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Application of Gustafson-Kessel algorithm in finding seismically co-pattern zones, A case study on Meybod city

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Abstract

The current paper deals with a new use of fuzzy logic in the domain of seismic zonation methodologies with a case study in Meybod, Iran. Determining the risk function of an earthquake is an important issue and for the complete solution, the seismic specialist shall necessarily find the soil response and present an appropriate zonation output to the civil engineer. For tackling this problem, a fuzzy clustering method has been applied in acquiring microtremor data more specifically in the city of Meybod. Dataset is divided into four subsets based on its intrinsic complexity by GK fuzzy clustering. Features in this classification practice are including the coordinates, the output dominant frequency of H/V method and the related amplitudes. Euclidian distance matrix norm is constructed to detect hyper ellipsoidal clusters with different orientations (shape and size) in the dataset. The cluster means are then refreshed in an iterative manner so as to identify the uniform seismic answer into the isolated gatherings. We used this method to determine the four divided seismicity regions with different range of frequencies. In addition, various type of soil structures in Meybod city with high and weak risky area have been cleared and can be applied in hazard and earthquake engineering projects. This approach was significantly well matched with clay and silt dominant on soil observed in the boreholes. Finally zonation maps based on this new method is provided.

Keywords: Seismic microzonation, fuzzy logic, fuzzy clustering, Meybod city, site effect

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1 Introduction

The analysis of regional seismic hazard through the finding of zones with seismically similar behavior is named seismic microzonation. It categorizes and symbolizes stable zones that are prone to local amplification of seismic motion as well as zones prone to seismic hazards. Seismic microzonation represents an extremely valuable tool for seismic prevention and risk assessment in the land management studies, for the design of buildings or constructions and for emergency preparation and seismic strengthening plans. It provides a knowledge on local seismic hazards in different zones and permits the establishment of hazard hierarchies that may be used to plan seismic risk mitigation measures at various scales.

Central Asia is an area with a high probability of great earthquakes, mostly due to the Asia-India crash where the northward-moving Indian plate collides the Eurasian plate (see e.g., Molnar and Tapponnier, 1975; Hatzfeld and Molnar, 2010). High seismic activity in this packed and fixed area was carried out for quantifying the level of seismic hazard. In 1969, Seed and Idriss carried out a study of the ground motion records of 1957, the San-Francisco earthquake. Their results obviously confirmed in the same urban area and only at a distance of a few hundred kilometers apart, different types of ground motions were recorded. This may mostly depend on the thickness and features of shallower and softer soil layers (Bramerini et al., 2015). Since now, many earthquakes (e.g. Mexico City, 1986; Kobe, 1992; Izmit, 1999) have been verified that local ground specifications may meaningfully control the seismic response on the surface. The second stage of severe studies happened in 1991 in Russia, the seismic hazard in terms of intensities was re-assessed for many capitals of recently independent lands in Central Asia. However, the studies, mainly following a probabilistic approach, were carried out on a national level and therefore there is not a standardized workflow available. In recent studies (see Ansal et al., 2004), it has been showing again (Faccioli, 1991; Ansal, 1994; Bard, 1994; Chavez-Garcia et al., 1996; Gueguen et al., 1998; Ansal, 1999; Athanasopoulus et al., 1999; Hartzell et al., 2001) based on the recorded earthquake damage and strong ground motions that there are numerous source and site effects (i.e. near field effects, directivity, duration, focusing, topographical and basin effects, soil nonlinearity, etc.) that are significant in measuring ground motion responses. In Iran, similar studies are done for site effect analysis in North of Tehran (Jafari, et al, 2004), Qom city (Jafari et al., 2008), Kamyaran city (Maazalahi & Hashemi, 2013), Baneh city (Hashemi, et al., 2007).

A ground motion prediction is an important key to assess and mitigate the earthquake hazard. There are some factors by which the level of strong ground motion is controlled. Site quality played an important role in the damage plan to the structures. It is mainly due to the experiences from previous San Francisco and Mexico earthquakes. It is important to validate the effect of the native site conditions for estimation of the strong ground motion and mitigation of earthquake hazards. For this purpose, methods for describing site effects are required. It is also required for the study of soil response during the strong ground shaking. As it has been noticed from many past earthquakes, the major damage to property and man-made structures is mostly found in the region of soft sediments.

