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ORIGINAL ARTICLE

Taiwan Highway Bridge Disaster Management Platform with GIS Technology

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Abstract: In response to the need for seeking ways to help mitigate damage resulting from the occurrence of natural disasters, CECI Engineering Consultants, Inc., Taiwan (CECI), by applying GIS technology, has developed the "Highway Bridge Disaster Management Platform" which integrates a great deal of important information; such as (1) a basic information of bridges database, (2) a disaster prevention resource database, (3) a natural environment database, (4) a socio-economic environment database, (5) a terrain database, and (6) an aerial image database. This integrated information can be an invaluable reference and tool to assist in the decision-making process for handling disaster prevention related matters. A bridge quick-screening function built in the platform can screen out dangerous and old bridges and a grade management function helps bridge management authorities focus on management related matters by prioritizing bridge assessments and retrofits. When dangerous and old bridges have subsequently been strengthened and retrofitted, the resilience of bridges is greatly enhanced which thereby ensures the safety of travelers and creates a sustainable living environment.

Keywords: highway bridge disaster management platform, hazard curve, fragility curve, quick-screening

1. Introduction

The recent extremities of the global climate have brought about heavy rains causing floods, debris flows, and landslides. The complex chain of natural disasters, coupled with strong earthquakes, threatens people's lives, property and bridges, and indirectly affects national competitiveness. The risk of climate change comes from the combination of vulnerability (lack of preparation) and exposure (people or assets at risk) with various hazards (triggering

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climate events or trends). All three elements need to be considered when taking action to reduce risk. The impact of climate change disaster risk is due to the degree of hazard, exposure, and vulnerability. These three interactions have been evaluated and Taiwan is the country with the highest global disaster risk, as shown in Figure 1.

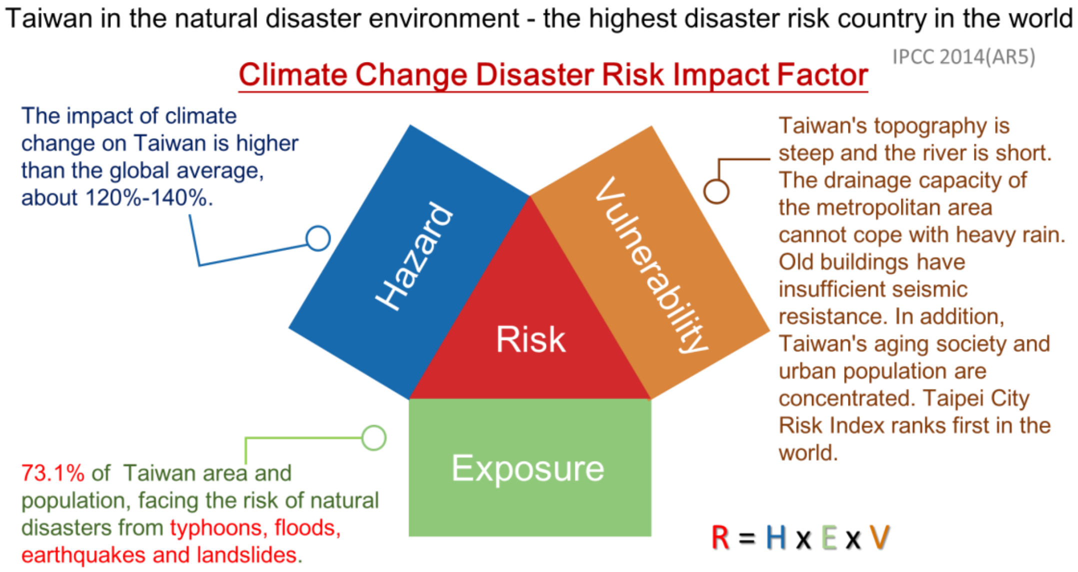

Figure 1 Climate change disaster risk impact factors

Taiwan is situated at the border of the Eurasian continental plate and the Philippine sea plate, which is an earthquake belt in the Pacific Rim, and has frequently experienced earthquakes and typhoons. In recent years, the frequency and intensity of those disasters has become more severe, causing great harm and impact not only on the safety of peoples lives and property and related industries, but also on the competitiveness of enterprises and the economy of nation. Hence, the resulting impact is not conducive to making improvements to national competitiveness. In July 2001, the government promulgated the "Disaster Prevention Act" in response to addressing the importance of disaster prevention and mitigation work, and in July 2003, the "National Disaster Prevention and Rehabilitation Technology Center" was formally established to promote and conduct disaster prevention and rehabilitation activities. Furthermore, owing to its commitment to social responsibility and premise of giving back to the community, CECI established its own "Center for Integration and Preparation of Disaster Mitigation Engineering Technology" on April 21, 2017 (the 82nd anniversary of the Hsinchu Taichung Earthquake on April 21, 1935). The primary purposes of the Center are to:

(1) Research and analyze the causes of disaster types, study the engineering technique of disaster prevention and mitigation, and
(2) Conduct disaster prevention education. training and disaster relief drills,
(3) Assist the authorities during the disaster emergency response period in disaster relief, technical support, and provision of a channel to support disaster response operations, and
(4) Provide emergency engineering and technical support for emergency reconstruction and permanent reconstruction during disaster recovery and reconstruction.

