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Documentation through digital methods and seismic soil classification for preserving built heritage

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ABSTRACT

Introduction. The Indian subcontinent is renowned for its numerous structural heritage wonders, which reflect the region's rich cultural history. To preserve the historical significance of these marvels, systematic documentation through digitization is essential. Utilizing advanced techniques like photogrammetry and 3D modeling, surpassing traditional methods, ensures precise and accurate data capture, processing, and representation of heritage information. Combining digital documentation with seismic surface wave techniques to characterize subsoil seismic velocities is vital for sustainable heritage conservation, particularly against natural hazards such as earthquakes. This study focuses on the digital documentation of the Post Master General (PMG) Office in Trivandrum, an iconic structure celebrated for its cultural and architectural significance.
Materials and methods. Close-range photogrammetry was employed to capture and analyze images and Multichannel Analysis of Surface Waves (MASW) tests were conducted at the PMG office site to estimate soil shear wave velocities.
Results. From the photogrammetric images, 3D models, 3D rendered walkthroughs, and 2D line drawings were created resulting in the as-built documentation of the built heritage. These outputs serve as digital records, enhancing visual perception and aiding in the extraction of semantic information for heritage conservation and management. Additionally, the study attempts to characterize subsoil properties by developing a shear wave velocity (*Vs*) profile from the MASW test results which is crucial for seismic response analysis. The paper also suggests optimal parameters for data collection to effectively characterize the study area.
Conclusions. Thus, this paper presents a comprehensive approach for documenting the built heritage along with assessing and managing their seismic risk combining advanced digital documentation techniques with surface wave methods.

KEYWORDS: digital documentation, built heritage, subsoil characterization, heritage management, 3D models, surface wave methods, photogrammetry, shear wave velocity

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Цифровое документирование и классификация грунтов по реакции на сейсмические воздействия для сохранения культурного наследия

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АННОТАЦИЯ

Введение. Индостан славится многочисленными чудесами архитектурного наследия, которые отражают богатую культурную историю региона. Систематическое документирование с помощью оцифровки необходимо для сохранения исторического значения таких архитектурных объектов. Использование передовых технологий, таких как фотограмметрия и трехмерное моделирование, превосходящих традиционные методы, обеспечивает точный и аккуратный сбор данных, обработку и представление информации о наследии. Сочетание цифровой документации с методами поверхностных сейсмических волн для определения скоростей распространения сейсмических волн в недрах земли имеет важное значение для сохранения наследия, особенно в условиях таких стихийных бедствий, как землетрясения. Данное исследование посвящено цифровой документации Главного почтового управления (ГПУ) в Тривандруме — культового сооружения, известного своей культурной и архитектурной значимостью.

Материалы и методы. Фотограмметрия с близкого расстояния использована для получения и анализа изображений, многоканальный анализ поверхностных волн осуществлен на территории офиса ГПУ для оценки скорости поперечных волн в грунте.
Результаты. На основе фотограмметрических снимков созданы 3D-модели, 3D-визуализации и 2D-чертежи, что позволило получить исполнительно-техническую документацию по объектам культурного наследия. Такие результаты служат цифровыми записями, улучшая визуальное восприятие и помогая в извлечении семантической информации для сохранения наследия и управления им. Кроме того, в исследовании предпринята попытка охарактеризовать свойства грунта путем создания профиля скорости поперечной волны (*Vs*) на основе результатов многоканального анализа поверхностных волн, что имеет решающее значение для анализа сейсмической реакции. Предложены оптимальные параметры сбора данных для эффективного установления характеристик исследуемой территории.
Выводы. Представлен комплексный подход к созданию документации для объектов культурного наследия, а также к оценке и управлению сейсмическим риском, сочетающий передовые методы цифровой документации с методами поверхностных волн.

КЛЮЧЕВЫЕ СЛОВА: цифровое документирование, историческое наследие, характеристика недр, управление наследием, 3D-модели, методы поверхностных волн, фотограмметрия, скорость поперечной волны

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INTRODUCTION

India has a rich heritage, culture, and history with an abundance of art and architecture and ranks sixth in the world being the home of the 40 most UNESCO heritage sites. In addition, the country has another 49 sites on the tentative list and nearly 3,700 centrally protected monuments/sites under the Archaeological Survey of India (ASI) attracting many domestic and international visitors each year. In recent years, heritage tourism has grown rapidly but it has yet to realize its full economic potential. Due to the increase in urbanization, there is a need for reuse of more of the heritage buildings. The need for the conservation and protection of heritage sites and buildings is well understood by the experts and stakeholders to retain its originality and cultural significance. So the Government of India has taken various initiatives and issued guidelines for the architects and engineers concerning conservation and restoration of heritage sites. The first step in any conservation and restoration project is to collect the information and assess its physical condition before any action or intervention that causes the change in the objects/built environment. Hence, heritage sites and buildings have to be well documented in the long-term interest of society. Moreover, the integrity and functionality of these heritage structures face numerous threats, including environmental factors, natural hazards, fire, vandalism, urban development, and aging. As the heritage buildings are unreinforced masonry structures, they remain vulnerable to natural disasters, especially earthquakes. To safeguard these structures, it is essential to conduct seismic risk assessments at cultural sites, which are critical for the preservation and retrofitting efforts needed to make these heritage buildings earthquake-resilient.