In relation to diverse contexts and objectives, seismic microzonation studies may be carried out at various levels of growing complexity and commitment, from level 1 to level 3 (Bramerini et al., 2015):

• **level 1** is an introductory level for real seismic microzonation studies; it consists of a collection of existing data that are treated to divide the explored area into qualitatively homogeneous Micro-zones in relation to the above-described phenomena.

• **level 2** introduces a quantitative group associated with the homogeneous zones by using additional and focused investigations (where necessary), in addition to defining the seismic microzonation Map.

• **level 3** yields a detailed seismic microzonation map covering particular issues or areas.

A seismic microzonation study consists of three stages (Ansal et al., 2004):
(1) Estimation of the regional seismic hazard, (2) determination of the local geological and local geotechnical site conditions (3) assessment of the probable ground response and ground motion parameters on the ground surface. There may be differences between the adopted procedures with respect to these three stages (Marcellini et al., 1995a, 1995b; Lachet et al., 1996; Fäh et al., 1997; Ansal, et al., 2001).

In the design of new buildings or structures or in the projects concerning the existing buildings or structures, Seismic microzonation studies highlight possible phenomena of motion amplification induced by the lithostratigraphic and morphological characteristics of the area (Bramerini et al., 2015). Moreover, within the last 60 years, Central Asia has perceived a growth of its population (Andreev et al. 1993, Lutz 2010), accompanied by an extreme increase of the urbanization rate from around 25% in the 1950s to more than 50% nowadays (Pilz et al. 2015). Therefore, the level of seismic activity in the whole territory poses an endless danger to the safety of human life. In this article, the new method that was formerly used in seismic reflection noise suppression applications is used to find similar groupings of input attributes in seismic site response. Hence these groupings are correlated with seismic zonation of the area.

2 Central Iranian zone

The Central Iranian zone extends between Alborz and Kopehdagh from the north and Zagros and Makran in the west to south and east of Iran. The Central Iranian crust has been a decoupled part of Africa before the fetching part of Eurasia and after the opening of the Neotethys in Triassic. This microplate, which formed in pre-Paleozoic times, has no sign of any Variscan orogeny (Delaloye et al., 1981). It is fragmented by crustal faults (the Great Kavir, Nain–Baft, and Harirud faults) into several blocks. The blocks are partly surrounded by the Upper Cretaceous-to-Lower Eocene ophiolite and ophiolitic mélange (Takin, 1972). From east to west, three major crustal blocks can be distinguished: the Lut Block, the Tabas Block, and the Yazd Block (Berberian et al., 1981). The Tabas and Yazd blocks are detached by a 600-km-long and relatively narrow belt (the Kashmar- Kerman tectonic zone). The Lut block, that is the combination of Paleozoic to Mesozoic rocks, has different lithology from those of Central Iran (Crawford, 1972; Stöcklin, 1974) and hence relates to the microplate of Afghanistan-Pamir (Krumsiek, 1976; Gealey, 1977). It probably collided with Central Iran (Eurasia) during the Paleogene. The northern part of the Lut Block is covered by lava flows. (Fig. 1)

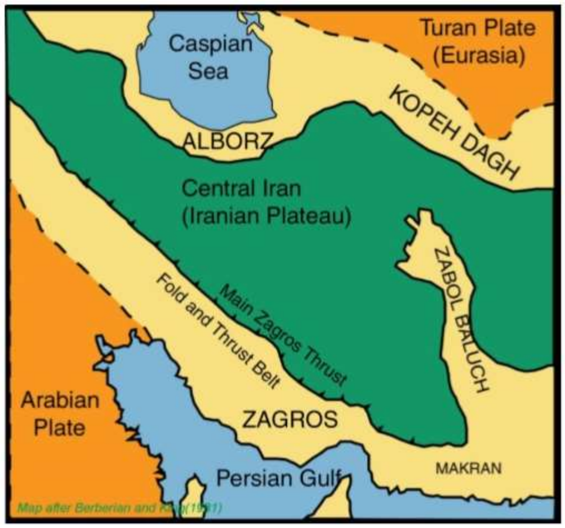

Figure 1. Simplified structural unit of Iran, between Arabian and Turan (Eurasia) Plates (Berberian & King 1981).

Central Iran plateau has a major structural geology unit, contains a number of tectonic and metallurgical structural subsystems. lithological and narrative units that have been practically continuous from Precambrian to the present (Tamimi, 2016).

