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Soft computing methods for estimating the uniaxial compressive strength of intact rock from index tests



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1. Introduction

Uniaxial compressive strength (UCS) is one of the most widely used rock mechanical parameters in rock engineering. Determination of this parameter in the laboratory, however, requires quality rock specimens. The use of various index tests that require little or no specimen preparation and are easier to perform as well as less expensive than the uniaxial compression test has always been attractive in order to predict UCS of rock materials empirically¹⁻¹⁶. Amongst different predictive models such as regression analyses, fuzzy inference system and neural network approaches; regression analyses are commonly employed to establish a predictive model to estimate UCS¹⁷. In the last decade or so, however, the use of soft computing methods (e.g. fuzzy inference system (FIS), artificial neural network (ANN) and adaptive neuro-fuzzy inference system (ANFIS)) in order to establish predictive models has also gained significant attention in the areas of rock mechanics and engineering geology. Several research works have dealt with the estimation of UCS and/or other intact rock properties from index test results using these soft computing methods^{17–36}. The present investigation, with a due need, sheds light on critical comparative evaluation of different soft computing techniques in predicting UCS of rock materials which are

inherently very different from each other. In this study, index tests involving determination of block punch index (BPI), point load strength ($I_{s(50)}$), Schmidt rebound hardness (SRH) and ultrasonic P-wave velocity (V_p) are performed and used for estimating UCS of granite, schist and sandstone. Subsequently, predictive performances of the adopted data analysis techniques (i.e. FIS, ANN and ANFIS) with reference to estimation of UCS from the determined indices are critically compared.

2. Samples and laboratory investigations

Three rock types, granite (igneous crystalline rock and virtually isotropic in nature), schist (metamorphic rock and anisotropic in nature) and sandstone (sedimentary rock and porous in nature), were considered for the present investigation in order to take account of a plausible wide range of rock strength. Granite, schist and sandstone cores (51/58, 54 and 47 mm in diameter correspondingly) were collected from Malanjkhand Copper Project, Malanjkhand (central India), UCIL mine at Jaduguda (eastern India), and Singareni Collieries Company Limited, Kothagudem (southern India) respectively. Each of the collected core samples (20 from each rock type) was cut into four pieces suitable for uniaxial compression, point load, block punch and Schmidt rebound hardness tests as per the stipulations by ASTM D4543³⁷ and ISRM³⁸. The test procedures for determining *UCS*, *BPI* and $I_{S(50)}$ were in accordance with ASTM D2938³⁹, Ulusay et al.⁴⁰, and

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ISRM 38 , respectively. Depth of cone penetration was also considered to calculate $I_{s(50)}$ as suggested by Basu and Aydin 12 . In case of schistose rocks, tests that had lead to failure of specimens along foliations were taken into account instead of discarding them as invalid tests after recommendations by Basu and Kamran 41 . SRH was determined according to ASTM D5873 42 and Aydin and Basu 11 . As the rebound hammer is a spring-loaded piston, the rebound value suffered gravity effect as the direction of application of the hammer was vertically downward and not horizontal. Therefore, to nullify the effect of gravity, rebound values were normalized in horizontal direction according to the method proposed by Basu and Aydin 43 . V_p was directly noted from a digital ultrasonic tester.

3. Test results and analysis

Results of the entire laboratory investigation are summarized in Table 1. For the granite and sandstone specimens that failed in invalid failure modes 38,40 , $I_{s(50)}$ and BPI were not calculated and were marked as 'Invalid' (Table 1). Samples, where any one of the four mentioned indices was unavailable because of invalid failure during testing or absence of specimens, were not considered in the analyses for obvious reasons. Therefore, a total of 44 samples were used for the analyses. It should be noted that UCS values obtained through laboratory investigation of three completely different rock types (i.e. granite, schist and sandstone) cover a large spectrum of rock strength as given in Table 1. Each of the determined indices (i.e. BPI, $I_{s(50)}$, SRH, and V_p) also depicts a wide range of values (Table 1).

