INFORMATION ACQUISITION AND SEISMIC DAMAGE PREDICTION OF MASONRY STRUCTURES IN RURAL AREAS BASED ON UAV INCLINED PHOTOGRAMMETRY

CHAO KONG

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Student	Mr. Chao Kong
Student ID.	64601193
Degree	Master of Engineering
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Thesis Advisor	Asst. Prof. Dr. Arthit Petchsasithon

ABSTRACT

Masonry structures are one of the most widely distributed and numerous building types in China's rural areas. Constrained by regional economic and other factors, rural masonry structures are plagued by problems such as differences in the quality of materials and non-standardised construction methods, resulting in their weak seismic performance. When earthquakes occur, these structures often suffer severe damage, leading to significant casualties and economic losses. Due to the general lack of data, randomness, and variety of structural forms of buildings in rural areas, obtaining building information is a prerequisite for achieving seismic damage prediction. Traditional manual inspection is inefficient and uneconomical. Therefore, UAV inclined photogrammetry and building information extraction techniques are utilised to efficiently acquire massive building and infrastructure information to improve survey efficiency, reduce costs and better respond to seismic risk.

This study aims to assess the seismic vulnerability of masonry structures in rural China for earthquake damage prediction through an innovative method of incremental dynamic analysis (IDA) and UAV positional analysis (POS). The method incorporates advanced UAV inclined photography technology to acquire a large amount of building information data and incremental dynamic analysis (IDA) to accurately predict seismic damage. For masonry structures, which are prevalent in rural areas of China, the study aims to develop effective seismic risk mitigation strategies. The research methodology focuses on capturing detailed images of rural masonry structures using high-resolution cameras mounted on unmanned aerial vehicles (UAV). The acquired data were finely processed to extract building characteristics and structural conditions. In addition, the study utilises the CHC Geomatics Office (CGO) dynamic post-processing software to decompose the UAV POS data into differences to improve the accuracy of the relative position between the UAV and the reference station. The results of the study provide a methodology for the study of seismic vulnerability of masonry structures in rural areas of China under uncertainty of ground shaking. Combined with the UAV inclined photography technique, it improves the efficiency of the investigation, reduces manpower and economic costs, and better responds to seismic risk.IDA and UAV POS analyses have far-reaching implications and provide indispensable information for the development of targeted earthquake preparedness and risk mitigation strategies. Policymakers, urban planners, and disaster management authorities will gain significant insights from this data-driven approach. Ultimately, this research will serve as an important resource, providing a sound methodology for assessing seismic risk and strengthening masonry structures to safeguard rural communities and create a more seismically resilient and safe built environment.

Keywords: Masonry structures; UAV inclined photogrammetry; information acquisition; seismic damage prediction; incremental dynamic analysis(IDA)

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INTRODUCTION

1.1 CONTEXT

China is located at the intersection of the Eurasian seismic belt and the Pacific volcanic seismic belt, and is subject to the combined influence of the Indian plate, the Pacific plate and the Philippine Sea plate, with a high degree of seismic activity, and belongs to the countries with frequent earthquakes, and the distribution of the seismic belt in China is shown in Figure 1-1. The casualties and economic losses caused by earthquakes are serious. For example, the 7.8-magnitude Tangshan earthquake on 28 July 1976 caused 242,769 deaths, 164,851 people were seriously injured, and the direct economic losses reached 10 billion yuan; the 8.0-magnitude Wenchuan earthquake on 12 May 2008 was even more serious, causing 69,227 deaths, 374,663 people were injured, and the direct economic losses were as high as 845.1 billion yuan; moreover , the 7.0 magnitude earthquake that struck Jiuzhaigou County, Aba Prefecture, Sichuan Province on 8 August 2017 had relatively low casualties, with only 25 deaths and 525 injuries, but still resulted in the destruction of more than 70,000 houses to varying degrees.

Fig 1-1 Distribution of seismic zones in China

In recent years, with the implementation of the national strategy of "rural revitalisation", more attention has been paid to the development and construction of village and township areas. The built-up area of villages and towns is expanding rapidly, but with the increase in investment and built-up area, the issue of seismic safety has become a key concern of the State. At the same time, ensuring seismic safety in village and township areas is also a prerequisite for the majority of village and township residents to live and work in peace and happiness. Village buildings in China cover a wide range of structural types, including concrete structures, raw earth structures, wood structures, masonry structures, etc. (as shown in Figure 1-2). These different types of structures have different characteristics and disaster resistance in each region, and there are significant regional differences. Among them, masonry structure is one of the most widely distributed and largest in number of structure types, and is also an important part of village and town buildings in China. Due to the relatively backward economy of village and town areas, many masonry structure buildings are built by villagers' self-financing and self-construction, so there are some potential risks and problems[1], such as: (1) Poor quality of construction materials. (2) Unstandardised construction process. (3) Lack of constructional measures (ring beams, constructional columns). The above problems lead to the poor seismic performance of most village masonry structures, which are prone to serious damage or even collapse in the event of an earthquake disaster, which can cause significant casualties and economic losses.

(a) Concrete structure

(b) Raw earth structure

(c) Wood structure (d) Masonry structure

Fig 1-2 Types of building structures in rural areas

Therefore, it is critical to focus on the seismic safety of masonry structures in village areas. Accurate seismic damage prediction is an important method for assessing seismic risk, and it can provide strong support for pre-earthquake reconstruction of hazardous houses, earthquake contingency plan development, and earthquake prevention and mitigation planning. In addition, by simulating the actual earthquake scene after the earthquake, the seismic damage loss of regional buildings can be analysed to provide clear guidance for the development of rescue and relief plans, and effectively reduce the casualties and economic losses caused by the earthquake[2]. Therefore, a comprehensive investigation of masonry structure information and accurate earthquake damage prediction in village and town areas are crucial and significant for assessing the seismic capacity of the area. However, the traditional manual on-site household survey methods are less efficient and more costly[3]. Therefore, the use of high-tech means, such as aerial photography technology and building information extraction technology, to achieve the acquisition of information on large-scale buildings and civil infrastructure is a feasible method. This can improve the efficiency of the survey, reduce manpower and economic costs, and thus better cope with earthquake risks.

1.2 OBJECTIVES OF THIS RESEARCH WORK

The research objectives are clear, focusing on the use of UAV inclined photography technology to establish a three-dimensional model, to extract building information and obtain hidden information inside the structure, and then to analyse the seismic vulnerability of the building through the IDA method, to study the effect of ground shaking uncertainty on the vulnerability of the masonry structure, and to obtain seismic vulnerability curves, so as to predict the seismic damage of the structure, which is of great significance for the assessment of the seismic performance of the region.

The objectives are summarised as follows :

(1) The first objective is to complete the field data acquisition of a village and town area by UAV equipped with tilt camera system to obtain UAV aerial photography images;

(2) The second objective is to use the UAV aerial image inspection software, the POS data differential processing software, and the ContextCapture 3D modelling software to complete the establishment of a 3D model of the actual scene;

(3) The third objective is to obtain the building appearance information through the mapping software, and the hidden information of masonry structure in the village area through fuzzy inference;

(4) The fourth objective is to analyse the structural model through SeismoStruct finite element software to study the effects of different seismic actions on the seismic performance of masonry structures;

(5) The final objective is to plot the seismic susceptibility curves of the structures based on the results of IDA method and to perform seismic susceptibility analyses of the structures for the purpose of earthquake damage prediction.

1.3 RESEARCH HYPOTHESIS

This study aims to extract the building information of masonry structures in villages and towns by adopting UAV inclined photography technology, then numerical simulation of the structures, and seismic vulnerability analysis of the structures based on the IDA method, so as to provide basic data for the seismic damage prediction work and carrying out the seismic hazard assessment after the earthquake. In this study, building information is extracted by adopting the UAV tilt photography technique, which has the advantages of high efficiency, less external workload, and low cost compared with the traditional manual inspection technique. The vulnerability analysis method based on theoretical calculation is adopted, and the accuracy of the calculation results of this method is high in the case of lack of earthquake damage information. In conclusion, the research content of this paper is of great significance for seismic performance assessment, risk assessment, seismic loss assessment, earthquake insurance, and disaster prevention and mitigation planning for all types of brick masonry structures within villages and towns nationwide.

1.4 RESEARCH TECHNICAL ROUTE AND PROCESS

This study is based on advanced UAV inclined photography technology to extract the appearance information and hidden information of masonry structure buildings in villages and towns, and then finite element analysis is used to study the seismic susceptibility of masonry structures for the purpose of earthquake damage prediction. The study includes UAV inclined photogrammetry software system, hardware system, theory and method, the method of acquiring appearance and hidden information of village and town buildings, and the method of seismic vulnerability analysis based on incremental dynamic analysis (IDA). Subsequent chapters of the study explain in detail the background of the analyses, the materials used, and the equations used in the study. These chapters are intended to provide a comprehensive understanding of the methodology and theoretical framework used in the study. The technical route and specific flow of the study are shown in Figures 1-3 and 1-4.

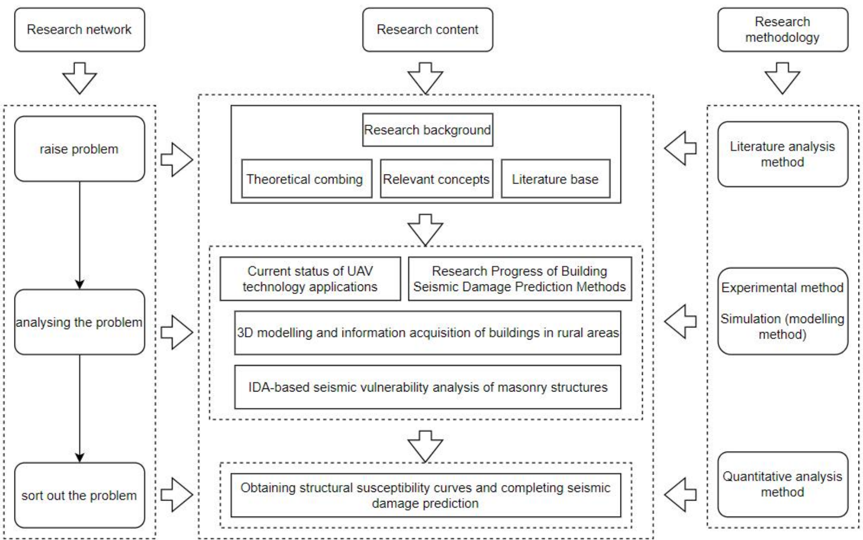


Fig 1-3 Research technical route

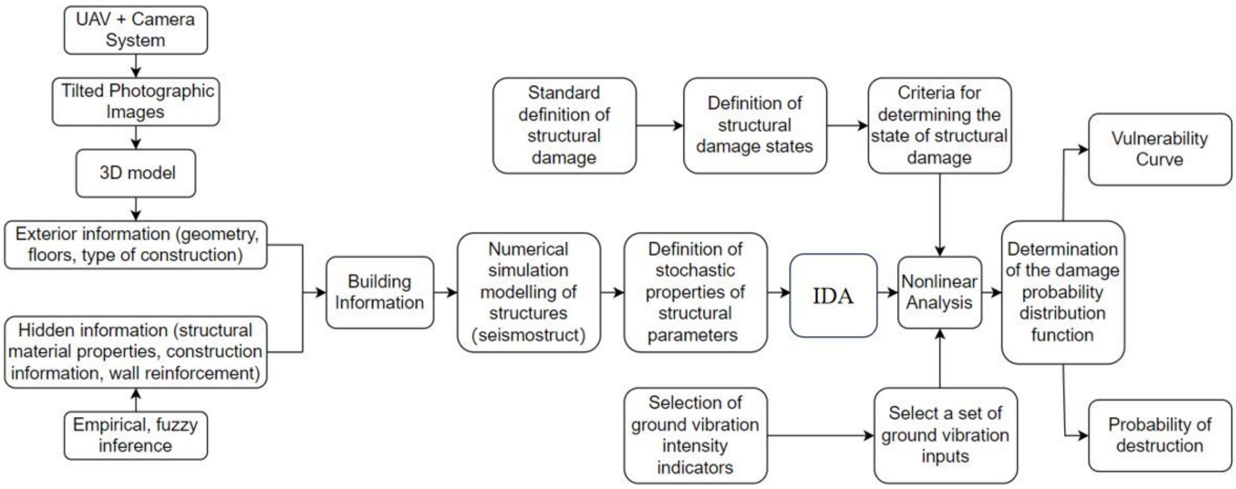


Fig 1-4 Research process

1.5 SCOPE OF RESEARCH

This research is mainly based on UAV tilt-photography technology and finite element calculation, and the research is divided into three different parts.

(1) The principle of UAV tilt photogrammetry technology and the operation process. Specifically introduces the theory and method of tilt photogrammetry technology as a means of measurement, explains the principle of POS-assisted analytical aerial triangulation, the principle of constructing TIN triangulation network, and the principle of producing 3D models based on ContextCapture software. The two major hardware devices, UAV aerial photography system and tilt camera system, are mainly introduced. It also discusses the commonly used software systems such as UAV aerial image inspection software, POS data differential processing software, tilt camera 3D modelling and mapping software.

(2) A method for extracting geometric information and structure types of village buildings is proposed, which combines image measurement with aerial photography technology to achieve the measurement of geometric information of village buildings, including geometric dimensions (length, width, and height), the number of floors, and structure types, etc.; a method for obtaining hidden information of masonry structures in village areas based on fuzzy reasoning is introduced, which is based on fuzzy mathematical theories and practical engineering experience. The method is based on fuzzy mathematical theory and practical engineering experience, and constructs fuzzy rules between the material properties,

construction information, wall reinforcement and economic income level and construction age of masonry structures in villages and towns, and establishes corresponding fuzzy inference models, which can effectively extract the hidden information of the masonry structures; and at the same time, based on the geometrical and geographic coordinates of the structures to achieve the prediction of their wall information.

(3) The structural model is analysed based on the IDA method to investigate the effects of different seismic actions on the seismic performance of masonry structures and to analyse the seismic vulnerability of the structure. Firstly, the model is subjected to incremental dynamic analysis (IDA) to analyse the effect of ground shaking uncertainty on the response of masonry structures; then, based on the IDA results, the seismic susceptibility curves of the structure are plotted, and the seismic susceptibility analysis of the structure is carried out to achieve the purpose of earthquake damage prediction.

In short, these objectives are to obtain the building information of masonry structures in village and township areas efficiently and accurately, and to predict the earthquake damage of masonry structures in village and township areas effectively by simulating and calculating the earthquake damage scenarios.

1.6 THESIS STRUCTURE

The thesis is structured into five chapters, each focusing on a specific aspect of the research. A brief overview of each chapter is provided below:

Chapter 1: Introduction

This chapter outlines the research problem, i.e. the need for information acquisition and earthquake damage prediction for village masonry structures. The chapter describes the objectives of the study, as well as the research methodology and assumptions that will be used throughout the study.

Chapter 2: Literature Review

This chapter provides a comprehensive introduction to the current status of this research. It includes the application of UAV remote sensing technology in civil engineering, building information extraction methods, research progress on regional building damage prediction methods and seismic vulnerability analysis methods. The literature review provides a theoretical background for subsequent analyses and assessments.

Chapter 3: Methodology

This chapter focuses on the methods used in the study. It includes UAV inclined photogrammetry software system and hardware system, theory and methods; methods for acquiring building appearance information and hidden information in villages and towns; and methods for seismic vulnerability analysis based on incremental dynamic analysis (IDA).

Chapter 4: Results and Discussion

This chapter presents the analysis of the numerical model and discusses the results obtained from the simulation. The seismic vulnerability of the structure is analysed based on the different seismic performance effects obtained for masonry structures under different ground shaking scenarios and then based on the results of Incremental Dynamic Analysis (IDA), the seismic susceptibility curves of the structure are plotted.

Chapter 5: Conclusion and Outlook

The last chapter summarises the main findings and conclusions of the study. The chapter concludes that the UAV tilt-photography technique can be used to efficiently extract building information and quickly compare the effects of different seismic actions on the seismic susceptibility of the structure, which makes the prediction of earthquake damage more efficient and convenient. It also identifies the need to analyse the effects of different values of design parameters on the susceptibility of masonry structures in the future, and to select more examples for the analysis of the susceptibility of masonry structures.

CHAPTER 2

LITERATURE REVIEW

2.1 APPLICATION OF UAV REMOTE SENSING TECHNOLOGY IN THE FIELD OF CIVIL ENGINEERING

Characterised by high flexibility and mobility, cost-effectiveness and safety, drone remote sensing technology is an advanced technology that uses drones carrying various sensors and photographic equipment to acquire ground images and data by means of aerial photography. In recent years, with the continuous enhancement and popularisation of UAV remote sensing technology, the technology has been widely applied in agriculture, environmental monitoring, natural resources management, emergency response and civil engineering, especially in the field of civil engineering, which has shown great potentials and advantages and has been developed significantly. At present, UAV remote sensing technology has been widely applied in all stages of construction and infrastructure development, covering the entire project life cycle.

In the engineering survey and design phase, it can effectively support tasks such as engineering terrain survey and topographic map mapping.In 2012, RAU J Y[4] and others successfully acquired a large amount of landslide-related data by using UAV remote sensing technology and developed a landslide detection algorithm based on image analysis.In 2016, WANG DONG[5] and others, with the help of UAV remote sensing technology, successfully constructed a high-resolution engineering survey realistic model, which provides an important reference basis for tasks such as terrain survey, geological exploration and landslide measurement in railway construction.2016 Liu Jun[6] et al. used UAV technology to establish a three-dimensional model of the slope system, which provides a solid theoretical basis for the assessment of slope stability.2017 Ma Jing[7] et al. improved the traditional large-scale mapping method of topographic maps, making up for the shortcomings of traditional mapping means and achieving high-precision results. UAV tilt photography technology has been widely used in the process of large-scale topographic map mapping. Wu Liang[8] (2017) and others pointed out that UAV remote sensing technology can efficiently acquire image data of large-scale urban buildings and roads, which provides key references for the design scheme and the calculation of planning indexes in urban spatial planning.

In the engineering construction stage, the use of drone remote sensing technology can build three-dimensional live model and real-time monitoring of the construction site, which can clearly and accurately reflect the quality of the project, and provide a convenient acceptance of the completion of the project.In 2014, Ren Jiang[9] et al. used drone remote sensing technology to build a three-dimensional live model of a large-scale regional building, which was used to monitor the changes of the building and carry out the calculation of the amount of work.IRIZARRY J[10] (2012) et al. proposed that UAV remote sensing technology can achieve real-time monitoring, risk assessment and feedback of construction progress.LIN J J[11] (2015) proposed a construction site progress supervision method based on UAV remote sensing technology, which realises intelligent management of construction progress. Japanese scholar Tsuneyuki Miyake[12] (2015) realised quality monitoring and diagnosis of the construction process of building facades using a UAV equipped with an infrared camera.

In the operation and maintenance phase after the end of construction, the UAV remote sensing technology can effectively support maintenance and conservation, safety inspection, emergency management and other work to provide the necessary protection. For example, in 2010, RATHINAM S[13] et al. used UAV remote sensing technology for pipeline inspection and road inspection. A research team from Chiba University in Japan[14] created a UAV power patrol system based on 3D modelling and fault monitoring in 2015, enabling it to automatically detect structural damages such as cracks, material corrosion and other structural damages in transmission towers.In 2019 Zhong Xingu[15] et al. successfully achieved the identification of crack width and monitoring of deformation of bridges with the help of 3D imaging technology from UAVs. In addition, in 2022, Liu Xi[16] pointed out the advantages of using drones to participate in fire-fighting and rescue work, put forward the typical scenarios of the application of drones in fire-fighting and rescue work, and provided certain reference to the fire and rescue team scheduling and commanding, fire-fighting and rescue.

Due to the frequent occurrence of seismic disasters in China, reasonable earthquake damage prediction is crucial to the assessment of seismic risk, and the acquisition of three-dimensional information of building structures plays a key role in earthquake damage prediction, which includes the geometric appearance of building dimensions, height, and the number of floors, etc. The acquisition of three-dimensional information of building structures plays a key role in earthquake damage prediction. With the continuous improvement of the clarity and resolution of satellite remote sensing images, the research on automatic acquisition of regional building heights using high-resolution remote sensing images has gradually matured and performed well in terms of accuracy.CHENG F and THIEL K H[17] (1995) achieved automatic segmentation of building shadows in SPOT panchromatic remote sensing images with the help of the thresholding method and established a correlation relationship between the building shadows and the heights of buildings. In 2012, Huang Rong[18] et al. extracted the height information of 66 buildings in Licang District, Qingdao using QuickBird high-resolution satellite remote sensing images, and achieved the accurate division and automatic calculation of building shadow dimensions by adopting an object-oriented classification method, thus significantly reducing the errors caused by manual measurement. And with the continuous development of UAV technology, the rapid upgrading of various hardware and software, it can quickly carry out data acquisition to complete the model establishment and carry out building information extraction, which has the advantages of high scanning accuracy, fast data acquisition, real-time, proactive, and reusable, etc. In 2021, Luo Mingqian[19] used the UAV remote sensing technology to study the area of the Beichuan Earthquake Site, and established a UAV technical framework for data acquisition, automated image segmentation, image seismic damage identification and regional earthquake simulation. Ji Zhihao[20] (2022) proposed the use of UAV inclined photogrammetry technology to replace the traditional manual mapping work of premises integration, to quickly extract the geometric appearance of the building dimensions, coordinates, and structural attributes and other information, which can effectively improve the efficiency and reduce the cost.2022 Zhou Wenhua[21] used the UAV laser point cloud scanning technology to extract, organise and reconstruction, completing the digital archive of architectural information of regional traditional villages.