3 Seismic Zonation of Yazd Province

Yazd area and its surrounding between central Iran Block and the vicinity of the Central desert is the study area. The significant effects of stress on the area are,

1) Compressive with strike-slip factor (right lateral)
2) Strike-Slip (right lateral) with tensional part)
3) Tensional
4) Strike-Slip with wide faults with activating the potential in this region is Kuhbanan, Bahabad, Rafsanjan, Anar, north of Yazd, and Dehshir- Baft faults.

Generally, this region is calm seismically. Concerning statistics studies of occurred earthquakes and analytic studies based on concentration and activity of faults in this area, five separated zones including very high risk, high risk, low risk, and very low-risk zones are identified. East and Southern parts of the region have higher seismic potential (Adib et al., 2003). So it is worth studying microzonation and find soil responses of each city separately as the result of the active tectonics of Yazd province.

4 Geology and Geotechnical Evidence of Meybod city

The microtremor data were collected from the City of Meybod, north of Yazd Province (central Iran) on a flat and clayey desert located at longitude 54°2′10″E and latitude 32°14′4″N. (Fig. 2)

Using the geotechnical studies and information from five boreholes (drilled to a depth of 70–95 m), the dominant soil type of the investigated region is clay and silt with low and high plasticity (PI = 5–80) where only in some parts, the percentages of silt and clay changes (Adib et al. 2015).

In the north and northeast of the region (station P5 and borehole BH-5), clay and silt with high plasticity are visible and to the northwest (P2 and BH-4) highly plastic clay has been increasing with depth. In the eastern part of the area, from the north to the south, (P5–P4) silt content is decreasing while clay and highly plastic clay deposits are dominant. Also, silt

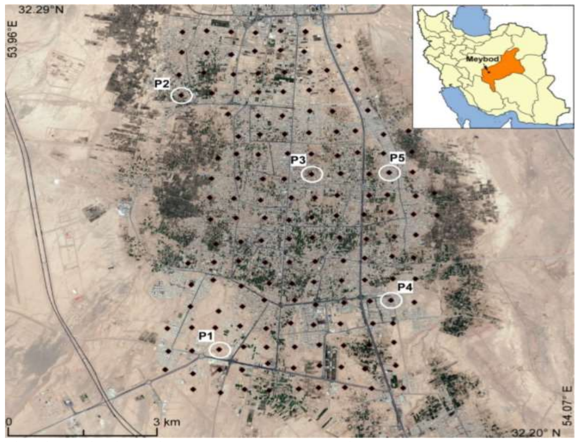

Figure 2. The location of the borehole where microtremor data were measured in the city of Meybod on the satellite image, central Iran (Mousavi et al., 2018).

content drops from P2 to P1 however, it is still dominant. Finally, the middle part of the area (P3) has silty clay as the main deposit (Mousavi et al., 2018).

5 Hyperellipsoidal algorithm for fuzzy clustering

Fuzzy sets and fuzzy logic were first introduced by Zadeh (1965). Zadeh and Wilkinson (2004) also discussed some possible presentations of fuzzy logic in geosciences data analysis. The idea of automatically separating data in subsets is known as clustering. The exact job of clustering is to define the best grouping in a set of data, where the term 'best' is achieved by mathematical validation techniques. It will be found usually by optimization of a cost function. One of the standard routines for fuzzy clustering is hyperellipsoidal discussed by Gustafson and Kessel (1978) and known as an abbreviation by GK algorithm. This algorithm uses an adaptive distance norm to detect hyperellipsoidal clusters of different directions in the dataset. So, the conventional fuzzy c-means clustering is preferred which induces the same, usually spherical, shape for all clusters. It is primarily introduced in seismic for random noise detection (Hashemi et al., 2008). In the current paper, the distance norm which is computed from the observed amplitudes in the data space is GK one,

$$\mathbf{D}^2_{\mathrm{ik}\mathbf{A}_\mathrm{i}} = (\mathbf{z}_\mathrm{k} - \mathbf{v}_\mathrm{i})^\mathrm{T}\mathbf{A}_\mathrm{i}(\mathbf{z}_\mathrm{k} - \mathbf{v}_\mathrm{i}) \quad 1 \leq \mathrm{i} \leq \mathrm{c}\,, 1 \leq \mathrm{k} \leq \mathrm{N} \tag{1}$$

