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Innovative Life-Cycle Inspection Strategy of Civil Infrastructure: Smartphone-Based Public Participation

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The life-cycle inspection of civil infrastructure can guide decisions on structural safety and reliability. This paper proposes a strategy for smartphone-based public participation in the life-cycle inspection of civil infrastructure (SPIC). The SPIC strategy consists of three parts: participants, Urban Brain, and Global View. Next, the feasibility of this strategy is verified by simulation experiments implemented in Unity3D. Civil infrastructure inspection modes include routine inspection, focus inspection, and emergency inspection. The activation and transition of the three inspection modes are tested. Test results show that routine inspection with public participation could timely identify pre-set damaged civil infrastructures. All abnormal civil infrastructures are observed by the Urban Brain. The focus inspection mode is activated when an abnormal civil infrastructure is detected, and the focus inspection provides a detailed and professional assessment of the abnormal civil infrastructure. Then, the inspection of all civil infrastructures in emergency inspection mode is completed in the test. Furthermore, this paper carries out a factor sensitivity analysis of this strategy. The proposed strategy establishes the mechanism for the assign-accept-feedback inspection task. In addition, the simulation performed in Unity3D is one of the next alternatives for large-scale urban disaster prevention and mitigation experiments in the real world. The SPIC strategy can effectively enhance the disaster prevention and mitigation capabilities of civil infrastructure.

1. Introduction

The service life of civil infrastructure is usually decades or even centuries. During its service life, civil infrastructure is subject to various adverse factors, such as environmental erosion, aging, overloading, and extreme natural disasters, resulting in structural damage, failure, and even collapse [1–3]. According to the 2021 America's Infrastructure Report Card given by the American Society of Civil Engineers (ASCE), 42% of bridges in the United States have been in service for more than 50 years [4]. In addition, 46,154 bridges are deemed damaged, representing 7.5% of the total number of bridges in the United States. Destruction of civil infrastructure may threaten the safety of citizens [5, 6]. Therefore, it is vital to continuously pay attention to the reliability and durability of civil infrastructure throughout its life cycle.

The life-cycle requirement of civil infrastructure is the reliability of the structure. The life-cycle inspection of civil infrastructure is a fundamental strategy for maintaining its performance above the safety threshold [7, 8]. The inspection identifies structural response parameters at various stages in the life cycle of civil infrastructure and provides references for the assessment of structural safety and durability [1, 9]. Common options for structural life-cycle inspection include inspection and monitoring. For inspection, traditional techniques rely on technicians using specialized equipment to obtain structural response parameters. However, limited technicians and equipment could not satisfy the current demand for rapid inspection of clustered civil infrastructures. For monitoring, structural health monitoring (SHM) systems are used to monitor the condition of structures in real time and online [10–13]. Nevertheless, it is unrealistic to install SHM systems for all civil infrastructures to implement real-time monitoring over their life cycle due to the high cost of purchasing, installing, and maintaining specialized sensors [14]. When natural disasters occur, the public is not informed about the condition assessment of the civil infrastructure. A questionnaire survey on the awareness of housing safety among 330 citizens in Dujiangyan showed that the average score for the option "willing to use the house safely" was 4.08 (on a scale from 1 to 5, with 1 being the lowest and 5 being the highest) [15]. This also indicates that citizens are greatly concerned about the safety of the buildings they live in. If we can mobilize the power of citizens, then inspection of the clustered civil infrastructures is possible. Therefore, it is necessary to research the life-cycle inspection method of civil infrastructure with public participation [16, 17].

The difficulties of public participation in civil infrastructure inspection are measurement methods, information exchange, and personnel scheduling. Fortunately, the innovation and popularization of smartphones initially solved the above challenges. In 1994, IBM and BellSouth teamed up to develop the world's first recognized smartphone, which could answer cell phones and send E-mail [18]. Since then, the communication, computing, and perception capabilities of smartphones have continued to increase. Therefore, many researchers have studied inexpensive and convenient methods for measuring structural response parameters based on smartphones. This also establishes the basis for public participation in structural inspections. Nowadays, a smartphone is not only a communication tool but also an important connection link for the "Internet of Everything" in smart cities [19]. The combination of "People + Smartphones" inspires many industries. For example, O2O platforms such as Uber, DiDi, and Meituan have expanded rapidly in recent years, providing the public with smarter and more convenient services for shopping, travel, education, and smart home. Also, the integration of smartphones with artificial intelligence (AI), machine learning (ML), deep learning (DL), Internet of Things (IoT), and blockchain will present a greater improvement to society in the future. At present, the collaborative work between people and smartphones is still at the primary stage of the mobile communication terminal, and then it may develop to the stage of the wearable communication terminal and eventually to the stage of the transplantable communication terminal [20]. The collaborative work of people and smartphones also affords opportunities for public participation in the civil infrastructure life-cycle inspection.

Depending on the level of intelligence, three stages of the development of smartphone-based public participation in civil infrastructure life-cycle inspection are as follows:

Stage 1. Research on smartphone-based techniques for acquiring structural response parameters: The effective collection of structural response parameters is fundamental for assessing structural safety conditions. In this stage, structural response parameters such as accelerations, bridge cable forces, displacements, cracks, and strains were acquired by numerous researchers with the help of high-performance sensors (e.g., accelerometers, GPS, gyroscopes, and cameras) built into smartphones [21]. These techniques show great promise in the field of structural inspection. For example, Zhao et al. developed a smartphone application, called Orion CC, that measures the cable force of the Dalian Xinghai Bay Bridge by invoking the smartphone's built-in accelerometer and gyroscope [22]. In 2014, Vittorio et al. used accelerometers and GPS in smartphones to track the vibration response of vehicles on the road [23]. Ozer et al. used multiple smartphones to collect acceleration data from the Golden Gate Bridge to determine the modal frequency and modal shape of the bridge [24]. Jo et al. proposed a method of bridge displacement measurement based on multi-image processing, which has good robustness to image rotation [25]. Ratnam et al. achieved the identification of structural surface cracks using images captured by smartphones and computational processing by cloud servers [26]. Xie et al. adopted a smartphone as the acquisition equipment to obtain structural surface strain based on the microimage strain sensing technique [27]. In general, the capture of the critical structural response parameters has been achieved by smartphones and low-cost assistance. In addition, AI and DL are involved in the acquisition of structural response parameters by smartphones. For example, Li et al. designed a fully convolutional network (FCN) to detect four types of concrete damage (cracks, spalling, flooding, and holes) in images and measure the pixel area of the damage [28].

Stage 2. Study of smartphone-based public participation in civil infrastructure inspection: Those involved in public participation include experts, technicians, and ordinary citizens. As demonstrated by many studies, public participation can leverage group intelligence and person mobility to tackle complex, large-scale, and distributed spatial tasks [29, 30]. A new idea of mobile SHM using smartphones was proposed by Yu et al. in 2012 [31]. They asserted that smartphones could serve as mini SHM systems, while they pointed out the feasibility of smartphones in mobilizing public participation in SHM during emergencies. Han et al. proposed a smartphone-based cyber-physical system for real-time monitoring of the movement of steel girder elements during the hoisting process [32]. Multiple smartphones were networked to form the collector and controller of a cyber-physical system.

