 10        | 3     |
|      | 5   | 7.12738 | 0.02222 | 20         | 111   | 101      | 2           | 4         | 3     |
|      | 6   | 7.14736 | 0.02222 | 20         | 122   | 101      | 14          | 14        | 1     |
|      | 7   | 7.14736 | 0.02117 | 20         | 122   | 101      | 14          | 4         |       |
|      | 8   | 7.07731 | 0.07310 | 20         | 131   | 101      | 10          | 4         | 10    |
|      | 9   | 7.07734 | 0.07310 | 20         | 130   | 111      | 10          | 10        | 1     |
|      | 10  | 7.07617 | 0.07427 | 20         | 10    | 140      | 7           | 10        | 3     |
|      | 11  | 7.12738 | 0.02927 | 20         | 126   | 10       | 14          | 4         | 10.25 |
|      | 12  | 7.12738 | 0.02909 | 20         | 126   | 10       | 14          | 4         | 10.25 |
|      | 13  | 7.12738 | 0.02909 | 20         | 126   | 10       | 14          | 4         | 1     |
|      | 14  | 7.07731 | 0.07300 | 20         | 140   | 10       | 1           | 4         | 10.25 |
|      | 15  | 7.07731 | 0.07470 | 20         | 140   | 10       | 1           | 1         | 10    |
|      | 16  | 7.07614 | 0.07470 | 20         | 130   | 101      | 1           | 1         | 7     |
|      | 17  | 7.07614 | 0.07331 | 20         | 131   | 11       | 100         | 1         | 4     |
|      | 18  | 7.14638 | 0.02079 | 20         | 122   | 10       | 26          | 9.9       | 7     |
|      | 19  | 7.14638 | 0.02909 | 20         | 122   | 10       | 140         | 4         | 1     |
|      | 20  | 7.14638 | 0.02730 | 20         | 122   | 10       | 140         | 10        | 10    |
|      | 21  | 7.07631 | 0.07400 | 20         | 130   | 10       | 100         | 14.0      | 7     |
|      | 22  | 7.07631 | 0.07400 | 20         | 130   | 10       | 100         | 10        | 3     |
| B    | 23  | 7.07631 | 0.07360 | 20         | 147   | 10       | 100         | 14.0      | 10    |
|      | 24  | 7.14638 | 0.02709 | 20         | 126   | 10       | 140         | 9.9       | 10    |
|      | 25  | 7.14638 | 0.02110 | 20         | 126   | 10       | 140         | 14.0      | 10    |
|      | 26  | 7.14638 | 0.02110 | 20         | 130   | 121      | 14          | 10        | 10    |
|      | 27  | 7.10011 | 0.03366 | 20         | 130   | 121      | 10          | 10.0      | 10    |
|      | 28  | 7.07631 | 0.07360 | 20         | 130   | 121      | 10          | 10        | 10    |
|      | 29  | 7.07631 | 0.0736  | 20         | 130   | 121      | 10          | 1         | 10    |
|      | 30  | 7.1427  | 0.02109 | 20         | 130   | 121      | 10          | 4         | 3     |

|                 |     |        |        |   |     |     |     |       |       |
|-----------------|-----|--------|--------|---|-----|-----|-----|-------|-------|
| Electron & hole | 10  | 7.4475 | 0.000  | 0 | 100 | 100 | 0   | 1     | 0     |
|                 | 11  | 7.4481 | 0.0010 | 0 | 11  | 11  | 11  | 11    | 1     |
|                 | 12  | 7.4470 | 0.0010 | 0 | 100 | 100 | 0   | 11    | 1     |
|                 | 13  | 7.4461 | 0.0000 | 0 | 100 | 111 | 0   | 1     | 0     |
|                 | 14  | 7.4471 | 0.0000 | 0 | 100 | 0   | 100 | 0     | 0     |
|                 | 15  | 7.4471 | 0.0000 | 0 | 100 | 0   | 100 | 10.0  | 10    |
|                 | 16  | 7.4471 | 0.0010 | 0 | 100 | 0   | 100 | 0     | 0     |
|                 | 17  | 7.4471 | 0.0010 | 0 | 100 | 0   | 100 | 0     | 1     |
|                 | 18  | 7.4460 | 0.0010 | 0 | 100 | 0   | 100 | 1.0   | 1     |
|                 | 19  | 7.4460 | 0.0010 | 0 | 100 | 0   | 100 | 0     | 0     |
|                 | 20  | 7.4470 | 0.0010 | 0 | 100 | 0   | 100 | 0     | 0     |
|                 | 21  | 7.4470 | 0.0000 | 0 | 100 | 0   | 100 | 0     | 0     |
|                 | 22  | 7.4470 | 0.0000 | 0 | 100 | 11  | 100 | 0     | 0     |
|                 | 23  | 7.4470 | 0.0000 | 0 | 100 | 100 | 0   | 1     | 1     |
| Electron        | 10  | 7.4461 | 0.0010 | 0 | 11  | 100 | 0   | 1     | 10    |
|                 | 11  | 7.4460 | 0.0010 | 0 | 1   | 100 | 1   | 1     | 1     |
|                 | 12  | 7.4460 | 0.0000 | 0 | 100 | 100 | 0   | 1     | 10    |
|                 | 13  | 7.4460 | 0.0000 | 0 | 100 | 100 | 0   | 0     | 10.00 |
|                 | 14  | 7.4461 | 0.0000 | 0 | 100 | 100 | 0   | 1     | 10    |
|                 | 15  | 7.4461 | 0.0000 | 0 | 100 | 100 | 0   | 10.00 | 10    |
|                 | 16  | 7.4460 | 0.0010 | 0 | 100 | 100 | 0   | 0     | 10    |
|                 | 17  | 7.4460 | 0.0010 | 0 | 100 | 100 | 100 | 11    | 1     |
|                 | 18  | 7.4460 | 0.0000 | 0 | 100 | 11  | 100 | 1     | 1     |
|                 | 19  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 1     |
|                 | 20  | 7.4460 | 0.0010 | 0 | 100 | 0   | 100 | 1.0   | 1     |
|                 | 21  | 7.4460 | 0.0010 | 0 | 100 | 111 | 0   | 11    | 1     |
|                 | 22  | 7.4460 | 0.0010 | 0 | 11  | 100 | 11  | 1     | 1     |
|                 | 23  | 7.4460 | 0.0010 | 0 | 100 | 111 | 100 | 1     | 1     |
|                 | 24  | 7.4460 | 0.0010 | 0 | 100 | 111 | 100 | 11    | 0     |
|                 | 25  | 7.4460 | 0.0010 | 0 | 100 | 111 | 100 | 11    | 0     |
|                 | 26  | 7.4460 | 0.0010 | 0 | 100 | 111 | 100 | 1.0   | 0     |
|                 | 27  | 7.4460 | 0.0010 | 0 | 100 | 111 | 100 | 1     | 0     |
|                 | 28  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 29  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 30  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 31  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 32  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 33  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 34  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 35  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 36  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 37  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 38  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 39  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 40  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 41  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 42  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 43  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 44  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 45  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 46  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 47  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 48  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 49  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 50  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 51  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 52  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 53  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 54  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 55  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 56  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 57  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 58  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 59  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 60  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 61  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 62  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 63  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 64  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 65  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 66  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 67  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 68  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 69  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 70  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 71  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 72  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 73  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 74  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 75  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 76  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 77  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 78  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 79  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 80  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 81  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 82  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 83  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 84  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 85  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 86  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 87  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 88  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 89  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 90  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 91  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 92  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 93  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 94  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 95  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 96  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 97  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 98  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 99  | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |
|                 | 100 | 7.4460 | 0.0010 | 0 | 100 | 11  | 100 | 1     | 0     |

