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Spatial and Engineering Risk Assessment of Single-Span Bridges Located near Active Faults in Western Thailand Utilizing GIS

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Abstract

This article presents a seismic risk assessment of single-span bridges in western Thailand, a region with the highest density of active faults. This study integrates engineering calculations based on AASHTO LRFD (AASHTO, 2017) and DPT 1302 (DPT, 2009) standards with spatial analysis using Geographic Information Systems (GIS) to establish a per-bridge Risk Index. The research focuses on examining "seat width," a critical factor in preventing unseating failure. The analysis of a case study in Kanchanaburi Province reveals that bridges constructed prior to 2007 possess seat widths significantly below the required values, resulting in a high risk of collapse during major earthquakes. The utilization of GIS to overlay bridge location data, active faults, and soil conditions facilitates the efficient prioritization of structural retrofitting. Policy recommendations include the expansion of bearing seats, the installation of cable restrainers (FHWA, 2018), and the implementation of the Risk Index model for budget management in bridge maintenance within high-risk areas.

Discipline: Civil Engineering.

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1 Introduction

Western Thailand, specifically Kanchanaburi, Tak, and Ratchaburi provinces, is classified as a moderate-to-high seismic risk area (Seismic Zone 2-3) according to the Department of Public Works and Town & Country Planning (DPT, 2009; 2019). This classification is due to the presence of major active fault zones, namely the Sri Sawat Fault and the Three Pagodas Fault, which have a history of generating earthquakes with magnitudes of $M_w > 5.0$ on several occasions over the past century.

The most vulnerable transportation infrastructure in this context is the "Single-Span Bridge." These are typically reinforced concrete bridges crossing rivers or irrigation canals on local highway routes. As highlighted by Warnitchai (2016), the primary risk for this bridge type does not stem from pier damage, but rather from the relative displacement between the superstructure and the substructure. When this displacement exceeds the capacity of the seat width, it results in unseating, immediately severing transportation routes.

2 Literature Review

Earthquakes in Asia are expected to occur more often, as we are seeing an increase in earthquakes in Myanmar, Vietnam (Tran, 2012), and Thailand. There are numerous road and rail bridges in these regions. The seismic hazards from earthquakes can lead to economic losses for individuals, buildings, and the bridge infrastructure itself (Ozsarac, 2023).

Ornthammarath (2011) conducted a seismic hazard assessment for Thailand. Tung (2004) assessed road vulnerability to earthquakes utilizing GIS. Kim (1993) explored a GIS-based method for analyzing regional risks to bridges from natural hazards. Miller (2014) investigated the seismic risk assessment of intricate transportation networks, whereas Cardona (2014) utilized GIS to assess seismic risks for bridges in Colombia. Kameshwar & Padgett (2014)I assessed multi-hazard risks for highway bridges that are affected by earthquakes and hurricanes. Amirsardari (2019) examined the effects of earthquakes on Indonesia's transportation infrastructure. Jena (2021) created semi-quantitative models for assessing earthquake risk by using machine learning, multi-criteria decision-making, and GIS. Suwanprasit (2024) performed spatial analysis for bridge and road site selection for North and Northeast Thailand.

This study will create risk modeling and bridge prioritization by establishing a "Risk Index" model to quantify potential hazards, facilitating the systematic prioritization of infrastructure retrofitting and maintenance.

3 Geological Setting and Seismic Hazard

Surveys by the Department of Mineral Resources (DMR, 2019; 2020) indicate that faults in the Thailand Western region are primarily strike-slip faults. These faults can possibly generate seismic waves with short to medium vibration periods. This energy directly impacts stiff structures, such as single-span bridges. Key spatial risk factors include

- **Distance to Fault:** Areas within a 10-kilometer radius of a fault line (Near-Fault Zone) may experience "Killer Pulses" or high-velocity shock waves, resulting in sudden ground displacement.
- **Site Classification:** The river floodplains in Kanchanaburi often consist of deep soft clay layers (Soft Soil), classified as Site Class D or E under ASCE 7-16 standards. This soil type can amplify seismic signals by 1.5 - 2.0 times compared to stiff soil.

4 Engineering Framework: Seat Width Analysis

To prevent unseating failure, the design of the bearing seat must provide sufficient width to accommodate relative displacement. This study references two primary standards for analysis.

