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Determination of Seismic Site Class and Potential Geologic Hazards using Multi-Channel Analysis of Surface Waves(MASW) at the Industrial City of Abu Dhabi, UAE

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ABSTRACT
Geophysical investigation activities were conducted at ICAD-II, Abu Dhabi, UAE using Multi-Channel Analysis of Surface Waves (MASW) to determine subsurface geology , material stiffness, potential weak zones down to ~35 m depth, and to propose the appropriate seismic site classification for a proper foundation design. A total of 20 MASW lines were carried out over a grid layout of 5 m spacing. Data acquisition, processing and inversion have been parameterised and selected to produce shear velocities that represent subsurface conditions. The estimated average shear-wavevelocity (Vs_{30} = 577.97 m/s) suggests that the investigated site can be classified as Class C (V.D. Soil & Soft Rock). The constructed geological model comprises sand, weak sandstone, weak mudstone, and hard mudstone. Analysing the shear wave velocities indicates the absence of apparent cavities/ hazardous zone . However, a relatively weak layer of sandstone/mudstone rocks intercalations was detected from ~7m to ~25m. Meanwhile, the uncorrelated part of 2D MASW data indicates potentially harder mudstone encountered at a depth starting from ~25 m to >35 m. Hence, the foundation layer may be placed on the upper surface of the sandstone bed (~7 m) depending on the height and load of the proposed building and following the construction standards and requirements of the structural engineer.

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MASW; vs_{30}; site class; foundation layer; abu dhabi; UAE

1. Introduction

The importance of site characterisation studies in the UAE has been increasing significantly over the past 20 years due to massive construction activities and growing human needs in both the housing and industrial sectors. At present, the municipalities of major cities of the UAE do not allow any construction unless the owners provide evidence that the results of geophysical studies indicate that there are no serious geological problems that could prevent safe design and construction.

Recently, different soil settlements were occurred and recorded at some cities of the UAE due to the predominance of cavernous limestone at shallow depths. This gave rise to the urgent need to apply modern geophysical techniques that can examine the soil and provide the owners with the necessary information about the existing soil and the nature of the subsurface layers. Therefore, geophysical investigation has become imperative in the soil inspection work in the UAE in order to support the consultant and site engineers with all possible data about the subsurface conditions.

Studying the subsurface geology for site class determination and potential hazard assessment is an important approach to save the engineering structures and human life from any future unexpected catastrophic consequences. Ambiguity about the upper 50 m of the earth is still a subject for study by many researchers and scientists who are interested in solving this unrevealed important part of the near-surface geology in order to provide all possible information on soil properties, elastic moduli, bedrock depth, cavity and sinkhole threats, ground stiffness, site class, water table determination, etc. Geophysical methods carried out on surfaces and in boreholes are currently considered to be the most widespread and fastest techniques for solving this ambiguity, and also supporting appropriate and feasible solutions that may be proposed by the lead design engineer. Seismic methods with different technologies, strategies, and applications are among several applicable geophysical techniques to explore this shallow part of the earth (i.e. 50 m) and provide more details about the nature of the existing findings and their effect on the design of the foundation.

The study area (Figure 1) occupies 27,030.00 m^2 at ICAD-II, the Industrial City of Abu Dhabi, UAE. The study area was topographically flat and covered with marine deposits composed of silty sand. Coordinates of the measured MASW lines and drilled boreholes are presented in WGS 84, Zone-39, and the elevations were relative to NADD (New

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This article has been corrected with minor changes. These changes do not impact the academic content of the article.

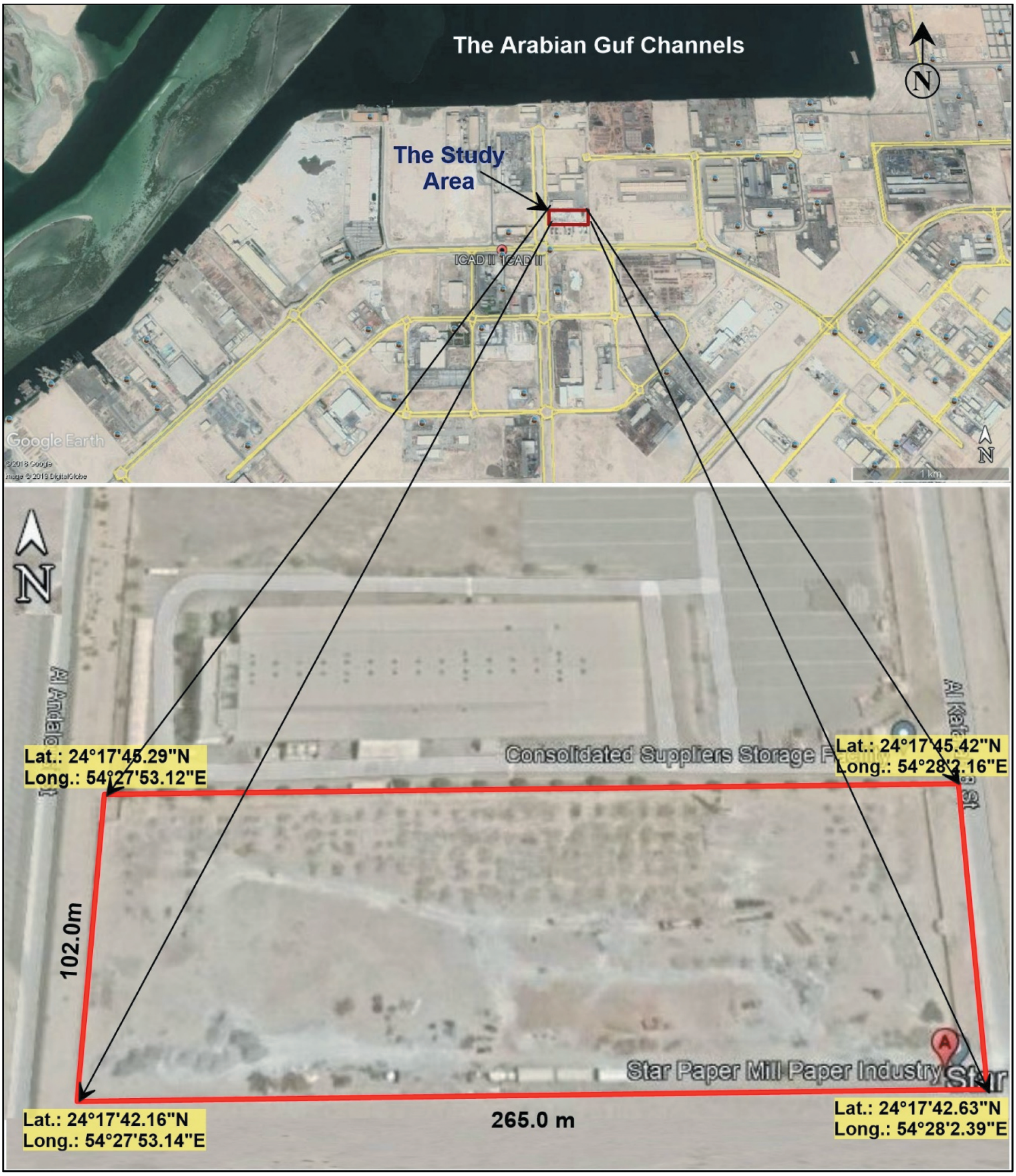

Figure 1. Satellite Google Image showing the location of the study area.

Abu Dhabi Datum). No sources of noises or construction obstacles were found in the study area during the data acquisition, so the existing site conditions were favourable for high-quality measurements of the shear-wave velocity.

The main objective of this study is to investigate the subsurface geologic hazardous features at the ICAD-II of Abu Dhabi using MASW seismic survey and thus ascertain whether the study area is acceptable and suitable for safeguarded construction and invulnerable facilities. This can be done by estimating the average Vs_{30} and providing the site class required for proper foundation.

2. Methodological background of MASW survey

Seismic waves are mainly classified into two noteworthy categories: body waves and surface waves. The first category propagates into subsurface geological layers and penetrates deeper parts, while the second one propagates near the surface in elliptical form. It is therefore very important to study and analyse both types of waves in order to obtain the required dynamic properties of the near-surface regions, which in turn is essential for the engineering design of a wide scale of projects. The main components of either body or surface waves are compressional (Vp) and shear (Vs) wave velocities that are generally estimated and analysed through a wide range of methods including seismic refraction and reflection, vertical seismic profiling, downhole, cross-hole testing, ReMi, SASW, MASW, etc. The utilisation of Multi-Channel Analysis of Surface Waves (MASW) has been increasingly applied in most engineering projects, in particular for characterising the necessary geotechnical parameters and its impact on the design of a proper foundation bed at shallow depths.

Although the application of surface wave analysis was initiated to investigate the earth's crust and upper mantle (Ewing et al. 1957; Dorman et al. 1960; Dorman and Ewing 1962; Bullen 1963; Knopoff 1972; Kovach 1978; Mokhtar et al. 1988; Herrmann and Al-Eqabi 1991; Al-Eqabi and Herrmann 1993); however, several authors extended the analysis of surface waves for different engineering purposes by developing the methodology (McMechan and Yedlin 1981; Park et al. 1999a, 1999b; Socco et al. 2002; El-Eraki et al. 2012), apply it for site characterisation studies (Gabriels et al. 1987; Tokimatsu 1997; Xia et al. 1999; Foti 2000; Jwngsar 2011), use it for the estimation of the soil dynamic characteristics (Jongmans and Demanet 1993), and compare its results with other geophysical results (Hiltunen and Woods 1988; Foti et al. 2002). The effect of proper selection of data acquisition and signal pre-processing parameters was also studied (Jumrik and Arindam 2018) for better resolution of dispersion images from the active MASW survey. Comparing surface geophysical techniques of refraction wave method (RWM) and MASW with borehole traditional PS logging method for thick soil sites indicates that RWM and MASW are very cost-effective alternatives to traditional PS logging method (Dewan and Woobaidullah, 2018). The limitations of the MASW method were also inspected by Chong Zeng et al. (2012) who studied proper ways of numerical modelling of Rayleigh waves under surface topography (and subsurface discontinuity like void). In addition, Limin et al. (2015) reported surface wave effects on the dispersion images when surface "depression" and "uplift" are encountered within the receiver spread.

