Research on the spatial analysis method of seismic hazard for island

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Abstract. Seismic hazard analysis(SHA) is a key component of earthquake disaster prevention field for island engineering， whose result could provide parameters for seismic design microscopically and also is the requisite work for the island conservation planning's earthquake and comprehensive disaster prevention planning macroscopically, in the exploitation and construction process of both inhabited and uninhabited islands. The existing seismic hazard analysis methods are compared in their application, and their application and limitation for island is analysed. Then a specialized spatial analysis method of seismic hazard for island (SAMSHI) is given to support the further related work of earthquake disaster prevention planning, based on spatial analysis tools in GIS and fuzzy comprehensive evaluation model. The basic spatial database of SAMSHI includes faults data, historical earthquake record data, geological data and Bouguer gravity anomalies data, which are the data sources for the 11 indices of the fuzzy comprehensive evaluation model, and these indices are calculated by the spatial analysis model constructed in ArcGIS's Model Builder platform.

Keywords: Seismic hazard analysis, spatial analysis method of seismic hazard for island, fuzzy comprehensive evaluation model

1. Introduction

Island is the land area which is surrounded by water and above water at high tide, according to the definition in "United Nations convention on the law of the sea", and such definition is also referenced in "People's Republic of China island protection act" [1]. Since the majority islands are quite small, island is defined as a small piece of land scattered in the ocean whose area is more than 500 square meters in "National Standard Oceanographic Terms Marine Geology". According to "The bulletin of island statistic survey in 2015", there are 11000 islands in China, accounting for 0.8% of the total land area in China. Chinese island resource is relatively abundant, since the world island area does not exceed 1/15 of the world's total land area.

Among Chinese islands, there are more than 400 islands with permanent residents, which accounts for more than 98% of the Chinese total island area. For the uninhabited islands, the first uninhabited islands exploitation list is published, including 187 islands, in 2011, following the promulgation of "Island Protection Act". The list shows that the dominant uses are tourist & recreation, transportation & industry. Facing the increasing islands exploitation projects, it is a fundamental work to carry out the island Seismic hazard analysis (SHA).

Chinese island laws and regulations systems are gradually improving, and it is put forward in "Island Protection Act" that Island Management Information System should be constructed [2]. With the fast development of spatial science & technology and information technology, spatial analysis tools and spatial decision support models are facilitating this work. In the exploitation and construction process of both inhabited and uninhabited islands, SHA is a key component of island engineering's earthquake disaster prevention work, whose result could provide parameters for seismic design microscopically and also is the requisite work for the island conservation planning's earthquake and comprehensive disaster prevention planning macroscopically. Under this background, the research content of this paper is designed as constructing a specialized spatial analysis method of seismic hazard for island (SAMSHI) which is suitable for island and serves as the basement for island earthquake resistance and disaster prevention planning, under the application analysis of the existing SHA methods and island feature.

2. Application analysis of the existing SHA method

SHA is the scientific evaluation work of the probable earthquake influencing degree of the engineering construction site in the differently defined following years, which is under the foundation of the detailed research and analysis of seismic and geologic environment, and providing the probability level of the site earthquake influencing degree in the differently defined following years, considering all seismic influences in and surrounding the site, using rigorous mathematical statistics method [3]. The influencing degree is finally indicated by acceleration peak, acceleration response spectrum, duration of ground motion, etc.

SHA works can be Zoning Map of Ground Motion Parameters (ZMGMP) of China, Seismic Zoning (SZ), and Seismic safety evaluation (SSE) for different application area, and these applications all adopt Probabilistic Method. For the SHA works of island, the most convenient way is referencing GB18306-2015, i.e. ZMGMP of China. But the accuracy and scale could not satisfy the requirement for island [4]. The specialized SZ and SSE works could satisfy the accuracy while the expense is high and the field exploration equipment is not convenient in island for transportation difficulties [5]. The SHA method for island, researched in this paper, is used directly in the phase of earthquake resistance and disaster prevention planning, but not engineering construction phase, in which SZ and SSE methods are more appropriate. Since three existing methods are all not suitable for the research purpose of this paper, an island SHA method need be explored for the phase of disaster prevention planning.

