DELINEATION OF UNCERTAINTIES IN ANISOTROPIC SHALLOW SUBSURFACE BY INTEGRATED GEOPHYSICAL AND GEOMECHANICAL EXAMINATION

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ABSTRACT: This study focused on geophysical and geomechanical analyses to arbitrate weak zones in Limestone of Gaj formation. Two boreholes were drilled and used to facilitate downhole seismic experiment down to 30 meters of depth. The downhole seismic method was supplied compressional waves velocities for inspection of shallow subsurface properties to evaluate local site condition. The primary data of P-waves velocities are varying from 566 m/s to 1225 m/s (BH-1) 570 m/s to 1320 m/s (BH-2). The information of elastic moduli were derived from primary waves data through empirical relationships. The core samples were collected and examined for geotechnical investigation in the laboratory. This study contributes to ensure the engineering strength of the ground and concluded that the ignorance of substrate conditions may lead to instability or construction failure.

Keywords: Downhole seismic, shallow subsurface, foundation surveying, Karachi.

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INTRODUCTION

Downhole seismic (DHS) is a one-dimensional vertical seismic profiling method deployed to study ground response by compressional waves in near-surface strata (Balia and Manca, 2018; Allo *et al*., 2019). The DHS is effectively used in civil engineering projects to delineate the engineering parameters like densities of rock layers, lithological composition, compressive strength, weathered and un-weathered ground layers, angle of dipping in shallow subsurface, fractures, weak zones, displacements, interbedded slit/clay (Du and Pan, 2016; Dammal and Krishna, 2019). The compressional and shear waves velocity is sensitive to the geological conditions which are significant for evaluating seismic site response (Kolawole *et al*., 2012; Foti *et al*., 2017) modelling heterogeneities, mapping low velocity layer (LVL) associated with clay, sand and gravels (Uko *et al*., 2012; Kolawole *et al*., 2012; Kar and Berenjian, 2013; Garofalo *et al*., 2016). The raw data of DHS is compressional waves travelling from source on the surface to the geophones in the borehole (Ayolabi *et al*., 2009; Chiemeke and Aboh, 2012) (Schematic diagram in fig. 1). A hammer is used as seismic source, powerfully hit on iron plate which generates elastic waves. The triaxial 3D geophones lowered down in boreholes which are sensitive to receive seismic signals with frequencies (60-600 Hz). Seismic waves are not dispersive and scattered rather propagate in a vertical or horizontal plane. P-waves are moving vertically, they are also called as compressional waves, and horizontal movement of the rock particles co-existence to the vertically propagating (P-waves) is called S-waves (shear waves). First arrival can be easily pick from top to bottom rather than picking trough of each trace at different interval, picking of seismic waves in BH-1 & BH-2 shown in fig 1b and 1c.

Civil engineers have concerns about soil behavior for foundation of buildings. The construction of mega structure is technical and risky project that demands careful study to ensure sustainable ground and failure protected construction structure. Identification of low velocity zones coupled with geomechanical/geotechnical examination of respective core samples envisioned to map stable building ground. The elastic parameters (bulk modulus, shear modulus, poisson ratio, etc) derived from body waves velocities which contributed in foundation designing (Régnier *et al*., 2016; Tropeano *et al*., 2019) of buildings, bridges and roads. These moduli can infer multi-dimensional ground-parameters from composite of P and S-waves (if recorded separately). It is estimated that 70% of received signals are surface wave's signals which are mostly noises in shallow seismic surveys (Sun and Kim, 2017).

The purpose of this study is to investigate a specific site before construction of mega civil project in newly established housing city. The specific objectives are i) acquisition of geophysical and geotechnical data to find out engineering properties of the ground layers, ii) to know the contrast of elastic properties to inspect weak zones, fractures, and presence of water if encountered. Mostly fundamental objectives of the site are same but according to site situation, building type, construction type and ground behavior it varies. Different soils have different types of engineering properties so site specific investigations are needed (Butchibabu *et al*., 2019; Sitharam *et al*., 2018). The study area is nearby

Nooriabad in northeast outcrops of Karachi. The under-investigation site is selected for a mega commercial center, of newly developed town on Karachi-Hyderabad M-9 motorway. The Gaj formation of Miocene age dominantly exposed in the structural highs in and around Karachi. The younger units (Drigh clay-variegated clay and Talawa Limestone - fossiliferous limestone) stratified in exposed strata adjacent to site.