As per the given name, MASW analyses the dispersion properties of certain types of seismic surface waves (fundamental-mode Rayleigh waves) that propagate horizontally along the surface of measurement directly from the impact point to the receivers. Rayleigh wave is one of the several surface waves that can be generated (Sauvin et al. 2016) as it is considered a common type of surface wave and arises from the interference of compressional (P) waves and vertically polarised shear-waves (Sv). Shear-wave velocity can therefore be used to determine the behaviour of the Rayleigh wave and other elastic parameters. Calculating in situ Vs using MASW is primarily based on the characteristics of surface wave propagation and velocity dispersion (Stokoe II et al. 1994). Thus, the stiffness of the subsurface material can be assessed for geotechnical engineering purposes.

Like other common surface geophysical methods, MASW is a non-invasive technique, primarily used to create 1D velocity profile (variation of Vs with depth), and with certain configuration and inversion processes, 2D velocity model can be obtained, which can thus provide clear information on the thickness of the subsurface beds, display the heterogeneity of the near-surface stratigraphy and delineate cavities/weak zones down to 30 m below the ground level (bgl). The main advantage of the MASW technique over other seismic methods is its ability to identify a low-velocity layer/zone under a high-velocity layer/zone in contrasting geology.

The surface slope along the receiver span can also affect the accuracy of the resulting dispersion curves. Results of numerical investigations presented by Chong Zeng et al. (2012) displayed that dispersion characteristics can be estimated with less than 4% error where the topography slope (θ) along the receiver span is less than 10°. Thus, optimised results can be obtained when geophones are placed on relatively flat terrain. For greater accuracy, surface reliefs must be considered and observed during data acquisition (Park and Carnevale 2010). If the surface reliefs are larger than the length of the receiver spread, poor quality data are likely to be expected.

Recent studies and applications indicate that method can be efficiently used to calculate the distribution of shear wave velocity (Vs_{30}) in both soil and rock (Ashraf et al. 2018) and to estimate accordingly the site class of shallow subsurface geology; provides guidelines for good practices in real projects (Sebastiano et al. 2018), shows its applicability in less accessible areas in alluvial deposits using sparse MASW profiles with a fixed receiver and multi-source offset geometry (Faisal Rehman et al. 2018), classifies the seismic site effect of Dikili-İzmir in western Anatolia using MASW and ReMi methods (Savaş Karabulut 2018) and to estimate seismic site classification with the correlation of VS and SPT-N for deep soil sites in Indo-Gangetic Basin.

The entire methodology and standards applied in this study were critically following common MASW survey practices to obtain an accurate determination of the shear wave velocity of the upper 30 metres (i.e. Vs_{30}) which is essentially required to determine the material stiffness, to delineate potential weak zones (i.e. cavity) down to ~35 m depth, and to finally suggest the appropriate seismic site classification for proper foundation design.

In this paper and as opposed to previous studies that applied general geophysical surveys for geotechnical purposes, we developed the site methodology of the MASW technique to allow broad coverage of measurements across the entire study area, to analyse the resulting data laterally and vertically, and to correlate the final results with borehole data so that an appropriate site characterisation can be obtained. In practice, a grid with evenly spaced lines (5 m interval) was set up to allow recording of MASW data with proven acquisition parameters.

3. Geological background & geotechnical data

The United Arab Emirates is located on the eastern end of the Arabian Peninsula and occupies land belts extending from Abu Dhabi to Ras Al-Khaima (western area), and from Fujairah to Dibba (eastern area) (Ketan and Anbazhagan 2019). The western area forms part of a wide low-lying coastal plain narrowing to the north and consists largely of accumulations of coastal and dune deposits. The surface geology of the United Arab Emirates is masked by a sand cover. Therefore, the regional geology of the UAE is mostly inferred from subsurface information resulting from the borehole and/or geophysical data. Experts (Ketan and Anbazhagan 2019) stated that the interplay of changes in sea level, crustal movements, and climatic variations largely controlled the Abu-Dhabi sedimentation process. The sands form dune ridges reaching heights of 150 m inland. These dune ridges are separated by plain gravel areas, which so-called "desert floor". Rocky outcrops are not seen in most of the UAE land except at Al Fujairah Mountains to the northeast and Al-Ain area to the East where the Oman mountains are part of that region.

Conditions in the Abu Dhabi Island area consist of a complex of intertidal flats with related lagoons and coastal barriers (Ketan and Anbazhagan 2019). Dominant superficial deposits in these areas comprise carbonate muds, silts, and sand. Onshore wind-blown sand deposits predominate, however, wind erosion, capillary action and evaporation have led to extensive development of Sabkha deposits along the coastal plains extending more than 80 km southwards into the sandy deserts. These deposits are underlain by alternating beds of calcarenite, carbonate sandstones, calcisiltitic (carbonate siltstones), and limestone, which generally overlie gypsiferous carbonate siltstone or carbonate mudstone and gypsum at depth.

The study area (Figure 2) is located within Abu Dhabi Emirate, which lies in an area dominated by flat-lying sedimentary rocks and a seismically stable region. The study area and its surroundings can be divided into three main physiographic regions: the offshore barrier Islands and intertidal lagoons; the coastal plain; and the Miocene outcrop in the southeast.

The study area is dominated by the sediments of Abu Dhabi Formation, which comprise calcareous silty sand with some gravel and bioclasts, clay, and silt layers (sometimes lenses). The sands of this formation change laterally and downward to cemented sand pieces and very weak fractured sandstone. Abu Dhabi Formation is underlain by the Gachsaran Formation which is not outcropping on

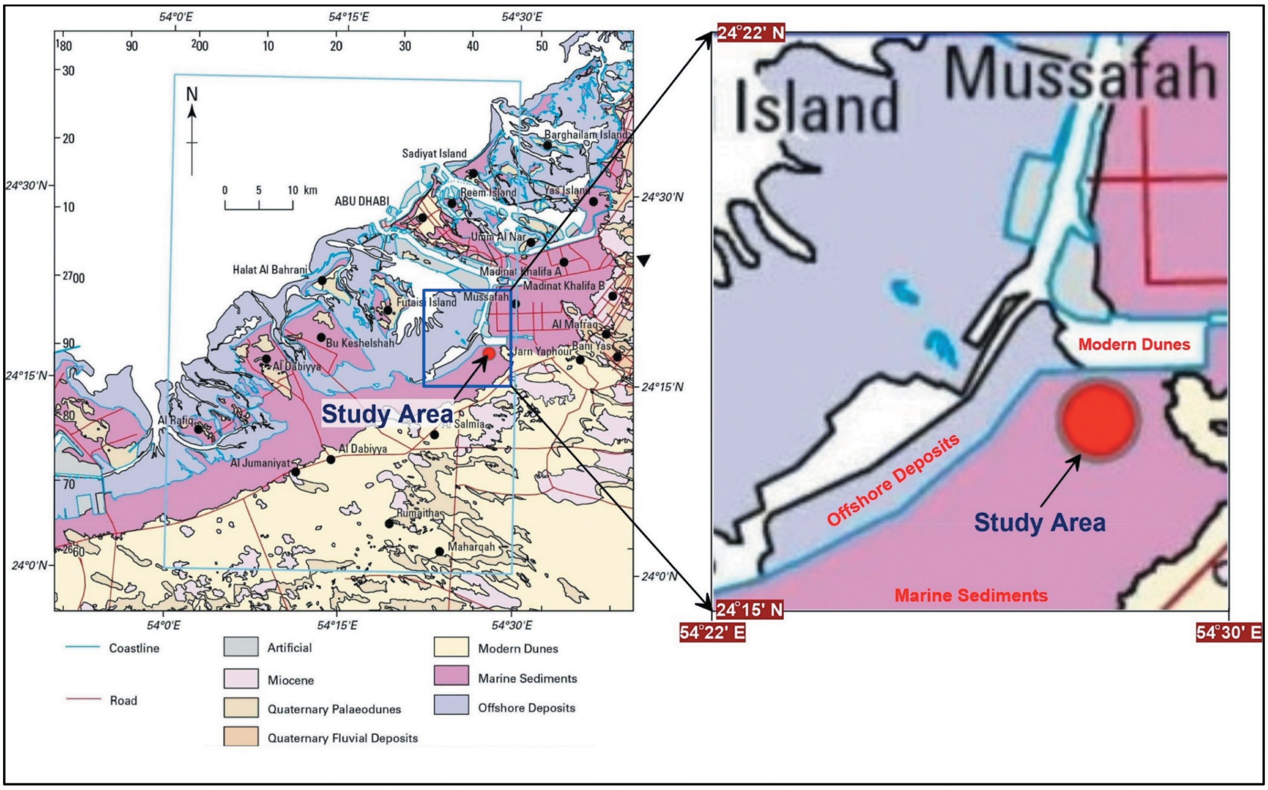

Figure 2. Geological map of Abu Dhabi city shows the dominant geological units at the study area.

the surface but represents the main bedrock of the urbanised area of Abu Dhabi. The Gachsaran Formation is concealed by the Abu Dhabi Formation along the coastal area, and by younger Miocene and Quaternary sediments inland. The formation is composed of mudstone and siltstone with interbeds of massive or nodular gypsum in the upper part of the formation. The local site geology of the study area was briefly described from the available geological and geotechnical information provided by the National Laboratory for Soil & Building Materials Testing (National Laboratory for Soil & Building Materials Testing 2017) which carried out geotechnical investigations in 2017 at eight (8) boreholes Figure 3 down to 20 m depth. The results of laboratory testing of the recovered core samples were utilised to construct a geological cross-section across the whole study area in order to delineate and highlight the existing subsurface geological conditions. This geological cross-section (Figure 4) generally indicates relatively homogeneous subsurface geology consisting of the following three layers:

(1) Silty Sand with cemented sand pieces/cemented silty Sand,
(2) Very weak to weak, moderately fractured Sandstone, and
(3) Intercalations of weak to moderately weak and fractured Mudstone and Gypsum

The encountered layers of the silty Sand and Sandstone belong to the Pleistocene Ghayathi Formation, while the underlying mudstone and gypsum interbeds belong to the Miocene Gachsaran Formation. The above-mentioned geological units have been encountered at different depths in the eight drilled boreholes. Among them, borehole BH-02 was selected for correlation with the MASW data to provide comprehensive and realistic information about the existing subsurface conditions down to ~35 m depth.