[illegible]

## Appendix B1

### Multichannel Analysis of Surface Electromyography (MUSE) Studies

#### Equipment used

A 24-channel signal measurement electromyograph (EMG) manufactured by M3 Electronics Inc., USA was used in this study. It has a 24-bit A/D and 24-bit sample-and-hold measurements (filter gain: 25V) amplifier, followed by an A/D converter sampling at 11,114 measurements/seconds. The filtering gain enables a 40-bit filtering gain digital signal processor (DSP) which performs multi-sample processing to increase the effective resolution and dynamic range. Minimum input signal is above 100mV p-p and input impedance is 20K ohm. It has 16 built software filter sample processing effects (reference and reference-free). Sample rate is in the range of 11.12 to 1200 and selectable record length is in the range of 100 to 10 seconds. The system can be triggered with a hardware switch, contact closure, computer input, external 100V capacitor, or positive or negative voltage. It includes digitally summing of up to 16 channels into a 12-bit register, allowing threshold of each channel clipping. Listing is the added feature of this instrument.

#### Dispersion Curves and Inversion

Dispersion curves are displayed to show velocity versus frequency and the estimation can be evaluated by reconstructing the phase velocity from the linear slope of each component of the group frequency record. The accuracy of a dispersion curve can be assessed by the relative and several of values to ground truth data. The solution potential of each frequency component, a mathematical solitary wavelets (Yuan, 1987) can be applied to a ground truth seismogram. A frequency-domain approach (Park, et al., 2009) for calculating the dispersion curve can also be used to invert data. The dispersion analysis is repeated till a good S/N ratio slope is achieved.

The  $V_s$  profiles are calculated using a iterative inversion process that requires the dispersion data and estimates of Poisson's ratio and density. A least-square approach allows estimation of the process (Xu, et al., 1999). After each iteration, only the shear wave velocity is updated with Poisson's ratio, density and model thickness remaining unchanged throughout the iteration. An initial model can be specified as a starting point for the iterative inversion process consists of velocity (P-wave and S-wave velocity), density, and thickness parameters (Gedamangana and Rukmangana, 2012). Each dispersion curve is minimally inverted into depth velocity model. For inversion, four initial model parameters are required namely, density,  $V_p$ ,  $V_s$  and thickness. The inverted profile values for density and  $V_s$  is estimated and included



When  $H \pm Z$ , consolidation depth is  $z_0$ , it and  $v$  denote the thickness of sample and shear wave velocity in m/s of the  $P$  formation at layer respectively, then a total of 3 layers, comprising the top 3m.

#### • **Stiffness**

The stiffness measured using field seismic method represents the maximum stiffness ( $G_{max}$ ) (Mellors, et al., 1997). The maximum value of stiffness will therefore be measured using wave modulus by using the  $G_{max} = \rho V_s^2 \rightarrow (2)$

where  $\rho$  is the density of soil,  $V_s$  is the shear wave velocity measured using the MASW testing. For this reason the stiffness parameter measured in this manner is referred to as  $G_{max}$  and  $E_{max}$ . These parameters provide valuable benchmarks against which other stiffness values measured in the laboratory or in situ can be compared.

#### • **Liquefaction Potential**

The liquefaction hazard is commonly measured with standard sandy and clay soils during low plasticity and density. The controlling factors are soil type, density and water table. Liquefaction susceptibility is the capacity of soil to reach liquefaction and the presence of sandy layers at depths <10m and water table <10m. The liquefaction is depth-decouple considering soil layer from the underlying ground allowing is appeared to oscillate back and forth and up and down in the form of ground motion. Earthquake test suggests that the local ground liquefaction cannot occur at a depth greater than 20-30m in a sandy soil deposit.

The safety factor from liquefaction is shown in Table below (Hibamoto, et al., 2000).