2. Highway bridge disaster management platform

Taiwan features both densely populated areas and steep mountain ranges, and relies heavily on a well-developed highway network for its regional transportation and economic development. Bridges are often considered the most critical link in the highway network and are the most important lifeline when disasters occur. When an earthquake takes place, besides potentially causing some significant loss of life and property, it is very likely to cause some damage to bridges and road disruption, resulting in a serious impact on disaster response and relief work. Consequently, the damaging effects of the disaster will continue to expand and the subsequent losses might be considerably more than at the moment that the earthquake disaster occurred. Therefore, special attention needs to be made on lessons learned from past disaster experiences and the need to carry out effective retrofit work on bridges that have an insufficient seismic capacity with the aims of (1) reducing damage of bridges; (2) preventing traffic disruption; and (3) mitigating the socio-economic impact in the aftermath. In addition, with the proper functioning of roads and bridges, the resulting loss of life and properties will be reduced and the post-disaster recovery of industrial and commercial activities will be accelerated. Overall, the scope of disaster prevention engineering activities and facilities is very wide and complex, but the first priority targets and focuses on assessing the condition and retrofitting of bridges. Disaster management primarily consists of four phases, that is: (1) mitigation, (2) preparedness, (3) response and (4) recovery. For the development of the bridge disaster management platform, CECI first focuses on a "quick screening analysis" at the mitigation phase to select dangerous and old bridges, and then conducts a hierarchical management for arranging the selected bridges in order of priority for the need of treatment. According to the survey data, each bridge management authority has a large number of bridges; therefore, it is impractical and quite difficult to carry out inspection and maintenance work on all of the bridges with such limited resources. Even advanced countries in Europe, North America and Japan face the same difficulties. Hence, to perform the "quick screening analysis", the system adopts two stages of screening and provides a recommended course of action for each bridge authority to consider and deploy while focusing on bridge management and a referenced order of priority for carrying out a detailed assessment and retrofit in the next stage. The bridge disaster management and disaster reduction process is shown in Figure 2.

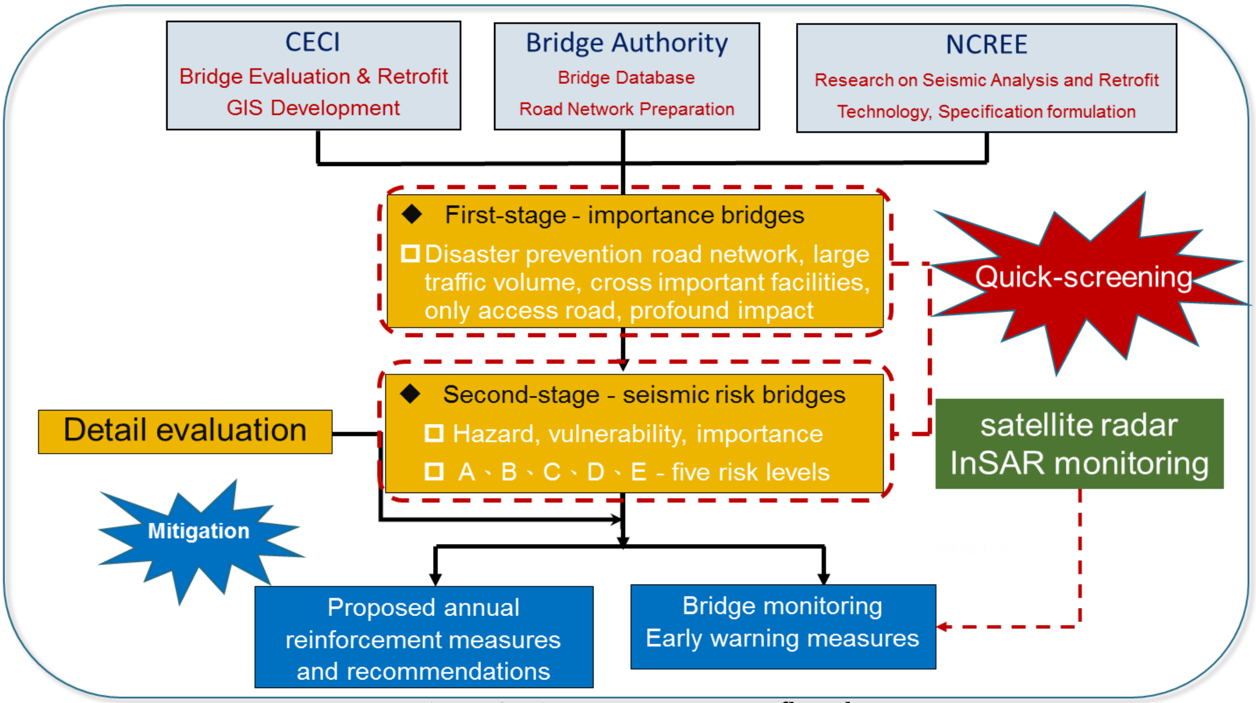

Figure 2 Disaster management flowchart

3. Quick screening mechanism of bridge's damage assessment

The "quick screening mechanism of bridge's damage assessment" mainly includes a calculation method for the bridge's seismic risk assessment, which consists of "fragility curve", "hazard curve" and "bridge importance". The calculation process depends on the bridge's basic data and assessment data for a detailed evaluation of seismic resistance. However, since most of the bridges have not been subjected to a detailed seismic analysis, it is impossible to obtain the collapse acceleration (A_c) and the yielding acceleration (A_y) of the structure which are referred as the basis for establishing the fragility curve. Therefore, the platform (Highway Bridge Disaster Management Platform) uses the basic information of the bridge and the method described in Section 3.1 to obtain the estimated bridges A_y and A_c, which are not evaluated by the seismic capacity detailed evaluation, so that the risk assessment calculation of the bridge earthquake damage can be carried out.

