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Surface Soil Assessment in the Ubhur Area, North of Jeddah, Western Saudi Arabia, Using a Multichannel Analysis of Surface Waves Method

Maher Aldahri[1]; Saad mogren[2], Kamal Abdelrahman[2,3,*], Hani Zahran[1], Sherif El Hady[3,4] and Mahmoud El-Hadidy[3]

[1]Saudi Geological Survey, Jeddah, Saudi Arabia
[2]Geology and Geophysics Dept., King Saud University, Riyadh, Saudi Arabia
[3]Seismology Dept., National Research Institute of Astronomy & Geophysics, Egypt
[4]Geophysics Dept., King Abdul-Aziz University, Jeddah, Saudi Arabia
E-mail: *khassanein@ksu.edu.sa*

ABSTRACT

Ten boreholes drilled in Ubhur area up to the depth of bedrock indicted the shallow depth of bedrock where the average depth ranges between 10 and 15 m. The standard penetration test N-values of these boreholes were measured and averaged. Based on N-values to the depth of bedrock, Ubhur area can be classified as site class C and D. Multichannel analysis of surface waves technique has been applied along seventy six profiles using 24-channel geophone array and 4.5Hz vertical geophones with 1m geophone spacing and sledgehammer and/or weight drop as seismic energy sources. Values of shear wave velocity to 30 m are calculated and then averaged (Vs30) where it ranges between 310.08 m/s and 1139.8 m/s. Therefore, Ubhur area can be classified into site class B, C and D based on site classification of the national earthquake hazards reduction program (NEHRP) recommendations. Accordingly, the greatest part of the study area falls in site class C while class B and D covered limited areas in the western and the eastern parts respectively. Depending on the shallow depth of bedrock in the study area, the Vs30 parameter is not applicable in the study area so the average values of Vs for the soil thickness, excluding the bedrock, have been calculated and mapped for site class C and D only. So Vs30 approach is not applicable for areas with shallow depth of bedrock which gives higher classification.

INTRODUCTION

Ubhur lies to the north of Jeddah along the Red Sea coast between latitude (21°48' 47.95" N - 21°44' 53.88" N) and longitude (39°06' 49.21" E - 39°11' 44.60" E) (Fig. 1). The area is considered as the northern expansion zone of Jeddah city where several urban communities, commercial centres, high-rise buildings, and developmental projects have been constructed during the last 10 years. Moreover, it is important to mention here that the Jeddah area in general suffered from strong earthquakes during both historical and recent periods (Merghalani and Gallanthine 1981; Ambraseys et al., 1994; Al-Amri, 2004; Al-Saud, 2008; Fnais et al., 2015), with the most significant recent earthquake being the 1967 earthquake of 7.2 M_w located in the Red Sea southwest of Jeddah.

Mories (1975), Bahafzullah et al. (1993), Al-Safi and Qari (1996) and Ageel (2007) have each found that the soil structure of the Ubhur area is composed of quaternary sediments and sabkha soil. The sabkha hazard lies at the northern part of Ubhur where the surface soil is composed of clay, silt and silty to clayey sand while the sub-surface sabkha can be classified vertically into thin sabkha and thick sabkha. The thin sabkha are composed of soft clay with low plasticity and loose to medium poorly graded sand, whereas, thick sabkha consist of soft to stiff clay with low plasticity, containing some clay minerals in small amounts. These poor geotechnical properties of the sediments in the Ubhur area are associated with a risk of damage in the event of strong earthquakes.

The main purposes of this study are to estimate both lateral and vertical variations of surface soil in Ubhur area using geotechnical SPT N value and MASW profiling. These methods have been widely used for site characterization (e.g. Kockar et al., 2010; Anbazhagan and Sitharam, 2009b; Anbazhagan, 2012). MASW method is used to evaluate the stiffness of the ground for urban planning and civil engineering purposes through site soil characterization, lateral extension and thickness. This method depends mainly upon the generated surface waves from various seismic sources. Then, shear-wave velocity (Vs) discrepancies below the surveyed area are then provided in 1-D and 2-D through inversion of dispersion curve (Park et al., 1999; Xia et al., 1999; Xia et al., 2000b; Park et al., 2004; Park and Miller, 2005a,b; Park et al., 2006; Ryden and Park, 2006; Park et al., 2007; Suto, 2007; Anbazhagan et al., 2008; Sairam et al., 2011).

GEOLOGICAL SETTING OF THE UBHUR AREA

More and Al-Rehaili (1989) and Ageel (2007) studied the surface geology of the Ubhur area, describing the geological setting (Fig. 1). The early Miocene age is represented by the formation at Al-Harra composed of sandy clay and soft limestone and also a 3 m thick gypsum bed inter-bedded with clay. The Quaternary deposits composed of alluvial fan deposits; talus deposits; wadi alluvium; aeolian sand and the sabkha deposits. In the western part of the study area, which is covered by reef limestone, and limestone, which are composed of coral and molluscs, are massive, cavernous and very porous. Along the Red Sea coast, the reef limestone is exposed in a discontinuous belt, while on the land the limestone rises from 3 m to 6 m above sea level, although it is poorly exposed due to a cover of fossil-rich sand and overlapping sabkha and alluvial deposits. On the western side of the study area, which is mostly covered by reef limestone, there are small dispersed zones of sabkha deposits surrounded by the reef limestone. Close to the coast, there are low-lying saline mud flats, characterized by moist, brown, terrigenous sand and clay, with interstitial gypsum (Moore and Al-Rehaili, 1989).

