Potential Location for Relief Center for Earthquake Hazards Using Bipolar Fuzzy Graphs Example from Kutch Area, Gujarat, India

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Abstract Seismic hazards are severe natural disasters for which we must stay prepared, especially at locations the hazard has its highest chance. The Kutch area in western India is one such terrain. In this work, we apply the bipolar fuzzy graph theory to locate the best possible relief centers in Kutch in the context of its future major seismicity event. Considering several geographic issues, Bhuj and Mandvi are found to be the two locations where such relief centers can be established. Bhuj being a city much better established than Mandvi, we apply "*human judgement*" and choose the former as the best possible location for the relief center.

Keywords Numerical modeling · Tectonics · Seismicity · Deformation of rocks · Rift basin · Rock mechanics

1 Introduction

Tectonic and structural geological modeling analyses spatial events and structures numerically. In a few simpler cases dealing with connection issues for several nodes, one can apply the graph theory (e.g., Mukherjee, (2019), Sanderson et al., (2019)). The theory works when there is a complete surety of interconnection of nodes/vertices through edges. Zadeh (1965) introduced the concept of fuzzy sets, which was applied to solve several scientific and engineering research problems where uncertainty was involved. In the geoscientific context, Justman et al. (2020) presented the broad applications of fuzzy set theory to deal with tectonic problems. Anand et al. (2021) presented a fuzzy set theory to explain the kinematics of the ductile shear zones. Manjusha et al. (2023) utilized fuzzy graph theory to demonstrate how to deal with

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uncertainties in fluid flow through fractured media. Klügel (2008) reviewed several numerical techniques used in seismic data analysis where (fuzzy) graph theory has been referred.

This article applied the concept of bipolar fuzzy graphs (BFG) to find the best possible locations for relief centers for future earthquakes that may hit the Kutch area in western India.

2 Bipolar Fuzzy Graphs (BFG)

Zhang (1994) presented the concept of bipolar fuzzy sets (BFS) by generalizing the concept of fuzzy sets. BFS has its membership degree ranging -1 to $+1$. A membership degree $= 0$ in a BFS connotes that the element is irrelevant to the corresponding property. Membership degree of an element to be [0, 1] indicates that it somewhat satisfies the property. Membership degree equal to $[-1, 0]$ indicates that the element approximately satisfies the implicit counter-property. Positive information implies that what is granted is plausible. On other hand, negative information denotes impossibility. The control set of vertices in the BFG is the dominant set. It refers to a critical position in analyzing fuzzy graphs. Appendix 1 provides the preliminaries of BFG. Geoscientific applications of BFGs have recently been reviewed by Gong et al. (2021).

3 Geology and Tectonics

The Kutch district, whose boundaries completely enclose the Kutch basin (Shaikh et al., 2020), is highly prone to earthquakes. As per India's seismic zonation, the district falls within the most destructive Zone V (e.g., Walling & Mohanty (2009), Rastogi et al., (2012)). We choose this region in this work keeping in mind its extreme seismicity.

The Kutch basin is an asymmetric graben tilted toward the south, flanked by the North Kathiavar Fault (NKF) at the southern margin and the Nagar Parkar Fault (NPF) at the north (Biswas, 2005). Further, the rift basin contains E-W trending uplifts bound by six sub-parallel intra-rift faults—Kutch Mainland Fault (KMF), Katrol Hill Fault (KHF), South Wagad Fault (SWF), Gedi Fault (GF), Gora Dongar Fault (GDF) and Island Belt Fault (IBF) (Biswas, 2005; Thakkar, 2017). The KMF remains the prime zone of activation, with most strain occurring at its intersection with the SWF. The 7.1 magnitude 2001 Bhuj Earthquake and its aftershocks concentrated around this fault junction (Biswas, 2005; Raval, 2001).