3.1 Basic assumptions and calculation methods for A_c and A_y estimation

Taiwan's *"Standard Specification for Highway Bridges"* has been revised numerous times. For the seismic design content and comparison of different versions, please refer to the "Evolution of Seismic Assessment and Retrofit Specifications for Highway Bridges" [1], which completely collects the bridge seismic design specifications issued by the Ministry of Transportation and Communications over the years, and explains the evolution and comparison of different versions' specifications. Taiwan's *Standard Specification for Highway Bridges* was originally published in 1954 and revised in 1974, 1987, 1995, 2000, 2009, and the latest version of 2019. However, the most recent update to the bridge database currently stored in Taiwan's Bridge Management System (TBMS) is prior to 2019. Therefore, the basis for the theory adopts the bridge design specifications from the year 2000 edition of the Specifications to estimate A_c and A_y while corresponding to the bridge's respective design year.

The basic data required for the A_c and A_y estimation mainly comes from the basic data of TBMS, but TBMS does not have the complete design details of the bridge. Therefore, when applying the *Standard Specification for Highway Bridges* to estimate A_c and A_y, if the necessary data of the design parameters cannot be obtained by TBMS, there are basic assumptions for the missing data used to estimate the A_c and A_y. For example, there is no data on the basic vibration period of the bridge structure in the TBMS. When this parameter is required, the basic vibration period of the bridge structure is assumed to be located in the horizontal section of acceleration response spectrum. $S_{aD}=S_{DS}$ (S_{aD}: design seismic horizontal spectral acceleration coefficient; S_{DS}: site short-period design seismic horizontal spectral acceleration coefficient) is used as the basis for the calculation to reduce the problem of insufficient design parameters for estimating A_c and A_y.

3.2 Fragility curve

Structure damage assessment is often based on the fragility curve, which is the probability that different structures will produce different damage conditions under different peak ground accelerations or spectral displacement or maximum displacement responses. The system uses the Peak Ground Acceleration (PGA) as the ground motion parameter of the structural damage curve in the bridge damage assessment.

The seismic capacity of a structure is usually expressed by the ground acceleration that the overall structure can withstand at various seismic performance levels. The ground acceleration can be obtained from the capacity spectrum of push-over analysis, according to the site seismic horizontal acceleration spectrum coefficient, and other provisions of the capacity spectrum method, and the improved seismic capacity assessment method [2, 3, 4, 5]. The seismic capacity of the structure is represented by the bilinear relationship between PGA and spectral displacement as shown in Figure 3.

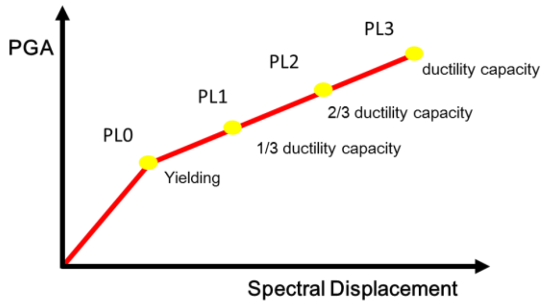

Figure 3 Structure seismic capacity

The bridge damage assessment refers to the recommendations of the current seismic design specifications and the Taiwan Earthquake Loss Estimation System, TELES [6], and takes the following four structural performance levels as the basis for the seismic damage assessment:

1. Structural performance I (PL0): When the displacement of the structure reaches the spectral displacement.
2. Structural performance II (PL1): When the displacement of the structure reaches 1/3 of the ductility capacity.
3. Structural performance III (PL2): When the displacement of the structure reaches 2/3 of the ductility capacity.
4. Structural performance IV (PL3): When the displacement of the structure reaches the ductility capacity.

According to the definition of the four structural performances, the damage state of the structure can be set to five stages (refer to Equation 1), respectively: no damage probability $P_r(R_1)$, slight damage probability $P_r(R_2)$, moderate damage probability $P_r(R_3)$, serious damage probability $P_r(R_4)$ and near collapse probability $P_r(R_5)$, as shown in Figure 4. The corresponding probability of occurrence $P_r(R_i)$ can be expressed as:

$$P_r(R_1) = 1 - P_1$$
$$P_r(R_i) = P_{i-1} - P_i \, , i = 2 \sim 4 \qquad (1)$$
$$P_r(R_5) = P_4$$