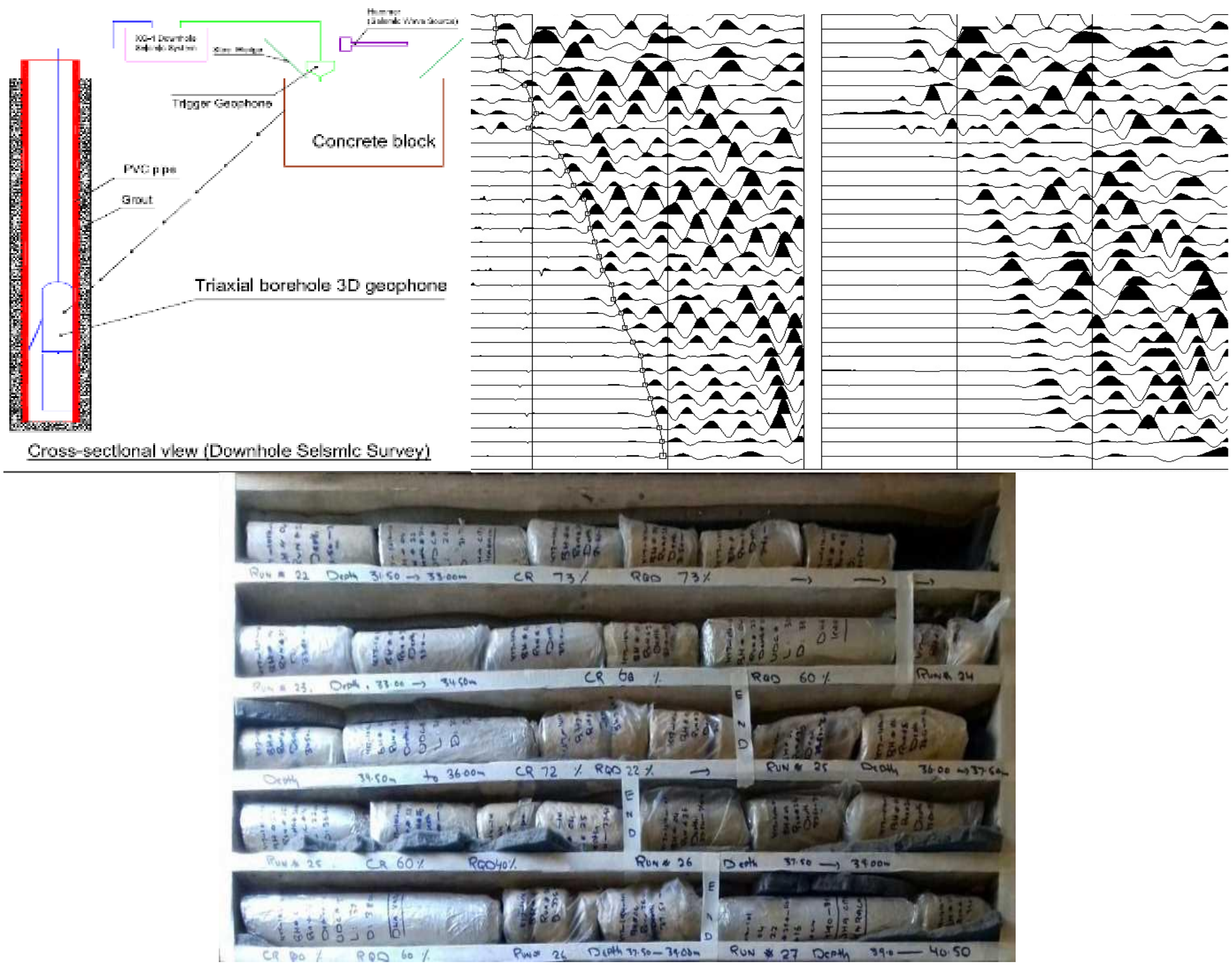

Figure-1. A) Schematic diagram of downhole seismic acquisition B) Seismic wave picking from BH-1 c) Seismic wave picking from BH-2 D) Core samples from specific depth in boreholes.

