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ORIGINAL PAPER

New methods to improve the assessment of shear wave velocities and seismic hazard parameters in Jeddah city, western Saudi Arabia

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Abstract Seventy-five geotechnical boreholes were drilled in Jeddah city to identify the soil characteristics and calculate the shear wave velocity. The depth of boreholes extends up to 40 m in some sites, where the standard penetration test (SPT) was assigned at each 1.5 m depth interval. The groundwater table fluctuated between 0.5 and 9 m below the ground level. In addition, the multichannel analysis of surface waves (MASW) method was applied at the same borehole locations to estimate the shear wave velocity of the subsurface layers. 1D shear velocity profiles were processed using *SeisImager* software. The calculated shear wave velocity at the mid-point of each surveying line was compared with that of the borehole because the mid-point of the surveying line coincides with the borehole location. In addition, horizontal–vertical-spectral ratio inversion (INV_HVSR) of microtremor measurements recorded at the borehole locations represents a third method to estimate the shear wave velocity of subsurface layers. Results of these three methods are then compared and, finally, the average shear wave velocity values, up to a depth of 30 m, were assessed for Jeddah city. According to V_s (30) values, the soil classes for Jeddah city can be classified into three classes as "site class D," "site class C," and "site class B," according to the National Earthquake Hazard Reduction Program (NEHRP). These results should be added to the Saudi Building Code (SBC) to improve the requirements for the design of earthquake-resistant structures in Jeddah city.

Keywords Soil · Shear wave velocity · Hazard assessment · Jeddah city

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Introduction

Jeddah city is located along the eastern coastal plain of the Red Sea (Fig. 1). It is not only one of the most densely populated cities in Saudi Arabia but also receives millions of visitors each year to perform Hajj and/or Umrah. Unfortunately, this city lies in the downstream of major wades meaning a thick section of soft soil. These soils are characterized by great variations in type, thickness, and facies. From an earthquake hazard point of view, shear wave velocity is a critical factor to identify the stiffness of the sediment and thus to determine the amplitude of ground motion (Joyner and Fumal 1984; Boore et al. 1993) and might also be a useful parameter to characterize local geologic conditions quantitatively for calculating site response. The presence of soft soil will greatly affect the earthquake ground motion since it can amplify the site response by several times compared to bedrock, which in turn will increase the earthquake hazard potential of Jeddah city. The estimation of soil shear wave velocity (V_s) structure is an essential component of site-response ground-shaking parameters, and has proved to be an important indicator of the amplification characteristics that are produced in geologic units by the strong ground motions associated with earthquakes (Fumal and Tinsley 1985; Borcherdt and

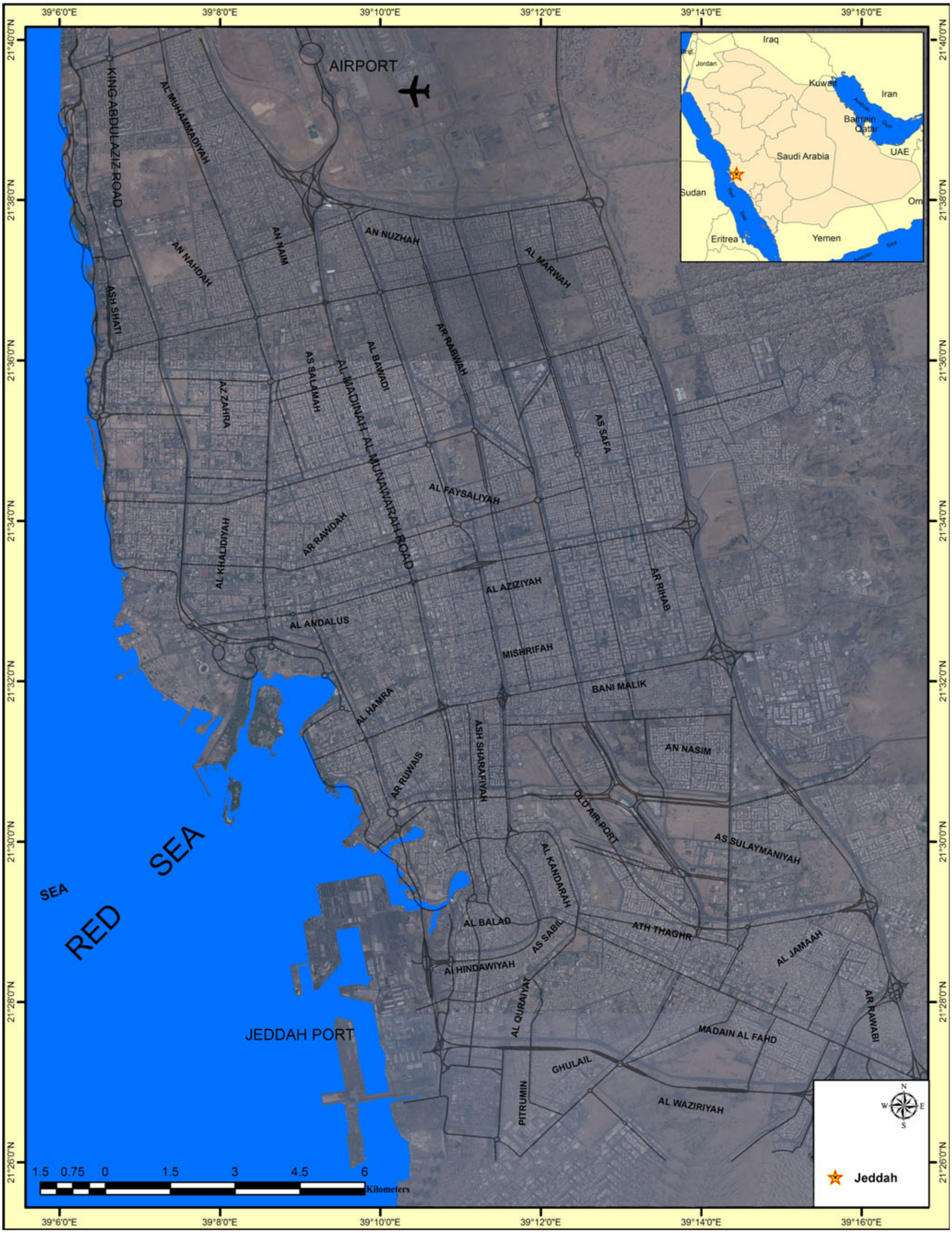

Fig. 1 Areal image of Jeddah city showing its different districts (Reference: Google Earth)

Glassmoyer 1994). The average shear wave velocity values up to a depth of 30 m (V_s30) have become a widely used parameter for classifying surface soil distribution (Dobry et al. 2000) and thus loss estimation. Due to the strength of the V_s30 parameter, it has been accepted by the National Earthquake Hazard Reduction Program (NEHRP) (International Code Council 2006) as the standard for soil classification in seismic hazard analysis.