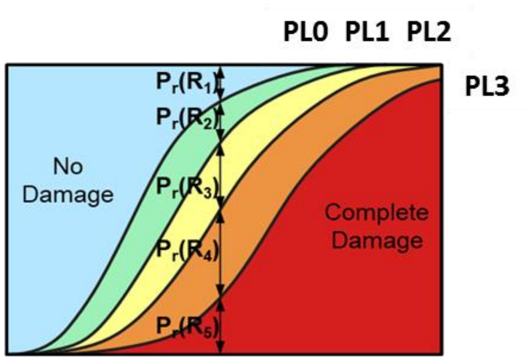

Figure 4 Structural fragility curve

3.3 Hazard curve

Curve fitting is carried out to simulate the seismic ground acceleration of $0.4S_S^D/3.25$ corresponding to the 30-year return period; and the designed seismic ground acceleration of $0.4S_S^D$ corresponding to the 475-year return period; and the designed seismic ground acceleration of $0.4S_S^M$ for the 2500-year return period (refer to Equation 2). This is in order to establish a seismic hazard curve (Figure 5) in accordance with the administrative area, which is calculated by the corresponding period of $0.4S_S^D/3.25$ and $0.4S_S^M$ in the region. Substituting into Equation 2, respectively, a_0 and a_1 are solved.

$$\frac{x}{0.4S_S^D} = \left[\frac{T_r}{475}\right]^{a_0 + a_1 x^{0.1}} \qquad (2)$$

Where x is the effective PGA, S_S^D is the short-period design horizontal spectral acceleration coefficient, T_r is the return period corresponding to the effective PGA, and a_0 and a_1 are the undetermined coefficients. After solving a_0 and a_1, the PGA of the earthquake can be substituted to solve the return period T_r, and then T_r is substituted into the Equation 3 to calculate the year exceeding probability of PGA.

$$P = 1 - e^{-\left(\frac{1}{Tr}\right)\times t} \quad (3)$$

Where T_r is the return period corresponding to the effective PGA, t is the bridge design lift-time.

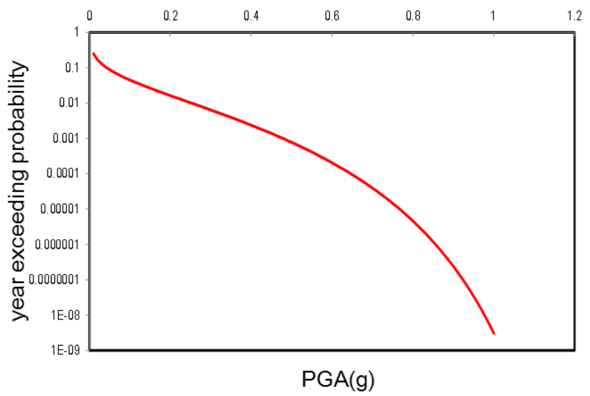

Figure 5 Seismic hazard curve

3.4 Bridge importance

The bridge importance is a weight coefficient. Different bridge management organizations can design the calculation method of bridge importance differently according to the strategy of resource allocation. The bridge importance is based on key factors such as traffic flow, regional environment, disaster relief, whether or not it is the only access road, and distance to large hospitals or disaster prevention command centers to determine the bridge importance.

Whether or not the bridge is to be retrofitted depends mainly on the retrofit benefit. The risk of earthquake damage to the bridge depends on two factors: the risk of damage and the vulnerability. The vulnerability is also related to the scale of the bridge, the traffic flow, the regional environment, and the impact of the disaster. Factors, such as secondary disasters and earthquake hazards, are also closely related. It is not easy to quantify the vulnerability because it is time-consuming and labor-intensive. Therefore, the system adopts the "weighted importance simple decision method" to facilitate the screening and grading of a large number of bridges, and provides the basis for a subsequent detailed evaluation. Its weight calculation is as shown in Equation 4.

$$W_T = W_{LN} \cdot \beta + W_R + W_I + W_{HC} + W_{CR} \quad (4)$$

Where, W_T: total weight, the meaning of the other symbols are shown in Table 1.

Table 1 Weight of bridge importance

Weight of importance	Value	Description
W_{LN} (total traffic lanes)	1	traffic lanes: less than 2
	1.5	traffic lanes: 3~4
	2	traffic lanes: 5 or more
β (important correction factor)	1	Important roadways (national freeways, provincial highways)
	2	general roadways
W_R (regional attribute)	1	suburb (outside the urban planning area)
	1.5	county-administered towns
	2	Metropolitan area
W_I (disaster prevention road network)	0	located outside the disaster prevention road network
	6	located on the disaster prevention road network
W_{HC} (hospital)	0	NO large hospitals within 2 km of the bridge.
	3	There are large hospitals within 2 km of the bridge
W_{CR} (over cross)	0	NO cross rivers, national roads, provincial roads, railways and roads (4 or more traffic lanes)
	3	Cross over rivers, national roads, provincial roads, railways and roads (4 or more traffic lanes)

3.5 Bridge damage assessment

The above estimates of "fragility curve", "hazard curve" and "bridge importance" are combined to obtain the estimate Seismic Loss Ratio by Equation 5:

$$\frac{\int_0^{PGA_{max}}[\sum_{i=1}^{5} Loss_i \times P_r(R_i)]f(PGA)dPGA}{\int_0^{0.4S_S^M}[\sum_{i=1}^{5} Loss_i \times P_{r.ref}(R_i)]f(PGA)dPGA} \times (Weight \times \frac{1.5}{18}) \qquad (5)$$

The composition of Equation 5 can be divided into three parts: (1) the annual average seismic loss of the bridge (the part of the numerator), (2) the annual average earthquake loss (the part of the denominator) required by the bridge to the latest specifications, and (3) the weight and scaling factor.