Liquefaction potential (F) ranges

| Factor of safety range | Soil response |
|------------------------|---------------|
| <1                     | High          |
| 1 to 1.5               | Moderate      |
| 1.5 to 2               | Low           |
| >2                     | Nil           |
| See Liquefaction       | Nil           |

# Profile 2024-1

The 3-axis velocity image with respect to depth pertaining to profile 2024-1 is presented in Fig. 1. This site is located near Janyou Camp, Vientiane, Mekong River. The profile is consisting of two layers sequentially from the surface. Layer 1 is up to a depth of 10 m from the surface with a velocity of 100 to 160 cm/s might be presence Dense fish formation. A dense low-velocity formation (30 to 50 cm/s) is identified within the Dense formation in surface with formation of filaments and bubble like pattern. The low-velocity formation is observed at surface to deeper levels. The Conditional fish formation (Layer 2) is formed with a velocity  $10 < V < 160$  cm/s below 10 m depth. This formation are uniformly distributed throughout the profile. According to MEMP code, observed layer (Fig. 1) are classified as Class C to E. The observed  $V_{avg}$  is 47 cm/s corresponds to Dense fish formation classified as Class C (Table 2).

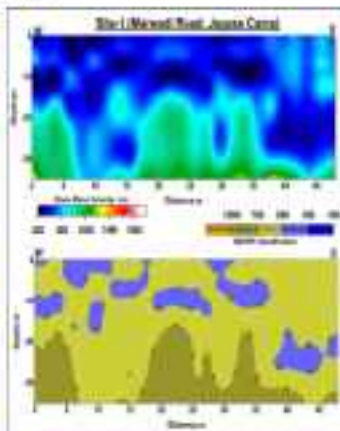


Figure 1. 3D fish velocity image of Profile 2024-1 (Janyou Camp) and corresponding fish regions according MEMP classification (bottom layer).

## Profile B001-1

The L-wave velocity image with respect to depth pertaining to profile B001-1 is presented in [Fig. 5](#). This site is located near B01 Tunnel, Miraflores. This profile is consisting of two layers sequentially from the surface. The lower velocities of the same profile runs from 100 to 1500 m/s up to a depth of 15 m. Layer-1 is extending up to a depth of 15 m from the surface with a velocity of 160 to 180 m/s might be present Dense Soil materials. A slower low velocity layer (80 to 100 m/s) is identified & within the Dense Soil might be soft soil with structure is Elasmobranch-like fish structure. The low-velocity formation is observed from 15m depth. The Consolidated Soil formation (layer-2) is observed with a velocity of >1500 m/s below 15 m depth. This formation not uniformly distributed throughout the profile. According to NECEP 2016, observed layers ([Fig. 5](#)) are identified as Class D to E. The estimated  $V_p/V_s$  is 1.61 that corresponds to Dense Soil, classified as Class C ([Table 6](#)).

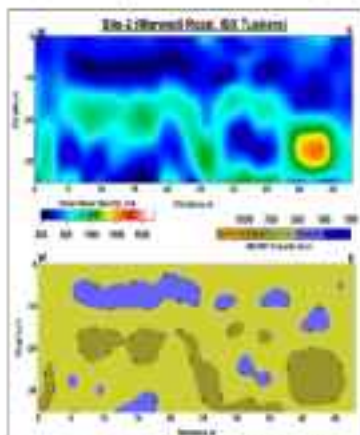


Figure 5: (a) L-wave velocity image (m/s) of profile B001-1 at Miraflores (b) Shear modulus (GPa) image (GPa) of profile B001-1 at Miraflores



### Profile B03-1

The L-wave velocity image with respect to depth (according to profile B03-1) is presented in Fig. 4. This site is located at Marston Road. This profile is consisting of two layers sequentially from the surface. These wave velocities of the upper profile ranges from 150 to 1140 m/s up to a depth of 40 m. Layer-1 is spreading up to a depth of 40 m from the surface with a velocity of 350 to 750 m/s might be possible Dense Soil material. A discrete low-velocity formation (250 to 350 m/s) is identified within the Dense Soil might be difficult with granular or filled zone and loose soils which occurred. In this section, the low-velocity layer is spread at shallow levels (about 10m). The Consolidated Sand formation (Layer-2) is noticed with a velocity of >750 m/s below 30 m depth. This formation not uniformly distributed throughout the profile. According to SWSIP code, observed layers (Fig. 4) are classified as Class Dm-B. The estimated  $V_{s1}^d$  is 450 m/s corresponds to Dense Soil formation classified as Class-C (Table E1).

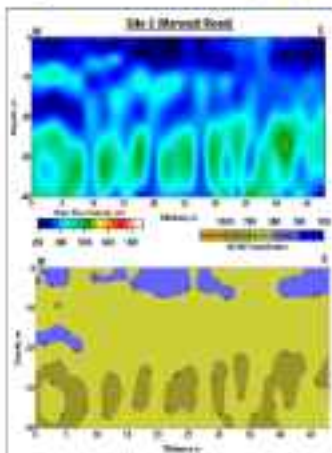


Figure 4. L-Wave Velocity Image of Profile B03-1 (Top Panel) and corresponding soil Property according SWSIP classification (Bottom Panel)

#### Profile 3034-4

The 5-wave velocity image with respect to depth pertaining to profile 3034-4 is presented in Figure 5. This site is located at Hagfish. This profile is consisting of six layers ascending from the surface. Near zero velocities of the water profile extend from 150 to 2000 m/s up to a depth of 40 m. Layer-1 is ascending up to a depth of 40 m from the surface with a velocity of 300 to 700 m/s might be present. Dense bed material. A discrete low-velocity formation (50 to 100 m/s) is identified within the Dense bed might be difficult interpretation or filled area and localized depth around 10 m section. A higher velocity layer is spread at shallow levels (above 10m). The Consolidated Rock formation (Layer-2) is vertical with a velocity of >7000 m/s at the depth. The formation are uniformly distributed throughout the profile. According to 3034-4 data, observed layers (Figure 7) are classified as Class-Div-B. The estimated  $V_p/V_s$  is 491 are corresponds to Dense bed formation classified as Class-C (Table E1).