In summary, research based on UAV remote sensing technology can well serve the whole process of urban construction and civil infrastructure engineering and construction, and with the continuous development of UAV technology, which provides efficient, economical and flexible data collection solutions in various application areas, it is expected that its application areas will be further expanded and play a key role in more industries.

2.2 BUILDING INFORMATION EXTRACTION

Building information extraction provides key input data and fundamental information for the mechanical analysis of buildings, which helps engineers and researchers to better understand the structure and behaviour of buildings, leading to reliable structural analysis, design and maintenance to ensure the safety and sustainability of buildings. Information about village building objects is key to modelling their mechanical analysis, which includes geometric appearance information (geometric dimensions, number of floors, type of structure, etc.) and hidden information (internal wall arrangement, construction measures, material properties, wall reinforcement, etc.).

The geometric dimensions, number of floors and structure type can be quickly obtained by image measurement based on the 3D model of the area or based on Convolutional Neural Network (CNN) image recognition technology. Image recognition technology originated in the 1940s, but its development was not rapid due to the lack of theoretical foundations and limited by early hardware facilities. It was not until the 1990s that the combination of artificial neural networks and support vector machines drove the rapid development of image recognition technology. With the arrival of the 21st century, the improvement of computer computational efficiency, the emergence of new methods and technologies, and the rapid increase of data resources, image recognition technology has been widely used in various fields.In 1998, LECUN Y[22] and others used convolutional neural networks to establish the LeNet-5 model, and achieved good results by using the model to achieve image recognition of handwritten letters. Hinton[23] et al. proposed the concept of deep learning in 2006, which is a nonlinear artificial neural network structure with multiple hidden layers and perceptrons, which gives it an excellent feature learning capability, and thus it has been widely recognised in academia. Currently, many researchers have widely applied deep learning techniques in the civil engineering field. As an example, in 2017, Guo Kun[24] et al. constructed a convolutional neural network containing nine layers for recognising the style of buildings. Dongqi Jiang[25] used the VGG-16 model for migration learning in 2019 to achieve prediction of the number of floors of urban buildings in Baidu Street View. Also in 2019, Zhe Li[26] et al. used a UAV to obtain the image data of house doors in Liukeng Village, Jiangxi Province, and proposed a migration learning-based classification method for house doors of traditional village buildings.

The above information acquisition method based on the UAV 3D model can effectively acquire the geometric information and structural type of the building. However, for the hidden information of the building, such as the internal wall arrangement, construction measures, material properties and wall reinforcement of the masonry structure, it is usually necessary to obtain them by traditional means such as household surveys, field inspections or consulting engineering drawings, whereas for the strength of mortar and blocks, testing methods such as rebound method and shot peg method are commonly used. These methods can accurately and scientifically detect the hidden information of masonry structures, but when facing large-scale regional buildings, they will consume a large amount of manpower, material resources as well as time. Therefore, it is usually difficult to strike a balance between efficiency and accuracy when acquiring concealed information in large-scale buildings, and it is a feasible idea to adopt logical reasoning methods in order to achieve rapid acquisition of structural concealed information. Fuzzy mathematical theory has been widely used in the fields of expert systems, system control and civil engineering, and is often used to solve problems that cannot be quantified or precisely described[27]. Zhou Ming[28] et al. proposed a power system fault detection system based on fuzzy inference theory in 2001, and also developed model building as well as databases for fuzzy mathematical theories; Zhang Huikang[29] et al. introduced fuzzy inference into the field of expert diagnostic system in 2003, and formulated multiple fuzzy rules based on relevant theories and expert views, and by inputting different symptoms and examination results, they carried out the condition The fuzzy inference of masonry structure has high practical application value; in 2021, Pengcheng Zhang[1] constructed the fuzzy rules between the material properties of masonry structure in villages and towns, constructional information, wall reinforcement and economic income level, construction age, and built the corresponding fuzzy inference model, which effectively extracted the hidden information of masonry structure.

2.3 RESEARCH PROGRESS ON BUILDING SEISMIC DAMAGE PREDICTION METHODS

Seismic damage prediction is the process of estimating and predicting the potential damage and effects of earthquakes. This process aims to identify in advance the threats that earthquakes may pose to the safety of specific areas, buildings, infrastructure, and people so that preventive measures, emergency preparedness, and response measures can be taken. It is an emerging and comprehensive discipline with a very broad scope that includes socio-economics, engineering, earthquake engineering and other related disciplines[30]. Seismic hazard prediction is divided into single and group prediction, as well as static and dynamic prediction, and is a crucial component of earthquake disaster prevention. It not only provides an important basis for pre-earthquake seismic reinforcement, damage assessment and economic benefit analysis, but also provides the basis for the development of earthquake disaster prevention planning. In the reduction of seismic risk, pre-earthquake planning, the development of plans, and post-earthquake rapid assessment and rescue work all play a key role, and all of these work can not be separated from the seismic damage prediction of buildings[2].

The research on earthquake damage prediction originated in Japan, dating back to the 1964 Niigata earthquake, which caused severe damage. Immediately after, the United States in the 1971 San Fernando earthquake prediction achieved satisfactory results for the global seismic hazard prediction research opened up a new situation, attracting the interest of the world's earthquake engineering researchers. In contrast, China's research in the field of earthquake damage prediction started late. The first field survey report on earthquake economic losses in China began after the 1980 Drift Sun earthquake, and larger-scale scientific research did not begin to emerge until 1985. Despite the late start and the gap compared with the United States and Japan, the research on earthquake damage prediction in China has gradually formed and developed, with its own characteristics and potential[31].

At present, domestic and foreign research on building seismic hazard prediction methods has been more perfect. Cui Yuhong[32] (2001) and others reviewed the prediction methods of earthquake damage for single buildings at home and abroad (e.g., Table 2.1) and discussed their advantages and disadvantages. Guo Mingzhu[33] et al. in 2016 systematically sorted out the current status of academic research on the prediction of seismic hazard for group buildings at home and abroad, and summarised the methods in Table 2.1 and their improved research progress, which provide new perspectives and basic information for the research on the prediction of seismic hazard for group buildings. Comprehensively, the above earthquake damage prediction methods can be concluded that there are a variety of earthquake damage prediction methods for buildings, which are used differently because of the complexity of earthquake damage prediction for buildings and the different information of buildings.

Table 2-1 Statistics of domestic and overseas seismic hazard prediction methods

Monolithic Buildings - Seismic Damage Prediction Methods	Historical earthquake damage statistics (empirical judgement of damage, stepwise regression statistics)
	Expert assessment methodology
	Fuzzy analogue method (fuzzy comprehensive judgement method, fuzzy inference method)
	Semi-empirical and semi-theoretical methods (vulnerability analysis method, Bayesian step-by-step discrimination method)
	Structure theory calculation method
	Dynamic analysis method
Group buildings - Seismic Damage	Empirical-statistical methods (empirical summary method, statistical analysis method, fuzzy comprehensive judgement method, expert assessment method, rapid method for group seismic hazard prediction in urban areas)

Prediction Methods	Theoretical calculation methods
	Semi-empirical and semi-theoretical methods
	Other methods (fuzzy analogy method, dynamic analysis method, earthquake damage prediction based on grey system theory, earthquake damage prediction method for group buildings based on ground shaking parameters, earthquake damage prediction based on artificial neural network method)

Seismic hazard prediction has formed an independent discipline under the current development, and its basic structure is shown in Figure 2-1[34]. Seismic hazard prediction consists of the following five key steps: first, the target area is reasonably divided into a number of units; next, a comprehensive census is conducted to collect data on the type, distribution, and current use of structures; the third step is to conduct a sufficient sampling survey to validate and improve the applicability of the unit census data; then, based on the sampling data, the resistance calculations of the structures in the area are carried out , generating the susceptibility matrix and evaluating it accordingly; finally, combining the hazard and risk information, the possible damages of the target area under different seismic intensities are calculated[35].

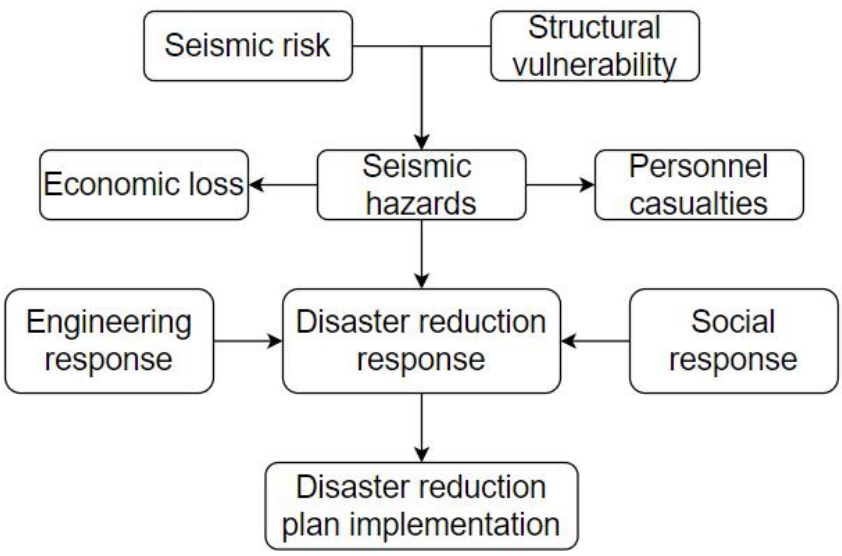


Fig 2-1 Basic structure of seismic damage prediction

Earthquake prediction, seismic damage assessment, and earthquake prevention and mitigation efforts usually require attention to the susceptibility of various types of structures in a given area or region, and many experts and scholars have carried out extensive research on the susceptibility aspects of buildings, and have achieved a series of results. The structure of masonry houses is characterised by the fact that the walls are the main load bearing elements and these walls are made up of blocks and mortar, the walls exhibit a large stiffness but relatively low tensile and shear strengths, as well as a more limited deformability and ability to withstand reciprocating loads[36]. However, masonry structures are widely used in villages, towns and small and medium-sized cities in China due to their advantages of simple construction, high efficiency and low cost. Therefore, the study of seismic vulnerability analysis of masonry structures is crucial and can also provide the necessary basic data for earthquake damage prediction and destructive seismic hazard assessment.

2.4 SEISMIC VULNERABILITY ANALYSIS METHODS

According to different research needs and research objectives as well as different analyses methods, there are some differences in scholars' definitions of susceptibility.Lind N C[37] defined susceptibility as the ratio of the probability of failure of an undamaged system to the probability of failure of a damaged system. Liu W Z[38] and others define susceptibility as the sensitivity of a structure to larger damage consequences from smaller external influences. Currently, the common definition of susceptibility is from the perspective of probability, i.e., the conditional probability of each damage level occurring in a structure under a specific seismic intensity. As for the seismic vulnerability analysis methods, they mainly include the following: historical damage statistics, expert assessment, semi-empirical and semi-theoretical methods, analogue prediction, artificial neural network method, experimental method, and theoretical calculation method.

2.4.1 Historical Earthquake Statistics Method

The historical seismic damage statistics method mainly relies on the records and survey results of actual earthquake damage, and through collation and statistical analysis, information on the proportions of different types of structures with various damage levels under different seismic intensities can be obtained. 2012, Sun Baitao[39] and others collected the damage data of 2782 masonry houses in the Wenchuan earthquake, and statistically obtained the seismic susceptibility matrix of these houses; in 2010, Gao Huiying[40] and others derived the susceptibility curve of brick masonry houses based on the Wenchuan earthquake damage data and statistical analysis, and gave the maximum damage curve considering the discrete nature of the damage data. et al. statistically analysed the vulnerability curves of brick masonry residential houses based on the seismic damage data of the Wenchuan earthquake, and gave the maximum, average, and minimum vulnerability curve envelopes considering the discrete nature of the seismic damage data.

The advantage of the empirical seismic damage statistics method is that the data are directly derived from the results of seismic damage surveys, and therefore can reflect the actual conditions of the building structures, including structural types, structural characteristics, construction age, construction quality, and other factors. However, seismic damage surveys are usually conducted by region, and there are differences in the seismic capacity of houses in different regions. Moreover, with the continuous revision of seismic codes and the improvement of construction quality, the seismic performance of buildings of different ages may also have large differences, so the seismic damage matrix needs to be adjusted and updated periodically.

2.4.2 Expert Assessment Method

The expert assessment method is a method that relies on the knowledge and experience of seismic experts to estimate the seismic vulnerability of a structure. This method mainly relies on basic information such as the characteristics of the building itself, the level of design, the site on which it is located and the topography etc. In 1990, Yucheng Yang[41] and others developed an expert system for vulnerability assessment and seismic damage prediction of multi-storey masonry houses called PDSMSMB-1, which can be used for assessing the extent of damage to existing buildings in earthquakes.

The advantage of the expert assessment method is that it is relatively simple to operate, but it requires a high level of practitioners. The assessors need to have certain professional knowledge and rich experience in seismic damage investigation.

This method is highly dependent on the knowledge level and experience of the seismic experts, and different experts may come to different conclusions on the same issue, or even differ greatly at times.

2.4.3 Semi-empirical and Semi-theoretical Method

The semi-empirical and semi-theoretical method of vulnerability analysis is a combination of seismic damage experience and theoretical calculation. When there is a lack of sufficient earthquake damage data, it can be analysed with the help of theoretical calculations, or by statistically analysing the existing earthquake damage data, an earthquake damage prediction model can be established and used to predict the degree of damage of unknown samples.In 1985, by analysing the damage data of 237 brick-column factory buildings, Wu Yucai[42] successfully derived a calculation model for the degree of seismic damage index of brick-column factories. for predicting the degree of earthquake damage in such buildings.

The half-empirical and half-theoretical method has multiple advantages, on the one hand, it can be used to make supplementary calculations when there is a lack of seismic damage data, on the other hand, it can be used to establish a theoretical prediction model by analysing the existing seismic damage data for the prediction of seismic damages, which increases the basis of the analysis.

2.4.4 Analogical Prediction Method

Analogical prediction method is an earthquake damage estimation method based on the principle of similarity, whose core idea is that buildings under similar conditions will have similar levels of damage under the same intensity of seismic action. Typically, the target prediction area is divided into sub-areas, and then the known earthquake damages of typical buildings are used to speculate the extent of damages of other buildings in the area.In 1989, Xu Xiangwen[43] et al. based on the principle of fuzzy inference, damage prediction is carried out by using fuzzy relationship between structural response and empirical seismic damages. Jianyun Chen[44] (2009) et al. selected the main factors affecting the seismic performance of a structure and determined the weights of the factors by the entropy weighting method in order to calculate the similarity between the target structure and a typical structure to predict the damage of the target structure.

The analogue prediction method has the advantages of simplicity and low data requirement in seismic vulnerability analysis, but the reliance on the similarity assumption and the selection of typical structures may lead to inaccurate prediction. Therefore, it can be used for preliminary assessment under specific conditions, but its limitations need to be considered carefully.

2.4.5 Artificial Neural Network Method

The artificial neural network method is used to make predictions for unknown samples by establishing relationships between input parameters and output results from known samples. The inputs usually include various structural factors and seismic action intensities, and the output is the damage state of the structure.In 2000, Cheng Xiaoping[45] et al. proposed a method for vulnerability analysis of multi-storey brick houses based on an artificial neural network model; in 2006, Tang Hao[46] et al. established a BP neural network model for the prediction of seismic damages of multi-storey brick houses, with peak acceleration as the index of ground shaking intensity; in 2010 , Chen Dachuan[47] and others attempted to apply the BP neural network method to analyse the seismic vulnerability of brick masonry structures in village areas.

The artificial neural network method has the advantages of nonlinear modelling, adaptability, handling of large-scale data and generalisation ability in seismic vulnerability analysis, but it relies on a large amount of high-quality data, has poor model interpretability, is easy to overfitting, and requires high computational resources.

2.4.6 Experimental Method

The experimental method is similar to the historical seismic damage statistics method, which can be used to collect a large amount of experimental data for susceptibility analysis.Ruiz-Garcia Jorge[48] et al. used the experimental data of 118 reinforced wall pieces in 2009 to analyse the seismic susceptibility of walls with different block materials.

The test method has the advantages of observing the damage process, identifying weak links, and accurately assessing the seismic performance, but the reliability is limited by the number of samples, the size of the specimens, and the test conditions, which cannot take into account the foundation soil interaction. However, the test is still one of the main means to study the seismic performance of structures.

2.4.7 Theoretical Calculation Method

In recent years, with the popularity of structural analysis software, the susceptibility analysis method based on theoretical calculations has been widely used, especially in the absence of seismic data. The seismic response of the structure is usually obtained by static nonlinear analysis and elastic-plastic time-range analysis, and then combined with probabilistic methods to obtain the susceptibility results.The process of solving the susceptibility curves and susceptibility matrices using the theoretical susceptibility method is shown in Fig. 2-2.In 2002, Yu Derhu[49] et al. computed elastic-plastic seismic response of reinforced masonry structures by writing a time-range analysis program for the reinforced masonry structure; in 2008 Park Joonam[50] et al. developed a finite element analysis model and analysed the seismic susceptibility of a two-storey unreinforced brick masonry structure with the help of spring elements; in 2013 Su Qi-wang[51] et al. modelled a 2-storey masonry structure residential house by using the equivalent frame method for pushover and IDA analyses, and plotted the structure's seismic susceptibility curve.

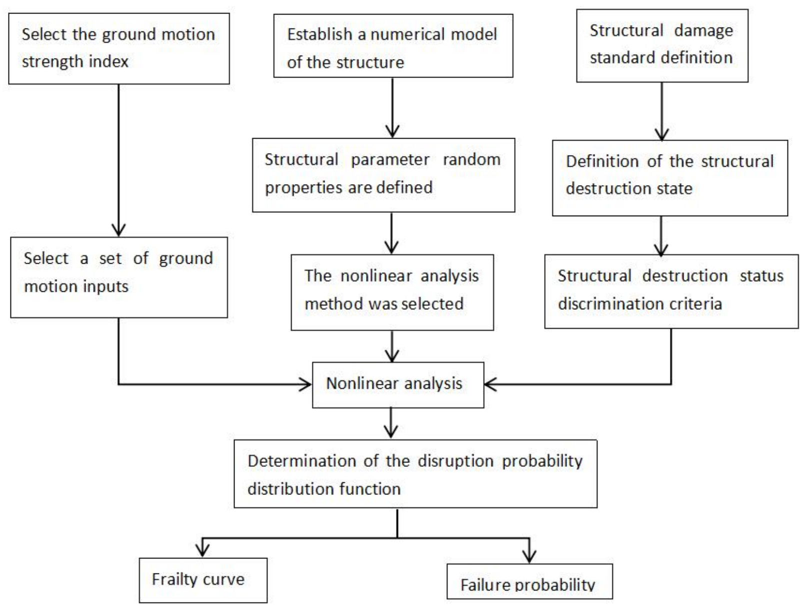


Fig 2-2 Calculation flow for resolving fragility

The method of susceptibility analysis based on theoretical calculations has been very popular in recent years, especially along with the development of various finite element analysis software, which provides a powerful tool for the analysis of elastic-plastic seismic response of structures. The accuracy of this method is affected by the reasonableness of the constructed model and the performance of the computational equipment, etc. Therefore, it is necessary to establish an effective analytical model and configure efficient computational equipment to improve the reliability and computational efficiency. Therefore, in this paper, the seismic susceptibility analysis method based on theoretical calculations is used for the study, and the incremental dynamic analysis (IDA) method is used to more accurately study the seismic susceptibility of masonry structures under the uncertainty of ground shaking in order to achieve the purpose of seismic damage prediction.

2.5 SUMMARY OF THIS CHAPTER

This research aims to investigate the whole process of earthquake damage prediction, which is a complex process that involves three modules: unmanned aerial tilt photogrammetry (UAV), building information extraction, and seismic vulnerability analysis. In this chapter, the application of UAV remote sensing technology in the field of civil engineering, the building information extraction method, the research progress of building seismic hazard prediction method, and the seismic vulnerability analysis method are comprehensively elaborated, which provides a theoretical background for the subsequent analysis and assessment.

CHAPTER 3
METHODOLOGY

3.1 THEORY AND METHODS OF UAV INCLINED PHOTOGRAMMETRY

Unmanned Aerial Vehicles (UAV), known as unmanned aerial vehicles , are operated using advanced components, including physical models, ground control stations (GCS), modern sensors, and communication platforms. In the past, UAVs were mainly used in civil and military fields for purposes such as search and rescue, weather monitoring, surveillance, weather forecasting, and mapping. And with the continuous development of modern technology and the innovation of the Internet, the application areas of drones have undergone a radical change. Nowadays, drones are also widely used to respond to natural disasters, such as storms, floods and bushfires, for tasks such as emergency evacuation and disaster monitoring[52]. The applications of UAVs in various fields are shown in Figure 3-1. In recent years, with the rapid development of high-performance lithium battery technology and the continuous optimisation of UAV flight control equipment, the prospect of consumer UAVs has never been broader. Numerous enterprise units gradually use UAV tilt photogrammetry technology to carry out surveying work, which not only improves the work efficiency, but also reduces the cost. In this subsection, the theory and method of UAV inclined photogrammetry are introduced in detail.