At present, some scholars began to study the application of soft computing in disaster risk zoning to express the fuzzy feature of disaster probability [6]. In this paper, fuzzy mathematics theory and spatial analysis technology, based on geographic information system (GIS), are adopted to develop the spatial analysis method of seismic hazard for island (SAMSHI). The SAMSHI mainly serves for the disaster prevention planning, included the models of fuzzy mathematics, statistics, etc., bases on the spatial database of faults data, historical earthquake record data, geological data and Bouguer gravity anomalies data, uses the software platform of GIS and spatial analysis modeling tools, and finally generates the island's fuzzy identification result for each seismic hazard degree.

3. Spatial database for SAMSHI

3.1 Data processing

Like other SHA methods, the basic data for SAMSHI include faults data, geological data and seismic data. All these data needed for SAMSHI are stored in a basic spatial database, Geodatabase in the Platform of ArcGIS 9, as vector data. The coordinate system (geographic coordinate system and projection) are uniformed [7]. The geographic coordinate system select the frequently-used GCS_Beijing_1954, and projection coordinate system select Beijing_1954_GK_zone_20N, because the research areas are mainly located on the longitude range of 114-120 which is the 20th zone of the 6 degree-zoning system. The parameters for all SAMSHI's spatial data are unified as:

Horizontal coordinate system
Projected coordinate system name: Beijing_1954_GK_Zone_20N
Geographic coordinate system name: GCS_Beijing_1954
Map Projection Name: Transverse Mercator
Scale Factor at Central Meridian: 1.000000
Longitude of Central Meridian: 117.000000
Latitude of Projection Origin: 0.000000
False Easting: 500000.000000
False Northing: 0.000000
Planar Coordinate Information
Planar Distance Units: meters
Coordinate Encoding Method: coordinate pair
Coordinate Representation
Abscissa Resolution: 0.000362
Ordinate Resolution: 0.000362
Geodetic Model
Horizontal Datum Name: D_Beijing_1954
Ellipsoid Name: Krasovsky_1940
Semi-major Axis: 6378245.000000
Denominator of Flattening Ratio: 298.300000

Even after the uniformed setting of coordinate system, some maps may not overlap each other well, then Geo-referencing is needed to rectify them. For example, 3 times of affine transforming and 2 times of projection transforming are used to adjust the geologic data to match the fault map.

IOP Conf. Series: Journal of Physics: Conf. Series **842** (2017) 012024 doi:10.1088/1742-6596/842/1/012024

3.2 The fault data

The Chinese Fault Map is shown in figure 1. In the table of content column, there are 27 categories of faults, i.e. compressive torsional fault, measured detachment fault, measured right-lateral strike-slip fault, measured composite fault zone, measured active fault, measured thrust fault, etc. there are 32522 features in this map, whose spatial and attribute data are stored in the Geodatabase.