3.1. Fuzzy Inference System (FIS)

Fuzzy sets, introduced by Zadeh in 1965 as an extension of classical set theory, permit the gradual assessment of the membership of elements in a set described with the aid of a membership function valued in the real unit interval [0 and 1]. For the present investigation, Sugeno-type fuzzy inference system, which is compact and has got computational efficiency, was employed to construct the predictive models for estimating *UCS* of all three concerned rock types. The present model includes four inputs (*BPI*, $I_{S(50)}$, *SRH* and V_p) and one output (*UCS*); Fig. 1.

FIS can be structured in three parts: (i) development of membership functions and derivation of fuzzy sets; (ii) construction of inference rules to combine fuzzy descriptors; and (iii) defuzzification process. Membership values were assigned to linguistic variables of all the inputs and the output in the first part of the model. Baglio et al. 44 suggested that parameters and shapes of the membership functions strongly influence the model accuracy. Consequently, two sets of membership function plots were prepared for this study, one for granite and sandstone and the other for schist. In case of schist, the parameters of the membership function plot of BPI and V_p are slightly different from that of granite and sandstone, as the BPI and V_p values are high when compared with their corresponding UCS. It should be noted that the membership function parameters were chosen after the considered ranges for each variable (inputs and output) in order to obtain the best possible outcome. The pictorial representation of the membership function plots are given in Figs. 2 and 3 for the input variables (i.e. BPI, $I_{s(50)}$, SRH and V_p).

Fuzzy logic deals with linguistic expressions, also known as fuzzy propositions, in rule-based modeling⁴⁵. For inferences in a rule-based fuzzy model, the fuzzy propositions need to be represented by an implication function called a fuzzy 'if-then' rule. In this study, these rules were developed by using expert knowledge. Some impossible combinations (e.g. when *BPI* is very strong

Table 1Laboratory test results.

