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Spatial Variability of the Depth of Weathered and Engineering Bedrock using Multichannel Analysis of Surface Wave Method

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Abstract—In this paper an attempt has been made to evaluate the spatial variability of the depth of weathered and engineering bedrock in Bangalore, south India using Multichannel Analysis of Surface Wave (MASW) survey. One-dimensional MASW survey has been carried out at 58 locations and shear-wave velocities are measured. Using velocity profiles, the depth of weathered rock and engineering rock surface levels has been determined. Based on the literature, shear-wave velocity of 330 ± 30 m/s for weathered rock or soft rock and 760 ± 60 m/s for engineering rock or hard rock has been considered. Depths corresponding to these velocity ranges are evaluated with respect to ground contour levels and top surface levels have been mapped with an interpolation technique using natural neighborhood. The depth of weathered rock varies from 1 m to about 21 m. In 58 testing locations, only 42 locations reached the depths which have a shear-wave velocity of more than 760 ± 60 m/s. The depth of engineering rock is evaluated from these data and it varies from 1 m to about 50 m. Further, these rock depths have been compared with a subsurface profile obtained from a two-dimensional (2-D) MASW survey at 20 locations and a few selected available bore logs from the deep geotechnical boreholes.

Key words: MASW, shear-wave velocity, weathered rock, engineering rock and rock depth.

1. Introduction

Spatial variability of the bed rock with reference to ground surface is vital for many applications in geotechnical engineering and geosciences. Rock depth in a site is a very useful parameter for the geotechnical and geotechnical earthquake engineers to find their basic requirement of hard strata (shear-wave velocity of more than 700 m/s) and to arrive at the depth of the foundation or to assign input ground motion for ground response analysis. In most of the geotechnical investigations, knowledge of the hard strata or rock is essential to decide the type of foundations and to design a suitable foundation for a structure. Among the ground response analysis, Peak Ground Acceleration (PGA) and response spectrum for the particular site is evaluated at the bed rock level and further on at the ground level considering local site effects.

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Determination of rock depth is an essential step to evaluate site amplification and liquefaction hazard of a site and further to estimate seismic induced forces on the structures. Hence it is necessary to evaluate the depth of the bed rock from the ground level. In this paper an attempt has been made to evaluate the depth of weathered and engineering rock in the study area using measured shear-wave velocities from Multichannel Analysis of Surface Wave (MASW) survey.

A number of geophysical methods have been proposed for near-surface characterization and measurement of shear-wave velocity by using a great variety of testing configurations, processing techniques, and inversion algorithms. The most widely-used techniques are SASW (Spectral Analysis of Surface Waves) and MASW. MASW is a seismic method which can be used for geotechnical characterization of near-surface materials (Park *et al.*, 1999; Xia *et al.*, 1999; Miller *et al.*, 1999a; Park *et al.*, 2005; Kanli *et al.*, 2006). The MASW has been found to be a more efficient method for unraveling the shallow subsurface properties (Park *et al.*, 2001; Zhang *et al.*, 2004). MASW is increasingly being applied to earthquake geotechnical engineering for microzonation and site response studies. In particular, MASW is used in geotechnical engineering for the measurement of shear-wave velocity and dynamic properties, identification of subsurface material boundaries and spatial variations of shear-wave velocity. MASW is a non-intrusive and less time-consuming geophysical method, which identifies each type of seismic waves on a multichannel record based on the normal pattern recognition technique that has been used in oil exploration for several decades. The identification leads to an optimum field configuration that assures the highest signal-to-noise ratio (S/N). Effectiveness in signal analysis is then further enhanced by the data processing step (Ivanov *et al.*, 2005). MASW is also used to generate a two-dimensional shear-wave velocity profile, which represents the subsurface material characteristics. In this paper, MASW has been used to measure the shear wave velocity at 58 locations in the study area. The measured shear-wave velocities are further used to identify the depth of weathered/soft rock and bed/engineering rock surface. In the literature, the weathered rock is identified corresponding to shear-wave velocity of above 300 m/s, and hard or engineering rock is identified corresponding to shear-wave velocity of above 700 m/s (Miller *et al.*, 1999a; Santamarina *et al.*, 2001; Ryden, 2004; Nath, 2007;). In this study the depth corresponding to shear wave velocity of more than 330 ± 30 m/s is considered as surface of the weathered rock. Similarly, the depth corresponding to shear-wave velocity more than 760 ± 60 m/s is considered as the surface of the hard or engineering rock. The rock depths derived from shear-velocity profiles are used to prepare maps showing the depth of weathered and engineering rock surface in the study area by interpolating data using natural neighborhood method. Additionally at about 20 locations two-dimensional shear-wave velocity profiles have been obtained, which are used to cross verify the maps prepared using 1-D Vs profiles. The study shows that the rock depth mapped using one-dimensional shear-wave velocity profiles matches well with the 2-D shear-wave velocity profiles. Also comparison has been presented with actual boreholes drilled in the study area for the various construction projects.

2. *Study Area and Geology*

The study area is limited to Bangalore Metropolis area (Bangalore Mahanagar Palike) having a near circular area of 220 km^2. Bangalore is situated on a latitude of 12^{o}58′ north and longitude of 77^o 36′ east and is at an average altitude of around 910 m above the mean sea level (MSL). It is the principal administrative, industrial, commercial, educational and cultural capital of Karnataka state and lies in the southwestern part of India (see Fig. 1). Bangalore City is the fastest growing city and fifth biggest city in India. Besides political activities, Bangalore possesses many national laboratories, defense establishments, small- and large-scale industries and information technology companies. These establishments have made Bangalore a very important and strategic city. It experiences temperate and salubrious climate and an annual rainfall of around 940 mm. In this study the base map is prepared using the geographical information system (GIS) with several layers of information in ArcGIS 9.2. Some of the important