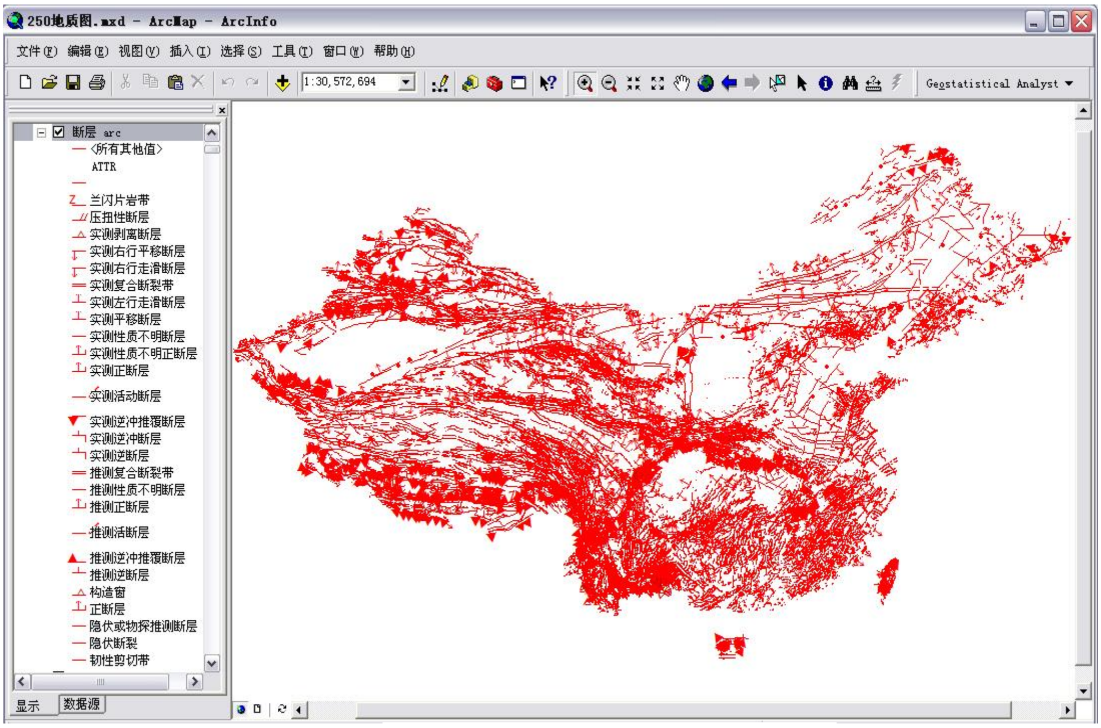
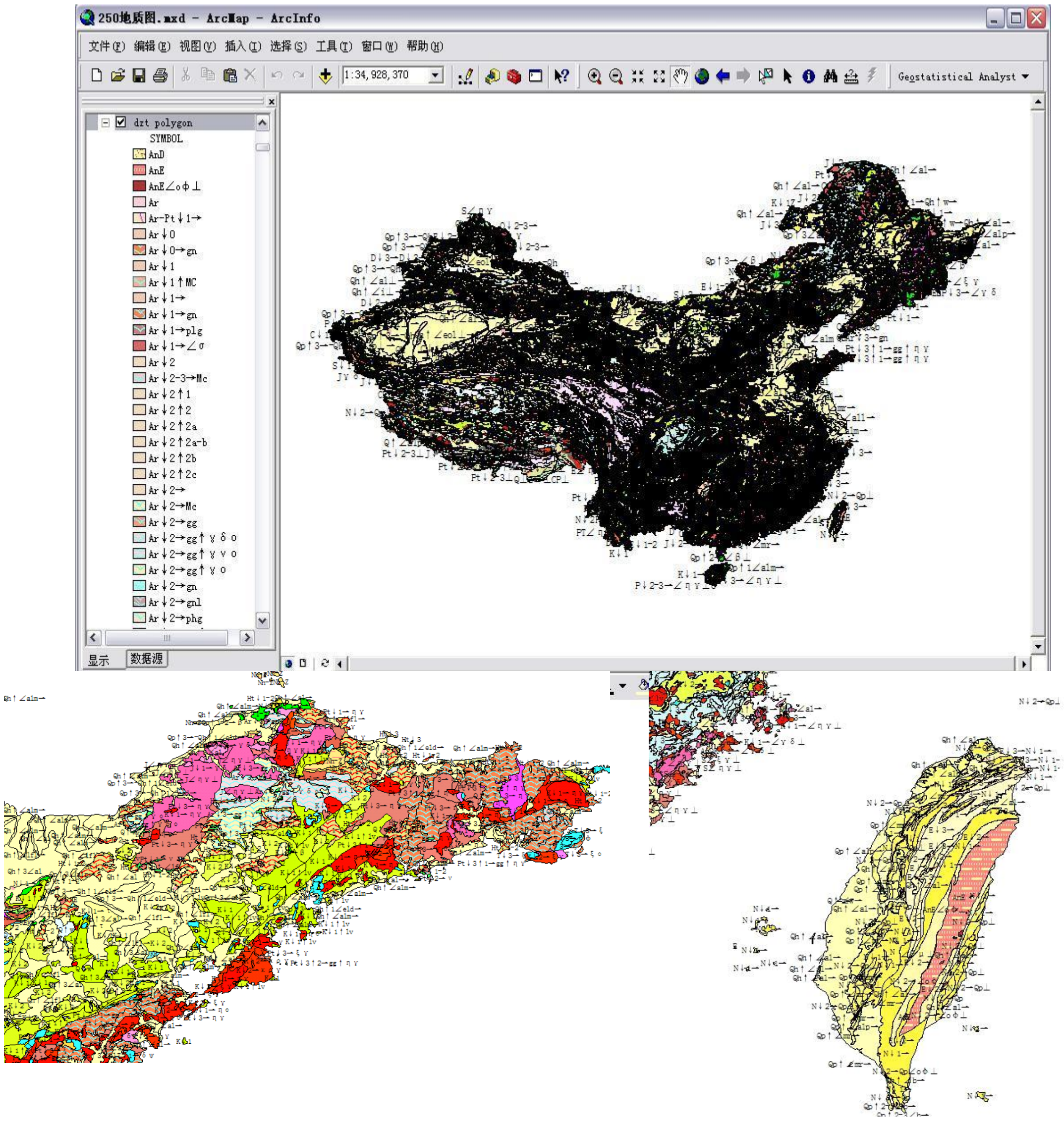