Kutch has also witnessed several major earthquakes, with significant earthquake events since the 1800s (Table 1). The Government of Gujarat State set up the Gujarat State Disaster Management Authority to prepare programs for disaster preparedness, especially for future earthquakes. Since this agency is nodal in nature, selecting

Table 1 Known earthquake events in the Gujarat region with magnitudes >5.5 on the Richter scale (reproduced from Rastogi et al., 2012)

Year	Location	Magnitude
1668	Samaji, Indus	7.8
1819	Kachchh	7.8
1845	Lakhpat	6.3
1845	Lakhpat	5.7
1848	Mount Abu	5.7
1856	Surat	5.7
1864	Ahmedabad	5.7
1903	Kachchh	5.6
1919	Ghogha (Bhavnagar)	5.7
1921	Indus, Kachchh	5.5
1935	Surat	5.7
1938	Paliyad	5.7
1956	Kachchh	6
1969	Mount Abu	5.5
2001	Kachchh	7.7
2006	Gedi	5.7
2006	Lakadia	5.6

appropriate towns in the Kutch district is essential for earthquake preparedness, be it for emergency response teams or emergency equipment warehouses.

4 The Present Work

In this work, we use the theory of dominating sets in BFGs to select the most appropriate towns in Kutch district for such emergency measures. Figure 1 presents the Kutch district with the taluka boundaries. Each taluka's main town or city was chosen as a node/vertex in the graph, with the assigned vertex labels as in Table 2. The selected towns are considered representatives of the respective talukas. The goal is to choose a small number of towns to build emergency/relief centers by using a BFG. Roads that connect these cities (nodes/vertices) are considered edges of the graph.

Each node/town was assigned a bipolar score keeping in mind various uncertainties and qualities of the towns. The main criteria for these assignments are:

(i) The seismic hazard associated with the town. The scores for this were borrowed from the preliminary seismic hazard map of the Kutch district from Pancholi et al. (2022). Pancholi et al. (2022) used a GIS-based multi-criteria approach, considering various aspects such as peak ground acceleration, amplification, geology/geomorphology, liquefaction potential of the soil, tsunami hazard,

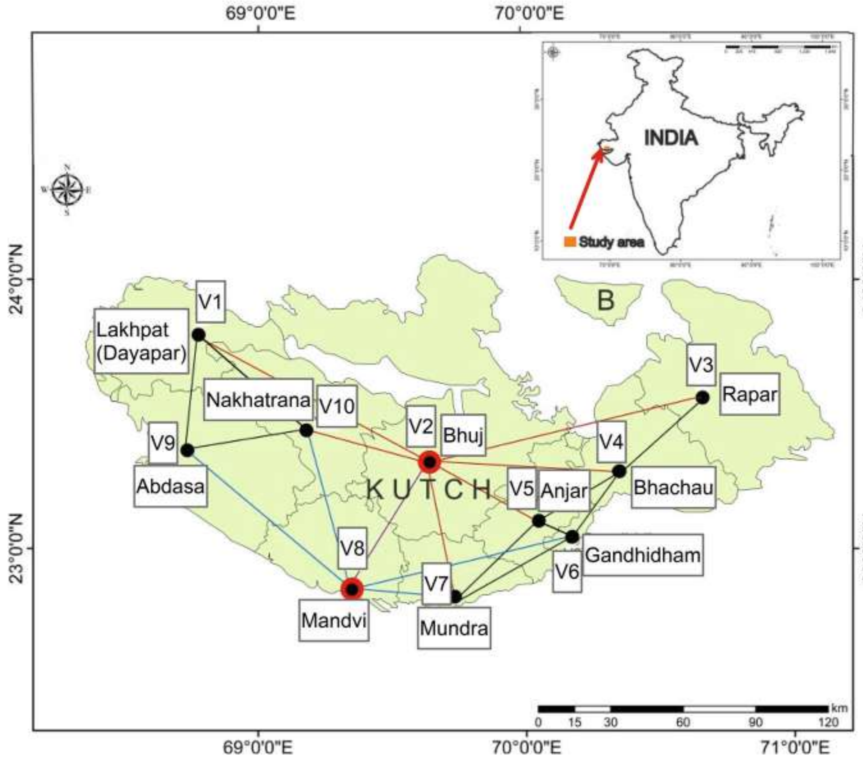

Fig. 1 Taluka map of the Kachchh district, Gujarat, India. The towns considered in this study are marked. Bhuj- district capital. The graph with the various towns connected by direct roads (edges). Vertices marked in bold: major towns (Bhuj and Mandvi). Edges marked in red and blue: roads connecting Bhuj and Mandvi with the other towns, respectively. Purple edge: road connecting Bhuj and Mandvi. Black edges: roads connecting towns with a common taluka boundary