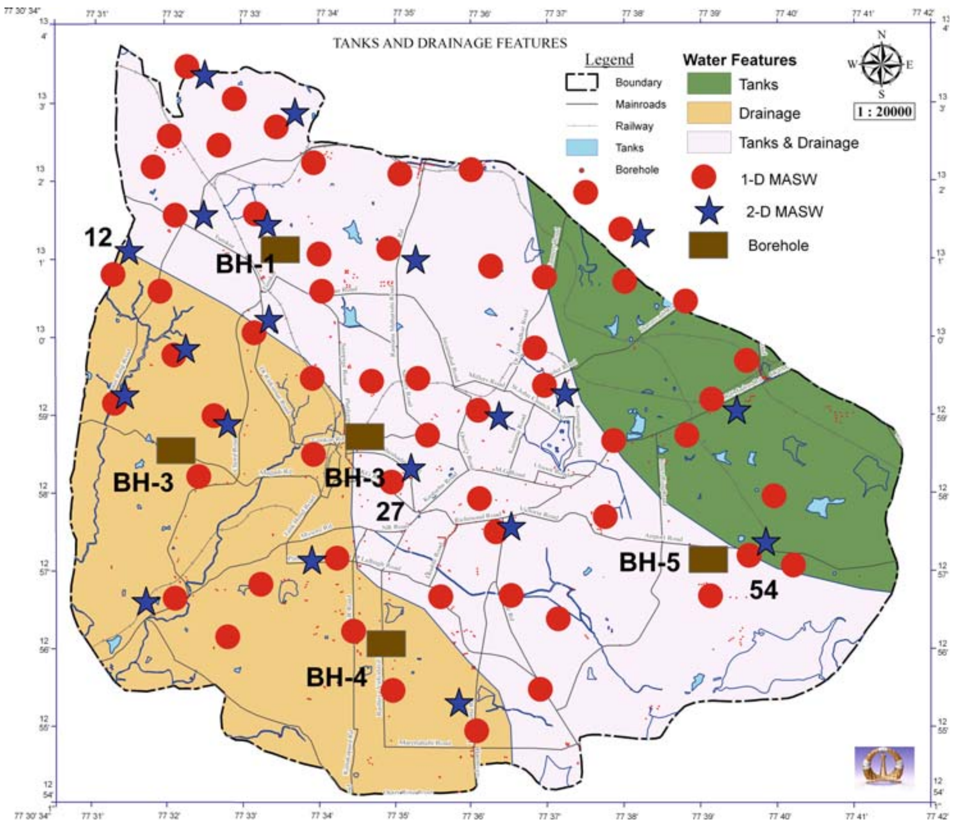

Figure 1
MASW testing locations in the study area along with India map.

layers considered are the boundaries (outer and administrative), highways, major roads, minor roads, streets, railroads, water bodies, drains, landmarks and bore locations.

The main rock types found in the study area are Gneissic rock and also intrusions of Granites and Migmatites rocks. Bangalore City lies over a hard and moderately dense Gneissic basement dated to the Archean era (2500 Ma–3500 Ma). A large granitic intrusion in the south central part of the city extends from the golf course in the north central area to Vasantpur-VV Nagar south of the city (almost 13 km in length) and on an average 4 km from east to west in transition. A migmatite intrusion formed within the granitic intrusion extends for approximately 7.3 km, running parallel with Krishna Rajendra Road/Kanakpura Road from Puttanna Chetty Road in Chamrajpet until Bikaspura Road in the south. A 2.25 km Quatrzite formation is found in Jahahalli East. These basic intrusions mark the close of the Archean era (Lower Proterozoic; 1600 Ma – 2500 Ma) and mainly constitute hard massive rocks such as Gabbro, Dolerite, Norite and Pyroxenite. For the study area a three-dimensional subsurface model has been generated using geotechnical bore logs (SITHARAM *et al.*, 2007). Geotechnical borelog data was basically collated from archives of the Torsteel Research Foundation in India (TRFI) and Indian Institute of Science (IISc) from geotechnical investigations carried out for several major projects in Bangalore. The three-dimensional model contains 850 borelogs information; most of the data thus far selected for the database is on an average a depth of 20 m below the ground level with an interval of 0.5 m. In this study this data base is used to compare or validate the rock depths determined using the MASW survey.

3. Experimental Studies

MASW is a geophysical method which generates a shear-wave velocity (Vs) profile (i.e., Vs versus depth) by analyzing Raleigh-type surface waves on a multichannel record. The term "Multichannel record" indicates a seismic data set acquired by using a recording instrument with multiple channels using a geode seismograph. An MASW system consists of a 24-channels Geode seismograph with 24 geophones of 4.5 Hz capacity has been used in this investigation. The seismic waves are created by an impulsive source of 15 pound (sledge hammer) with 300 mm $\times$ 300 mm size hammer plate with ten shots. These waves are captured by vertical geophones/receivers and further analyzed using SurfSeis software. SurfSeis is designed to generate *Vs* data (either in 1-D or 2-D format) using a simple three-step procedure: i) Preparation of a Multichannel record (sometimes called a shot gather or a field file), ii) dispersion-curve analysis, and iii) inversion.

The MASW test locations are selected based on the space required for the testing and close to important buildings such as hospitals, temples, government buildings and schools. Approximately 58 one-dimensional (1-D) and 20 two-dimensional (2-D) MASW surveys have been carried out. The locations of the testing points in the study area are shown in Figure 1. An effective result from MASW depends on the highest signal-to-noise ratio (S/N) of surface waves. The optimum field parameters such as source to first and last receiver, receiver spacing and the spread length of survey lines are selected in such a way that the highest S/N ratio and required depth of information can be obtained. In this study, to obtain the highest signal-to-noise ratio, tests have been carried out with a geophone interval of 1 m. The source has been kept on both sides of the spread line with a distance of 5 m, 10 m and 15 m, to avoid near- and far-field effects. These source distances have helped to record good signals in very soft, soft and hard soils. These are in conformity with the original recommendations of PARK *et al.*, (2002) and XU *et al.*, (2006). Typical recorded surface wave arrivals using source to first receiver distance as 5 m with a recording length of 1000 ms are shown in Figure 2.

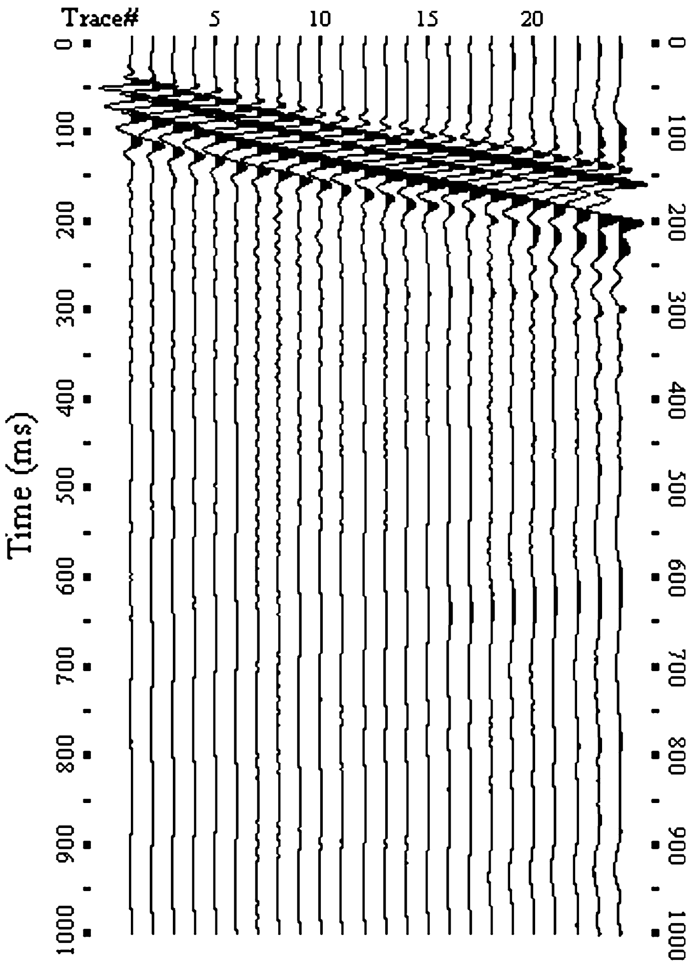

Figure 2
Typical seismic waves recorded in geode seismograph.