Figure 1. Chinese fault map.

3.3 The fault data

The Chinese Geological Map is shown in figure 1. In this map, there are 61825 geological units. In the table of content column, the displaying symbols and labels of geological units reference Stratigraphic Code of China [8]. Zooming to Shandong Province and Taiwan Province, the Geological Map can be shown more clearly. There are 61825 features in this map, whose spatial and attribute data are stored in the Geodatabase.



（**a**） Chinese Shandong Province. （**b**）Chinese Taiwan Province.

Figure 2. Chinese geological map

3.4 The earthquakes data

Parts of Chinese historical earthquakes data are shown in figure 3 as Chinese earthquakes (above magnitude 6) map, and the histograms based on year and magnitude are also appended. The attribute data include earthquake time, location, magnitude, focal depth, etc. There are six feature classes of earthquake data, i.e. modern earthquake swarm, modern sequence, historical earthquake swarm, historical sequence, modern seismic data and historical seismic data in the Geodatabase.

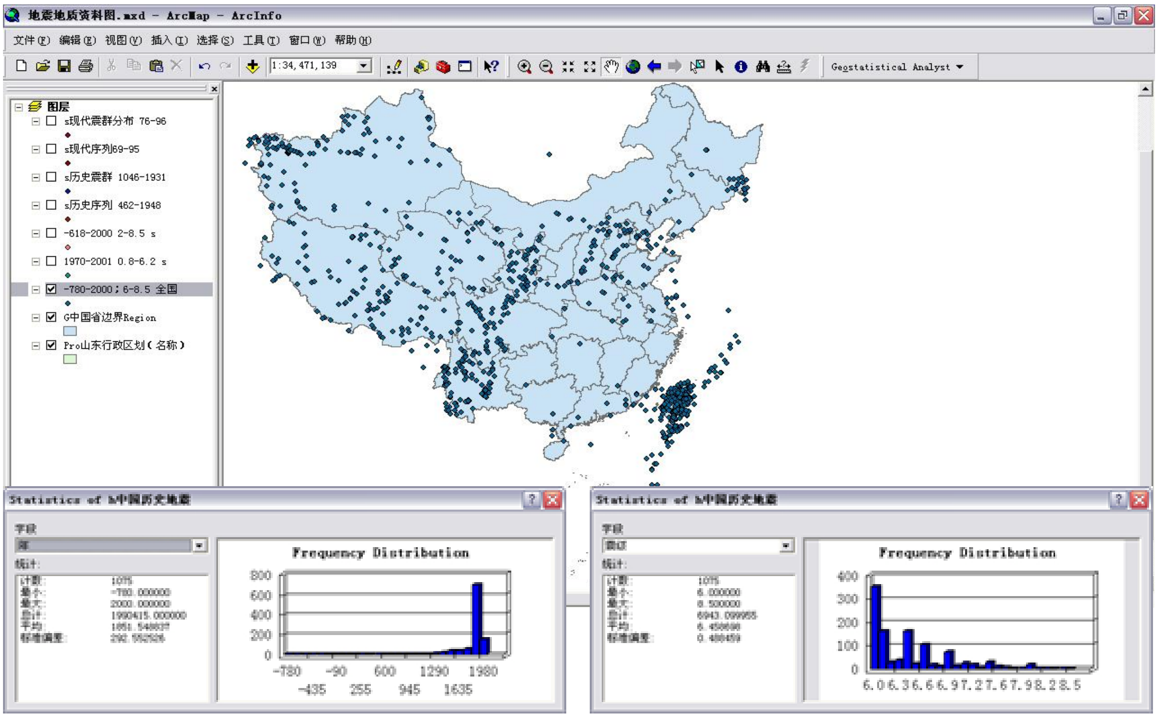


Figure 3. Chinese earthquakes (above magnitude 6) map

4. Fuzzy comprehensive evaluation model of SAMSHI

The ultimate calculation model of SAMSHI is based on fuzzy comprehensive evaluation method (FCEM). The SHA is an essentially comprehensive evaluation process of multiple factors, i.e. converting statistical index of the evaluation object in different aspects and dimensions to dimensionless relative evaluation values and synthesizing these relative evaluation values.