4.1 AASHTO LRFD Standard

The American Association of State Highway and Transportation Officials (AASHTO) defines an empirical formula for minimum seat width (N) as follows (AASHTO, 2017):

$$N = (305 + 2.5L + 10H) \times (1 + 0.000125S^2) \quad (1),$$

where

N = Minimum seat width (millimeters)

L = Bridge span length (meters)

H = Average pier height (meters)

S = Skew angle of the bridge in degrees

Physical interpretation, the term 10$\boldsymbol{H}$ reflects the effect of pier flexibility (swaying), while the term S^2 reflects the effect of the bridge girder's in-plane rotation, which frequently occurs in skewed bridges, necessitating increased support area at critical corners. Figure 1 exhibits an example of the seat width of a bridge.

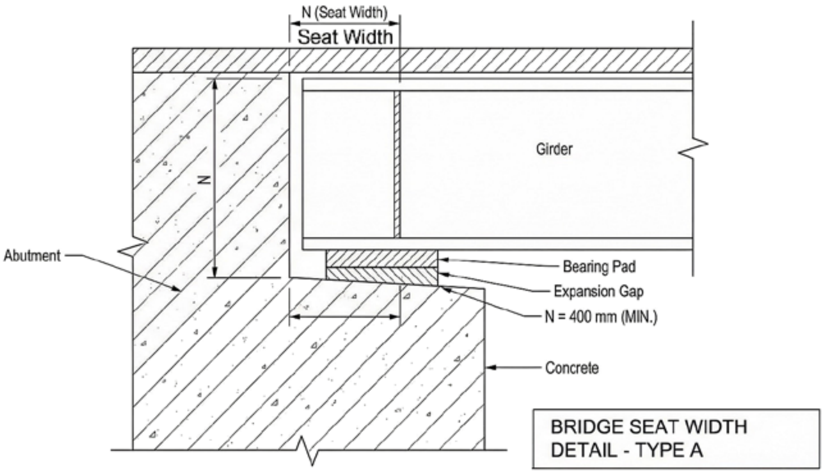


Figure 1: an example of the seat width of a bridge.

4.2 DPT 1302 Standard (DPT Standard)

"DPT 1302" refers to the Thai standard for earthquake-resistant building design issued by the Department of Public Works and Town & Country Planning (DPT). It is a key regulation for structural engineers in Thailand.

DPT (2009) adapted standards for Thailand, stipulating that bridges in high-risk areas (including the Western region) must include an additional safety factor,

$$\boldsymbol{N}_{req} = 1.5 \times \boldsymbol{N}_{AASHTO} \quad (2).$$

Equation (2) indicates that bridges in the Kanchanaburi and Tak areas should have seat widths 50% larger than the normal standard to accommodate the uncertainty of fault behavior. Table 1 shows an example of minimum seat width calculation.

Table 1: Example of Minimum Seat Width Calculation

Bridge	L (m)	H (m)	*Skew* (°)	N (mm)	$N_{required}$ (mm)
A	30	8	20	483	725
B	25	6	0	455	683
C	20	5	10	420	630
D	35	9	25	510	765
E	28	7	15	470	705

5 GIS Methodology

Risk assessment covering a wide area requires GIS for database management and spatial analysis, utilizing the following steps.

5.1 Data Acquisition & Management

The GIS 3-layer is developed using the collected data.

- **Layer 1: Bridge Inventory (Point):** Import GPS coordinates of single-span bridges with an Attribute Table specifying ***L***, ***H***, ***S,*** and year of construction.
- **Layer 2: Active Faults (Polyline):** Shapefile data of the Three Pagodas and Sri Sawat fault lines (DMR, 2019).
- **Layer 3: Seismic Hazard Map (Raster):** Map of Peak Ground Acceleration (PGA) for a 2,500-year return period.

5.2 Spatial Analysis

Two basic GIS analyses are performed.

- **Proximity Analysis (Near Tool):** Calculate the distance from each bridge to the nearest fault to classify risk zones (Near-field vs. Far-field).
- **Buffer Analysis:** Create buffer zones of 2 km, 5 km, and 10 km around fault lines to screen for high-risk bridge groups.