4. Masw data acquisition

A group of 20 MASW lines at 5 m spacing was prepared and designed for data acquisition. The planned MASW lines were first located by Trimble SPS985 GPS Receiver (RTK-System) by stacking out starts (S1, S2 ... S11) and ends (E1, E2 ... E11) of each line. To estimate shear wave velocity, MASW measurements were carried out across the investigated area (Figure 5) using the GEODE24 seismic acquisition system of Geometrics Incorporation. This system consists of a 24-channel seismograph and a towed seismic land streamer carrying twenty-four 4.5 Hz vertical-displacement pressure coupled geophones spaced at 2 m intervals. Generation of surface waves was made by hitting a metal plate, tightly coupled to the ground surface, by a 10 kg sledgehammer. Surface waves propagate outwards from the impact point with cylindrical wavefronts, generate a variation in both wavelength and frequency, and commonly decay more slowly with the distance of propagation, which is called dispersion.

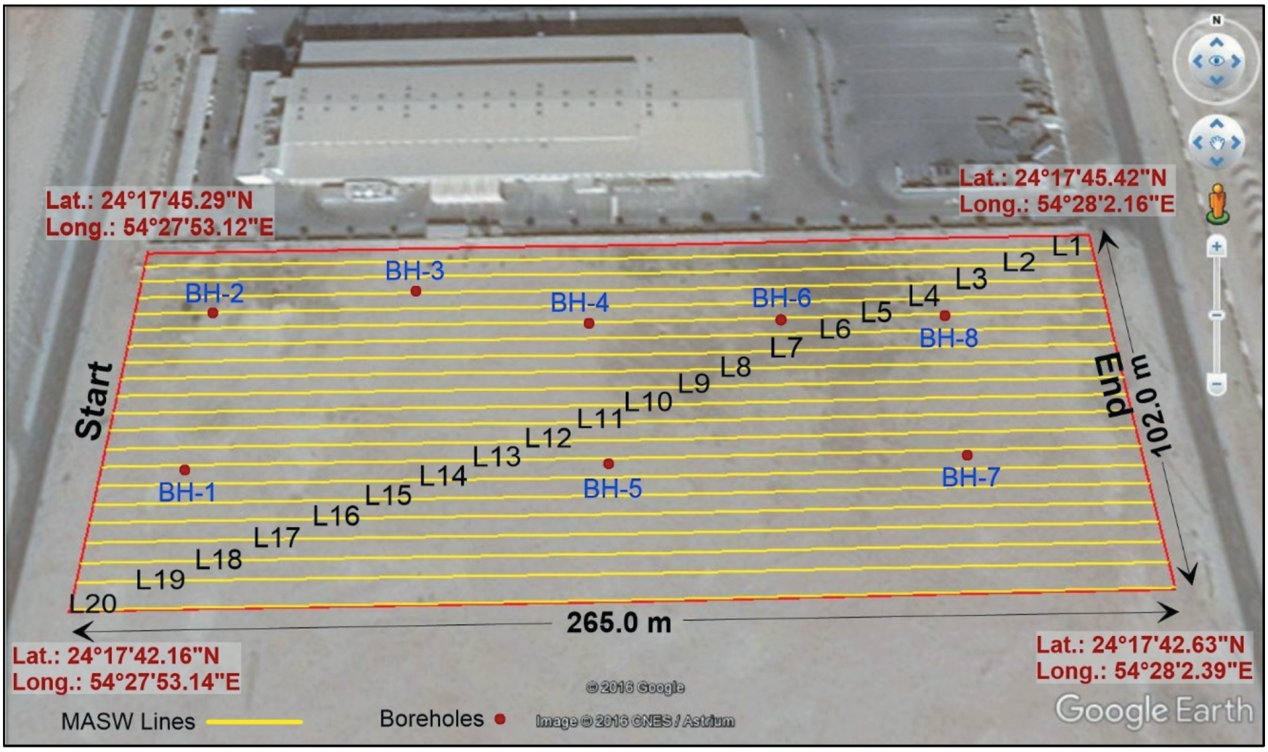

Figure 3. Layout of geophysical MASW lines and geotechnical boreholes.

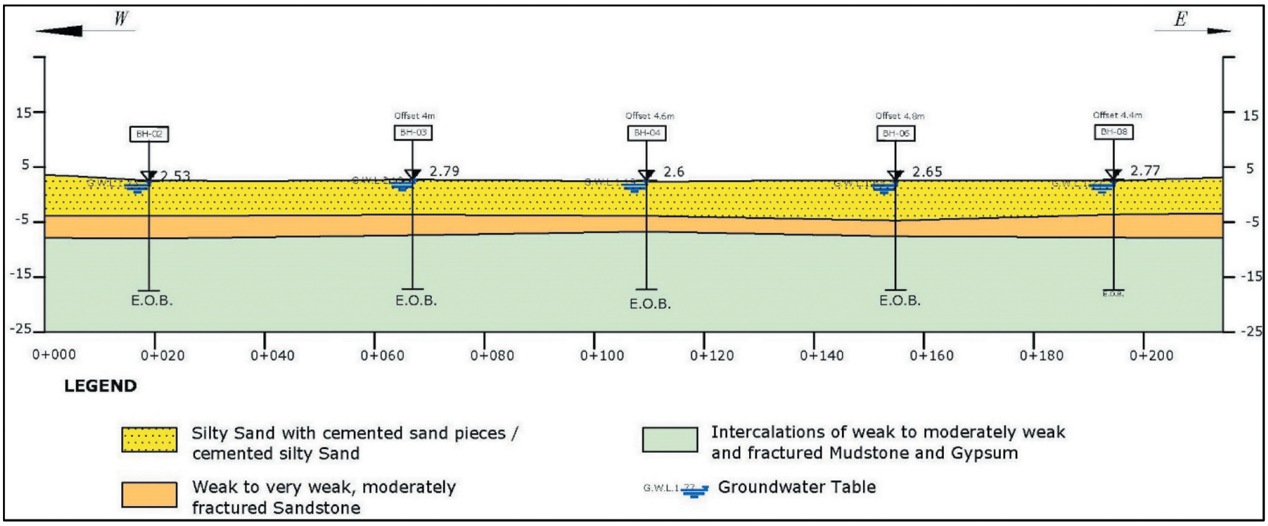

Figure 4. General geologic cross section shows the lithological units encountered at five boreholes drilled by National Laboratory for Soil & Building Materials Testing (National Laboratory for Soil & Building Materials Testing).

The geophones towed by the land streamer convert ground movement (displacement) into voltage, and thus are recorded by the recording station as shown in Figure (5). MASW acquisition parameters considered in the present study are listed in Table 1.

During the MASW measurements, the number of impacts (i.e. stacks) at each shooting point was 4–5 to increase the signal-to-noise ratio and thus improve the data quality. In a similar manner to other seismic refraction/reflection data, MASW data was collected in the time-distance domain (travel time vs distance along with geophone spread).

5. Masw data processing and inversion

Processing of MASW data was conducted using the packaged software (Surfseis 5.0) of the Kansas Geological Survey (KGS, 2016). The processing sequence scheme prepared for this study is presented in Figure 6. Processing is initiated by importing recorded data (in Seg-2 format), into Surfseis Software. The geometry information is applied to the seismic traces, and dispersion curves are generated from the Rayleigh wave window identified by the software. After picking the dispersion curves, and creating an initial starting model, an inversion routine is run to generate the shear-wave velocity profiles. Data inversion to

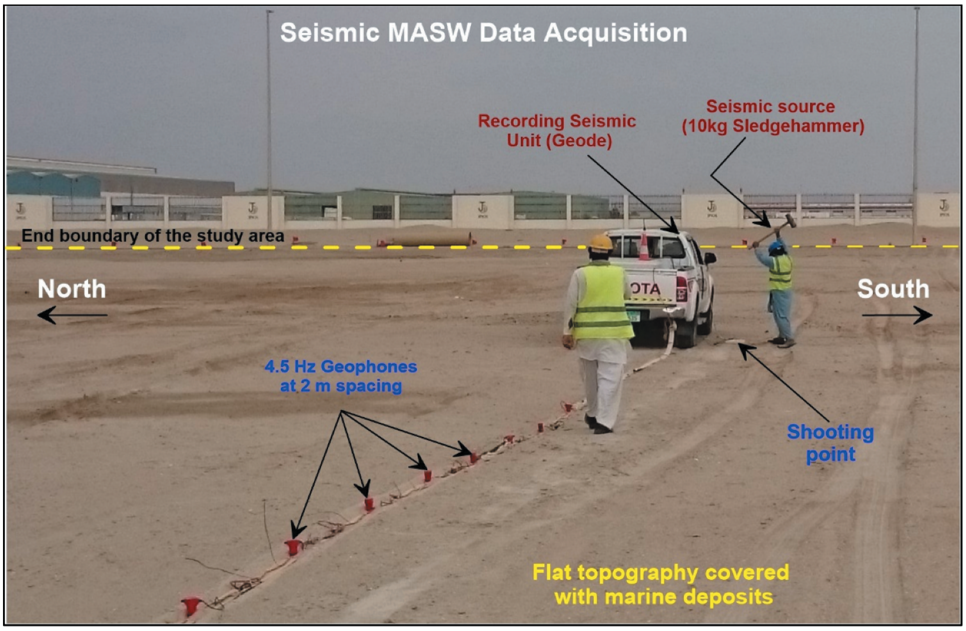

Figure 5. MASW data acquisition at the study area.

Table 1. MASW acquisition parameters.

Line spacing	5 m
Geophone frequency	4.5 Hz
Geophone interval	2 m
Shoot interval	10 m
Shoot displacement	6 m
No. of stacks	4–5
Energy Source	10 kg Sledge hammer
Acquisition approach	Roll along liner profiles
Sample interval (dt)	0.125 ms
Record length (L)	1 Sec.
Delay	0 ms
Acquisition filter	Filters out
Preamp gains	High 36 dB
Number of records/station	1
File type	Seg-2

obtain S-wave velocity is carried out by creating synthetic dispersion curves derived by well-established numerical methods and comparing synthetic to field data. The method to improve each subsequent fit to the field data is based upon the calculation of the Jacobian matrix, which determines the partial derivatives of the field velocity data with respect to the S-wave data of the model. Critically, the data processing strategy employed yields an estimate of uncertainty or error in the derived S-wave values.

The entire procedure for MASW data processing generally comprises of four steps:

(a) Acquiring Multi-channel records (or shot gathers),
(b) Extracting the fundamental-mode dispersion curves (one curve from each record),
(c) Inverting these curves to obtain 1D (depth) Vs models (one profile from one curve),
(d) Interpolation of the obtained 1D models to construct the 2D Vs model for each line.