4.1 Evaluation set of FCEM

The seismic hazard degrees of SAMSHI are defined as large, medium and small, which form the evaluation set of FCEM for SAMSHI. The Evaluation set and its corresponding ground motion parameters are shown in table 1.

Table 1. Evaluation set of FCEM for SAMSHI.

	Seismic hazard degrees	Earthquake magnitude beyond the probability of 10% for the next 50 years
v_1	Small	$M < 6$
v_2	Medium	$6 \le M \le 7$
v_3	Large	$M > 7$

4.2 Evaluation indices system of FCEM

The domestic and foreign research scopes of seismic hazard analysis generally include the following four aspects: analysis of uncertainty of earthquake location, analysis of uncertainty of earthquake occurrence time, analysis of uncertainty of earthquake magnitude and analysis of uncertainty of earthquake motion propagation [9]. The construction of evaluation indices system of FCEM for SAMSHI should consider and combine these scopes.

Following the systematic, concise, independent and operable principles, this paper uses system analysis, frequency statistics and expert consultation method to select evaluation index, and finally form the evaluation indices system of FCEM for SAMSHI, which is shown in table 2. It should be noted that all of these indices selected are quantitative, so as to avoid the subjectivity of qualitative indices and ensure the objectivity of the evaluation.

Table 2. Evaluation indices system of FCEM for SAMSHI.

	Indices	Weight
B_1	Within 150 km of the evaluation area, the area of Bouguer gravity anomalies slope grid map in set threshold.	0.0472
B_2	Within 150 km of the evaluation area, the average value of geological parameter.	0.0265
B_3	Within 150 km of the evaluation area, the earthquakes number above M6.	0.2252
B_4	Within 150 km of the evaluation area, the maximum earthquake magnitude.	0.0805
B_5	Within 150 km of the evaluation area, the maximum earthquake magnitude in recent 200 years.	0.1218
B_6	Within 150 km of the evaluation area, the M-lnY curve's area integral ratio of the recent 200 years to the 200 years before last	0.0572
B_7	Within 150 km of the evaluation area, the seismic frequency ratio of the recent 200 years to the 200 years before last	0.026
B_8	Within 150 km of the evaluation area, the intercept of Gutenberg curve based on the seismic frequency statistics.	0.1143
B_9	Within 150 km of the evaluation area, the absolute value of the slope of Gutenberg curve based on the seismic frequency statistics.	0.1143
B_{10}	Within 150 km of the evaluation area, the annual average incidence rate of earthquakes above magnitude 4 in recent 100 years.	0.1275
B_{11}	Within 150 km of the evaluation area, the total length of fault	0.0595

4.3 Weights of indices

The Analytic Hierarchy Process method, which is put forward by T. L. Saaty, is adopted to calculate the weights of indices [9]. The decision matrix for evaluation indices system of FCEM for SAMSHI is shown in table 3.

Table 3. Decision matrix for evaluation indices.

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11
B1	1	3	1/5	1/4	1/4	1	3	1/3	1/3	1/3	1
B2	1/3	1	1/5	1/3	1/4	1/3	1	1/3	1/4	1/5	1/3
B3	5	5	1	3	2	3	5	3	3	2	4
B4	4	3	1/3	1	1/2	2	3	1/2	1/2	1/2	1
B5	4	4	1/2	2	1	2	4	1	1	1	2
B6	1	3	1/3	1/2	1/2	1	2	1/2	1/2	1/2	1
B7	1/3	1	1/5	1/3	1/4	1/2	1	1/5	1/4	1/5	1/3
B8	3	3	1/3	2	1	2	5	1	1	1	2
B9	3	4	1/3	2	1	2	4	1	1	1	2
B10	3	5	1/2	2	1	2	5	1	1	1	3
B11	1	3	1/4	1	1/2	1	3	1/2	1/2	1/3	1

According to the consistency test result, the consistency ratio value 0.0251 can satisfy the consistency test demand of being smaller than 0.1, and the weights set result is:

Wi (i =1，2，…，11)=（0.0472，0.0265，0.2252，0.0805，0.1218，0.0572，0.0260，0.1143，0.1143，0.1275，0.0595）, which is shown in the column weight in table 2.