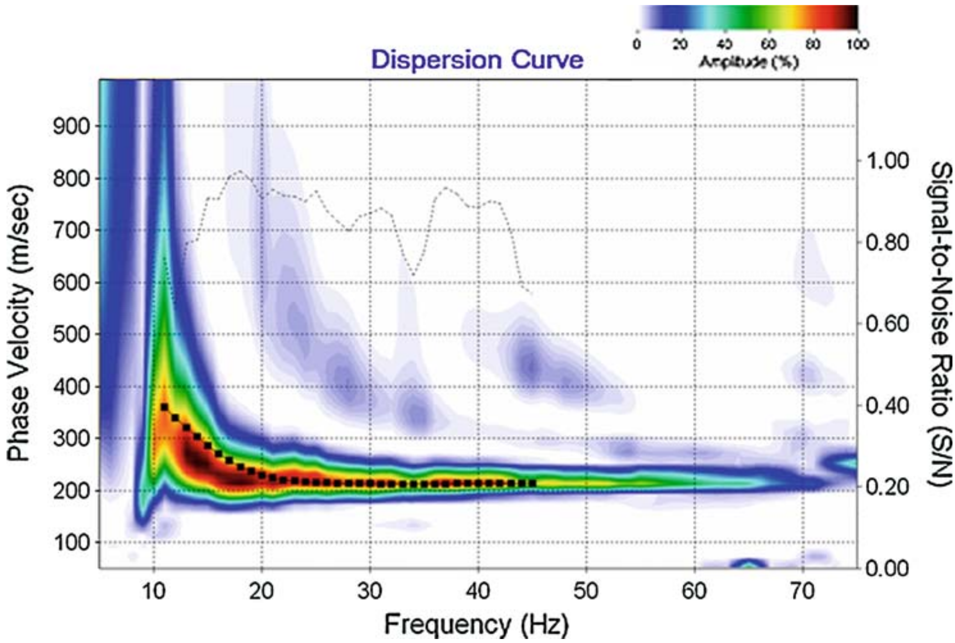

Figure 3
Typical dispersion curve.

The generation of a dispersion curve is an important step in the MASW method. A dispersion curve is generally displayed as a function of phase velocity versus frequency. Phase velocity can be calculated from the linear slope of each component on the swept-frequency record. The lowest analyzable frequency in this dispersion curve is around 5 Hz and the highest frequency of 75 Hz has been considered. A typical dispersion curve is shown in Figure 3. Each dispersion curve obtained for corresponding locations has a very high signal-to-noise ratio of 80 and above. A shear-wave velocity profile has been evaluated using an iterative inversion process that requires the dispersion curve developed earlier as input. A least-squares approach allows automation of the process (Xia *et al.*, 1999). Typical one-dimesional shear-wave velocity with depth is shown in Figure 4.

4. *Spatial Variability of Rock Depth*

Rock classification based on the shear-wave velocity (Vs) in geotechnical, earthquake geotechnical engineering and geosciences is in practice. However, it depends on the application. As per NEHRP (National Earthquake Hazard Research Programme) site classification, very dense soil and soft rock has the 30 m average velocities of 360 m/s to

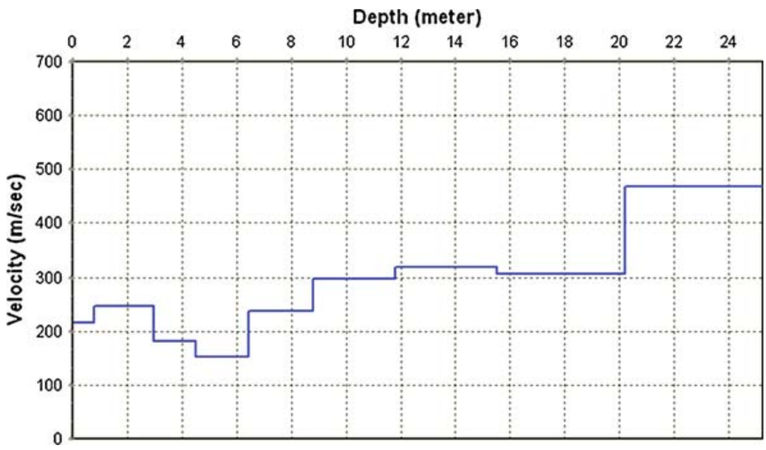

Figure 4
Typical 1-D shear-wave velocity profile.

760 m/s. The rock which has 30 m average shear-wave velocity of more than 760 m/s is classified as hard rock. NATH (2007) has defined that the seismic bed rock correspond to shear-wave velocity of 3000 m/s and above, and engineering bed rock has the shear-wave velocity of 400 m/s to 700 m/s for the purpose of seismic microzonation. SANTAMARINA *et al*. (2001) and RYDEN (2004) have reported the ranges of shear-wave velocity for geotechnical materials such as clay and silt −40 m/s to 300 m/s (if saturated −40 m/s to 250 m/s); sand −100 m/s to 500 m/s (if saturated −80 m/s to 450 m/s); weathered rock (Till) −300 m/s to 750 m/s (if saturated −250 m/s to 700 m/s and Granite, Gneiss (Hard rock) −1700 m/s to 3500 m/s. MILLER *et al*. (1999b) mapped the bed rock by considering Vs of 244 m/s (800 ft/s) and above as a value for bed rock using MASW survey.

In this study shear-wave velocity of 330 ± 30 m/s is considered for the weathered rock and 760 ± 60 m/s is considered for the engineering bed rock. The survey data are well distributed in the northern part when compared to the southern part of the study area. Limited survey points in the southern part are attributed to nonaccessibility of the free land/site as they fall in the defense establishment area. Shear-wave velocity obtained from 58 locations is used to identify the top level of the layer corresponding to shear-wave velocity of 330 ± 30 m/s. These depths are tabulated and used to prepare the depth of the weathered rock map using ArcGIS 9.2. The data between the survey points are interpolated using the natural neighborhood technique to depict the variation of rock levels in the study area. Similarly, the top level of the layer corresponding to Vs of 760 ± 60 m/s is considered as the engineering bed rock. Among the 58 locations of the MASW survey, only 42 locations have been reached with rock having a shear-wave velocity of more than 760 m/s. The data of these 42 locations have been used to prepare the engineering bed rock map. Further equivalent shear-wave velocity has been estimated up to the depth of the weathered and engineering rock level. Equivalent shear-wave velocity is the weighted average shear-wave velocity for the depth (H) by considering each layer and its properties with depth. The equivalent shear-wave velocity for the depth of "d" of soil is referred to as V_H. The equivalent shear-wave velocity up to a depth of H (V_H) is computed in accordance as follows:

$$V_H = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{di} \left[\frac{d_i}{Vs_i}\right]} \tag{2}$$

where $H = \sum d_i =$ cumulative depth up to weathered/engineering rock in m, where d_i and v_i denote the thickness (in meters) and shear-wave velocity (at a shear strain level of 10^{-5} or less, m/s) of the i^{th} formation or layer, respectively, in a total of n layers within the depth of H. A simple spreadsheet has been generated to make the calculation using window macros in excel. The summary of depth and average shear-wave velocity corresponding to Vs of 330 ± 30 m/s and 760 ± 60 m/s is estimated and presented in Table 1. It is noted that the equivalent velocity of the overburden varies from 180 m/s to