G 1 23.77 8.35 55.38 5865 139.04 G 2 35.36 10.85 65.38 5836 177.37 G 3 31.39 10.02 64.43 5945 167.17 G 3 4 33.51 9.92 66.51 6047 176.75 G 5 30.93 11.73 65.57 5905 160.82 G 6 Invalid 14.13 67.07 6250 198.15 G 6 Invalid 14.13 67.07 6250 198.15 G 7 31.29 10.63 60.48 6030 148.34 G 8 15.99 6.93 56.7 5491 117.95 G 9 23.2 8.49 58.59 5753 134.76 G 10 24.37 7.87 58.59 5422 124.89 G 11 Invalid 8.41 57.64 5514 138.22 124.89 G 12 28.04 7.85 55.76 5428 130.06 G 12 28.04 7.85 55.76 5428 130.06 G 13 25.27 5.99 57.64 5911 122.74 138.98 Invalid 67.64 6214 201.73 G 16 35.03 11.36 65.38 6214 182.33 G 17 Invalid 9.23 61.8 5729 150.42 G 18 25.59 6.92 60.48 5566 127.47 G 19 23.69 9.72 57.64 6030 158.69 G 20 17.21 5.66 52.92 5384 91.48 51 12.54 13.55 5 15.49 4.03 52.17 5172 47.05 5 5 15.49 4.03 52.17 5172 47.05 5 5 15.49 4.03 52.17 5172 47.05 5 6 7.89 3.17 43.46 5820 26.55 5 15.49 4.03 52.17 5172 47.05 5 6 7.89 3.17 43.46 5820 26.55 5 15.49 4.03 52.17 5172 47.05 5 6 7.89 3.17 43.46 5820 35.31 10 Invalid 3.27 43.46 5820 35.57 5 14.41 3.07 45.36 5675 32.07 51.41 10	Sample name	BPI (MPa)	<i>I</i> _{s(50)} (MPa)	SRH (%)	USV (m/s)	UCS (MPa)
G 3	G 1	23.77	8.35	55.38	5865	139.04
G 4 33.51 9.92 66.51 6047 176.75 6 6 6 10valid 14.13 67.07 6250 198.15 6 7 31.29 10.63 60.48 6030 148.34 6 8 15.99 6.93 56.7 5491 117.95 6 9 23.2 8.49 58.59 5753 134.76 6 10 24.37 7.87 58.59 5422 124.89 6 10 24.37 7.87 58.59 5422 124.89 6 11 10valid 8.41 57.64 5514 138.22 6 12 28.04 7.85 55.76 5428 130.06 6 13 25.27 5.99 57.64 5911 122.74 6 13 25.27 5.99 57.64 5911 122.74 6 13 25.27 5.99 57.64 5911 122.74 6 16 35.03 11.36 65.38 6214 182.33 6 16 35.03 11.36 65.38 6214 182.33 6 17 1nvalid 9.23 6 1.8 5729 150.42 6 18 25.59 6.92 60.48 5566 127.47 6 19 23.69 9.72 57.64 6030 158.69 6 20 17.21 5.66 52.92 5384 91.48 5 1 1 7.6 3.93 46.3 5993 37.97 5 1 1 2 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	G 2	35.36	10.85	65.38	5836	177.37
G 5 30.93 11.73 65.57 5905 160.82 G 6 Invalid 14.13 67.07 6250 198.15 G 7 31.29 10.63 60.48 6030 148.34 G 8 15.99 6.93 56.7 5491 117.95 G 9 23.2 8.49 58.59 5753 134.76 G 10 24.37 7.87 58.59 5422 124.89 G 11 Invalid 8.41 57.64 5514 138.22 G 12 28.04 7.85 55.76 5428 130.06 G 13 25.27 5.99 57.64 5911 122.74 G 14 38.98 Invalid 67.64 6214 201.73 G 15 Invalid 7.29 No sample 5820 153.55 G 16 35.03 11.36 65.38 6214 182.33 G 17 Invalid 9.23 61.8 5729 150.42 G 18 25.59 6.92 60.48 5566 127.47 G 19 23.69 9.72 57.64 6030 158.69 G 20 17.21 5.66 52.92 5384 91.48 S 1 7.6 3.93 46.3 5993 37.97 S 2 Invalid 2.8 No sample 5874 43.97 S 3 4.61 3.58 45.36 6188 47.05 S 4 19.31 4.49 52.55 6074 