Several field and laboratory methods have been developed to measure, either directly or indirectly, the soil shear wave velocity. In this study, shear wave velocity has been estimated using three methods. The first method is the standard penetration test (SPT), which has always been one of the most convenient ways to identify subsurface soil profiles consisting of cohesion-less soils or relatively stiff soils, and finally V_s30 can be estimated using Boore (2004) relationships. The second method is the inversion of the multichannel analysis of surface waves (MASW) technique, which has been widely used to estimate shear wave velocity all over the world (Park et al. 1999; Sitharam et al. 2005; Sairam 2011). The third method

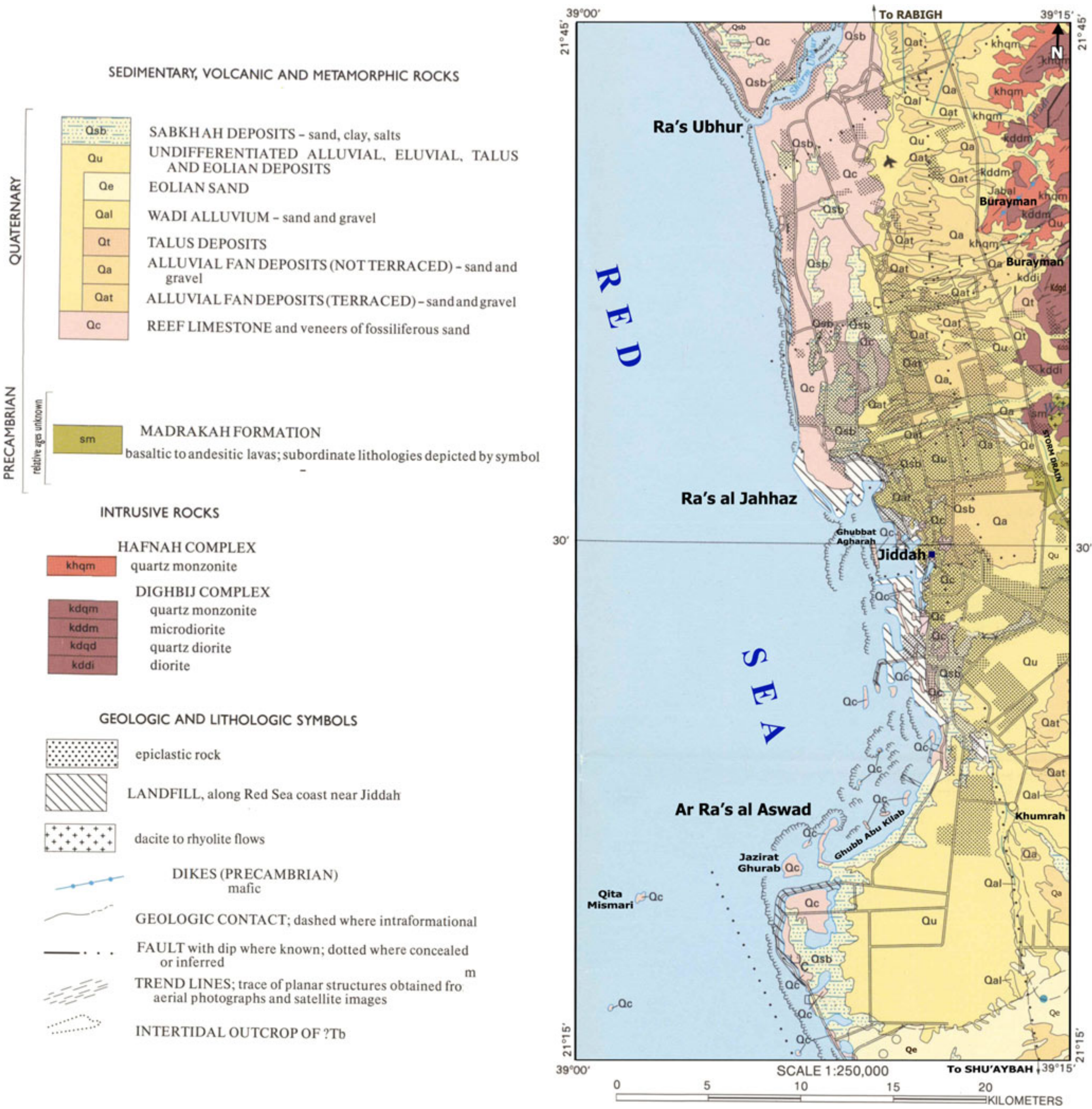

Fig. 2 Geologic map of Jeddah city (Moore and Al-Rehaili 1989)

used in this study is the INVersion of the Horizontal-Vertical Spectra Ratio for microtremor measurements (INV-HVSR) (Herak 2008).

Surface geology of Jeddah city

The surface geology of Jeddah is constituted by recent sediments that spread north and south along the coastal plain of the Red Sea (Fig. 2). The Quaternary deposits have been divided into several units (Moore and Al-Rehaili 1989; Bahafzullah et al. 1993); the oldest is raised coralline limestone that crops out along the coast; north of Jeddah the outcrop is 5–10 km wide but to the south it is less than 1 km wide. Inland, the coralline limestone is covered by terraced gravels, alluvial fan deposits and, in the south, by wind-blown sand. Talus deposits have accumulated at the foot of the steep mountainous slopes. The most recent deposits are the alluvial sands and gravels of Wades, and Sabkhah gypsiferous sands, silts, and clays overlying the coralline limestone. The thickness of the alluvial cover varies widely, from a few centimeters to several meters thick over large areas of the coastal plain. Some of drilled boreholes, in south Jeddah, have about 85 m of alluvial deposits, suggesting that there is substantial thickening of the alluvial cover inland.