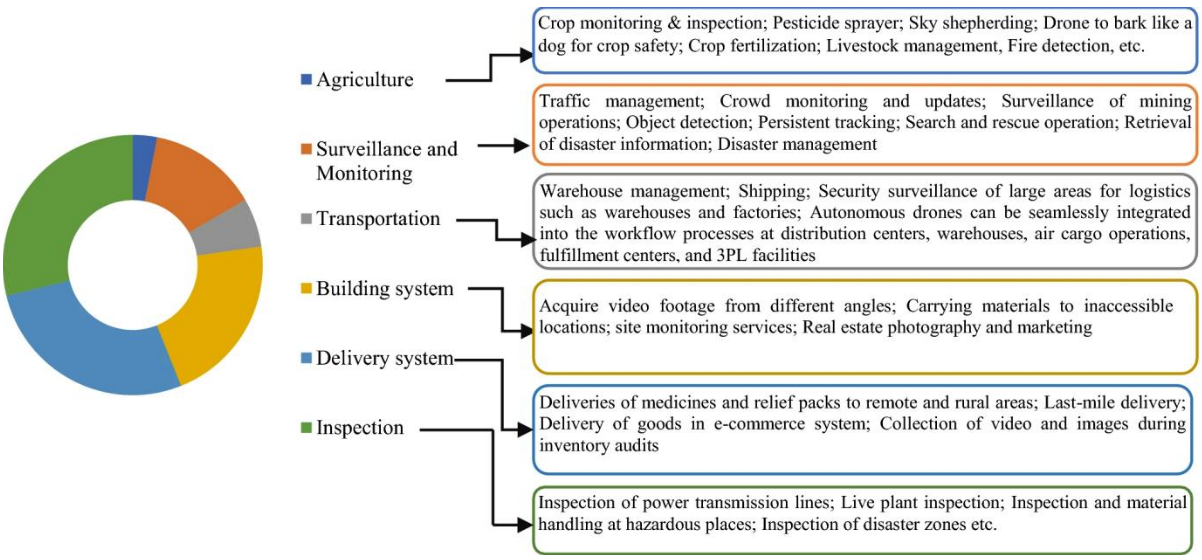


Fig 3-1 Application of drones in various fields (image reproduced from [52])

3.1.1 Fundamental Theory of Photogrammetry

3.1.1.1 Coordinate systems commonly used in photogrammetry

Photography is the process by which a light-sensitive element captures the light reflected from an object that has passed through the lens of a camera to form an image, transforming what was originally three-dimensional information about the object into a two-dimensional image. In this three-dimensional to two-dimensional imaging process, the path of light rays undergoes three key parts from the actual ground object to the camera lens and then to the light sensor. Photogrammetry, on the other hand, is the process of reducing the 2D coordinates of the points in the image film to the 3D coordinates in the object space, which can be regarded as the inverse process of photography, realising the recovery of the information from 2D image to 3D[53]. Usually, the coordinate systems involved in the photogrammetric field mainly include image plane coordinate system, image space coordinate system and object space coordinate system.

(1) Image plane coordinate system (photographic element)

Take the vertical foot o (i.e., the main point of the image) of the photographic centre S in the image plane as the origin of the coordinate system, take the direction of the frame mark of the camera as the x-axis, and the other direction perpendicular to the x-axis as the y-axis, and set up a coordinate system according to the right-hand rule to determine the direction of the x-axis and y-axis, so as to construct the image-plane coordinate system o-xy (as shown in Fig. 3-2).

(2) Like the space coordinate system (camera lens)

According to the small hole imaging model, it can be seen that the camera centre S is located in the image point a and the object point A on the connection line, and the projected centre S and like the main point o of the line is perpendicular to the image plane, and at the same time, the projected centre S to like the main point o of the line is perpendicular to the image plane. By combining the centre of photography S with the image-plane coordinate system of the principal point, a transitional coordinate system, called the image-space coordinate system S-xyz (e.g., Fig. 3-2), can be established for describing the relationship between the object-square coordinate system and the image-plane coordinate system[54].

However, the direction of the axes of the image-space coordinate system S-xyz is determined by the image frame scale connecting lines and the direction of the optical axis, so the direction of the optical axis is not the same for each image, resulting in a non-uniform image-space coordinate system for each image. In order to improve the ease of analysis, we can adopt the coordinate axis direction of the object space coordinate system D-XYZ as a unified standard[55]. By rotating the coordinate system of each image film to make the direction of its coordinate axis consistent with the ground photogrammetric coordinate system, the image space auxiliary coordinate system S-XYZ is obtained (Figure 3-2).

(3) Object space coordinate system (actual ground feature)

The object-square space coordinate system D-XYZ (Figure 3-2) is a three-dimensional right-angle coordinate system defined according to the dimensional characteristics of the object to be measured and the demand for measurement. It is used to describe the position of ground points in the object space including photogrammetric coordinate system, ground measurement coordinate system and ground photogrammetric coordinate system[32]. Usually, the corresponding coordinate system is established according to the engineering situation, such as the most commonly used in surveying is the Gaussian plane coordinate system.

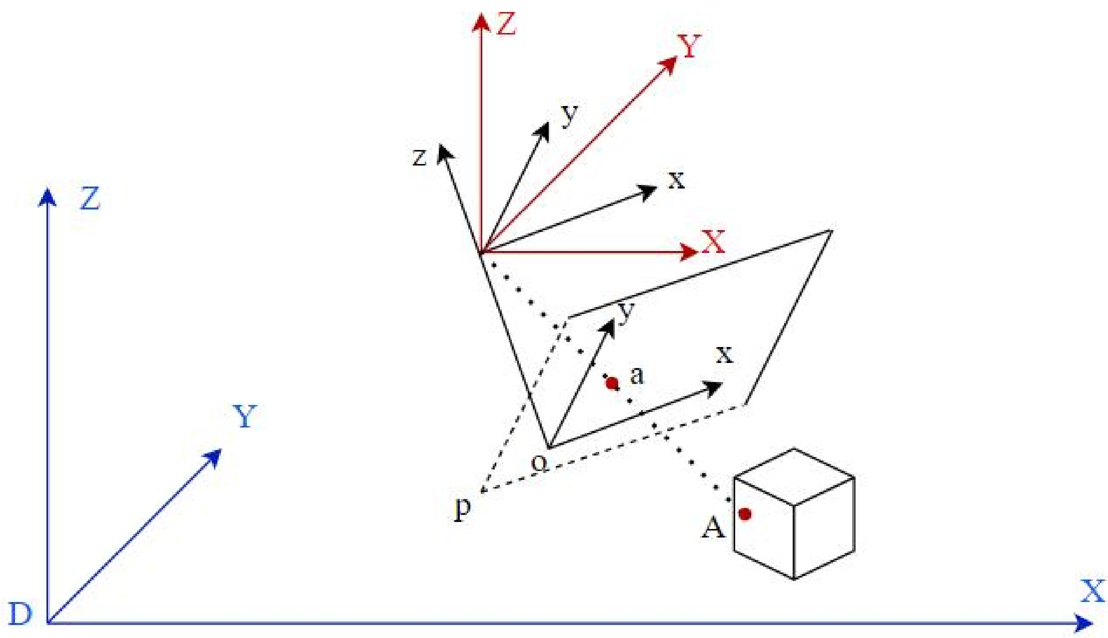


Fig 3-2 Schematic diagram of commonly used coordinate systems

3.1.1.2 Internal and external orientation elements of the film

In order to transform the coordinate systems in photogrammetry, it is necessary to define the mutual positional relationship between the centre of projection, the image and the ground. Determination of the relative position between the centre of projection and the image is called the internal orientation of the image, and the parameter used to describe the internal orientation is called the internal orientation element. The outer orientation element is used to determine the position and attitude of the image in the object space coordinate system [56][57].

(1) Internal orientation elements

The three internal orientation elements of the aerial camera film are x_0, y_0, and f (Figure 3-3). Among them, the focal length of the aerial camera is denoted by the symbol f, which represents the vertical distance from the projection centre to the image plane in the vertical space. x_0 means the position of the pendant foot of the image principal point o in the X-axis direction on the image film, and y_0 means the position of the pendant foot of the image principal point o in the Y-axis direction on the image film. The main function of these internal orientation elements is to change the coordinates, converting the coordinate values in the frame coordinate system of the image point to the values in the image space coordinate system.

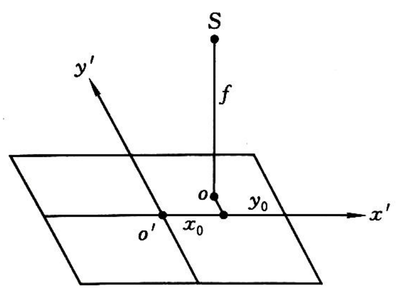
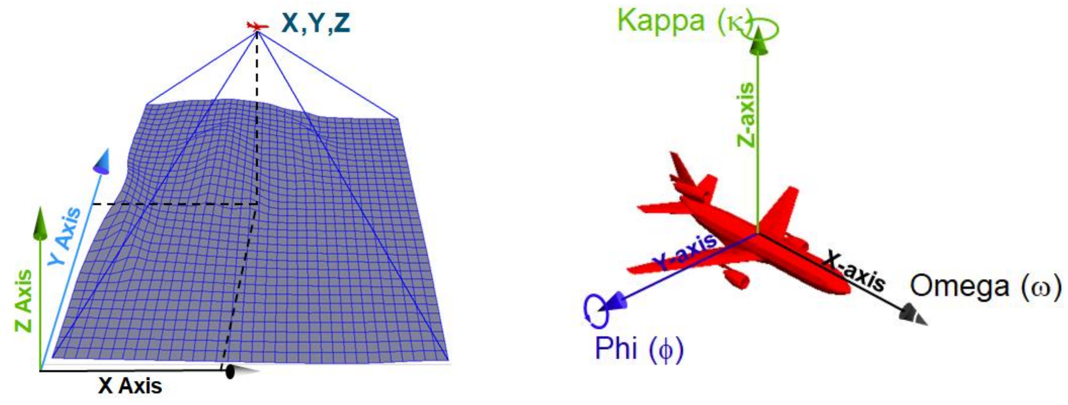


Fig 3-3 Schematic diagram of azimuthal elements within an image film

(2) External orientation elements

The six external orientation elements of the aerial camera are X, Y, Z, and ϕ, ω, κ, as shown in Figure 3-4. X, Y, Z represent the position of the projection centre of the aerial camera in the object space coordinate system, while ϕ, ω, κ corresponds to the attitude information of the aerial camera, i.e., the direction information of the aerial camera, such as pitch, roll, and swivel.



(a) Image position information (b) Image orientation information

Fig 3-4 Schematic diagram of the external orientation elements of the image film

3.1.1.3 Covariant conditional equation

In photogrammetry it is common to establish a mathematical relationship of the image to describe the geometric relationship between the ground point and the image point. This established mathematical expression is known as the covariance equation. In the covariance equation, the covariance condition is often expressed in terms of and Two space vectors are used and $SA = \lambda S\mathrm{a}$.

In the equation of the co-linearity condition, X_S 、 Y_S 、 Z_S are the coordinates of ground point A in the coordinate system of the camera station, and the actual coordinates of ground point A are X, Y, Z, and satisfy[58]:

$$
\begin{aligned}
x - x_0 + \Delta x &= -f \frac{a_1(X - X_S) + b_1(Y - Y_S) + c_1(Z - Z_S)}{a_3(X - X_S) + b_3(Y - Y_S) + c_3(Z - Z_S)} \\
y - y_0 + \Delta y &= -f \frac{a_2(X - X_S) + b_2(Y - Y_S) + c_2(Z - Z_S)}{a_3(X - X_S) + b_3(Y - Y_S) + c_3(Z - Z_S)}
\end{aligned}
\tag{3.1}
$$

(1) If it is not possible to measure the coordinates of the image point with the main point of the image as the origin, it is necessary to introduce the value of the main point coordinates(x_0, y_0).

(2) By the image point coordinates themselves need to introduce some kind of systematic error correction value($\Delta\mathrm{x}$, $\Delta\mathrm{y}$).

(3) a_i、b_i、$\mathrm{c}_i(\mathrm{i}=1、2、3)$ in Eq. is an element of the rotation matrix R, which is a function of the three independent direction angles (Φ , ω , κ) of the camera's outer azimuthal elements, and can be written as:

$$R = \begin{bmatrix} a_1 & b_1 & c_1 \\ a_2 & b_2 & c_2 \\ a_3 & b_3 & c_3 \end{bmatrix} \quad (3.2)$$

included among these:

$$\begin{aligned} & a_1 = \cos\phi\cos\kappa + \sin\phi\sin\omega\sin\kappa, \quad a_2 = \cos\phi\sin\kappa - \sin\phi\sin\omega\sin\kappa \\ & a_3 = \sin\phi\cos\omega, \quad b_1 = \sin\phi\cos\omega, \quad b_2 = \cos\omega\sin\kappa, \quad b_3 = \sin\omega \\ & c_1 = -\sin\phi\cos\kappa + \cos\phi\sin\omega\sin\kappa, \quad c_2 = -\sin\phi\cos\kappa - \cos\phi\sin\omega\sin\kappa \\ & c_3 = \cos\phi\cos\omega \end{aligned} \quad (3.3)$$

The covariance equation has various forms of expression, but its meaning is the same, and equation (3.1) is one of the common expressions, which is widely used in photogrammetry and plays an important role in determining the spatial position of ground points. In addition, the covariance equation is usually used as a mathematical model for the air-three beam method of levelling when performing air-three levelling, and it is also used as a mathematical basis for back-calculating coordinates.

3.1.1.4 Aerial triangulation

Aerial triangulation is an important part of photogrammetry, and its basic principle is that according to the distribution characteristics of spatial objects, the positional relationship between field objects and photogrammetric images can be determined. Firstly, by laying image control points in the field, the actual coordinate information of the image control points can be obtained; then, combined with the coordinate position information of the image control points on the image, the covariance equations are established; finally, these equations are solved by the corresponding algorithms, and the planar coordinates and elevation information of the other points on the image, i.e., the spatial position information, are calculated. Photogrammetry accurately measures the dimensions and position information of ground entities, so it has been widely used and recognised in large-area mapping work. Based on the different mathematical basis, airborne triangulation can be divided into independent model method, aerial tape method, and beam method; based on the different ranges when the aerial tape levelling is performed, airborne triangulation can be divided into aerial triangulation by aerial tape method, airborne triangulation by single model method, and airborne triangulation by area network method[59][60].

Aerial triangle encryption is the process of determining the outer azimuth elements of all images in a specific area by photogrammetric resolution method, this step is usually the first stage of data product production, and the level of aerial triangle accuracy directly affects the accuracy level of the final map or data product produced[61]. Chen Ying[62] (2021) summarised the mainstream aerial triangle encryption processing software at home and abroad, such as ContextCapture, Pix4DMAPPER, PHOTOSCAN, INPHO, Pixel Grid, Pixel Factory, Aerospace Vision, SVSUAV, etc., and comprehensively reviewed different issues such as the operation difficulty, visual effect, accuracy, etc., of the software. We comprehensively review different issues of each software, and synthesise the advantages of each software in processing data, and study the methods and techniques of aerial triangulation encryption processing of UAV data with the combination of multiple software.

3.1.2 Theory and Methods of Inclined Photogrammetry

UAV tilt photography technology is an aerial image acquisition technology, in which ground targets are photographed at a number of different angles and directions by a UAV carrying a photographic camera with tilt photography capability, as shown in Figure 3-5, which is designed to acquire high-resolution, multi-angle, large-coverage area images and geographic information data. Inclined photogrammetry technology can simultaneously acquire the top and side image information of a building, and therefore can generate a high-precision, realistic 3D model of the building. However, tilted photogrammetric images also have some drawbacks. In order to ensure that the side profile information of an object is observed, the phase amplitude of tilted photogrammetric images is usually smaller than that of normal orthophotogrammetric images, and these images usually have a large rotation angle[20]. These problems lead to a high overlap between tilt photogrammetric images, which poses a challenge for analytical processing. Therefore, it is necessary to collaborate with each other through multiple steps, such as multi-view image joint levelling, multi-view image dense matching, TIN triangulation, texture mapping, etc., in order to generate a high-precision and realistic 3D model[63].

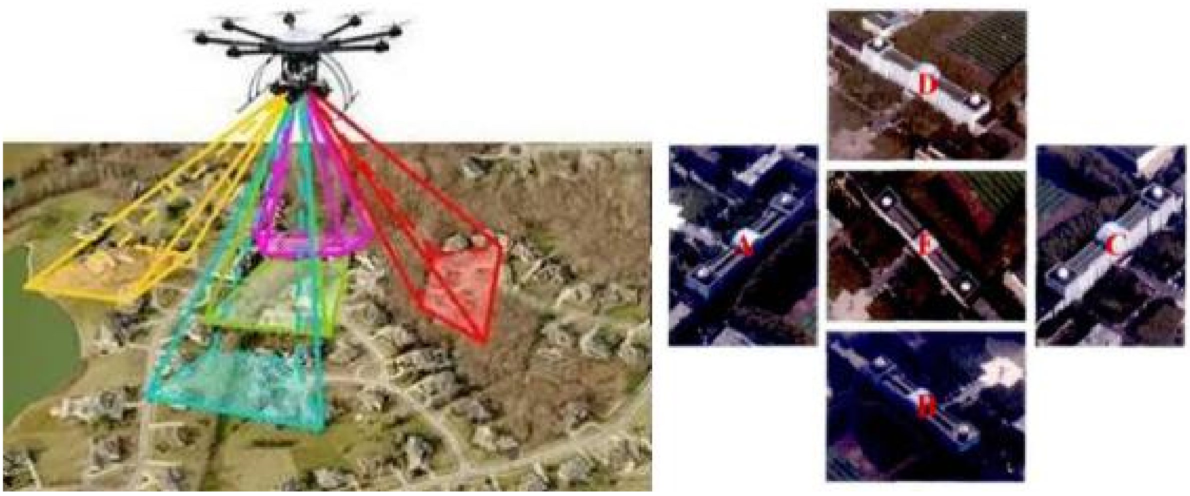


Fig 3-5 Schematic of tilt photography and photographs

3.1.2.1 Multi-view image combined with parallax

Multiview image joint levelling is a method of measuring and reconstructing spatial three-dimensional information using multiple images. Its main principle is to find the three-dimensional coordinates of ground points by performing operations such as image-point matching, image-sheet association and triangulation on multiple images. Image point matching is to match the image points of the same ground point in multiple images to determine its positional relationship in different images; image film association is to combine multiple images for processing to eliminate errors between images; triangulation is to calculate the 3D coordinates of the ground point based on the geometrical relationship between the image point and the image plane.

In the joint levelling of multi-view images, the beam method is a commonly used method, which uses the beam composed of each image to serve as the basic levelling unit, and the error equations are listed according to the co-linear condition[64]. The beam method has high levelling accuracy[65], but the computational complexity is large, which requires more control points and computational resources, Figure 3-6 shows the schematic diagram of the beam method area network levelling.

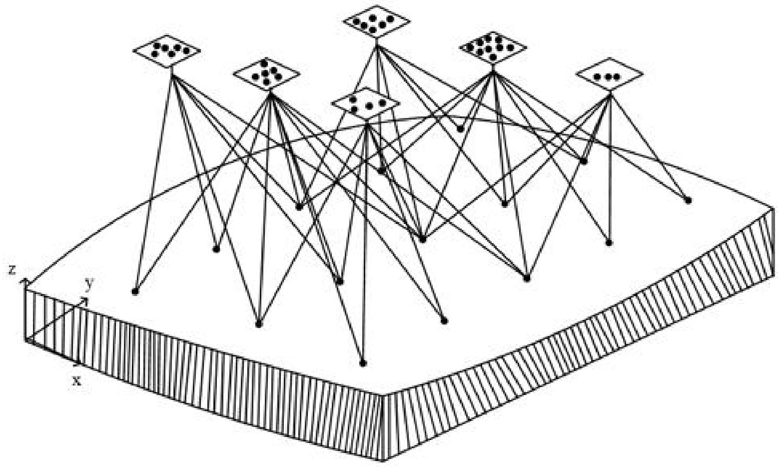


Fig 3-6 Schematic diagram of beam method regional network levelling

3.1.2.2 Multi-view image intensive matching

Multi-view image dense matching is a method for 3D point cloud reconstruction using multiple viewpoint images. In this process, homonymous point matching between multiple viewpoint images is required to obtain the 3D coordinate information of each pixel[66]. Since multi-view images have different viewing angles and lighting conditions, homonymous point matching needs to overcome different image variations such as translation, rotation, scaling and deformation. This process can help to generate high-density 3D point clouds for building accurate 3D models or maps.

3.1.2.3 Construction of the TIN triangle network

TIN (Triangulated Irregular Network) triangular mesh construction is a method used for 3D modelling to generate an irregular triangular mesh from discrete point data collected from the ground for visualisation and analysis of terrain surfaces. The principle is to connect the vertical bisectors of two neighbouring points to form a continuous polygon, which is calculated and operated several times to form an irregular triangular mesh[67]. The process of constructing the mesh can be divided into the following two stages: one is to construct the initial triangular mesh according to the constraints and threshold conditions with a certain feature point as the centre; the other is to take the line elements obtained from the multi-view image matching as the constraints, and adopt the diagonal exchange method to adjust each line segment in the triangular mesh by using the locally optimal process (LOP), and use distance thresholds repeatedly for optimization to form the irregular triangular mesh with the constraints. conditions of the irregular triangular mesh, as shown in Figure 3-7. In the TIN construction, it is also necessary to consider the features and morphology of the terrain surface, such as terrain undulations, slopes, geomorphological elements such as rivers, lakes, and artificial structures such as buildings, roads, bridges, etc., all of which need to be reasonably processed and expressed in the TIN construction.

Fig 3-7 Schematic of the effect of TIN triangular mesh with texture mapping

3.1.2.4 Texture map (computing)

Texture mapping is a process of mapping a 2D image (texture) onto the surface of a 3D model[68], which aims to increase the appearance effect of the 3D model, including colour, texture, material, etc., in order to enhance the realism and detail presentation of the model, as shown in Fig 3-7.The basic principle is to map the coordinates of the texture image to the corresponding positions on the surface of the 3D model, thus combining the colour information of the texture image with the 3D model's The basic principle is to map the coordinates of the texture image to the corresponding locations on the surface of the 3D model, thus combining the colour information of the texture image with the geometric information of the 3D model. The process usually consists of the following steps: first, the 3D model surface is divided into several triangles, and UV coordinate mapping is generated for each triangle to ensure that the texture image can be accurately fitted on the triangle surface. Next, for each vertex, its corresponding texture coordinate is computed based on its position within the triangle. Finally, based on the calculated UV mapping, the texture image is pasted onto the triangle surface to generate the texture mapping effect.