Table 2 Town and vertex correlation table

Town	Vertex
Lakhpat	V_1
Bhuj	V_2
Rapar	V_3
Bhachau	V_4
Anjar	V_5
Gandhidham	V_6
Mundra	V_7
Mandvi	V_8
Abdasa	V_9
Nakhatrana	V_{10}

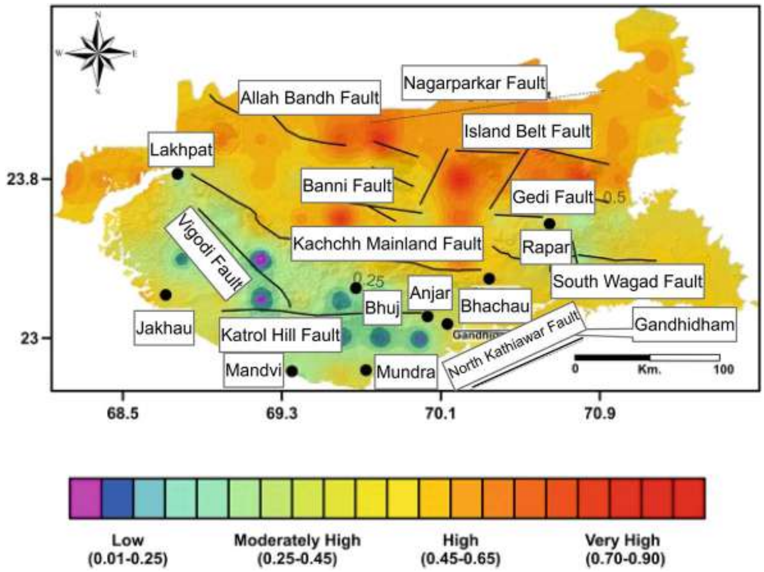

Fig. 2 A macro-scale seismic hazard zonation map of Kachchh district. Reproduced from Pancholi et al. (2022)

groundwater depth, amplification, and shear wave velocity to construct a macro-scale seismic zonation map for the Kutch district (Fig. 2).

(ii) The scores pertaining to the infrastructure of the towns were assigned based on the number of households in the town. Higher the number of households, the better the score. The number of households for each town was taken from the Indian census data.

(iii) The number of public healthcare centers (PHCs) plus community health centers (CHCs) in each taluka was considered to gauge the health facilities, and scores were assigned based on them. Data was taken from the Gujarat Government health website.

Based on these criteria, each selected town was given a score in the intervals of [0, 1] and [−1, 0]. Negative values are given to properties that are unfavorable or have a negative impact, while positive values are given in the opposite situation. While the seismic hazard for the town were represented by the final negative score, the number of healthcare centers and households were denoted by positive scores.

Table 3 presents the combined scores for each town. Based on these scores, Bhuj and Mandwa (plotted in Fig. 1) were considered the dominating towns/nodes in the graph. It was also checked whether each town or node in the graph is connected with at least one of these two locations by a direct road. See Appendix 2 for the associated work.

In due course, a graph was constructed with each town/node connected to at least one of Bhuj or Mandwa (Fig. 1). Edges representing the road connections were also

Table 3 The weights assigned to the towns based on the three criteria. The earthquake hazard score contributes to the negative polarity assigned, and the number of households and healthcare scores contribute to the positive polarity assigned equally. The red boxes mark the highest earthquake hazard score, number of households and number of PHCs + CHCs, respectively (PHC: Public Healthcare Centers, CHC: Community Healthcare Centers). Final weights are marked in orange