Table 1

Depth and equivalent shear-wave velocity corresponding to weathered and engineering rock

Testing location	Longitude	Latitude	Depth of rock (m)		Equivalent shear-wave velocity (m/s)	
	(°E)	(°N)	Weathered	Engineering	Weathered	Engineering
1	77.5842	13.0249	17.3	54.5	263	372
2	77.5866	13.0415	9.7	31	310	449
3	77.5668	13.0441	7.2	25	209	355
4	77.546	13.0492	3.8	*	299	*
5	77.5376	13.0499	8.8	*	202	*
6	77.5345	13.0434	1	22.2	335	512
7	77.5585	13.0519	6.5	33.8	280	452
8	77.5527	13.0603	1.8	*	331	*
9	77.5411	13.0642	4.7	*	190	*
10	77.5369	13.0324	7	*	230	*
11	77.5337	13.0183	7.1	31.4	258	409
12	77.5222	13.021	3.7	25	230	381
13	77.5362	13.0027	3.2	12.9	340	551
14	77.5531	13.0064	0.5	0.5	*	*
15	77.5447	12.9909	12.3	*	215	
16	77.5228	12.9918	6.4	19	339	423
17	77.5665	12.9976	7.3	32.8	220	397
18	77.5537	13.0349	9.2	31.7	265	407
19	77.5793	12.9952	6.8	*	263	*
20	77.5899	12.984	5.6	37.7	254	387
21	77.5885	12.9966	7.9	*	247	*
22	77.6019	12.9899	8.7	*	232	*
23	77.6149	13.0025	19.8	*	196	*
24	77.6175	12.995	6.1	19	217	356
25	77.6035	13.0428	7.1	22.3	253	385

Table 1

Contd.

Testing location	Longitude	Latitude	Depth of rock (m)		Equivalent shear-wave velocity (m/s)	
	(°E)	(°N)	Weathered	Engineering	Weathered	Engineering
26	77.6287	13.0382	8	27.3	222	378
27	77.6351	13.0295	8.5	29.7	247	399
28	77.6488	12.9822	5.6	12.1	284	385
29	77.6626	12.9987	4.6	8	229	305
30	77.6553	12.9914	9.5	29.6	278	440
31	77.5755	12.942	9.4	*	295	*
32	77.585	12.9336	7.5	19.6	310	445
33	77.5541	12.9517	1	11.6	360	675
34	77.6073	13.02	11.1	34.6	237	380
35	77.6179	13.0204	13.4	30.7	292	391
36	77.6347	13.0167	7.6	20	259	349
37	77.6474	13.013	13.5	24	274	329
38	77.6066	12.9633	8.5	26.7	221	356
39	77.6085	12.9479	11.2	*	215	*
40	77.604	12.9692	16.6	38.1	270	337
41	77.6304	12.9658	12.7	29.1	212	287
42	77.633	12.9823	13.8	27	288	376
43	77.6186	12.9445	15.8	*	227	*
44	77.5409	12.9751	5.7	14.8	269	402
45	77.5362	12.9488	2.3	5.2	204	216
46	77.5473	12.9395	3.2	20.8	243	414
47	77.5844	12.9732	2.5	6.6	324	466
48	77.572	12.9576	14.7	*	241	*
49	77.5667	12.9795	11.6	26.8	280	391
50	77.5948	12.9465	8.9	39.8	206	381
51	77.6159	12.9269	12	*	302	*
52	77.6015	12.9186	13.1	30	241	348
53	77.5695	13.0154	5.8	17.3	260	399
54	77.6621	12.9552	12.4	39.4	256	327
55	77.6678	12.9526	13.7	31.4	246	292
56	77.6693	12.9523	3.7	19.3	224	314
57	77.6704	12.9512	10.2	23.5	259	318
58	77.6712	12.9543	20	*	284	*

* Data is not available

360 m/s up to weathered rock and 200 m/s to 680 m/s up to engineering bedrock. Most of the areas have the average shear-wave velocity of 200 to 400 m/s and may classified as medium to dense soil.

5. *Discussions*

Shear-wave velocity obtained from each of the survey locations was carefully studied and the depth of weathered rock and engineering rock has been identified in relation to

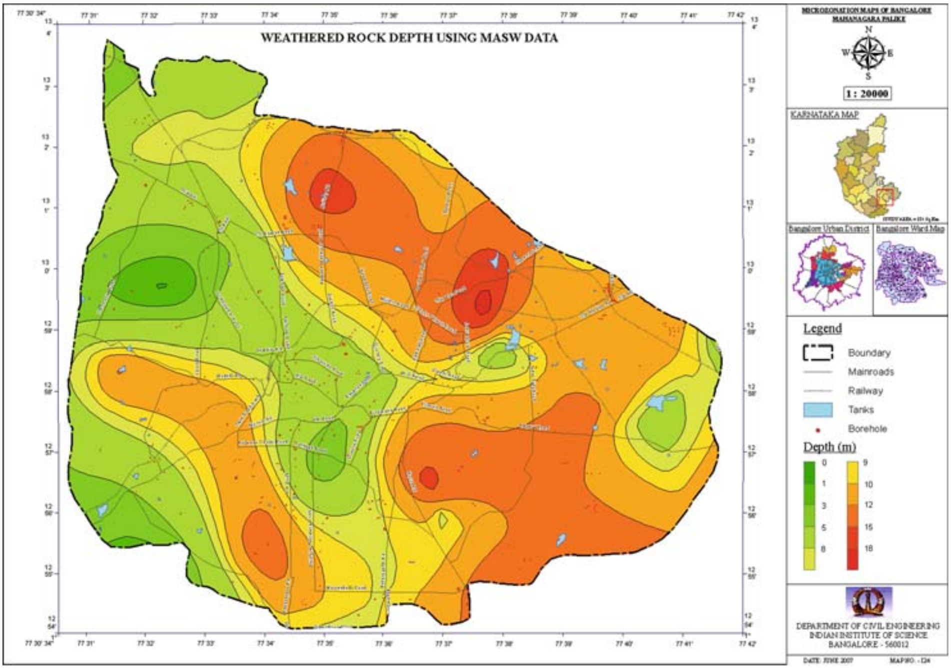

Figure 5
Weathered rock surface in the study area using MASW.