Soil profiles in Jeddah city

More than 440 boreholes have been drilled in different districts of Jeddah for the evaluation of the subsurface soil profiles. In general, the coastal deposits in the Jeddah area can be classified into two categories. The first category is chiefly depositional coralline, while the other is mainly sand and silt originating from variable rocks. Clays are occasionally encountered, but are less prevalent. Coral reefs are abundant, however, both on and offshore, and vary in thickness from centimeters to tens of meters. These coral deposits are sometimes completely weathered. The subsurface conditions are highly variable across different areas (Table 1). Some selected soil profiles encountered in Jeddah city are given below.

Wadi Ghalil profiles

Wadi Ghalil channel runs across the southern part of Jeddah. Soil types encountered in this wadi are as follows:

1. Silty gravelly sand in the upper 3 to 9 m. The soil is dry and medium to very dense.
2. A stratum of gravelly sand to sand and gravel with rock boulders with a maximum thickness of 8 m. This material is saturated and dense to very dense.

Table 1 Soil profiles in some districts of Jeddah city

Depth (m)	Description
Soil profile in the Al-Marwah district	
0.0–4.5	Silty sand
4.5–7.5	Poorly graded sand
7.5–13.5	Poorly graded gravel with sand
13.5–18.0	Silty sand with gravel
18.0–30.0	Poorly graded sand with gravel
Soil profile in Al-Mushrefah district	
0.0–6.0	Poorly graded sand
6.0–13.5	Poorly graded gravel with sand
13.5–20.0	Poorly graded sand with gravel
20.0–30.0	Poorly graded gravel with sand
Soil profile in the Eastern Side of Jeddah	
0.0–3.0	Silty sand
3.0–4.5	Poorly graded gravel
4.5–20.0	Poorly graded sand
20.0–30.0	Poorly graded gravel with silt
Soil profile in the King Abdul-Aziz University	
0.0–4.5	Silty sand with gravels
4.5–6.0	Cobbles and boulders
6.0–15.0	Poorly graded sand with silt
15.0–30.0	Silty sand with gravels
Soil profile in the Al-Hindawiyah district	
0.0–9.0	Poorly graded sand
9.0–20.0	Poorly graded sand with silt
20.0–30.0	Poorly graded sand with gravel

3. The third layer consists of very dense silty to clayey sand with rock boulders and a maximum thickness of about 15 m.
4. At a depth of 26 to 40 m from the ground, a layer of highly to moderately weathered meta-andesite is encountered.

The groundwater level in this wadi is at a depth of about 8 m.

Wadi Fatimah profile

Wadi Fatimah slopes gently toward the sea. The rocks of this wadi consist of gravelly sand to sand gravel and/or sand and gravel. The subsoil strata in this area are as follows:

Fig. 3 Borehole locations in Jeddah city

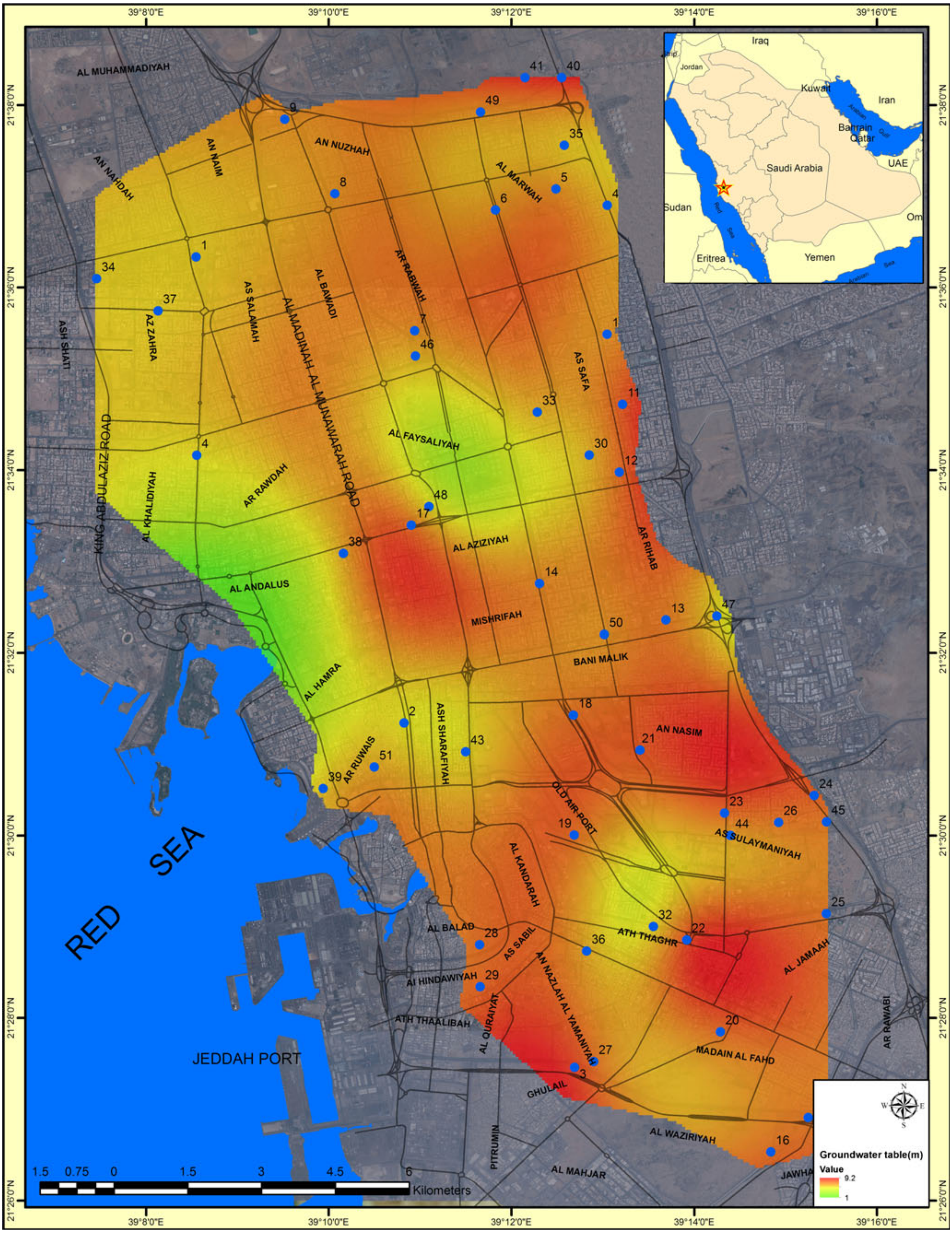

Fig. 4 Groundwater levels in Jeddah city

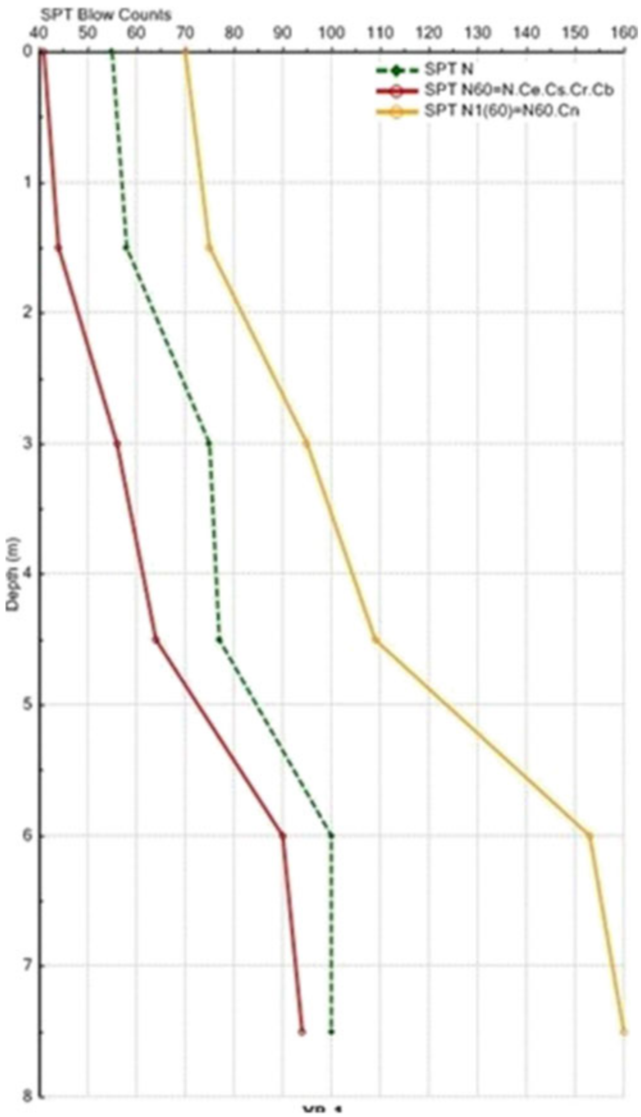

Fig. 5 SPT corrections for borehole No. JB-10

1. The upper 1–2 m is silty gravelly sand. It is saturated and very dense.
2. The second layer consists of silty fine to coarse, saturated and very loose to loose (SPT varies from 5 to 15). The average thickness of this layer is 6 m.
3. The third layer consists of saturated and very dense sand to sandy gravel with various amounts of silty soil and clay, and extends to a depth of 40 m below the ground.

The ground water level is at a depth of 1 m.

Southern coastal plain

The subsoil strata in the coastal plain which is bounded by Wadi Fatimah on the east and the Red Sea (Naval Base) on the west are as follows:

1. The first layer consists of clayey silty sand, saturated and very loose to loose. The thickness of this layer is about 2 m.
2. A layer of clayey to silty carbonate sand and gravel (mainly derived from the disintegration and decomposition of coral formations) is encountered below the first layer. The soil is saturated and of medium to very dense state (SPT varies from 20 to 50).
3. A layer of silty gravelly, sandy gravel, and/or silty sand and gravel underlies the second layer to a depth of 40 m below the ground. It is saturated and in a very dense state.

Northern coastal plain

The coastal deposits in Al-Shatee district consist of the following layers:

1. 0–3 m—a layer of loose silty soil with coral fragments (SPT value = 6) or a layer of silty sand with gravel in a medium dense to very dense state (SPT ranges between 15 and 100).
2. (a) 3–10 m—a layer of clayey sand with gravel that is medium dense to very dense. (b) 3–5 m—a layer of coralline sand with boulders and coral fragments, very dense.
3. 5–30 m coralline sand with coral fragments, medium dense to very dense.

The groundwater level is at 2 m below the ground surface.

Sabkha profile

Sabkha soils are present in Abhur, Al-Khalidiya, Al-Salama, Al-Hamra, Al-Ruwais, Al-Corniche, and Jeddah sea port districts. The following is a typical soil profile in Al-Hamra district:

1. 0–3 m—a layer of silty sand with gravel and coral fragments, saturated loose to medium dense (SPT varies from 10 and 17).
2. 3–20 m—a layer of coralline sand with coral fragments saturated, loose to medium dense (SPT ranges between 8 and 25).

The ground water level is at 1 m below the ground surface.