where c is the number of clusters, N is the number of seismic trace samples, $\mathbf{z}_\mathrm{k}$ is the value of the k_{th} sample and i is the i_{th} cluster center. The matrices $\mathbf{A}_\mathrm{i}$ are used as optimization variables allowing each cluster to tune the distance norm to the topological shape of the data. In this way, each cluster has its specific shape. The objective function for the GK algorithm is defined as

$$\mathrm{J}(\mathrm{X};\mathrm{U},\mathrm{V},\{\mathbf{A}_\mathrm{i}\}) = \sum_{i=1}^{C}\sum_{k=1}^{N}(\mu_{ik})^m\,\mathbf{D}^2_{\mathrm{ik}\mathbf{A}_\mathrm{i}}, \tag{2}$$

where $\mu_{ik} \in$ **[0,1]** are the membership functions, which represent the degree of membership of the k^{th} sample to the i^{th} cluster. The fuzziness of the clusters is determined by the value of m (higher values result in softer margins between the clusters. The matrix containing the membership functions is $\mathbf{U} = [\mathbf{0},\mathbf{1}]_{C\times N}$ and **V** is the matrix of the cluster centers, **V = [V1,V2,...,Vc].** The mission now is to minimize **J** which could in principle be done simply by making $\mathbf{A}_\mathrm{i}$ less positive definite. However, this result is not anticipated and therefore $\mathbf{A}_\mathrm{i}$ must be well constrained. One usual way for this hard constraint is defined on its determinant value. Thereby the shapes of the clusters are optimized while their volumes remain constant, i.e.,

$$\det(A_i) = \rho_i\ ,\ \rho > 0 \qquad (3)$$

The covariance matrix for the ith cluster is defined by

$$\mathbf{F}_i = \frac{\sum_{k=1}^{N}\left(\mu_{ik}^{(L-1)}\right)^{m}(\mathbf{z}_k-\mathbf{v}_i^{(L)})(\mathbf{z}_k-\mathbf{v}_i^{(L)})^{T}}{\sum_{k=1}^{N}(\mu_{ik}^{(L-1)})^{m}} \qquad (4)$$

Robust methods for computing the covariance are discussed in Babuska et al (2002). The best number of clusters can be found based on a validity measure. Xie and Beni (1991) introduced a fuzzy cluster validity measure which is known as the Xie–Beni (XB) index. This index quantifies the data distribution inter-cluster with respect to the distance of intra-cluster. So having a smaller XB means the clustering is more successful in finding well-separable structures in the data. Knowing the cluster centers and membership functions, the definition of XB is

$$\mathrm{XB}(c) = \frac{\sum_{i=1}^{c}\sum_{k=1}^{N}(\mu_{ik})^{m}\|\mathbf{z}_k-\mathbf{v}_i\|^{T}}{\mathrm{N}.\min_{i,k}\|\mathbf{z}_k-\mathbf{v}_i\|^{T}} \qquad (5)$$

The XB index is evaluated for each partition. An abrupt fall of the index shows a sufficient number of the clusters to be chosen.

Where α_k are set by the user for each clustered section. The above formula yields a section with reduced random noise contamination using the numerical criterion of inter-cluster correlation and user weights.

6 Results of clustering

The fuzzy G-K algorithm is used for 160 microtremor stations in the city. The data is processed using fractal techniques by Adib et al. (2015). The processed data for 160 stations in 4 columns (X, Y, Peak Frequency and Peak Amplitude) are the input features (attributes) for the clustering routine. The aim of choosing these attributes is to find spatial correlations as a hard constraint (X and Y of the stations), dependencies of zones to the recorded peak frequency and finally the dependency on amplification factors. Primarily, the 4 cluster means are randomized by fuzzy clustering algorithm and in each iteration, the means are updated accordingly. (Fig. 3)

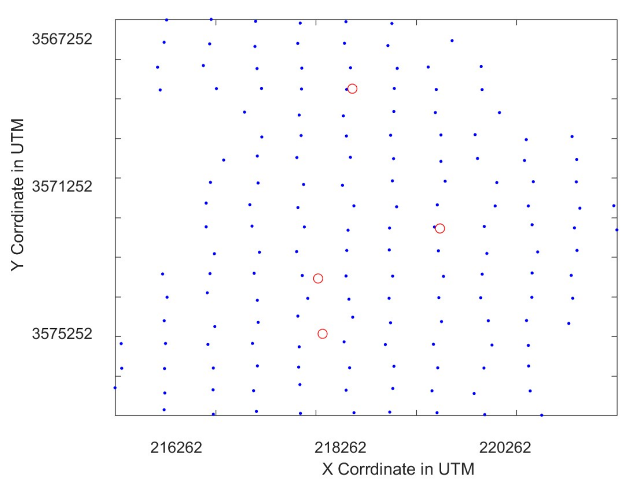

Figure 3. The coordinates of 160 stations for microtremor recording signals is presented by blue points. The red dots are the initial mean for four fuzzy clusters.