GEOTECHNICAL BOREHOLE DATA

Ali and Hossain (1988) differentiated five soil units and three rock units with maximum depth of 15 meters as: (1) grey to light-brown soft to medium sandy silty clay with gypsum crystal and shells;

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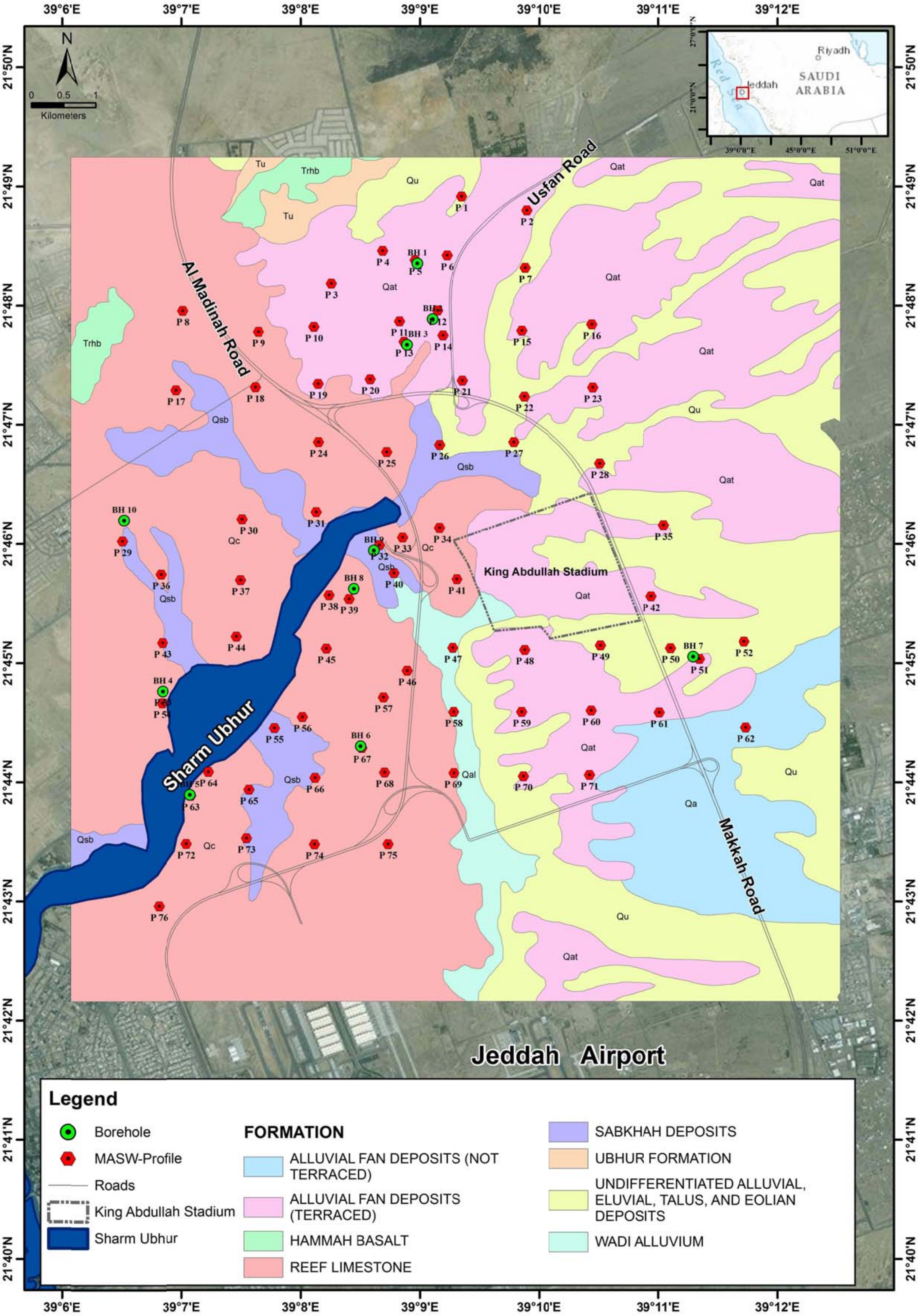

Fig.1. Location map of Ubhur area including borehole and multi-channel analysis of surface waves locations overlying geologic map.

(2) stiff to very stiff brown sandy silty clay; (3) grey very loose to loose silty sand to sandy silt; (4) light brown to grey very loose carbonate silty sand: (5) grey medium carbonate gravelly sand; (6) yellowish to creamy white coarse grained shelly coralline limestone; weak to moderately weak; (7) tertiary sediments consisting of sandstone, siltstone or claystone.

Standard penetration test (SPT) N-value was developed by Raymond Concrete Pile Company in 1927. Since then, the SPT has been performed worldwide where about 80-90% of geotechnical investigations consist of SPT (Sy and Campanella, 1994; Sy et al., 1995). SPT N-values have been correlated to numerous soil properties. In cohesion less soils (sands), the SPT can be used to predict the relative density of sands (i.e., very loose, loose, medium, etc).

In this study, ten boreholes were drilled in Ubhur area (Fig. 1) up to the depth of bedrock that has a shear wave velocity of 760 m/sec (BSSC, 2001) and SPT N-value of more than 100 for 5 cm of penetration (Sitharam et al., 2007; and Anbazhagan, 2012). The SPT N-values were measured at regular depths and correlated with the