Shear wave velocity estimation

Geotechnical investigations

Several worldwide correlations between shear wave velocity and physical properties can be identified (Fumal 1978) (i.e., SPT). These relations can be applied to areal distribution,

Table 2 Estimation of shear wave velocity from borehole No. 21

Depth	Soil type	H	SPT	N60	(N1)60	V_s(N60)	Vav	Vs30
0	On surface 0 10-cm-thick asphalt pavement	0.5						
0.5	Light gray, hard, sandy silt	0.5						
1		0.5	40	30.06	55.61	271.04	375.00	379.70
1.5		0.5						
2	Ditto	0.5	63	47.34	87.59	340.46		
2.5		0.5						
3	Ditto, with gravel	0.5	50	37.58	69.51	303.17		
3.5	Brown, highly weathered, closely spaced, dull lustred, strong, fractured limestone with few voids (2–6 cm)	0.5						
4		0.5						
4.5		0.5						
5	Ditto, with gravel	0.5						
5.5		0.5						
6		0.5						
6.5	Ditto, gray	0.5						
7		0.5						
7.5		0.5						
8	Ditto, whitish gray, moderately weathered	0.5						
8.5		0.5						
9		0.5						
9.5	Ditto, interbedded with silt	0.5						
10		0.5						
10.5		0.5						
11	Ditto	0.5						
11.5		0.5						
12		0.5						
12.5	Brown, moderately weathered, closely spaced, dull lustred, strong, fractured limestone	0.5						
13		0.5						
13.5		0.5						
14	Ditto	0.5						
14.5		0.5						
15		0.5						
15.5	Ditto	0.5						
16		0.5						
16.5		0.5						
17		0.5						
17.5	Ditto, slightly weathered	0.5						
18		0.5						
18.5	Ditto	0.5						
19		0.5						
19.5		0.5						
20	Ditto	0.5						
20.5		0.5						
21		0.5						
21.5	Ditto	0.5						
22		0.5						
22.5		0.5						
23	Ditto	0.5						
23.5		0.5						
24		0.5						
24.5		0.5						
25		0.5						
25.5		0.5						

physical properties, and the thickness of the geologic units in order to estimate shear wave velocity.

The method used here identifies soil profiles and merges in situ measurements of dynamic properties with geologic

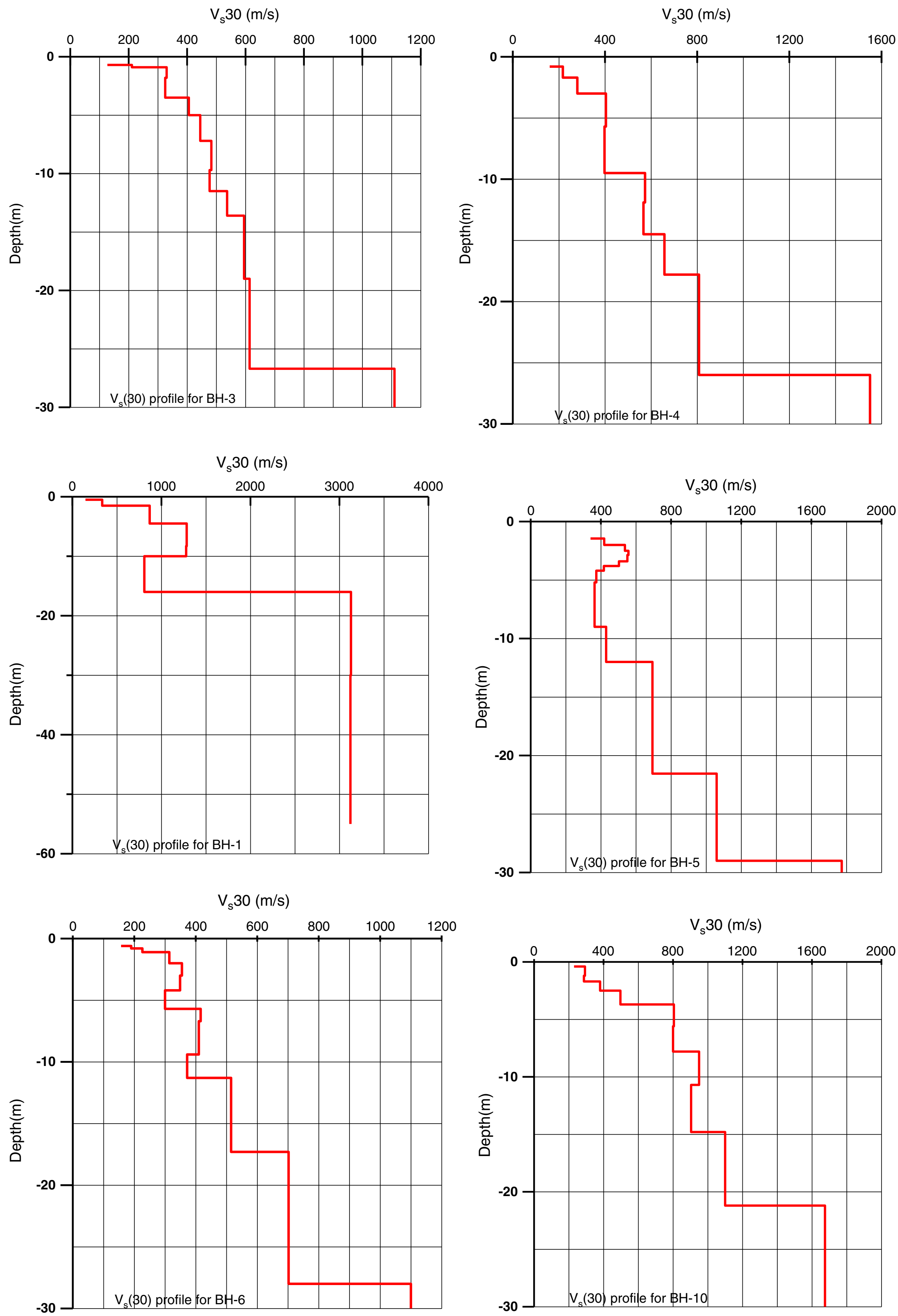

Fig. 6 1D Vs profiles from MASW profiling

information according to the design code of IBC 2006. In this study, 75 boreholes were drilled through Jeddah city (Fig. 3). The SPT was performed at depth intervals of 1.5 m, particularly in cohesionless materials (ASTM D1586-84). SPT values show the general soil profile consisting of a variable thickness of soil overburden. The thickness of the overburden varies from 4.5 to 30 m from the ground surface at borehole locations. The maximum penetrated depth is about 30 m. Underneath this soil, the disintegrated weathered rock exists, having a refusal strata with $N > 100$. The water table depth in Jeddah city during the period of investigation fluctuated between 0.5 and 9 m below the ground level (Fig. 4).