5.3 Risk Scoring Model

The Risk Index ($\boldsymbol{R}_i$) for each bridge is calculated by weighting various factors using a linear combination model:

$$R_i = (W_1 \times H_F) + (W_2 \times V_s) + (W_3 \times C_I) \quad (3),$$

where

$\boldsymbol{H}_F$ (Hazard): Score derived from fault distance and PGA value.

$\boldsymbol{V}_s$ (Vulnerability): Vulnerability Factor (score from bridge properties such as construction year, Skew).

$\boldsymbol{C}_I$ (Consequence): Importance of the route (e.g., bridge importance, Traffic Volume/AADT).

W_1, W_2, W_3 : Weight of each factor (e.g., 0.4, 0.35, 0.25 based on AHP).

Table 2 presents an example of inspected bridges to ultimately obtain the risk index.

Table 2: Example of Risk Index

Bridge	Distance (km)	PGA	Year	Skew (°)	Traffic Volume	H_F	V_S	C_I	R_I	Risk Level
A	5	0.45	2545	20	High	9	8	7	8.15	Critical
B	15	0.35	2560	0	Medium	6	4	5	5.3	Moderate
C	30	0.25	2538	10	Low	4	7	3	5	Moderate
D	8	0.4	2540	25	High	9	9	7	8.5	Critical
E	12	0.38	2555	15	Medium	7	5	5	6	High

5.4 Advanced Geospatial Dynamics for Disaster Risk Analysis

Historically, bridge assessments were site-specific. However, in the context of regional disasters, the lack of a holistic view is a weakness. This study elevates the use of GIS from merely "locating" to "Crisis Simulation" through the following complex analysis processes:

5.4.1 3D Terrain & Geomorphological Modeling

Western Thailand is not flat but characterized by valleys and steep slopes. Risk does not arise solely from seismic vibration. By overlaying high-resolution DEM (Digital Elevation Model) data (Figure 2) with soil layers (Soil Raster) and calculating Slope & Aspect, 56the system can identify which single-span bridges face "Double Hazard"—being at risk of unseating due to faults and simultaneously at risk of substructure burial from landslides if an earthquake occurs during the rainy season.

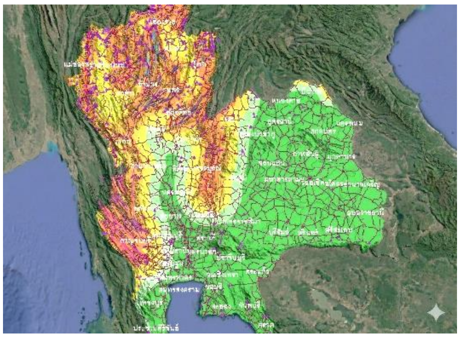


Figure 2: Overlaying a high-resolution DEM (Digital Elevation Model).

5.4.2 Multi-Ring Buffer & Directivity Analysis

Instead of relying solely on Euclidean Distance, the "Near-Fault Directivity" theory is applied. *Process:* Create Buffers with 3 intensity levels (Figure 3):

- **Zone A (Killer Pulse Zone: 0 - 2 km):** Critical area prone to Pulse-like effects capable of immediately destroying single-span bridges (Weight = 1.0).
- **Zone B (High Acceleration: 2 - 10 km):** Area subject to high acceleration (Weight = 0.7).
- **Zone C (Far Field: > 10 km):** Area affected by vibration periods (Weight = 0.4). *Result:* This zoning method grades risk more accurately than simply stating a location is "near a fault."

5.4.3 Weighted Overlay Analysis

Converting raw data into Map Algebra using the Raster Calculator for pixel-by-pixel processing:

$$Risk\_Score = (PGA_{raster} \times W_1) + (Soil\_Class_{reclass} \times W_2) + (Fault\_Dist_{inverse} \times W_3) \qquad (4).$$

This involves taking the PGA (Peak Ground Acceleration) value derived from Probabilistic Seismic Hazard Assessment (PSHA) (Ornthammarath et al., 2011) and converting it into a Raster to visualize the actual G-force load at specific bridge locations.