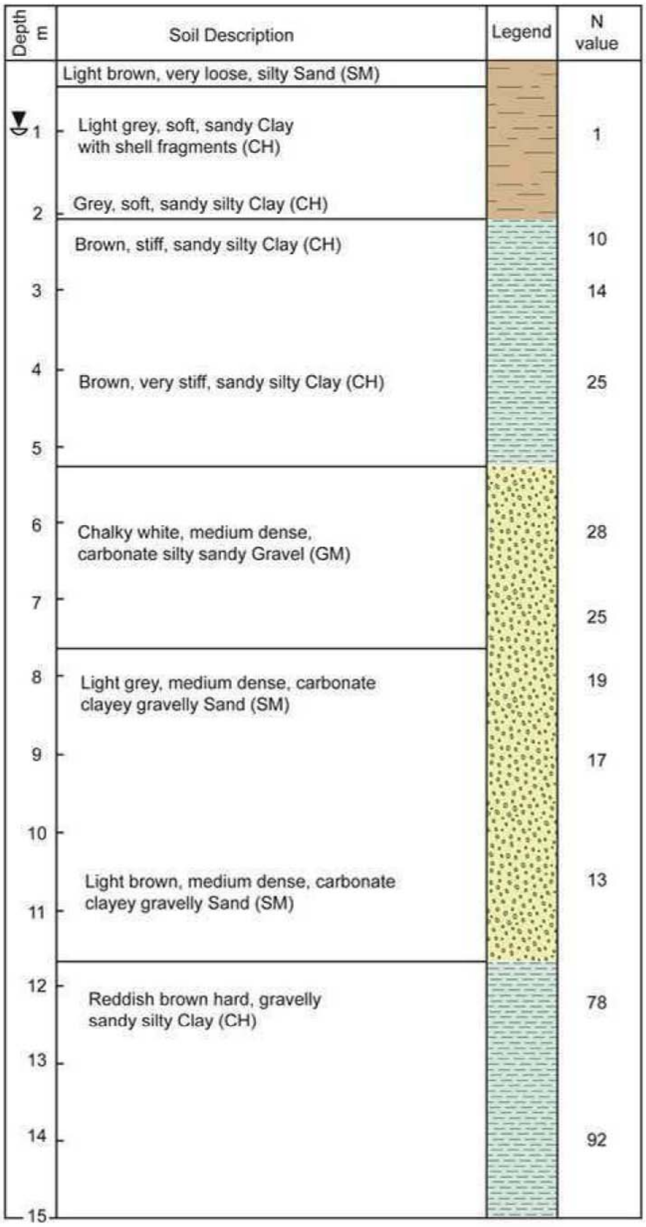

Fig.2. Geotechnical parameters of BH-4 in the study area.

lithology of the sub-surface layers (Table 1 and Fig. 2). The depths of these boreholes vary from 10m to 15m while two of them extend up to 25 m depth.

The depth of bedrock in the study area ranges from 0.5m to 22m (Fig. 3). Figure 3 illustrates that the depth of bedrock increases eastward away from the Red Sea coastal plain, where the southwestern part has a shallow bedrock depth than the central and eastern parts. Due to the shallow depth of bedrock in the study area, the site classification needs another approach than the shear wave velocity to 30 m depth (Kokusho and Sato, 2008; Kim and Yoon, 2006; Anbazhagan, 2012; Anbazhagan et al., 2013). Therefore, the average SPT N-value for the soil materials has been measured and mapped (Fig. 4). Figure (4) illustrates that Ubhur area can be classified into site class C and D according to NEHRP recommendations (Building Seismic Safety Council, BSSC, 2001) (Table 2).

MASW DATA ACQUISITION

In this study, StrataView seismograph was used to collect MASW data along seventy six profiles (Fig. 1) using 4.5 Hz geophones with 1.0 *ms* sampling interval and 1024 *ms* recording length, geophone spacing of 1 m, 4 m shot-point interval. The source to the nearest receiver offset was fixed as 10 m, which was selected in order to reach the required depth. In this study two seismic energy sources were applied and they are weight drop and sledgehammer of 8 kg (Fig. 5). The selection of energy source based on the type of surface soils, their characteristics and lateral extension and to fulfil the desired purpose from MASW profiling as well. The major part of MASW surveying profiles was conducted using weigh drop energy source.

Table 1. Soil profiles in the study area

Soil Description	Depth	Thickness	SPT	V*av*	Vs30
BH-1					
Silty sand with gravel. Medium dense to very dense, light brown to brown, dry (Fill material)	0	1.5	18	375.3	491.6
	1.5	1.67	0		
Silty sand with gravel. Very dense, brown, dry	3.1	1.5	74		
	4.6	1.4	100		
Clayey sand with gravel Very dense, brown, dry	6	1.7	100		
	7.7	2.3	100		
	10		100		
BH-2					
Silty sand with gravel. dense to very dense, brown, dry	0	1.8	31	373	450
	1.8	1.3	32		
	3.1	1.5	100		
	4.6	1.6	77		
Clayey sand with gravel Very dense, brown, dry	6.2	1.3	51		
	7.5	1.5	73		
	9	1.5	100		
	10.5	1.5	100		
	12	1.6	100		
	13.6	1.4	100		
	15		100		
BH-5					
Silty sand. Medium dense, brown, dry.	0	1.5	15	352	461
Silty sand with gravel and calcareous sediments. Medium to very dense, light brown, damp to wet	1.5	1.5	13		
	3	1.5	100		
	4.5	1.5	100		
	6	1.5	100		
	7.5	1.5	100		
	9	1	100		
	10		100		

Table 2. Site classification (BSSC, 2001)

Soil class	Soil Definition	Average shear wave velocity to 30 m (m/s)
A	Hard rock	>1500
B	Rock	760 < Vs ≤ 1500
C	Very dense soil and soft rock	360 < Vs ≤ 760
D	Stiff soil 15 ≤ N ≤ 50 or 50 kPa ≤ Su ≤ 100 kPa	180 ≤ Vs ≤ 360
E	Soil or any profile with more than 3 m of soft clay defiled as soil with PI > 20, N < 15, w ≥ 40%, and Su < 25 kPa.	≤180

MASW Data Processing and Results

MASW data was processed with *SurfSeis* software. Each shot gather consisted of 24 channel data, although this required some pre-processing according to the following scheme: I) conversion of SEG-2 format into KGS format, joining all shots into a single file. II)