The calculation method of the average annual earthquake loss of the bridge is the same. If the bridge has the A_y and A_c, obtained from the detailed seismic capacity evaluation, then they can be used to establish the fragility curve; otherwise, the design requirements of the bridge seismic design specifications of different years are used as the benchmark, and the design seismic force is used as the basis for the estimation of the bridge A_c and A_y, and the fragility curve is substituted and established. Since the basic information does not have the data of the bridge construction cost, in the estimation of $Loss_i$, only the unit cost is considered, and the cost ratio of repair of different damage degree is replaced by 0%, 2%, 10%, 70%, 100% respectively.

The bridge considers the annual average seismic loss required by the latest specifications. It is also calculated with reference to the same equation, but the assumptions of A_c and A_y take into account the design factors required for the type of bridge in the latest design specifications. Referring to Figure 6, consider the bilinear relationship between PGA and structural spectral displacement, and linearize with ($A_c=0.4S_S^M$, $S_d=4\Delta y$) and ($A=0.4S_S^D$, $S_d=2\Delta y$), respectively. The relationship is substituted and the inverse solution is solved (A_y, $S_d=\Delta y$), thereby obtaining A_y and A_c. After establishing the fragility curve by A_y and A_c, the probability of occurrence of various degrees of damage is further obtained as $P_{r.ref}(R_i), i = 1 \sim 5$.

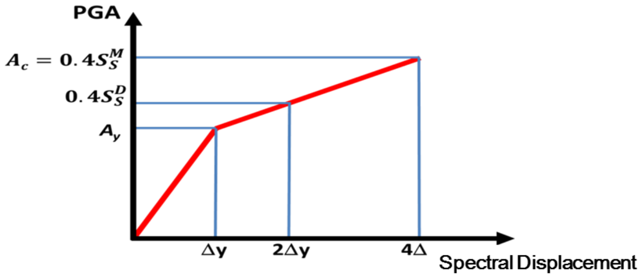

Figure 6 Bridge seismic capacity required by the new code

The results obtained by Equation 5 can be used as sorting or grading. In this study, $\frac{1.5}{18}$ is used as the scaling factor, and Table 2 is used as the basis for grading. Depending on cost considerations, the bridge management authority can have its own way to adjust the grading values.

Table 2 Reference value of seismic damage grade classification

Grade	Value	Suggestion
A	Above 1.5	Shall be processed immediately
B	1.2 ~ 1.5	Shall be processed
C	0.8 ~ 1.2	Should be treated
D	0.5 ~ 0.8	Could be processed later
E	Below 0.5	Do not be processed temporarily

4. Platform function development and build-up

4.1 System environment architecture

The system environment uses virtual mainframe (VM) to provide APs and GIS, and DB Server. It provides considerable flexibility and advantages for management, data backup and resource utilization.

Internet geospatial software: ESRI ArcGIS Server 10.5 map service platform, with the support of a geography database of images, tiles, vectors, provides GIS map service publishing, such as Map Services, Feature Services, OGC WMS, OGC WFS, etc., and can be integrated and developed with AJAX or HTML technology through the application API to provide web GIS analysis and display services.

Database software: Microsoft SQL Server is used as the system database software. It has the advantages of high security and stability, easy operation, convenient query syntax and high compatibility. The database format can be developed by various methods used by the platform to provide the fastest and safer information services.

4.2 System layout planning

When considering the intuition of the user in the operating system, the display window is divided into four areas. The main window display is the "map operation area", and according to the system function attributes, the functional area is divided into "main menu function column", “map tool function column” and "information area" as shown in Figure 7. In addition, users often need to switch between the map and the function window or query each other. Therefore, the functional areas are designed with the concept of "open/close" and can be switched at any time to take into account the "maximum map image" and "function operation convenience."