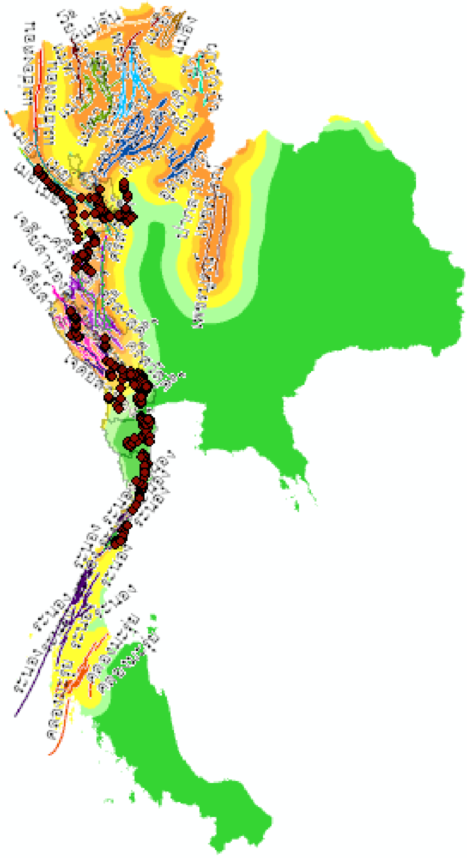


Figure 3: Buffer of active faults affecting roads and bridges

5.4.4 Network Analysis for Isolation Risk

Answering the question: "If this bridge fails, what happens?" *Technique:* Service Area & Closest Facility via Network Analyst Extension to simulate the scenario where "Bridge A" is severed (inserting a Barrier into the road network):

- Which villages become "Isolated Zones" that are inaccessible?
- How many minutes will the Travel Time for an ambulance from the provincial hospital to the incident site increase? *Scoring:* Any bridge whose failure isolates a community or forces emergency vehicles to detour more than 30 minutes is immediately adjusted to a "Catastrophic" risk level, regardless of structural strength.

5.5 Automation Workflow with ModelBuilder

To demonstrate professional execution, this research employs a Geoprocessing Model (ModelBuilder Diagram) capable of immediate re-runs upon the acquisition of new earthquake data or new bridge construction, ensuring reproducibility for the Department of Highways.

This study applied the "Bridge Seismic Risk Evaluator (BSRE)" model, designed with 3 main process parts (Swimlanes): Input Parameters (dynamic input data), Core Processing, and Decision Output.

5.5.1 Conceptual Design of ModelBuilder Diagram

To visualize the connections of tools, the data flow diagram is outlined in Figure 4.