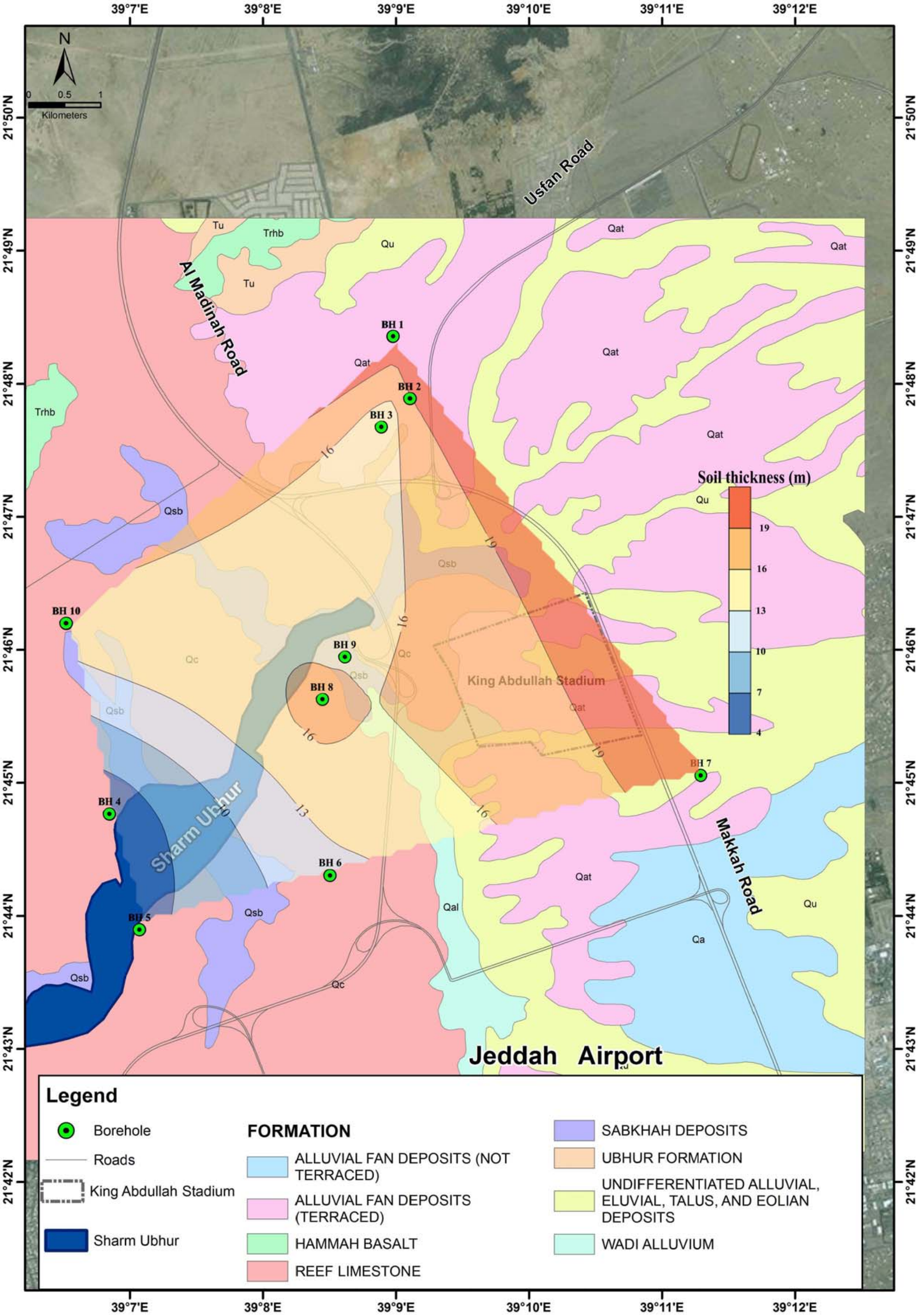

Fig.3. Soil thickness in the study area.

Inspection of data to remove bad records/traces. Ill) check that the surface wave arrangement was consistent with adjacent shot records. IV) control of factors that interfere with analysis. Noise sources can be controlled to a limited extent during data acquisition, but cannot be eliminated. These noises have to be identified, eliminated through filtration and muting. V) assessment of the optimal ranges of frequency and phase velocity (Fig. 6).

The dispersion process started with the calculation of phase velocities within the specified frequency range as per the control parameter input (either user input or selected automatically by the program). This calculation could be run several times using different values and sets of input parameters, examining the output curves until an optimum solution was identified, with the highest signal-to-noise ratio (SNR) representing the best choice. Finally, the estimated Vs section of the high SNR indicates the highest confidence level for the phase velocity-frequency curve (Fig. 7).