Since the recording length of the acquisition parameters was set to 1 sec, only this portion of the recording length (i.e. 1 sec) of the acquired converted data can be used to consider most of the active surface waves for proper picking and further processing requirements. In this study, the first 0.7-sec portion of a selected shot gather along Line-16 (Figure 7) is presented as an example of the acquired MASW data.

The displayed seismic traces of 24-channels were examined primarily in terms of frequency, original signals, noises, and other geometric attributes that are essential for further data processing and inversion.

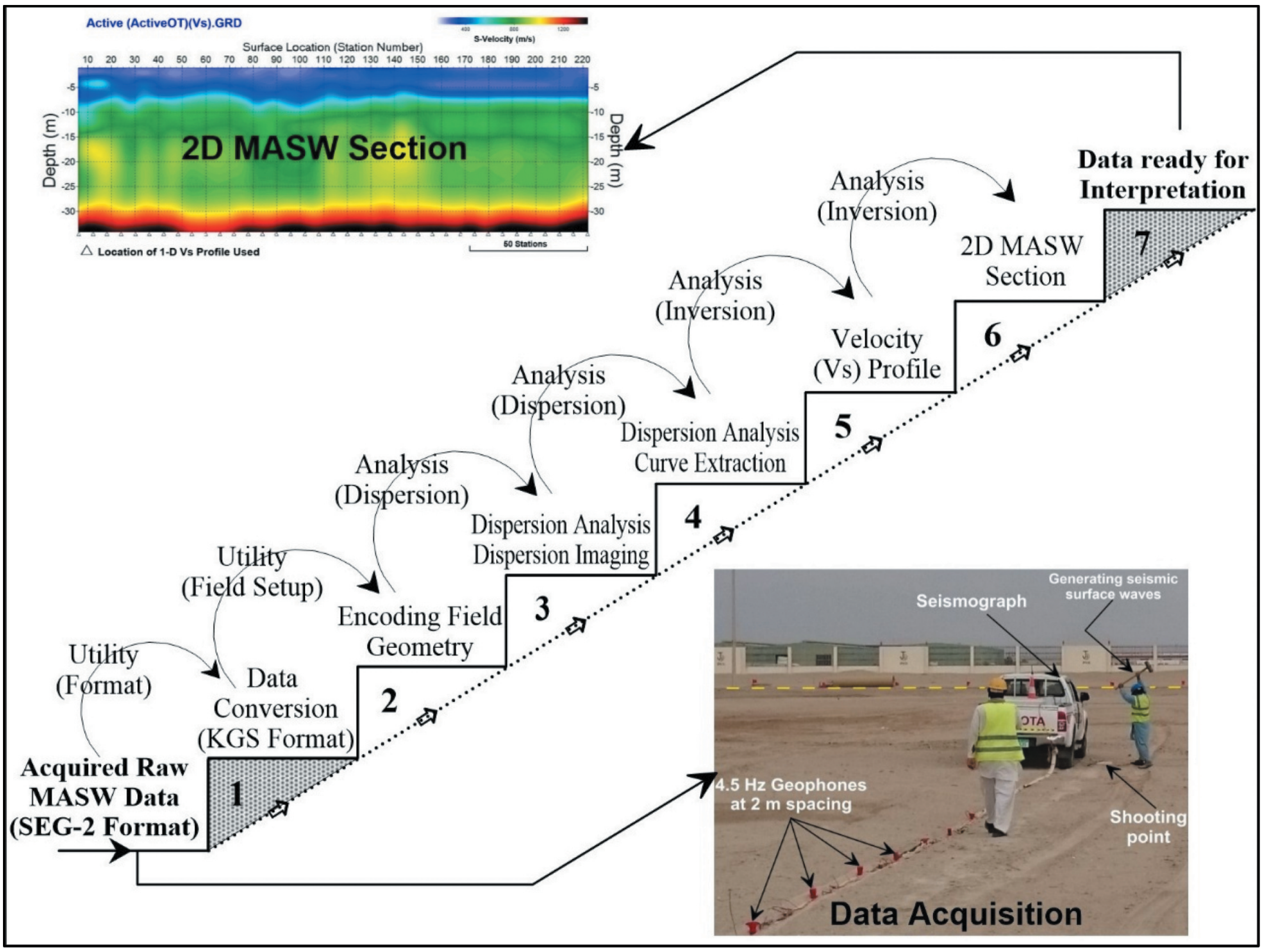

Figure 6. MASW Processing sequence scheme applied in this study using SurfSeis software (KGS, 2016).

The multi-channel shot record is uploaded to SurfSeis (KGS, 2016), and a dispersion curve is produced (Figure 8) after applying step 2 (Figure 6) based on the arrival times of the different frequencies, their energy or amplitudes, and apparent phase (Wathelet 2005).

The analysed dispersion curve reveals both modes of the Rayleigh waves: the fundamental and higher (overtones) represented by the shallow subsurface geology. Data is then transformed to the frequency-wave number domain by a 2D Fast Fourier Transform with appropriate spatial windowing applied to minimise processing artefacts and by a further simple step to the phase velocity–frequency domain. The relationship between phase velocity and frequency facilitates the discrimination of a dispersion curve. The dispersive characteristics of Rayleigh-type surface waves were used to image the shallow subsurface layers by estimating the 1D (depth) and 2D (depth and surface location) shear wave velocities.

The dispersion function of SurfSeis software (KGS, 2016) was used to calculate the phase velocities within a specified frequency range. Figure 8 shows the dispersion curve of Line-16 after picking the fundamental mode of the Rayleigh surface wave, which is used as an input for the final inversion process. The inverted MASW data are generally presented as 1D (Vs vs. depth) lines of shear-wave velocity versus depth (Figure 9) or as 2D sections (Vs vs. depth and distance) comprising a set of adjacent 1D lines (Figure 10). Accordingly, by placing each 1D Vs profile at a surface location corresponding to the middle of the receiver line, a 2D (surface and depth) Vs map is constructed. A typical 2D MASW section of Line-16 is shown in Figure 10.

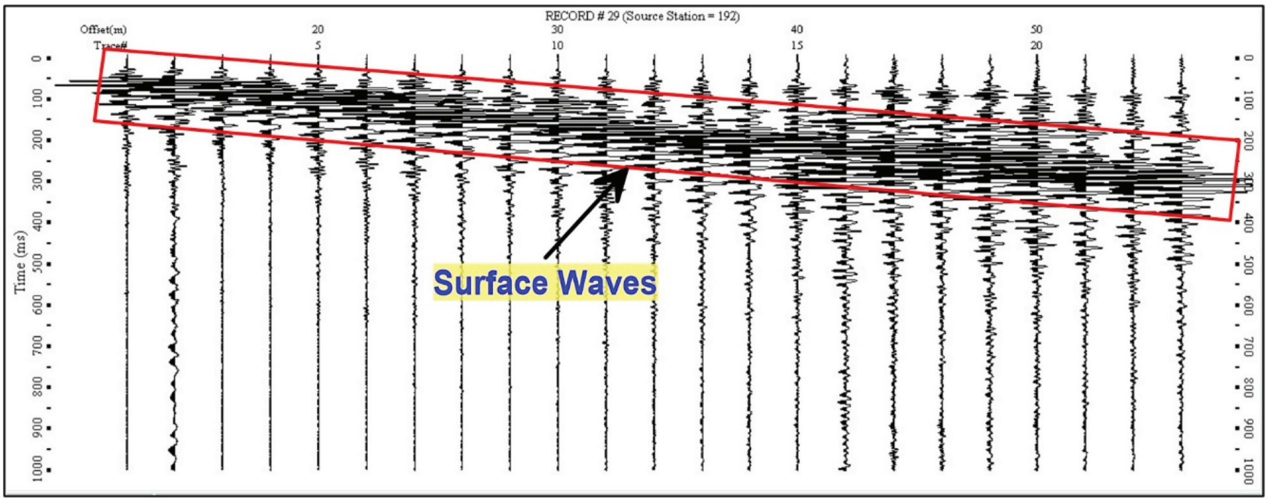

Figure 7. Typical MASW shot gather of Line-16.

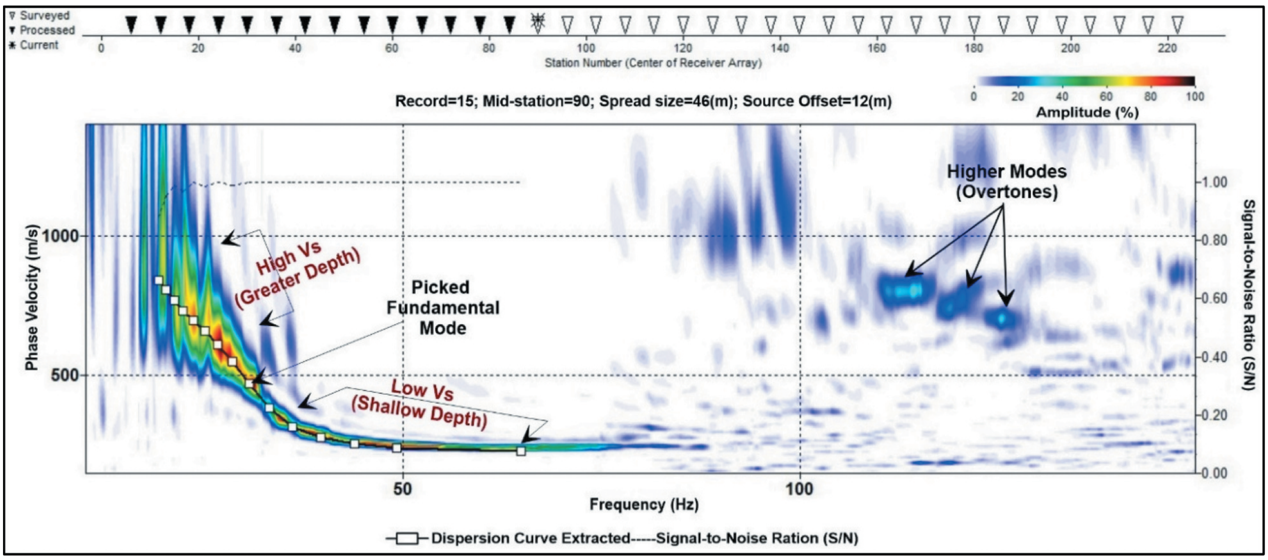

Figure 8. A dispersion curve of Line-16 shows the fundamental mode picked manually using SurfSeis software. Multiple overtones are also clearly identifiable.