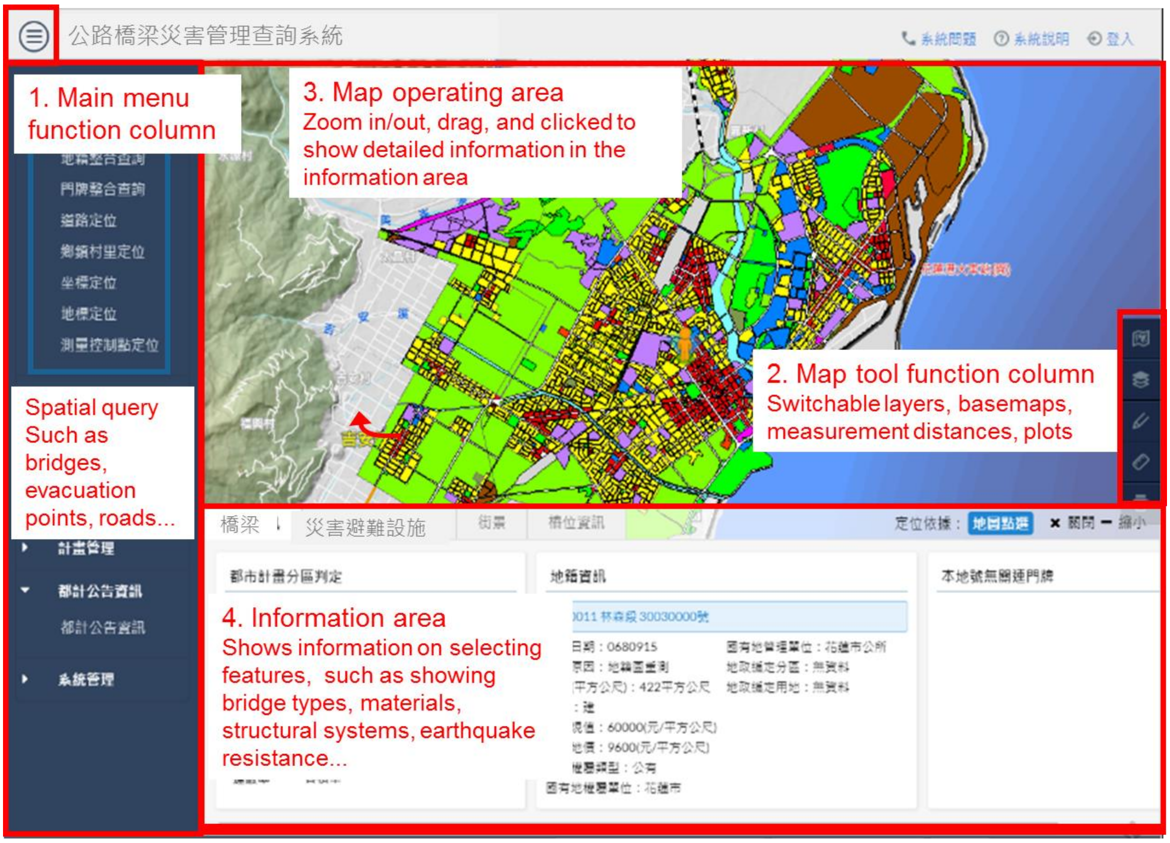

Figure 7 System display and functional menu

4.3 Spatial database collection and finished results

The spatial database collection and finished results are according to the following four categories, (1) bridge data, (2) disaster prevention resources, (3) natural resources, and (4) social economic resources. The platform presents the bridge as the main target; and, the disaster prevention, natural and social economic resources are used as reference maps, which are presented as separate layers on the platform, convenient for users' reference. At the same time, one can sort out the bridge project numbers in the CECI database via the platform to query the company's internal projects data.

The following describes the establishment methods of each database, data sources and finished results for each database content:

(1) Bridge data: The bridge data is provided by each bridge management organization, and transformed into GIS format. The bridge data, such as the usage statues, as-built year, maintenance record, affiliated organization, structural type, location, etc., are recorded in the platform system. It is classified by the bridge management authority and the total number of bridges that has been collected is more than 20,000.

(2) Disaster prevention resources: Collects data on the disaster prevention road network and the location of large hospitals in each county and city, as shown in Figure 8.

(3) Natural resources: Collects data on all active faults, geological sensitive areas, and river basin data.

(4) Social economic resources: Collects data on the range of urban planning areas in each county.

(5) Bridge design data: Integrates info and data from CECI's finished projects and connects the database to the platform for surveying.

(6) Basemap data: Open data for electronic maps, orthophotos, OpenStreetMap, geological maps, land use survey results, and the images from Satellite Fuwei No. 2.

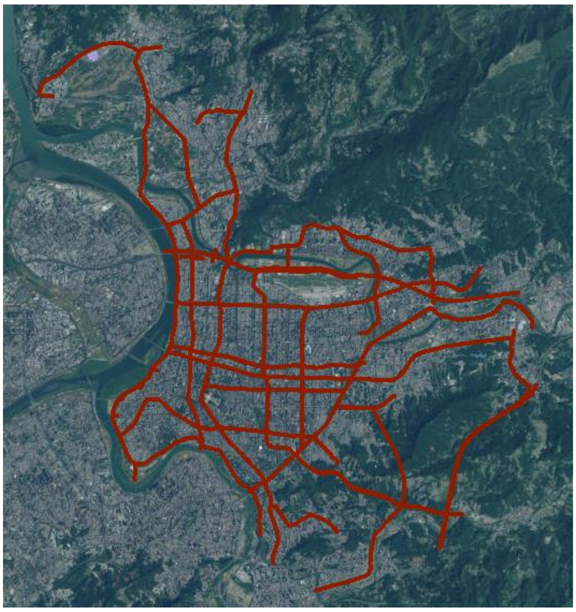

Figure 8 Taipei city disaster prevention road network

4.4 System function planning and development results

The functional architecture diagram of the highway bridge disaster prevention management system consists of four modules, namely (1) map operation, (2) bridge information query, (3) layer and (4) analysis attribute query. The contents of each module are explained below.

4.4.1 Map operation module

(1) Zoom in/out and drag the view: Use the cursor and scroll wheel to move the map screen and adjust the scale to display different levels of detail.

(2) Drawing tools: One can add points, lines, planes, etc. and text notes to the drawing.

(3) Measurement tool: Line segment or range can be drawn on the drawing surface to measure the actual distance or area.

(4) Printing tool: Export the current map range to the file of PDF or PNG format at the set scale

and paper size.

4.4.2 Bridge information query module

(1) Bridge query: Use the keywords, county/city, structure type, as-built year and other parameters to screen the bridges that meet the conditions, as shown in Figure 9.

(2) Quick screening analysis: the management conditions, structure type, as-built year, maximum span, total weighted importance are used as screening conditions.

(3) Screening level query: The screening criteria are based on the management authority and the seismic damage screening grade.

