Original article

Assessment of land subsidence as an environmental threat facing Dammam city, eastern Saudi Arabia based on soil geotechnical parameters using downhole seismic approach

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ABSTRACT

To meet the increasing in population, urbanization and public transportation needs of Dammam big city a new transportation infrastructure network is planned and being developed. In the same time, environmental threats of land subsidence on network has been raised and needs to be addressed. Site characterization for designing this transportation lines is crucial to ensure reliable and economic substructure design, because weak site soil conditions may cause land subsidence problems. Downhole seismic (DS) testing is commonly used to determine compression wave (P) and shear wave (S) velocity profiles in geotechnical engineering, which are required in evaluating responses to shaking of geotechnical sites and structures. A DS survey was conducted through boreholes at the center of the Dammam metropolitan city, Saudi Arabia. A sledgehammer horizontally striking a wooden plate generated shear (S) waves polarized in the crossline and inline directions, whereas a vertical hammer hitting a metal plate generated the P wave. Data were obtained using Freedom Data PC, a downhole tool with a triaxle geophone package, and a seismograph. In the downhole technique, the geophones were equestrian on an internal rotating block, and a built-in fluxgate compass as well as servo motor system maintained the orientation of the geophones inside the borehole. The instrumentation and processes complied with the standard test methods for downhole seismic testing (Standard and D7400-08, 2008). This represents, a versatile platform for evaluating structures/infrastructures and geophysical seismic engineering surveys. The estimated seismic velocities were used in estimating the various elastic moduli and density variations within the mapped boreholes. The integrated approach of proper geotechnical characterization and 1D velocity profile proved to be a helpful tool for assessment of subsidence of Dammam city in the future which, in turn, will reduce the environmental threats facing the city.

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1. Introduction

There are several environment threats facing big cities in the future, such as Dammam city in the eastern province of Saudi Arabia, which is constantly exposed to recurring environmental problems that cause collapses in the topsoil and subsidence. These problems, in turn, cause stifling traffic congestion in light of the regular population increase in Dammam. Dammam city located along the coastal plain of the Arabian Gulf in the eastern Province of Saudi Arabia (Fig. 1). This city is one of the most crowded cities in Saudi Arabia, which leads to the occurrence of a lot of environmental threats, for example soil subsidence (which often occurs in coastal cities where the soft and weak soils, as sabkha sediments, are common). The problem of soil subsidence threatens important installations. Several cases of subsidence were recorded in the city all over the city and prevails in the city center where sabkha sediments are found with considerable thickness. Land subsidence threats cost the state hundreds of millions annually for treatment and remediation operations. Therefore, this study aims to calculate these properties nearby one of the big commercial centers in the city. This is will achieved from the calculated geotechnical

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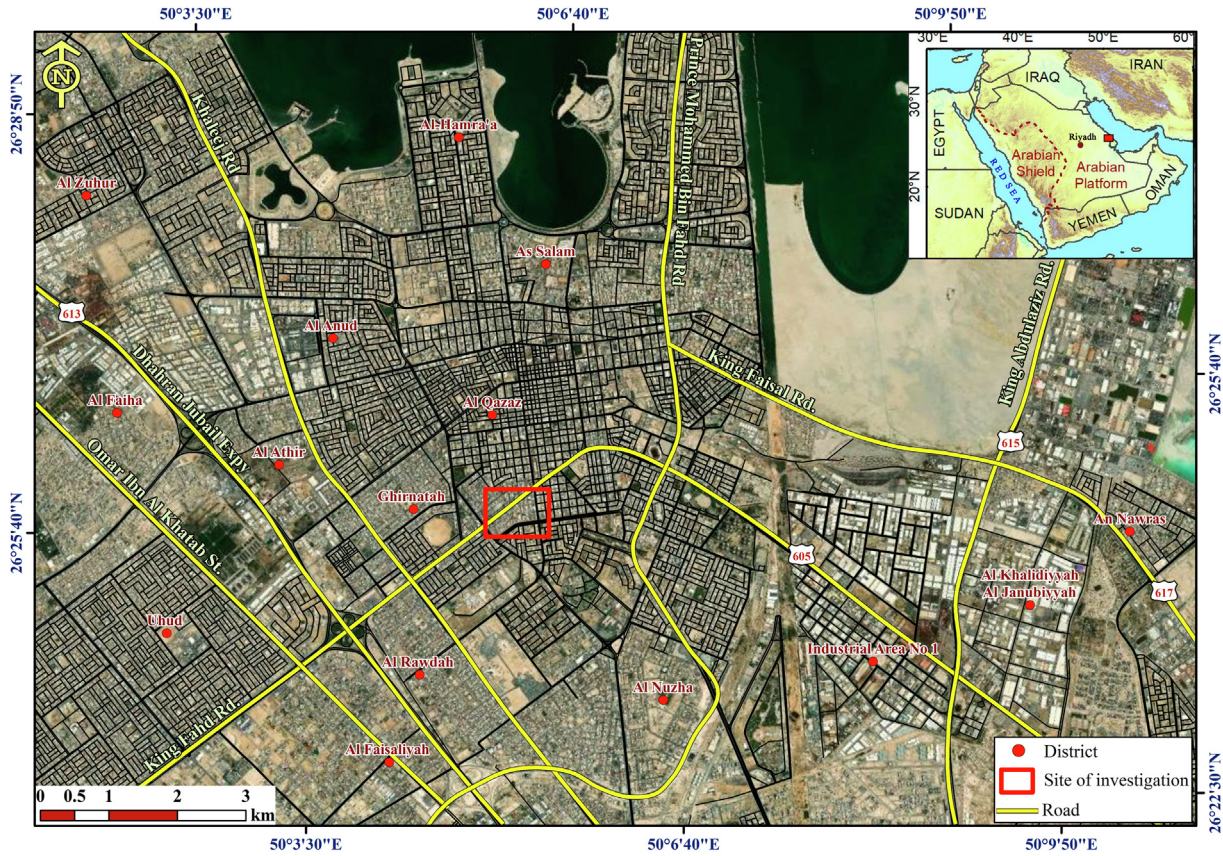Peer review under responsibility of King Saud University.