49.22 S 5 15.49 4.03 52.17 5172 47.05 S 6 7.89 3.17 43.46 5820 26.55 S 10 Invalid 3.27 43.46 5820 36.55 S 11 Invalid 3.27 43.46 5820 35.00 S 11 Invalid 3.27 43.46 5882 39.06 S 11 Invalid 3.27 43.46 5882 39.06 S 11 Invalid 3.47 41.25 5850 35.57 S 13 1.441 3.07 45.36 5675 32.07 S 14 17.69 4.85 54.18 6145 60.82 S 15 14.41 2.96 49.14 5882 49.08 S 16 5.57 1.15 33.95 53.21 21.36 S 17 20.07 6.06 46.3 6145 70.47 S 18 Invalid 1.49 80.89 37.79 56.82 S 5 1.41 1.79 4.85 54.18 6145 60.82 S 19 Invalid 1.79 3.58 53.66 33.89 19.66 S 15 1.41 1.33 3.14 46.3 3658 51.29 S 5 1.549 4.91 3.24 35.67 6024 49.33 S 8 7.74 1.52 37.76 5116 22.83 S 8 7.74 1.52 37.76 5116 22.83 S 8 7.74 1.52 37.76 5116 22.83 S 10 1.81 1.81 1.81 1.81 1.81 1.81 S 11 1.81 1.81 3.31 4.49 3.66 3.88 3.89 3.66 S 12 2.70.5 7.42 58.59 6250 95.14 3.18 S 13 1.81 1.81 1.81	G 3	31.39	10.02	64.43	5945	167.17
G 6 Invalid 14.13 67.07 62.50 198.15 G 7 31.29 10.63 60.48 6030 148.34 60.8 15.99 6.93 56.7 5491 117.95 G 9 23.2 8.49 58.59 5753 134.76 G 10 24.37 7.87 58.59 5422 124.89 G 11 Invalid 8.41 57.64 5514 138.22 G 12 28.04 7.85 55.76 5428 130.06 G 13 25.27 5.99 57.64 5911 122.74 G 13 25.27 5.99 57.64 5911 122.74 G 14 38.98 Invalid 67.64 6214 201.73 G 15 Invalid 7.29 No sample 5820 153.55 G 16 35.03 11.36 65.38 6214 82.33 G 17 Invalid 9.23 61.8 5729 150.42 G 18 25.59 6.92 60.48 5566 127.47 G 18 25.59 6.92 60.48 5566 127.47 G 18 25.59 6.92 60.48 5566 127.47 G 19 23.69 9.72 57.64 6030 158.69 G 20 17.21 5.66 52.92 5384 91.48 S 1 7.6 3.93 46.3 5993 37.97 S 2 Invalid 2.8 No sample 58.74 43.97 S 3 4.61 3.58 45.36 6188 47.05 S 4 19.31 4.49 52.55 6074 49.22 55.55 6774 49.22 57.64 67.64 67.65 67.89 31.7 43.46 5820 26.55 S 7 9.37 3.48 46.3 5445 33.31 58 7.74 1.52 37.76 5116 22.83 59 11.44 3.07 45.36 5675 32.07 511 Invalid 3.27 43.46 5882 49.08 511 Invalid 3.27 43.46 5882 49.08 512 27.05 7.42 58.59 6250 95.14 512 27.05 7.42 58.59 6250 95.14 513 Invalid 3.47 41.25 58.59 35.57 514 17.69 4.85 54.18 6145 60.82 515 14.41 2.96 49.14 5882 49.08 512 27.05 7.42 58.59 6250 95.14 515 19.04 4.25 43.08 6043 42.95 515 14.41 2.96 49.14 5882 49.08 51.20 51.25 51.20 51.20 51.25 51.20 51	G 4	33.51	9.92	66.51	6047	176.75
G 7 31.29 10.63 60.48 6030 148.34 G 8 15.99 6.93 56.7 5491 117.95 G 10 24.37 7.87 58.59 5753 134.76 G 10 24.37 7.87 58.59 5753 134.76 G 10 24.37 7.87 58.59 5422 124.89 G 11 Invalid 8.41 57.64 5514 138.22 G 12 28.04 7.85 55.76 5428 130.06 G 13 25.27 5.99 57.64 5911 122.74 G 14 38.98 Invalid 67.64 6214 201.73 G 15 Invalid 7.29 No sample 5820 153.55 G 16 35.03 11.36 65.38 6214 182.33 G 17 Invalid 9.23 61.8 5729 150.42 G 