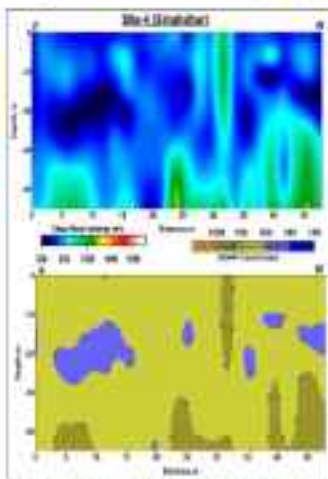


Figure 5. (a) Wave Velocity image of profile 3034-4 (Hag fish) and corresponding 2d frequency-wavenumber (WVD) magnitude (Hag fish)

### Profile TBM-1

The L-wave velocity image with respect to depth pertaining to profile TBM-1 is presented in Figure 3. The site is located at Harinagar Mandir Road, near PWD office. This profile is consisting of two layers sequentially from the surface. These two velocities of the same profile range from 120 to 1330 m/s up to a depth of 40 m. Layer-1 is extending up to a depth of 40 m from the surface with a velocity of 760 to 780 m/s which is presents Dense Soil material. A distinct low velocity formation (210 to 260 m/s) is identified a while the Dense Soil might be stiff soil with saturation or fluidness and highly elastic material. In this section, the low velocity layer is spread at different depth levels. The Consolidated Rock formation (Layer-2) is arrived with a velocity of  $\approx 1300$  m/s below 50 m depth. This formation is uniformly distributed throughout the profile. According to IS:15027 code, observed layers (Figure 3) are classified to Class D to E. The assumed  $V_{s0}$  is 401 m/s corresponding to Dense Soil formation identified as Class C (Table 3C).

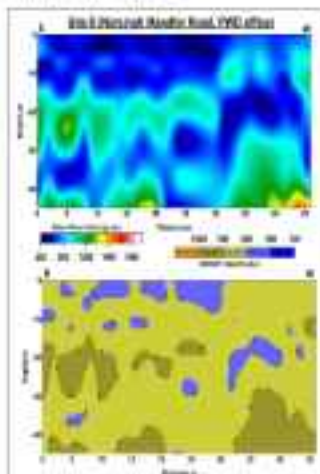


Figure 3 (a) Wave Wave Velocity Image of Profile TBM-1 (Top Part) and corresponding (b) binary image by MATLAB software (Bottom Part)

### Profile B&B.8

The 2-D near-radiotracer images with respect to depth pertaining to profile B&B.8 is presented in [Figure 7](#). This site is located at Garret's Boats near our Faculty office's house. This profile is consisting of two layers respectively from the surface. Near more reflection of the entire profile exists from 100 to 1940 m/s up to a depth of 40 m. Layer-C is extending up to a depth of 40 m from the surface with a velocity of 1600 to 1700 m/s might be presents Dense Soil materials. A distinct low-radiotracer formation (111 to 160 m/s) is identified a while the Dense Soil might be diff soil with saturation or fluidness and bedlike debris material. In this section, the low-radiotracer layer is spread at shallow level. The Considered Rock formation (Layer-C) is extended with a range of 1600 to 1700 m/s depth. This formation not uniformly distributed throughout the profile. According to SESSP rock-covered layer [Figure 7](#) are identified as Class II to B. The assumed  $\gamma_{\text{eff}}$  is III as a consequence of Dense Soil formation identified as Class C/Type III.

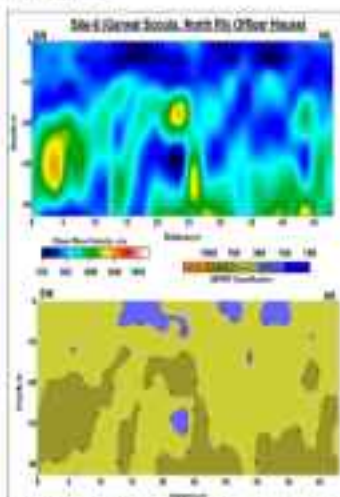


Figure 7: 2D Near-Radiotracer Images of Profile B&B.8 (Top Panel) and corresponding Geo-Targeting secondary (SESSP) visualization (Bottom Panel)

### Profile 3004.1

The 2-verse velocity image with respect to depth pertaining to profile 3004.1 is presented in [Figure 8](#). This site is located at Ash Road near Sami Kaka Mossy Bay. This profile is consisting of two layers sequentially from the surface. Near-surface velocities of the entire profile varies from 200 to 3400 m/s up to a depth of 30 m. Layer-1 is extending up to a depth to 30 m from the surface with a velocity of 500 to 700 m/s might be presence of dense soil materials. A continuous low-velocity formation (200 to 300 m/s) is identified a within the Dense Soil might be soft soil with numerous or thinness small boulders debris scattered. In the center, this low-velocity layer is spread from surface to a depth of 30m. The Consolidated Rock formation (layer 2) is extend with a velocity of >3000 m/s below 30 m depth. This formation not uniformly distributed throughout the profile. According to NZS1171 code, observed layers ([Figure 9](#)) are classified as Class C to B. The estimated  $V_p/V_s$  is 0.61 are corresponds to Dense Soil formation classified as Class C ([Table 5.1](#)).