Feng et al. proposed the concept of "Citizen Sensors" and developed a smartphone-based crowdsourcing platform for post-disaster damage assessment [33, 34]. A website, https://www.eexplorer.cn/, was created by Han et al. for collecting big data on emergency communications and earthquake damage information [35]. The information collected on the website is provided by residents who own smartphones. A participatory pavement performance monitoring system based on crowdsourced spatiotemporal data was proposed by Chuang et al. [36]. Mei and Gül used smartphones placed in moving vehicles as sensors to monitor and evaluate a group of bridges [37]. The US Army Engineering Research and Development Center (ERDC) developed an integrated digital system called Mobile Information Collection Application (MICA) [38]. Smartphones equipped with MICA software are helpful tools for collecting and organizing data for infrastructure assessments. Matarazzo et al. proposed the integration of crowdsourced smartphone-acquired bridge vibration data streams into a bridge condition database, which is helpful to the routine maintenance of infrastructure systems [39]. Staniek developed a method to identify and evaluate road pavement defects based on crowdsourced data from smartphone users in the traffic system [40].

Stage 3. The establishment of an intelligent life-cycle inspection system for clustered civil infrastructures: The core of the civil infrastructure inspection system is called the "Urban Brain." Some researchers proposed similar concepts before. Casares mentioned the concept of a future brain for public governance [41]. This brain has the properties of human agents and AI systems interacting to solve problems of social organization. Yu et al. proposed a solution to achieve intelligent operation and maintenance of roads in smart cities [42]. In addition, several researchers conducted large-scale SHM inspections based on smartphones in the field. Ozer et al. used smartphone accelerometers for modal identification on the transportation network of 20 bridges, extending the health monitoring from individual bridges to urban areas [43]. Castellanos-Toro et al. compared the fundamental frequencies and damping ratios of 12 bridges collected by smartphones and commercial devices and successfully extended them to 451 bridges in Santiago de Cali [44]. Chuang et al. conducted a crowdsourcing test of the road network in Taipei City and obtained pavement performance of 118,76 km from 141 devices [36]. Matarazzo et al. tested modal frequencies of the Harvard Bridge (660 m long, 25 spans) in Massachusetts, United States, monitored by multiple smartphones [30]. The Urban Brain is an intelligent hub for perceptual connectivity, fusion interaction, resource allocation, management decision making, and digital clustering of civil infrastructure. The Urban Brain mainly consists of digital neuron networks and cloud reflex arcs. The neural network can achieve information interaction between people to people, people to things, and things to things in the city. Cloud reflex arcs could generate rapid and intelligent responses to urban services. Eventually, a self-updating and automatically interacting intelligent civil infrastructure inspection system will be established.

However, most current research on smartphone-based public participation in civil infrastructure life-cycle inspection focuses on Stage 1 and Stage 2. Research on Stage 3 is progressing slowly due to some practical difficulties [45, 46]. This also prevents public participation in civil infrastructure inspection from being promoted to practical application scenarios. The first difficulty is the mechanism of assignment-acceptance-feedback inspection tasks. Inspection tasks need to be allocated to citizens in a reasonable manner, so that citizens have shorter walking distances to reach the target location and less time for overall inspection. There is no well-developed model for the interaction between management platforms and ordinary citizens. The second difficulty is mechanism testing. The conventional validation method is to conduct comprehensive experiments in the real world. Nevertheless, it is difficult to carry out experiments on a scale of cities due to practical limitations. The third difficulty is the mobilization of citizens. Public participation is influenced by the cooperation of government departments and the attitude of the public. Therefore, it is necessary to study the influence of factors such as public cooperation on inspection efficiency. The authors' team conducted a preliminary exploration of related work for seismic emergency inspection [47]. This study used a game engine to simulate the whole process when an earthquake strikes a city. However, the previous study has the following limitations. (a) Potential hazards of structures in daily life could not be detected because the inspection was only done after an earthquake. (b) Citizens were numbered to complete tasks in the previous study, which did not consider that people are dynamically distributed in the city. (c) It is unlikely that all citizens are willing to perform the task. The degree of public willingness to participate in inspections varies between seismic and usual conditions [48]. In summary, it is necessary to establish a framework for the life-cycle inspection of civil infrastructure considering the mechanism of task assignment.

Therefore, this paper innovatively proposes a strategy for smartphone-based public participation in the life-cycle inspection of civil infrastructure (SPIC). Then, the task assignment-acceptance-feedback mechanism for the life-cycle inspection of civil infrastructure is illustrated in the SPIC strategy. Inspection modes and parameters in different scenarios are also presented in detail. Moreover, the feasibility of this strategy is verified by simulation experiments implemented in Unity3D. Factors affecting the inspection efficiency of the SPIC strategy are also analyzed in this paper. In conclusion, the SPIC strategy can effectively enhance the disaster prevention and mitigation capabilities of civil infrastructure.

2. Strategy Formulation

Figure 1 shows an overview of the SPIC strategy for smartphone-based public participation in the life-cycle inspection of civil infrastructure. The SPIC strategy consists of three parts: (1) Urban Brain; (2) participants; and (3) Global View. The Urban Brain is a management platform for public participation. The function of the Urban Brain is to assess the health of civil infrastructure using values of structural response parameters measured by public participation. Participants refer to ordinary citizens with smartphones who are willing to perform inspection tasks. The Global View is a third-party perspective that is used to judge the validity of inspection results. The critical values of the structural response are given based on the structural reliability and risk analysis. The critical values are used for data comparison with the measured structural response characteristics. The Urban Brain captures the location of citizens through smartphones or other mobile terminals and then sends tasks to citizens. After that, citizens accept inspection tasks and perform tasks. Citizens upload their measurements to the Urban Brain. In this way, the Urban Brain can obtain values for a range of structural response parameters to evaluate the health of entire civil infrastructures. In particular, seismic information gathered by crowdsourcing participants can be effectively incorporated into probabilistic seismic hazard analysis (PSHA) and probabilistic seismic demand modeling (PSDM) to improve seismic risk decisions [49]. To verify the feasibility of the SPIC strategy, this study uses the powerful Unity3D platform to simulate the process of public participation in civil infrastructure inspections. Citizens and the Urban Brain collaborate to perform tasks and collect structural response parameters about civil infrastructure.

2.1. The Mechanism for Participants. Participants are modeled as agents that could move around in real time. Agents are artificial intelligence programmed to perform pre-set actions. The complexity of agent behavior can range from basic decisions (yes or no) to random behavior. Kang and Han's pedestrian model was adopted in this study [50]. The location of participants in the pedestrian model is initially distributed randomly. A sufficient pre-run period is used to eliminate the effects of initial conditions. Citizens can perform inspection tasks after being trained on SHM. Be aware that citizens are always in a safe environment when performing inspections. Figure 2 illustrates a flowchart of participants completing civil infrastructure inspection tasks.

2.2. The Mechanism of Management Platform. The Urban Brain in this paper can be considered as the management platform of the clustered civil infrastructure inspection. The Urban Brain dynamically assigns inspection tasks by grasping the locations of crowdsourced participants. Here, the location of participants can be accessed via the smartphone's Global Positioning System (GPS). Consider the time of task execution and the location of the structure being inspected when recruiting crowdsourced participants. Finally, the crowdsourced participants using their smartphones measure structural response parameters and upload inspection results to the Urban Brain. Figure 3 presents a frame diagram of the Urban Brain assigning inspection tasks to citizens.

The Urban Brain is modeled as a special agent. $M = \{m_1, m_2, m_3, \ldots, m_k\}$ corresponds to the set of inspection tasks released by the Urban Brain, while $U = \{u_1, u_2, u_3, \ldots, u_g\}$ corresponds to the set of crowdsourced participants. The time cost for participant u_i to perform task m_j is $\mathrm{Cos}\, t_{ij}$, and the time cost is correlated with the distance from the crowdsourced participant to the structure to be inspected. T_{SUM} is the time interval from the time the Urban Brain releases tasks until all k tasks are completed. The parameters involved in the Urban Brain's model are shown in Table 1.