Town	Seismic hazard score [16]	Seismic hazard polarity	Number of Households (2011)	Households polarity	Number of CHC+PHC	Healthcare polarity	Negative values	Positive values
Lakhpat	0.275	-0.46	12155	0.17	6	0.4	-0.5	0.3
Abdasa	0.325	-0.54	24070	0.34	5	0.33	-0.5	0.3
Mandvi	0.275	-0.46	31508	0.45	11	0.73	-0.4	0.6
Mundra	0.425	-0.71	35192	0.50	10	0.66	-0.7	0.6
Bhuj	0.325	-0.54	64496	0.92	13	0.86	-0.5	0.9
Anjar	0.375	-0.62	33032	0.47	8	0.53	-0.6	0.5
Gandhidham	0.45	-0.75	16882	0.24	3	0.2	-0.7	0.2
Bhachau	0.575	-0.95	32746	0.46	9	0.6	-0.9	0.5
Rapar	0.45	-0.75	36630	0.52	11	0.73	-0.7	0.6
Nakhatrana	0.375	-0.62	28608	0.40	7	0.46	-0.6	0.4

assigned bipolar scores based on the following criteria. Based on these, the scores were assigned to the roads or the graph's edges.

(i) Time taken to travel or the length of each road was considered. The time to traverse each road or edge considered in the graph was taken from Google Maps, considering minimal traffic conditions. The longer the time taken, the lower the score assigned to this criterion. The time taken was converted to minutes to compare all the edges and give a relative score for each edge.

(ii) The number of lanes each road has was considered as this decides the traffic movement rate, especially during an emergency. If a road or edge has a variable number of lanes along its length, the effective or weighted average number of lanes was calculated for each road using the length of each 2-, 4- or 6-laned segment, which constitutes the road.

(iii) Since bridges are major weak points during earthquakes, the number of bridges on each road was also considered a criterion for assigning scores. The number of bridges on each road was counted using satellite data from Google Maps and compared to give a score. Bridges going over the roads were also counted.

Higher the number of bridges encountered on the road, the higher the chance of the road closing after an earthquake.

The edges were given scores in a similar way to nodes, i.e. within the interval of [−1, 0] and [0, 1]. While the number of bridges and time taken were accounted by the negative weight in equal measures, the positive weight was assigned based on the number of lanes solely. Table 4 presents the initial weights assigned to the edges.

In the definition of bipolar fuzzy graphs, we use two values (positive values and negative values) for representing the weights of vertices and edges. In case of vertices, we can give any value between zero and one as positive node weight and any value

Table 4 Initial weights assigned to each road connection/edge. Edges marked in orange and blue: roads connecting Bhuj and Mandvi with the other towns in the graph, respectively. Green edge: road connecting Bhuj and Mandvi. Other edges are for roads connecting towns with a common taluka boundary. Final scores are marked in yellow. Red boxes mark the highest values for each criterion