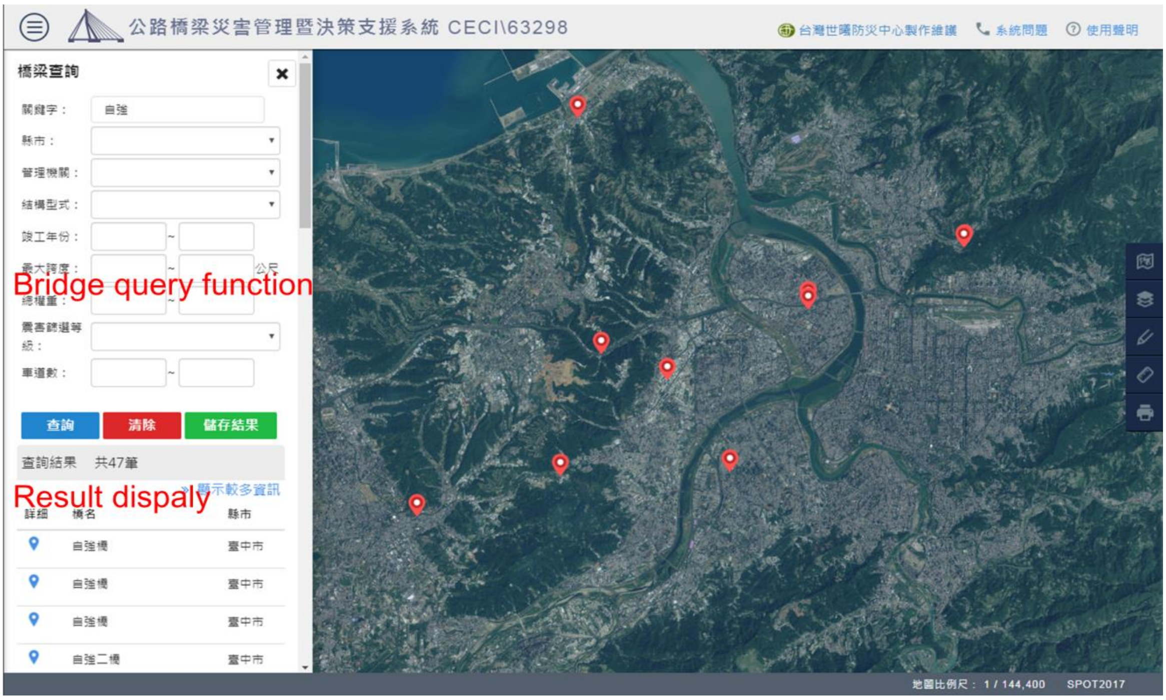

Figure 9 Bridge query function display

4.4.3 Layer module

(1) Background image switching: Users can use this function to switch background images, including electronic maps, orthophotos, satellite images, land use maps, and geological maps. The map layers can be overlapped, and each layer can be independently switched, adjusted for transparency, order, legend, and removed.

(2) Geological maps overlay: including drilling points, various thematic geological sensitive areas, all active faults, and soil layers.

(3) Orthographic image overlay: The orthophoto image layer is an orthophoto of the aerial survey in the Taipei area from 1945 to 2017.

(4) Disaster prevention resources overlay: including the disaster prevention road network in Taipei City and the 2km radius area of the hospital.

(5) Pipeline data overlay: including pipeline data such as power, tap water and rainwater in Taoyuan City.

(6) Bridge data overlay: It is divided into multiple bridge layers by the theme of cross-water bridge, construction year, structure type, central government administered river bridge, importance factor, and closed project information.

4.4.4 Analysis attribute query module

When you click on the bridge point, the property bar below will be expanded, and there are five tabs to switch.

(1) Bridge information: Click on the bridge point on the map to query the basic information of the bridge, including the name, management authority, mileage, construction year, design standards and parameters, and various structural types and structural dimensions, as shown in Figure 10.

(2) Bridge screening: including importance statistics, seismic damage screening grade statistics, importance analysis and quick screening analysis, as shown in Figure 11.

(3) Geological data: The geological drilling data closest to the bridge can be inquired, and whether or not the bridge is located in the geological sensitive area of various topics, as shown in Figure 12.

(4) Street View: Use Google services to view the streetscape of the bridge, one can move freely to understand the situation on site, as shown in Figure 13.

(5) In SAR: Integrate InSAR elevation variant monitoring database to query the cumulative variant layer of the bridge location, as shown in Figure 14, or link to the geological database query system to query the cumulative variation of time series at any point in the region. The graph is shown in Figure 15.