For the Urban Brain, the expectation is less action value and higher inspection efficiency. α and β are the weighting coefficients for the different reference indicators. Thus, the objective function of the Urban Brain for assigning tasks is

$$\min F = \alpha \sum_{i=1}^{g} \sum_{j=1}^{k} \mathrm{Cost}_{ij} x_{ij} + \beta T_{\mathrm{SUM}},$$
$$\text{s.t.} \begin{cases} \sum_{i=1}^{g} x_{ij} = 1, & j = 1, 2, 3 \ldots k, \\ \sum_{i=1}^{k} x_{ij} = 1, & i = 1, 2, 3 \ldots g, \end{cases} \tag{1}$$

where

$$x_{ij} = \begin{cases} 1, \text{if } u_i \text{ performs task } m_j, \\ 0, \text{if } u_i \text{ does not perform task } m_j. \end{cases} \tag{2}$$

2.3. Inspection Methods for Civil Infrastructure Supported by Smartphone. At present, structural response parameters that can be obtained by smartphones include displacement, strain, inter-story drift, crack, bridge cable force, tilt angle, and acceleration, which are important references for structural safety assessment. The method of collecting structural response parameters by smartphone can basically satisfy the engineering requirements. These smartphone-based inspection methods are listed in Table 2.

2.4. Inspection Modes. Inspection modes of the SPIC strategy include routine inspection, focus inspection, and emergency inspection. The routine inspection is periodically scheduled, with tasks assigned once a month. The setting of the routine inspection refers to the frequency of citizens participating in volunteer activities in the "Report on the Development of Voluntary Services in China (2021-2022)" [58]. This report mentioned that 61.27% of citizens maintain an average frequency of participating in voluntary service activities every 1–3 months. In addition, with reference to the recommendations in the "Administrative Measures for the Operation and Maintenance of Urban Rail Transit Facilities and Equipment" promulgated by the Ministry of Transport of China, the number of civil infrastructures for

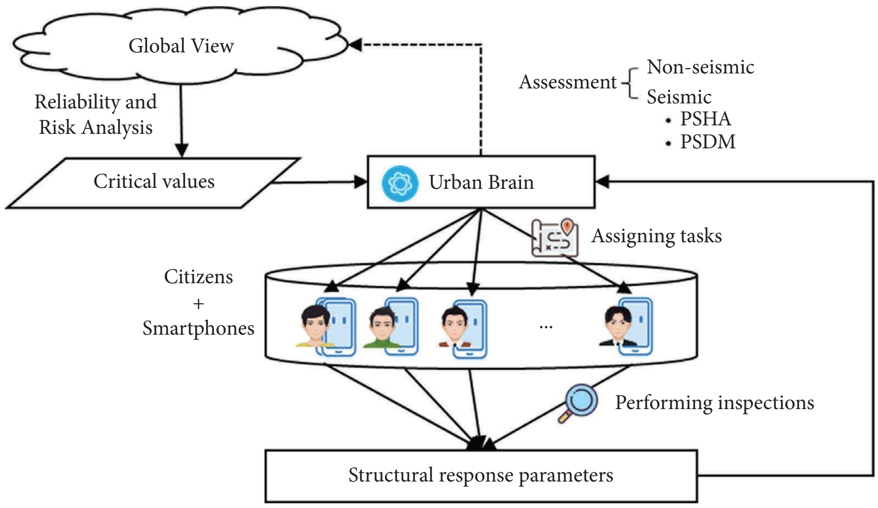

Figure 1: Overview of the SPIC strategy.

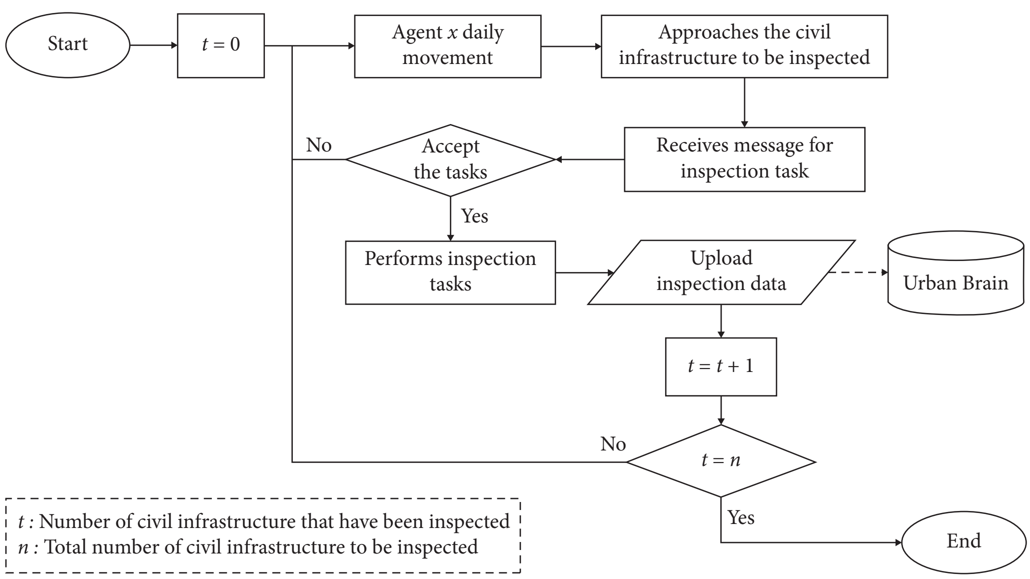

Figure 2: Flowchart of participants performing inspection tasks.

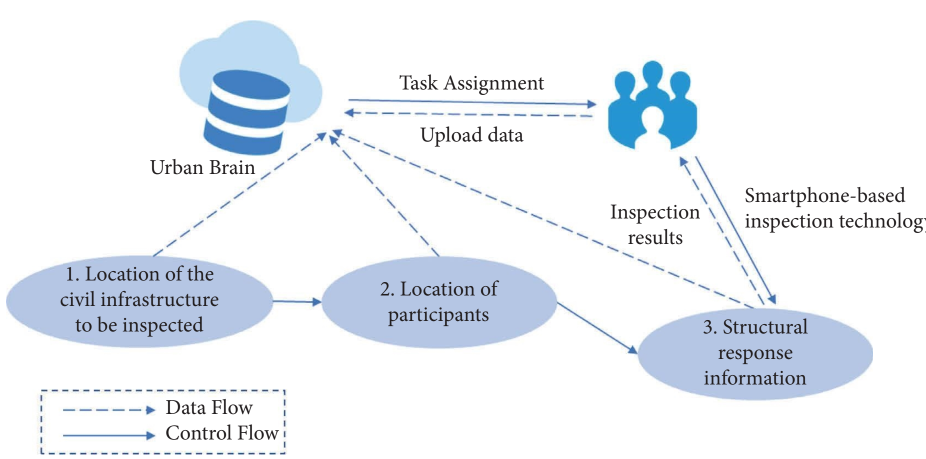

Figure 3: Frame diagram of the assignment of inspection tasks.

Table 1: Description of decision variables.