the corresponding ground-reduced levels in the study area. These depths are used to prepare the maps showing the surface level of weathered rock (WR) and engineering rock (ER) depth. Figure 5 shows the surface level (top level) of the weathered rock. In the total data points, about 6.9% of the data points show that the WR is within a depth of 1 m from the ground surface and mostly identified in the western part of the study area. About 15.5% of data points show that WR depth varies from 1.1 m to 5.0 m, situated on the central and western parts of the study area. About 44.8% of data points show that the depth of WR varies from 5.1 m to 10 m, which covers the major part of the study area. About 28.4% of data points show that WR depth varies from 10.1 m to 15 m, covering the eastern part of the study area. About 8.9% of data points show that the depth of WR varies from 15.1 m to 20 m, identified at two locations, one in the northern part of the study area and another in the southern part of the study area. In general, the study area has a wide variation in weathered rock levels. A similar approach is also used to evaluate the top level of the engineering rock surface. The data from 42 locations have been used to determine the top level of the engineering rock. The surface level of the engineering rock for the study area is shown in Figure 6. The depth of the engineering rock varies from 1 m to about 50 m in the study area. In the western part of the study area, the engineering rock depth is less than 10 m, with data coverage of 9.5%. Similarly in the eastern part of the study area the engineering rock depth varies from 10 m to 20 m with data coverage of

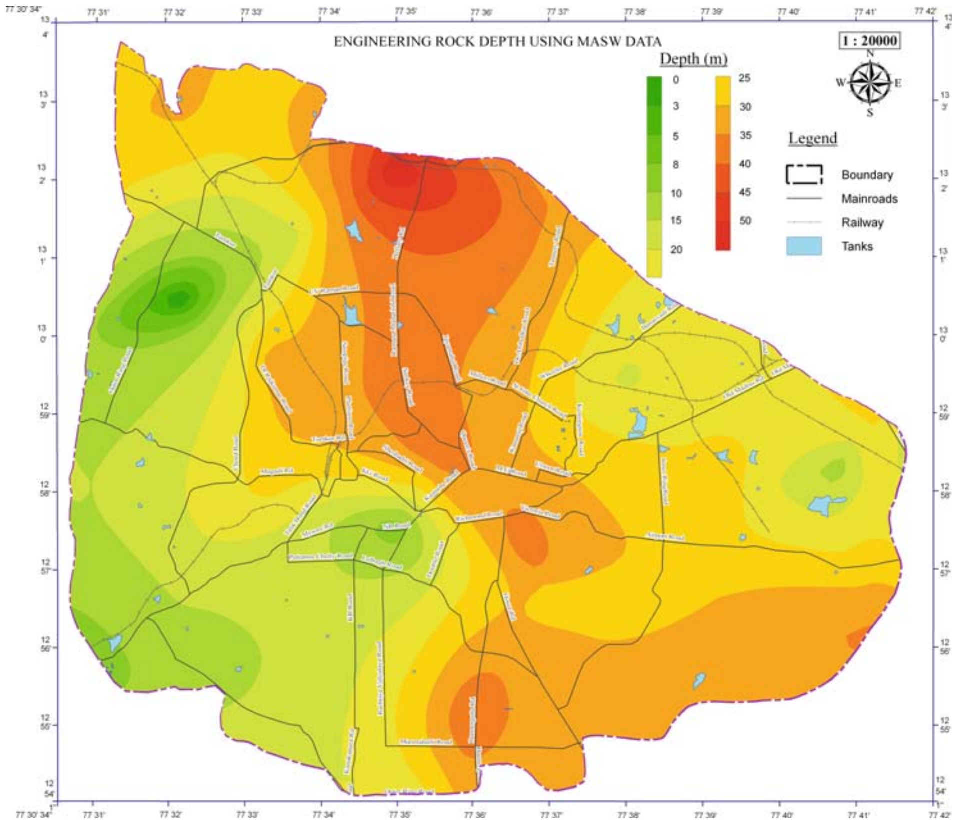

Figure 6
Engineering rock surface in the study area using MASW.

23.8%. About 66.7% of the data shows that in the central part of the study area the depth varies from 20 m to about 50 m from south to north. In the western part of the study area, the engineering rock is found at shallow depth. In the eastern part of the study area, the engineering rock is at moderate depth. In the central part of the study area, the engineering rock is available at deeper depths varying from south to north.

6. Depth of Rock Surface Using Two-Dimensional "Vs" Profiling

In this study a two-dimensional MASW survey has been carried out to crosscheck the rock depth maps (Figs. 5 and 6) generated using one-dimensional shear-wave velocity profiles. To get the 2-D shear-wave velocity profiles, a multiple number of shot gathers have been acquired in a consecutive manner along the survey line by moving both source and receiver spread simultaneously by a fixed amount of distance after each shot. Each shot gather is then analyzed for 1-D Vs profile in a manner previously stated. In this way a multiple number of Vs profiles are generated. The Vs data are assigned into 2-D (x-z) grid, various types of data processing techniques can be applied to get 2-D Vs. A countering, a simple interpolation, data smoothing, or a combination of these are applied at this stage. When the Vs data are assigned to the grid, there is ambiguity in the horizontal coordinate (x) to be assigned because each Vs profile was obtained from a shot gather that spanned a distance too large to be considered as a single point. The 2-D velocity profile has been used to find the layer thickness, subsurface layering information and rock-dipping directions. In this study about 20 two-dimensional surveys have been carried out to find shear-wave velocity distributions of the subsurface materials. Based on the shear-wave velocity values, the weathered and engineering rock surfaces have been interpreted. Typical 2-D shear-wave velocity profiles obtained from MASW are shown in Figure 7 for the southern side (location 12 in Fig. 1). Rock depths have been evaluated based on the ground surface level. Figure 7 shows that the depth of weathered rock found at about 7 m corresponding to a 12-m vertical line varies in the middle and the last 5 m on the right side (at 38 m line). Similar variations have also been seen in Figure 5. Engineering rock depth for location 12 varies from 17 m to 20 m in the 2-D Vs profile shown in Figure 7, which also match well with the engineering rock depth presented in Figure 6 based on 1-D survey. 2-D Vs profiles in the central part of the study area (location 27, in Fig. 1) show that the weathered rock depth varies from 7.5 m to 10.5 m for 12 m length (see Fig. 8), which matches well with the depth of weathered rock depth using 1-D Vs profiles shown in Figure 5. At this particular location, 2-D Vs profiles only show the maximum shear-wave velocity of 470 m/s, hence engineering rock depth is not recorded. Figure 9 shows the 2-D Vs profiling for the southwestern side of the study area (location 54 in Fig. 1), from this figure it is clear that the depth of weathered rock varies form 18 m and above, and it matches well with the depth based on 1-D Vs profiles as