MATERIALS AND METHODS

The geophysical data (downhole seismic tests) were performed in boreholes with X-GI seismograph system coupled with 3D geophone sensors. We have utilized the primary dataset of DHS experiments which provide compressional waves velocities i.e. V_P in respective boreholes (BH-1 and BH-2). The seismic data (primary waves data) were recorded at every 1 m interval (up to 30m depth) in the both wells. Acquired data run at wave velocity logging system software for processing and interpreting results. Vp further used to derive the shear waves velocity and other elastic parameters and their combinations to estimate the engineering properties at high resolution.

The primary and the shear wave velocities were used to determine the densities and the elastic modules for each layer delineated in the study area using following equations.

$$Vp = Vs*1.9 \quad (1)$$

From which we can also determine the remaining acoustic parameter. That is, the density by using equation

$$\rho = 0.31 * VP^{.25} \quad (2)$$

The bulk modulus can be calculated using equation

$$K = \frac{3\lambda+2\lambda}{3} \quad (3)$$

The shear modulus can also be obtained by using equation

$$\mu = \boldsymbol{E} \,/\, (\mathbf{2}(\mathbf{1}+\boldsymbol{\sigma})) \quad (4)$$

Also, other geotechnical parameters can be calculated, such as the Poisson's ratio,

$$\sigma = \mathbf{1 / 2\ [1 - \{1 / (Vp / Vs)^2 - 1)\}]} \quad (5)$$

Lames constant can be calculated by;

$$\lambda = \{\boldsymbol{\sigma E / (1+\sigma)(1-2\sigma)}\} \quad (6)$$

The Young's modulus can also be obtained using equation

$$E = \rho(\mathbf{3Vp^2 - 4Vs^2) / (\frac{Vp^2}{Vs^2}) - 1}) \quad (7)$$

Concentration index and stress ratio can be found by using equations

$$Ci = \mathbf{1 + \sigma / \sigma} \quad (8)$$

$$Si = \frac{\sigma}{1-\sigma} \quad (9)$$

The straight rotary drilling procedure was carried out at specific sites for sample collection. Later the drilling log is maintained to identify the rock type and characteristics as field observations. The coring samples of subsurface formations were collected at every 1.5 m interval (in 30 m depth of the wells). The cores were examined by geotechnical methods to validate the engineering properties. The unconfined compressive strength and density of samples were determined in the laboratory. The unconfined compressive strength test was carried out in accordance with ASTM D 7012.Unconfined compressive strength test involves uniaxial loading of cylindrical core sample with lateral force on the sample is zero.

RESULTS

The primary waves velocity (Vp) increases non-linearly with depth of the bore holes suggesting that the variation in composition and burial pressure, of lithological layers . Vp in BH-1 is ranging from 566 m/s to1214 m/s and estimated shear wave velocity (Vs) in the respective depth is ranging from 297.894 m/s to 638.947 m/s. Whereas, Vp in BH-2 is ranging from 570 m/s to 1320 m/s and Vs is ranging from 300 m/s to 694.736 m/s. The velocity gradient (rate of change in velocity per meter depth) in BH-1 is 21.6 m/sec and for Vs is 11.36 m/sec. The highest Vp may be indicating highly compacted/cemented Limestone. The least Vp indicating the loose interbedded lithology clay/shale or less cementation. The unusual decrease in Vp is interpreted as a week zone may be a cavit or fracture. . The estimated shear wave velocity (Vs) increases linearly in the respective depth of BH-1 ranging from 297.894 m/s to 638.947 m/s whereas, Vs is ranging from 300 m/s to 694.736 m/s in BH-2. The rock physics parameters such as density, bulk modulus, shear modulus, lame's constant, poisson's ratio, young`s modulus, concentration index and stress ratio are derived from Vp data which provide substantial information of strain under applied stresses , stiffness or compactness, and weak zones at places. Concentration Index of BH-1 and BH-2 is 4.2422 which is interpreted as subsurface is moderately compacted within 30 meters (down to the depth of well).