Parameter	Meaning
k	The number of inspection tasks
g	The number of crowdsourced participants
$\mathrm{Cos}\,t_{ij}$	Time cost of performing task
T	The set of inspection tasks
U	The set of crowdsourced participants
T_{SUM}	Time interval

each routine inspection is 1/4 of the total number of civil infrastructures [59]. This also means that all civil infrastructures will complete a routine inspection within four months, which fully guarantees the safety of all civil infrastructures throughout their life cycle. The routine inspection is mainly accomplished by citizens, and experts can also participate in routine inspections as volunteers. If there are abnormal results in the routine inspection, the Urban Brain will assign the focus inspection and organize experts or technicians to conduct specialized inspections. The object of focus inspection is the abnormal structure found in the routine inspection. The number of focus inspections is consistent with the number of abnormal structures identified in the last routine inspection. Once an abnormal structure is found in the routine inspection, a focus inspection will be carried out immediately. Based on the damage assessment of the identified structure during the routine inspection, experts utilize professional equipment to perform on-site tests and other supplementary assessments to evaluate the condition of the structure. There are two possible outcomes of the focus inspection. If the expert assessment determines that the structure is "in good condition," no repairs are required. In this case, only one focus inspection is conducted on the structure. After that, the structure is scheduled for routine inspection without repeated focus inspections. However, if the expert assessment indicates that the structure is "in poor condition," repairs, reinforcement, or even reconstruction may be necessary based on the extent of the damage. Similarly, only one focus inspection is performed on this structure. If the structure is repaired, it can be considered as a normal structure eligible for routine inspection. The emergency inspection refers to the inspection of all civil infrastructures in a city after special events such as floods, earthquakes, and other sudden disasters. The purpose of the emergency inspection is to swiftly evaluate the condition of civil infrastructures after sudden disasters. The similarities and differences between the three inspection modes are shown in Figure 4.

Additionally, SHM is combined with performance-based earthquake engineering (PBEE) to evaluate damage caused by earthquakes and improve seismic risk decision making. Post-earthquake assessment consists of four main steps (hazard analysis, structural analysis, damage analysis, and performance-based assessment). Figure 5 presents four generalized variables: *Measured Response* (*MR*), *Engineering Demand Parameter* (*EDP*), *Damage Measure* (*DM*), and *Decision Variable* (*DV*) [60, 61]. The decision variable can be expressed as a triple integral based on the total probability theorem:

$$p\{\mathrm{DV}\} = \iiint p[\mathrm{DV}\,|\,\mathrm{DM}]p[\mathrm{DM}\,|\,\mathrm{EDP}]p[\mathrm{EDP}\,|\,\mathrm{MR}]p[\mathrm{MR}]d\mathrm{MR}d\mathrm{EDP}d\mathrm{DM}, \tag{3}$$

where the expression $p[X\,|\,Y]$ refers to the probability density of X given the condition Y. $p[\mathrm{MR}]$ is the probability density of crowdsourced inspection.

The first step is the seismic hazard analysis, which uses seismic-related data collected by crowdsourced participants. Seismic hazard analysis needs to determine the source and magnitude distribution, which are usually issued by authoritative organizations such as the International Seismological Center (ISC), the Global Seismic Network (GSN), and the United States Geological Survey (USGS). Then, the distribution of source-to-site distances can be obtained by the GPS module of the smartphone since the source has been determined. By leveraging smartphones, crowdsourcing participants can collect acceleration vectors in three directions, enabling the estimation of ground motion intensity. Consequently, the measured response characteristics of $p[\mathrm{MR}]$ during the earthquake are obtained.

Next, unmeasured structural responses or *engineering demand parameters* (EDPs) can be estimated from the limited structural responses measured via smartphones. EDPs typically encompass inter-story drift, displacement, associated force, or other relevant quantities to characterize the response. Among them, some parameters can be measured using smartphones. Then, nonlinear finite element analysis models are constructed utilizing OpenSees (Open System for Earthquake Engineering Simulation) to model the structure and perform nonlinear dynamic analysis.

The third step involves conducting damage analysis, which aims to establish the relationship between EDP and DM. DM provides a quantitative description of damage to structural and nonstructural components. The result of this step is represented by $p[\mathrm{DM}|\mathrm{EDP}]$, which is the probability of DM given EDP.

Subsequently, the final step is to calculate the decision variable DV according to the different demands. Then, seismic risk decisions are made with the aid of performance-based assessment.

3. Strategy Implementation

Unity3D is a world-leading real-time development engine. Model editing and manipulation can be represented by intuitive scenes that can be previewed as needed. The physics engine built into Unity3D can simulate various physical phenomena, such as rigid body collisions and vehicle driving. Additionally, Unity3D supports scripting in multiple programming languages, including Java, C#, and Boo. Unity3D provides the opportunity to perform simulated experiments in virtual space. Therefore, experiments on the Unity3D platform are used to validate the SPIC strategy. The simulations in this paper correspond to the process of civil engineering infrastructure inspection, focusing on the interaction between agents.

Table 2: Smartphone-based inspection methods.

Parameter	Reference	Invoked sensor	Test scenarios		Test type	
			Laboratory	Field	Static	Dynamic
Displacement	Tian et al. [51]	Camera	√	√	●	●
	Zhu et al. [52]	Camera	√	—	○	●
Strain	Xie et al. [27, 53]	Camera	√	—	●	●
	Yu and Pan [54]	Camera	√	—	●	○
Inter-story drift	Li et al. [55]	Camera	√	—	●	●
Crack	Li et al. [28]	Camera	√	—	●	○
	Ni et al. [56]	Camera	√	—	●	○
Cable force	Zhao et al. [22]	Accelerometer	√	√	○	●
	Wang et al. [57]	Camera	—	√	○	●
Tilt angle	Han et al. [32]	Accelerometer Gyroscope	—	√	○	●
Acceleration	Ozer et al. [24]	Accelerometer	—	√	○	●

√ means yes; — means no; ● means yes; ○ means no.

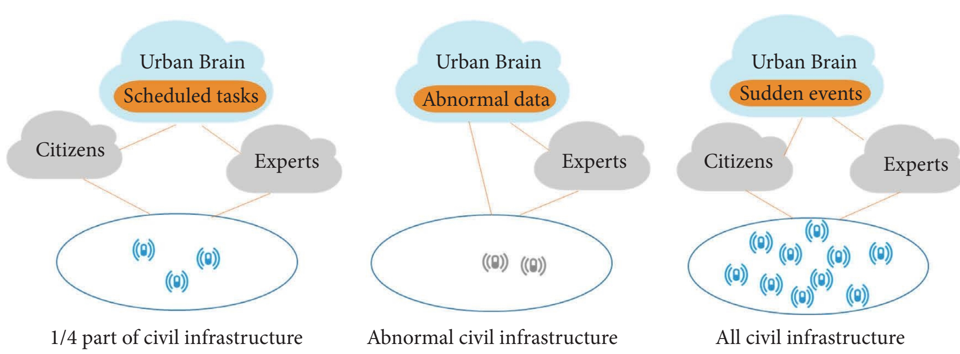

Figure 4: Three inspection modes.

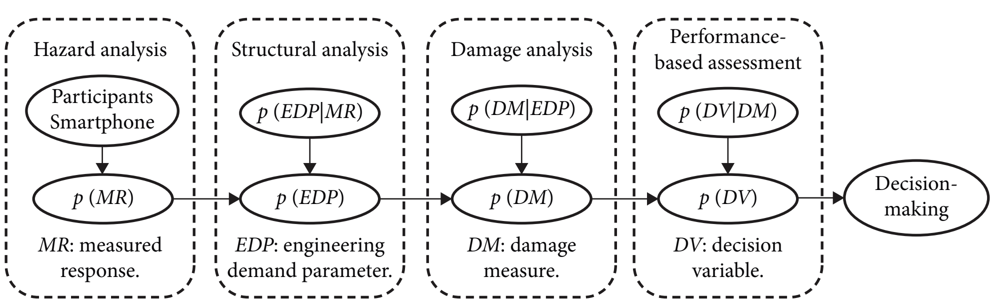

Figure 5: Performance-based post-earthquake assessment.