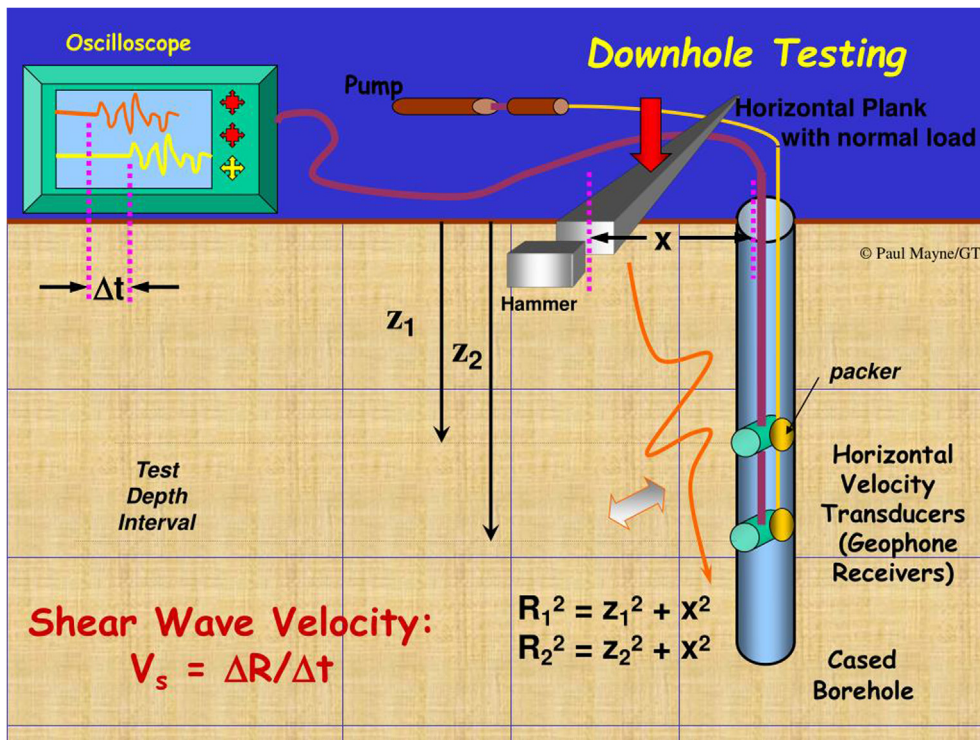**Fig. 1.** Location of the investigated site in Dammam City.

Fig. 2. Calculation of shear wave velocity by down hole seismic test. R1 = the distance from the source to top Geophone and R2 = the distance from the source to bottom Geophone (Modified after Enamul Haque et al., 2013).

properties of near-surface soil based on the P-and S- wave velocities using downhole seismic method which is one of the best seismic techniques.

In order to measure Vs with depth, various in-situ test methods were developed, such as downhole seismic (DS) approaches. DS is suitable for evaluating in-situ Vs profile due to the following reasons; First, it needs only one borehole and a simple surface source to achieve the test; hence, operating it in field testing is easy, and it is relatively cost-effective. Second, the travel times P-wave recorded by receivers placed at a series of testing depths within a single borehole. Third, Vs profile can be directly obtained using a simple interpretation procedure based on a velocity equation.

Dynamic soil properties are important information parameters in several types of civil engineering problems. Recently, problems related to ground conditions have been investigated by several authors, such as Stipho, 1984; Abd El Rahman, 1989; Abd El Rahman and Abd El Latif, 1990; Abd El Rahman et al., 1991, 1992, 1994; Kim et al., 2004. Moreover, Anbazhagan and Sitharam (2006) evaluated dynamic soil properties and ground profiles using the MASW method in Bangalore City; Fnais et al. (2010) assessed the soil properties in Yanbu city, Saudi Arabia; Roy and Bhalla (2017) examined the role of geotechnical soil properties on civil engineering structures; Ravi (2017) conducted intensive geotechnical investigations in difficult ground conditions in India; Yusof and Zabidi (2016) estimated the relationships between soil conditions and their geotechnical implications in Malaysia; kamal Abdelrahman et al. (2017a), Abdelrahman et al. (2017b), Abdelrahman et al., 2019 and Abdelrahman et al., 2020) evaluated the geotechnical properties of ground profiles in big cities Egypt and Saudi Arabia. Al humimidi M.S. (2020) assessed the near-surface deposits throughout Jizan City.