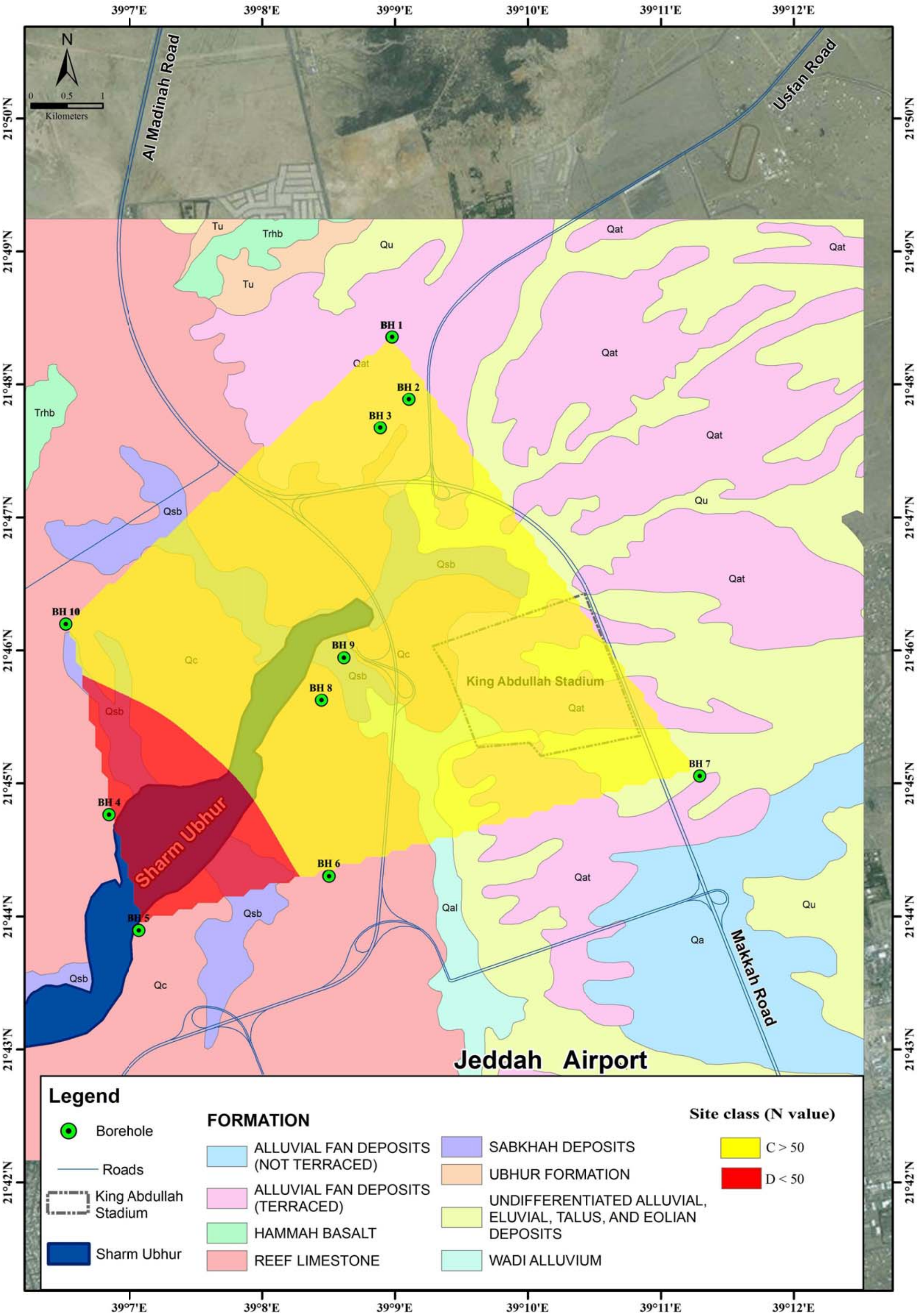

Fig.4. Site class based on soil SPT N values

One dimensional (l-D) shear-wave velocity profiles can be generated through dispersion curve inversion. The matching parameter between the theoretical and the experimental dispersion curves was estimated based on the root-mean square error (RMSE) between the two curves. These l-D profiles are representative of the material directly below the mid-point of the geophone spread (Fig.8). The generated sets of 1-D plots were interpolated in order to create 2-D shear-wave velocity profiles at each site (Fig. 9). The 2-D cross-section of shear wave velocity can be produced by gathering all the velocity traces in a sequential order according to the receiver station. The lower RMSE means the higher level of confidence (Xia et al. 1999) (Fig. 10).

Velocity depth profiles numbers 5, 51, 53 and 73 representing the northern, eastern, western and southern zones of Ubhur area respectively are shown in the 2D velocity model (Figs. 11 - 14). Profile 5 shows a normal 5 layer model with a shear wave velocity that indicates alluvial fan deposits covered the silty sand with gravel

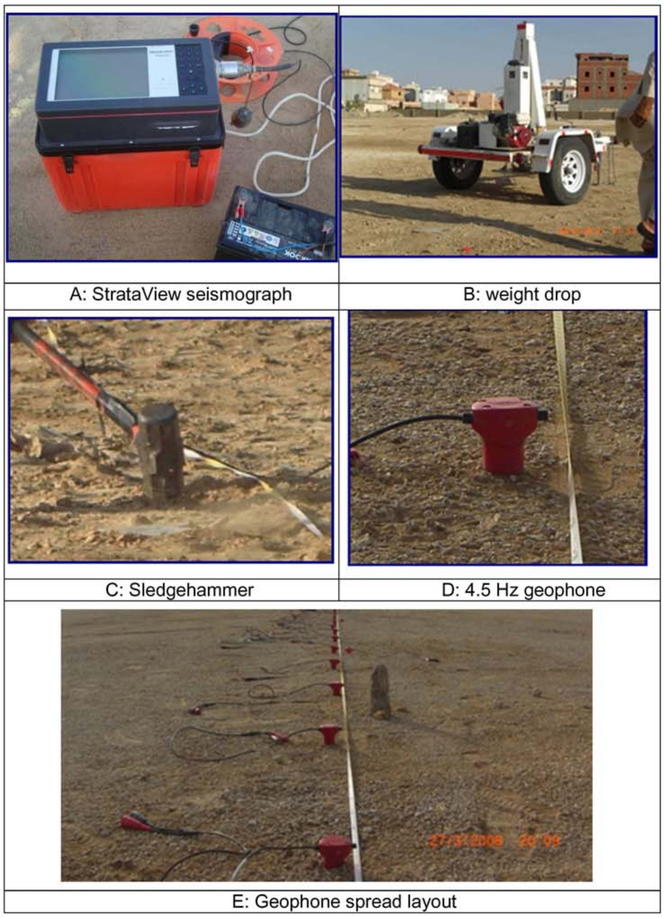

Fig.5. MASW Field data acquisition system.

that is medium dense to very dense, and then, beneath this layer, in sequences: silty sand with very dense gravel, clay sand with gravel and, finally, possibly, a layer of reef limestone which has been weathered due to the high water level in the area. The bedrock lies at a depth of 8 m.

Profile 51 is located in the eastern part of the study area, which is covered by alluvial fan deposits or (both terraced or non-

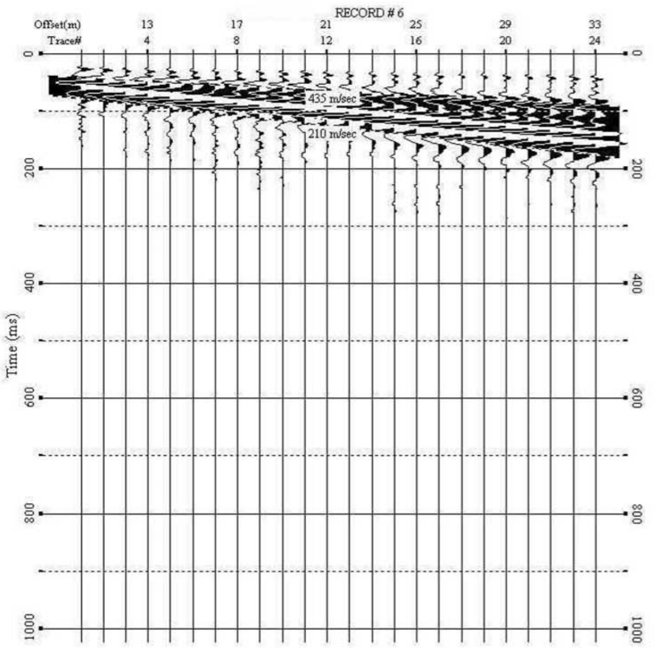

Fig.6. Seismic record with preprocessing parameters showing optimum ranges of frequency and phase velocity.