3.1. Parameters of the Simulation Model. In this study, Dalian (located in Northeast China) was selected as a reference city to establish a scale model of 1 : 30,000. Dalian has a population density of 592 persons per km^2 (in 2020: population = 7,450,785 persons; land size = 12,574 km^2) [62]. The area of the city model (named Spirit Water Island) established in the Unity3D scene was 0.4 km^2. Figure 6(a) presents an overhead view of the Spirit Water Island model, while Figure 6(b) displays a partial view of the Spirit Water Island model. Models for the different components of the city (buildings, roads, sidewalks, parks, etc.) were downloaded from the Unity Asset Store as prefabs, which were then assembled to form the entire city model. The Urban Brain in the Spirit Water Island model was named the Ground Eye. The model of Spirit Water Island consists of a Ground Eye graphical user interface (GUI), civil infrastructure, citizens, and several urban roads and rivers. In particular, the types of civil infrastructure include ordinary frame structures, arch bridges, suspension bridges, rigid frame bridges, and tunnels.

(a)

(b)

Figure 6: City model (Spirit Water Island): (a) overhead view of the city model and (b) partial view of the city model.

There are 1,279,000 registered volunteers in Dalian, accounting for about 22% of the total number of people in the city [63]. Although the willingness of volunteers to participate in different volunteering services varies, to some extent, registered volunteers can be considered as potential public to participate in infrastructure inspections. Adopting a similar proportion of volunteers, the number of citizens participating in inspections in the Spirit Water Island model was set to 52. Citizen avatars were created with the "Ready Player Me" online service and then imported into Unity3D [64]. Citizen models have animation behaviors, pathfinding behaviors, and virtual perception behaviors. Among them, the animation behavior means that the citizen model could imitate human natural movement and state management. Pathfinding behavior refers to the ability of the citizen model to automatically find the path to the target structure location. The realization of the pathfinding behavior relies on the pathfinding component NavMeshAgent that comes with Unity3D. With the help of the NavMeshAgent component, the citizen model finds the shortest path in the road network using the A* algorithm. The virtual perceptual behavior embodies the process of the citizen model receive-complete-feedback inspection task. The perceptual behavior is implemented mainly through the Behavior Designer plugin. The receive-complete-feedback task is implemented through a set of behavior trees. Behavior trees contain various nodes. Each node represents a behavior or a decision, and the connection between nodes indicates the relationship between these behaviors or decisions. Figure 7 illustrates the behavior tree of the citizen model [65]. The citizen model behavior tree contains two layers: one is the decision layer and the other is the behavior layer. The input is the citizen model agent's perception of the world, including whether it feels environmental occlusion, perceives other agents, and receives task information. The decision layer is responsible for making decisions, which is similar to an agent imitating the human brain for decision making. The behavior layer includes the animation control module and the mobile

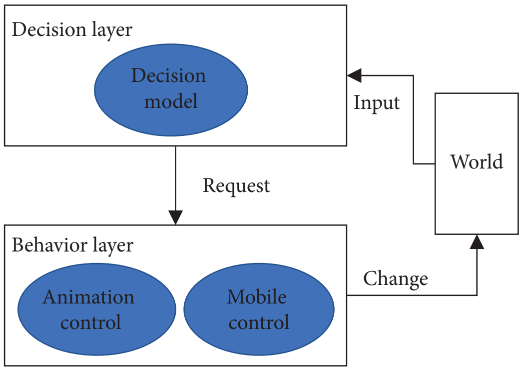

Figure 7: Architecture of the citizen model.

control module. Among them, the animation control module implements human actions. The mobile control module calls the pathfinding algorithm to calculate the optimal path and then updates the location of the citizen model.

Citizen models in Unity3D are designed to simulate the behavior and interaction of people in a realistic society, focusing on their perception, decision, and implementation:

(a) *Perception*. After inspection tasks are issued, the citizen model could receive the task information if it is within a certain range of the target structure.

(b) *Decision*. The citizen model decides whether to perform inspection tasks. Based on the given willingness rate, the citizen model randomly generates decision results that obey the Bernoulli distribution.

(c) *Implementation*. After the citizen model arrives at the location of the target structure, the structural response parameters are measured. The citizen model then uploads the data to the Urban Brain.

Admittedly, citizen models still lack features that affect human actions at the cognitive and emotional levels. For example, citizen models could not perform volunteer tasks during their working hours. The traffic flow in the realistic environment affects the movement of citizens. These limitations are expected to be addressed by developing more comprehensive and qualified citizen models. Deep learning and deep reinforcement learning may be powerful tools.

3.2. Ground Eye GUI. The Ground Eye is responsible for aggregating information about the civil infrastructure and dynamically assigning inspection tasks based on the location of citizens. All the information about civil infrastructure inspections is displayed on the GUI, which is also presented on citizens' smartphones. The GUI of the Ground Eye is demonstrated in Figure 8. The GUI of the Ground Eye consists of the following modules:

(1) Task frequency module: This module indicates the total number of tasks assigned by the Ground Eye. Urban inspection modes include routine inspection, focus inspection, and emergency inspection. When the Ground Eye assigns a routine inspection task, the number displayed on the "Routine Inspection" tab will be increased by one. The same is true for focus inspection and emergency inspection.

(2) Inspection status of civil infrastructure module: This module shows whether the current status of the civil infrastructure needs to be inspected. "Valid" means the civil infrastructure has been inspected within the validity period, "invalid" means the civil infrastructure needs to be inspected, and "inspecting" means the civil infrastructure is being inspected.

(3) Civil infrastructure health status module: This module provides statistical results on the health of all civil infrastructures in the city. The data uploaded by citizens are judged and analyzed by the Ground Eye. Civil infrastructure with abnormal inspection information will be marked as "Abnormal," waiting for further confirmation from technicians or experts.

(4) News module: This module displays the daily news of Spirit Water Island. In case of emergencies, this module will broadcast warning messages to remind citizens to take precautions.

(5) Citizen's perspective module: The citizen's perspective is shown on the control panel of the "Ground Eye." It is beneficial to make more accurate judgments about the health of civil infrastructure if the structure can be observed from the perspective of citizens. It is important to explain that the Ground Eye fully respects citizens' privacy. Only if a citizen decides to share their perspective can the Ground Eye gain information about their perspective.

(6) Civil infrastructure information module: Photos of civil infrastructure are displayed in this module. This module is also used to show basic information about civil infrastructures.

(7) Citizen information module: The number of citizens of different working states is summarized in this module. When a citizen chooses to perform an inspection task, the citizen is marked as "Working." When the task is completed, the citizen's marker status reverts to "Free."

(8) Civil infrastructure inspection result module: the structural response parameters of the civil infrastructure are displayed in this module.

3.3. Structural Response Parameters. The structural types of civil infrastructure in Spirit Water Island include frame structures, bridges, and tunnels. Typical inspection parameters of different structural types are summarized in Table 3.

4. Strategy Validation

This section shows the application of the SPIC strategy in the Spirit Water Island model established in Unity3D. In the Spirit Water Island model, some civil infrastructures were set as damaged structures. As mentioned above, the Spirit Water Island model was established with reference to Dalian, China. In 2020, the number of highway bridges in

Figure 8: GUI.

Table 3: Structural response parameters for inspection.

Type	Structural response parameters
Rigid frame bridge	Displacement Strain Acceleration
Suspension bridge	Displacement Strain Cable force Acceleration
Arch bridge	Displacement Strain Acceleration
Tunnel*	Strain Acceleration
Frame structure*	Tilt angle Strain Crack Acceleration

*Inspection of these structure types is presented in concept, but with field testing challenges.

China was 912,800, and the proportion PD_{bridge} of dangerous bridges was about 3.4% [66, 67]. The Dalian Emergency Management Bureau carried out a survey of the condition of self-built houses in 2022 [68]. The results showed that there were 64,968 self-built houses in urban areas and 1,018 houses with potential safety hazards, accounting for 1.6% of the total urban self-built houses. The proportion of hazardous tunnels was considered to be the same as that of hazardous bridges, $PD_{tunnel} = PD_{bridge} = 3.4\%$. The Spirit Water Island model included 138 frame structures, three bridges, and one tunnel. Therefore, the number of damaged structures in the Spirit Water Island model was two. The damaged structures were determined by simple random sampling.