18 25.59 6.92 60.48 5566 127.47 G 19 23.69 9.72 57.64 6030 158.69 G 20 17.21 5.66 52.92 5384 91.48 S 1 7.6 3.93 46.3 5993 37.97 S 2 Invalid 2.8 No sample 5874 43.97 S 3 4.61 3.58 45.36 6188 47.05 S 4 19.31 4.49 52.55 6074 49.22 S 5 15.49 4.03 52.17 5172 47.05 S 6 7.89 317 43.46 5820 26.55 S 7 9.37 3.48 46.3 5445 33.31 S 8 7.74 1.52 37.76 5116 22.83 S 11 Invalid 3.27 43.46 5882 39.06 S 11 Invalid 3.27 43.46 5882 39.06 S 11 Invalid 3.27 43.46 5882 39.06 S 11 Invalid 3.47 41.25 5850 35.57 S 13 Invalid 3.47 41.25 5850 35.57 S 14 17.69 4.85 5418 6145 60.82 S 15 15.49 4.03 52.17 5172 47.05 S 6 7.89 317 43.46 5882 39.06 S 11 Invalid 3.27 43.46 5882 39.06 S 11 Invalid 3.47 41.25 5850 35.57 S 13 Invalid 3.47 41.25 5850 35.57 S 14 17.69 4.85 541.8 6145 60.82 S 15 15.41 12.96 4.914 5882 49.08 S 16 5.57 1.15 33.95 5321 21.36 S 17 20.07 6.06 46.3 6145 70.47 S 18 Invalid 1.42 5 43.08 6043 42.95 S 19 Invalid Invalid 2.724 2.872 12.8 S 5 19 Invalid Invalid No sample 3773 56.82 S 5 10 Invalid Invalid No sample 3773 56.82 S 5 15 14 12.99 33.38 985 17.55 S 5 15 1.98 Invalid Invalid No sample 3773 56.82 S 15 1.11 19.81 30.89 2725 12.15 S 15 1.14 1.99 30.89 2725 12.75 S 15 1.14 1.99 30.89 2725 12.75 S 15 1.14 1.99 30.89 2725 12.75 S 15 1.14 1.49 No sample 4990 172.03 S 17 4.5 4.36 51.03 3474 60.79 S 19 10.39 3.7 41.09 3169 39.24	G 5	30.93	11.73	65.57	5905	160.82
G 8	G 6	Invalid	14.13	67.07	6250	198.15
G 9 23.2 8.49 58.59 5753 134.76 G 10 24.37 7.87 58.59 5422 124.89 G 11						
G 10						
G 11						
G 12						
G 13						
G 14 38.98 Invalid 67.64 6214 201.73 G 15 Invalid 7.29 No sample 5820 153.55 G 16 35.03 11.36 65.38 6214 182.33 G 17 Invalid 9.23 61.8 5729 150.42 G 18 25.59 6.92 60.48 5566 127.47 G 19 23.69 9.72 57.64 6030 158.69 G 20 17.21 5.66 52.92 5384 91.48 S 1 7.6 3.93 46.3 5993 37.97 S 2 Invalid 2.8 No sample 5874 43.97 S 3 4.61 3.58 45.36 6188 47.05 S 4 19.31 4.49 52.55 6074 49.22 S 5 15.49 4.03 52.17 5172 47.05 S 6 7.89 3.17 43.46 5820 26.55 S 7 9.37 3.48 46.3 5445 33.31 S 8 7.74 1.52 37.76 5116 22.83 S 9 11.44 3.07 45.36 5675 32.07 S 10 Invalid 3.27 43.46 5882 39.06 S 11 Invalid 2.45 31.66 5685 42.38 S 12 27.05 7.42 58.59 6250 95.14 S 13 Invalid 3.47 41.25 5850 35.57 S 14 17.69 4.85 54.18 6145 60.82 S 15 14.41 2.96 49.14 5882 49.08 S 16 5.57 1.15 33.95 5321 21.36 S 19 Invalid 3.24 41.25 5850 35.57 S 18 Invalid 3.24 35.67 6024 49.33 S 20 18.16 6.63 55.76 6179 84.44 S 19 Invalid 3.24 35.67 6024 49.33 S 20 18.16 6.63 55.76 6179 84.44 S 19 Invalid 3.24 35.67 6024 49.33 S 20 18.16 6.63 55.76 6179 84.44 S 19 Invalid 3.24 35.67 6024 49.33 S 20 18.16 6.63 55.76 6179 84.44 S 19 Invalid 1.25 43.08 6043 42.95 S 19 Invalid Invalid 2.724 2872 12.8 S 6 2.64 2.99 33.38 2985 17.55 S 7 12.63 6.75 51.79 4672 96.26 S 51 1.19 10.39 3.7 41.09 3169 39.24						