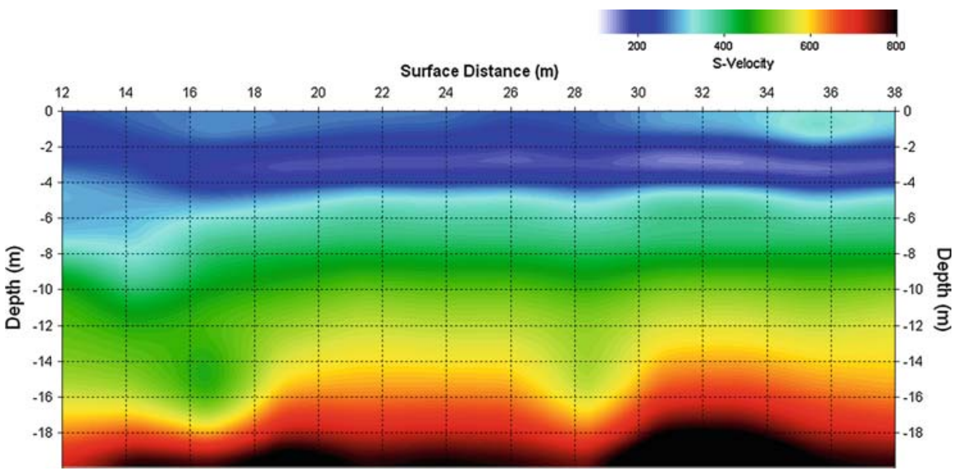

Figure 7
Rock depth using 2-D MASW Vs profiling for location 12.

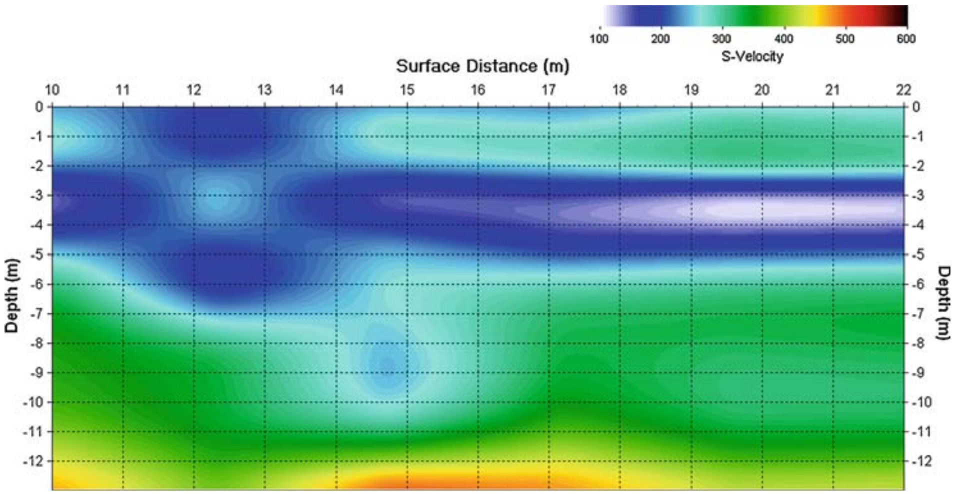

Figure 8
Rock depth using 2-D MASW Vs profiling for location 27.

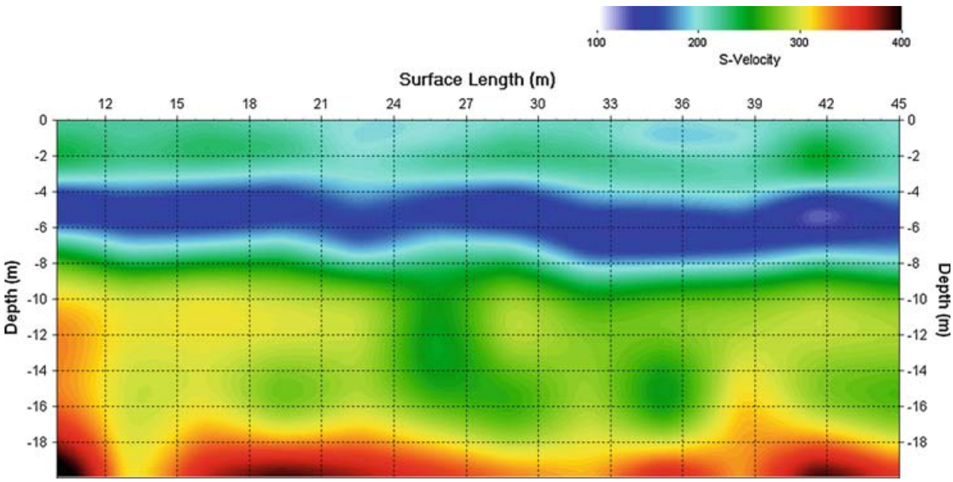

Figure 9
Rock depth using 2-D MASW Vs profiling for location 54.

shown in Figure 5. In general, the depths of weathered rock and engineering rock mapped using 1-D shear-wave velocity profiles match well with the 2-D shear-wave velocity subsurface profiles.

7. *Comparison with Borehole Data*

Rock depth obtained using MASW data has also been compared with the drilled boreholes where in standard penetration test "N" values are also available. The data

BORE LOG-1

BH No BH-1
Ground Water Table Not Encounted

Date of commencement 17.2.03
Date of completion 19.2.03

Depth Below GL(m)	Soil Description	Tickness of layer	Legend	soil classification	Samples Type	Depth (m)	SPT N values
0							
1	Reddish very dense silty sand with clay			SM	SPT	1.5	N=60
2.0					UDS*	2.5	
						3	N=48
4.0							
4.5		4.5			SPT	4.5	N=61
5.0	Greyish/brownish very dense silty sand			SM			
						6	N=102
6.0		1.5			SPT		
7.0	soft rock comprising of Brownish/Greyish/Whitish very dense silty sand having N value>100			SM		7.5	Rebound
7.5		1.5			SPT	8	
8.0							
9.0	Weathered rock 7.5to9.0m CR-47.3%,RQD-24%				SPT	9.5	Rebound
10.0	9.0to10.5m CR-29.33%,RQD-16.67%				SPT		
						11	Rebound
11.0					SPT		
12.0	10.5to12.0m CR-19%,RQD-14.33%						
					SPT	12.5	Rebound
15.0	Weathered rock 15.0to16.5m				SPT	15.5	Rebound
16.0							
					SPT	16.5	Rebound
		9					
17.0	Soft Hard rock				SPT	17	
					SPT	18	Rebound
18							
					SPT	19.5	Rebound
20.0							
21.0					SPT	21	Rebound
27.0					SPT	27	Rebound
27.5							
					SPT	28.5	Rebound
29.0							
30.0		12.5			SPT	30	Rebound

Note
Bore hole Terminated at 30.0m
CR-Core Recovery
RQD-Rock Quality Designation

SPT-Standard Penetration Test
UDS- Undisturbed Sample
GL- Ground level

Figure 10
Typical borelog BH-1 in the northern part of the study area.