3.2 UAV INCLINED PHOTOGRAMMETRY SOFTWARE AND HARDWARE SYSTEM

3.2.1 Hardware System and its Composition

The UAV inclined photogrammetry system is mainly composed of the UAV flight platform, mission equipment system, navigation and positioning system, ground control and security system, as shown in Figure 3-8:

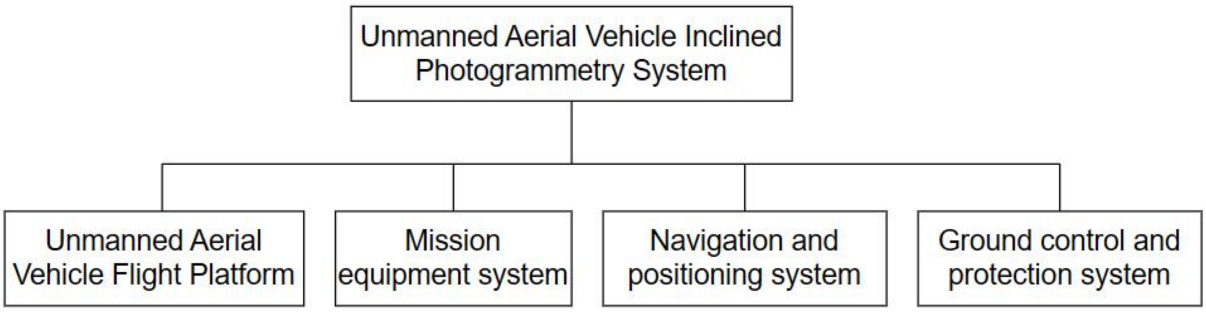


Fig 3-8 Structure of UAV inclined photogrammetry system

3.2.1.1 UAV flight platforms

A UAV is an unmanned aerial vehicle (UAV) that is autonomously manoeuvred by radio remote control equipment and computer preprogramming, and is fitted with an autopilot and navigation device[69]. The UAV flight platform generally consists of flight control system, communication system, power system, sensors and other components, and the appropriate model and configuration can be selected according to different application requirements and environments. The UAV flight platform usually carries a multi-view aerial camera, sets a fixed aerial altitude to plan the route, so that the UAV flies autonomously according to the route, and can collect the image information of the target area as well as the texture information of the ground objects. UAVs can be classified into fixed-wing, multi-rotor, and vertical take-off and landing fixed-wing UAVs according to their structural characteristics, and fixed-wing and multi-rotor UAVs are usually used.

In this study, we adopt the HuaCe V200 quadcopter UAV (shown in Figure 3-9), which adopts multiple redundant designs, intelligent self-diagnostic algorithms, and a 100Hz image-control-free differential system, and its reliable system can be used to fly more reliably.The V200 supports the carrying of multiple loads platforms, such as composite sensor pods, 30x zoom pods, aerial survey pods with talker reducers, throwers, searchlights, and other loads, and the maximum load is 2.1kg.The V200 multifunctional UAS system can be divided into fixed wing and multirotor, and vertical take-off and landing fixed wing UAV, according to its structural characteristics. The general protocol of V200 multifunctional UAS supports seamless docking with a variety of command platforms, and supports docking with video service platforms in line with GB/T 28181 protocol standard, to achieve remote monitoring of UAVs, so that the back-end command centre can grasp the on-site information in real time. Now it is mainly used in the fields of mapping and remote sensing, security monitoring, pipeline inspection, search and rescue, environmental protection and law enforcement, etc. It is an excellent choice for industrial applications. The technical parameters of the aircraft are shown in Table 3-1.

Fig 3-9 HuaCe V200 quadcopter UAV

Table 3-1 List of technical parameters of the flight vehicle

Items	Parameters
Wheelbase	653mm

Overall dimensions	885x902x340mm 500x518x140mm
Weight	3.06kg(with batteries)
Maximum take-off weight	5.16kg
GNSS	BDS B1/B2;GPS L1/L2;GALILEO E1/E5b;QZSS L1/L2
Positioning accuracy (RMS)	vertically:±2.5m(GNSS single point);±0.8m(DGPS);±1.5cm+1ppm(RTK)
	standards:±1.5m(GNSS single point);±0.4m(DGPS);±1.0 cm+1ppm(RTK)
Orientation accuracy (RMS)	0.45°
Maximum rise/fall speed	6m/s
Maximum horizontal flight speed	20m/s(manual flight)
Maximum flight altitude	7000m
Maximum wind speed	15m/s
Maximum endurance (note)	unladen:75min;0.35kg mount:65min
Working environment temperature	-20°C-55°C
Forward radar operating frequency	77-81GHz
Forward radar range	0.5-60m

Note: *The endurance of a cruise outside the ground-effective area at a speed of 10 m/s to the ground under static airflow atmospheric conditions with a barometric pressure of 101.325 KPa and a temperature of 20℃ when the power supply is completely depleted.*

3.2.1.2 Mission equipment systems

The mission equipment system usually consists of an aerial camera and a camera control unit. The aerial camera is a data acquisition device commonly used on UAV platforms for collecting and storing image data of the aerial photography area, and the common types of aerial cameras include single-lens and five-lens aerial cameras. The camera control unit is mainly responsible for controlling the camera's shooting angle, exposure time and other parameters.

In this study, the RuiBo D2M half-frame tilt camera (shown in Figure 3-10) is used with the HuaCe V200 UAV, which can be free of image control, adopts the MLS shutter camera control unit, and can automatically carry out image encoding and redundant data rejection. The technical parameters of the camera are shown in Table 3-2.

Fig 3-10 RuiBo D2M half-frame tilt camera

Table 3-2 Tilt camera technical parameters

Items	Parameters
Total pixels	1.3 hundred million
Product size	104.5*104.5*87mm
Product weight	≤630g
Exposure time interval	0.5s
Shutter speed	1/100-1/2000s
Camera memory	640GB*2
Data copy mode	external storage high-speed download
Camera synchronisation	1ms
Exposure feedback accuracy	50 μ s
Synchronisation monitoring	Passive
Control mode	Remote control/Bluetooth/Serial
Supply voltage	DC (12V-27V)
Power supply interface	Skyport/DC/Customised
Mounting method	Lifting/Under Bracket Mount
Shock absorption	Shock absorbing ball

Working environment	-20°C-65°C
Trigger signal	Skyport/Low Level/Serial Port
Optical focal length	25mm/35mm
Number of lenses	5
Lens tilt angle	45°
Lens layout	Surround
Closest focus distance	8m/10m
FOV viewing angle (Horizontal)	50.35°/37.12°
FOV viewing angle (Vertical)	34.66°/25.13°

3.2.1.3 Navigation and positioning systems

A navigation and positioning system, often referred to as a POS system, is a combination of the GNSS navigation system, which stands for Global Navigation Satellite System, and the INS inertial navigation system, which includes global, regional, and augmented navigation systems that are capable of providing accurate positioning information around the clock. In contrast, the inertial navigation system (INS) is an extrapolated navigation method that continuously obtains information about the specific position of a moving body by continuously measuring the carrier's heading angle and velocity and extrapolating the exact position of the next point from a known point[70]. In the inclined photogrammetry system, GNSS and INS navigation systems are integrated, which can accurately obtain the spatial positioning information of the camera station at the instant of exposure.

HuaCe V200 adopts self-developed multi-source fusion positioning algorithm, and the on-board differential receiver can provide real-time positioning data up to 100Hz, which, together with the CGO2.0 post-processing algorithm software, can finely model the ionospheric and tropospheric errors, further reduce the systematic errors, and achieve the image-control-free aerial survey operation. The module synchronises the high-frequency precision data to the payload and flight control system to ensure the stability of the aircraft's attitude while acquiring high-precision differential data, and then works with the high-precision PPK solver to obtain aerial images with high-precision POS. It is equipped with double GNSS system, triple IMU system and double antenna positioning and orientation to ensure the safety of flight operation and reliability of aerial survey results.

3.2.1.4 Ground control and protection system

The ground control and guarantee system includes the ground monitoring system and the data transmission system. The main tasks of the ground monitoring system include controlling the UAV and the aerial camera, monitoring the flight status and trajectory of the UAV, planning the flight mission and programme, and controlling the shooting mission of the aerial camera. The ground control system usually consists of a UAV remote control unit, monitoring software, and a tablet computer. The main functions of the monitoring software include flight monitoring, navigation map, route planning and aerial camera monitoring.

Fig 3-11 HuaCe V200 ground control system

The ground control system of Sinotest V200 UAV adopts Android tablet (Figure 3-11), which is easy to operate, and its main technical parameters are shown in Table 3-3. GCS2.0 App, which is specially designed for industrial applications, gives full play to the powerful functions of V200, and comprehensively improves the flight operation experience. Through Wi-Fi or wired network, the images acquired by the UAV can be shared to other display terminals, helping the team to work side by side and operate efficiently.

Table 3-3 Technical parameters of HuaCe V200 ground control system

Items	Parameters
Built-in Battery	18650 Li-ion battery (6400mAh@7.4V)
Endurance	Approx. 5 hours
Operating Frequency	1430-1444MHz
Transmit power	-40dBm-25dBm
Maximum communication distance (no interference, no obstruction)	17km
Maximum downlink image resolution	1080P@60fps

3.2.2 Software System and its Operation Process

Software system is the key part of UAV inclined photogrammetry technology, combined with the workflow of UAV inclined photogrammetry, it mainly includes the steps of image data checking, POS data difference decomposition, and inclined photographic three-dimensional modelling, etc. The following is a detailed discussion of the relevant software required for each step.

3.2.2.1 Image data checking

Image data checking is crucial in the data processing of UAV inclined photogrammetry. The image quality directly affects the accuracy and reliability of the final 3D modelling. Therefore, before data processing, image quality checking must be carried out to screen out problematic images in time and carry out supplementary flights and other operations as needed to ensure the efficiency and reliability of the whole inclined photogrammetry modelling. In traditional aerial surveys, it is usually necessary to print the images and check them manually, which is a time-consuming and unreliable process, and is easy to be missed due to human errors.

In this study, we used Fly Check Data (software interface in Figure 3-12) UAV image checking software to perform automated inspection. Typically, relevant data are imported into this software immediately after the completion of the flight mission. Through the POS observation information during the UAV flight, the software can visualise the position and flight situation of each image. If a mismatch between the POS information and the image is found, the software provides a data editing function, which can be edited directly on the graphical interface, including operations such as adding and deleting POS points, panning the aerial tape, and telescoping the aerial tape. In the absence of POS information, the software can also simulate the generation of POS data to ensure that each image can correctly correspond to the POS point coordinates. This process can be done without modifying the original POS file by exporting a new POS file containing the information that has been divided into zones and corresponds correctly to the images. By checking for missing images or POS information, it is also possible to determine if a make-up flight is required.

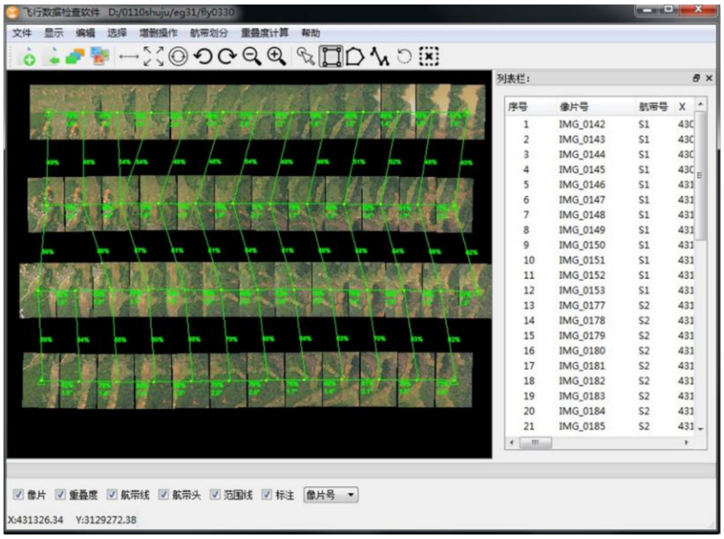


Fig 3-12 Fly check data image inspection software

The following are the specific steps for image data checking using this software:

(1) Creating a project

First, create a new project to import and check the data. The data that must be imported include original observation images, POS data and range line data. After importing the POS, the software will display the POS points and automatically divide the air strip and display the range line. In the information column of the software, the detailed information of each air strip, POS information and image name will be displayed.

(2) Aerial Belt Delineation

There are usually two modes to divide the air strip, manual mode and automatic mode. Generally, the automatic mode is adopted, and you only need to select the automatic zoning algorithm.

(3) Image and POS Inspection

This step is mainly to check the divided observation image and POS point information, and deal with the problems in time.

(4) Calculate the parameter information such as heading overlap, side overlap, film rotation angle and heading height.

When calculating these parameters, for example, when calculating the heading overlap, you can use the matching points to calculate the overlap between each image and the nearest image in the adjacent track, or you can also calculate the overlap between the two images before and after the same track. Typically, the software displays the overlap in colour, with green indicating that the overlap does not exceed the threshold and red indicating that the overlap exceeds the threshold.

3.2.2.2 POS data discretisation

In this paper, CGO (CHC Geomatics Office) dynamic post-processing software is used to perform the POS data difference decomposition, and its basic principle is as follows: by processing the observation data from the reference station with the same observation time and the observation data from the GPS receiver module on the UAV, the carrier phase difference decomposition is performed, so as to calculate the dynamic relative position between the UAV and the reference station. The next step is to determine the absolute position coordinates of the UAV by combining with the coordinate conversion.CGO software is the second generation of full-featured post-processing software developed completely by Huashe, which adopts a brand new data solving engine. The following is a detailed description of the process of POS data differential resolution using CGO dynamic post-processing software, including the software operation interface (Figure 3-13).

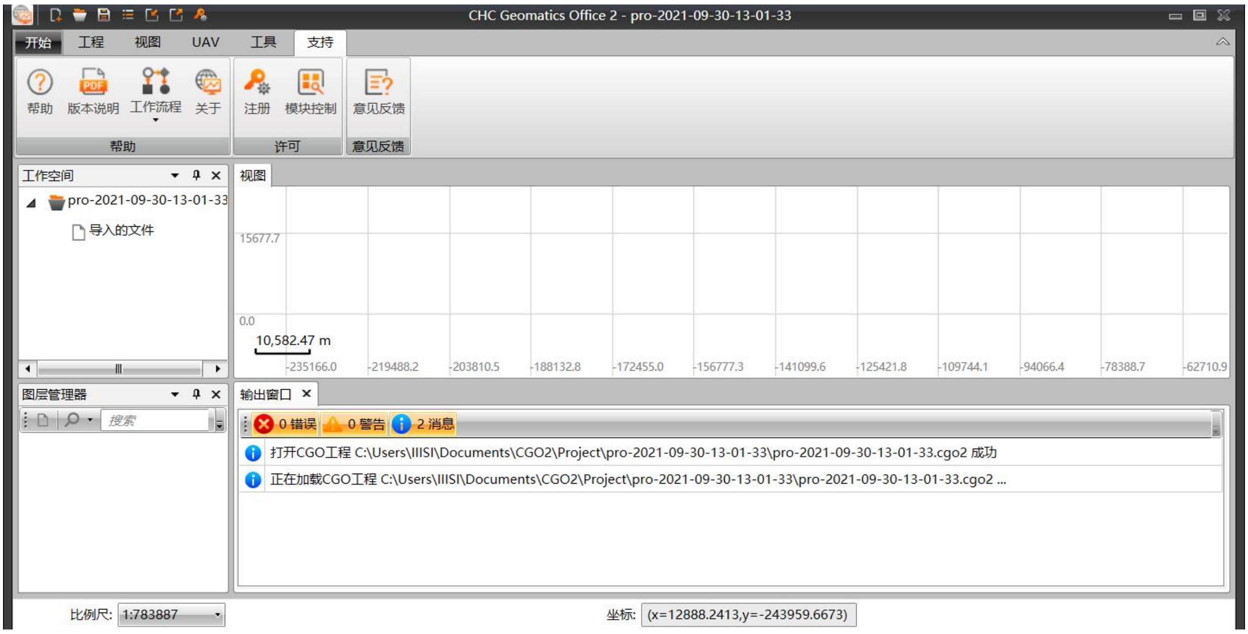


Fig 3-13 UAV POS data difference calculation

(1) New project

Open the software, click New Project, enter the project name, and at the same time, select the storage path of the project according to the prompts, and set the basic information of the project, such as coordinate system, unit, format and accuracy.

(2) Import data

In this step, there are many kinds of data to be entered, including base station data, UAV receiver and inertial guidance data.

(3) Base Station Configuration

Here mainly refers to the setting of the relevant attribute information of the GNSS base station, including the coordinate information of the base station, GNSS receiver type, antenna type, antenna height and other parameters.

(4) Solving Settings

The main settings include the satellite altitude cut-off angle, which is affected by the environment of the measurement area and the satellite signal quality; the camera photo delay, which depends on the camera model and photo parameters; the signal-to-noise ratio threshold, which is related to the accuracy of the data; and the number of satellite systems, which is based on the data collection situation to set up the solution start and end time, solution mode and solution interval.

(5) Data solving

After the mobile station data solving is completed, you can enable the Valley Map Index and Baidu Map Index through the network to view the positioning track and solving status, and view the POS solving pass rate and fixed solving ratio.

(6) Export data

After the data solving is completed, follow the software data export steps to export the UAV position information file.

3.2.2.3 Tilt photography 3D modelling

This study uses Context Capture Center, a real-life modelling software developed by Bentley in the United States. It adopts an automatic 3D modelling system with a simple modelling operation procedure, which automatically generates a tilted 3D model, and the whole process of modelling requires no human intervention and operation, and the processing speed of the model is fast, so it can make good use of the simple continuous image to generate the most realistic and most imaginative model of the real-life true 3D scene[71]. The modelling system can be used to restore various data sources and achieve smooth integration of data objects from different sources, such as photographs taken on the ground or images taken from the air. The software system is best suited for 3D modelling tasks such as buildings, structures, terrain and vegetation. However, for objects with complex geometry and matte-patterned surfaces, limitations in geometry and lighting may result in some inaccurate bump errors on the surface of the 3D model.

The Context Capture Center software consists of two main parts, the main console and the engine side, of which the main console is the core part of the software. The console is the core of the software. Typically, the user interface of the console allows the user to perform a series of operations, including inputting files, constructing processes, submitting tasks, monitoring the progress of the tasks, and visualising the results of the processes. The engine side consists of three tool modules, Context Capture Viewer, Context Capture Settings and Context Capture Scene Composer, which are used to support the work modules of the software. The details are as follows:

(1) Context Capture Viewer is a free and lightweight visualisation module. You can use Context Capture Viewer to control the production quality of the model, and you can also use it to browse the results of the final production model.

(2) Context Capture Settings manages software licences, task path settings and other related software configurations.

(3) Context Capture Scene Composer for Context Capture Viewer to modify, configure the three-dimensional index file.

Using Context Capture Center software for three-dimensional modelling of the detailed steps are as follows:

(1) Import data

This step mainly refers to importing POS files, external image control point data and original photogrammetric images into the software. When importing the tilt photogrammetric image, the size and focal length of the camera can be obtained directly from the EXIF metadata.

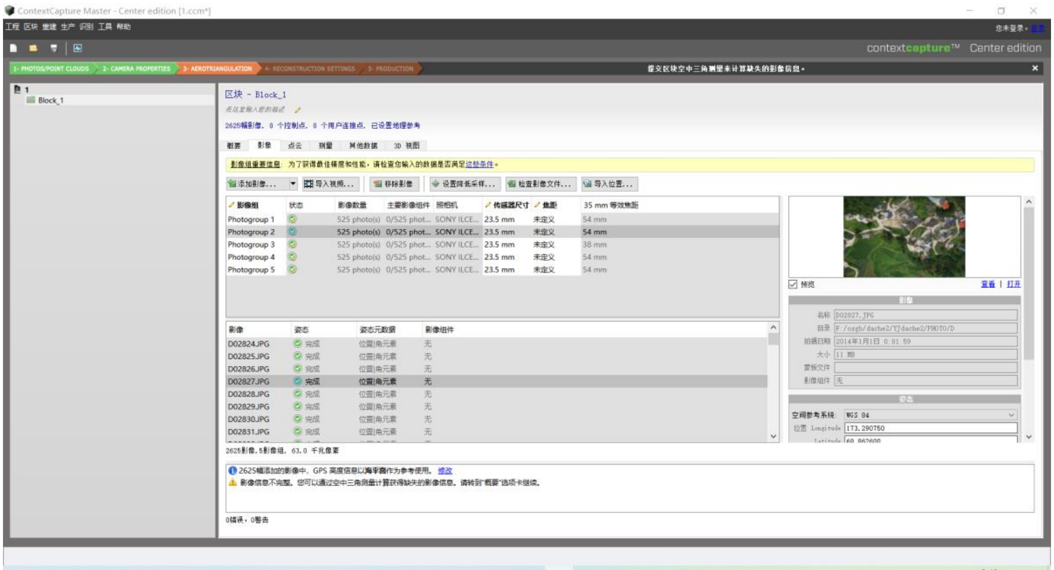


Fig 3-14 Data import interface

After importing the image files, it is also necessary to check whether the imported photogrammetric images are complete or not, and if there are missing or damaged images, it is necessary to carry out the flyback operation. If the project contains external control point data, first import the external survey control point file, then add the control point information and determine the coordinate system type. Next, select relevant images from those containing external control points and accurately mark the locations of the control points on these images. Special care is taken to ensure that points of the same name are also accurately marked on neighbouring images, and the marking is completed on all images where external control points are located in turn.