2. Methodology

2.1. Downhole seismic method

The downhole technique is a more economical technique where only one borehole is needed. In the downhole procedure, the instinct energy source is produced at the surface of ground close the top of the borehole, wherein one or several geophones are dropped at prearranged depths. Fig. 2 shows the schematics of the downhole test. Travel time of the body waves (P - and S - waves) between each geophone and the source are recorded (Standard and D7400-08, 2008; Mok and Stokoe, 1988). Then, the recorded travel time is plotted against depth as in the seismic refraction test. Finally, these plots are used to calculate P - and S-wave velocities (Vp and Vs) of the explored soil layers (SW-AJA, 1972; Woods, 1994; Gazetas, 1991).

In the seismic downhole, low velocity zones can be detected even if they are located between high velocity layers in case of geophone interval is nearby. The S-wave sources of seismic refraction can be used as well for the seismic downhole testing. Based on the depth of the investigated soil layers, the controlled seismic source varies from hand-generated sources to using large mechanical instrument. Additionally, in the seismic downhole test, the difficulty of picking up the first arrival of shear waves from the compression waves is resolved by reversing the polarity of the source that generated the wave pattern. The waveform is recorded twice using a horizontally oriented sledgehammer hitting a firmly fixed post that is struck in a direction parallel to the ground surface at first and then struck again in the opposite direction (180°). Reversing the course of the energy blow lets the shear waveform to be

Table 1
Empirical relationships used for estimation of near-surface soil geotechnical properties.

Parameter	Used equations	Reference
Poisson's Ratio	$\sigma = \frac{1}{2}\left(1 - \left\{\frac{1}{\left(\left(\frac{V_p}{V_s}\right)^2 - 1\right)}\right\}\right)$	Adams (1951)
Young's Modulus	$E = \rho\left[\frac{3V_p^2 - 4V_s^2}{\left(\frac{V_p}{V_s}\right)^2 - 1}\right]$	Adams (1951)
Bulk Modulus	$k = \frac{E}{3(1-2\sigma)}$	King (1966), Toksöz et al. (1976)
Shear Modulus	$\mu = \rho\,(V_s)^2$	King (1966), Toksöz et al. (1976)
Lame's constants	$\lambda = \frac{\sigma E}{((1+\sigma)(1-2\sigma))}$	King (1966), Toksöz et al. (1976)
Constrained modulus	$M = \rho * (V_p)^2$	IS: 5249-1992

Where, Vp and Vs are P-and S-waves velocities respectively.
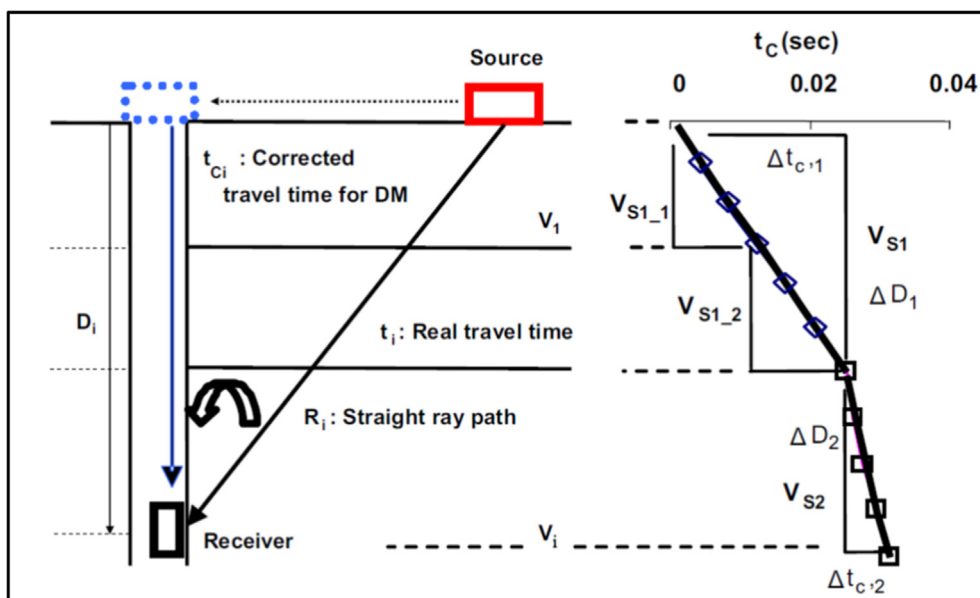

Fig. 3. Direct method concept (modified after Bang et al., 2014).

monitored in the reverse direction without moving the P-wave pattern. Through this process, the S-wave patterns are distinguished from P- wave.