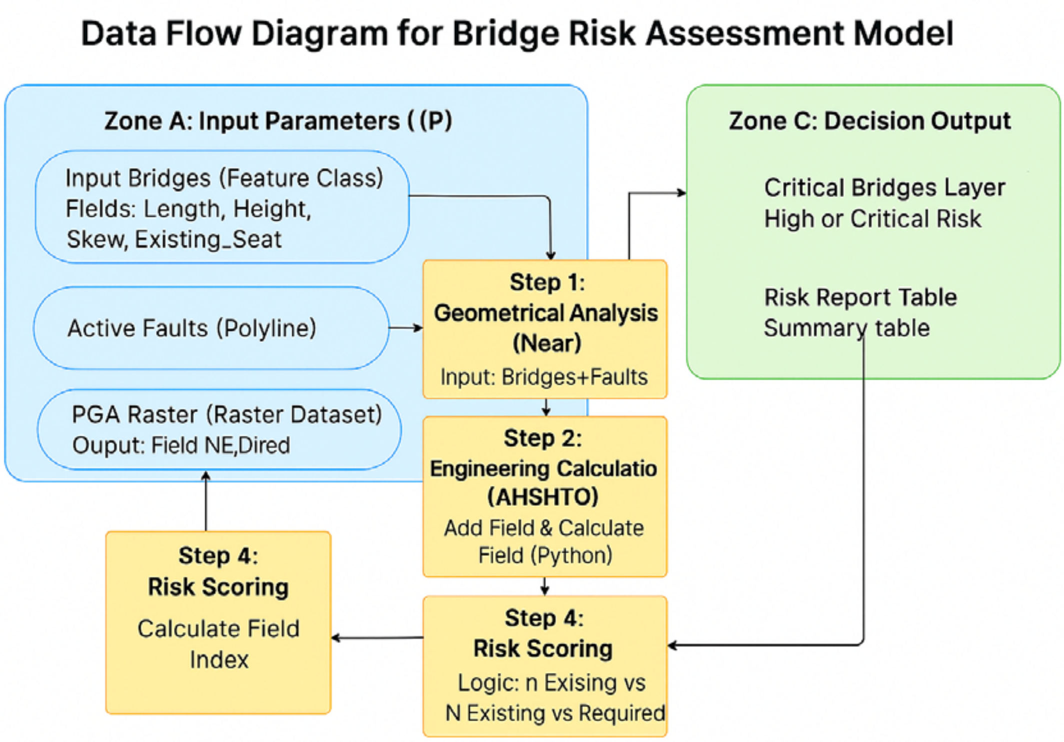


Figure 4: Data Flow Diagram

- Zone A: Input Parameters (Blue Oval - Parameter 'P')
  - **Input Bridges (Feature Class):** Bridge coordinate data (Must include Fields: Length, Height, Skew, Existing_Seat).
  - **Active Faults (Polyline):** Fault lines (Updated from DMR).
  - **PGA Raster (Raster Dataset):** Ground acceleration map (Updated upon new seismic events).

- Zone B: Core Processing (Yellow Rectangle - Processing Tools)
  - Step 1: Geometrical Analysis
    - **Tool:** Near
    - **Input:** Input Bridges, Active Faults
    - **Function:** Calculate the nearest distance from bridges to faults into Field NEAR_DIST.

- Step 2: Hazard Extraction
  - **Tool:** Extract Multi Values to Points
  - **Input:** Input Bridges (from Step 1), PGA Raster
  - **Function:** Extract PGA values at bridge coordinates into the Attribute Table.

- Step 3: Engineering Calculation (Core - AASHTO Formula)
  - **Tool:** Add Field & Calculate Field (Python Code Block)
  - **Logic:** Embed Python Script in ModelBuilder to perform calculation:

```
Python

def calc_seat(L , H, S):
  import math
  # AASHTO Formula
  base = 305 + (2.5 * L) + (10 * H)
  skew_factor = 1 + (0.000125 * (S**2))
  N_aashto = base * skew_factor
  # Apply Zone Factor (Western Thailand = 1.5)
  return N_aashto * 1.5
```

  - **Output:** New Field named N_Required.
- Step 4: Risk Scoring
  - **Tool:** Calculate Field (Risk Index) [100]
  - **Logic:** Compare N_Existing with N_Required.
  - **Condition:** If N_Existing < N_Required: Risk = "High".

* Zone C: Decision Output (Green Oval - Results)
  - **Critical Bridges Layer:** Shapefile showing only high-risk bridges.
  - **Risk Report Table:** Summary table of bridges requiring urgent maintenance.

5.5.2 Python Script Logic Engine Details

To automate the model, Python Logic is embedded into the Calculate Field box of ModelBuilder as follows:

Processing Box: "Calculate Seat Width Requirement"

- **Expression:** calculate_req(!Span_Length!, !Pier_Height!, !Skew_Angle!)
- Code Block:

```
Python

def calculate_req(length, height, skew):
    # 1. Prevent Null values
    if length is None: return 0
    # 2. AASHTO LRFD Formula (mm)
    # Term 1: Expansion & Vibration
    term_1 = 305 + (2.5 * length) + (10 * height)
    # Term 2: Skew Effect
    term_2 = 1 + (0.000125 * (skew * skew))
    # 3. Calculate Minimum Distance
    N_min = term_1 * term_2
    # 4. Multiply Safety Factor for Western Region (1.5)
    N_final = N_min * 1.5
    return N_final
```

- Processing Box: "Calculate Risk Level"
- Code Block:

```
Python

def assess_risk(n_exist, n_req, pga, dist):
    # Rule 1: If seat width is insufficient = Critical immediately
    if n_exist < n_req:
        return "CRITICAL: Unseating Risk"
    # Rule 2: If seat width is sufficient but PGA is very high (>0.4g) and
near fault (<2km)
    elif pga > 0.4 and dist < 2000:
        return "HIGH: Structural Damage Risk"
    # Rule 3: Others
    else:
        return "MODERATE / LOW"
```

Figure 5 gives a complete model data flow diagram.