Edge	Road connecting towns	No. of bridges	Bridge polarity	Equivalent no. of lanes	Lane polarity	Time without traffic (mins)	Time Polarity	Negative Values	Positive Values
V_1V_9	Lakhpat - Abdasa	6	-0.3	2.00	0.33	124	-0.62	-0.5	0.3
V_1V_{10}	Lakhpat - Nakhatrana	7	-0.35	2.00	0.33	97	-0.49	-0.4	0.3
V_1V_2	Lakhpat - Bhuj	10	-0.5	2.00	0.33	186	-0.93	-0.7	0.3
V_9V_{10}	Abdasa - Nakharatna	11	-0.55	2.00	0.33	62	-0.31	-0.4	0.3
V_8V_9	Abdasa - Mandvi	12	-0.6	2.00	0.33	76	-0.38	-0.5	0.3
V_8V_{10}	Mandvi - Nakhatrana	6	-0.3	2.00	0.33	83	-0.42	-0.4	0.3
V_2V_{10}	Bhuj - Nakhatrana	3	-0.15	2.00	0.33	66	-0.33	-0.2	0.3
V_2V_8	Bhuj - Mandvi	2	-0.1	2.00	0.33	73	-0.37	-0.2	0.3
V_2V_7	Bhuj - Mundra	10	-0.5	2.00	0.33	78	-0.39	-0.4	0.3
V_2V_5	Bhuj - Anjar	3	-0.15	2.00	0.33	62	-0.31	-0.2	0.3
V_7V_8	Mundra - Mandvi	10	-0.5	3.63	0.61	63	-0.32	-0.4	0.6
V_6V_7	Gandhidham - Mundra	7	-0.35	3.39	0.56	66	-0.33	-0.3	0.6
V_5V_7	Anjar - Mundra	3	-0.15	3.13	0.52	62	-0.31	-0.2	0.5
V_5V_6	Anjar - Gandhidham	2	-0.1	3.33	0.56	29	-0.15	-0.1	0.6
V_4V_5	Bhachau - Anjar	5	-0.25	3.50	0.58	52	-0.26	-0.3	0.6
V_4V_6	Bhachau - Gandhidham	10	-0.5	5.56	0.93	46	-0.23	-0.4	0.9
V_3V_4	Rapar - Bhachau	6	-0.3	3.71	0.62	69	-0.35	-0.3	0.6
V_2V_4	Bhuj - Bhachau	10	-0.5	2.74	0.46	105	-0.53	-0.5	0.5
V_2V_3	Bhuj - Rapar	18	-0.9	2.47	0.41	189	-0.95	-0.9	0.4
V_8V_6	Mandvi - Gandhidham	9	-0.45	3.36	0.56	125	-0.63	-0.5	0.6

between negative one (−1) and zero as negative node weight. But the edge weights are taken based on the positive value and negative value of its end vertices. The initial edge weights given in Table 4 were changed according to the following rule.

Consider two vertices, V_1 and V_2. Suppose they are connected by an edge called 'e', and we give the positive weight of V_1 as 0.6 and the negative weight as −0.2. Similarly, we give the positive weight of V_2 as 0.5 and the negative weight as −0.4.

Hence, we can give the positive weight of edge 'e' as ≤ 0.5 (as we have to take the weight less than or equal to the minimum among the vertex weights) and the negative weight of edge 'e' as ≥ -0.2. This is because we need to assign the weight greater than or equal to the maximum weight among the vertices. Subsequently, the weights given to the edges were modified (Table 5).

5 Discussions

This work has followed in this article Gong et al.'s (2021) and Mandal et al.'s (2021) approach to locating the relief center in the study area. Gong et al. (2021) developed the model from the Chinese Yunnan Province. They considered major cities as the vertices and ignored smaller cities. Likewise, Mandal et al. (2021) applied the BFG theory for seismicity in western India and proposed that the locations Kandle and/or Mount Abu can act as relief centers. We note that Mount Abu is a hilly area with narrow meandering roads. Therefore, even though Mandal et al.'s (2021) numerical work reveals Mount Abu as a possible relief center, choosing Kandle as the best location will be better.

In a similar line, as per the present work in the Kutch area, the cities of Bhuj and Mandvi can be considered for the location of relief centers. Beyond mathematical considerations, it can be stated that Bhuj is better developed as a city than Mandvi. Therefore, we can inform the policymakers to make a relief center in Bhuj.

We note two different cities have come up as per Mandal et al. (2021) and this work to establish the relief station while considering parts of western Indian terrain. The reason is that Mandal et al. (2021) considered a different portion of western India than what has been considered in this work. Therefore, BFG theory must be applied cautiously for regional and local cases to develop the best possible relief center. Human judgment will further be needed to negate a few possible centers where cities are not well established (e.g., Mandvi in this work) or where the location is at an adverse geographic location (e.g., Mount Abu in Mandal et al., (2021)).