2.1.1. Direct method

The direct method (DM; Fig. 3) is commonly used for obtaining DS date. DM has been extensively applied to estimate the Vs profile for simple-structured site (Auld, 1977; Kramer, 1996; and Bang et al., 2014). The Vs value of each detected layer can be identified by direct method. The first arrival time of an first arrival at the

receiver for each testing depth can be calculated from the DS test. In case of the inclined path, the estimated travel time (t) can be corrected to the traveltime (t_C) in the vertical path through the following equation (Joh and Mok, 1998; Mok, 1987):

$$t_C = D\frac{t}{R} \qquad (1)$$

where t_C, D, t, R denotes corrected travel time, the testing depth from the ground surface, the first arrival time from the test, and the distance between the source and the receiver respectively.
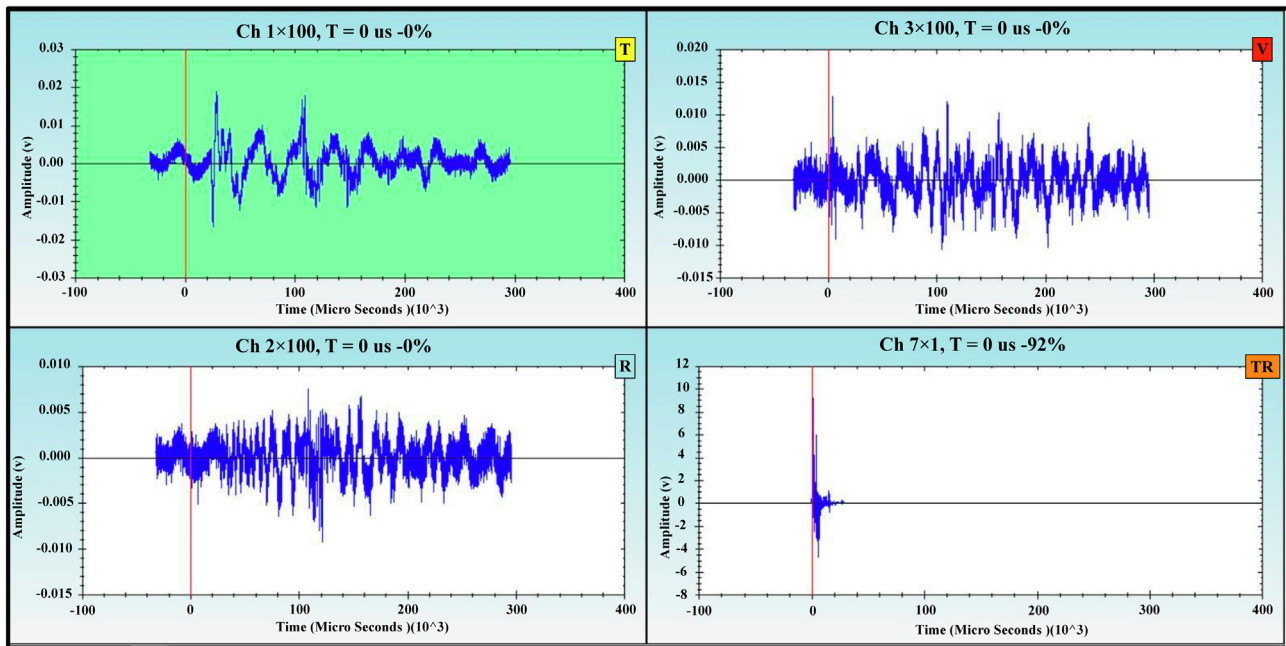

Fig. 4. Samples of collected data from the seismic borehole in the investigated site.
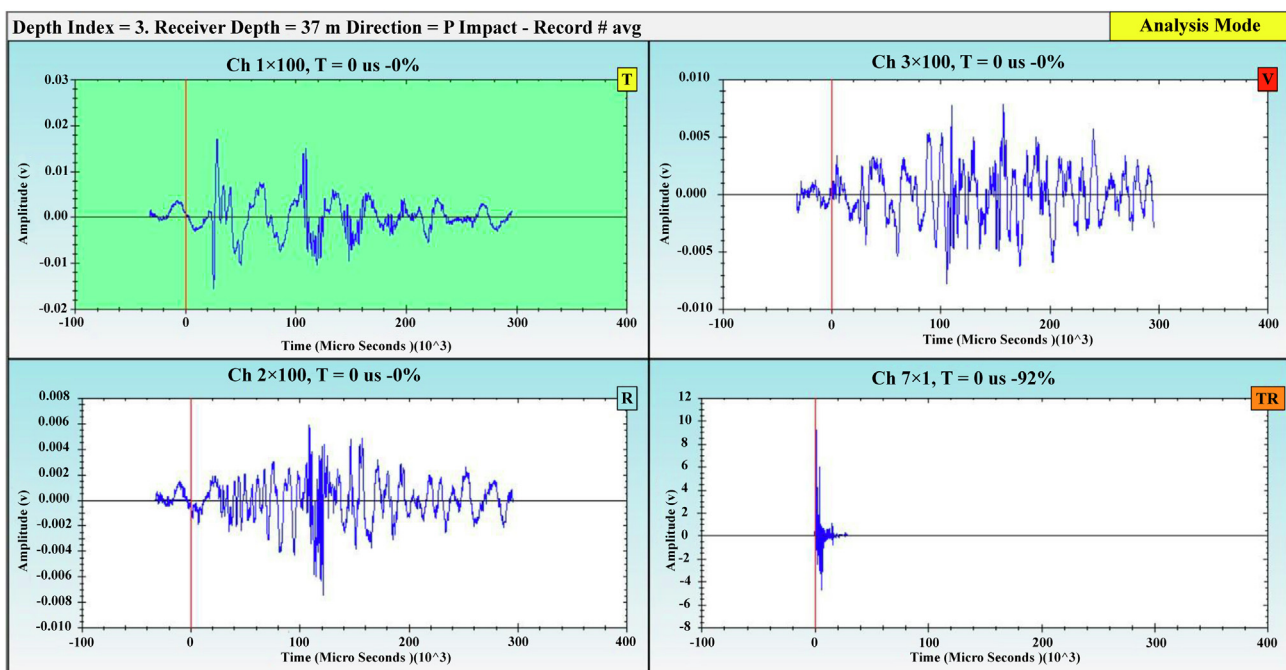

Fig. 5. Example of the applied filter to enhance collected data from the seismic borehole in the investigated area.