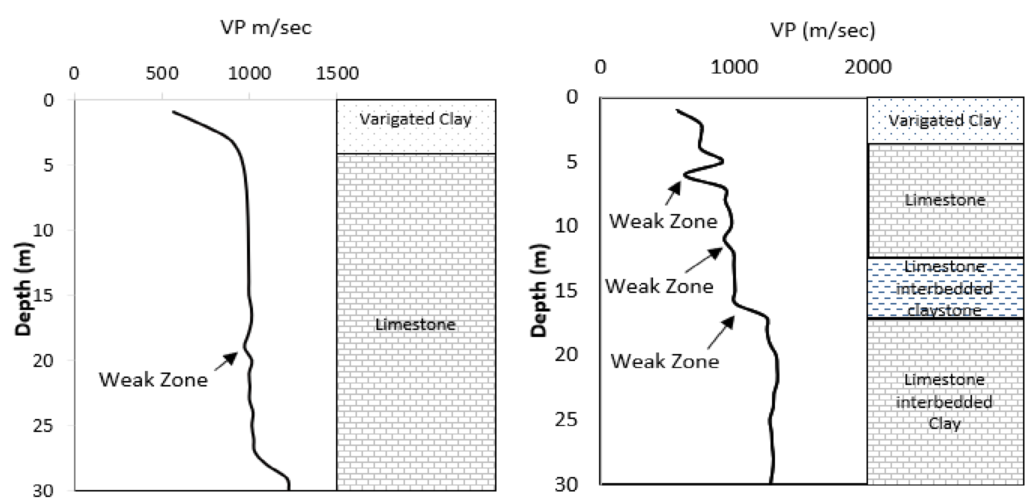

Figure-2. The Downhole seismic record a) The profile of V_P recoded in BH-1 b) The profile of Vp record in BH-2. The lithology column is placed

The velocities changing laterally and vertically down the borehole suggesting the variation in velocities within the study area. The derived densities from BH-1 is ranging from 1.512 gm/cc to 1.834 g/c^3 and in BH-2 is ranging from 1.515 g/c^3 to 1.869 g/c^3, respectively. Although, a linear relationship was observed between the density and the velocity as derived from indirect method. However, point density examination in geotechnical investigations helped us to delineate the the weak zones at depths (18 and 19 meters in BH-1) and (6, 7, 11, 23 and 30 meters in BH-2). The elastic modulus such as Young's modulus (E) determined from the combination of Vp, Vs and ρ. It is observed that the E increases with the depth, 351.133 KPa and 1994.991 KPa for the BH-1 and (Table-1). in BH-2 it ranges between 356.741 KPa and 2360.076 KPa (Table-2).. Both bore holes reveal that some changes in e bulk modulus (B) which defines the volumetric changes under stresses. The variation of B ranges between 737.54 to 4190.44 KPa in BH-1 (Table-1) whereas, B ranges between 749.329 KPa to 4957.300 KPa in BH-2, which implies that in higher B values Limestone will not undergo volumetric changes The shear modulus express that the estimated values varies from 134.181 KPa at the top to 762.361 KPa at base of the borehole-1 (Table-1) and for BH-2 136.324 KPa to 901.874 KPa (Table-2), respectively. The shear modulus is suggesting that less cemented zones are weaker then compacted stratums and these zones can be effected when further stresses applied on it. . Lame`s constant describes that the stiffness of material which ranges in BH-1 from 216.032 KPa – 1227.4.1 KPa (Table-1), and estimated from 219.482 KPa – 1452.017 KPa in BH-2 (Table-2).