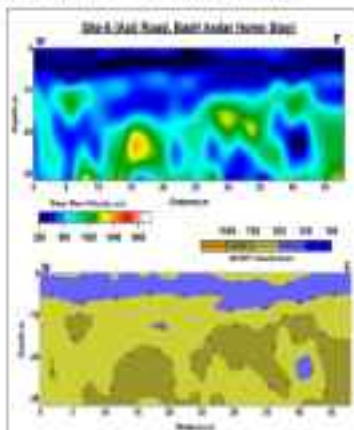


Figure 8: 2D Near-Surface Velocity Image of Profile 3004.1 (Top Part) with corresponding Soil Property according NZS1171 Classification (Bottom Part)

### Profile 2022.9

The L-wave velocity images with respect to depth pertaining to profile 2022-9 is presented in Figure 8. This site is located at JSC Bridge area near Thiruv. Govt. School. This profile is consisting of two layers sequentially from the surface. Near-surface velocities of the entire profile range from 150 to 180 m/s upto a depth of 40 m. Layer-1 is extending up to a depth to 40 m showing surface with a velocity of 700 to 750 m/s might be presence Dense Soil material. Mid-low velocity layer is observed with is for dense soil. The Consolidated Sand formation (Layer-2) is visible with a velocity of >750 m/s below 10 m depth. This formation are uniformly distributed throughout the profile. According to NEEP code, observed layer-2 (Figure 7) are classified as Class C to A. The observed  $V_p/V_s$  is 4.03 m/s corresponding to Class (a) formation classified as Class C (Table B1).

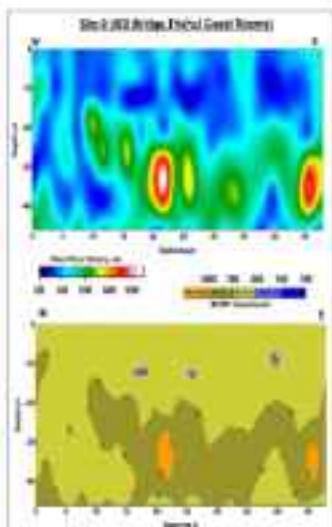


Figure 8.22 Near-Surface Velocity Images of Profile 2022.9 (top panel) and corresponding  $V_p/V_s$  images pertaining NEEP classification (bottom panel)

### Profile B004.10

The 5-msec velocity image with respect to depth armoring to profile B004.10 is presented in Figure 10. The site is located in Basin off Cape May area from Indiantown to Shell. This profile is consisting of two layers sequentially from the surface. Shallow velocity of the entire profile ranges from 150 to 170 m/s up to a depth of 10 m. Layer-1 is extending up to a depth of 10 m from the surface with a velocity of 160 to 165 m/s might be presents Dense Soil materials. A distinct low velocity formation (110 to 160 m/s) is identified a while the Dense Soil might be diff soil with saturation or fill of some sand/boulders debris material. In this section, this low velocity layer is spread as shallow to deeper levels. The Consolidated Rock formation (layer-2) is noticed with velocity of 170 m/s at a depth of 10 m and below the 10 m depth. The formation continuously dominated throughout the profile. According to USGS 2002 m/s, observed layers (Figure 10) are classified as Class 2 to 3. The estimated  $V_p/V_s$  is 0.65 m/s corresponds to Dense Soil formation classified as Class 2 (Table 5.1).

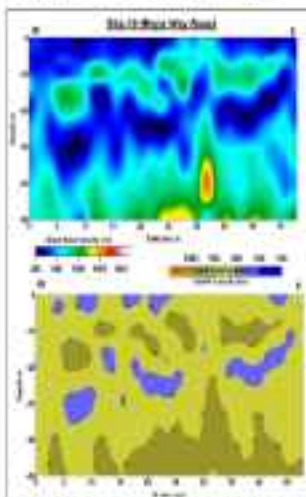


Figure 10. 10. 5-msec Velocity image of profile B004.10 (Cap May) and associated 500 Hz shear modulus (GPa) continuous record plot.

### Profile B00111

The 5-msec velocity image with respect to depth pertaining to profile B00111 is presented in [Figure 11a](#). This site is located in Lake Thomas Scatter area. This profile is consisting of two layers respectively from the surface. The lower velocities of the same profile runs from 100 to 1300 m/s up to a depth of 11 m. Layer-1 is extending up to a depth of 11 m from the surface with a velocity of 160 to 190 m/s might be present. These Soil consist of a Silty clay loam velocity formation (160 to 190 m/s) is identified & within the same soil might be affected with variation in field water and humidity. After analysis, the low-velocity layer is spread in the same part at a depth of 11m. The Consolidated Soil formation (Layer-2) is noticed with a velocity of  $>190$  m/s at a depth of 11m. This formation is uniformly distributed throughout the profile. According to IS2002 code, observed layer [Figure 11b](#) are classified as Class D to E. The estimated  $V_{u2}$  is 380m/s corresponds to Dense Soil formation classified as Class C ([Table 3.1](#)).

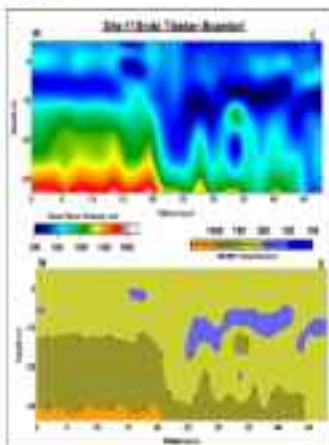


Figure 11.22: 5 msec Velocity Image of Profile B00111 (top) and corresponding Soil Depth Classification (IS2002) (bottom).