3. Calculation of dynamic soil parameters

Once seismic layers are graphically obtained, the average density (ρ) can be calculated from the Vp and Vs, and dynamic soil parameters. Soil dynamic properties can be determined using equations in Table 1 using IS: IS: 5249-1992. The definition of Poisson's ratio contains a minus sign; hence, normal materials can exhibit a positive ratio. Poisson's ratio is directly determined from P - and S- wave data, which is expressed by the ratio of transverse strain to longitudinal strain.

Shear modulus calculates the resistance to transverse deformations and is a valid index of elastic behavior only for small deformations. Large shearing forces lead to flow and permanent deformation or fracture. Shear modulus is obtained by the equation in Table 1. Young's modulus measures the solid material's stiffness which is a mechanical property of linear elastic solid materials. It defines the relationship between stress (force per unit area) and strain in a material. Its dynamic value is expressed by the equation in Table 1. Bulk modulus K or B measures the compression resistance of a substance. Its dynamic value is expressed by the equation in Table 1. In continuum mechanics, the Lamé parameter (Lamé coefficients, Lamé constants, or Lamé moduli) is a material-dependent quantity that arises in strain–stress relationships.

4. Data acquisition

In the downhole test, vertically propagating and horizontally polarized shear waves and vertically propagating compression waves travel from S - and P- wave sources on the ground surface, respectively, to receivers at a known depth in a borehole. Vertically traveling S - and P- waves are not converted to other waves via a horizontal boundary. As shown in Fig. 2, the horizontal distance between a source and a borehole is known, and the distance
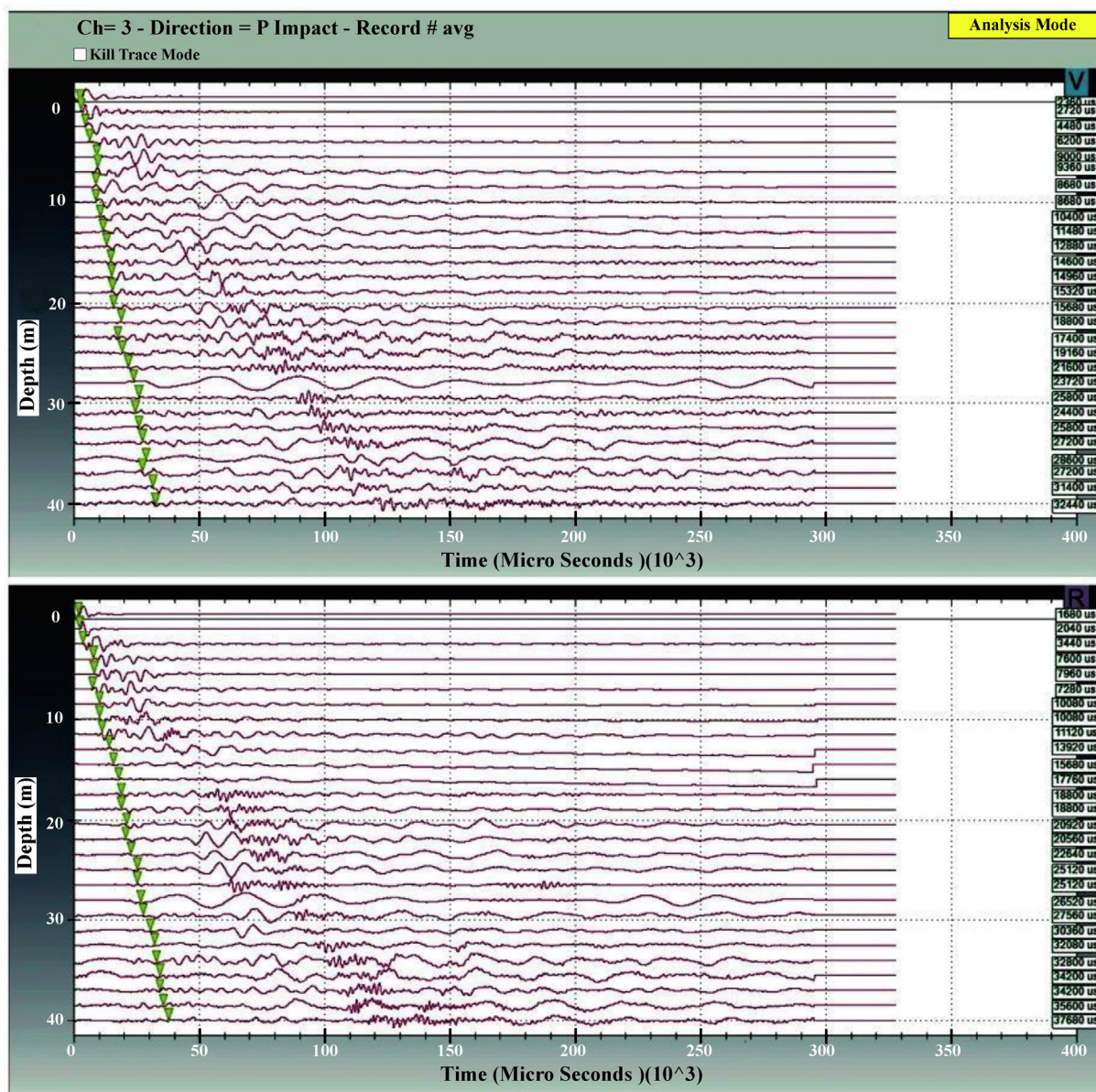