The optimum number of clusters is found as four for this dataset. The main criteria for this parameter selection is the minimization of inter-class to the intra-class distance that is named as Dunn index (Dunn, 1973) in fuzzy clustering literature. The result of clustering for a higher percentage of membership values (values between 0.5 and 1 for each class) is shown in Figure 4.

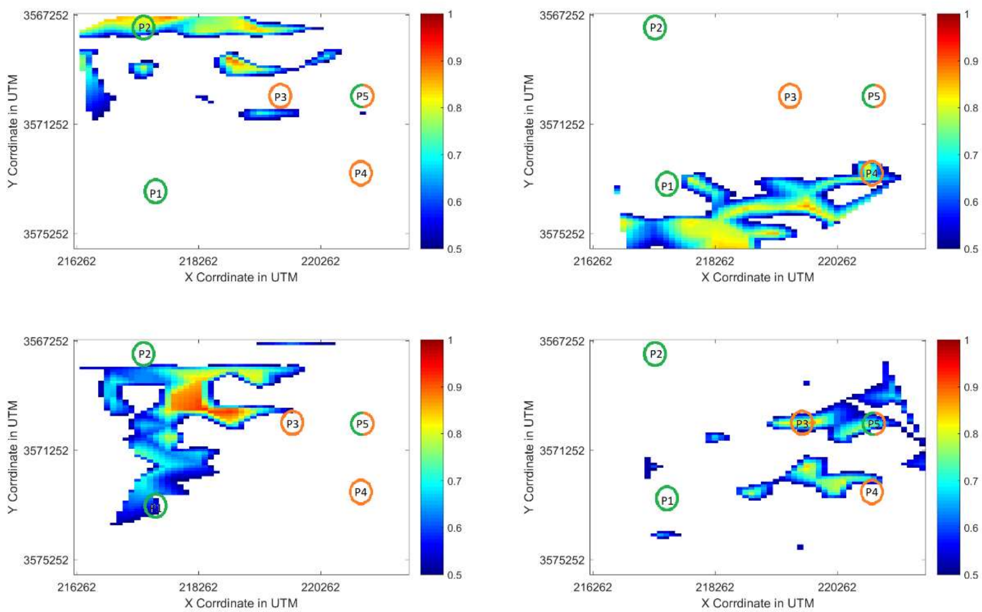

Figure 4. The results of fuzzy G-K clustering for Meybod microtremor data. Fuzzy membership values of four clusters are shown in four subplots. Only the membership values between 0.5 – 1 (higher probability for that class) is presented. P1, P2, P3, P4, and P5 fairly deep boreholes are shown by circles. Orange=Clay dominant, Green=Silt dominant, Orange-Green=Mix Clay and Silt

7 Interpretation of the results

The clustering results primarily show a nice correlation between observed lithology in boreholes. Silt is dominant in P1 and P2. So in Figure 4, it seems that no extra evident information like water level changes can distinct class 1 (top-left) and 3 (bottom-left). Moreover, morphological maps of cluster membership are good support to mix class 1 and 3 and interpret it as the lower plasticity and dried zone. Top right in the same figure, belongs to Clay with higher plasticity and finally, bottom right is a mixed continuous zone of silt and clay. Figure 5 illustrated the fuzzy clustering map. In Figure 6, a more tangible map of the city that is the final interpretation of Meybod zonation is shown. The city is regarded as a desert with very deep water levels. However, the evidence of subsidence in the south of Meybod is reported by Zare (2011). Our finding from the clustering shows that the green area has a risky soil structure regarding the other parts.