N values measured in the field using the SPT procedure have been corrected ($\boldsymbol{N_1 60}$) for different parameters (Fig. 5) such as overburden pressure (C_N), hammer energy (C_E), borehole diameter (C_B), presence or absence of liner (C_S), rod length (C_R), and fines content (C_{fines}) (Seed et al. 1983; Schmertmann et al. 1978; Skempton 1986; Sitharam et al. 2005; Anbazhagan and Sitharam 2008), according to the following equation:

$$N_{60} = N \times (C_N \times C_E \times C_B \times C_S \times C_R \times C_{\text{fines}}) \quad (1)$$

Then, shear wave velocity represents the key for calculating seismic hazard at a certain site where the average shear wave velocity for the depth "d" of soil is referred as V_H as follows; the average shear wave velocity up to a depth of H (V_H) is computed as:

$$V_H = \sum d_i / \sum \left({}^{d_i}/_{v_i} \right) \quad (2)$$

Where $H = \sum d_i$ = cumulative depth in meters.

For 30 m average depth, shear wave velocity is written as:

$$V_{s(30)} = \frac{30}{\sum_{i=1}^{N} \left({}^{d_i}/_{v_i} \right)} \quad (3)$$

Where d_i and v_i denote the thickness (in meters) and shear-wave velocity in m/s of the ith layer, respectively.

But for the remaining locations, the data is available for less than 30 m, (V_s30) was calculated using the "extrapolation assuming constant velocity" extrapolation method as proposed by Boore (2004) for boreholes of less than 30 m depth.

$$v_{s(30)=30/\left(tt\left(d \right) + (30-d)/v_{eff} \right)} \quad (4)$$

Where V_{eff} is the assumed effective velocity from depth d to 30 m and equals the velocity at the bottom of the velocity model:

$$v_{eff} = v_{s(d)} \quad (5)$$

Finally, the estimated shear wave velocity ranges between 286 and 989 m/s (e.g., Table 2).

Multichannel analysis of surface wave

Multichannel analysis of surface wave (MASW) generates a shear-wave velocity profile by analyzing surface waves (Raleigh-type) on a multichannel record (Park et al. 1999; Xia et al. 1999). It is a seismic method that can be used for site characterization of near surface materials (Park and Miller 2005The MASW acquisition system, in this study, consists of Geode seismograph with 24 geophones of 4.5 Hz capacity. Seventy-one one-dimensional MASW survey profiles were carried out in the Jeddah urban area. Shear velocity 1D profiles were processed using *SeisImager* software (Fig. 6). The shear wave velocity calculated at the mid-point of each survey line is comparable with that calculated at the borehole location because the survey line mid-point coincides with the borehole location. The average shear wave velocity values for 30 m depth have been achieved from surveying lines for the different layers fall within the parameters of the NEHRP soil characterization of site categories (Building Seismic Safety Council, BSSC 2003, Table 3). The average shear wave velocity values up to 30 m depth were obtained and ranged from 356 to 1158 m/s. These values were then used to construct a V_s (30) map for Jeddah city (Fig. 7).

According to the V_s (30) map and the NEHRP soil classification, three soil classes have been identified and constitute the soil deposits in Jeddah city. These soil classes are B, C, and D. As seen on the map, the soft soil units assigned as soil class D extend along the Red Sea coast. The other two soil classes, C and B, extend away from the coast and eastward of Jeddah city where the hard rocks outcropped.

HVSR inversion

HVSR inversion depends on the matching process of horizontal–vertical spectral response (HVSR) and subsurface soil parameters (Scherbaum et al. 2003; Wathelet et al. 2004; El-Hady et al. 2012). Microtremor measurements (Fig. 8) were recorded at the same sites as the boreholes, following the approach of Nakamura (1989). According to Herak (2008),

Table 3 BSSC (2003) site class definitions using the average shear wave velocity up to 30 m depth

Site class	Soil profile name	Shear wave velocity, V_s (m/s)
A	Hard rock	$V_s > 1500$
B	Rock	$760 \leq V_s \leq 1500$
C	Very dense soil and soft rock	$360 \leq V_s \leq 760$
D	Stiff soil profile	$180 \leq V_s \leq 360$
E	Soft soil profile	$V_s \leq 180$