BORE LOG-2

BH No BH-2
Ground Water Table Not Encounted

Date of commencement 4.2.03
Date of completion 6.2.03

Depth Below GL(m)	Soil Description	Tickness of layer	Legend	soil classification	Samples Type	Depth (m)	SPT N values
0	Brownish/Greyish loose to medium dense silty sand with clay						
1.5					SPT	1.5	N=6
				SM	UDS*	2.5	
3.0							
4.0		4			SPT	4	N=17
	Brownish/Whitish dense to vense silty sand				UDS*	5	
6.0					SPT	6.5	N=52
				SM			
7.0					SPT	8	N=39
8.0							
9.0							
9.5		5.5					
	soft rock comprising of Brownish/Greyish/Whitish very dense silty sand having N value>100				SPT	9.5	Rebound
11.0					SPT	10.5	Rebound
		3			SPT	12.5	Rebound
12.5	Weathered rock 12.5 to 14.0m CR-16%,RQD-14%				SPT	15.5	Rebound
15.0	15.5 to 17.0m CR-26%,RQD-NIL				SPT	18.5	Rebound
18	17.0 to 18.5m CR-26%,RQD-NIL						
	20.0 to 21.5m CR-96%,RQD-67%				SPT	21.5	Rebound
21	21.5 to 23.0 CR-28.6%,RQD-21.33%						
23.0		10.5					
24.0	Hard rock 23.0 to 24.5m CR-89%,RQD-72%				SPT	23	Rebound
25.0	24.5 to 26.0m CR-88%,RQD-88%						
26.0		3					

Note
Bore hole Terminated at 26.0m
CR-Core Recovery
RQD-Rock Quality Designation

SPT-Standard Penetration Test
UDS- Undisturbed Sample
GL- Ground level

◄

Figure 11
Typical borelog in the central part of the study area.

BORE LOG-3

BH No BH-3
Ground Water Table Not Encounted

Date of commencement 12.2.03
Date of completion 16.2.03

Depth Below GL(m)	Soil Description	Tickness of layer	Legend	soil classification	Samples Type	Depth (m)	SPT N values
0.0							
					SPT	1.5	N=15
1.0							
					UDS*	2.5	
2.0							
					SPT	3	N=40
4.0					UDS*	4	
	Filled up soil						
	consisting of stone pieces				SPT	4.5	N=50
6.0	with traces of organic matter						
					SPT	6	
		7.5			SPT	7.5	N=75
7.5	Weathered rock						
	7.5 to 8.0m						
9.5	CR-44%,RQD-NIL					9.5	Rebound
	8.0 to 9.5m						
11.0	CR-76%,RQD-NIL				SPT	11	Rebound
	9.5 to 11.0m						
	CR-23.3%,RQD-NIL						
					SPT	14	Rebound
12.0	11 to 12.0m						
	CR-27%,RQD-NIL						
13.0					SPT	15.5	Rebound
15.0	13.5 to 15.0m						
	CR-33.6%,RQD-NIL						
	15.5 to 17.0m				SPT	17.5	Rebound
17.0	CR65%,RQD-13%						
18.0		10.5					
					SPT	19	Rebound
	Hard rock						
19.0	18 to 19.5m						
	CR71%,RQD-47%						
					SPT	20.5	Rebound
20.0	19.5 to 21m						
	CR80%,RQD-45%						
21.0							
		3					

Note
Bore hole Terminated at 26.0m
CR-Core Recovery
RQD-Rock Quality Designation

SPT-Standard Penetration Test
UDS- Undisturbed Sample
GL- Ground level

Figure 12
Typical borelog in the western part of the study area.

presented in the 3-D subsurface model by the authors (SITHARAM *et al.*, 2007) have been compared with the present MASW survey data and they compare reasonably well. To present the comparison, five boreholes drilled up to hard rock are selected from the data base. These borehole locations (BH-1, BH-2, BH-3, BH-4 and BH-5) are marked in Figure 1. Typical borehole information (borelog) selected from the northern part of study

BORE LOG-4

BH No BH-4
Ground Water Table Not Encounted

Date of commencement 8.2.03
Date of completion 14.2.03

Depth Below GL(m)	Soil Description	Tickness of layer	Legend	soil classification	Samples Type	Depth (m)	SPT N values
0	Reddish/Brownish silty sand with clay			SM			
1.5					SPT	1.5	N=11
					UDS*	2.5	
3.0		3			SPT	3	N= 26
4.0	Brownish medium dense to very dense silty sand			SM	UDS*	4	
					SPT	4.5	N=52
5.0							
6.0		3			SPT	6	Rebound
7.0	Weathered rock						
9.0	7.5 to 8.0m CR-58%,RQD-52%				SPT	9	Rebound
	8.0 to 9.5m CR-73%,RQD-34%						
10.0					SPT	10.5	Rebound
11.0	9.5 to 11.0m CR-62%,RQD-50%						
12.0	11.0 to 12.5m CR-72%,RQD-54.66%				SPT	13.5	Rebound
14.0	12.5 to 14.0m CR-60%,RQD-41%						
15.0	14.0 to 15.5m CR-NIL,RQD-NIL				SPT	16.5	Rebound
17.0	15.5to17.0m CR15%,RQD-NIL	11					
	Hard rock				SPT	18	Rebound
18.0	17.0 to 18.5m CR-61.33%, RQD-48%						
					SPT		
20	18.5 to 20.0m CR-76%,RQD-52%	3					

Note
Bore hole Terminated :at 26.0m
CR-Core Recovery
RQD-Rock Quality Designation

SPT-Standard Penetration Test
UDS- Undisturbed Sample
GL- Ground level

Figure 13
Typical borelog in the southern part of the study area.

area (BH-1) is shown in Figure 10. Figure 10 shows that the weathered rock has been identified at a depth of 7.5 m from the ground surface, which matches well with Figure 5, where weathered rock depth varies from 5 m to 8 m. In this borehole hard rock strata starts at a depth of 16.5 m, which also compares very well with the depth of engineering rock (which varies from 15 m to 20 m using MASW survey). The second borelog (BH-2) is selected in the central part of the study area and it is shown in Figure 11. This borelog shows the weathered rock at two depths, one at a depth of 9.5 m designated as soft rock having SPT "N" of more that 100 and another at a depth of 12.5 m identified as weathered rock. At this location the weathered rock depth varies from 8 m to 10 m using the MASW survey (Fig. 5). In this location, the depth of engineering rock has been mapped at about 25 m to 30 m. Borehole shows that the hard rock is at a depth of 23 m

BORE LOG-5

BH No BH-5 Date of commencement 21.11.2005
Ground Water Table 1.4m Date of completion 22.11.2005

