Kochi Chapter

Indian Geotechnical Conference
IGC 2022
15th – 17th December, 2022, Kochi

Characterization of Subsurface using Vp/Vs and Poisson's ratio Prior to the Foundation of Critical Civil Structures

Bhowmick. S

Isotope Hydrology Div., CW&PRS, Pune, 411024, India
sudmik77@gmail.com

Abstract Geotechnical investigation, site characterization and assessment of foundation rock play a vital role in design of foundation for any major important civil engineering structures viz. Nuclear and Thermal Power Plants, bridges, dams etc. Geophysical techniques, complement and supplement to geotechnical investigations, provide compressional and shear wave velocities (i.e. Vp and Vs) of the subsurface layers in rapid and cost effective way, using seismic method. Acoustic velocity (Vp and Vs) versus depth provides detailed picture of the subsurface. As ratio of Vp and Vs (i.e. Vp/Vs) is better indicator of lithology than individual velocity values i.e. Vp and Vs, objective of this paper is to highlight nature and behaviour of Vp/Vs and Poisson's ratio, calculated using Vp/Vs, within near surface layer and rock under different geological and structural condition, useful in characterisation of subsurface. Vp/Vs and poison's ratio, used in this paper, was calculated using digitized value of Vp and Vs w.r.t depth from real-time examples, selected on the basis of literature survey where cross-hole seismic survey was conducted prior to the foundation of critical civil structures. The discussion on subsurface characterization and assessment of foundation rock using Vp/Vs and Poisson's ratio in this paper may be useful to geotechnical engineers and professionals dealing with design-foundation of important civil engineering structures.

Key words: Vp/Vs; Poisson's ratio; subsurface characterization; near surface layer; rock under different geological andstructural condition

1 Introduction

Foundation of important civil structure while construction of Nuclear Power Plant, Thermal Power Plant, dam, bridge etc. needs detailed information regarding engineering properties and deformational characteristics of rock mass (Lew 2001). Assessment of the foundation rock in terms of quality, strength and presence of structural disturbances, if any, are mandatory to verify the suitability of rock foundations and to determine natural frequency of the reactor-foundation rock system (IAEA Safety Guide 2004) and useful in deciding the load bearing capacity of the foundation (Bahremandi et al 2012), as well. The factors viz. lithology, density, porosity, clay content, saturation of subsurface lithology play an influential role in affecting the geomechanical properties of rock mass i.e. elastic modulus, Poisson's ratio (ν) and rock hardness (Garia et al 2020) etc.

Vp/Vs ratio is a better indicator of lithology than individual velocity values i.e. Vp and Vs and for near surface characterization (Mokhtar et al 2012, Zhang et al 2003), as well. Vp is controlled by both matrix and pore/fracture filling material (bulk and shear moduli) for a given density whereas Vs is controlled by rock matrix's shear modulus (Daley, 2004). A change in Vp/Vs is closely tied to a change in lithology as velocities vary with density and elastic properties or moduli (Poggiali et al 2019). Lithology, heterogeneity, degree of consolidation, clay content, porosity (Lee 2003) and water saturation etc. have effect on Vp/Vs and ratio (ν) (Lee 2003), directly proportional to Vp/Vs i.e. $\nu = [0.5 * (Vp/Vs)^2 - 1] / [(Vp/Vs)^2 - 1]$. High Vp/Vs ratio (> 2.0) and high Poisson's ratios (ν ~ 0.32 - 0.38) (Shearer 1988) indicates presence of unconsolidated, loose materials and fractured rock associated with the high near-surface porosity, whereas gradual decrease of Vp/Vs and Poisson's ratio with depth for a given lithology indicates presence of consolidated dry rock or unconsolidated sands (Vp/Vs < 2.0, ν ~ 0.1 – 0.2; Lee 2003), devoid of clay content and negligible effects of cracks and porosity under pressure, in general. Mean value of Vp/Vs and Poisson's ratio of rock provides an idea about the compactness and structural disturbance of rock (Bhowmick 2017), as well.