6. Results and Discussion

The final inversion results of applying the MASW survey to the study area were thus represented by 2D shear-wave sections (Figs. 11, 12, and 13). The rainbow colour scale was used to present the relative variation in shear-wave velocities. The dynamic range for the used colour scale was kept fixed (100–1400 m/s) to show better correlation and comparison between adjacent lines. The resulting high-resolution 2D slices clearly show the subsurface details found down to ~35 m depth,

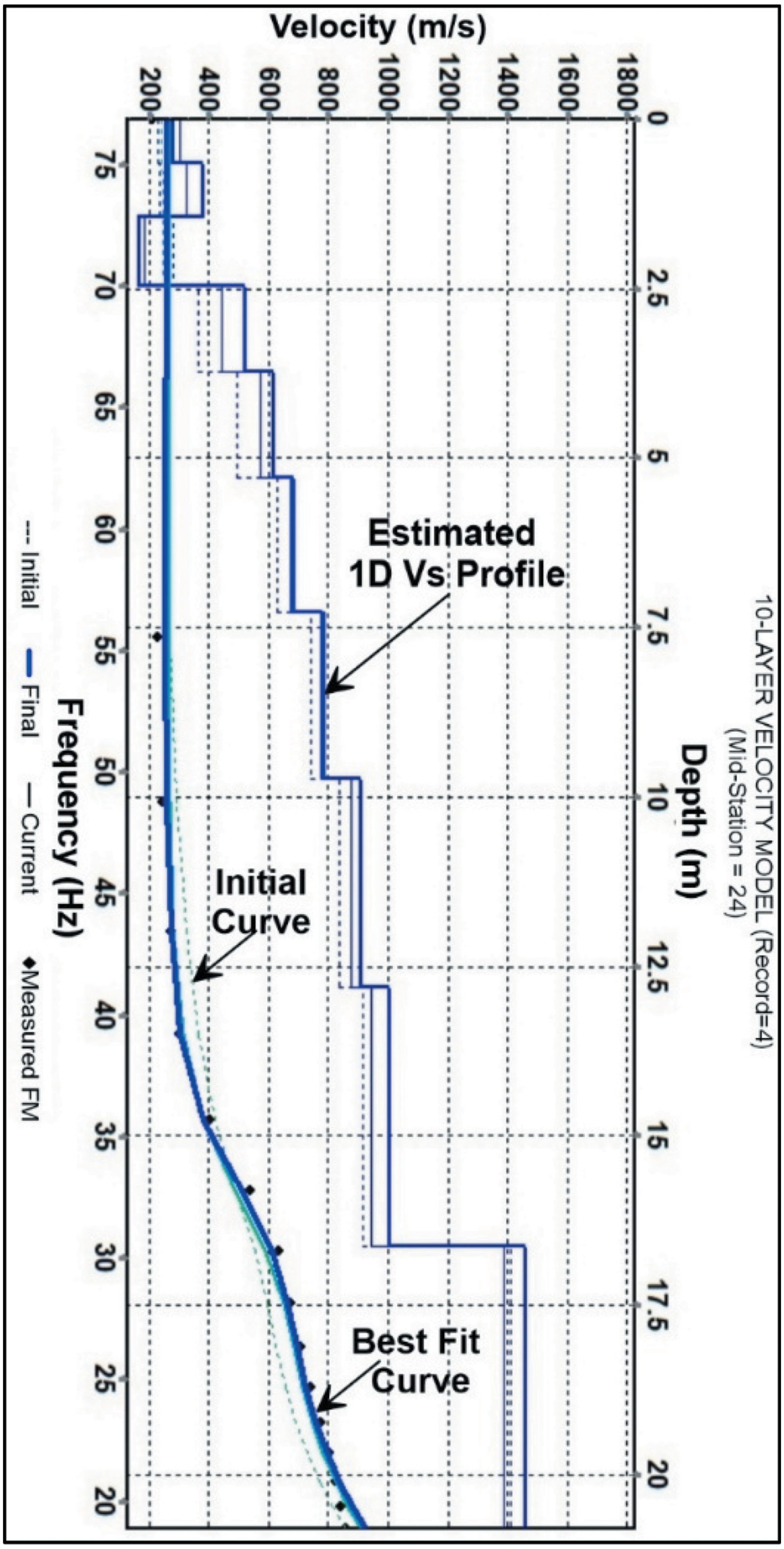

Figure 9. 1D shear-wave velocity model of MASW Line-16 using SurfSeis software.

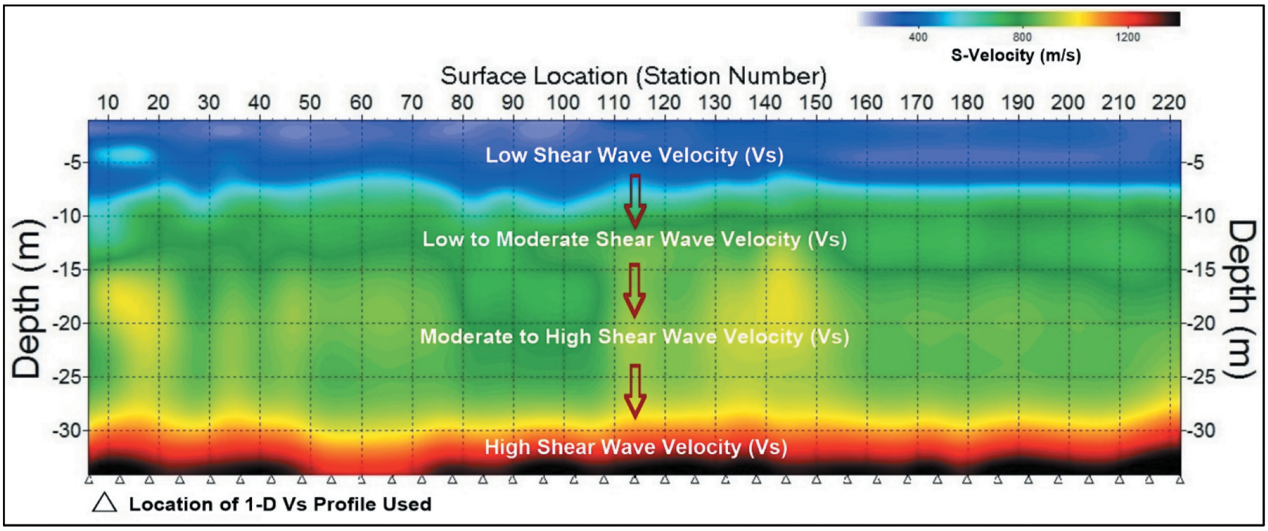

Figure 10. Typical 2D shear-wave velocity section of MASW Line-16 using SurfSeis software.

including soft layers of different degrees of compactness as well as rock materials of varying elastic properties and stiffness.

The resulting MASW data (Figure 13) yield conservative estimates of the average ground properties along the length of the receiver spread, and thus the shear-wave velocity and shear modulus are considered a good direct indicator of soil/rock stiffness. Therefore, potential zones of weakness and localised cavities can be easily identified if the resulting shear-wave section is calibrated/verified against geotechnical borehole results. For example, signs of complete or partial loss of drilling water, and direct tool drop are among the main indicators of cavity structures.

Other observations, such as low Standard Penetration Test (SPT-N value), low Rock Quality Designation (RQD), low Unconfined Compressive Strength (UCS), low Solid Core Recovery (SCR), and low Total Core Recovery (TCR) can point out the main indications caused by moderately to highly weathered or fractured rock sequence. However, a localised cavity feature can be ideally identified when the low shear velocity values (i.e. sediments or rocks of low stiffness) are encountered within higher velocity values (i.e. sediments or rocks of higher stiffness).

Hence, to characterise the study area and define the stiffness of the subsurface geology, the calculated shear-wave velocities across the conducted 20 lines were utilised to estimate the average shear-wave velocity of the upper 30-metres of the subsurface ground (average Vs_{30}). The average Vs_{30} is crucially important for civil and structural engineering design, seismic hazard assessment studies, and soil/rock stiffness estimation. Based on the average Vs_{30}, a specific site class can be assigned for the study area according to the certified International Building Code (IBC) (Chong Zeng et al. 2012) Classification as indicated in Table 2

The average shear-wave velocity for the depth (h) of soil referred to as V_H is computed as follows (Ali Ismet Kanlı and Zsolt Pr´onay 2006).

$$V_H = \sum h_i \Big/ \sum \left(h_i / v_i \right) \tag{1}$$

where $H = \sum^{h_i}$ is the cumulative depth in m. For 30 m average depth, shear-wave velocity is written as:

$$Vs^{30} = \frac{30}{\sum_{i=1}^{N} \left(h_i / v_i \right)} \tag{2}$$

where h_i and v_i denote the thickness (in metres) and shear-wave velocity in m/s (at a shear strain level of 10 − 5 or less) of ith formation or layer, in a total of N layers, existing in the top 30 m. Vs_{30} is accepted for site classification as per NEHRP Classification (BSSC, 2003) and also in the new provisions of Eurocode 8 (Sabetta and Bommer 2002; Sêco and Pinto 2002). It was also accepted later in the IBC (Chong Zeng et al. 2012) Classification.

For SI: 1 foot = 304.8 mm, 1 square foot = 0.0929 m^2. 1 pound per square foot = 0.0479 KPa. N/A = Not Applicable.

The average shear-wave velocity (Vs_{30}) of each line was calculated and represented in Figure 14, indicating a minimum value of shear wave velocity 512.84 m/s at Line-20 and a maximum value of 657.87 m/s at Line-19.

The average Vs_{30} of the whole site refers to a value of 577.97 m/s which, according to **IBC** (Chong Zeng et al. 2012) and the local Abu Dhabi Municipality (ADM) requirements, classifies the study area as Class C (Very Dense Soil & Soft Rock).