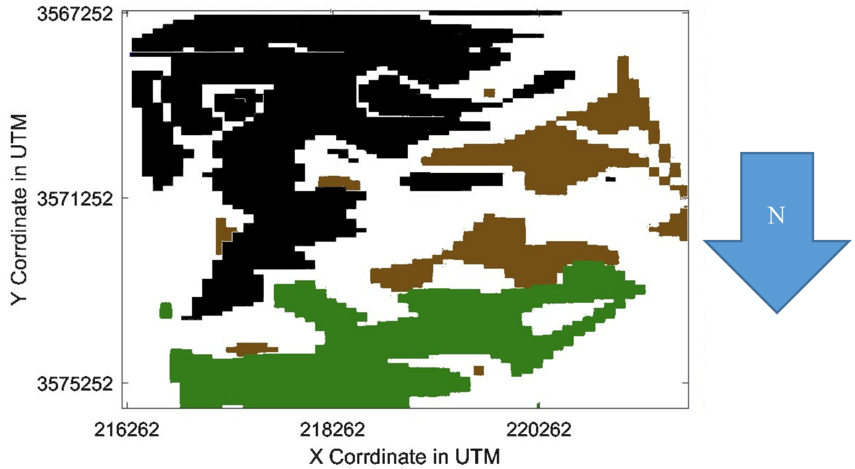

Figure 5. The ??? of fuzzy clustering maps. Black: interpreted as the lower plasticity and dried zone and silt dominant area of the city, Green: Interpreted as the higher plasticity and clay dominant, Brown: Interpreted as mixed clay and silt.

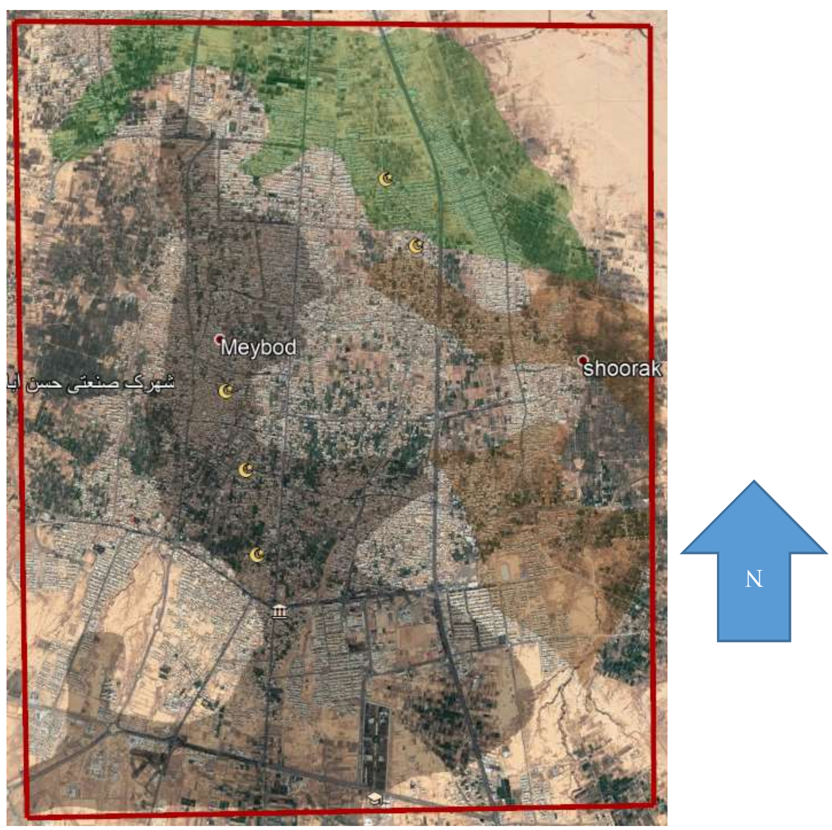

Figure 6. The final interpretation based on smoothing of Fuzzy G-K results. Green is high risk zone, Brown is medium risk zone, black is low risk zone. Other parts are not grouped with other parts.

8 Conclusion

Fuzzy clustering on X - Y coordinates, dominant frequency, dominant amplitudes of microtremor data shows interpretable zones (clusters). These four-zone have a high correlation with the most frequency lithology and they can combine to form 3 areas with successive high (green), mid (brown) and low (black) seismic risk probabilities. It is expected that under an abrupt change in the dynamic situation of soil (e.g. an earthquake), the behavior of soil is different. It is recommended to run more deterministic studies like seismic refraction/ shallow high resolution reflection and array microtremor to find better insights especially in the high risk black area.

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