The present paper discussed on the nature and behaviour of Vp/Vs and Poisson's ratio within subsurface and rock under different geological and structural condition, helping in characterization of subsurface in terms of identification of overburden and it's thickness and assessment of foundation rock in terms of quality, compactness and presence of structural discrepancy, if any, using two real time examples from published research papers (Wadhwa et al 2010, Soupios et al 2006). The foundation rock at two sites, mentioned in the published research papers, was compact quartzitic sandstone and fractured phyllites, karstified limestones and crystalline limestones, respectively. Cross-hole seismic survey was conducted at both sites upto a depth of 30.0 m and 40.0 m respectively to get Vp and Vs w.r.t depth prior to the construction of Nuclear Power Plants at Rajasthan Atomic Power Plant (RAPP), Rajasthan, India (Wadhwa et al 2010) and laying out foundation of dam at Ilarionas Dam site, Greece (Soupios et al 2006). Vp/Vs and Poisson's ratio as a function of depth at two sites were calculated using digitized value of Vp and Vs (Table-1), derived from the mentioned research papers.

2 DigitizeIt 2.5.0 software

The DigitizeIt 2.5.0 software, compatible with Windows 7.0 platform, is able to import almost all common image file formats, incl. gif, png, tiff, jpeg, bmp etc., pasting of graphs via clipboard or can capture screenshots and also digitize it automatically or manually. Data values can be saved in CSV format or copy and pasted directly into any other application, e.g. MS Excel or Origin Lab.

The digitized data set of Vp, Vs w.r.t depth of RAPP, Rajasthan (Wadhwa et al 2010) and Ilarionas Dam, Greece (Soupios et al 2006) using DigitizeIt 2.5.0 software are mentioned in Table – 1.

3 Characterization of subsurface using Vp/Vs and Poisson's ratio

3.1 Near surface weathered zone or overburden

Near surface high Vp/Vs ratio (> 2.0) at RAPP, Rajasthan and Ilarionas Dam, Greece sites (Fig. 1) alongwith Poisson's ratio (ν = 0.32 – 0.40) and (ν = 0.25 – 0.35), respectively indicated presence of unconsolidated, loose materials i.e. dry sand and gravelly sand (ν = 0.30 - 0.40) and fractured rock associated with the high near-surface porosity (Shearer 1988) and water saturation. The presence of lithology at Ilarionas Dam site, Greece, identified on the basis of Vp/Vs and Poisson's ratio, was matched with layer of weathered and fractured phyllites with unconsolidated, loose materials i.e. gravels, coarse sand, moraine, as mentioned in the original research paper (Soupios et al 2006)

The change of lithology from loose, unconsolidated condition (i.e. overburden) to consolidated layer (i.e. rock) is identified by the nature of Vp/Vs w.r.t depth where Vp/Vs > 2.0 is changed to Vp/Vs < 2.0 by crossing Vp/Vs = 2.0 at a single cross point (Bhowmick 2017), in general. Thickness of unconsolidated material or overburden i.e. 9.0 m and 10.0 m at RAPP, Rajasthan and Ilarionas Dam, Greece sites respectively was calculated using Vp/Vs w.r.t depth plot where Vp/Vs line crossed Vp/Vs = 2.0 (dotted line, Fig. 1) from right (Vp/Vs > 2.0) to left (Vp/Vs < 2.0) at a single point. The variation of Vp/Vs w.r.t Vp/Vs = 2.0 (Fig. 1b) upto a depth of 10.0 m from top at Ilarionas Dam, Greece indicated presence of both loose, unconsolidated overburden and a thin but hard layer of weathered and fractured phyllites at near surface as mentioned in the original research paper.