6 Conclusions

In this study, we used the mathematical concept of dominating set in BFG theory in assigning scores. We selected the most appropriate towns in the Kutch district to set up emergency response measures in the case of a major earthquake. Based on

Table 5 The final weights assigned to each edge/road connecting the nodes in the graph

Road connecting towns	**Edge**	**Negative values**	**Positive values**
Lakhpat - Abdasa	V_1V_9	-0.5	0.3
Lakhpat - Nakhatrana	V_1V_{10}	-0.4	0.3
Lakhpat - Bhuj	V_1V_2	-0.5	0.3
Abdasa - Nakharatna	V_9V_{10}	-0.4	0.3
Abdasa - Mandvi	V_8V_9	-0.4	0.3
Mandvi - Nakhatrana	V_8V_{10}	-0.4	0.3
Bhuj - Nakhatrana	V_2V_{10}	-0.2	0.3
Bhuj - Mandvi	V_2V_8	-0.2	0.3
Bhuj - Mundra	V_2V_7	-0.4	0.3
Bhuj - Anjar	V_2V_5	-0.2	0.3
Mundra - Mandvi	V_7V_8	-0.4	0.6
Gandhidham - Mundra	V_6V_7	-0.3	0.2
Anjar - Mundra	V_5V_7	-0.2	0.5
Anjar - Gandhidham	V_5V_6	-0.1	0.2

(continued)

Table 5 (continued)

Bhachau - Anjar	V_4V_5	-0.3	0.5
Bhachau - Gandhidham	V_4V_6	-0.4	0.2
Rapar - Bhachau	V_3V_4	-0.3	0.5
Bhuj - Bhachau	V_2V_4	-0.5	0.5
Bhuj - Rapar	V_2V_3	-0.5	0.4
Mandvi - Gandhidham	V_8V_6	-0.4	0.2

the scores assigned to the nodes and the road connectivity, Bhuj and Mandvi are suitable locations for establishing relief centers. Further, based on human judgment, we can negate Mandvi since Bhuj is a better-developed city. Note that this work is a preliminary study, and more parameters can be included to make such a selection.

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Appendix 1

Definition 1 Fuzzy set: Let V be a non-empty set. A **fuzzy subset** of V is a mapping σ: $V \to [0, 1]$ which assigns to each element $x \in V$, a degree of membership, $\sigma(x)$, such that $0 \le \sigma(x) \le 1$.

Definition 2 Let V and U be two sets, and let σ and τ be fuzzy subsets of V and U, respectively. A **fuzzy relation** μ from σ into τ is a fuzzy subset of $V \times U$ such that $\mu(x, y) \le \sigma(x) \wedge \tau(y)$, $\forall\, x \in V$ and $y \in U$.

Definition 3 G denotes a fuzzy graph: (V, σ, μ) where V is a set of objects (nodes), σ is a fuzzy subset of V, and μ is a fuzzy relation on σ. i.e. $\mu(x, y) \le \sigma(x) \wedge \sigma(y)$, $\forall\, x, y \in V$. We assume that V is finite and nonempty, μ is reflexive (i.e. $\mu(x, x) = \sigma(x)$, $\forall\, x$) and symmetric (i.e. $\mu(x, y) = \mu(y, x)$, $\forall\, (x, y)$).

Also, we denote the underlying crisp graph by G^*: (σ^*, μ^*), where $\sigma^* = \{u \in V\colon \sigma(u) > 0\}$ and $\mu^* = \{(u, v) \in V \times V\colon \mu(u, v) > 0\}$. We assume $\sigma^* = V$ and σ^* and μ^* are '**the node set**' and '**the arc set**' of the fuzzy graph G, respectively. Also, $\sigma(x)$ and $\mu(x, y)$ represent, respectively, the **degree of membership** (**membership values**) of nodes and arcs in G. If $\mu(u, v) > 0$, then u and v are called **neighbors** (**adjacent nodes**). The set of all neighbors of u is denoted by $N(u)$.

Definition 4 Let X be a non-empty set. A bipolar fuzzy set B in X is an object having the form $B = \left\{(x, \mu_B^P(x), \mu_B^N(x))/x \in X\right\}$, where $\mu_B^P : X \to [0, 1], \mu_B^N : X \to [-1, 0]$ are mappings. We use the positive membership degree $\mu_B^P(x)$ to denote the satisfaction degree of an element x to the property corresponding to a bipolar fuzzy set B and the negative membership degree $\mu_B^N(x)$ to denote the satisfaction degree of an element x to some implicit counter-property corresponding to a bipolar fuzzy set B.