The physical model of the character was generated by the website "Ready Player Me." The pathfinding component NavMeshAgent, which comes with Unity3D, could realize automatic pathfinding and obstacle avoidance. The Behavior Designer plugin was applied to control the movement of the person. The walking velocity of the citizens in the Spirit Water Island model was taken as 1.34 m/s [69]. The assumption of crowd willingness is necessary owing to the absence of specific data on crowdsourcing participants performing smartphone-based SHM for inspections. It is suggested that researchers investigate the effect of diverse behaviors on crowdsourcing participants in the future to obtain more accurate references. A survey on public participation in disaster risk management showed that 59.02% of citizens indicated that they would be willing to volunteer for disaster preparedness and response if they were able to do so [70]. A survey on public participation in urban governance reported that 36.4% of residents were "very willing" to participate in community risk assessments and 25.1% were "willing" to do so [71]. Therefore, the willingness W of citizens to perform the task was chosen as 0.5. The maximum distance D_{max} of citizens from the target structure was taken as 80 m. It is worth noting that the values of W and D_{max} were set arbitrarily, and the sensitivity analysis of these two parameter values will be performed in the next section.

In addition, inspection results in the Spirit Water Island model are explained here. In order to simplify the model and facilitate calculations, it was assumed that the structural response parameters inspected by citizens using smartphones obeyed normal distributions [27]. For example, the inspected value of the bridge cable force $F_c \sim N(\mu_c, \sigma_c^2)$, where μ_c was expected value and σ_c was standard deviation. The real value at this moment was denoted as F_{c0}. The inspected value F_c was correlated with the real value F_{c0}. Considering the uncertainty of sensors and crowdsourcing participation, the maximum deviation of F_c from $F_{c0,}$ was set to ±5%. The standard deviation σ_c is determined from the minimum and maximum bounds (95% confidence interval) of the boundary. Under this definition, the expected value $\mu_c = F_{c0}$ and the standard deviation $\sigma_c = 0.025F_{c0}$. In particular, the damage representativeness of indicators is a prominent challenge for SHM. Here, indicators are only used to depict an idealized framework. For realistic environment applications, more comprehensive statistical models would be essential.

F_{cc} was the bridge cable force critical value, which is the threshold value that cannot be exceeded when the structure is in the serviceability limit state. If $F_c > F_{cc}$, the inspection result of the bridge cable force would be considered abnormal. The values of other structural response parameters were similar to those of bridge cable forces. If this test was conducted in the real world, the citizens would of course collect realistic inspection results. However, this was a simulation test conducted in Unity3D, and the emphasis of the test was the application of the SPIC strategy in the Spirit Water Island model. So, the assumption about the values of the structural response parameters is acceptable. The process of citizens completing inspection tasks is exhibited in Figure 9.

This simulation process is a preliminary validation under ideal conditions. It is important to note that field validations are expected to be more complex. Challenges such as indirect damage indicators, crowd participation, and sensing quality will be addressed in the future. The simulation process simplifies the process of evaluating the structural state. The Ground Eye released routine inspection tasks once a month, and the number of civil infrastructures for each routine inspection was 1/4 of the total number of civil infrastructures.

After completing 12 routine inspections, the Ground Eye found two abnormal structures, which were consistent with the number of damaged structures pre-set in the model. The rigid frame bridge (status was "Normal") and the suspension bridge (status was "Abnormal") were used as representatives to illustrate the results of citizen inspections. Table 4 displays the routine inspection results of the rigid frame bridge. F_d/F_{dc} indicated the ratio of the inspection value of the bridge vertical displacement to the critical value, where F_d was the inspection value of the bridge vertical displacement and F_{dc} was the critical value. Similarly, F_s/F_{sc} represented the ratio of the inspection value of the bridge's maximum element strain to the critical value. As can be seen in Table 4, only the first, fifth, and ninth inspection results were available for the rigid frame bridge. This is because it took four months to complete the inspection of all civil infrastructures in the routine inspection mode. In addition, none of the structural response parameters inspected exceeded the critical values, so the status of the civil infrastructure was "Normal."

Table 5 shows the routine inspection results of the suspension bridge. For the suspension bridge, only the second, sixth, and tenth inspections were observed. Among them, none of the structural response parameters exceeded the critical value in the second routine inspection. In this case, the status of the bridge was evaluated as "Normal." In the sixth routine inspection, the bridge vertical displacement and cable force exceeded the critical values. As long as one of the structural response parameters was considered abnormal, the structure would be identified as "Abnormal." Therefore, the suspension bridge was assessed as "Abnormal" at this time. Similarly, the status of the suspension bridge in the tenth routine inspection was also "Abnormal." Inevitably, uncertainties associated with the measured values can affect the assessment. For instance, during the second routine inspection, the measured values of the structural response parameters were below the critical values. The suspension bridge was identified as "Normal" when in fact it could potentially be in an "Abnormal" state. However, it is important to note that the state assessment is not based on a single parameter but considers multiple structural response parameters. This multi-parameter approach helps reduce the probability of failing to identify an "Abnormal" structure due to uncertainties in a single parameter. Furthermore, this uncertainty in the measured values is unavoidable for any detection method in SHM. Even if all SHM measured values are below their critical values, it is crucial to recognize that this is only the result of one routine inspection. Subsequent routine inspections are scheduled monthly, thereby increasing the likelihood of detecting any omitted "Abnormal" structures.

Table 6 presents the statistical results of 12 routine inspections by the Ground Eye. No abnormal structure was found from the first to the fourth routine inspection. In the fifth routine inspection, one abnormal structure was detected. Then, the Ground Eye assigned one focus inspection, which is to inspect abnormal structures meticulously by citizens, technicians, and experts. Therefore, the number of focus inspections is one. In the sixth routine inspection, one more abnormal structure was observed. So, the number of abnormal civil infrastructures in the whole city was two. The number of focus inspections was two. No abnormal civil infrastructure was found in the seventh and eighth inspections, so the number of abnormal civil infrastructures and the number of focus inspections remained the same as before. Since routine inspection was carried out regularly, the number of civil infrastructures inspected each time was 1/4 of the number of all civil infrastructures. Therefore, the scope of the ninth routine inspection was the same as the fifth routine inspection. Although the ninth routine inspection discovered one abnormal civil infrastructure, the number of abnormal civil infrastructures remained at two as it was not a newly discovered abnormal structure. The focus inspection for the abnormal structure should be conducted again, so the number of focus inspections increased to three. Similarly, the number of abnormal structures remained at two, and the number of focus inspections changed to four. No abnormal structure was observed in the eleventh and twelfth inspections, so the number of abnormal structures was two, and the number of focus inspections remained at four.