### Profile B&B.11

The 5-msec velocity image with respect to depth, according to profile B&B.11 is presented in Figure 11. This one is located at east end of El Estero de San Mateo. This one. This profile is consisting of two layers sequentially from the surface. These were velocities of the same profile taken from 10 to 100 m up to a depth of 10 m. Layer-1 is extending up to a depth of 10 m from the surface with a velocity of 700 to 750 m/s which is presents Dense Soil materials. A distinct low velocity formation (100 to 500 m/s) is identified a within the Dense Soil might be soft soil with saturation or fluidness and includes debris material. In this section, the low velocity layer is a spread in shallow depth (about 10m). The Consolidated Rock formation (layer-2) is observed with a velocity of >1000 m/s at a depth of 10m. This formation not uniformly distributed throughout the profile. According to ICDMP data, observed layers (Figure 11) are classified as Class C to A. The estimated  $V_p/V_s$  is 0.71 are interpreted as Dense Soil formation classified as Class C (Data B1).

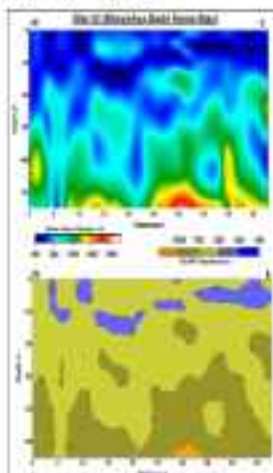


Figure 11. B&B.11 Velocity image (Depth-Dependent). The figure and corresponding low depth, according to ICDMP rock mass classification.

### Profile BHM-1a

The E-nmr velocity image with respect to depth, according to profile BHM-1a is presented in Figure 11a. This site is located on Auli road at Soc surface (near) area. This profile is consisting of two layers sequentially from the surface. These nmr velocities of the same profile varies from 180 to 1771 ms up to a depth of 60 m. Layer-1 is extending up to a depth of 40 m from the surface with a velocity of 1780 to 760 ms; it might be granitic Dabas Soil material. A distinct low velocity formation (1600 to 560 ms) is identified within the Dabas Soil might be difficult soil with variation in fluid pore water/solid ratio material. In this section, this low velocity layer is spread in shallow depth (within 10m). The Consolidated Hard Formation (Layer-2) is noticed with a velocity of  $< 160$  ms at a depth of 10 m. This formation is randomly distributed throughout the profile. According to ICDSP code, observed layer Figure 11b) are classified as Class D to E. The returned  $T_{wP}$  is 678 ms corresponds to Class B6d formation identified as Class C (Table 3C).

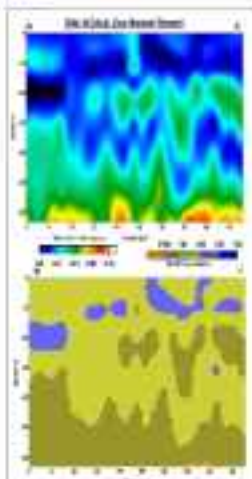


Figure 11: (a) E-nmr velocity image with respect to depth according to profile BHM-1a; (b) corresponding ICDSP formation according to ICDSP classification (Sharma, 2007)

## Appendix IV

### Ground Penetrating Radar (GPR) data profile:

#### Methodology

GPR survey is a portable and destructive EM method that can produce high resolution subsurface images in near real time. GPR uses high frequency EM energy to transmit through ground and receive the reflected signal (Joshi, 2014). Similar to the reflection seismology, it makes use of the same principle. A transmitter antenna on the ground surface emits a very short radio pulse, having only nanosecond duration. The path of the radio signal through the ground can be traced as a ray, which experiences refraction, reflection and diffraction at geological boundaries (mostly the contrast of lithological structures and structural discontinuities) with variable dielectric constant. The method is successfully utilising subsurface structural features such as caves, fractures, clay zones, ground water, buried pipes and other utilities etc. (Gardner and White, 2011; Durrant, 1992; Singh and Choudhary, 2000; Singh and Choudhary, 2011). It produces a two-dimensional image based on the propagation, reflection and scattering of EM waves across contrasting dielectric constant of the subsurface, which depends on pore size, water content, porosity, etc.

The EM waves frequency in GPR range from 10 MHz to 1.6 GHz and the smaller frequency offer greater penetration depth and vice versa (Joshi, 2014; Malin,1970; Singh and Choudhary, 2000, 2011). The penetration depth of the transmitted waves can be determined from the equation:

$$D = c/\gamma \sqrt{\epsilon}$$

where D is the depth of penetration (m); c the velocity of light in free space, the wave number (rad/meter);  $\epsilon$  is the dielectric constant.

In present study, 2400 MHz 4000 GPR system with 100 MHz and 40 MHz central frequency antenna was used. Data was acquired in the continuous mode (bistatic mode). The data collection was done at 377 mm/sec and 300 mm/sec in horizontal mode and 771 samples/sec and 70 kHz/sec in vertical mode. We used the conventional frequency setting for data acquisition, with high-pass equal to 1/10th the antenna frequency and low-pass higher than the antenna frequency. The dielectric value of the upper layer (surface permeability of asphalt) was equal to 4.0) was assigned with an estimated maximum depth of penetration is ~100 m. The field data was processed using Reflex-7 software with following steps, viz. time zero correction, background removal, Basic impulse response (BIR), gain, stretching and signal flow. The raw

anti-correlation function was applied to the raw data to detect the ground water peak positions. Followed by elimination of the portion where the trace was too small to be used, which led to small ground surface. Background removal was applied to remove all the horizontal coherent noise using hill pass background removal.

To increase the signal-to-noise ratio, low-pass ( $\sim 10$ – $100$  MHz) and high-pass ( $\sim 0.1$ – $10$  MHz) filters were applied. The values of filters were selected by the frequency spectrum of the neighborhood region including spectrum peak. Exponential gain (near  $\sim 2$ ) with depth was applied to reduce the formation of amplitude of noise, which reduced with depth. Bandpass stretching was applied to transfer the profile to original scale. The processed data is reliable up to a certain depth, which is given by the signal floor. The portion below the signal floor has been clipped from profile displayed after final processing.