Using the average values of shear-wave velocities calculated at each receiver on the conducted MASW lines (20 lines), a site Vs_{30} map (Figure 15) was prepared to show the general variation of Vs_{30} across the entire study

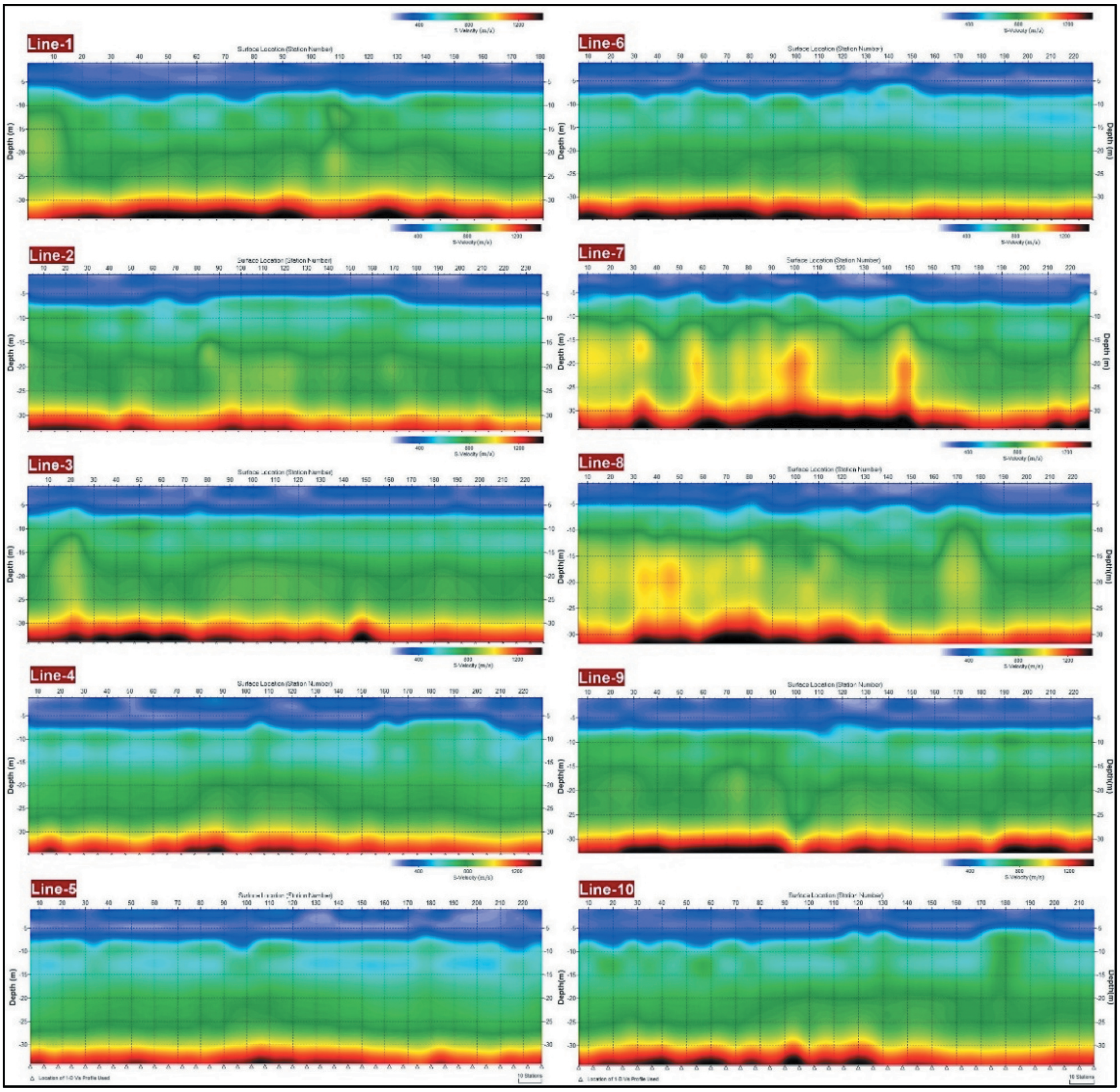

Figure 11. 2D MASW results show the lateral and vertical variation of the shear-wave velocities across lines (1–10) of the study area.

area. Figure 15 indicates a Vs_{30} ranging from 470.64 to 761.2 m/s, indicating an average value of 577.97 m/s for the whole study area. Although the average Vs_{30} map shows comparatively heterogeneous geology reflected by variable velocities over the study area, however, the average Vs_{30} increases from the upper part of the northwestern side towards the lower part of the southwestern side of the study area. This indicates harder subsurface ground and/or stiff soil materials as far as the area is distant from the seaside of the Arabian Gulf.

Calculating the average shear-wave velocity at the geophones of each line for different depth slices (Figure 16) indicates various ranges of the shear wave velocities (Vs = 215–451 m/s, Vs = 419–759 m/s, Vs = 610–1084 m/s, and Vs = 897–1425 m/s) at different depths ~1–7 m, ~7–12 m, ~12–25 m and ~25–35 m, respectively. These velocities suggest the existence of soil and rock materials (e.g. Sand, Sandstone, Mudstone). The constructed Vs slices (Figure 16) do not identify a clear low-velocity zone below the high-velocity one that can be interpreted as a cavity or serious hazardous zone, and thus there are no potential risks that can cause concern or fear before starting construction activities across the investigated area. However, a weak layer/zone is observed at a depth ranges from ~7 m to ~25 m indicating weak sandstone and mudstone rocks.

Considering the geotechnical results of the BH-02 borehole (Figure 17) that are important to support the seismic MASW data, they indicate that the SPT N value within the study area suggests medium dense to dense materials (N values ranging from 10 to >50), while the UCS (MPa) proposes weak to moderately weak materials (UCS values ranging from 0.9 to ~10 MPa).

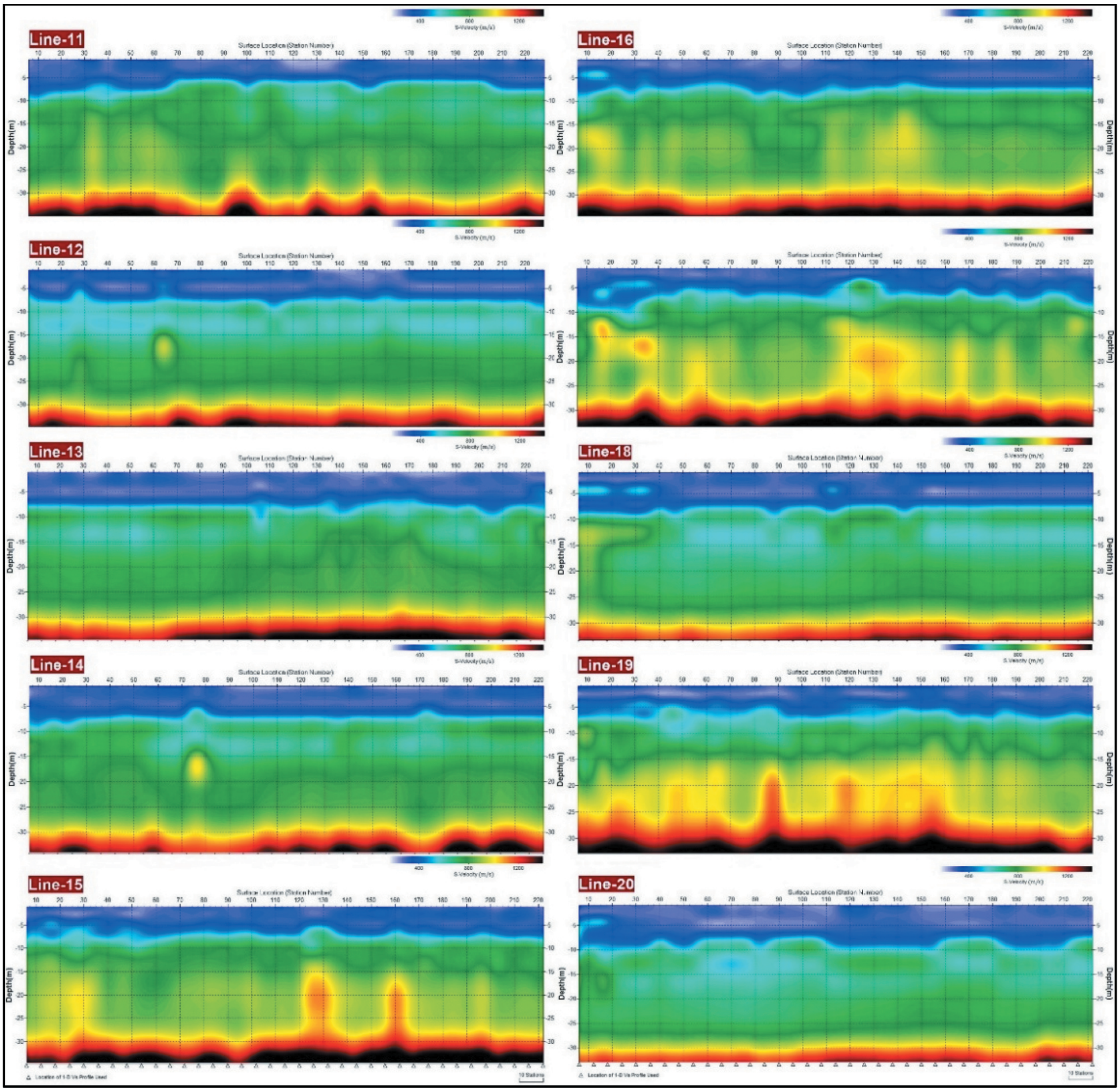

Figure 12. 2D MASW results show the lateral and vertical variation of the shear-wave velocities across lines (11–20) of the study area.

No cavities were encountered in any of the boreholes down to the drilled depths (i.e. 20 m) of the study area. During the period of investigation, groundwater was encountered at a very shallow depth in all the drilled boreholes (~0.6 to 1 m).

Correlation of both geophysical and geotechnical results Figure 17 is definitely required to comprehensively complete the data interpretation of this study and certainly justify the geophysical results by the ground truth methods (i.e. borehole drilling). Figure 17 presents an interpreted section that integrates both the results of the shear-wave velocity of MASW Line-4 (~35 m depth) and the geotechnical borehole of BH-02 (20 m depth) against the retrieved core samples, respectively. BH-02 is located at ~25 m offset from the starting point of line-4. The section illustrates a good correlation between the results of both data, showing a general stratification indicating a sequence of increasing shear-wave velocity with depth, from the ground surface to the bottom of the section down to ~35 m depth.