Table-1 The results of derived parameters in DHS test at BH-1.

Sample Depth (m)	VP m/s	VS m/s	Density g/cm^3	Young's Modulus	Lame's Constant	Shear Modulus	Bulk Modulus
1	566	297.8947	1.512	351.133	216.032	134.181	737.549
2	734	386.3158	1.614	630.160	387.701	240.808	1323.640
3	878	462.1053	1.687	942.969	580.154	360.344	1980.690
4	937	493.1579	1.715	1091.563	671.575	417.127	2292.809
5	963	506.8421	1.727	1160.897	714.232	443.623	2438.445
6	976	513.6842	1.733	1196.456	736.110	457.211	2513.136
7	984	517.8947	1.736	1218.635	749.755	465.686	2559.722
8	988	520	1.738	1229.809	756.630	469.956	2583.194
9	991	521.5789	1.739	1238.227	761.809	473.173	2600.876
10	993	522.6316	1.740	1243.857	765.273	475.325	2612.701
11	994	523.1579	1.741	1246.677	767.008	476.402	2618.625
12	995	523.6842	1.741	1249.501	768.745	477.481	2624.556
13	996	524.2105	1.742	1252.328	770.484	478.562	2630.495
14	997	524.7368	1.742	1255.159	772.226	479.644	2636.441
15	997	524.7368	1.742	1255.159	772.226	479.644	2636.441
16	1011	532.1053	1.748	1295.164	796.839	494.931	2720.470
17	1012	532.6316	1.748	1298.048	798.613	496.033	2726.529
18	994	523.1579	1.741	1246.677	767.008	476.402	2618.625
19	972	511.5789	1.731	1185.451	729.339	453.006	2490.021
20	1014	533.6842	1.749	1303.827	802.169	498.241	2738.667
21	998	525.2632	1.742	1257.994	773.970	480.727	2642.394
22	1003	527.8947	1.745	1272.219	782.722	486.163	2672.274
23	1000	526.3158	1.743	1263.673	777.464	482.897	2654.324
24	1021	537.3684	1.752	1324.167	814.682	506.014	2781.390
25	1014	533.6842	1.749	1303.827	802.169	498.241	2738.667
26	1025	539.4737	1.754	1335.868	821.881	510.485	2805.967
27	1031	542.6316	1.757	1353.526	832.746	517.233	2843.059
28	1102	580	1.786	1572.328	967.362	600.846	3302.649
29	1214	638.9474	1.830	1954.910	1202.742	747.045	4106.255
30	1225	644.7368	1.834	1994.991	1227.401	762.361	4190.444

Table-2. The results of derived parameters in DHS test at BH-2.

Sample Depth (m)	VP m/s	VS m/s	Density g/cm^3	Young's Modulus	Lame's Constant	Shear Modulus	Bulk Modulus
1	570	300	1.515	356.741	219.482	136.324	749.329
2	744	391.5789	1.619	649.642	399.686	248.252	1364.561
3	750	394.7368	1.622	661.489	406.975	252.780	1389.446
4	749	394.2105	1.622	659.506	405.756	252.022	1385.281
5	908	477.8947	1.702	1017.016	625.711	388.640	2136.225
6	628	330.5263	1.552	443.653	272.954	169.537	931.887
7	921	484.7368	1.708	1050.071	646.048	401.272	2205.657