(2) Aerial triangulation task

After completing the data import, it is necessary to use Context Capture Center software to carry out the aerial triangulation encryption task, which is the most important part of the inclined photogrammetry and mainly includes the following steps: extracting the connection points, matching the connection points, levelling the beam method area network, and creating blocks to submit the aerial triangulation task. Usually, the aerial triangulation report will be generated after the completion of aerial triangulation (the completion status is shown in Figure 3-15), which can be exported in the form of XML or KML to evaluate and analyse the accuracy of the aerial triangulation, in which the accuracy indexes of each parameter, such as the reprojection error, absolute orientation error, etc., will be displayed.

Fig 3-15 Aerial triangulation completion status

(3) Three-dimensional reconstruction

After completing the air-three solving work, the reconstruction of the solid 3D model can be started. Firstly, it is necessary to determine the spatial framework of the 3D model, the processing settings and the output format (e.g. OBJ format, OSGB format, DAE format, etc.). When building the 3D model, the block construction method is usually adopted, which in turn allows a large amount of high-precision point cloud data to be calculated. Subsequently, by loading filtering algorithms with different characteristics, irregular point cloud data with anomalies or bumps can be filtered to optimise the quality of the 3D model.

The irregular triangular mesh is constructed on the basis of the digital point cloud, resulting in a TIN model and a 3D white model, which is able to express a realistic 3D scene, but without mapping the real texture mapping. The point cloud data is densely matched and has a large amount of data, so it is necessary to cut the high-density point cloud obtained by chunking, and construct the irregular triangular mesh TIN on the point cloud data after chunking. The effect of constructing the triangular mesh is shown schematically in Figure 3-16.

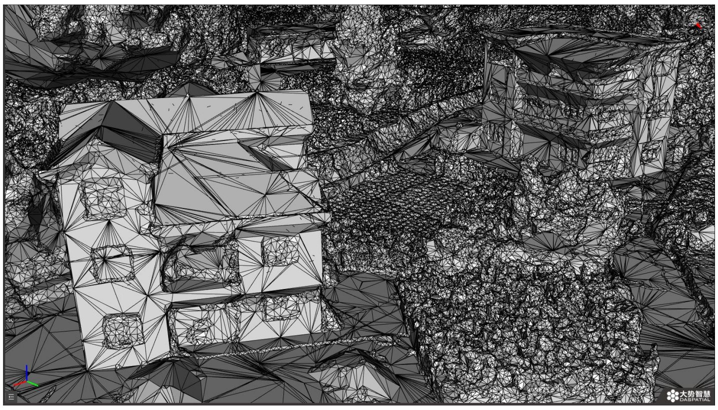


Fig 3-16 Schematic diagram of the effect of constructing a triangular network

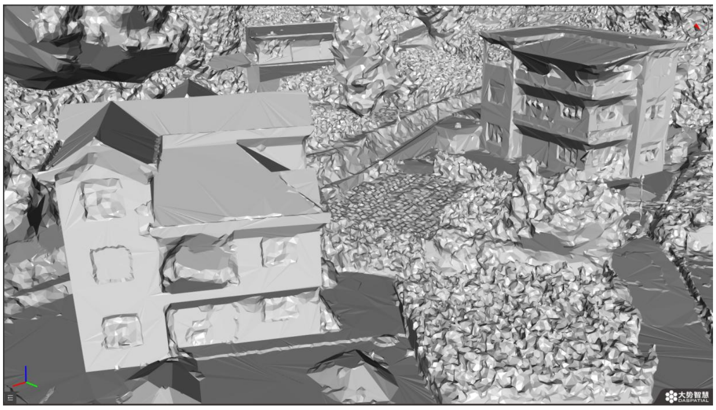


Fig 3-17 3D white film effect schematic

According to the spatial location information of the 3D TIN, the chunks are cut and formed into an untextured 3D model, i.e., the white mould. The schematic diagram of the 3D white film effect is shown in 3-17.

Context Capture Center can match the coordinates of each triangular surface in the TIN model with the mapping information of the corresponding coordinates, and then automatically cut and map them to the triangular surfaces, so as to achieve automatic mapping of the TIN model, and ultimately generate a real 3D model with real mapping information, as shown in Figure 3-18.

Fig 3-18 Schematic of the effect of the 3D model after texture mapping

3.3 ACQUISITION OF APPEARANCE INFORMATION AND HIDDEN INFORMATION OF RURAL AREAS BUILDINGS

3.3.1 Acquisition of Building Geometric Information Based on Three-dimensional Models

The geometric information of the village building is the key to establish its mechanical analysis model, using the UAV tilt photography technology to establish a real-life 3D model, the clarity and resolution of the data can meet the basic accuracy requirements of the building dimensions, so the use of 3D model image measurement to extract the appearance of the building dimensions of the village is an effective method. The key to obtaining the geometric dimensions of buildings in 3D models lies in accurate image acquisition, high-quality POS data differential decomposition, accurate image alignment, effective building extraction algorithms, and reliable measurement principles and algorithms. The geometric dimensions of the building in the 3D model, including the building appearance, height, door and window positions and dimensions (Figure 3-19), acquired using Cass 3D as well as DasViewer 3D software, are highly accurate and reliable. At the same time, the 3D model can also visualise the type of structure and material of the building.

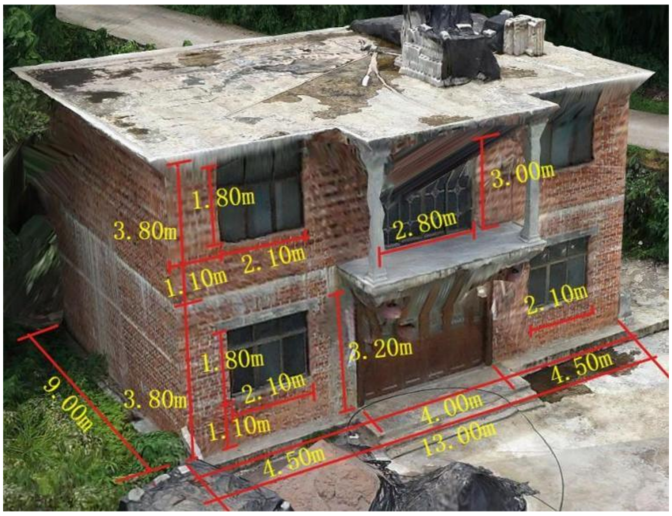


Fig 3-19 Schematic diagram of the measurement of the exterior dimensions of the 3D model

In addition to the above intuitive access to building information, image recognition technology can also be used to quickly and efficiently obtain the type of village building structure and the number of floors. In recent years, with the improvement of computer computing speed and efficiency, deep learning has developed rapidly, and many algorithms and models have emerged, mainly including deep belief networks, convolutional neural networks and recurrent neural networks. Therefore, image recognition of village building structure types can be achieved using Convolutional Neural Networks (CNN). Convolutional neural networks introduce optimisation methods such as dropout, weight sharing, pooling operations, non-linear activation and stochastic gradient descent, thus providing the neural network model with superior autonomous learning capabilities.CNN is a feed-forward neural network that usually contains multiple hidden layers, and its basic network structure is illustrated in Fig. 3-20[72].CNNs are essentially an end-to-end mapping model that works by learning a large number of mapping relations (datasets) to establish a mapping function between inputs (image samples) and outputs (classification probabilities) for image recognition and classification[73]. This mapping relation can be expressed as:

$$Y = F(H) \tag{3.4}$$

Where Y denotes the probability distribution for classification of this image sample, $F(\bullet)$ denotes the CNN model; H denotes the input image sample.

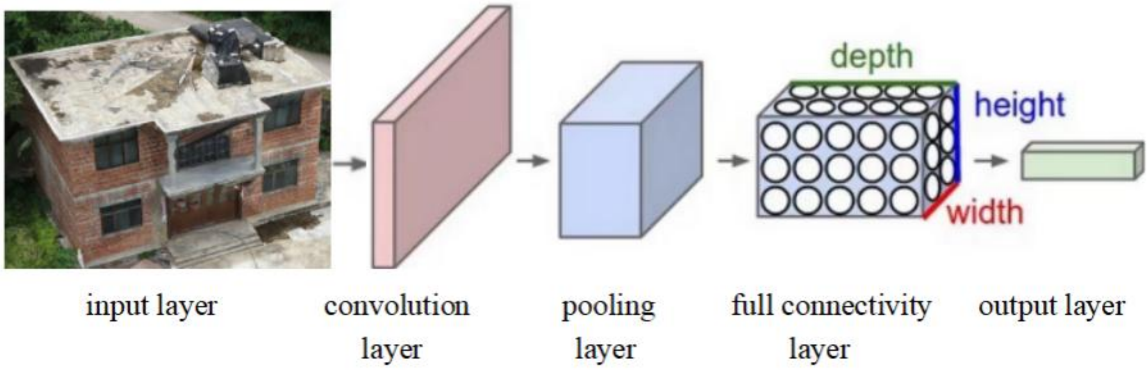


Fig 3-20 Convolutional neural network structure

The models were trained through the TensorFlow platform, a deep learning framework in Python environment, and the training results showed that the final test accuracies of the village and town building structure type classification models and the floor classification models were 80% and 88%, respectively. These models can effectively predict the structure types of common buildings in villages and towns, including masonry, wood, concrete, and earth structures, as well as the number of floors in buildings of different structure types, with high efficiency and accuracy.

3.3.2 Acquisition Method of Building Material and Structure Information Based on Fuzzy Inference

Measurement and image recognition based on 3D models can effectively obtain the structure type and exterior dimension information of village and township buildings, but it is more difficult to extract the hidden information of the internal structure, such as the layout of the inner wall, building construction, material properties and wall reinforcement. Buildings in village areas are mostly constructed by the villagers themselves, and despite a certain degree of randomness, they usually follow local customs and traditional building rules. Therefore, it is a feasible method to utilise reasonable rules of thumb to infer hidden information.

3.3.2.1 Wall information

The masonry structures of village buildings in different regions have significant differences in wall materials and thicknesses. Yin Zhiqian[74] classified them into three categories of regions based on the latitude and longitude of the country. The first category is the area above 43 degrees north latitude, where the climate is cold and the winters are long, and solid brick walls with added insulation are usually used, with a wall thickness of about 490 mm; the second category is the area located between 35-43 degrees north latitude, with hot and rainy summers, cold and dry winters, and distinct seasons, and the thickness of the exterior walls is moderate, and 370 mm thick exterior walls are usually used; and the third category is the area below 35 degrees north latitude, where rainfall is The third category is the area below 35 degrees north latitude, with abundant rainfall, warm and humid climate, and short winters, which usually adopts 240mm-thick external walls for sheltering from wind and rain, and heat preservation and insulation. Therefore, the regional category of the target village or town can be determined based on its latitude and longitude information, so as to predict the thickness of the external wall of masonry structure in the village or town, and the information of the wall of masonry structure in some regions of China is shown in Table 3.4.

Table 3-4Information on walls in selected areas

Region	Type	Thickness/mm
Northeast China (Liaoning)	Solid Brick Wall	370-620
Northern China (Shanxi)	Solid Brick Wall	370-600
Eastern China (Anhui)	Hollow Brick wall	330-350
Southwest China (Guizhou, Sichuan, Chongqing)	Hollow Brick wall	180-240
Northwest China (Shaanxi)	Solid Brick wall	240-370

In addition to the thickness of the walls, the arrangement of the internal walls of the masonry structure also has some influence on the seismic performance of the structure. In order to improve the lighting conditions, village buildings usually have a large area of windows and doors in the north-south direction. Traditional houses often adopt the structural form of one light, two dark and three openings, and the number of windows usually corresponds to the number of openings. Therefore, orthophotos of village buildings can be used to predict the layout of interior walls by combining information on the number and location of windows and doors and the length of the building. The opening size of a masonry structure is usually 3-4 m[75], so when the length of the building is between 6-8 m, the building can be empirically judged as a two-opening structure, which requires only one horizontal internal wall; when the length is 9-12 m, it can be recognised as a three-opening structure, which needs to be equipped with two horizontal internal walls, and so on. For the longitudinal internal wall, it can be reasonably surmised based on the depth of the building. Some survey data show[76] that masonry structures with a depth of 5-7m are usually single-depth and do not need a longitudinal internal wall; while in buildings with a depth of more than 8m, they are usually north-south and two-depth, and there is a longitudinal internal wall.

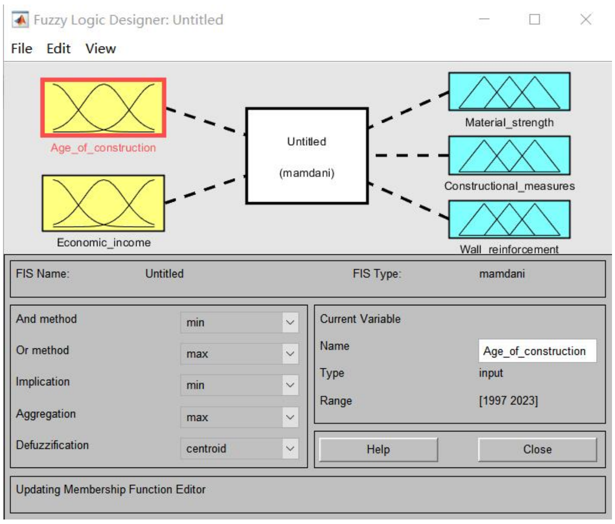
3.3.2.2 Building materials and construction information

The building materials (mortar, blocks), seismic construction measures (ring beams, structural columns) and wall reinforcement of masonry structures are important factors in determining their seismic performance. For many years, village buildings in China have been in a state of unsupervised and self-built by villagers, not designed and constructed in accordance with the code requirements, and the production and use of building materials have not been up to standard. Therefore, it is difficult to speculate on their materials, structural information and wall reinforcement based on the codes. However, there is a significant correlation and law between the construction time of the building and the economic income level of the occupants and the material and structural information: the earlier the construction time of the structure, the lower the possibility of the existence of seismic-resistant structural measures, and at the same time, the more serious the weathering and corrosion, the more the strength of the material decreases, and the lower the probability of the structure being reinforced masonry; the lower the economic income level of the occupants, the lower the cost invested during the construction process, and the lower the probability of the structural measures, and the lower the probability of using the structural measures. The lower the economic income level of the household, the lower the cost invested in the construction process, the lower the probability of setting up structural measures, and the lower the strength of the materials used, the lower the probability that the structure is reinforced masonry[77].

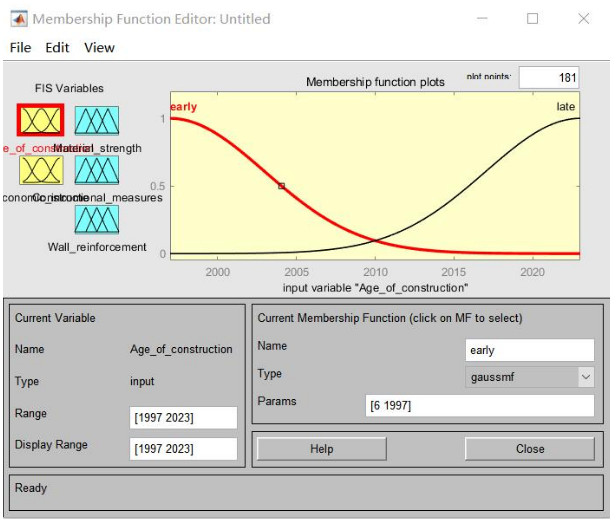
Based on the above empirical laws, the use of fuzzy language to describe the "early" and "late" construction time, the "high" and "low" economic income, and the "high" and "low" material strength, the probability of the structure being reinforced masonry is lower[77]. "and "late" of construction time, "high" and "low" of economic income, and "strong" and "weak" of material strength, and can consider the combined influence of multiple factors on a certain event, applying the idea of fuzzy theory to infer the hidden information of masonry structure[78]. Combining the practical engineering experience and research literature to construct the fuzzy rules between the construction age of masonry structure, economic income level and construction measures, material strength and wall reinforcement as shown in Table 3.5. The establishment of fuzzy inference model is achieved through the fuzzy logic toolbox in Matlab, and the fuzzy variables, thesis domain, affiliation function and fuzzy rule setting process of the fuzzy inference model are shown in Figure 3-21.

Table 3-5 Fuzzy rules

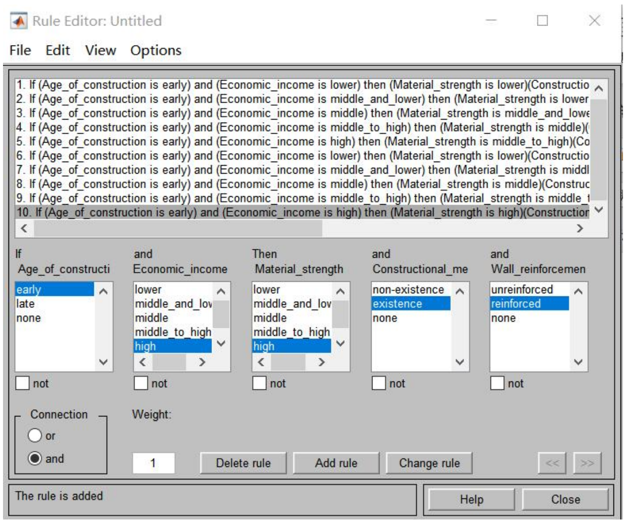
Age of construction	Economic income	Material Strength	Structural measures	Wall reinforcement
Early	Low	Low	Non-existent	Unreinforced
Early	Lower middle	Low	Non-existent	Unreinforced
Early	Medium	Lower middle	Non-existent	Unreinforced
Early	Upper middle	Medium	Non-existent	Unreinforced
Early	High	Upper middle	Existing	Unreinforced
Early	Low	Low	Non-existent	Unreinforced
Early	Lower middle	Lower middle	Non-existent	Unreinforced
Early	Medium	Medium	Existing	Unreinforced
Early	Upper middle	Upper middle	Existing	Reinforcement
Early	High	High	Existing	Reinforcement



(a) Fuzzy variable setting



(b) Theory domain and affiliation function settings



(c) Fuzzy rule setting

Fig 3-21 Fuzzy inference model parameter settings

3.4 SEISMIC VULNERABILITY ANALYSIS BASED ON INCREMENTAL DYNAMIC ANALYSIS (IDA)

3.4.1 Incremental Dynamics Analysis (IDA) Process

Incremental dynamic analysis (IDA) is a method used to evaluate the performance of structures under seismic actions. Its basic principle is to perform multiple elasto-plastic dynamic time-course analyses to obtain the correspondence between the intensity index of ground shaking (IM) and the structural damage index (DM), and to reduce the randomness of the traditional time-course analyses by loading different ground shaking recordings[79].IDA analyses are able to provide a detailed picture of the structural response covering the whole range from the elastic phase to the whole process of collapse, and at the same time clearly show the differences between different ground vibration records. Currently, IDA analysis is widely used in the field of construction engineering.

The steps of incremental dynamic analysis method are as follows:

(1) Establish finite element model: Create a suitable finite element model to reflect the dynamic characteristics of the structure and select appropriate limit performance state points.

(2) Select ground vibration records: According to the site conditions, select multiple ground vibration records and perform amplitude modulation to obtain a series of ground vibration records.

(3) Define ground vibration intensity and structural damage index: Select appropriate ground vibration intensity index (IM) and structural damage index (DM).

(4) Perform non-linear time-course analysis: Use the ground vibration records prepared in the previous stage to perform non-linear time-course analysis and record points（IM_i, DM_i）. If the slope of the line connecting a point（IM_i, DM_i）to the previous point（IM_{i-1}, DM_{i-1}）is less than 0.2 K_e （K_e being the slope of the line connecting the origin and the first point), the structure is considered to have collapsed and loading is stopped. Finally, these points are connected to obtain an IDA curve.

(5) Repeat the analysis: Repeat step (3) to perform IDA analysis using other ground shaking records and plot the IDA curve clusters.

(6) Processing the results: The results of the IDA analysis are processed, and

the mean and standard deviation of each DM value are calculated to obtain three quantile curves of 50%, 84%, and 16%, respectively(DM, μ_{IM})、（DM, $\mu_{IM} \times e^{\delta_{IM}}$）、（DM, $\mu_{IM} \times e^{-\delta_{IM}}$）. Where the 50% curve is the mean curve, the 84% and 16% curves indicate the degree of dispersion of the analysis results.

(7) Evaluation of structural seismic performance: Based on the analysis results, the seismic performance of the structure is evaluated to understand the response of the structure.

3.4.2 Selection of Ground Vibration Records

With the development of nature-based seismic theory, the seismic design of engineering structures is no longer limited to the use of response spectrum theory. Instead, structural dynamic time-range analyses based on ground-shaking inputs have been widely adopted[80]. In this process, the selection of appropriate ground vibration recordings becomes a prerequisite for obtaining reliable results. Domestic and foreign studies have achieved some results with practical application value, while the existing methods of ground vibration record selection can be classified into the following three main categories when considering them comprehensively:

(1) Selection methods based on seismic environment and seismic information: this method takes into account the geological and seismic source characteristics of the place where the earthquake occurred, as well as the seismic history of the region where the structure is located. It usually relies on analysing databases of seismic environments and seismic information to select ground shaking records suitable for a particular site.