Based on this integrated interpretation of MASW and geotechnical results, the following geological model can be suggested Figure 17:

(1) Layer-1: medium to very dense silty SAND with cemented pieces: Having a thickness of ~6.33 m and a shear-wave velocity of 211.49–523.33 m/s (Average = 290.33 m/s). It is comprised of dense to very dense, brown, locally grey, fine to medium SAND, with fine to medium cemented pieces, shell fragments and gypsum. The basal part of this layer is dominated by very dense fine to medium-grained silty cemented SAND (locally gypsiferous). The encountered SPT N-values at

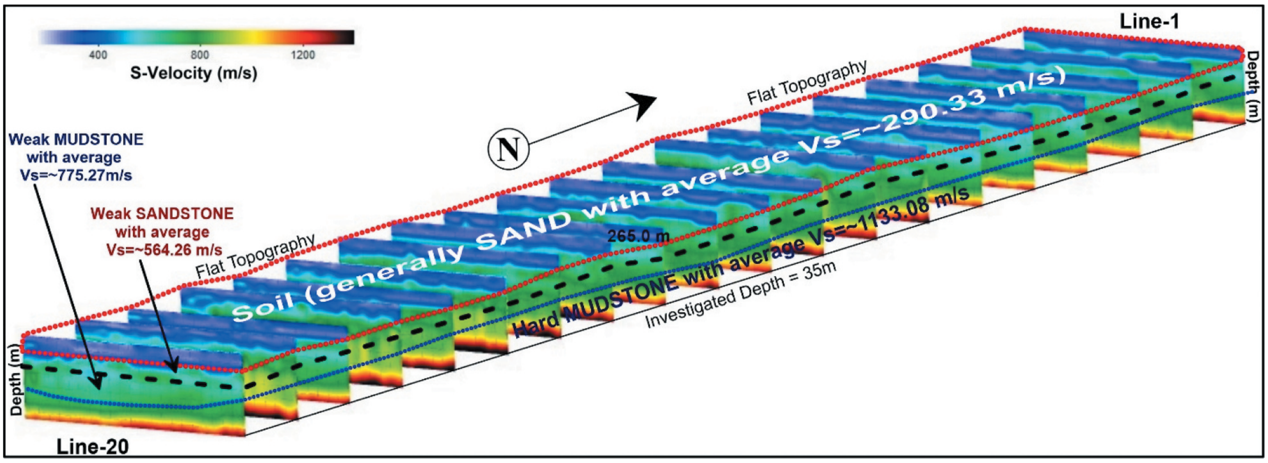

Figure 13. 2D slices of the resultant shear-wave velocities of the conducted twenty (20) lines at the study area of ICAD-II, Abu Dhabi, UAE.

Table 2. Site classification based on site-specific conditions established by the International Building Code (IBC, 2012), listed below in SI units.

SITE CLASS	SOIL PROFILE NAME	AVERAGE PROPERTIES IN TOP 100 FEET			
		Soil shear wave velocity		Standard penetration resistance, N	Soil undrained shear strength, S_u (psf)
		V_s (ft/s)	V_s (m/s)		
A	Hard rock	$Vs_{30} > 5000$	$Vs_{30} > 1524$	N/A	N/A
B	Rock	$2500 < Vs_{30} \le 5000$	$762 < Vs_{30} \le 1524$	N/A	N/A
C	Very dense soil and soft rock	$1200 < Vs_{30} \le 2500$	$366 < Vs_{30} \le 762$	$N > 50$	$S_u \ge 2000$
D	Stiff soil profile	$600 \le Vs_{30} \le 1200$	$183 < Vs_{30} \le 366$	$15 \le N \le 50$	$1000 \le S_u \le 2000$
E	Soft soil profile	$Vs_{30} < 600$	$Vs_{30} < 183$	$N < 15$	$S_u < 1000$
Ez	-	Any profile with more than 10 feet of soil having the following characteristics: (1) Plasticity index $PI > 20$, (2) Moisture content $w \ge 40\%$, and (3) Undrained shear strength $S_u < 500$ psf			
F	-	Any profile containing soils having one or more of the following characteristics: (1) Soils vulnerable to potential failure or collapse under seismic loading such as liquefiable soils, quick and highly sensitive clays, collapsible weakly cemented soils. (2) Peats and/or highly organic clays ($H > 10$ feet of peat and/or highly organic clay where H = thickness of soil) (3) Very high plasticity clays ($H > 25$ feet with plasticity index $PI > 75$) (4) Very thick soft/medium stiff clays ($H > 120$ feet)			

the top 5 – 6.0 m range between 13 and 31, while the encountered SPT N-values below this depth and till the end of this unit are more than 50.

(2) Layer-2: weak to very weak SANDSTONE: Having a thickness of ~4.07 m and a shear-wave velocity of 411.20–791.87 m/s (Average = 564.26 m/s). It is comprised of weak to very weak, brown, slightly to moderately weathered, fractured, fine to medium-grained SANDSTONE. The extracted cores from the SANDSTONE layer show total core recovery (TCR) values range from 72% to 100%, while the rock quality designation (RQD) values range from 20% to 90% with some levels of intensive fracturing that show a 0% RQD value.

(3) Layer-3: weak to moderately weak MUDSTONE with interbeds of gypsum: Having a thickness of ~9.6 m and a shear-wave velocity of 605.71–1140.54 m/s (Average = 775.27 m/s). It is composed of weak to moderately weak, light yellowish grey to dusky red, slightly to moderately weathered, fractured, gypsiferous, MUDSTONE with medium spaced crystals of gypsum. The extracted cores from the Mudstone layer show total core recovery (TCR) values that range from 72% to 100%, while the rock quality designation values range from 30% to 90%.

(4) Layer-4 (Based only on MASW interpretation): Potentially harder MUDSTONE with gypsum crystals: Having a thickness of ~14.0 m and a shear-wave velocity of 851.0–1458.54 m/s (Average Vs = 1133.08 m/s). The interpretation of this layer generally coincides with the common practices and expectations of a normal extension of the same lithology of the previous layer with a predictable increase in solidification and also the accompanying shear-wave velocity.

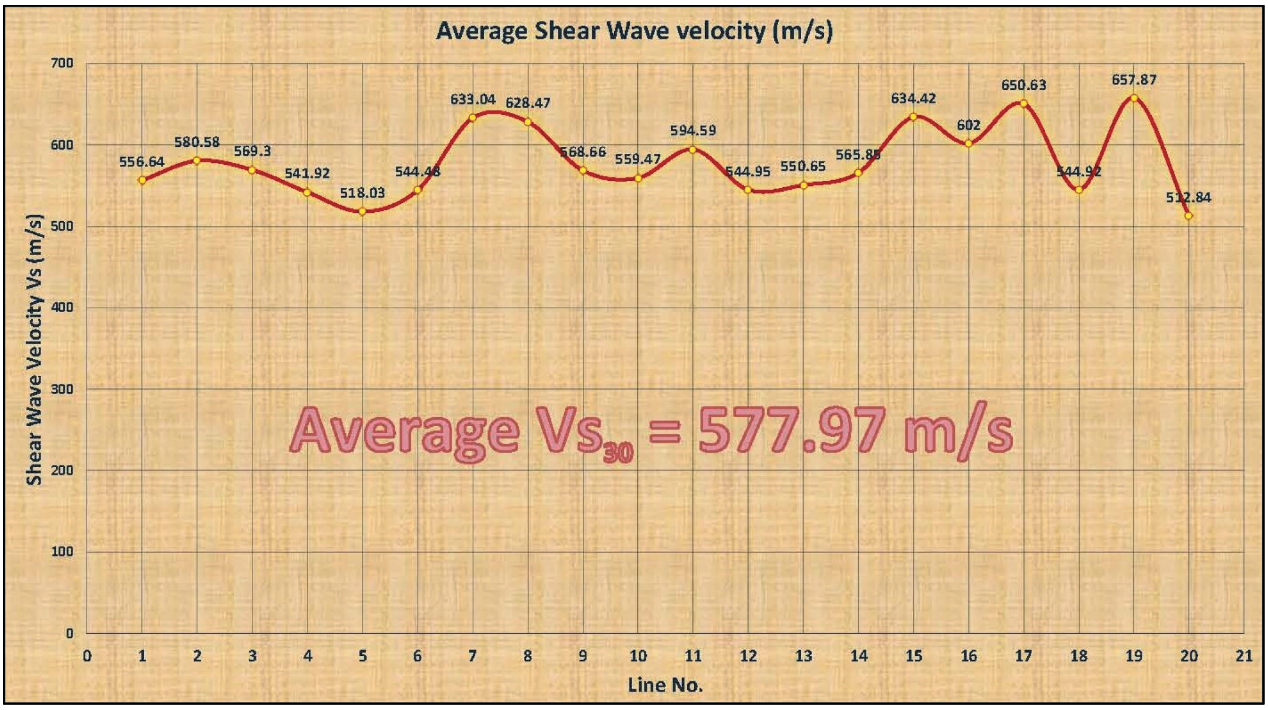

Figure 14. Average Vs_{30} of all measured lines showing an average site value of (577.97 m/s).

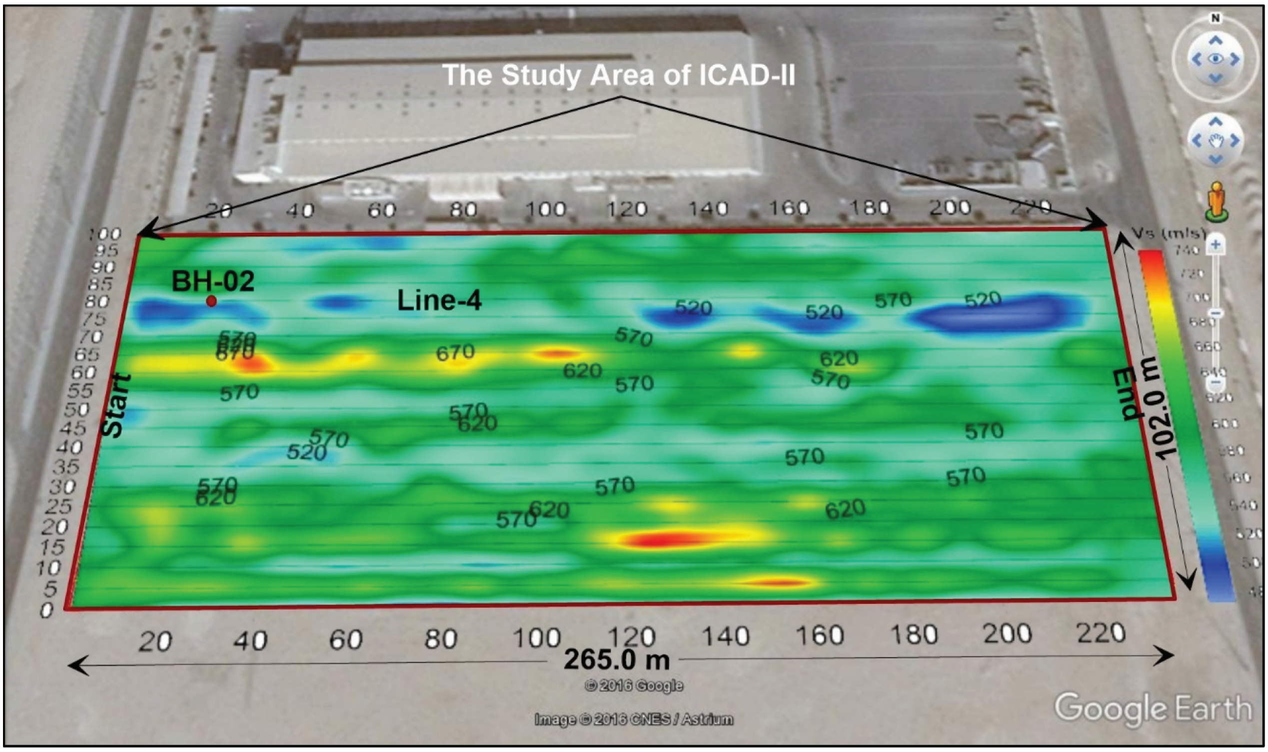

Figure 15. Average Vs_{30} map of the study area of ICAD-II, Abu Dhabi, UAE.