3.2 Rock under different geological and structural conditions

The presence of compact and consolidated rock at depth, devoid of major structural disturbances and suitable for the foundation of important civil structures is identified by the nature and behaviour of Vp/Vs (Vp/Vs ~ 1.5 – 2.0) and Poisson's ratio (ν ~ 0.1 – 0.33) (Bahremandi et al 2012, Bhowmick 2017), in general. Presence of high pore fluid and crack anisotropy is identified by high Vp/Vs (Wang et al 2012) whereas heavily jointed rock, sparsely jointed rock and moderate quality of rock are identified by the mean (or average) value of Vp/Vs > 1.89 and ν > 0.30; Vp/Vs < 1.80 and ν < 0.28 and Vp/Vs ~ 1.80 - 1.89 and ν ~ 0.28 - 0.30, respectively (Barton 2007). The major structural discontinuity or subsurface fault is identified by Vp/Vs ~ 2.08 - 2.4 and ν ~ 0.35 - 0.4 (Hung et al 2007).

(a) Compact and undisturbed rock

Vp/Vs and Poisson's ratio (Fig. 1a) of the basement rock i.e. quartzitic sandstone from 9.0 m upto 30.0 m at RAPP, Rajasthan was in the range of Vp/Vs ~ 1.78 – 1.97 (i.e. Vp/Vs < 2.0) and ν ~ 0.27 – 0.33 (Table-1). A dotted rectangle was plotted from the depth of 9.0 m upto 30.0 m (Fig. 1a) with a width of Vp/Vs (~ 1.5 – 2.0) and Poisson's ratio (ν ~ 0.1 – 0.33), the range of Vp/Vs and Poisson's ratio for compact and consolidated rock (Bahremandi et al 2012, Bhowmick 2017), w.r.t x-axis (horizontal axis) to study condition of rock using the nature and behaviour of both parameters. Vp/Vs and Poisson's ratio w.r.t depth were confined within the dotted rectangles (Fig. 1a), without much deviation, indicating the presence of compact rock without much structural disturbances as mentioned in the original research paper (Wadhwa et al 2010). The range of Vp/Vs within campact quartzitic sandstone is 1.5 – 1.7 (Garia et al 2020), in general, however, a fractured or cracked zone within compact rock is identified by Vp/Vs ~ 1.82 (Guéguen et al 2009). Therefore, there was a possibility of presence of a fractured or cracked zone within quartzitic sandstone at RAPP, Rajasthan as Vp/Vs (~ 1.83 – 1.97, Table-1) w.r.t depth was close to Vp/Vs = 2.0 (dotted line) from 9.0 m to 22.5 m (Fig. 1a).

Vp/Vs and Poisson's ratio of subsurface lithology from the depth of 9.0 m upto 30.0 m at RAPP, Rajasthan were plotted w.r.t Poisson's ratio (vertical axis) and Vp/Vs (horizontal axis) (Fig.2a) for the assessment of quality of foundation rock. It was observed that all points were confined within the dotted rectangle box bounded by Vp/Vs (~ 1.5 – 2.0) and Poisson's ratio (ν ~ 0.1 – 0.33), indicating presence of compact rock at site (Bahremandi et al 2012, Bhowmick 2017). However, cluster of points were close to higher value of Vp/Vs (~ 2.0) and poisson's ratio (ν ~ 0.33), indicating possibility of presence of cracked or fractured zone within compact rock as it was seen in Figure 1a.