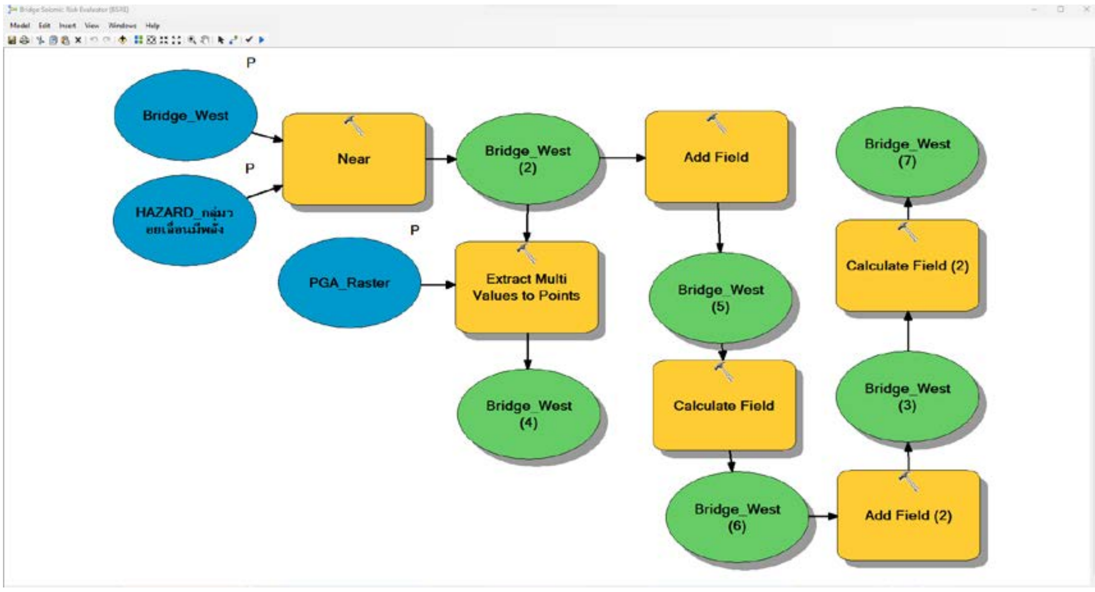


Figure 5: Complete Model Data Flow Diagram

5.5.3 Benefits for Highway Regulators

The creation of this ModelBuilder completely satisfies the requirement for **Reproducibility**:

- **Future-Proof:** When the Department of Mineral Resources announces "new fault lines" (DMR, 2020) or seismic data is updated, Department of Highways officials can simply replace the Input file in the blue slot and click "Run." The system recalculates the risk for all bridges in the province within seconds.
- **Standardization:** Reduces human error from manual calculations. Since the AASHTO formula is embedded in the code, the results remain consistent regardless of which engineer runs the model.
- **Budget Prioritization:** The final results can be exported as Excel files or Dashboards, allowing executives to prioritize maintenance budgets by viewing the *Risk_Level* column immediately.

6 Case Study Simulation

To illustrate the concept concretely, a simulation was conducted on a sample bridge, "Huai Mae Phlu Bridge (Hypothetical)," located in Thong Pha Phum District, Kanchanaburi Province.

Input Data:

- Span Length (L): 25 meters
- Pier Height (H): 6 meters
- Skew Angle (S): 30 degrees (Highly skewed)
- Actual Surveyed Seat Width)N_{act}): 400 mm
- **Calculation Steps:** Calculate N_{base} according to AASHTO (AASHTO, 2017):

$$N = (305 + 2.5(25) + 10(6)) \times (1 + 0.000125(30)^2)$$

$$N = 427.5 \times 1.1125 = 475.6 \text{ mm.}$$

Adjusted according to DPT 1302 (DPT, 2009):

$$N_{req} = 475.6 \times 1.5 = 713.4 \text{ mm.}$$

Analysis Result: It is found that N_{act} (400 mm) < N_{req} (713.4 mm) significantly.

This bridge has a Critical Risk index because it lacks 313.4 mm of seat width. If an earthquake with high ground displacement occurs, there is a very high probability that the bridge girder will twist and dislodge from its base.

7 Mitigation & Retrofitting

This study proposes a GIS model for optimization in structural improvement planning as follows.

7.1 Maintenance Clustering with Spatial Clustering (Logistics Optimization)

Dispatching machinery and teams to repair bridges individually in remote areas (e.g., Umphang or Thong Pha Phum districts) incurs high mobilization costs.