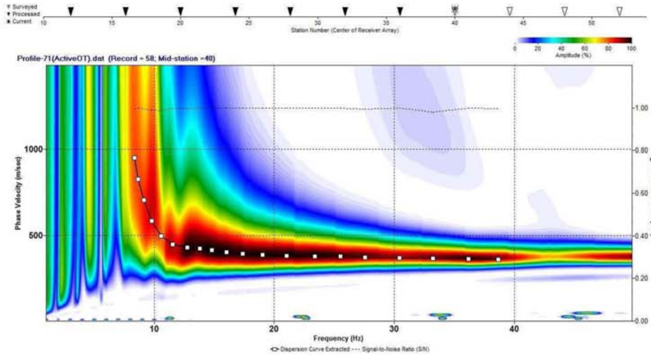

Fig.7. The dispersion curve with overtone image for Profile No. 71.

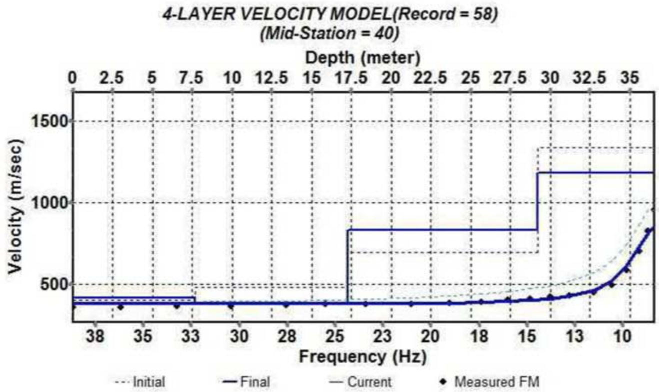

Fig.8. ID velocity-depth inversion at Profile No. 71.

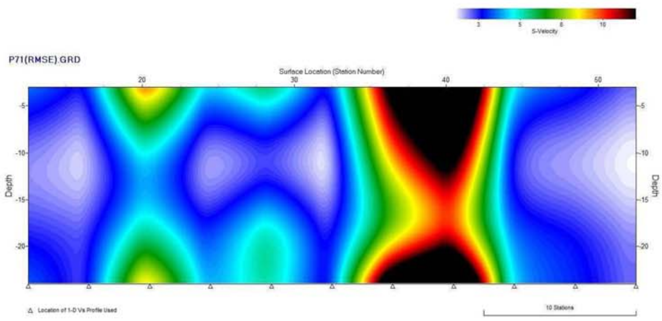

Fig.9. 2D velocity model for Profile No. 71.

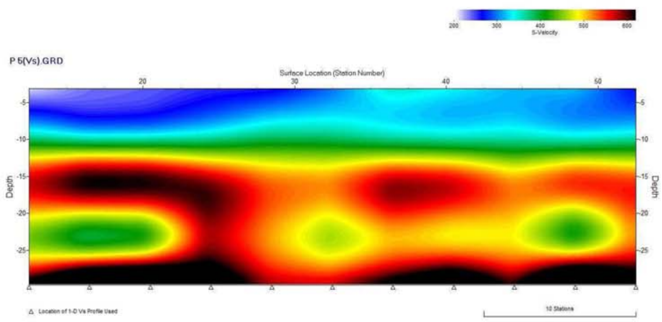

Fig.10. 2D RMSE model for site No. 71.

terraced),undifferentiated alluvial-talus and aeolian deposits, meaning that the shear wave velocity increases with depth started from 123 m/s to 762 m/s, with the bedrock starting at 8 m depth. The average shear wave velocity (394.89 m/s) is due to the presence of silty sand with gravels and calcareous sediments. Profile 53, located in the western part of the study area (north of Ubhur creek and mostly covered by reef limestone with some sabkhah zones), shows a normal four layer

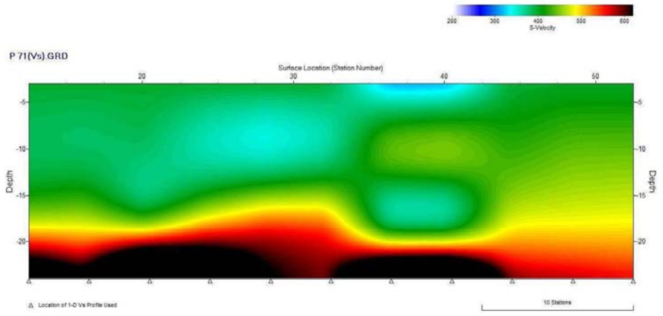

Fig.11. 2D velocity model at profile No. 5.

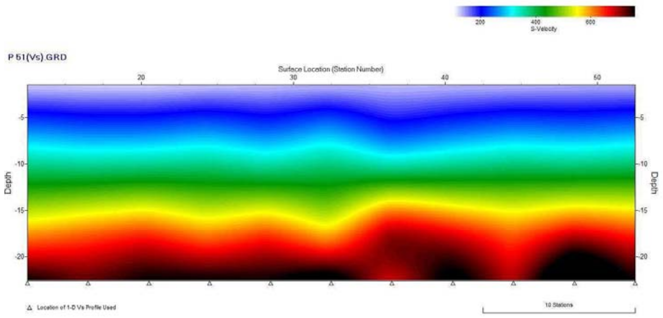

Fig.12. 2D velocity model at profile No. 51.