G 15						
G 16						
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G 20 17.21 5.66 52.92 5384 91.48 S 1 7.6 3.93 46.3 5993 37.97 S 2 Invalid 2.8 No sample 5874 43.97 S 3 4.61 3.58 45.36 6188 47.05 S 4 19.31 4.49 52.55 6074 49.22 S 5 15.49 4.03 52.17 5172 47.05 S 6 7.89 3.17 43.46 5820 26.55 S 7 9.37 3.48 46.3 5445 33.31 S 8 7.74 1.52 37.76 5116 22.83 S 9 11.44 3.07 45.36 5675 32.07 S 10 Invalid 3.27 43.46 5882 39.06 S 11 Invalid 3.27 43.46 5882 39.06 S 11 Invalid 3.47 41.25 5850 35.57 S 14 17.69						
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S 3 4.61 3.58 45.36 6188 47.05 S 4 19.31 4.49 52.55 6074 49.22 S 5 15.49 4.03 52.17 5172 47.05 S 6 7.89 3.17 43.46 5820 26.55 S 7 9.37 3.48 46.3 5445 33.31 S 8 7.74 1.52 37.76 5116 22.83 S 9 11.44 3.07 45.36 5675 32.07 S 10 Invalid 3.27 43.46 5882 39.06 S 11 Invalid 2.245 31.66 5685 42.38 S 12 27.05 7.42 58.59 6250 95.14 S 13 Invalid 3.47 41.25 5850 35.57 S 14 17.69 4.85 54.18 6145 60.82 S 15 14.41 2.96 49.14 5882 49.08 S 16 5.57	S 1	7.6	3.93	46.3	5993	37.97
S 4 19.31 4.49 52.55 6074 49.22 S 5 15.49 4.03 52.17 5172 47.05 S 6 7.89 3.17 43.46 5820 26.55 S 7 9.37 3.48 46.3 5445 33.31 S 8 7.74 1.52 37.76 5116 22.83 S 9 11.44 3.07 45.36 5675 32.07 S 10 Invalid 3.27 43.46 5882 39.06 S 11 Invalid 2.45 31.66 5685 42.38 S 12 27.05 7.42 58.59 6250 95.14 S 13 Invalid 3.47 41.25 5850 35.57 S 14 17.69 4.85 54.18 6145 60.82 S 15 14.41 2.96 49.14 5882 49.08 S 16 5.57 1.15 33.95 5321 21.36 S 19 Inva	S 2	Invalid	2.8	No sample	5874	43.97
S 5 15.49 4.03 52.17 5172 47.05 S 6 7.89 3.17 43.46 5820 26.55 S 7 9.37 3.48 46.3 5445 33.31 S 8 7.74 1.52 37.76 5116 22.83 S 9 11.44 3.07 45.36 5675 32.07 S 10 Invalid 3.27 43.46 5882 39.06 S 11 Invalid 2.45 31.66 5685 42.38 S 12 27.05 7.42 58.59 6250 95.14 S 13 Invalid 3.47 41.25 5850 35.57 S 14 17.69 4.85 54.18 6145 60.82 S 15 14.41 2.96 49.14 5882 49.08 S 16 5.57 1.15 33.95 5321 21.36 S 17 20.07 6.06 46.3 6145 70.47 S 18 Inva	S 3	4.61	3.58	45.36	6188	47.05
S 6 7.89 3.17 43.46 5820 26.55 S 7 9.37 3.48 46.3 5445 33.31 S 8 7.74 1.52 37.76 5116 22.83 S 9 11.44 3.07 45.36 5675 32.07 S 10 Invalid 3.27 43.46 5882 39.06 S 11 Invalid 2.45 31.66 5685 42.38 S 12 27.05 7.42 58.59 6250 95.14 S 13 Invalid 3.47 41.25 5850 35.57 S 14 17.69 4.85 54.18 6145 60.82 S 15 14.41 2.96 49.14 5882 49.08 S 16 5.57 1.15 33.95 5321 21.36 S 17 20.07 6.06 46.3 6145 70.47 S 18 Invalid 3.24 35.67 6024 49.33 S 20 1	S 4	19.31	4.49	52.55	6074	49.22