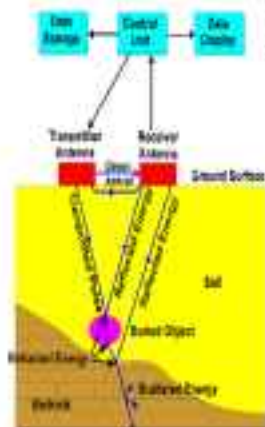


Fig. 21. Working principle of Ground Penetrating Radar (GPR).

GPR does along different profile.

### Harwell Region (701, 702 & 703)

Multiple -CH is long profile, sandy 701, 702, and 703, are obtained from the location along the Harwell Road (Figure 2c). The site is acquired using a 40 MHz frequency antenna with a depth of signal floor of ~40m (Figure 2c, 701, and 703). Topsoil (Layer-7) up to 4-m depth is partly removed and does not cause signal penetration. The second layer-8 up to 30-m depth is partially removed debris with areas of low column depth correlation with the multiple particle lenses which become wide in depth and extend up to 40m from the surface. Many areas of layered particle surfaces with higher correlation represent roots and some propagately become horizontal assuming Urethra ball geometry. The third layer is largely removed. Apart from the actual structural features, natural objects like underground pipes and rocks are also detected from the GPR sections. Vertical root type signatures are identified at a distance of 2m, 30 m, and 50 m apart from their start nodes are also observed. A prominent feature is detected at deeper levels in 70-1 and 70-2 sections (Figure 2c and 2b). However, in section 70-1 (Figure 2c) a continuation of feature is identified from the surface to the deeper level.





#### 4.1. Highline Tapes (NO-1, NO-2, NO-3, NO-7a, and 7b)

Multiple +100 m long profiles, usually 10-4 to 10-7, are obtained from the locations along the Highline Road (Figure 1 a to Figure 3d). Topsoil (5-10 m<sup>2</sup>) up to +1m depth is poorly sorted and does not show rip-up structure. The second layer 12 up to +20 m depth is partially sorted, later with zones of very coarse, large, coarse with the multiple vertical fissures which become with in depth and extend up to +40m from the surface. Many zones of coarse vertical surfaces with higher amounts also represent cracks and some progressively become horizontal assuming Lorenz fish geometry. The basal layer is largely unsorted, different.

A vertical crack type signature not identified in a distance of 1m, 5m, 5m, 10m, 15m, 20 m, 25 m, 30m, 35m and 40m (Figure 1a to 3d). Apart from these a minor crack are also observed in NO-4 (Figure 3a) and a highly sorted zone a distance of 10 to 20 m and 10 m to 150 m identified. They are unsorted zone are found with a partially sorted zone with cracks and fissures. In NO-5 (Figure 3b), a horizontal unsorted zone is observed. Near the surface to a depth of 12 m underlain by a structure (delphinus) surface. Here, fissures are observed below the 12 m depth in NO-4 (Figure 3c) section is similar to section 52 (Figure 3d) across the GPR sections of NO-7a and NO-7b are broadest and narrowest. It is observed from the surface is a sorted, soil is observed up to depth of 1.2m with fissures (at a distance of 1 m and 10 m). A structure (delphinus) surface are identified at depth of 12 m.



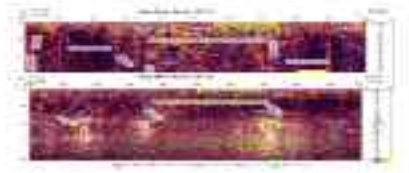




Figure 1. A large, rectangular, textured surface, possibly a wall or a large piece of fabric, with a mottled pattern of brown, tan, and reddish-brown colors. The texture appears rough and uneven.

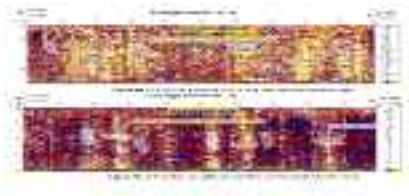


Figure 2. Two smaller, rectangular, textured surfaces, similar to the one above, but with a more uniform, reddish-brown color and a slightly different texture.

### 4.3. Hanging Mudflats (308 and 769)

Mudflats ~ 100 m long profiles, usually 35-45 m wide, are observed from the locations along the Houghs-Mudflats Road (Figures 4a to 4d). Topsoil (Layer 1) up to ~ 3 m depth is poorly structured and does not cause rapid erosion. The second layer (2) up to ~ 20 m depth is partially structured (with some areas of very coarse layer) combined with the multiple vertical fissures which become wider in depth and extend up to ~ 40 m from the surface. Many areas of coarse vertical surfaces with higher amounts also represent cracks and cause progressively become horizontal assuming Lorenz flow geometry. The third layer is largely structure deficient.

A vertical crack type exposure was identified at a distance of 110 m and 115 m (Figures 4e and 4f). Apart from these a minor crack was also observed. In 15-5 (Figure 4g) a distinct unconsolidated and less structured areas with absence of cracks and fissures are observed from surface to a depth of 40 m. It is observed from the 15-4 exposure (Figure 4h), most of the surface occupied by a highly structured zones with fissures and cracks.



#### 4.4. Muskege High Region (X01, X03, X04, X04a, X04b, and X04c)

Multiple (10 to 15) profiles, namely T5-1 to T5-13, are obtained from the locations along the Muskege High (Figures 34 to 35). Topsoil (Layer 1) up to 45m depth is partly covered and does not cause signal saturation. The second layer (2) up to 45m depth is partly covered down with areas of dry stream largely coincide with the multiple vertical fractures which become wide at depth and extend up to 45m from the surface. Many areas of stream within surface with higher intensity also represent cracks and some progressively become horizontal mimicking Loma fault geometry. The third layer is largely saturated (Figure 36).