After that, an emergency inspection was tested in the Spirit Water Island model. The scope of emergency inspection included all civil infrastructures in the city. The experiment was a rapid assessment of all civil infrastructures in the city after a sudden disaster. Similar to the routine inspection, the number of damaged civil infrastructure in the Spirit Water Island model was two. The damaged structures were determined by simple random sampling. The walking

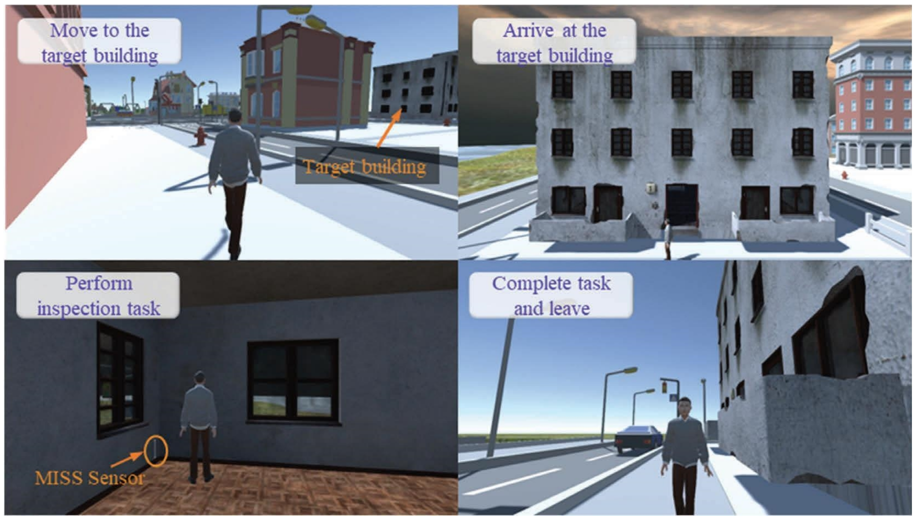

Figure 9: The process of citizens completing inspection tasks.

Table 4: Routine inspection results of rigid frame bridge.

Parameter	Routine inspection		
	1	5	9
Displacement (F_d/F_{dc})	0.49	0.51	0.51
Strain (F_s/F_{sc})	0.48	0.51	0.50

Table 5: Routine inspection results of suspension bridge.

Parameter	Routine inspection		
	2	6	10
Displacement (F_d/F_{dc})	0.97	1.03	1.04
Strain (F_s/F_{sc})	0.98	0.99	0.98
Cable force (F_c/F_{cc})	0.96	1.02	1.02

velocity of the citizens was 1.34 m/s. The willingness W of citizens to perform the task was 0.5. The maximum distance D_{max} of citizens from the target civil infrastructure was 80 m.

The result of the emergency inspection is displayed in Figure 10. At the 5th minute, the emergency inspection was activated. As the testing process proceeded, the number of valid civil infrastructures increased and the number of invalid civil infrastructures decreased. At the 77th minute, the inspection was completed and all the civil infrastructures' tags became "Valid." The time for emergency inspection of all civil infrastructures was approximately 72 minutes. The result of the emergency inspection showed that the status of two civil infrastructures was "Abnormal," the status of 142 civil infrastructures was "Normal," and the percentage of "Normal" civil infrastructure on the Spirit Water Island was 98.6%. It can also be observed that the pre-introduced damaged civil infrastructures were all detected.

5. Discussion

The values of some parameters may affect the time and cost of the SPIC strategy implementation. Therefore, the values of these parameters are analyzed to better guide practical application. Besides, this section also discusses some proposed application scenarios for simulation models of public participation experiments.

5.1. Factor Sensitivity Analysis. This study conducted a factor sensitivity analysis to investigate the effect of these parameters in Table 7 on the SPIC strategy. Experiments were still conducted in the Spirit Water Island model. W is the willingness of citizens to perform inspection tasks. The willingness of citizens is affected by public social background (including gender and education level), organizational integrity (including security, safety training, and rewards), and social perception (including social culture and government mobilization capabilities) [72]. The value of W is directly related to whether citizens choose to perform or refuse the task when they receive the task. If a citizen rejects the task, the Ground Eye will reassign the task to other participants. D_{max} is the maximum distance between the citizen and the target civil infrastructure. If the value of D_{max} is too small, the task of inspecting a civil infrastructure will not be accepted for a long time. If the value of D_{max} is too large, the citizen who accepts the task may be far away from the target civil infrastructure, and it will take the citizen a lot of time to complete the task. Therefore, sensitivity analysis of these parameters can provide insight into the choice of reward allocation policies under different conditions.

The range of parameter values is presented in Table 7. Following the questionnaire survey conducted by Ma et al. [72], the value range of W was set at 0.3–0.7. Specifically, 0.3 represents the typical proportion of citizens who are "very willing," and 0.7 signifies the typical combined proportion of citizens who are "very willing," who have "a little bit of interest," and who are "not sure." The values of W were 0.3, 0.4, 0.5, 0.6, 0.7, and the values of D_{max} were 60, 70, 80, 90, 100 m, respectively. The effect of different parameter values on the civil infrastructure inspection time (CIT) and the average inspection time for single civil infrastructure (ASIT) were tested during the emergency inspection. Figure 11

Table 6: Statistical results of 12 routine inspections.

Routine inspection	Focus inspection	Normal structure	Abnormal structure
1	0	142	0
2	0	142	0
3	0	142	0
4	0	142	0
5	1	141	1
6	2	140	2
7	2	140	2
8	2	140	2
9	3	140	2
10	4	140	2
11	4	140	2
12	4	140	2

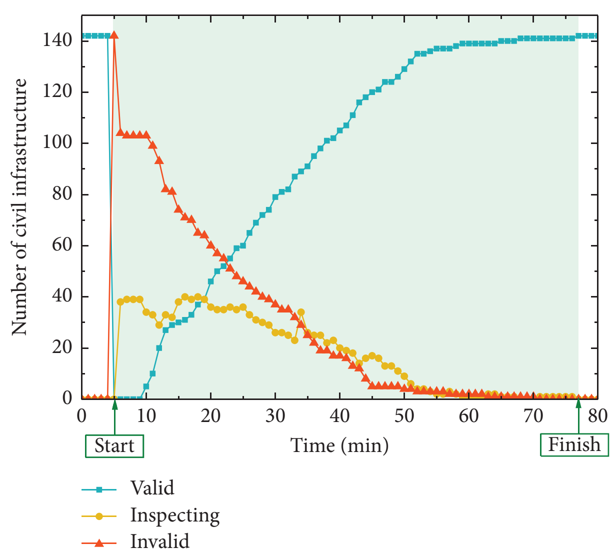

Figure 10: The whole process of emergency inspection.

Table 7: A set of representative parameters of the SPIC strategy.

Parameter	Meaning	Range
W	Voluntary participation rate of citizens performing inspection tasks	0.3~0.7
D_{max}	The maximum distance between the citizens and the target civil infrastructure	60~100 m

exhibits the inspection efficiency of the Spirit Water Island model at different parameter values. As shown in Figure 11(a), the value of ASIT gradually increases with the increase of D_{max}. This is because the value of D_{max} is related to the time the citizen takes from accepting the task to arriving at the target civil infrastructure. A larger D_{max} means that some citizens are farther away from the target civil infrastructure, so it takes longer to reach the target civil infrastructure. However, a larger D_{max} also makes inspection tasks more likely to be received by citizens, so the CIT also exhibits a certain reduction.

W represents the willingness of citizens to perform the inspection task after receiving it. As indicated in Figure 11(b), a larger value of W means a shorter waiting time for the target civil infrastructure. Therefore, the value of CIT decreases as the willingness of citizens to participate in the task increases. However, the downward trend of CIT values is not significant when the value of W exceeds 0.5. This is because the high willingness of citizens already satisfies the needs of the inspectors at the current city size. Figure 11(b) also shows that the value of ASIT is barely correlated with W, and the fluctuation of this value is mainly due to the randomness of the distribution location of citizens.