Fig. 6. First break picking for P – wave (up) from the vertical component and corresponding picking for S – wave (down) from the vectorial sum component for the surveyed borehole.

between a source and a receiver is calculated. The first arrival times of S - or P-waves are measured in each depth. The time difference for the first arrival times of S - or P-waves and the difference in distance in each depth are used to estimate wave velocities.

To perform downhole tests, the procedure can be subdivided into three categories: (1) seismic S - and P - wave sensors, (2) triggering systems, and (3) data acquisition systems to record output signals. To estimate dynamic soil properties, DS measurement with a 40-m maximum depth was performed. The P - and S-wave sources are at a distance of 1 m from the DS location. DS was acquired using a digital 3-C receiver at 1.5-m intervals for each reading. The first reading is located approximately at a 2-m depth. In the images shown below, the X, Y, and Z components of every source (P - wave, S-crossline wave, and S-inline wave) are given. Then, a sledgehammer strikes a simple plank located approximately 1 m from the borehole horizontally and vertically generates both P - and S - waves.

The generated waves by the source are recorded using a freedom data PC recording system from Olson Instruments. A triggering device that is connected to the sledgehammer triggers the recording system. The CS/DS-1 Model is used for DS testing. The acquired raw data outputs from the recording device are time–depth graphs presenting signals of arrival waves. Examples of the acquired raw signals are given in Fig. 4 at various depths within the mapped area.

5. Data processing

Processing of DS data requires a rigorous procedure of QA/QC to prevent inverting information that are not representative of the subsurface. This is extremely important in areas where the signal-to-noise ratio of data is low. Analog seismic wave propagation data directly result from the field measurement equipment. The seismograph acquisition unit converts analog data into digital data format. Seismic data are then uploaded to the computer and processed using different modules of the PSLog™ data analysis software package. The main processing steps for analysis of the acquired data are summarized as follows:

1) Raw data is imported into the analysis program, which are processed by editing recorded traces and applying frequency filters to enhance the first arrival time information. Filters can also be applied to reduce both high-frequency random noise and long-period noise of uncertain origin. Fig. 5 shows an example of applied filters to enhance collected data from the seismic borehole in the area.

2) The second step after enhancing the acquired signals is picking DS first arrivals. Then, phase readings of the first arrivals of P - and S - waves are obtained. These "first arrival times" are determined by selecting the time at which each receiver component records the first coherent energy. Picking first
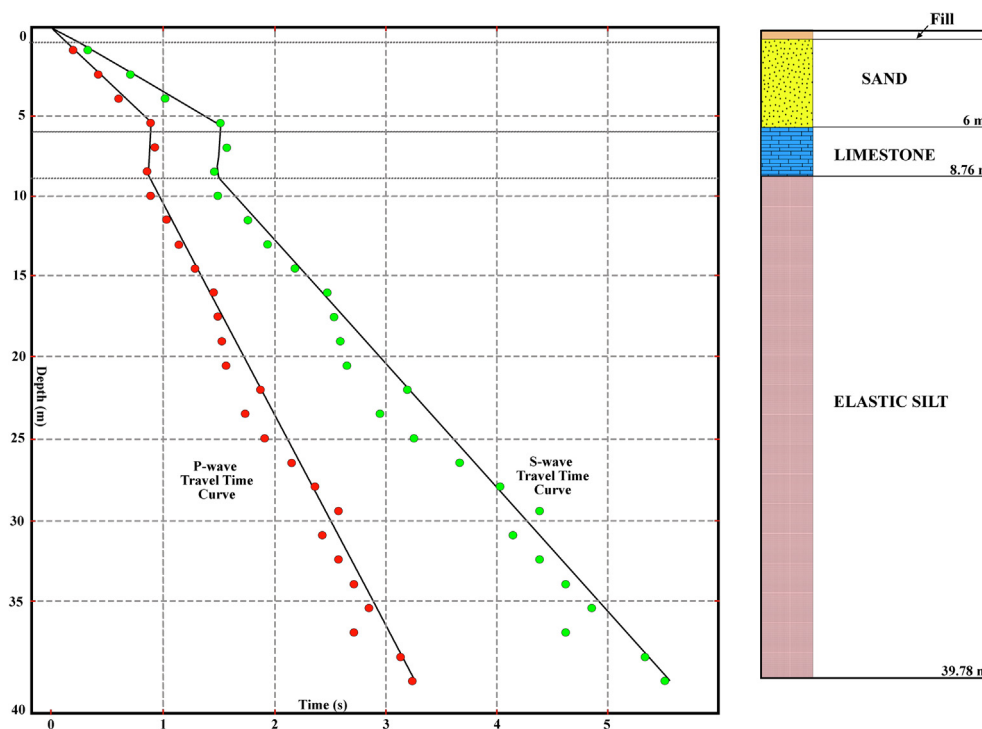

Fig. 7. Interpreted time travel graphs used for determining velocity values for the surveyed borehole.