(2) Target Spectrum-Based Selection Method: This method translates the design objectives and performance requirements of a structure into a target response spectrum, and then selects ground shaking records so that the structure meets or approaches the target response spectrum under these ground shaking. This helps to ensure that the structure meets the design requirements under earthquakes.

(3) Least Favourable Ground Shaking Selection Method: This method attempts to select those ground shaking records that are likely to result in the most unfavourable response of the structure in order to assess the ultimate performance of the structure. Typically, these ground shaking records are selected to bring the structure to the most unfavourable condition in terms of certain performance

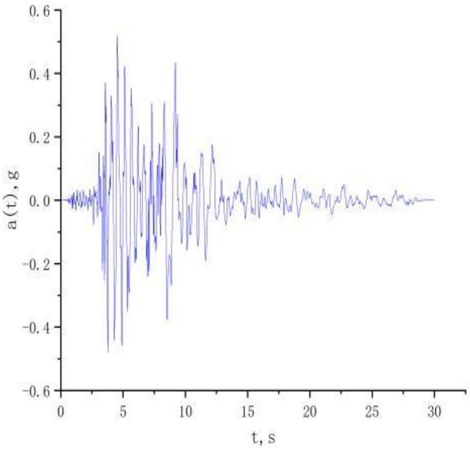
indicators (e.g., displacement, shear, etc.).

The selection of ground shocks directly determines the results of the IDA analysis. Ground shaking is a highly complex stochastic process, the nature of which is affected by a variety of factors, such as the source mechanism, site conditions, propagation medium, distance from the source, etc. The same ground shaking can occur at different locations or at different times of the day. The recording of the same earth tremor at different locations or in different directions may be significantly different. With the advancement of modern technology, ground shaking recordings are becoming more and more abundant, and each earthquake generates abundant ground shaking data. Therefore, the selection of ground shaking becomes particularly critical. Based on the peak acceleration, holding time and spectral characteristics of ground shaking, this paper selects 10 ground shaking records from the database of the Pacific Earthquake Research Centre in the United States, and their characteristics are shown in Table 3.6.

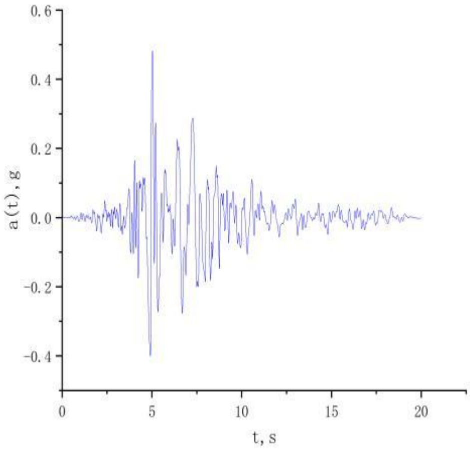
Table 3-6 Ground shaking information

No.	Step length	Step count	Hold time	PGA (g)
GM001	0.01	29.98	2998	0.52
GM002	0.01	19.98	1998	0.48
GM003	0.01	55.89	5589	0.82
GM004	0.01	45.30	4530	0.34
GM005	0.01	40.95	4095	0.25
GM006	0.005	39.95	7990	0.68
GM007	0.005	39.94	7988	0.17
GM008	0.02	35.98	1799	0.55
GM009	0.005	90.00	18000	0.42
GM010	0.005	36.34	7268	0.35

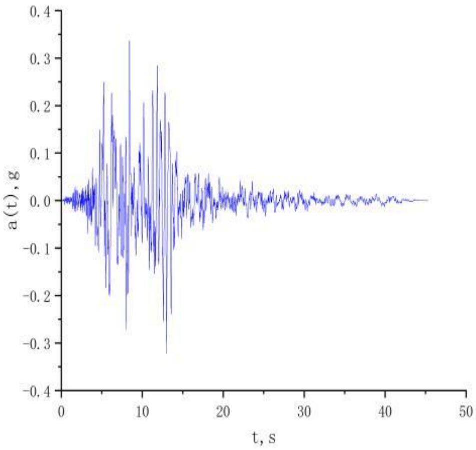
As shown in Figures 3-22 and 3-23, there are significant differences between these ground shocks in terms of peak acceleration, spectral characteristics, and holding time. This means that the uncertainty of the ground shaking itself can be fully taken into account when analysing the seismic vulnerability of structures.



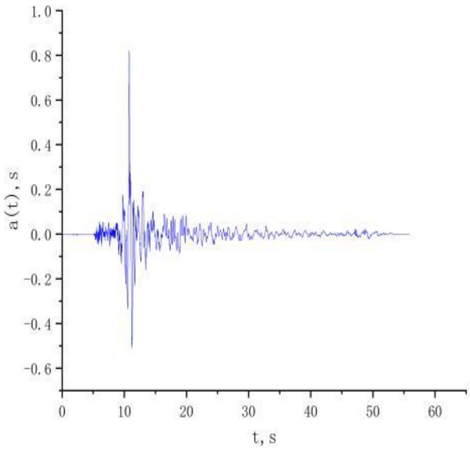
(a) GM001



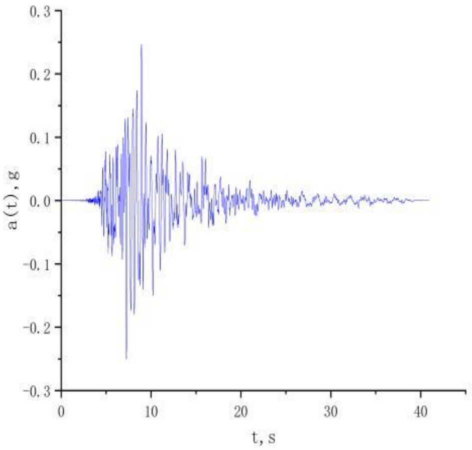
(b) GM002



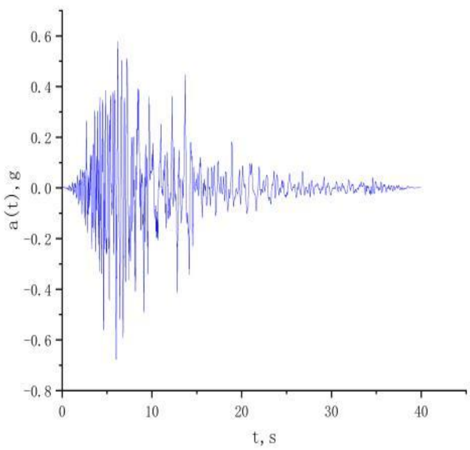
(c) GM003



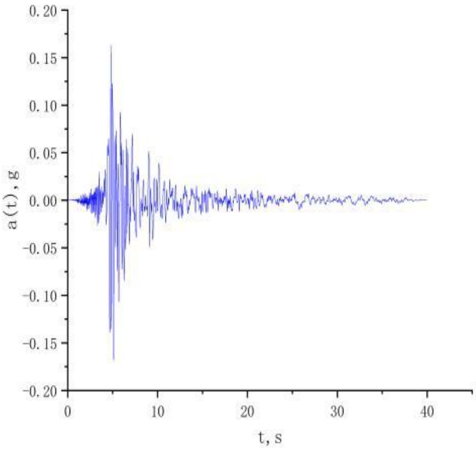
(d) GM004



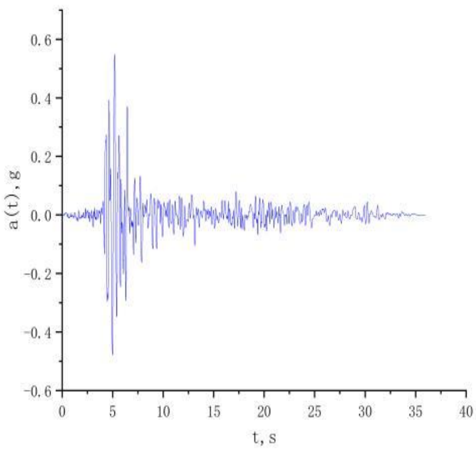
(e) GM005



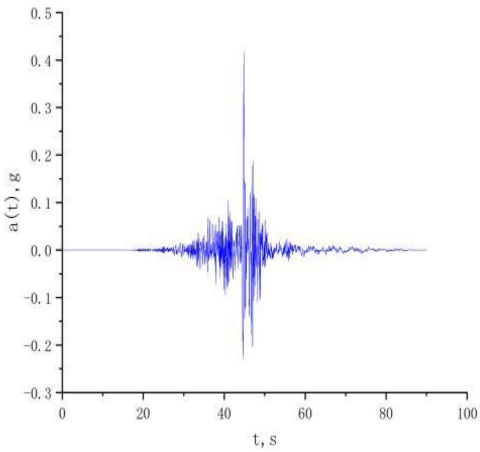
(f) GM006



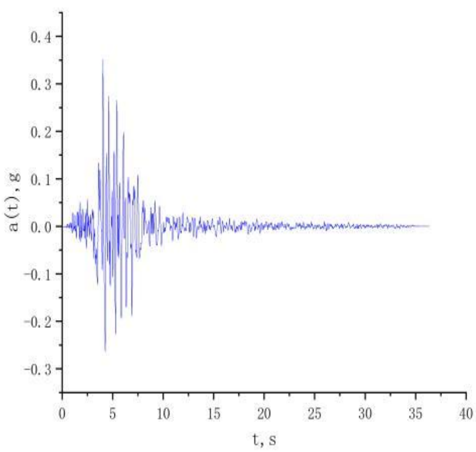
(g) GM007



(h) GM008



(i) GM009



(j) GM010

Fig 3-22 Ground vibration time-range curve

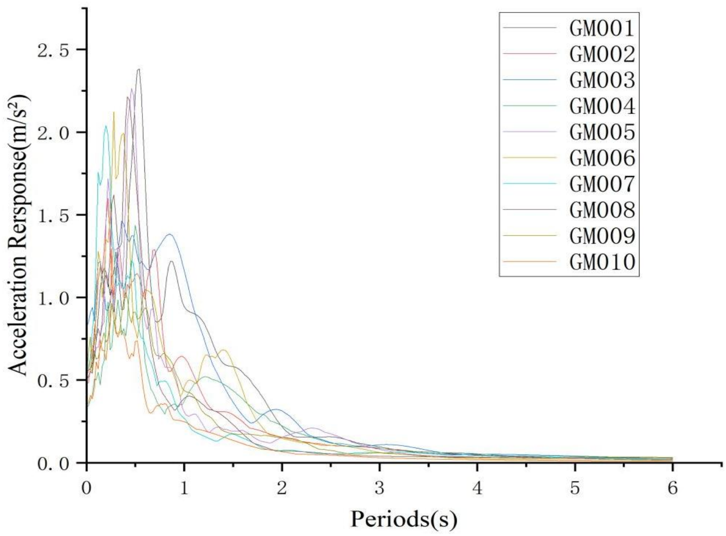


Fig 3-23 10 ground shaking response spectra

3.4.3 Selection of Ground Vibration Intensity Indicators and Structural Damage Indicators

The selection of ground shaking intensity indicators and structural damage indicators is the key to incremental dynamic analysis and needs to meet the requirements of correlation and sensitivity. Correlation implies that the selected indicators should be closely related to the ground shaking intensity, i.e., they should change with the change of ground shaking intensity and should show the same trend for different ground shaking. Sensitivity requires that the indicators should be able to accurately reflect the response process of the structure[81].

Currently, common indicators of ground shaking intensity (IM) include peak seismic acceleration (PGA) and spectral acceleration at a damping ratio of 5% S_a(T1,5%). In this study, PGA is chosen as the ground shaking intensity indicator.PGA usually reflects the intensity of earthquakes more intuitively.

The more mainstream structural damage indicators (DM) include maximum interstorey displacement angle, interstorey shear ratio and base shear, and so on. The maximum interstory displacement angle ($\theta_{\max}$) is a common choice because it provides intuitive damage information and is widely used in seismic codes of various countries. $\theta_{\max}$ is an intuitive and sensitive indicator suitable for describing the deformation of a structure under seismic action.

Therefore, in this study, PGA was selected as the ground shaking intensity indicator and $\theta_{\max}$ as the structural damage indicator for incremental dynamic analysis. These choices are intended to ensure that the selected indicators have high correlation and sensitivity to more accurately reflect changes in the response and performance of the structure.

The ground vibration amplitude modulation method in this paper applies the equal step method. The equal-step method is simple to operate and specifies a specific step size1 to amplitude modulate the ground vibration from large to small, as shown in Eq:

$$\lambda_{i+1} = \lambda_i + \Delta\lambda \qquad \textbf{(3.5)}$$

where i is an integer greater than or equal to 0, and λ_i represents the corresponding IM metric after the i amplitude adjustment.

Generally speaking, the smaller $\Delta\lambda$ is, the more IDA analyses are performed, the higher the computational cost is and the lower the computational efficiency is; the larger $\Delta\lambda$ is, the less IDA analyses are performed and the lower the accuracy is, thus making it difficult to accurately estimate the structural limit state points. Considering more loading ground vibration and higher computational cost of 3D solid model, $\Delta\lambda$ is taken as 0.025 g when PGA is less than 0.4 g, and 0.05 g when PGA is more than 0.4 g, taking into account the operation difficulty, computational cost and relative accuracy.

3.4.4 Determination of Structural Performance Levels

In probabilistic seismic capacity analysis, the classification of damage states (DS) and the definition of limit states (LS) are two key issues[82]. Compared with traditional earthquake engineering, an important advancement of performance-based earthquake engineering is that both seismic design and performance assessment of structures are considered as a multilevelling process, i.e., the possibility of different states of damage of structures under different ground shaking levels is considered. The performance level of a structure is also referred to as the limit state of the structure. When the structure is between neighbouring limit states, we can consider it as the damage state of the structure. The relationship between limit states and damage states is shown in Figure 3-24.

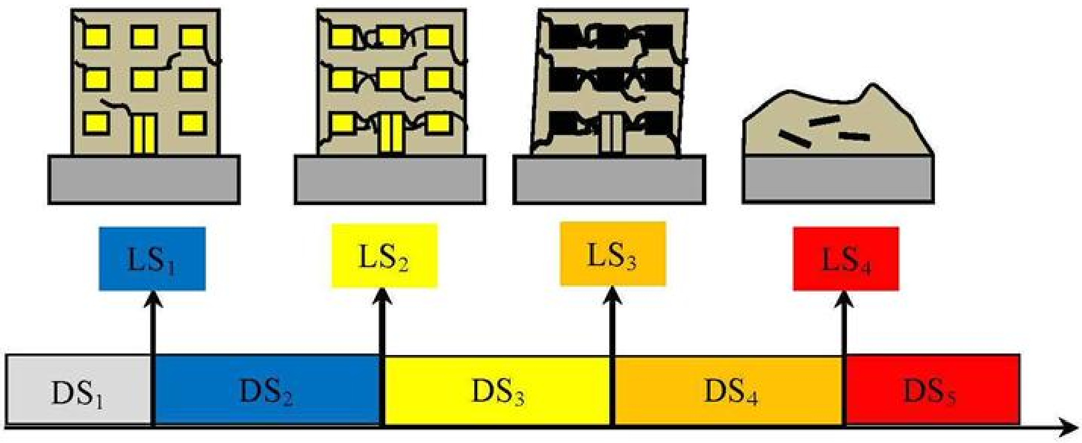


Fig 3-24 Limit state and damage state

The damage state of masonry structure is usually classified into five levels[83]: basic intact (DS1), slight damage (DS2), moderate damage (DS3), severe damage (DS4), and collapse (DS5), so the limit state should be classified into four levels: slight damage (LS1), moderate damage (LS2), severe damage (LS3), and collapse (LS4).

The deformation damage criterion is used to classify the damage class of masonry structures, and the inter-story displacement angle is mostly used as the deformation index for classification. Xiong Li-hong[84] (2004) gave reference mean values of maximum interstorey displacement angle limits ($\theta_{\max} \mid DS$) corresponding to different damage states by conducting a large number of tests on masonry walls, and the limit state points are shown in Table 3.7.

Table 3-7 Angular limits of interstorey displacement at limit state points

limit state	slight damage(LS1)	moderate damage(LS2)	severe damage(LS3)	collapse (LS4)
$\theta_{\max}$	1/1600	1/700	1/350	1/200

3.4.5 Methods for Analysis of Seismic Vulnerability of Structures

The seismic susceptibility of a structure is a prediction of structural damage under seismic action in the form of beyond probability[85], with the expression shown below:

$$P_{DV-IM}(0 \mid PGA) = \sum P_{DV-LS}(0 \mid C) P_{DV-IM}(Z > C \mid PGA) \quad \textbf{(3.6)}$$

where $P_{DV-IM}(0 \mid PGA)$ is the probability that the structure will reach its limit state under the action of a specific peak acceleration PGA, i.e., beyond probability; $\sum P_{DV-LS}(0 \mid C)$ represents the probability that the structure will reach its limit state at a specific seismic capacity C, i.e., structural capacity analysis; and $P_{DV-IM}(Z > C \mid PGA)$ is the probability that the structure will have a seismic response Z greater than the seismic capacity C under the action of a peak acceleration PGA, i.e., structural seismic demand analysis.

The relationship between the sample structural engineering demand parameters (EDP) and the ground shaking parameters (IM) satisfies Eq:

$$EDP = \alpha (IM)^{\beta} \quad \textbf{(3.7)}$$

According to Eq. (3.7), the median value of the structural seismic demand parameter $\hat{D}$ is set to obey an exponential relationship with the IM (peak acceleration PGA), i.e:

$$\hat{D} = \alpha (PGA)^{\beta} \quad \textbf{(3.8)}$$

Take logarithm on both sides of the equation:

$$\ln \hat{D} = \alpha + \beta \ln(PGA) \tag{3.9}$$

where α、β is the coefficient, which is obtained by regression of the probabilistic seismic demand model.

The probability of structural failure represents the conditional probability that the structural response D exceeds the structural demand capacity parameter defined for the damage stage under seismic actions of different intensities:

$$P_f = P(C \mid D < 1) = P(C - D < 0) \tag{3.10}$$

Let $Z = C - D$,the average value is $\lambda_Z = \lambda_C - \lambda_D$,The standard deviation is $\beta_Z = \sqrt{\beta_C^2 + \beta_D^2}$.

P_f can be expressed as:

$$P_f = P(Z < 0) = \int_{-\infty}^{0} \frac{1}{\beta_Z \sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{Z - \lambda_Z}{\beta_Z} \right)^2 \right] dZ = \Phi\left[-\frac{\ln \hat{C} - \ln \hat{D}}{\sqrt{\beta_C^2 + \beta_D^2}} \right] \tag{3.11}$$

Substituting Eq. (3-8) into Eq. (3-11), the stage-specific failure probability is:

$$P_f = \Phi\left[\frac{\ln(PGA)^{\beta} / \ln \hat{C}}{\beta_Z} \right] \tag{3.12}$$

When the susceptibility curve takes the spectral acceleration S_a(T1,5%) at 5% as the independent variable, β_Z taken as 0.4; when the susceptibility curve takes the PGA as the independent variable, β_Z taken as 0.5.The resulting curve is the seismic susceptibility curve of the model.

3.5 SUMMARY OF THIS CHAPTER

This chapter comprehensively and systematically introduces the theoretical methods of UAV inclined photogrammetry, the software and hardware systems adopted for experiments and their operation processes; it introduces the building geometric information (building exterior dimensions, door and window opening dimensions, structural type, and the number of floors) obtained based on the three-dimensional model, and at the same time it establishes the fuzzy reasoning model of the village and township masonry structure's hidden information based on the fuzzy reasoning theory and based on the empirical law to obtain the building's Finally, the IDA-based structural seismic vulnerability analysis method is comprehensively elaborated, including the incremental dynamic analysis process, the selection of ground shaking records, the selection of ground shaking intensity indexes and structural damage indexes, the determination of structural performance level and the structural seismic vulnerability analysis method. The theoretical framework and research methodology of this thesis are established to provide clear guidance and background for subsequent research work.

CHAPTER 4

RESULT AND DISCUSSION

4.1 THREE-DIMENSIONAL MODELLING OF BUILDINGS IN RURAL AREAS

4.1.1 Description of the Study Area and Acquisition of Image Data

The study area is located in a village and town in Tongren City, Guizhou Province, China, with the geographical coordinates ranging from 108°35′42″ to 109° 23′30″ east longitude and 27°49′40″ to 28°30′20″ north latitude, with a total area of about 0.05 square kilometres, as shown in Figure 4-1. This area is typically representative of rural Chinese villages and towns and consists primarily of 2-4 story masonry buildings, with a few wood-framed or 1-story brick structures. The construction dates of these buildings are roughly centred on the 1980s to the present, and were built by local villagers themselves. Information on the structural housing in the region is useful for assessing the effects of earthquakes on this building type and provides important data on structural improvements and seismic risk management. Therefore, detailed seismic vulnerability analyses and seismic performance studies in this region are of great value for scientific research and practical applications.