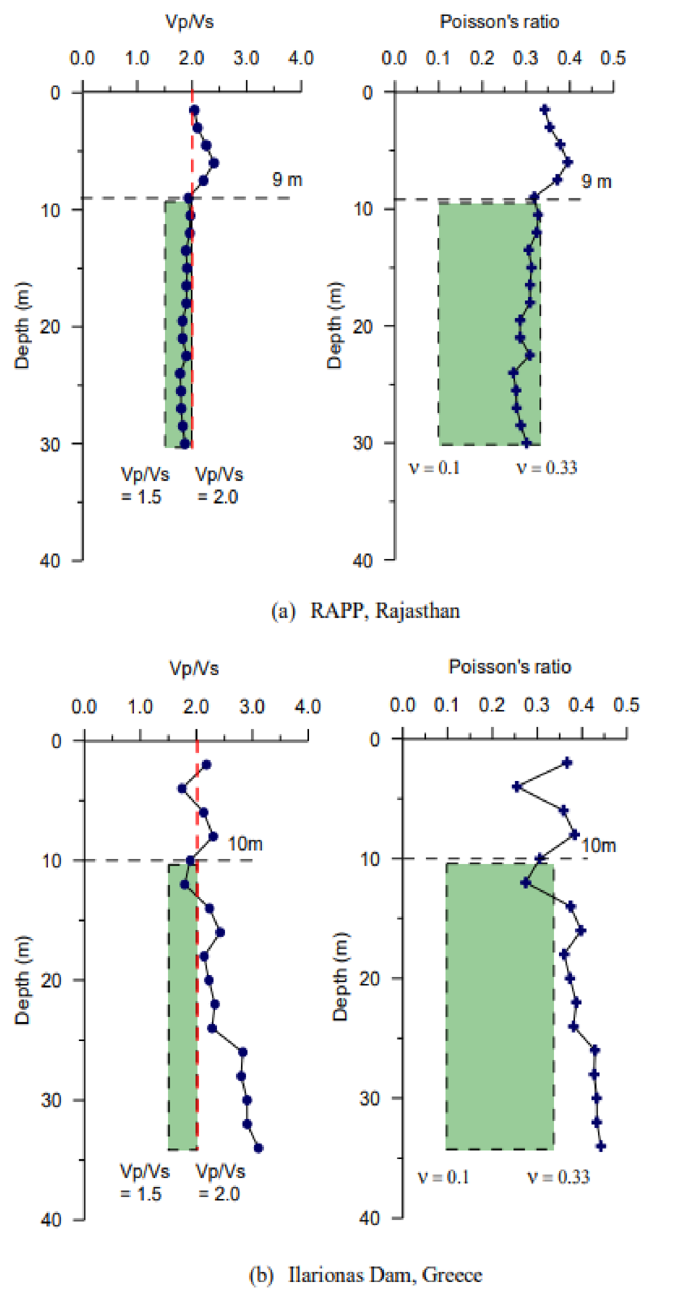
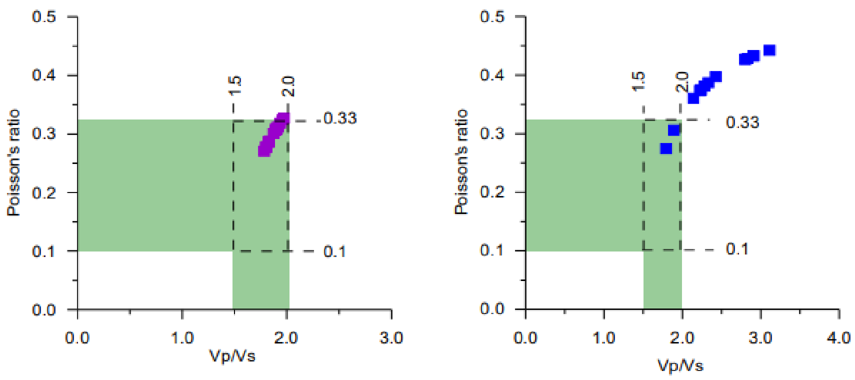


Fig. 1. Vp/Vs and Poisson's ratio as a function of depth under different geological and structural conditions at RAPP, Rajasthan and Ilarionas Dam, Greece



(a) RAPP, Rajasthan (b) Ilarionas Dam, Greece

Fig. 2. Assessment of foundation rock using Vp/Vs and Poisson's ratio at RAPP, Rajasthan and Ilarionas Dam, Greece

Mean value of Vp/Vs and Poisson's ratio (Vp/Vs = 1.88, ν = 0.30) of quartzitic sandstone at RAPP, Rajasthan, while plotted w.r.t Poisson's ratio (vertical axis) and Vp/Vs (horizontal axis) (Fig.3) for identification of the structural condition of the foundation rock (Bhowmick 2017), were confined within dotted rectangle and close to the edge of Vp/Vs ~ 1.89 and Poisson's ratio ~ 0.30 (Fig. 3), indicating presence of moderate quality of rock i.e quartzitic sandstone without major structural disturbances at site.