Table 2a
Estimated velocities for the investigated site.

Depth (m)	Vp$_{avg}$ (m/s)	Vs$_{avg}$ (m/s)	(Vp/Vs) Ratio	Lithological description
0.503	537	316	1.69	Loose soil
6.017	22,258	1407	1.60	sand
8.769	2964	1828	1.62	limestone
39.78	2518	1522	1.65	Elastic silt

Table 2b
Estimated geotechnical parameters for the investigated site.

ρ kgm⁻³	M (GPa)	σ	E (GPa)	μ (GPa)	λ (GPa)	K (GPa)
1493	0.43	0.235	0.37	0.15	0.13	0.23
2136	10.9	0.183	10.01	4.23	2.43	5.25
2287	20.09	0.193	18.24	7.64	4.81	9.90
2195	13.92	0.212	12.33	5.09	3.75	7.14

arrivals on DS records relies on subjective estimates of first break positions, which may be difficult at deeper geophones where a poor signal-to-noise ratio occurs. Fig. 6 shows the picked first arrival times (red symbols) for the three surveyed boreholes. Picking of the S - wave arrivals are done after applying the vectorial sum of the radial and transverse components using the Wingeo-T™ software.

Data extracted from the DS survey consist of sets of times (first arrival times) measured at different depths from the source positions. If the arrival times lie on a number of clearly defined straight-line segments, best-fit lines may be drawn. In the current project, the corrected time for the P - and S - waves were calculated; hence, the average velocity of seismic waves in homogeneous soil layers was represented by the inclination of the line segments that are aligned with experimental data (Fig. 7).

6. Results and conclusions

The current DS survey was used to determine elastic parameters (Poisson's ratio, shear modulus, elastic bulk modulus, Lamé parameter, etc.) for rock competence in geotechnical application. The direct interpretation method was used in the current project. With DM, the travel times (t) measured along the source-receiver paths had to be corrected to consider the inclination of wave paths, and then the chart tcor-z must be considered for both P - and S - waves. Thus, the average velocity of seismic waves in homogeneous soil layers was represented by the inclination of the line segments that were aligned with experimental data. Once seismic layers are graphically obtained, geotechnical parameters can be estimated (Tables 2a & b).

It can be concluded that, the estimation of seismic velocities of a rock provides valuable information about the bulk physical properties of the rock, including how the rock will deform under a given stress. This information can be of great value during the design and construction phases. The state of stress within a given volume of rock is a common concern in constructing large structures. The computed values of the elastic constants agree with the values obtained in other sedimentary areas. The values showed that rocks within the study areas are soft to stiff, porous, and poorly sorted.

The integrated approach proposed and applied in this study can be used for a quick estimation of land subsidence along entire districts of Dammam city. As the next steps, the 2D and 3D P- And S- wave velocity profiles are recommended to be done in future so that an effective subsidence forecast system for Dammam city can be developed for all types of infrastructure. This, in turn, will reduce the environmental threats of land subsidence in the Dammam big city.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

References

Abd El Rahman, M., 1989. Evaluation of the kinetic moduli of the surface materials and application to engineering geologic maps at Ma'Barrisabah area (Dhamar province), Western Yemen. Egypt J. Geol. 33 (1–2), 229–250.

Abd El Rahman, M., Abd El Latif, T., 1990. Geophysical interpretations for shallow engineering site investigations at the area north of Sana'a, Yemen Arab Republic. MERC 4, 41–51.

Abd El Rahman, M., Setto, I., El Werr, A., 1991. Seismic refraction interpretation for shallow engineering site investigations at the distinctive district 6th of October City. E.G.S. Proc. of the 9th Ann. Meet., pp. 229–242.

Abd El Rahman, M., Setto, I., El-Werr, A., 1992. Inferring mechanical properties of the foundation materials at the 2nd Industrial zone. In: 10th of Ramadan City, from geophysical measurements. E.G.S. Proc. of the 10th Ann. Meet., pp. 50–61.

Abd El Rahman, M., Helal, A.N., Mohamed, H., El-Malqi, I., 1994. Exploration seismic for site evaluation at the new city of El-Minya, Egypt. E.G.S. Proc. of the 12th Ann. Meet., pp. 59–74.

Adams, L.H., 1951 Elastic properties of materials of the earth's crust. Internal construction of the earth (edited by Gutenberg): Dover Publications, Inc., New York.

Al humimidi, M.S., 2020. Geotechnical assessment of near-surface sediments and their hazardous impact: case study of Jizan city, southwestern Saudi Arabia. J. King Saud Univ. Sci. 32, 2195–2201.

Anbazhagan, P., Sitharam, T.G., 2006. Evaluation of dynamic properties and ground profiles using MASW: Correlation between Vs and N60. In: 13th symposium on earthquake engineering, Indian Institute of Technology, Roorkee, Dec. 18–20, Paper No. 008.