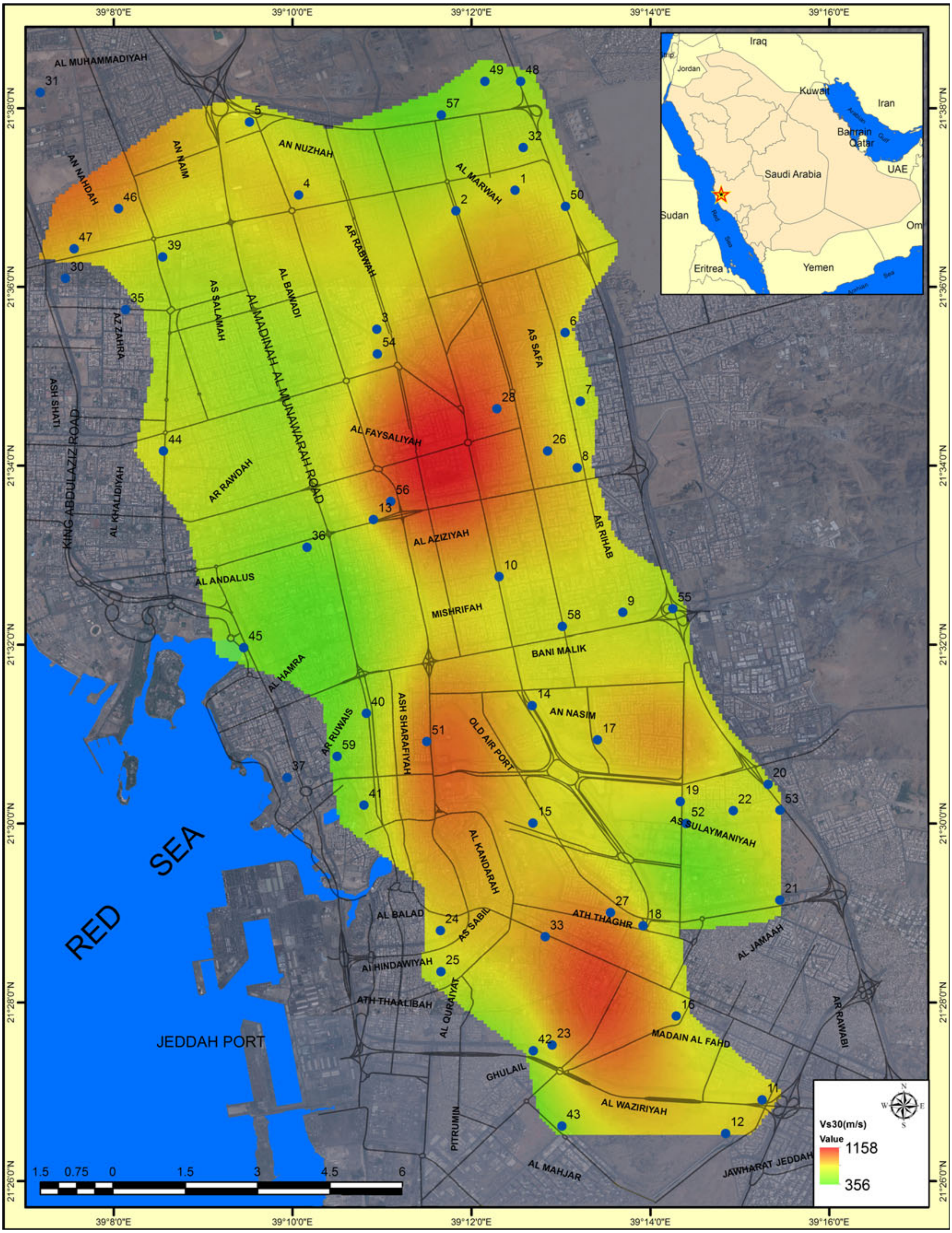

Fig. 7 V_s (30) distribution in Jeddah city

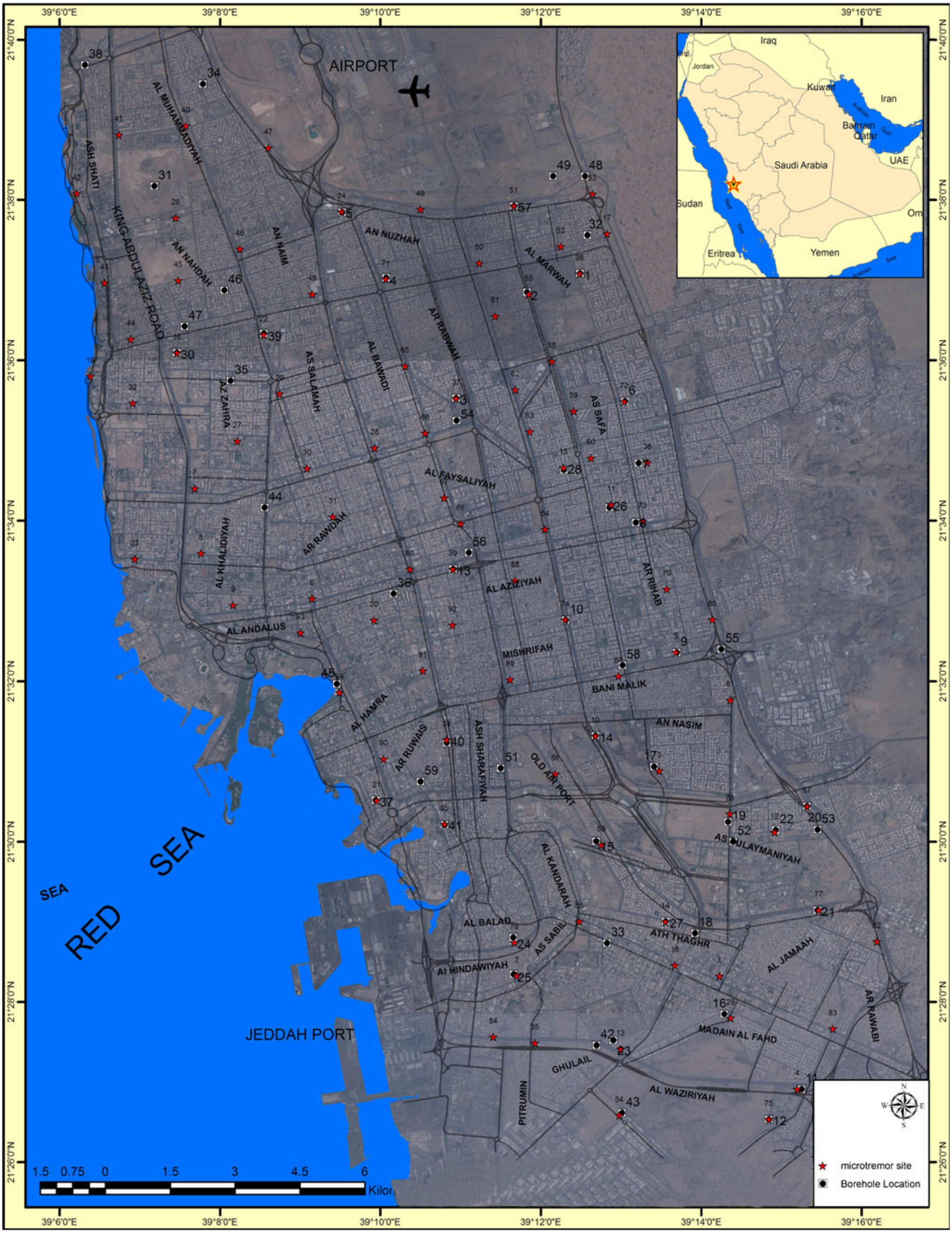

Fig. 8 Microtremor measurements and borehole locations

the INV_HVSR module inverts the observed HVSR to find the soil models describing it depending on the combination of the simple and the guided Monte Carlo search which minimizes the misfit function as follows:

$$m = \sum\{[\mathrm{HVSR}_{OBS}(f_i) - \mathrm{HVSR}_{\mathrm{THE}}(f_i)]W_i\}^2 \quad (6)$$

Where OBS and THE mean the observed and the theoretical HVSR, and W_i is the weight defined by:

$$W_i = \lfloor \mathrm{HVSR}_{OBS}(f_i)\rfloor^E, \mathrm{E} \geq 0 \quad (7)$$

In this study, the INV_HVSR carried out based on the initial model (Table 4) of the 1D MASW profiles at each microtremor measurement site are depending on the correlation between the theoretical and observed HVSR (Fig. 9). This figure shows that there is a realistic fit between the theoretical and observed HVSR curves. The v_p and density values are resulted from the inversion process.