- **GIS Technique:** Use Grouping Analysis or Density-based Clustering tools to group high-risk bridges in proximity into a "Sub-project Package."
- **Result:** Instead of contracting individual bridges, the Department of Highways can organize "Package A: Mae Klong Basin Bridge Group (5 bridges)" to auction to a single contractor, reducing machinery and material transportation costs by over 20-30%.

7.2 Prioritization based on "Network Resilience"

We should not necessarily repair the most risky bridge first, but rather the bridge that, if it failed, would cause the most distress.

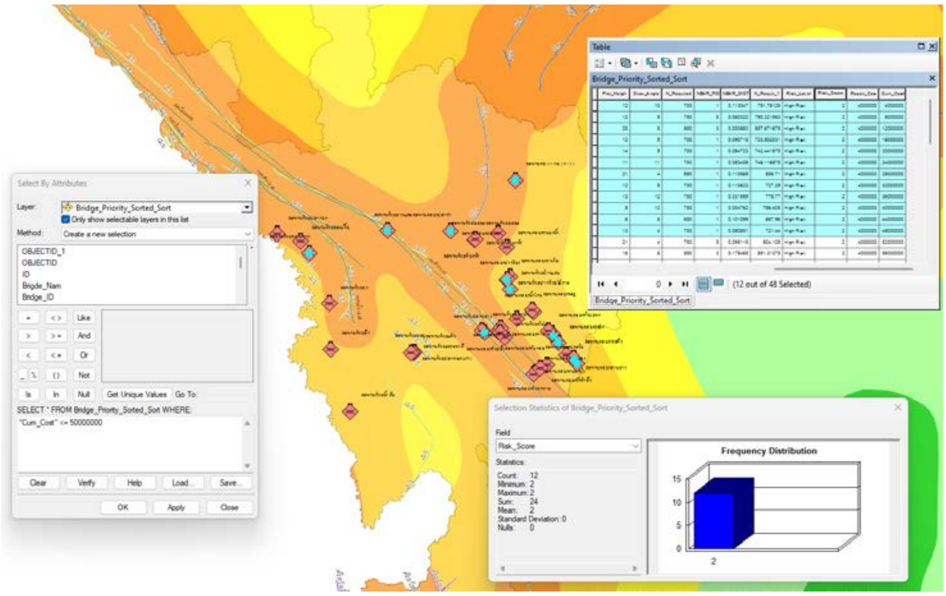


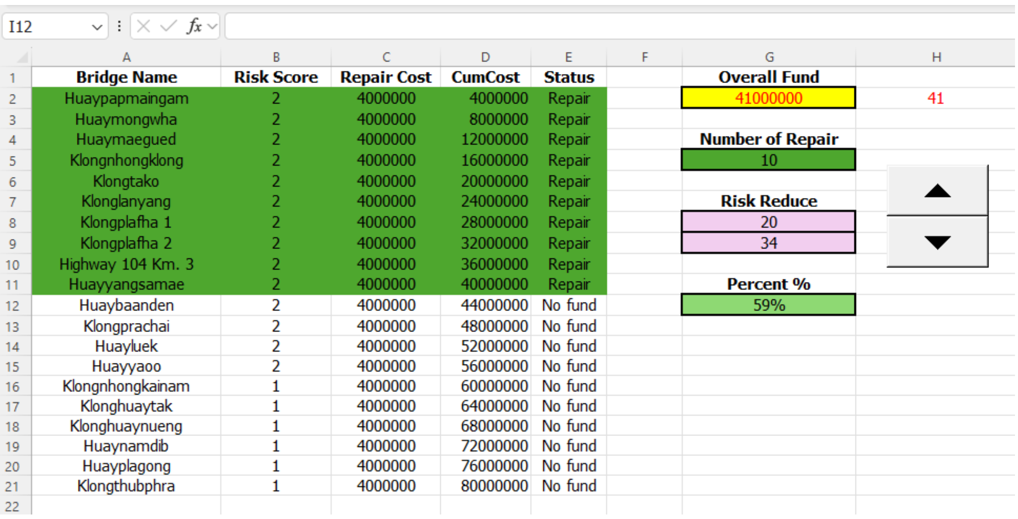
Figure 6: GIS technique network disruption simulation analysis.