S 7 9.37 3.48 46.3 5445 33.31 S 8 7.74 1.52 37.76 5116 22.83 S 9 11.44 3.07 45.36 5675 32.07 S 10 Invalid 3.27 43.46 5882 39.06 S 11 Invalid 2.45 31.66 5685 42.38 S 12 27.05 7.42 58.59 6250 95.14 S 13 Invalid 3.47 41.25 5850 35.57 S 14 17.69 4.85 54.18 6145 60.82 S 15 14.41 2.96 49.14 5882 49.08 S 16 5.57 1.15 33.95 5321 21.36 S 17 20.07 6.06 46.3 6145 70.47 S 18 Invalid 4.25 43.08 6043 42.95 S 19 Invalid 3.24 35.67 6024 49.33 S 20 <		15.49	4.03	52.17	5172	47.05
S 8 7.74 1.52 37.76 5116 22.83 S 9 11.44 3.07 45.36 5675 32.07 S 10 Invalid 3.27 43.46 5882 39.06 S 11 Invalid 2.45 31.66 5685 42.38 S 12 27.05 7.42 58.59 6250 95.14 S 13 Invalid 3.47 41.25 5850 35.57 S 14 17.69 4.85 54.18 6145 60.82 S 15 14.41 2.96 49.14 5882 49.08 S 16 5.57 1.15 33.95 5321 21.36 S 17 20.07 6.06 46.3 6145 70.47 S 18 Invalid 4.25 43.08 6043 42.95 S 19 Invalid 3.24 35.67 6024 49.33 S 20 18.16 6.63 55.76 6179 84.44 SS 1		7.89	3.17	43.46	5820	26.55
S 9 11.44 3.07 45.36 5675 32.07 S 10 Invalid 3.27 43.46 5882 39.06 S 11 Invalid 2.45 31.66 5685 42.38 S 12 27.05 7.42 58.59 6250 95.14 S 13 Invalid 3.47 41.25 5850 35.57 S 14 17.69 4.85 54.18 6145 60.82 S 15 14.41 2.96 49.14 5882 49.08 S 16 5.57 1.15 33.95 5321 21.36 S 17 20.07 6.06 46.3 6145 70.47 S 18 Invalid 4.25 43.08 6043 42.95 S 19 Invalid 3.24 35.67 6024 49.33 S 2 18.16 6.63 55.76 6179 84.44 SS 1 10.97 5.8 51.22 3935 53.63 SS 2		9.37	3.48	46.3	5445	33.31
S 10 Invalid 3.27 43.46 5882 39.06 S 11 Invalid 2.45 31.66 5685 42.38 S 12 27.05 7.42 58.59 6250 95.14 S 13 Invalid 3.47 41.25 5850 35.57 S 14 17.69 4.85 54.18 6145 60.82 S 15 14.41 2.96 49.14 5882 49.08 S 16 5.57 1.15 33.95 5321 21.36 S 17 20.07 6.06 46.3 6145 70.47 S 18 Invalid 4.25 43.08 6043 42.95 S 19 Invalid 3.24 35.67 6024 49.33 S 20 18.16 6.63 55.76 6179 84.44 SS 1 10.97 5.8 51.22 3935 53.63 SS 2 3.17 4.5 35.86 3389 19.66 SS 3					5116	22.83
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SS 19 10.39 3.7 41.09 3169 39.24						

Note: G – granite; S – schist; SS – sandstone. USV refers to ultrasonic P-wave velocity (V_p) .

(VS), $I_{s(50)}$ is weak or very weak (VW)) of input parameters were discarded. Based on the nature of the concerned rock types, a set of 290 rules was thus developed for granite and sandstone whereas a separate set of 290 rules was written for schist.

The last stage of FIS is defuzzification. To obtain a crisp value, the output variable needs to be defuzzified. In sugeno-type fuzzy inference system, defuzzification can be carried out mainly by two

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