(b) Fractured and structurally disturbed rock

Vp/Vs and Poisson's ratio of fractured phyllites, considered as basement rock at Ilarionas Dam, Greece was in the range of Vp/Vs ~ 1.79 – 3.11; ν ~ 0.27 – 0.44 from 10.0 m to 40.0 m (available data upto 34.0 m, Table-1). The scattered nature of Vp/Vs (> 2.0), not confined within the dotted rectangles plotted from the depth of 10.0 m upto 34.0 m with a width of Vp/Vs (~ 1.5 – 2.0) and Poisson's ratio (ν ~ 0.1 – 0.33) respectively, indicated presence of water-saturated unconsolidated or densely fractured rock having clay content and porosity (Lee 2003, Mooney et al 1986) at site (Fig. 1b). Vp/Vs and Poisson's ratio below 10.0 m upto 24.0 m were little close to the dotted rectangles in comparison to the points below 24.0 m. Vp/Vs upto a depth of 24.0 m indicated presence of thin cracks within rock, saturated with water whereas more deviation and scattering of both parameters below 24.0 m indicated presence of highly densed crack (Vp/Vs > 2.5, Wang et al 2012) or fracture (Mooney et al 1986) within rock as mentioned in the original research paper (Soupios et al 2006).

Vp/Vs and Poisson's ratio of fractured phyllites from depth of 10.0 m upto 34.0 m at Ilarionas Dam, Greece, plotted w.r.t Poisson's ratio (vertical axis) and Vp/Vs (horizontal axis) (Fig.2b) for the assessment of foundation rock, showed maximum points were out of the dotted rectangle box i.e. Vp/Vs > 2.0 and Poisson's ratio (ν) > 0.33, indicating presence of structurally disturbed or fractured rock at site as it was seen in Figure 1b.

Mean value of Vp/Vs and Poisson's ratio (Vp/Vs = 2.45, ν = 0.39) of fractured phyllites at Ilarionas Dam, Greece, while plotted w.r.t Poisson's ratio (vertical axis) and Vp/Vs (horizontal axis) (Fig.3) for identification of the structural condition of the foundation rock, was confined within the area or zone of heavily jointed rock (Fig.3), indicating presence of weak, fractured and structurally disturbed rock at site.

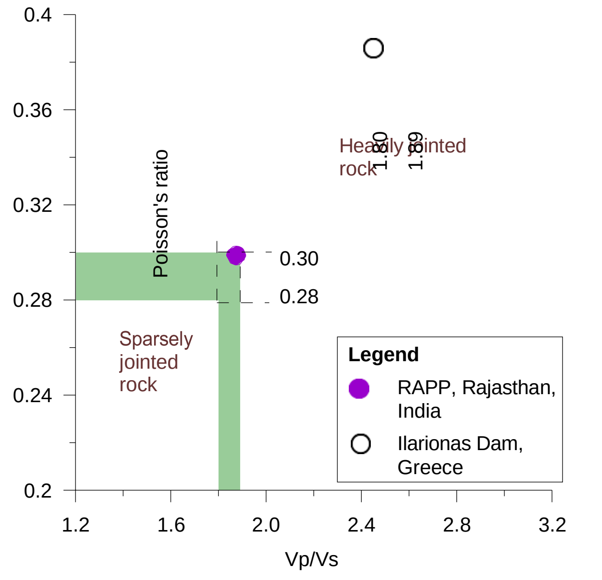


Fig. 3. Assessment of structural disturbances within rock at RAPP, Rajasthan and Ilarionas Dam, Greece using Vp/Vs and Poisson's ratio