4.4 Spatial analysis models of the 11 indices

The spatial analysis models for the 11 indices of the evaluation indices system of FCEM for SAMSHI are all constructed in the Model Builder of ArcGIS 9 which is embedded in Arcmap and can use all the spatial analysis tools in ArcToolbox. An island in Yantai of Shandong Province is taken as a sample, and its spatial analysis process of index B1 is elaborated as an example.

Bouguer Gravity Anomalies (BGA) is the observation result of gravimeter, a gravity difference after the rectification of latitude, height, interface layer and terrain, reflecting the depth change of Moho surface, i.e. the change of crust depth [10], [11].

The original BGA map is contour map. After the spatial analysis process of "contour→TIN→DEM→slope", the slope grid map of BGA is generated and shown in figure 4. It also reveals that the value distribution of the slope grid has strong correlation with the earthquake distribution, with the overlapping and further comparison of the distribution map of historical earthquakes above magnitude 6.

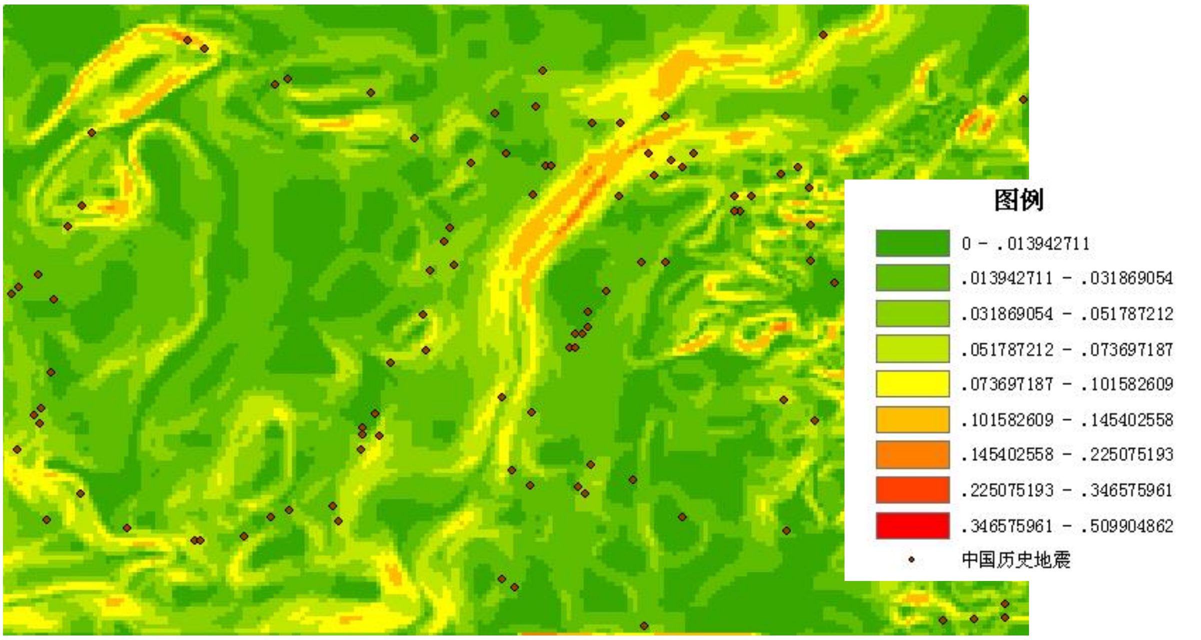


Figure 4. Slope grid map of BGA

According to the statistical analysis of the slope grid, the threshold is set to be 0.086, and the area of slope grids whose values are smaller than 0.086 is 7124.83 square kilometers, in the slope grid map of BGA, within 150 km of the evaluation area, i.e. an island in Yantai of Shandong Province.