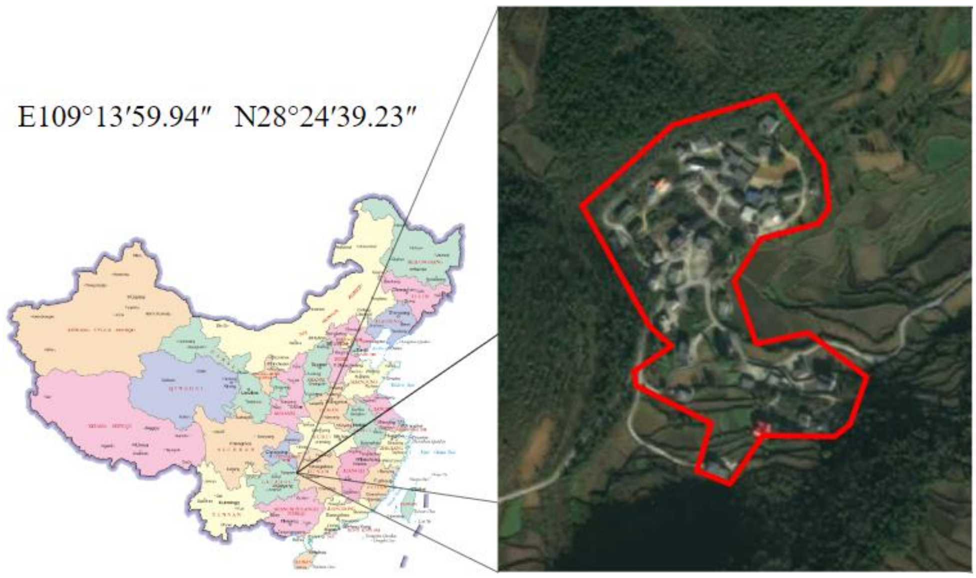


Fig 4-1 Schematic of the study area

In this study, the HuaCe V200 equipped with a RuiBo D2M half-frame tilt camera was used for tilt photogrammetry, and since the aircraft has a built-in 100Hz high-frequency differential module, no additional ground control points were required. Considering the height of the buildings in the study area and the ground resolution requirements, the flight parameters shown in Table 4-1 were used. After the flight, a total of 2610 images were obtained from five different viewpoints.

Table 4-1 Table of field flight parameters

Items	Parameters
Ground resolution	1.7cm
Course overlap	80%
Bypass overlap	70%
Flight height	Ground-mimicking flight, 100m

4.1.2 3D Model Building and Accuracy Verification

Through the steps of image data checking, POS data difference decomposition and 3D modelling by tilt photography, the aerial flight images were processed to generate a real 3D model of the study area as shown in Figure 4-2.

Fig 4-2 Schematic diagram of the live 3D model of the study area

In order to analyse whether the data accuracy of the 3D model can meet the requirements for use, the data in the experimental area were collected twice, and the secondary collection used the HuaCe i93 Pro GNSS receiver to measure the coordinates of the plane points of five ground feature points using the (GPS) RTK mode, and the points were uniformly distributed in the experimental area, and the specific distributions of the ground feature points (points A1-A5) are shown in Figure 4-3.

Fig 4-3 Distribution of checkpoints in the experimental area

In order to reduce the adverse effect of incidental error on the accuracy of the verification results when RTK collects the points, when collecting the coordinate data of the check (A1-A5) points, under the premise of good signals, the point-time coordinate smoothing is adopted for 20 times, and the true value of the points is the average coordinate value of 20 times of the actual measurements, so that according to the formula for calculating the error in the points (4.1), the error in the points between the check points and the corresponding three-dimensional model points is calculated, and the precision of its The statistical results are shown in Table 4.2.

$$m = \pm\sqrt{\frac{\sum_{i=1}^{n}(x_i - X) + \sum_{i=1}^{n}(y_i - Y)}{n}} \quad \textbf{(4.1)}$$

where (X,Y) are the 3D model extraction coordinates and(x_i , y_i)are the field acquisition coordinates.

Table 4-2 Experimental area checkpoint planar point midpoint error

Inspection point number	Median error of checkpoint position (m)
A1	0.027
A2	0.024
A3	0.018
A4	0.030

A5	0.042
Maximum point centre error of checkpoints	0.042
Average point centre error of checkpoints	0.028

A number of representative houses in the study area three-dimensional model imported into Cass 3D, through the software collection of uniformly distributed in the measurement area of the line drawing of multiple houses, and measure the distance between the inflection points of the house, as shown in Figure 4-4, and then in the field using a hand-held laser rangefinder, and then again to collect the length of the house side of the data and with the Cass software processed house house side of the data for a one-to-one comparison and verification of precision, precision results of the comparison table as shown in Table 4.3.

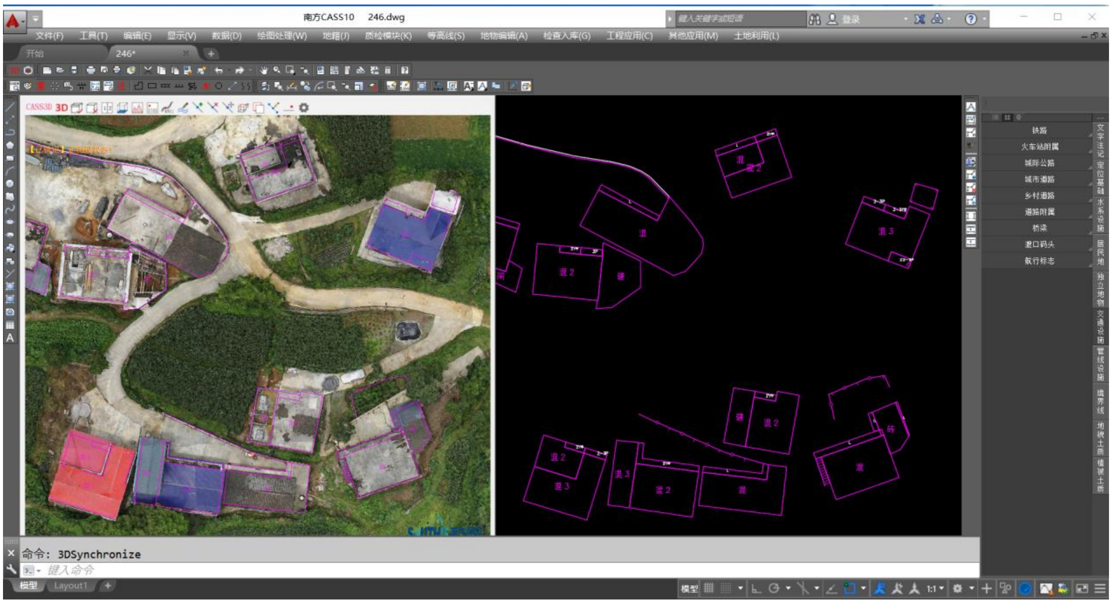


Fig 4-4 Distance verification accuracy model diagram

Table 4-3 Comparison of accuracy of house side lengths

Side number	serial number	Measured side length (m)	Detection side length (m)	Difference (m)
1	House 1	12.666	12.62	0.046
2		4.319	4.26	0.059
3		7.938	7.95	-0.012

4		1.009	0.98	0.029
5	House 2	12.294	12.27	0.024
6		8.349	8.34	0.009
7	House 3	10.958	10.98	-0.022
8		4.015	4.03	-0.015
9		4.194	4.16	0.034
10		1.796	1.85	-0.054
11	House 4	11.848	11.77	0.078
12		7.903	8.18	-0.277
13	House 5	3.37	3.38	-0.01
14		2.9	2.87	0.03
15		11.855	11.83	0.025
16		6.135	6.17	-0.035
Maximum difference in side length (m)				0.078
Average difference in side length (m)				0.047

Through the point and distance accuracy verification in Tables 4-3 and 4-4, the accuracy of the 3D model produced by UAV photogrammetry meets the accuracy standard, has reliability and accuracy, and can be used for subsequent experiments and research.

4.2 BUILDING INFORMATION ACQUISITION RESULTS

According to the building geometry information acquisition method based on 3D model in Chapter 3, a masonry structure house in the experimental area is selected for numerical simulation, the structure is a more typical masonry structure in the experimental area, which has two floors, a total length of 13m, a total width of 9m, and a storey height of 3.8 m. Based on the method of obtaining hidden information of the building in Chapter 3, the masonry structure shown in Figures 4-6 is located at the latitude of 29 degrees north, and the building size is 13m*9m. 13m*9m, and its wall information is predicted based on the above experience as follows: thickness of the external wall 240mm, the existence of a horizontally distributed internal wall, and two longitudinal internal walls with a thickness of

180mm, and its wall information is shown in Figure 4-6. Its structural plan is shown in Figure 4-5, and the masonry structure wall information is shown in Figure 4-6.

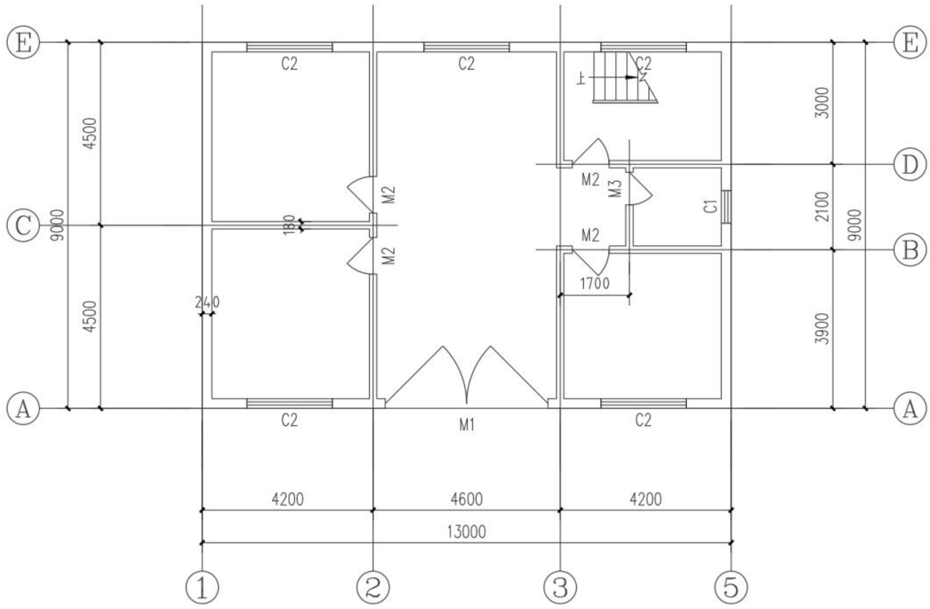


Fig 4-5 Plan of two-story village masonry structure

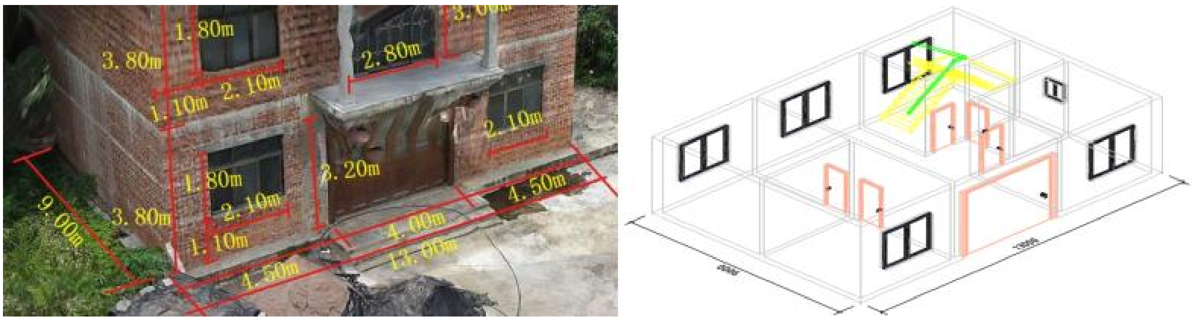


Fig 4-6 Prediction of wall information for masonry structures

The construction year of the building and the economic income at that time are inputted into the fuzzy inference model in chapter 3, for example: the construction year 2008, the economic income is 50,000 yuan, the input vector is [2008, 5], and the fuzzy inference result is [1.79, 0.45, 0.25], which corresponds to the output value of the material strength of 1.79, the output value of the constructional measures of 0.45, and the output value of the reinforcement of the wall of 0.25,. The results show that the building material strength is medium-low, without seismic construction measures, and unreinforced masonry.

4.3 IDA-BASED SEISMIC PERFORMANCE ANALYSIS OF MASONRY STRUCTURES

4.3.1 Numerical Modelling of Masonry Structures

4.3.1.1 Masonry Modelling Approach

Masonry is a combination of blocks and mortar, which belongs to two-phase composite materials with anisotropy. As the research on the bond and slip between these two materials is still immature, in finite element numerical simulation, two methods, separated modelling and integral modelling, are usually adopted according to the different research objects[86].

In masonry wall studies, separated modelling is usually adopted. This involves the creation of two solid models, block and mortar, which consider the material principal, the damage model, and the contact between them separately. Although the separated model provides a more accurate description of the force properties of the masonry structure, the use of more units, nodes and contact boundary conditions increases the complexity of the modelling, significantly increases the computational cost and makes it difficult to achieve convergence.

The macroscopic study of masonry structural models is applicable to holistic modelling. In monolithic modelling, the blocks and mortar are considered as a continuous homogeneous and isotropic whole, without considering material differences and contact slips. Integral modelling is relatively simple, and on the one hand, it can significantly accelerate the modelling speed and shorten the computation time, and on the other hand, the nonlinear model is easier to reach convergence. However, the study of the internal microscopic properties of masonry still needs to be further.

In this paper, the seismic performance analysis of village masonry structures is carried out by loading seismic waves and performing dynamic time course analysis, which belongs to the macroscopic damage study of structural models. Considering the computational cost and model accuracy, therefore, a holistic modelling approach is adopted to construct the masonry model.

In the nonlinear finite element analysis of masonry, if holistic modelling is used, the assumptions of continuity, homogeneity and isotropy need to be satisfied: firstly, the masonry is regarded as a continuous whole; secondly, it is assumed that the masonry materials are composed of the same kind of composition; and lastly, the masonry materials are regarded as isotropic homogeneous bodies[87].

4.3.1.2 Ontological Modelling

The three-line masonry model given in the SeismoStruct software was selected for the masonry ontology, as shown in Figure 4-7. This is a simplified uniaxial trilinear material model assuming no tensile forces and a residual strength plateau. In order to fully describe the mechanical properties of the material, five model calibration parameters are defined: average compressive strength; initial stiffness; post-peak stiffness; residual strength; and density.

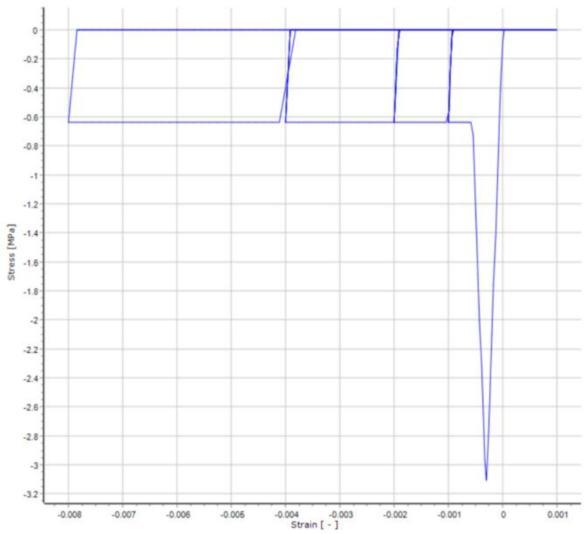


Fig 4-7 Masonry material intrinsic model

4.3.1.3 Material parameters

The modulus of elasticity of the masonry structure was calculated according to the expression of modulus of elasticity studied by Liu Guiqiu[88] et al:

$$E = 370 f_m \sqrt{f_m} \quad \textbf{(4.2)}$$

f_m is the average value of axial compressive strength of masonry.

The Poisson's ratio of masonry is generally calculated by the following formula after experimental study.

$$v = 0.14 + 0.3\left(\frac{\sigma}{f_m}\right)^4 e^{\frac{\sigma}{2f_m}} \quad \textbf{(4.3)}$$

Comprehensive related literature, it is determined that Poisson's ratio is generally between 0.14- 0.18. Therefore, Poisson's ratio in this paper is taken as 0.15 and kept constant.

According to the third chapter through the fuzzy inference model on the masonry structure material strength reasoning, corresponding to the material strength output value of 1.79, the results show that the strength of the building material for the lower middle, so the compressive strength is taken as 3.2mPa, the density of sintered ordinary brick masonry is taken as 1800kg/m³.

4.3.2 Finite Element Modelling Based on SeismoStruct

SeismoStruct is a finite element software package designed to predict the large displacement behaviour of structures under static or dynamic loading, taking into account the effects of geometric nonlinearity and material inelasticity. The software offers a wide range of material models, including concrete, steel, FRP and SMA, as well as a large library of 3D elements supporting a variety of predefined steel, concrete and composite section configurations. SeismoStruct provides engineers with powerful tools for analysing and evaluating the performance of structures under loading conditions such as earthquakes.

SeismoStruct is used to numerically simulate the masonry house in chapter 4.2, which has two floors, total length of 13 m, total width of 9 m, and storey height of 3.8 m. No ring beams and structural columns are provided, and its 3D model and numerical simulation finite element model are shown in Fig. 4-8. According to the "Code of Practice for Structural Load Specification of Buildings", the live load for the floors and staircases is 2.0kN/m², and that for the unoccupied roof is 0.5kN/m². is 0.5kN/m².

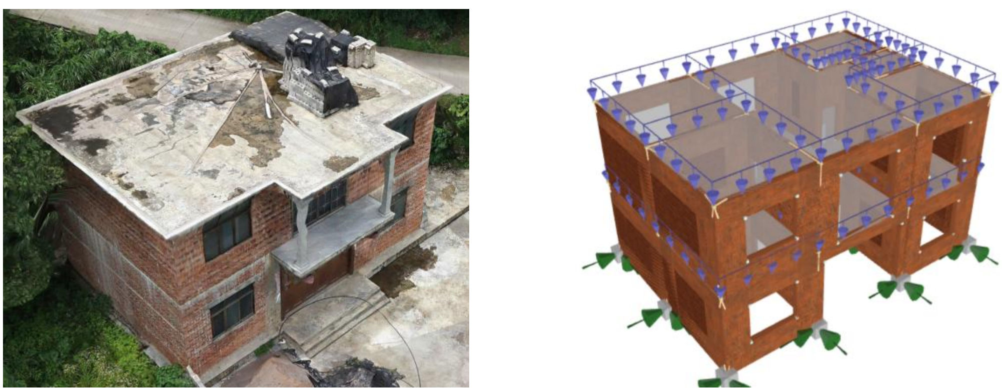


Fig 4-8 Schematic diagram of 3D model and finite element model

In the modal analysis of the 3D model, the first three order formations of the structure are translation and torsion in two directions respectively. Wang Guangjun et al. proposed an empirical formula for the fundamental frequency of masonry structures back in the 1980s[89]. Their empirical formula is.

$$T_1 = 0.0168(H + 1.2) \tag{4.4}$$

Where H is the height of the house (m).

According to equation (4-4), the empirical formula can be calculated to obtain the fundamental period of 0.1478, and the fundamental period obtained from the computational model is 0.1421, with an error of -3.88%, so it is considered that the model can simulate the elasticity performance of the actual structure better.

4.3.3 Cluster of IDA Curves for Multiple Ground Shaking Records

Since the structural response varies greatly under different seismic actions, a single IDA curve cannot completely predict the likelihood of the seismic response that the structure may suffer in the future. Therefore, in order to predict the seismic potential of the structure more comprehensively, this paper selects the 10 ground shaking records in Table 3.6 to carry out IDA analyses on single-story masonry structures, and compiles the 10 IDA curves obtained from the structure into IDA curve clusters, as shown in Figure 4-9.

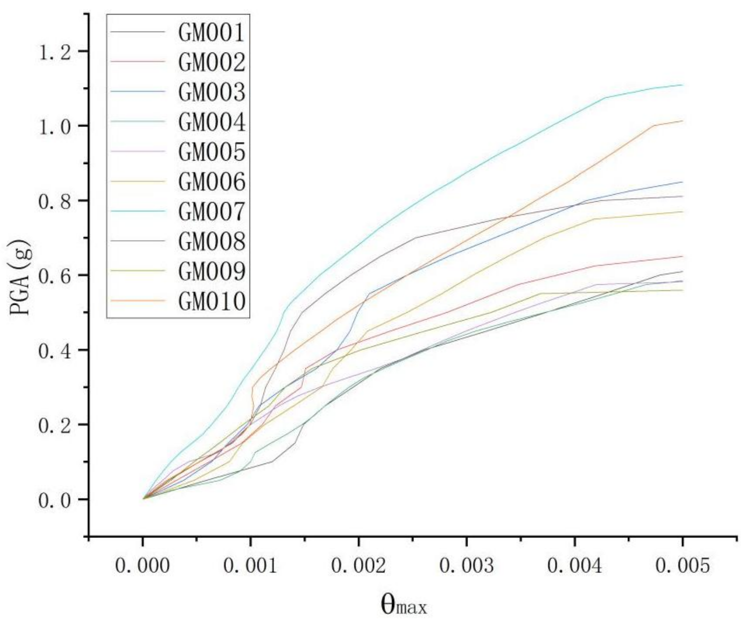


Fig 4-9 IDA curve clusters

The IDA curve clusters fully show the large effect of ground shaking uncertainty on the structural response: when the PGA is small, the IDA curves of each ground shaking are more or less the same, and with the increase of PGA, the dispersion of the curves is more and more obvious, and the maximum peak acceleration of ground shaking in the case of structural collapse reaches 1.1g in some cases, but only 0.6g in others, which is a huge difference between the two.

4.3.4 IDA-based Analysis of Structural Seismic Performance

By taking the mean value of the 10 IDA curves, the 50% IDA quantile line, i.e. the mean value curve, is drawn. The four limit state points corresponding to this mean value curve are shown in Figure 4-10, and the damage state of the structure can be predicted by knowing the earthquake-related information. The 16%, 50%, and 84% quantile curves at each seismic stage are shown in Figure 4-11, and these three curves reflect the performance and degree of dispersion of the structure under different peak acceleration earthquakes. The dispersion of the quantile curves reflects that the uncertainty of ground shaking effects has a large impact on this two-story masonry structure.