7. Conclusions

Conducting of MASW survey over a grid of 5 m line-spacing has provided the most relevant and applicable seismic techniques on the UAE land for characterising the study area of ICAD-II, Abu Dhabi. Using the geotechnical data of a drilled borehole is a good approach to verify and correlate soil properties obtained by geophysical investigations. Correlation of both geophysical and geotechnical data provided a thorough site characterisation of the subsurface conditions in the study area, in particular the presence or absence of potential zones of risks within the investigated depth. Sorting and taking the average of the resulting shear-wave velocities at different depth slices in conjunction with the ground truth obtained from the borehole data led to an obvious understandable geological model for the encountered

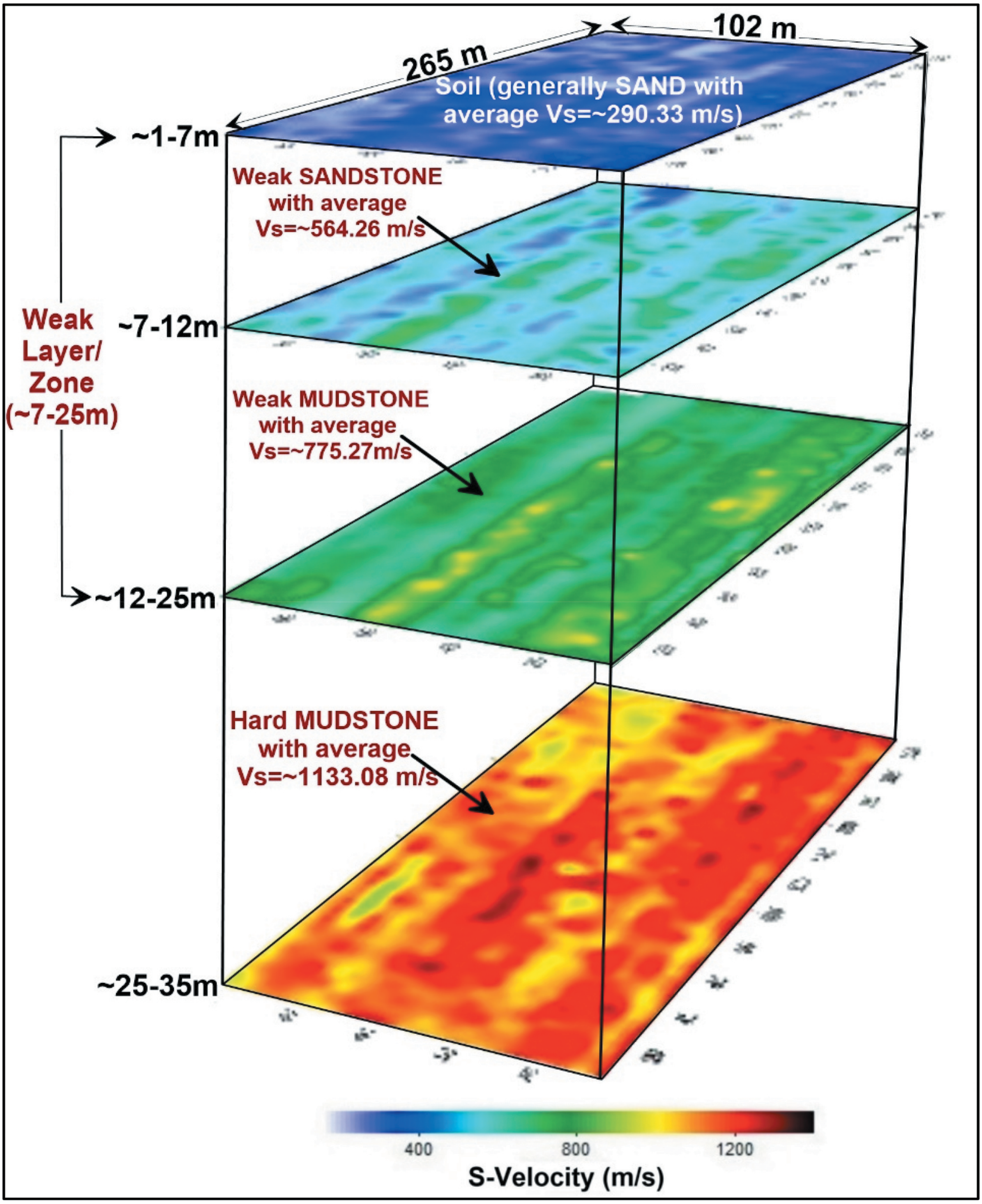

Figure 16. Average Vs at different depth slices.

lithological units down to ~35 m depth. The upper three layers (0–20 m depth) of this model were suggested from both MASW and borehole data, while the fourth layer (20–35 m depth) was only interpreted according to the MASW data. There are no clear zones of cavernous nature identified from the MASW results. The likelihood of a geologic risk for the existence of currently open subsurface cavities within the upper ~35 m is therefore very low. The estimated average site shear-wave velocity (Vs_{30}) of the entire site is equal to ~577.97 m/s, which classifies the investigated site as Class C (very dense soil & soft rock) according to IBC (2012) and ADM requirements. This result is supported by the SPT N values across the study area, which refer to medium dense to dense

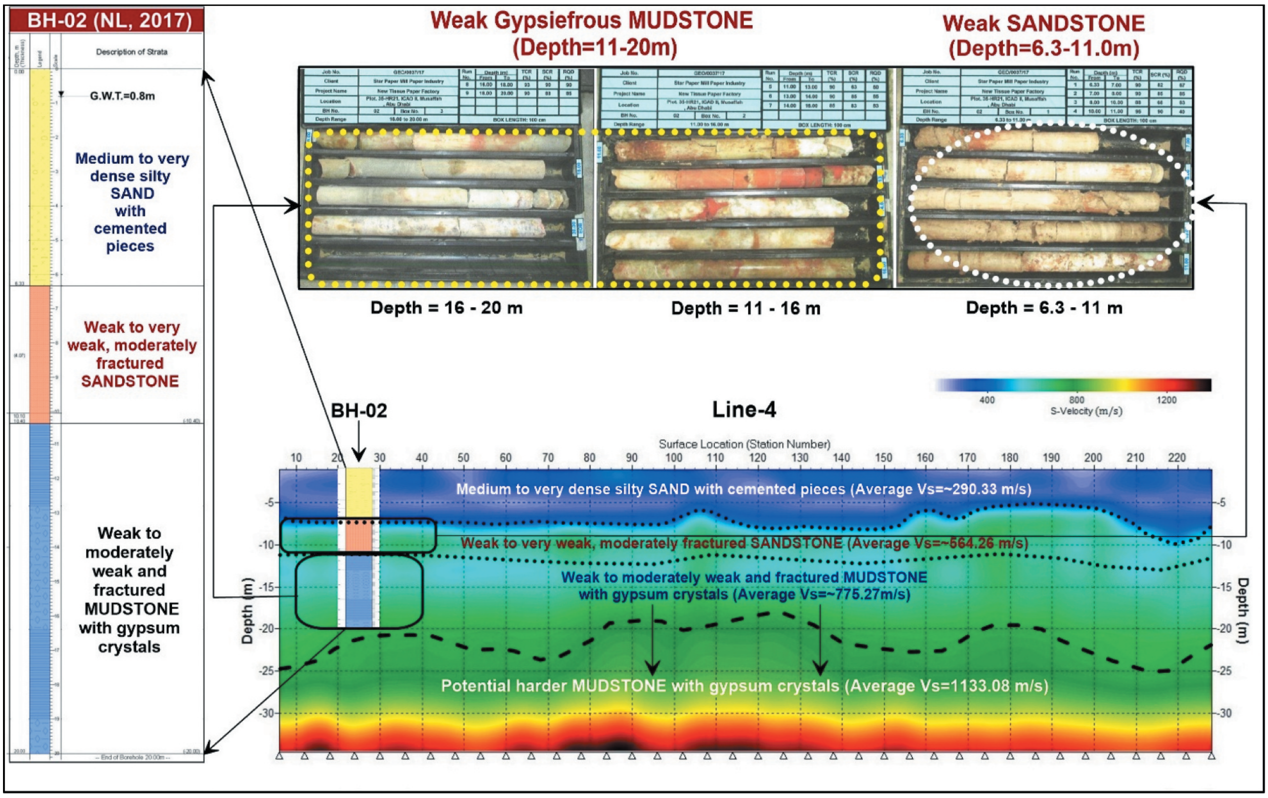

Figure 17. MASW inverted section of Line-4 correlated against retrieved core samples of BH-02. The location of BH-02 is at ~25 m from the start of the line, indicating a good correlation against the well log data, (the lower section is presented in 1:1 scale).

materials. The interpreted 2D MASW data (20–35 m depth) indicate a relatively harder mudstone bed encountered at variable depths starting from ~18 m to 22 m at the end of the interpreted section. The foundation layer is thus recommended to be designed on the mudstone bed at a proposed depth of ~7 m.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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