Finally, the other 10 indices of an island in Yantai of Shandong Province are all calculated, and another sample of an island in Qingdao of Shandong Province's analyzed for comparison. These two samples' calculated results are shown in table 4.

Table 4. 11 indices value of FCEM for two samples

	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	B_9	B_{10}	B_{11}
An island of Yantai	7124.83	0.474	4	7.4	7.4	435/162.2 2.682	126/42 3	3.875	0.778	0.2	638119
An island of Qingdao	14362.16	0.342	3	7	6.2	293/95.2 3.078	114/26 4.38	3.252	0.668	0.07	1519401

5. Membership function of the indices

The membership function of all the 11 indices for v_1 fuzzy subset uses the descending half trapezoid distribution function. The membership function expression is:

$$\frac{\tilde{A}(x)}{v_1}=\begin{cases}1 & 0\le x\le a_{i1},\\ \dfrac{a_{i2}-x}{a_{i2}-a_{i1}}, & a_{i1}<x\le a_{i2},\\ 0 & a_{i2}<x,\end{cases}$$

i=1,2,⋯,11, indicating 11 indices.

The membership function of all the 11 indices for v_3 fuzzy subset uses the ascending half trapezoid distribution function. The membership function expression is:

$$\frac{\tilde{A}(x)}{v_3}=\begin{cases} 1 & 0 \le x \le a_{i3}, \\ \dfrac{a_{i4}-x}{a_{i4}-a_{i3}}, & a_{i3} < x \le a_{i4}, \\ 0 & a_{i4} < x, \end{cases} \quad i=1,2,\cdots,11, \text{ indicating 11 indices.}$$

The membership function expression of all the 11 indices for v_2 fuzzy subset is ：

$$\frac{\tilde{A}(x)}{v_2}=1-\frac{\tilde{A}(x)}{v_1}-\frac{\tilde{A}(x)}{v_3}.$$

The parameter values of a_{i1}、a_{i2}、a_{i3}、a_{i4}, the membership degrees for the evaluation set of the two samples are shown in table 5.

Table 5. Membership degrees for the evaluation set of the two samples.

B_i	a_{ij}	r_{mn}(An island in Yantai)	r_{mn}(An island in Qingdao)	Transformation of x
B_1	$a_{11}=0.03$ $a_{12}=0.08$ $a_{13}=0.12$ $a_{14}=0.22$	$r_{11}=0$ $r_{12}=1$ $r_{13}=0$	$r_{11}=0$ $r_{12}=0.17$ $r_{13}=0.83$	$x/\pi \cdot 150^2$
B_2	$a_{21}=0.3$ $a_{22}=0.35$ $a_{23}=0.39$ $a_{24}=0.55$	$r_{21}=0$ $r_{22}=0.47$ $r_{23}=0.53$	$r_{21}=0.14$ $r_{22}=0.86$ $r_{23}=0$	no
B_3	$a_{31}=2$ $a_{32}=5$ $a_{33}=7$ $a_{34}=10$	$r_{31}=0.33$ $r_{32}=0.67$ $r_{33}=0$	$r_{31}=0.67$ $r_{32}=0.33$ $r_{33}=0$	no
B_4	$a_{41}=6.5$ $a_{42}=7.0$ $a_{43}=7.5$ $a_{44}=8.5$	$r_{41}=0$ $r_{42}=1$ $r_{43}=0$	$r_{41}=0$ $r_{42}=1$ $r_{43}=0$	no
B_5	$a_{51}=6.0$ $a_{52}=6.5$ $a_{53}=7.0$ $a_{54}=7.5$	$r_{51}=0$ $r_{52}=0.2$ $r_{53}=0.8$	$r_{51}=0.6$ $r_{52}=0.4$ $r_{53}=0$	no
B_6	$a_{61}=0.5$ $a_{62}=1.5$ $a_{63}=2.0$ $a_{64}=3.0$	$r_{61}=0$ $r_{62}=0.32$ $r_{63}=0.68$	$r_{61}=0$ $r_{62}=0$ $r_{63}=1$	no
B_7	$a_{71}=1.0$ $a_{72}=3.0$ $a_{73}=3.5$ $a_{74}=5.0$	$r_{71}=0$ $r_{72}=1$ $r_{73}=0$	$r_{71}=0$ $r_{72}=0.41$ $r_{73}=0.59$	no
B_8	$a_{81}=2.5$ $a_{82}=3.0$ $a_{83}=3.5$ $a_{84}=4.0$	$r_{81}=0$ $r_{82}=0.25$ $r_{83}=0.75$	$r_{81}=0$ $r_{82}=1$ $r_{83}=0$	no
B_9	$a_{91}=1.25$ $a_{92}=1.32$ $a_{93}=1.4$ $a_{94}=1.5$	$r_{91}=0.5$ $r_{92}=0.5$ $r_{93}=0$	$r_{91}=0$ $r_{92}=0.03$ $r_{93}=0.97$	x^{-1}
B_{10}	$a_{10,1}=0.03$ $a_{10,2}=0.08$ $a_{10,3}=0.15$ $a_{10,4}=0.25$	$r_{10,1}=0$ $r_{10,2}=0.5$ $r_{10,3}=0.5$	$r_{10,1}=0.2$ $r_{10,2}=0.8$ $r_{10,3}=0$	no
B_{11}	$a_{11,1}=5$ $a_{11,2}=5.5$ $a_{11,3}=6.0$ $a_{11,4}=6.5$	$r_{11,1}=0$ $r_{11,2}=1$ $r_{11,3}=0$	$r_{11,1}=0$ $r_{11,2}=0.64$ $r_{11,3}=0.36$	log(x)