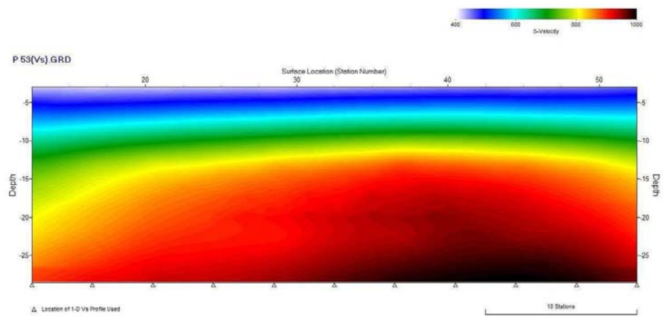

Fig.13. 2D velocity model at profile No. 53.

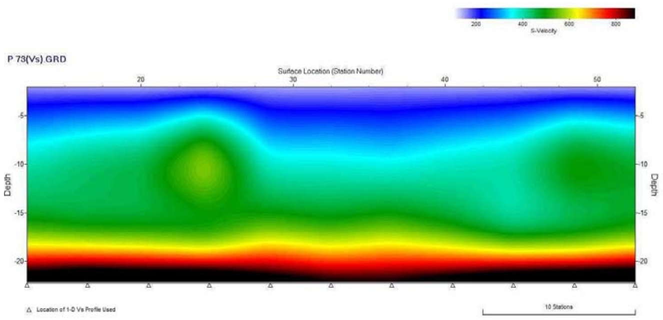

Fig.14. 2D velocity model at profile No. 73.

model with a shear wave velocity indicating silty sand with coral fragments and moderately dense. This may be related to the velocity for the first layer (307.05 m/s); while the second layer is coralline sand with coral fragments that are dense to very dense, starting from 3 m to 13.49 m, the average shear wave velocity for this layer being 950.42 m/s. The velocity increases with the depth ranges from 307.05 to 999.05 m/s. In Profile 73 there are lower velocity layers near the surface while bedrock is recorded at a depth of 17.8 m.

DISCUSSION AND CONCLUSION

The average shear-wave velocity to a depth of 30 m is an important parameter for classifying sites in recent building codes (Dobry et al., 2000; Building Seismic Safety Council (BSSC) 2001a & b). NEHRP (2001) used the following formula to classify seventy-six selected sites:

$$V_{S30} = \frac{\sum_{i=1}^{n} di}{\sum_{i=1}^{n} di/V_{Si}}$$

where d_i and V_{si} are the thickness and velocity of the i^{th} layer between 0 and 30 m. Table 1 shows the NEHRP classification code as it is defined in terms of Vs along with the corresponding site classifications for Ubhur.

The average shear wave velocities calculated at a depth of 30 m in Ubhur vary between 310.08 m/s and 1139.80 m/s. These Vs30 are then correlated with site class classification of NEHRP (BSSC, 2001) guidelines (Table 2) and site class of the study area is mapped (Fig. 15). Figure (15) shows that, the study area can be classified into C, B, and D sites. The majority of the Ubhur area belongs to the C category. On the other hand, the western part belongs to the rocky areas (B class in the NEHRP category). These parts have higher velocity values compared to the eastern parts. Some limited areas in the eastern zone was classified as D category.

The results show two sites of class D (P23 & P35), sixty four sites of class C and ten sites of class B (P30, P44, P46, P53, P54, P57, P68, P72, P75 and P76). All sites that were interpreted to be NEHRP site class C have relatively thick sections of silty sand and angular to sub-angular gravel and cobble deposits. The two NEHRP class D sites have alluvial fan deposits (terraced) and undifferentiated alluvial, talus and aeolian deposits. Velocities for these formations vary with depth depending on site location, as seen at site 35 (i.e. as low as Vs =141.87 m/s, but the velocity increases at the depth of

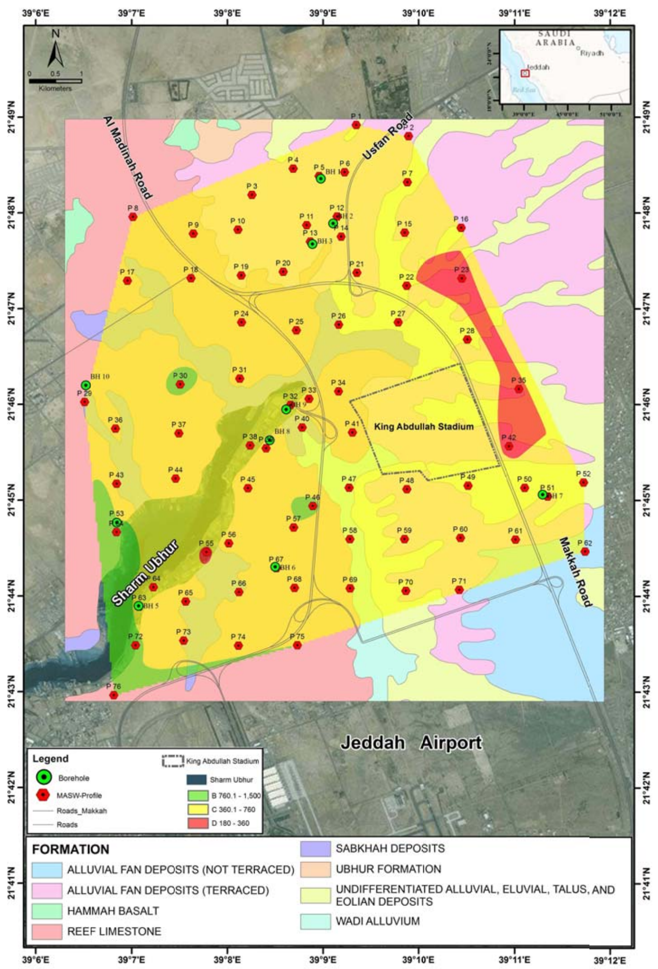

Fig.15. Site class based on Vs30 values.