Figure 10 Bridge information display

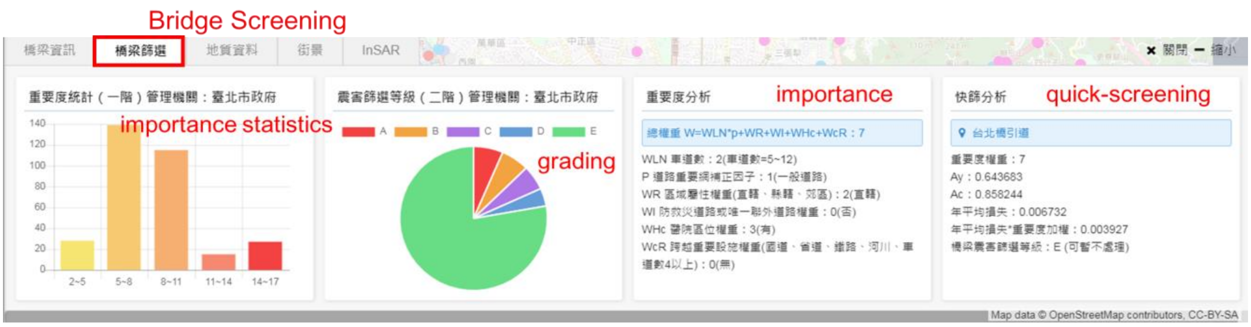

Figure 11 Bridge screening display

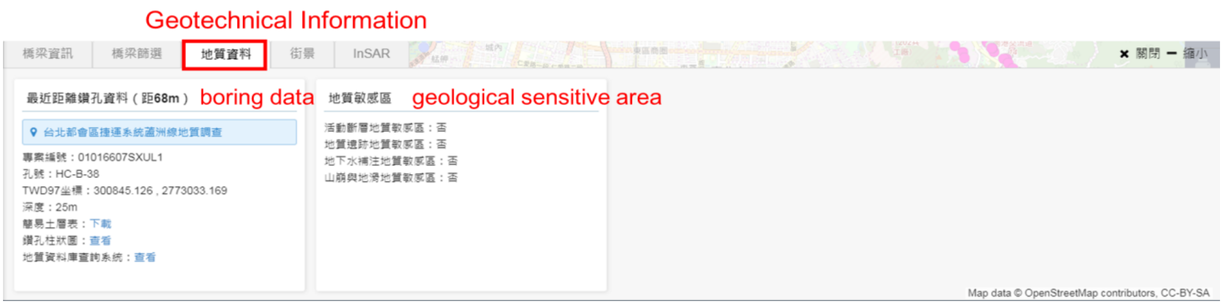

Figure 12 Geotechnical data display

Figure 13 Street view display

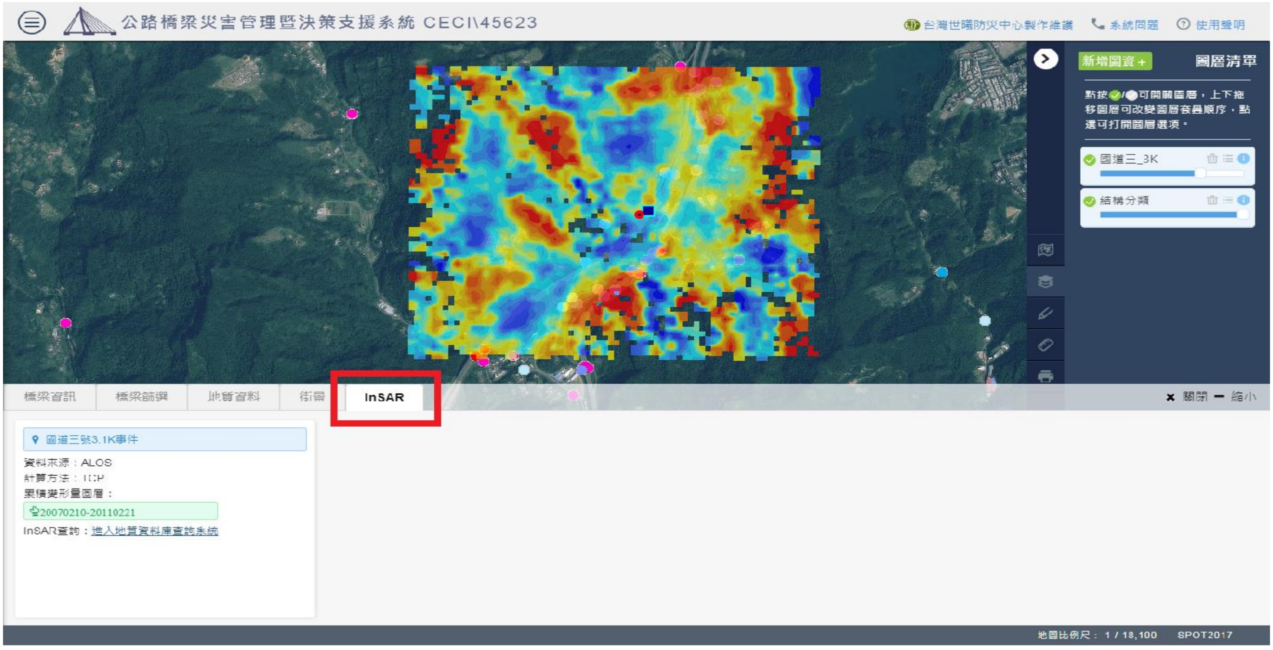

Figure 14 InSAR display

Figure 15 InSAR single point accumulated deformation display

5. Conclusion

Bridge safety is closely related to people's lives and plays a prominent role in the country's economic development, whereas module development on a bridge disaster management platform; such as, “bridge quick screening analysis” and “bridge detailed evaluation” plays a key role in extending the bridge service life as well as activating bridge data innovation applications and optimizing bridge service functions. As verified by its usage in the Taiwan domain, this platform has proven to achieve good results. CECI has thus opened up the platform freely to those bridge management authorities who are willing to provide their basic bridge information. Owing to this success, its subsequent application will greatly help the government accelerate its work of homeland safety enhancement.

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