- **GIS Technique:** Use Network Disruption Simulation analysis by simulating the severance of each bridge and observing the impact on the "Average Travel Time" of the entire province (Figure 6).
- Decision Criteria:
- Bridge A: High risk but has a nearby Detour ➔ Secondary priority.
- Bridge B: Moderate risk, but it is the only "Choke Point" to a hospital ➔ Highest priority (Critical Link).

7.3 Budget Scenarios Dashboard

To assist executive decision-making, the presentation should be in an Interactive Dashboard connected to the GIS database (Figure 7).

- **Feature:** Create a Budget Slider (e.g., 10 million, 50 million, 100 million Baht).
- **Function:** When the budget bar is moved, the GIS system immediately calculates:
- How many bridges can be repaired with this amount (selecting from Top Priority first).
- By what percentage will the Total Risk Exposure of the province decrease?
- **Benefit:** Gives weight to budget requests, as the Budget Bureau can be shown that "if the budget is cut by 10 million Baht, the risk to public life will increase by X%."



Bridge Name	Risk Score	Repair Cost	CumCost	Status
Huaypapmaingam	2	4000000	4000000	Repair
Huaymongwha	2	4000000	8000000	Repair
Huaymaegued	2	4000000	12000000	Repair
Klongnhongklong	2	4000000	16000000	Repair
Klongtako	2	4000000	20000000	Repair
Klonglanyang	2	4000000	24000000	Repair
Klongplafha 1	2	4000000	28000000	Repair
Klongplafha 2	2	4000000	32000000	Repair
Highway 104 Km. 3	2	4000000	36000000	Repair
Huayyangsamae	2	4000000	40000000	Repair
Huaybaanden	2	4000000	44000000	No fund
Klongprachai	2	4000000	48000000	No fund
Huayluek	2	4000000	52000000	No fund
Huayyaoo	2	4000000	56000000	No fund
Klongnhongkainam	1	4000000	60000000	No fund
Klonghuaytak	1	4000000	64000000	No fund
Klonghuaynueng	1	4000000	68000000	No fund
Huaynamdib	1	4000000	72000000	No fund
Huayplagong	1	4000000	76000000	No fund
Klongthubphra	1	4000000	80000000	No fund

Overall Fund	
41000000	41
Number of Repair	
10	
Risk Reduce	
20	
34	
Percent %	
59%	

Figure 7: Budget Scenarios Dashboard. (costs are in units of baht (1 baht ≈ 0.031 USD)).

7.4 Post-Retrofit Monitoring (Digital Twin)

Once protective equipment (e.g., Cable Restrainers) is installed, the status in GIS is immediately updated from "High Risk (Red)" to "Retrofitted (Green)."

This can be expanded to install accelerometers on critical bridges and connect real-time data to the GIS system. When an earthquake occurs, the system will immediately alert which bridges received vibrations exceeding the Design Limit and require engineering inspection before opening to traffic.

7.5 Engineering Solutions

Based on the above analysis, the appropriate and economically viable engineering improvement measures for single-span bridges in the Western region include:

- **Concrete Corbel Installation:** Casting reinforced concrete extending from the original pier to expand the seat width to meet N_{req}.
- **Cable Restrainers Installation:** Using high-strength cables to anchor the bridge girder to the pier to limit displacement to within 400 mm (existing distance). This method is more economical and easier to install than pier expansion (FHWA, 2018).
- **Shear Keys Installation:** To limit transverse displacement, especially in highly skewed bridges, to prevent girder rotation.

8 Conclusion

The risk analysis of active faults on single-span bridges in Western Thailand using GIS in conjunction with AASHTO and DPT calculation formulas (AASHTO, 2017; DPT, 2009) enables engineers and policymakers to precisely identify critical risk bridge locations. The study results indicate that bridges with skew and located within a 10 km radius of a fault should undergo seat width inspection as a primary priority. Implementation of the suggested Retrofitting Plan will help reduce the risk of loss of life and maintain critical transportation routes during disasters.

Shifting the perspective from simply "how to repair" (Engineering Solution) to "how to manage repairs most cost-effectively" (Strategic Management Solution) at the policy level reveals that the problem is not technical engineering (we already know Cable Restrainers are needed), but rather "limited budget, which bridge to repair first, and how to plan logistics." This article aims to present steps and analytical methods to demonstrate that GIS is not merely a "map" but a "Risk Management Tool" that can genuinely save budgets and lives.

9 Availability of Data and Materials

All information is included in this article.

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