ASTM Standard D7400-08, 2008. Standard Test Methods for Downhole Seismic Testing. ASTM International, West Conshohocken, PA. DOI: 10.1520/D7400-08, www.astm.org.

Auld, B., 1977. Cross-hole and down-hole V_S by mechanical impulse. J. Geotech. Eng. Div. ASCE 103, 1381–1398.

Bang, Eun-Seok, Cho, Seong-Jun, Kim, Dong-Soo, 2014. Mean refracted ray path method for reliable downhole seismic data interpretations. Soil Dyn. Earthquake Eng. 65, 214–223. https://doi.org/10.1016/j.soildyn.2014.06.009.

Enamul Haque, D.M., Maksud Kamal, A.S.M., Woobaid Ullaha, A.S.M., Badrul Alama, Md., 2013. Comparison of shear wave velocity derived from PS logging and MASW – a case study of Mymensingh Pourashava, Bangladesh. Bangladesh J. Geol. 26, 84–97.

Fnais, M.S., Abdelrahman, Kamal, Al-Amri, A.M., 2010. Microtremor measurements in Yanbu city of Western Saudi Arabia: a tool for seismic microzonation. J. King Saud Univ.-Sci. 22, 97–110.

Gazetas, G., 1991. Formulas and charts for impedances of surface and embedded foundations. https://doi.org/10.1061/(ASCE)0733-9410(1991)117:9(1363).

IS: 5249-1992. Indian Standard determination of dynamic properties of soil - method of test (2nd revision). Foundation Engineering Sectional Committee, bureau of Indian standards. 16p.

Joh, S.H., Mok, Y.J., 1998. Development of an inversion analysis technique for downhole testing and continuous seismic CPT. J. Korean Geotech. Soc. 14, 95–108.

Abdelrahman, Kamal, Al-Amri, A., Al-Arifi, N., Abdelmoneim, E., 2017a. Seismic risk assessment at the proposed site of gemsa wind power station, South-western Coast of Gulf of Suez, Egypt. J. Geol. Soc. India 89, 192–196.

Abdelrahman, Kamal, Fnais, M., Enayat, Abdelmonem, Khaled, Magram, Saadoon, Abdullah Bin, 2017b. Seismic vulnerability assessment in the new urban area of Diriyah Governorate, Riyadh. Saudi Arabia. Arab. J. Geosci. 10, 434. https://doi.org/10.1007/s12517-017-3222-7.

Abdelrahman, Kamal, Abdullah, Al-Amri, Al-Otaibi, Naif, Fnais, Mohammed, Abdelmonem, Enayat, 2019. Ground motion acceleration and response spectra of Al-Mashair area, Makkah Al-Mukarramah, Saudi Arabia. Arab. J. Geosci. 12, 346. https://doi.org/10.1007/s12517-019-4526-6.

Abdelrahman, Kamal, Alamri, Abdullah M., Al-Otaibi, Naif, Fnais, Mohammed, 2020. Geotechnical assessment for the ground conditions in Makah Al-Mukarramah

city, Saudi Arabia. J. King Saud Univ. – Sci. 32, 2112–2121. https://doi.org/10.1016/j.jksus.2020.02.011.

Kim, D.S., Bang, E.S., Kim, W.C., 2004. Evaluation of various downhole data reduction methods to obtain reliable Vs profile. Geotech. Test. J. 27, 585–597.

King, M.S., 1966. Wave velocities in rocks as a function of changes in overburden pressure and pore fluid saturants. Geophysics 31 (1), 50–73.

Kramer, S.L., 1996. Geotechnical Earthquake Engineering. Prentice Hall, Upper Saddle River, New Jersey, pp. 207–208.

Mok, Y.J., 1987. Analytical and experimental studies of borehole seismic methods (Ph.D. dissertation). The Department of Civil Engineering. The University of Texas at Austin, USA.

Mok, Y.J., Stokoe, K.H., II, Wilson, C.R., 1988 Analysis of downhole seismic data using inverse theory. Proc. Ninth World Conf. Earthquake Eng. 3(1), 65–70, Tokyo, Japan.

Ravi, S., October 2017. 2017 Geotechnical investigations in difficult ground conditions – Indian experiences. Sixth Madhav Lecture, JNTU Hyderabad.

Roy, S., Bhalla, S., 2017. Role of Geotechnical Properties of Soil on Civil Engineering Structures 7, 103–109. https://doi.org/10.5923/j.re.20170704.03.

Stipho A.S., 1984. Soil conditions and foundation problems in the desert region of the Middle East. First Int Conf case Hist Geotech Eng. May 6–11, St Louis, Missouri.

SW-AJA, 1972. Soil behavior under earthquake loading conditions. U.S. atomic energy commission. .

Toksöz, M., Cheng, C., Timur, A., 1976. Velocities of seismic-waves in porous rocks. Geophysics 41 (4), 621–645.

Yusof, N., Zabidi, H., 2016. Correlation of mineralogical and textural characteristics with engineering properties of granitic rock from Hulu Langat, Selangor. Procedia Chem. 19, 975–980. https://doi.org/10.1016/j.proche.2016.03.144.

Woods, 1994. Geophysical Characterization of Sites. International Science Publisher, 141p.