Depth Below GL(m)	Soil Description	Thickness of Strata (m)	Legend	Details of Sampling Type	Details of Sampling Depth (m)	SPT N Value
0.0 2.0	Filled Up Soil	2		SPT	1.5	N=8
3.0 4.5	Reddish Clayey sand	2.5		UDS SPT UDS	3.0 3.5 4.5	 N=29
6.0	Yellowish Sandy Silt	1.5		SPT	5.0	N=23
7.0 12.0 14.0 16.5	Greyish/ Yellowish Silty sand with mica	10.5		UDS SPT SPT SPT SPT	6.0 6.5 7.5 9 10.5	 N=52 N=52 N=109 75R for 5cm Penetration
17.0	Weathered Rock 16.5m to 17m CR=15%,RQD=Nil	0.5		SPT	12* and Below	75R for no Penetration

Bore hole Terminated at 17m
* Sample not retrived
CR-Core Recovery
RQD-Rock Quality Designation

Note
SPT Standard Penetration Test
UDS Undisturbed Sample
R Rebound

Figure 14
Typical borelog in the eastern part of the study area.

from the ground surface. A typical borelog for the western part of the study area is shown in Figure 12 (BH-3). This area has the weathered rock at shallower depth. The borelog shows that up to a depth of 7.5 m, if filled up with materials and followed by weathered rock. This matches well with the weathered rock depth of 6 to 8 m based on the MASW survey. Engineering rock has been identified at a depth of 18 m in the borehole and 15 to 20 m in the MASW survey. BH-4 is selected from the southern part of the study area and it is shown in Figure 13. This borelog shows that weathered rock starts at 6 m corresponding to a depth of weathered rock (6 to 8 m) using MASW (Fig. 5). From Figure 6, the depth of engineering rock varies from 15 to 20 m using MASW and the borelog shows the hard rock at 17 m. A typical borelog (BH-5) from the eastern part of the study area shows that depth of weathered rock at 16.5 m from the ground surface (Fig. 14), which is matches well with Figure 5. This borehole was terminated at a depth of 17 m and thus the depth of hard rock is not presented in the borelog. MASW study shows that the depth of engineering rock in this particular location varies from 25 to 30 m. These comparisons show that the depth of weathered and engineering rock mapped using the MASW survey compares very well with the borehole data. Thus, MASW is an ideal tool for mapping the rock depth for large areas, as this is a non-destructive method and a quick and cost-effective technique.

8. *Conclusions*

In this study an attempt has been made to map the depth of weathered rock and engineering rock by carrying out detailed field shallow geophysical surveys. A multichannel analysis of surface waves system has been used with a geode seismograph along with 24 vertical geophones of 4.5 Hz. 58 one-dimensional and 20 two-dimensional MASW surveys have been carried out in an area of 220 km^2. The criteria of shear-wave velocity of 330 ± 30 m/s for weathered rock and 760 ± 60 m/s for engineering bed rock have been used. The weathered rock depths are obtained from 58 locations and engineering rock depths are obtained from 42 locations. These depths are compiled and presented in the form of map for the study area using ArcGIS 9.2. The mapped depths of weathered and engineering rock have also been cross-checked using 2-D subsurface Vs profiling and these results matched very well. The depth of weathered rock varies from 1 m to 20 m in the study area. In general, the weathered rock has been found on the western side of the study area at shallow depths (within 5 m), on the central part at deeper depths (about 20 m) and on the eastern part at moderate depths (5 m to 15 m). A similar pattern is also identified for engineering rock depths, which varies from ground surface to about 50 m. On the western side of the study area engineering rock depth is present at shallow depths (within 15 m), on the central part, at deeper depth (about 50 m) and on the eastern part at moderate depths (15 to 35 m). Rock depth obtained from MASW compares very well with depth obtained from boreholes drilled for geotechnical investigations. The comparison shows that the rock depths obtained from MASW matches well with the borelog data. The MASW survey can be used effectively to map weathered rock and engineering rock depths, which are very important for geotechnical applications, site response and microzonation studies.

References

Ivanov, J., Park, C.B., Miller, R.D., and Xia, J. (2005), Analyzing and filtering surface-wave energy by muting shot gathers, J. Environm. Engin. Geophys. ***10***(3), 307–321.

Kanli, A.I., Tildy, P., Pronay, Z., Pinar, A., and Hemann, L. (2006), *Vs^{30} mapping and soil classification for seismic site effect evaluation in Dinar region, SW Turkey,* Geophys. J. Int. ***165*,** 223–235..

Miller, R.D., Xia, J., Park, C.B., and Ivanov, J. (1999a), *Using MASW to map bedrock in Olathe, Kansas* [Exp. Abs.], Soc. Explor. Geophys. ***1*,** 433–436.

Miller, R.D., Xia, J., Park, C.B., and Ivanov, J. (1999b), *Multichannel analysis of surface waves to map bedrock,* The Leading Edge ***18***(12), 1392–1396.

Nath, S.K. (2007), *Seismic microzonation framework — principles and applications,* Proc. Workshop on *Microzonation, Indian Institute of Science*, Bangalore, 26 – 27 June 2007, India, pp. 9–35.

Park, C.B., Miller, R.D., and Xia, J. (1999), *Multi-channel analysis of surface waves,* Geophys. ***64***(3), 800–808.

Park, C.B., Ivanov, J., Miller, R.D., Xia, J., and Ryden, N. (2001), *Seismic investigation of pavements by MASW method—geophones approach,* Proc. SAGEEP 2001, Denver, Colorado, RBA-6.

Park, C.B., Miller, R.D., and Miura, H. (2002), *Optimum field parameters of an MASW survey* [Exp. Abs.]. SEG-J, Tokyo, 17–18 May 2002, 22–23.

Park, C.B., Miller, R.D., Xia. J., and Ivanov, J. (2005), *Multichannel seismic surface-wave methods for geotechnical applications* [online]. Available from http://www.kgs.ku.edu/Geophysics2/Pubs/Pubs PAR-00-03.pdf [accessed 10 October, 2006].

Ryden, N. (2004), *Surface Wave Testing of Pavements*. Doctoral Thesis, Departments of Engineering Geology, Lund Institute of Technology, Lund University.

Santamarina, J.C., Klein, K.A., and Fam, M.A., *Soil and Waves* (John Wiley& Sons, Inc., New York (2001)).

Sitharam, T.G., Anbazhagan. P., and Mahesh. G.U. (2007), *3-D subsurface modelling and preliminary liquefaction hazard mapping of bangalore city using SPT data and GIS*, Indian Geotech. J. ***37***(3), 210–226.

Xia, J., Miller, R.D., and Park, C.B. (1999), *Estimation of near-surface shear-wave velocity by inversion of Rayleigh wave,* Geophys. ***64***(3), 691–700.

Xu, Y., Xia, J., and Miller, R.D. (2006), *Quantitative estimation of minimum offset for multichannel surface-wave survey with actively exciting source,* J. Appl. Geophys. ***59***(2), 117–125.

Zhang, S.X., Chan, L.S., and Xia, J. (2004), *The selection of field acquisition parameters for dispersion images from multichannel surface wave data,* Pure Appl. Geophys. ***161***, 185–201.

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