8	928	488.4211	1.711	1068.114	657.148	408.167	2243.556
9	968	509.4737	1.729	1174.503	722.603	448.822	2467.024
10	974	512.6316	1.732	1190.947	732.720	455.106	2501.564
11	921	484.7368	1.708	1050.071	646.048	401.272	2205.657
12	990	521.0526	1.739	1235.418	760.080	472.100	2594.974
13	993	522.6316	1.740	1243.857	765.273	475.325	2612.701
14	998	525.2632	1.742	1257.994	773.970	480.727	2642.394
15	1002	527.3684	1.744	1269.367	780.967	485.073	2666.283
16	1007	530	1.746	1283.663	789.763	490.536	2696.312
17	1231	647.8947	1.836	2017.044	1240.969	770.788	4236.766
18	1241	653.1579	1.840	2054.098	1263.767	784.948	4314.599
19	1259	662.6316	1.847	2121.742	1305.384	810.797	4456.683
20	1310	689.4737	1.865	2320.038	1427.384	886.574	4873.201
21	1318	693.6842	1.868	2352.038	1447.072	898.802	4940.417
22	1320	694.7368	1.869	2360.076	1452.017	901.874	4957.300
23	1294	681.0526	1.859	2256.767	1388.457	862.396	4740.302
24	1289	678.4211	1.857	2237.195	1376.415	854.916	4699.189
25	1263	664.7368	1.848	2136.940	1314.734	816.605	4488.605
26	1276	671.5789	1.853	2186.748	1345.378	835.639	4593.227
27	1280	673.6842	1.854	2202.202	1354.886	841.544	4625.688
28	1290	678.9474	1.858	2241.102	1378.819	856.409	4707.396
29	1283	675.2632	1.855	2213.832	1362.042	845.989	4650.117
30	1268	667.3684	1.850	2156.021	1326.474	823.897	4528.686

The compressive strength and density of core samples were determined in BH-1 is ranging from 13.03 KPa – 166.1 KPa and in BH-2 ranges from 22.63KPa – 132.79KPa. In all bore holes it is observed that change in compactness is varying depth to depth (Table-3). At some points it shows some harder strata and while at some points it shows some less compacted core samples or weak behavior. It is also observed that these changes are not continuous either vertically or horizontally. In geophysical investigation (rock physics) it is observed that some change in density found in the BH-2 (Cavity-fracture zones) which is consistent to geotechnical examination of the samples.

Table 3 Lab test of geotechnical properties of Core Samples, Tallawa Limestone, Gaj Formation.

Borehole ID	Core Sample	Core Sample Depth (m)	Compressive Strength KPa	Density (gm/cm^3)
1	1	1.60 - 1.76	13.03	1.59
	2	3.12 - 3.25	166.1	1.64
	3	9.14 - 9.50	14	1.99
	4	12.30 - 12.45	14.28	2.09
	5	15.90 - 16.15	108	2.24
	6	16.90 - 17.25	29.29	2.28
	7	24.91 - 25.09	13.53	2.4
2	1	6.20 - 6.70	44.72	1.71
	2	18.20 - 18.39	24.12	2.46
	3	21.35 - 21.60	87.35	2.42
	4	25.90 - 26.06	22.63	2.56
	5	27.25 - 27.39	132.79	2.6
3	1	14.40 - 14.90	15.23	2.29
	2	17.10 - 17.50	15.83	2.38
	3	24.15 - 24.30	37.56	2.432
	4	29.23 - 29.46	96.46	2.472
4	1	13.70 - 13.84	202.61	2.12
	2	18.20 - 18.34	101.04	2.51
5	1	3.20 - 3.35	133.76	1.68
	2	23.20 - 23.32	47.64	2.58
	3	29.50 - 29.63	41.73	2.51

DISCUSSION

DHS is helpful for determining strength of subsurface; distinguishing weathered and unweathered layers; provide hint for rock fractures, clay lenses etc. The strata are found highly weathered near the surface often due to surface run-off. Some fractured zones are found cemented with clays at locations of bore hole 1 and 2. These cavities must not be overlooked and suggested to be well cemented to avoid any harm for construction.

We have observed that the bulk density is varying from point to point in the understudy wells (Fig. 3). The bed rock of limestone is unstable and exhume spatial changes in rock character, indicating uncertainty in cementation of strata, might be cavities due to some chemical dissolution. The field survey indicates some fissure and fractures exposed in surroundings of site. The extent of those openings are high angle dipping without any significant displacement (in x and y plan) may be the growing fault traces near the surface. We speculate these surface openings are analogs to anomalous zones which are categorized in this study as weak zones.