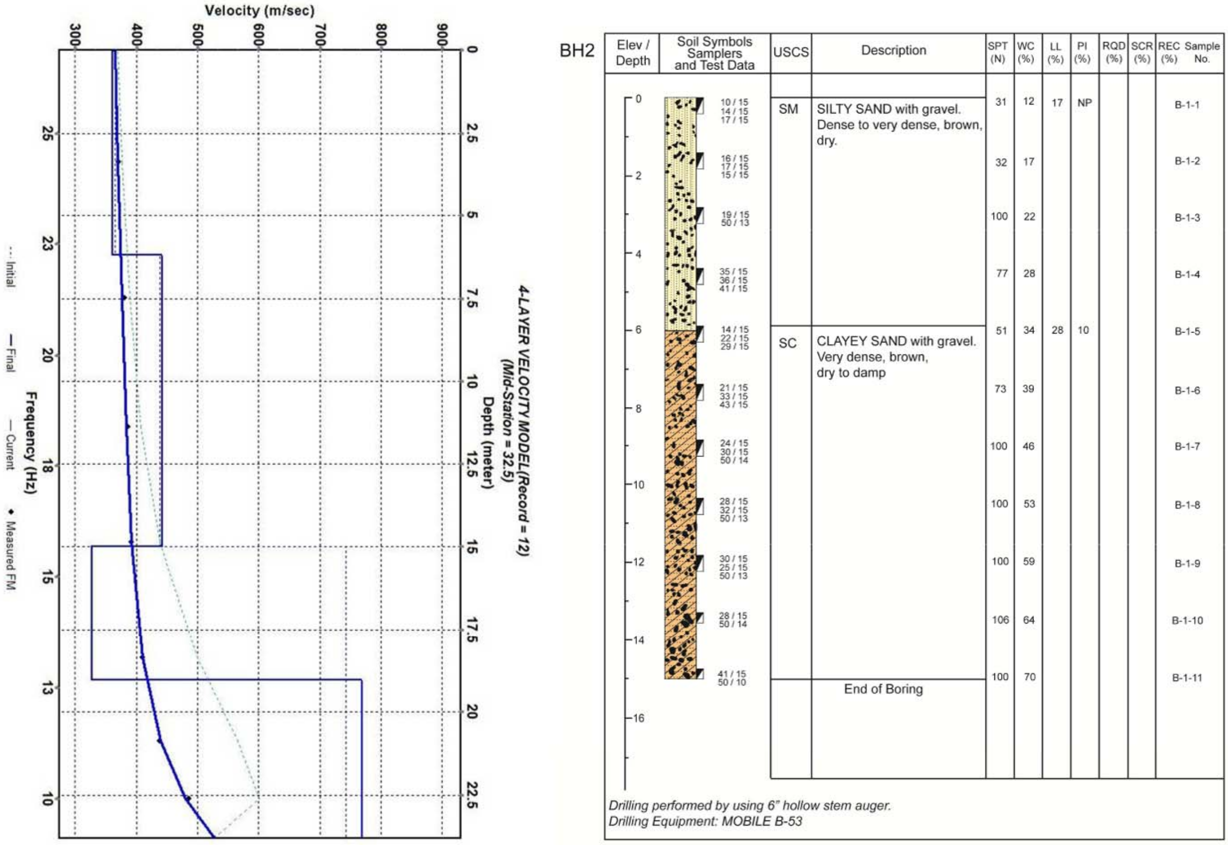

Fig.16. Correlation between 1D MASW model (left) of profile 51 and borehole 2 (Right).

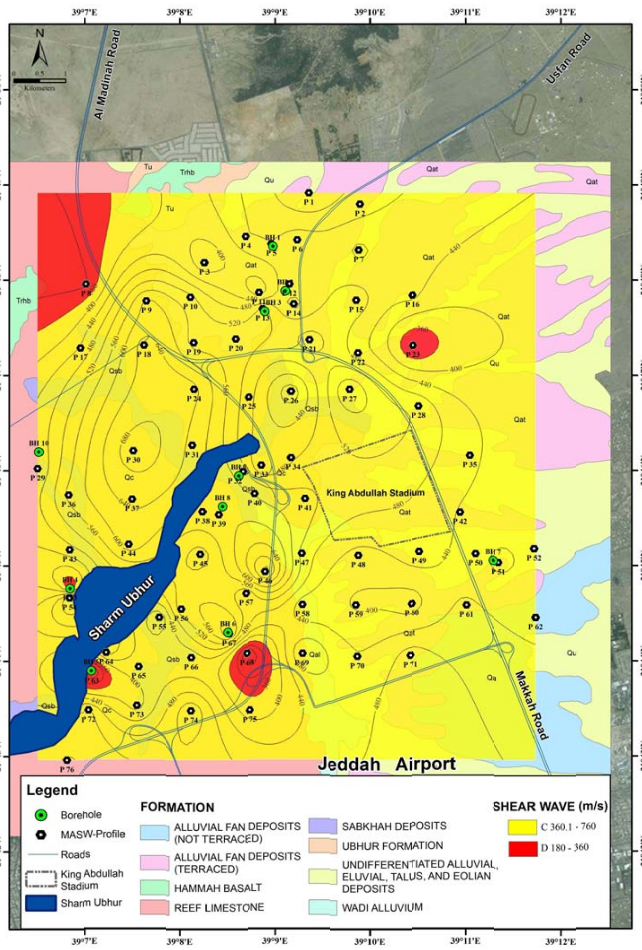

Fig.17. Site class based on shear wave velocity for soil thickness.

27.09 m when it reaches the bed rock at Vs = 749.91 m/s). In these sites, the Vs_{30} value of 358.76 m/s is close to the lower limit of NEHRP class C.

The depths of bedrock resulted from Vs30 profiles at boreholes locations are in agreement with that of the boreholes where the average depth ranges from 10 m to 15 m (Fig. 16). As mentioned earlier and due to the shallow depth of bedrock in the drilled boreholes in the study area (the average depth varies between 10 m and 15), Vs for the soil layers up to the depth of bedrock was calculated based on the depth of soil thickness from boreholes or shear wave velocity less than 760 m/s from MASW results. Then, these values were mapped (Fig. 17). According to Figure (17), the study area can be classified into site class C and D are major part of the study area falls in site class C whereas a limited area belongs to class D.

In conclusion, Vs30 technique is not applicable for regions with depth of bedrock less than 30 m because it leads to higher site class classification because it includes the shear wave velocity of rocks. Instead in this case it is appropriate to calculate the average shear wave velocity for the soil materials.

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