4 Conclusion

Vp/Vs and Poisson's ratio of quartzitic sandstone at RAPP, Rajasthan, India w.r.t depth were within the range of Vp/Vs (~ 1.5 – 2.0) and Poisson's ratio (ν ~ 0.1 – 0.33) (Bahremandi et al 2012, Bhowmick 2017) indicating presence of compact rock, however, Vp/Vs close to Vp/Vs =2.0 indicated presence of saturated cracks within rock at depth. The same nature was also seen when Vp/Vs and Poisson's ratio were plotted w.r.t each other. Vp/Vs and Poisson's ratio of fractured or geologically disturbed rock i.e. phyllites at Ilarionas Dam, Greece w.r.t depth or plotted w.r.t each other, were scattered and away from the above mentioned range of compact rock. Presence of compact rock and fractured and structurally disturbed rock at two sites were identified by the mean value of Vp/Vs and Poisson's ratio.The nature and behaviour of Vp/Vs and Poisson's ratio within different geological and structural condition are important in geotechnical engineering in characterization of subsurface and also helps in assessing quality of foundation rock prior to the design-foundation of important civil structures.

5 Acknowledgement

Author is grateful to Dr. R.S. Kankara, Director and Dr. Prabhat Chandra, Additional Director, C.W & P.R.S, Pune, India for their constant support, encouragement and permission in publishing this paper. Author is also thankful to Shri B. Suresh Kumar, Scientist D, Isotope Hydrology division for his valuable suggestions and guidance during writing the paper. Author also acknowledges with thanks to authors whose published works are referred in this paper.

Table 1. Computed Vp, Vs w.r.t depth using DigitizeIt 2.5.0 software.

RAPP, Rajasthan (Wadhwa et al 2010)						**Ilarionas Dam, Greece** (Soupios et al 2006)				
Depth (m)	**Vp (m/sec)**	**Vs (m/sec)**	**Vp/vs**	**PR***		**Depth (m)**	**Vp (m/sec)**	**Vs (m/sec)**	**Vp/vs**	**PR***
1.5	1770	866	2.04	0.34		2	846	388	2.18	0.37
3	3870	1840	2.10	0.35		4	950	545	1.74	0.25
4.5	4250	1880	2.26	0.38		6	1360	638	2.13	0.36
6	4660	1940	2.40	0.40		8	1680	730	2.30	0.38
7.5	4930	2230	2.21	0.37		10	1800	952	1.89	0.31
9	5170	2670	1.94	0.32		12	1990	1110	1.79	0.27
10.5	5010	2540	1.97	0.33		14	2210	989	2.23	0.37
12	5060	2580	1.96	0.32		16	2420	998	2.42	0.40
13.5	5200	2750	1.89	0.31		18	2290	1070	2.14	0.36
15	5280	2760	1.91	0.31		20	2780	1250	2.22	0.37
16.5	5190	2730	1.90	0.31		22	3100	1330	2.33	0.39
18	5190	2730	1.90	0.31		24	3330	1460	2.28	0.38
19.5	5080	2780	1.83	0.29		26	3680	1300	2.83	0.43
21	5190	2840	1.83	0.29		28	3950	1410	2.80	0.43
22.5	5320	2800	1.90	0.31		30	4040	1390	2.91	0.43
24	5190	2910	1.78	0.27		32	4100	1410	2.91	0.43
25.5	4970	2760	1.80	0.28		34	4260	1370	3.11	0.44
27	5160	2860	1.80	0.28		36	4030			
28.5	5130	2800	1.83	0.29		38	4750			
30	5210	2780	1.87	0.30		40	4530			