Note: i=1,2,⋯,11； j=1,2。 r_{mn}(m=1,2,⋯,11; n=1,2)

Weighted average fuzzy operator is used here, i.e. $B=W \circ R$, to get the fuzzy comprehensive evaluation result, which is shown in table 6.

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Table 6. The fuzzy comprehensive evaluation result of SAMSHI for two samples.

vi	An island in Yantai	An island in Qingdao
v1	0.1315	0.2532
v2	0.5687	0.5028
v3	0.2998	0.2440
result	v2	v2

Although Seismic hazard degrees of the two samples are all evaluated as being medium, the membership degrees for each subset are totally different, and the seismic hazard degrees of an island in Yantai is obviously higher.

6. Conclusion

The existing seismic hazard analysis methods are not applicable for island seismic hazard analysis, a specialized spatial analysis method of seismic hazard for island (SAMSHI) is given to fit the island feature and support the further related work of earthquake disaster prevention planning. The basic spatial database, the fuzzy comprehensive evaluation model, and the spatial analysis process of the indices are introduced, taking two islands in Yantai and Qingdao of Shandong province as samples.

7. References

[1] Zelin W 2006 Analysis on island system in the law of the sea stipulates of united nations *Journal of Huazhong University of Science and Technology* **1** pp 51-55
[2] Yang G 2013 *The comparative study of island management system between China and foreign countries* (Qingdao: The ocean university of China) pp 65
[3] Huiteng C 2006 *The seismic risk analysis in downtown areas of Chongqing* (Chongqing: Chongqing University) pp 134
[4] Mengtan G and Shoude L 2006 The discussion on principles of seismic zonation of the next generation *Technology for earthquake disaster prevevtion* **1** pp 1-6
[5] Xingxian H, Yuming Z, Mengtan G, Rongyu T , Guoxing C, Xiaojun L and Fengxin Z 2005 *Evaluation of seismic safety for engineering sites* (Beijing: Standards Press Of China)
[6] Hemetsberger M, Klinger G, Niederer S and Benedikt J 2002 Risk assessment of a avalanches - a fuzzy GIS application *Proc. of the 5th int. FLINS Conf.* pp 395-402
[7] Banggu L and Xuepei H 2004 A study on coordinate transformation of multi-spatial data in GIS *Geomatics & Spatial Information Technology* **1** pp 26-30
[8] LiwenX, Zhaoling Z and et al 1999 *Stratigraphical lexicon of China* (Beijing: Seismological Press) p 95
[9] Saaty T L 1980 *The Analytic Hierarchy Process* (New York: McGraw-Hill)
[10] Shengming F and Rui F 1997 Seismicity and characteristics of anomalous isostatic gravity in central Asia *Acta Seismologica Sinica* **6** pp 650-654
[11] Shaoan S, Aimin X and Hui L 1999 Research on evolution of western Yunnan and Beijing regional gravity fields and their relationship with earthquake *Earthquake* **1** pp 97-106