Definition 5 Let X be a non-empty set. Then we call a mapping $A = (\mu_A^P, \mu_A^N) : X \times X \to (-1, 1) \times (-1, 1)$ a bipolar fuzzy relation on X such that $\mu_A^P(x, y) \in [0, 1]$ and $\mu_A^N(x, y) \in [-1, 0]$.

Definition 6 (*Bipolar fuzzy graph*) By a bipolar fuzzy graph, we mean a pair $G = (A, B)$ where $A = (\mu_A^P, \mu_A^N)$ is a bipolar fuzzy set in V and $B = (\mu_B^P, \mu_B^N)$ is a bipolar fuzzy relation on V such that $\mu_B^P(x, y) \le \min\left\{\mu_A^P(x), \mu_A^P(y)\right\}$ and $\mu_B^N(x, y) \ge \max\left\{\mu_A^N(x), \mu_A^N(y)\right\}$.

Definition 7 An edge (u, v) is said to be a *strong edge* in BFG, $G = (A, B)$ if $\mu_B^P(x, y) = \min\left\{\mu_A^P(x), \mu_A^P(y)\right\}$ and $\mu_B^N(x, y) = \max\left\{\mu_A^N(x), \mu_A^N(y)\right\}$.

Definition 8 Let $G = (A, B)$ be a BFG on A. Let $u, v \in A$. We say that u dominates v in G if there exists a strong edge between them.

Definition 9 A subset S of A is called a *dominating set* in Gif for every $v \in A \backslash S$ there exists $u \in S$ such that u dominates v.

Definition 10 A dominating set of a BFG is said to be a *minimal dominating set* if no proper subset of is a dominating set.

We use the concept of dominating sets in bipolar fuzzy graphs to set an experiment to select the most appropriate towns in Kachchh district for setting up emergency response centers.

(1) Time taken to travel or the length of each road was considered. The time to traverse each road or edge considered in the graph was taken from Google Maps, considering minimal traffic conditions. The longer the time taken, the lower the score assigned to this criterion. The time taken was converted to minutes to compare all the edges and give a relative score for each edge.
(2) The number of lanes each road has was considered as this decides the traffic movement rate, especially during an emergency. If a road or edge has a variable number of lanes along its length, the effective or weighted average number of lanes was calculated for each road using the length of each 2-, 4- or 6-laned segment which makes up the road.

(3) Since bridges are major weak points during earthquakes, the number of bridges on each road was also considered a criterion for assigning scores. The number of bridges on each road was counted using satellite data from Google Maps and compared to give a score. Bridges going over the roads were also counted. Higher the number of bridges on the road, the higher the chance of the road closing after an earthquake.

Appendix 2

Calculations to assign scores for each criterion accounting for the final node scores are made as follows (Table 3):

(i) The highest seismic hazard score assigned by Pancholi et al. (2022) is 0.575 to Bhachau. It was considered that a score of 0.6 would be equivalent to a seismic hazard polarity of −1. Bhachau was hence given a seismic hazard polarity of −(0.575/0.6) = −0.95. The same method was used for the other towns.
(ii) The highest number of households is in Bhuj (= 64,496). It was considered that Bhuj has a household polarity of 64,496/70000 = 0.92. The same method was used for other towns.
(iii) The highest CHCs + PHCs are in Bhuj = 13. Bhuj has a Healthcare polarity of 13/15 = 0.86. The same method was used for the other towns.

Calculations to assign scores for each criterion accounting for the final edge scores are made as follows:

(i) The highest number of bridges is on the Bhuj-Rapar road = 18. Thus, it was considered that it has a bridge polarity of −(18/20) = −0.9. The same method was used for the other edges.
(ii) The highest number of lanes is on Bhachau-Gandhidham road, = 5.56. Thus, it was considered that it has a lane polarity of (5.56/6) = 0.93.
(iii) The highest amount of time taken for traveling is on the Bhuj-Rapar = 189 min. Hence, it was considered it has a time polarity of −(189/200) = −0.95.

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