It is noted from the X0-13 (Figure 34) a partially saturated zone is identified from the surface to a depth of 11 m which has numerous diphasic features. Very few cracks and fractures are observed in this section. In T5-13 section (Figure 35), a sequential layering (partly covered, partially covered (dike) and saturated (diphasic dike)) are observed from the surface. A mixture of fractures and cracks are also observed in the partially saturated dike zone. Similarly, it is observed in this section, a central objective (the deep seated pipe) acts as the main structure in deep levels. The depth of these objectives could not be traced from the GPR sections due to interference are also observed from the multiple which are like features of the actual picture of the object. In X0-13 section (Figure 34), a vertical zone of dike is observed at a distance of 40 to 11 m from the surface to a depth of 11 m. This zone is juxtaposed in the all the observed sequential layers. Further a minor fracture and cracks are also observed at distance of 7m, 11 m and 15 m. In X0-14 section (Figure 34), minor fractures and cracks are also observed at distance of 7m, 11 m, 15, 17m and 19m. In X0-15 section (Figure 34), a large vertical zone of dike is observed at a distance of 10 m to 40 m and 70 m to 90 m from the surface to a depth of 15 m. These zones are juxtaposed in the all the observed sequential layers. Further a minor fracture and cracks are also observed at distance of 1 m, and 11 m. X0-16 section (Figure 34) juxtaposed two partially saturated zone up to a depth of 15m with two fracture zones at a distance of 10 m and 15 m.







Figure 1: A photograph of a large, ornate, dark-colored wooden cabinet or wardrobe with multiple doors and drawers, set against a light-colored wall.



Figure 2: A photograph of a large, ornate, dark-colored wooden cabinet or wardrobe with multiple doors and drawers, set against a light-colored wall.

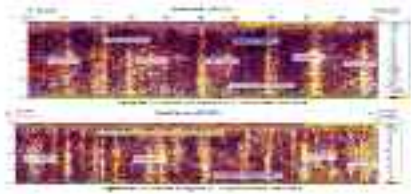


Multiple = 10 is long profile, namely 30-11 to 35-34, and obtained from the locations along the shoreline (Figure 4a to 4f). Topsoil (Layer 1) up to 4-10 depth is poorly sorted and does not cause signal attenuation. The second layer II up to 4-20 at depth is partially sorted debris with areas of dry crumb. Layer 3 contains with the multiple surface flumes which become more at depth and extend up to 4-30m from the surface. Many areas of flume surface surface with higher surface, the represent more and more progressively become horizontal extending linear their presence. The basal layer is largely structure defined.

It is noted from the 30-35 (Figure 4a), the flumes are observed at a distance of 1 m, 50, 40m, 15m, and 60m and where flumes are a distance of 15m, 15m, and 15m. In the 35-19 section (Figure 4b), the flumes are observed at a distance of 15 m, 70, 15m, and 15m, and where flumes are a distance of 15m, and 15. Further, a cultural object is observed at a distance of 15 m. The flumes could be affected deep inside pipes, perhaps by water. In the 35-19 section (Figure 4c), except by complete highly returned areas no observed without surface of flumes and rocks. In the 35-11 section (Figure 4d), a common area of the flume is identified at a depth of 15m throughout the profile and it is extending up to a depth of 15 m. In the 35-12 section (Figure 4e), the flumes are observed at a distance of 15 m, 50, 30m, 10m, 70m, 50m, 40m, and common flumes. In the 35-11 section (Figure 4f), some flumes are identified throughout the profile. In the 35-11 section (Figure 4g), some flumes are identified throughout the profile. In the 35-34 section (Figure 4h), a wide flume area is identified in the middle part of the profile up to a distance of 10m. In this profile, the maximum area is occupied by a highly returned area.









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#### 4.8.12 Road area

Two  $\times 100$  m long profiles, namely 10-11 and 10-13, are obtained from the locations along the Mandak Singh (Figures 1a and 7a). Typical (Layer 1) up to 4 m depth is poorly cemented and does not cause signal attenuation. The second layer (2) up to 6 m at depth is partially cemented debris with areas of dry crumms largely continuous with the multiple vertical fissures which become more at depth and extend up to 6 m from the surface. Many areas of denser vertical surfaces with higher resistance also represent cracks and zones progressively become horizontal extending laterally their presence. The basal layer is largely structure deficient.

It is revealed from the 10-13 (Figure 7a), a narrow fissure zone is observed at a distance of 70 to 40 m. In 10-19 section (Figure 7b), a local fissure zone is observed at a distance of 15 m. Further, a cultural object observed throughout the profile might be indicative of the undisturbed ground level.



#### 4.7. Representative cores

40 to 110 m long profiles, namely 11b-C'0 and 11b-C'1, are obtained from the locations along the Mendota Shelf (Figures 1a and 1b). Topsoil (Layer 1) up to +1 m depth is poorly sorted and fine to coarse sand accumulation. The second layer (2) up to +20 m depth is partially sorted debris with zones of dry crinoid largely overlies with the multiple vertical flutes which become more at depth and extend up to 40 m from the surface. Many zones of diameter variable surfaces with higher amplitudes also represent crinoid and more progressively become horizontal extending 100 m from present. The basal layer is largely structure deficient.

To understand the crinoid and flutes in this area GPR data was collected along the two profiles by using different antennas i.e. 400MHz (Figure 1c) and 100MHz (Figure 1d).

Several flutes within a short distance up to a depth of 11 m are observed in the survey area (Figure 1c). A highly sorted zone is observed at shallow levels up to a depth of 1m (Figure 1d).





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