5.2. Proposed Application Scenarios. The running process of the SPIC strategy can be mapped to the multi-scale and multi-physics Unity3D simulation platform. Experiments on public participation in civil infrastructure inspection could be performed in the simulated model. Furthermore, such simulated models are expected to have more

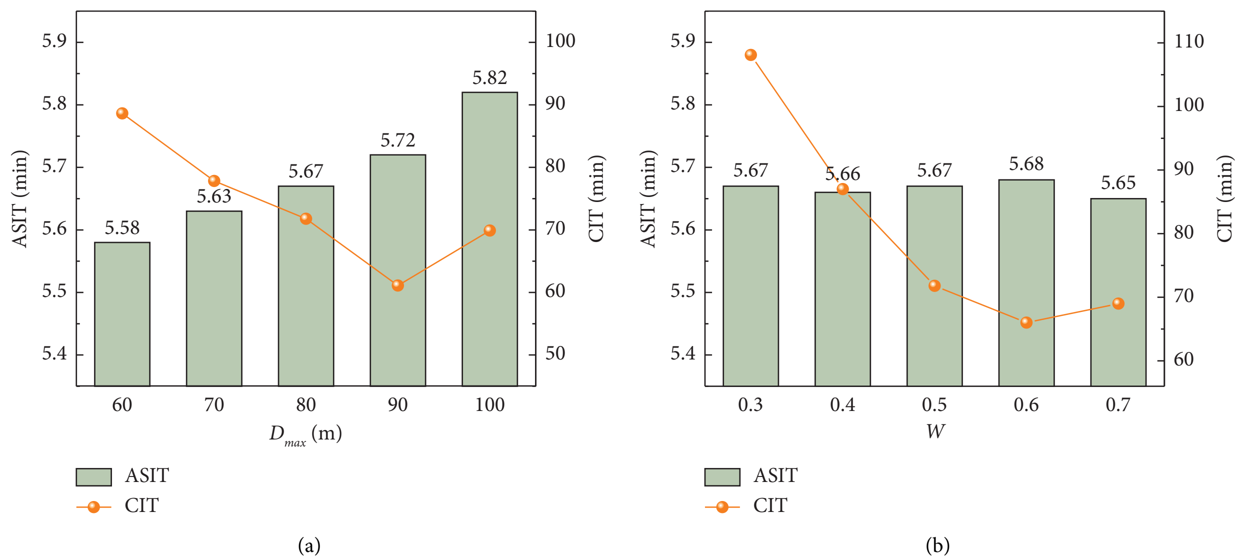

Figure 11: Factor sensitivity analysis in SPIC strategy: (a) the effect of $D_{\max}$ and (b) the effect of W.

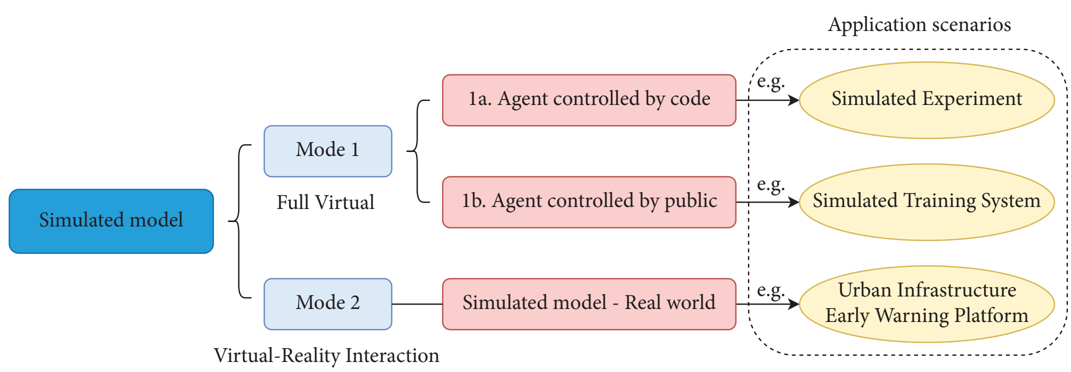

Figure 12: Two modes of the simulated model.

application scenarios. According to the intelligence level, the application of simulated models can be summarized into two models: full virtual mode and virtual reality interaction mode. The comparison of the two modes and typical applications are presented in Figure 12.

Mode 1. Full virtual mode: The model is established, manipulated, and exhibited based on a simulated platform. The model is used to simulate a series of tests that are not easily performed in reality (e.g., large-scale natural disaster experiments). The structural performance in the simulated model can be derived from the results of published literature and experiments. The behavior of agents in the simulated model is driven by code or the public (similar to NPCs or player characters in games). Agent controlled by code: Human group behavior can be simulated according to the code. The model can be applied to large-scale urban disaster prevention experiments. Agents controlled by the public: The simulated model could overcome time, space, and cost constraints to iteratively train people in different environments. One possible application scenario for the simulated model is a training system for urban disaster prevention and mitigation.

Mode 2. Virtual reality interaction mode: The virtual model drives real people to measure real structures, and inspection results are reflected in the simulated model. The simulated model then adjusts to guide the deployment of realistic civil infrastructure inspections. Continuous data exchange is possible between the virtual model and the real world. This simulated model can be applied to a civil infrastructure early warning platform for evaluating structures ranging from single to multiple to urban agglomerations.

6. Conclusion

This paper proposes a strategy for public participation in the life-cycle inspection of civil infrastructure. The interaction process between the Urban Brain and the general citizens is illustrated in the SPIC strategy. Meanwhile, experiments conducted by Unity3D verify the feasibility of this strategy. This is an alternative to large-scale urban disaster prevention and mitigation experiments in the real world. The conclusions of this paper are as follows:

(1) This paper proposes the SPIC strategy for civil infrastructure inspections. This strategy contains three parts: Urban Brain, participants, and Global View. The Urban Brain and participants cooperate to perform civil infrastructure inspection tasks and collect information on structure health. The Global View is a third-party perspective that holds all the information about the city. Therefore, the comparison between the evaluation of the Urban Brain and the real information grasped from the Global View is also used to verify the effectiveness of the SPIC strategy.

(2) This study tests the running process of the SPIC strategy using Unity3D. Civil infrastructure inspection modes include routine inspection, focus inspection, and emergency inspection. The routine inspection is scheduled periodically. When an abnormal civil infrastructure is detected, the focus inspection is activated. The emergency inspection is initiated in the event of a sudden disaster. The activation and transition of three inspection modes were tested. Test results show that routine inspection with public participation could timely identify preset damaged civil infrastructure. All abnormal civil infrastructures are observed by the Urban Brain. In the emergency inspection mode, all civil infrastructure inspections are successfully completed.

(3) This paper analyzes the effect of two parameters, the maximum distance D_{max} of citizens from the target civil infrastructure and the willingness W of citizens to perform inspection tasks, on the SPIC strategy. Results show that CIT gradually decreases with an increase of D_{max}. But ASIT increases as D_{max} increases. It is also found that larger W has a decreasing effect on CIT, with little effect on ASIT.

The method of public participation experiments with simulation models has the potential to be applied to various scenarios, such as large-scale experiments, collaborative training systems, and civil infrastructure early warning platforms. Future research in this direction will help enhance the disaster prevention and mitigation capabilities of clustered civil infrastructure throughout its life cycle.

While it is hoped that this study could serve as a basis for further research on public participation in civil infrastructure inspection, the present research also has certain limitations. First, this strategy is based on the smartphone inspection methods and the structural condition assessment theory. It could also be incorporated into the proposed strategy if more reliable inspection methods are developed. Next, the volunteer statistics and the willingness of the public to participate in the inspection deserve further investigation. Moreover, ordinary citizens involved in civil infrastructure inspections may suffer complications, and more ethical issues of public participation need to be explored. The inspection data presented in this paper are based on simulations. In fact, focus inspection data obtained from large-scale field tests can provide valuable insights for optimizing the frequency and content of routine inspections. We recommended future work to assess citizen knowledge of SHM, mission routes, operational errors, actual experiments, the subjectivity of reported data, and citizen safety, which we did not evaluate here owing to limited scope.

Data Availability

Some or all data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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