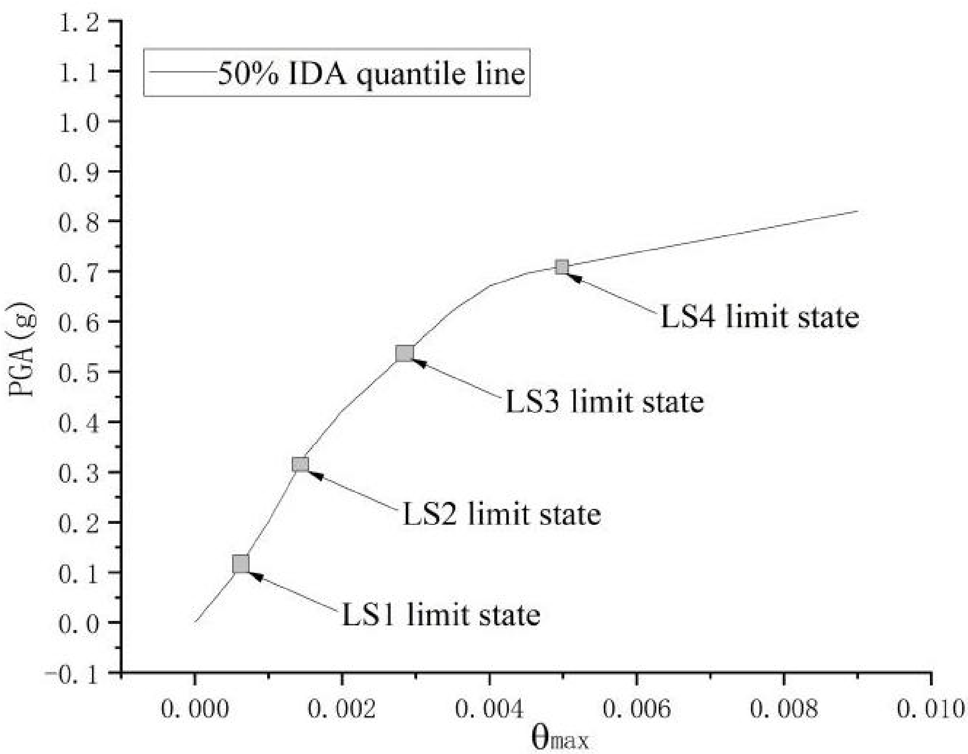


Fig 4-10 Four limit state points

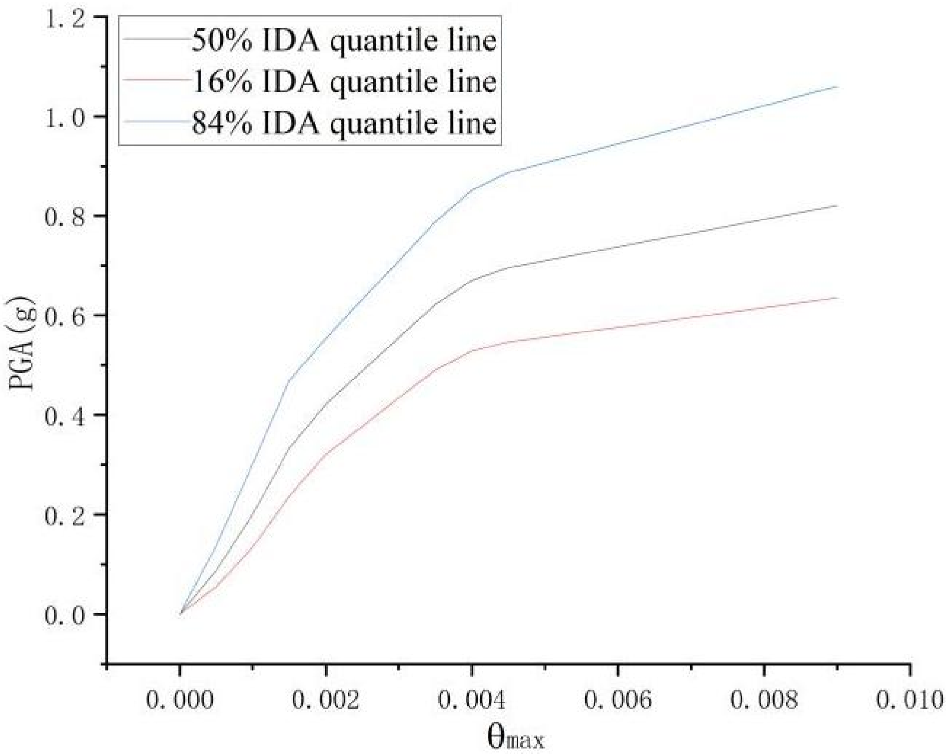


Fig 4-11 IDA curves for 16%, 50%, and 84% quartiles of the statistics

Through the analysis and comparison of the four limit state points in Fig. 4-10 and the 16%,50%,84% quantile IDA curves in Fig. 4-11, under the action of mean earthquake, when the peak ground shaking acceleration is less than 0.5g, the structure is in the elastic stage, and the interstorey displacements are relatively small; in the elasto-plastic stage, the stiffness decreases obviously with the increase of the PGA, and the slope of the IDA curves decreases obviously; after that, the plateau section of the IDA curves appears when the PGA reaches 0.7g, at which time, it can be said that the structure is in the elastic stage. PGA reaches 0.7g, the IDA curve appears a platform section, at this time, it can be considered that the structure reaches the collapse state.

4.4 ANALYSIS OF SEISMIC VULNERABILITY OF STRUCTURES

According to the steps of seismic vulnerability analysis in Chapter 3, the probability function of structural engineering demand parameters with respect to ground shaking parameters needs to be calculated. The logarithm of IM and DM is taken according to Eq. (3.7) and a linear regression analysis is performed. The regression line is shown in Figure 4-12, and the regression equation:

$$\ln(\theta_{\max}) = -5.4237 + 0.9157\ln(PGA) \quad \textbf{(4.5)}$$

Based on equation (4.5), the susceptibility curve is drawn as shown in Figure 4-13. The horizontal coordinate of the curve is the PGA and the vertical coordinate is the probability of exceeding P_f . With the gradual increase of PGA, the fragility curve as a whole shows an S-shape, with the slope increasing and then decreasing; from the LS1 curve to the LS4 curve, the susceptibility curve tends to flatten out, indicating that the structure has relatively good seismic performance after entering the plastic phase, i.e., the structure remains relatively stable in the face of seismic loading and is not prone to serious damage. Based on the susceptibility curves, the failure probability of the masonry structure is predicted and quantified for different damage states under small, moderate and large earthquakes.

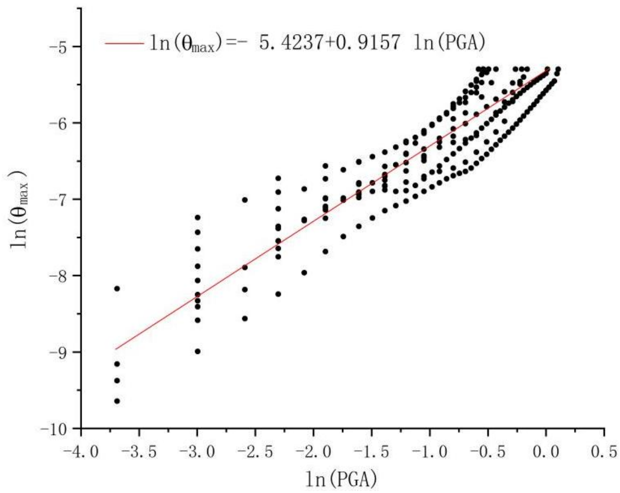


Fig 4-12 Seismic record regression analysis

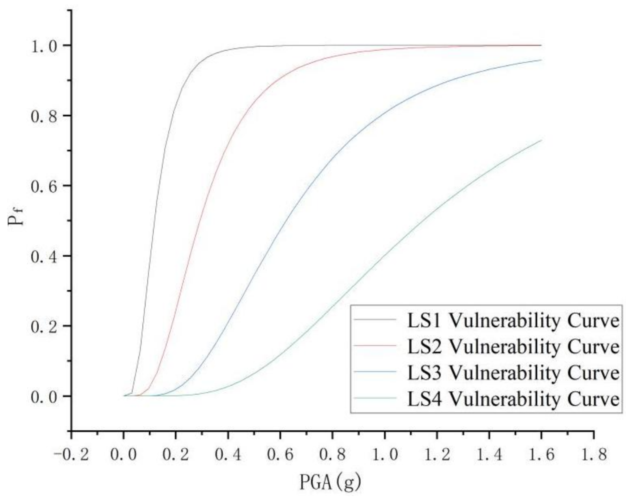


Fig 4-13 Vulnerability curves

The structure exceeding probability matrix is shown in Table 4.4. Under the action of a minor earthquake, the structure has a high probability of minor damage, and the probability of reaching the limit state LS1 is 66.18%. Under moderate seismic action, the probability of exceeding LS2 is 71.69%, and the structure shows more significant damage. The probability of failure of LS3 is 67.72 per cent under a major earthquake, indicating that the structure is seriously damaged, and the probability of failure of LS4 is 25.48 per cent, indicating that the structure is prone to collapse under the action of a major earthquake, proving that the structure can, due to the age of its construction, the low grade of the building materials and the absence of constructional measures, fail to satisfy the requirements for seismic defences, and that the structure should be strengthened in advance or take appropriate preventive measures.

Table 4-4 Structural transcendence probability matrix

Seismic Level	PGA(g)	LS1	LS2	LS3	LS4
Minor Shock	0.15	0.66183	0.11353	0.00501	1.16E-04
Medium Shock	0.4	0.98688	0.7169	0.20928	0.0271
Great Shock	0.8	0.99977	0.96756	0.67717	0.25481

4.5 SUMMARY AND DISCUSSION

Based on the theoretical foundation in Chapter 3, a village and town located in Tongren City, Guizhou Province, China, was selected as the study area, and a three-dimensional model was established and accuracy verified, in which a typical masonry structure was selected as the study object, and building information was obtained and numerical simulation was performed. In order to study the effect of uncertainty of ground shaking on the seismic vulnerability of the structure, incremental dynamic analysis (IDA) was carried out for the structure. The quantitative relationship between ground shaking and structural damage was analysed by carrying out multiple elasto-plastic dynamic time-course analyses of the structure, the seismic performance of the structure under different ground shaking effects was assessed from a probabilistic point of view, and the susceptibility curves were plotted. The following conclusions are drawn:

(1) The inclined image of the study area was acquired by UAV to establish a 3D model of the building in the village and town area and verify its accuracy; finally,

based on the 3D model, the geometric information of the building was acquired, and at the same time, based on the theory of fuzzy inference, a fuzzy inference model of hidden information of masonry structure in the village and town was established based on the empirical law, and the hidden information of the building was acquired. The results show that the method is feasible and can be used for large-scale building information extraction.

(2) The 50% IDA mean curve is drawn by checking the self-oscillation period of the finite element model structure and taking the mean value of 10 IDA curves. The results show that under different ground shaking effects, the analysis results and IDA curves are basically in line with the requirements both in terms of value and trend, which proves the reasonableness of IDA analysis of this finite element model.

(3) The IDA curves under different earthquakes show discrete nature, that is, the response of the structure under different ground shaking is different, therefore, if only one ground shaking is used for analysis, the result is accidental, and the IDA analysis chooses to use multiple ground shaking for the statistical analysis, which is more reflective of the response of the structure under the excitation of different ground shaking.

(4) Based on the results of IDA analysis, the seismic susceptibility curves of the structures were plotted, and the exceeding probabilities of the structures in the four limit states were calculated. The seismic susceptibility curves can better guide the future seismic damage assessment and seismic design of structures.

After earthquake damage prediction through UAV technology and IDA methods, communities can take a series of measures to better educate and prepare for them in order to raise seismic awareness and mitigate potential earthquake risks. First, communities can use the prediction results to develop detailed education programmes to communicate structural vulnerability and possible earthquake damage to residents. Through training sessions, symposiums, and outreach activities, communities can introduce residents to earthquake-resistant building techniques and ways to use locally available materials to raise awareness of the importance of retrofitting and strengthening masonry buildings.

Second, communities can promote the development and implementation of earthquake-resistant building codes and encourage the use of advanced building techniques and materials to improve the seismic performance of houses in rural areas. By working with a team of building professionals, communities can develop building standards that are tailored to local characteristics and economic conditions, and guide rural residents to safer building structures. This process requires the cooperation of government, professional organisations and community residents to ensure that standards are implemented and promoted.

In addition, communities can develop specific evacuation and emergency response plans using detailed images and 3D models provided by advanced technologies such as drones. By analysing the geometry of structures and potential vulnerabilities, communities can more accurately identify evacuation routes and safety zones, improving the efficiency of emergency response in the event of a disaster. These plans can be implemented through training exercises and regular simulation drills to ensure that community residents are familiar with response procedures and to enhance the emergency response capacity of the community as a whole.

Community participation plays a key role in implementing these measures. Education and training programmes can be facilitated through the establishment of community committees and volunteer teams. Community participation not only enhances the cohesion of the entire community, but also provides suggestions for improvement in practice and promotes the continuous improvement of earthquake preparedness. Through active community participation and education, rural areas can better understand potential earthquake risks and take practical measures to improve overall earthquake resilience.

CHAPTER 5

CONCLUSIONS AND OUTLOOK

5.1 CONCLUSION

In order to carry out seismic damage prediction of masonry houses in village and township areas, this paper is based on drone tilt-photography technology for building information acquisition, and then incremental dynamic analysis (IDA) to explore the effect of ground shaking uncertainty on the seismic susceptibility of the structure, and the following work is carried out: firstly, a typical village and township area which is in Guizhou of China is selected to carry out drone tilt-photography image acquisition to complete the establishment of a real-life 3D model and The accuracy is verified; secondly, the appearance information of the building (appearance size, structure type, number of floors, etc.) is obtained through 3D mapping software and image recognition based on convolutional neural, and the hidden information of the building (material strength, wall information, construction measures, etc.) is obtained based on empirical and fuzzy reasoning; lastly, based on the obtained information of the building, a typical two-storey masonry structural model in the study area is selected for the SeismoStruct finite element modeling, incremental dynamic analysis (IDA), by comparing the difference of IDA curves under different seismic effects, analyzing the effect of ground shaking uncertainty on the dynamic response of the structure, and drawing the susceptibility curve, predicting and quantifying the failure probability of the masonry structure under the action of small, medium and large earthquakes in different damage states.

The conclusions drawn in this paper are as follows:

(1) Image data acquisition is carried out through UAV tilt photography technology to establish a real-life 3D model, which has high model accuracy and practicality. It can greatly enhance the investigation efficiency and reduce the labour cost. The advancement of UAV technology provides an efficient and precise method for strengthening earthquake preparedness and reducing losses in earthquake-prone areas.

(2) It is proposed to obtain the building geometric information based on the 3D model, and at the same time, based on the fuzzy inference theory, establish the fuzzy inference model of the hidden information of village masonry structure based on the empirical law, and obtain the hidden information of the building. The method is feasible and can be used for large-scale building information extraction. It effectively solves the problem of high difficulty and low efficiency in acquiring building information of masonry structures in villages and towns.

(3) Through the IDA analysis of typical masonry models, the IDA curve clusters under 10 different seismic actions are obtained, and the results fully prove that the ground shaking uncertainty has a large impact on the structural response, and the impact becomes more and more obvious with the increase of PGA.

(4) The synergy between UAV technology and incremental dynamic analysis (IDA) plays a key role in improving the accuracy and depth of seismic vulnerability assessment. This integration simplifies the identification of structural vulnerability and provides an important basis for understanding the seismic vulnerability of masonry structures. There are a number of measures that communities can take to better educate and prepare themselves based on the results of seismic hazard prediction to increase seismic awareness and mitigate potential seismic risks, for example, high modulus of elasticity, high tensile strength, and low deadweight of masonry materials should be ensured as much as possible when conditions allow, and high grade mortar as well as concrete blocks can be used to ensure seismic performance of masonry structures.

5.2 OUTLOOK

In this paper, information acquisition and incremental dynamic analysis (IDA) of building objects are based on UAV tilt-photography to study the effect of uncertainty in ground shaking action on the seismic vulnerability of structures, but there are some shortcomings due to the limitation of time and conditions, which need to be improved in the future. It can be improved in the following aspects next:

(1) This paper is based on the three-dimensional model created by the UAV tilt photography technology to extract the information of building objects, which is limited and unable to accurately obtain the hidden information of the structure, and

can be followed up by combining with the radar point cloud technology to optimise the technology of obtaining information of buildings.

(2) This paper only predicts the seismic damage of a single structure, although the analysis results are accurate, but the procedure is more complicated, and the analysis method can be optimised in the future, so that the seismic vulnerability of group buildings can be quickly analysed, and rapid seismic damage prediction can be realised for regional buildings.

(3) In this paper, we only study the effect of uncertainty of ground shaking action on the seismic vulnerability of structures, while the uncertainty of structural parameters cannot be neglected in vulnerability research. Especially under strong seismic effects, the nonlinearity of the structure will be significantly enhanced, which amplifies the effect of structural parameters on the susceptibility, so it is necessary to correct the susceptibility curve considering the structural uncertainty in the analysis of the seismic susceptibility of the structure, in order to better respond to the seismic susceptibility of the structure.

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Research Article

Information Acquisition and Seismic Damage Prediction of Masonry Structures in Rural Areas Based on UAV Inclined Photogrammetry

Chao Kong[1],Arthit Petchsasithon [2*]

[1] Master's degree student,School of Engineering,King Mongkut's Institute of Technology Ladkrabang,Bangkok,10520,Thailand.
https://orcid.org/0009-0004-4746-1303

[2] Assistant Professor,School of Engineering,King Mongkut's Institute of Technology Ladkrabang,Bangkok,10520,Thailand.
https://orcid.org/0000-0002-2401-6969

*** Corresponding Author:** arthit.pe@kmitl.ac.th

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ABSTRACT

This study focuses on assessing the seismic vulnerability of rural masonry structures in China through an innovative approach using incremental dynamic analysis (IDA) and UAV Positioning (POS) analysis. The method involves a fusion of advanced UAV oblique photography technology for extensive data acquisition and the incorporation of IDA analysis to precisely forecast seismic damage. Targeting the prevalence of masonry structures in rural China, the research seeks to tailor effective seismic risk mitigation strategies. The methodology revolves around capturing detailed imagery of rural masonry structures using high-resolution cameras mounted on Unmanned Aerial Vehicles (UAVs). The acquired data undergoes meticulous processing to extract architectural features and structural conditions. Moreover, the study harnesses CHC Geomatics Office (CGO) dynamic post-processing software for UAV POS data difference decomposition, refining the precision of the relative position between the UAV and the reference station. The results offer a methodology for studying the seismic vulnerability of masonry structures in village areas in China amidst the uncertainty of ground shaking. Additionally, the integration of UAV tilt-photography enhances investigation efficiency, minimizing manpower and economic costs. This amalgamation facilitates a more effective response to seismic risks. The implications of this IDA and UAV POS analysis are profound, offering indispensable information for crafting targeted seismic preparedness and risk mitigation strategies. Policymakers, urban planners, and disaster management authorities stand to gain significant insights from this data-driven approach, which extends beyond China, contributing to global seismic engineering and disaster resilience efforts. Ultimately, this research serves as a pivotal resource, safeguarding rural communities by providing a refined methodology to assess seismic risks and fortify masonry structures, fostering a more resilient and secure built environment in seismic-prone regions.

Keywords: Masonry structure, building information acquisition, seismic damage prediction, UAV inclined photogrammetry, incremental dynamic analysis.

INTRODUCTION

Seismic events have had major effects on communities and infrastructure in many parts of the world. This makes it essential to have effective methods for assessing and reducing seismic risk around the world (Freddi et al., 2021). This is especially clear in rural China, where the high number of brick buildings has been a problem for a long time. The preceding research conducted by Yating Zhang et al. (2022) has unequivocally demonstrated the inherent vulnerability of these edifices to the destructive forces unleashed by seismic events. The Wenchuan earthquake of 2008, which struck the province of Sichuan, stands as a poignant testament to the sheer devastation that earthquakes can unleash upon the rural landscapes (C. Wang et al., 2021). In these regions, where brick structures abound and the specter of earthquakes looms ominously, the imperative arises for novel methodologies to swiftly and precisely gauge and mitigate the perils of seismic activity (Aydogdu et al., 2023).

Unmanned Aerial Vehicles (UAVs), or drones, have

AUTHOR BIOGRAPHY AND PROCEDURES

Name	Mr. Chao Kong
Date of Birth	Jan 16, 1996, in China
Address:	ChangGui Town, Wuxi County, Chongqing City 405804
Email:	2211514732@qq.com/64601193@kmitl.ac.th

Educational Background:

2020:	Bachelor of Engineering in Civil Engineering, Chongqing University of Arts and Sciences.
2024:	Master of Engineering in Civil Engineering, King Mongkut's Institute of Technology Ladkrabang.

Work Experience and Research Achievements:

Work experience and research results:

July 2020-December 2020: counsellor of Sichuan Hope Automobile Technician College;

January 2021-September 2021: Staff of Chongqing Spice Surveying and Mapping Technology Co;

October 2021 - December 2023: Project Manager, Guangzhou Array Geographic Information Technology Co.

Journal:

2021, July : Published the journal "Research on the Development Trend and Connotation of Civil Engineering for Intelligent Construction";

2019, August : Publication of the journal "Design,Fabrication and Analysis of Large span Spatial Structure Model".

Patent:

2019, April : Authorized utility model patent "A kind of constrained masonry structure house construction teaching model";

2019, April : Authorized utility model patent "A block model, unconstrained masonry structure and house building";

2019, June : Authorized utility model patent "Demonstration device for loading experiments on construction beams";

2019, June : Authorized utility model patent "Teaching model of architectural beam structure".