* PR indicates Poisson's ratio

References

1. Bahremandi M, Mirshahani M, Saemi M: Using of compressional-wave and shear-wave velocities ratio in recognitionof reservoir fluid contacts case study: a Southwest Iranian oil field. J Sci Res Rev 1(2):015–019 (2012).
2. Barton, N: Rock Quality, Seismic Velocity, Attenuation, and Anisotropy, Taylor & Francis, London, pp. 729 (2007).
3. Bhowmick, S: Role of Vp/Vs and Poisson's Ratio in the Assessment of Foundation(s) for Important Civil Structure(s);Geotech Geol Eng; Vol. 35; pp 527–534 (2017).
4. Daley, T. M, Majer. E. L, Peterson. J. E: Crosswell seismic imaging in a contaminated basalt aquifer --- Case History;GEOPHYSICS; Vol. 69, No. 1 (Jan.-Feb.); pp. 16–24 (2004).
5. Garia, S, Pal, A K, Nair. A M and Ravi, K: Elastic wave velocities as indicators of lithology-based geomechanical behaviour of sedimentary rocks: an overview; Applied Sciences; Vol. 2**,** Art. No. 1521; pp. 1-21 (2020).
6. Guéguen, Y, Sarout, J, Fortin, J, Schubnel, A, Supérieure, E. N: "Cracks in porous rocks: Tiny defects, strong effects"; Special Section: Rock Physics; The Leading Edge; Jan.; pp. 40-47 (2009).
7. Hung, J.H, Wu, Y.H, Yeh, E.C, Wu, J.C: Subsurface Structure, Physical Properties, and Fault Zone Characteristics in the Scientific Drill Holes of Taiwan Chelungpu-Fault Drilling Project Terr. Atmos. Ocean Sci., Vol. 18, No. 2, pp. 271-293(2007).
8. International Atomic Energy Agency Vienna: Geotechnical Aspects Of Site Evaluation And Foundations For NuclearPower Plants, Safety Guide, IAEA Safety Standards Series No. Ns-G-3.6 (2004).
9. Lee, MW: Velocity ratio and its application to predicting velocities; U.S. Geol. Survey Bulletin 2197; U.S; pp 1-19(2003).
10. Lew, M: Geotechnical Design Considerations, Chap. 3 in The Seismic Design Handbook, (F. Naeim editor), KluwerAcademic Publishers (2001).
11. Mokhtar, E.A, Vega S, Hassan A.A, BaloushiM.A: Porosity and heterogeneity effect on Vp/Vs ratio in carbonate rocks from a reservoir in the Middle East, poster presentation, AAPG international conf. and exhibition, Milan, Italy, Oct. 23– 26 (2012).
12. Mooney, W. D and Ginzburg, A: Seismic Measurements of the Internal Properties of Fault Zones; PAGEOPH, Vol. 124,Nos. ½; pp 141-157 (1986).
13. Poggiali, G, Chiaraluce, L, Stefano, R D and Agostinetti N P: Change-point analysis of *V P* /*V S* ratio time-series using atrans-dimensional McMC algorithm: applied to the Alto Tiberina Near Fault Observatory seismic network (Northern Apennines, Italy); *Geophys. J. Int.;* 217; 1217–1231; doi: 10.1093/gji/ggz078 (2019).
14. Shearer, P M: Cracked media, Poisson's ratio and the structure of the upper oceanic crust, Geophysical Journal, 92, pp.357-362 (1988).
15. Soupios, P., Papazachos, C.B., Vargemezis, G., Savvaidis, A: In Situ Geophysical Investigation to Evaluate DynamicSoil Properties at the Ilarionas Dam, Northern Greece; Proceedings of the 2nd Intl. Conf. on Advances in Mineral Resources Management and Environmental Geotechnology (AMIREG 2006); Sept. 25-27; Hania, Greece (2006).
16. Wadhwa, RS., Ghosh, N., Subba Rao, Ch.: Empirical relation for estimating shear wave velocity from compressionalwave velocity of rocks, J. Ind. Geophys. Union (Jan), Vol.14, No.1, pp.21-30 (2010).
17. Zhang, J. J., Bentley, L. R: Pore geometry and elastic moduli in sandstones; CREWES Research Report; Vol. 15 (2003).
18. Wang, XQ., Schubnel, A., Fortin, J., David, EC., Guéguen, Y., Ge, HK.: High Vp/Vs ratio: Saturated cracks orAnisotropy effects? Geophysical Research Letters, Vol. 39, L11307 (2012).