The core samples density is tested in laboratory which is termed as direct density. Density is proportional to the core compactness or stiffness. Denser the material higher the density. We observed among five bore holes that density is also varying from point to point. The compressive strength and density of core samples were determined in BH-1 is ranging from 13.03 KPa – 166.1 KPa and in BH-2 ranges from 22.63 KPa – 132.79 KPa. In all bore holes it is observed that change in compactness is varying depth to depth. At some points it shows some harder strata and while at some points it shows some less compacted core samples or weak behavior.

In geophysical investigation, it is observed that the change in rock-physics parameters are found consistent to geotechnical examination of the samples. It is also observed that these changes are not continuous either vertically or horizontally rather encountered at BH-1 and BH-2 (Fig. 3). Thus, the information supplied by DHS strengthened the geomechanical/geotechnical evaluation and recommended elsewhere for any development of civil engineering project.

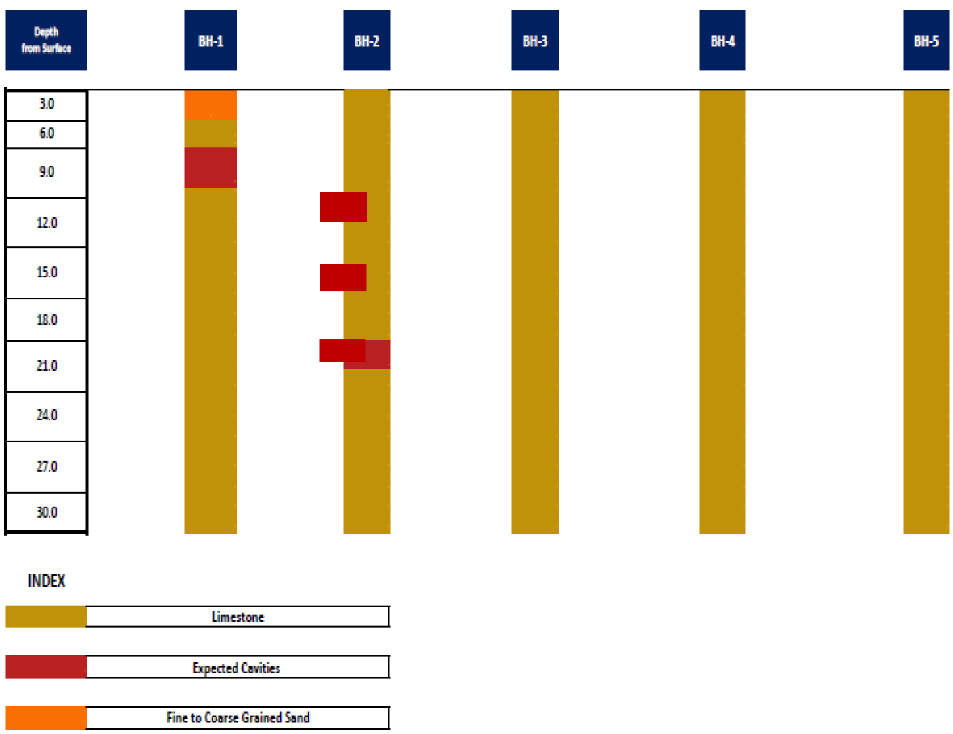

Fig. 3: Correlation of boreholes in the study area

Conclusion: This integrated study contributed to adopt the utilization of near surface geophysics in sustainable engineering construction projects. The interpretation of downhole seismic velocity data and cores analysis of geotechnical evaluation delineated weak zones in fossiliferous Limestone of Miocence age (Gaj formation). The changes in velocities and uniaxial compressive strength verses depth helped in identification of rock type, thickness of layers, inspection of weak zones. The anomalous weak zones might be cavities, high angle vertical fracture, loosely cemented with clays. These cavities are suggested to be well cemented or the limestone bed might be excavated to ensure foundation safety.

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