Discussions and conclusions

Different soil deposits have been identified throughout Jeddah city based on geological, geotechnical, and geophysical investigations. Seventy-five geotechnical boreholes have been drilled in Jeddah city to identify the soil characteristics and their geotechnical parameters. The depth of these boreholes extends up to 40 m at some sites. The standard penetration test (SPT or N value) was assigned at each 1.5-m depth interval. The water table fluctuated between 0.5 and 9 m below the ground level. The measured N value has been corrected and then used to calculate the shear wave velocity up to 30 m depth. The calculated values of V_s (30) vary from 286 to 989 m/s.

In addition, 75 one-dimensional MASW surveying profiles were carried out at the same location as the boreholes and the respective shear wave velocity profiles were obtained. These values range between 356 and 1158 m/s. According to estimated v_s values from MASW and SPT methods are correlated well (where, correlation coefficient, R^2 = 0.87). Three soil classes were identified according to the NEHRP soil classification, and these are "site class D," "site class C," and "site class B." The soft soil units are assigned as soil class D extends along the Red Sea coast, while the other two soil classes, C and B, extend away from the coast and eastward of Jeddah city where the hard rocks outcropped.

Furthermore, the shear wave velocity was estimated through HVSR inversion for microtremor records at the same borehole locations. This method is based on the matching process between the site response spectra and the subsurface dynamic properties. The results of inversion process are correlated well with those of the other two methods. According to NEHRP recommendations, soils with lower shear-wave velocity values, i.e., NEHRP soil class letters further from A,

Table 4 Examples of initial models for soil parameters in Jeddah city

V_s	V_p	Thickness
BH-3		
127	219	0.7
211	365	0.2
330	572	0.8
324	562	1.7
406	701	1.6
440	763	2.2
483	837	2.3
477	827	2
538	931	2.2
585	1031	4.4
613	1062	6.5
BH-4		
160	277	0.8
216	375	1.0
279	484	1.3
404	698	2.7
388	688	3.8
573	993	2.4
567	982	2.5
689	1140	3.2
908	1400	8.5
BH-8		
229	397	0.4
293	507	0.8
287	497	0.5
380	658	0.7
497	961	1.1
805	1395	1.9
795	1384	2.2
956	1656	1.2
850	1646	1.7
804	1565	3.8
1092	1892	6.7
BH-10		
229	397	0.4
293	507	0.8
287	497	0.5
380	658	0.7
497	961	1.1
805	1395	1.9
795	1384	2.2
956	1656	1.2
850	1646	1.7
804	1565	3.8
1092	1892	6.7

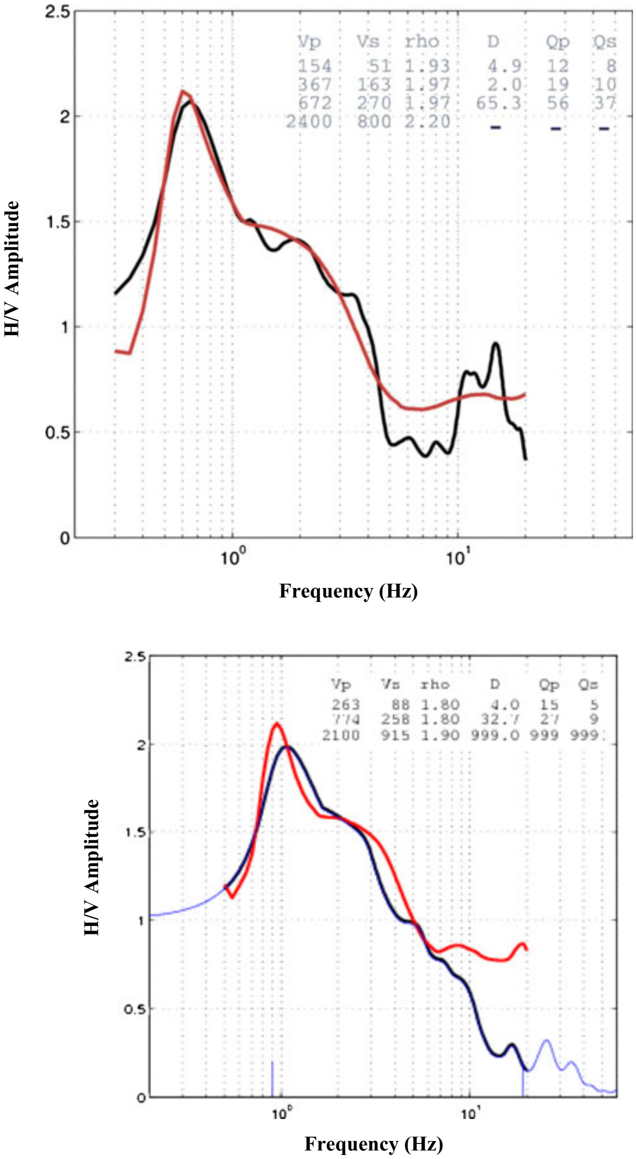

Fig. 9 Examples of matching theoretical and observed HVSR curves and the resulting velocity model

will experience more earthquake ground shaking than bedrock, due to the wave-amplifying properties of the soil. This means that most parts of Jeddah city will experience soil amplification from earthquake ground motion and thus a full earthquake hazard assessment of Jeddah city is highly recommended.

Based on results of this study, it can be concluded that MASW is the most powerful technique to estimate the engineering properties of soil in spite of its cost-effective tool.

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