Heritage documentation is a continuous process enabling maintenance, monitoring, and providing information for conservation and management. In this regard, the use of digital technologies in digitization, preservation, and extraction of semantic information is essential for heritage conservation and management. Pertaining to their different architectural styles, most heritage buildings have complex (non-parametric) geometries which make their digital documentation a very time-consuming process when done through conventional techniques. To achieve accuracy and precision in data capturing, processing, and representation of heritage information, it is necessary to use the latest techniques, such as photogrammetry and 3D modeling techniques that exceed conventional methods [1–8]. In addition, these data and information will serve as a digital record as a memory to future generations for understanding and reconstruction process if required.

To assess the seismic risk of built heritage, understanding local site conditions is crucial, as the amplification of earthquake ground motion at the bedrock level is significantly influenced by the properties of the overlying soil. Shear wave velocity (*Vs*) is a key parameter for evaluating site amplification and estimating the stiffness of a site, which is essential for predicting ground response during seismic events. The National Earthquake Hazards Reduction Program (NEHRP) classifies sites based on local conditions, particularly the *Vs* of the top 30 m of soil, to enhance the seismic resilience of structures and reduce earthquake damage risk. Various surface wave methods have been developed for near-surface characterization and shear wave velocity (*Vs*) measurement, employing different testing configurations, processing techniques, and inversion algorithms. Among these, Spectral Analysis of Surface Waves (SASW) and Multichannel Analysis of Surface Waves (MASW) are the most widely used. The MASW test is the most commonly used seismic method for geotechnical characterization of near-surface materials [9–14]. Therefore, conducting in-situ tests at heritage sites to estimate the shear wave velocity profiles of the subsurface is essential for understanding site effects during earthquakes.

This study focuses on the digital documentation and creation of a 3D model of the Post Master General (PMG) office, an iconic heritage structure in Trivandrum known for its cultural and architectural significance, using close-range photogrammetry technique. The resulting digital model serves as a detailed record, providing valuable information to support the conservation and management of this historic building. To conserve and preserve the PMG office building against earthquakes, an attempt has been made to characterize the soil properties at the site. This was achieved by carrying out surface wave analysis using Multi-Channel Analysis of Surface Waves (MASW) test equipment. The shear wave velocity profiles obtained from these tests are essential for seismic site classification, which is a critical component in site response analysis.

STUDY AREA

The study is carried out at the Post Master General (PMG) office located at PMG junction, Trivandrum, Kerala, which stands as one of the iconic structures in the city affirming its cultural and architectural richness as shown in Fig. 1. The building, which once served as the original campus of the College of Engineering, Trivandrum, has a significant historical background. The college was founded on July 3rd, 1939, originally occupying an area of approximately 5,200 square meters. In the late 1950s, with the creation of the Directorate of Technical Education, the administrative control of the college was transferred directly to the government. This transition marked a new era for the institution, culminating in the relocation of the college in 1960 to its current expansive campus, which spans 101 hectares (about 250 acres) in Kulathoor. The former college building, with its historical significance and architectural grandeur, now serves as the office of the Postmaster General.

This two-storey structure is a remarkable blend of architectural styles, combining Indigenous elements with grand neoclassical designs. It also incorporates the distinctive Indo-Saracenic aesthetic, a style that emerged during the British colonial period, reflecting a fusion of traditional Indian and Islamic architecture with European influences. This blend of styles not only showcases the building's historical importance but also highlights its role as a symbol of the city's architectural and cultural diversity.

MATERIALS AND METHODS

Digital documentation

The Handbook of Conservation of Heritage Buildings published by the Central Public Works Department, Government of India defines 'Conservation' as all the processes of looking after a place to retain its historical and/or architectural and/or aesthetic and/or cultural significance [15]. To accomplish holistic heritage conservation, advanced tools and techniques for storing, sharing, and managing information on the past, present, and future status of heritage buildings are essential [16]. The digital photogrammetric technique, facilitated by the advanced software, allows the use of diverse image types obtained using Charge Coupled Devices (CCD) cameras or scanned images [6, 17].

In this study, a close-range photogrammetric technique has been employed to comprehensively document the built heritage in a digital format. This approach offers numerous advantages, including a seamless flow of data, stringent quality control, automation potential, and favourable geometric accuracy, making it an ideal choice for capturing intricate architectural details. Various image processing methods are utilized, tailored to the specific characteristics of the heritage structure being documented. The workflow for generating a three-dimensional (3D) model of the building is outlined in Fig. 2. The process begins with the systematic capture of images of the structure's superstructure, encompassing both the exterior and interior of the building, using high-resolution DSLR cameras. To ensure optimal accuracy in the 3D reconstruction, the photographs are taken with an overlap of 80–85 % between successive images, as

Fig. 1. Study Area — Post Master General (PMG) office, Trivandrum, Kerala, India

Рис. 1. Район исследования — офис главного почтового управления (ГПУ), Тривандрум, штат Керала, Индия

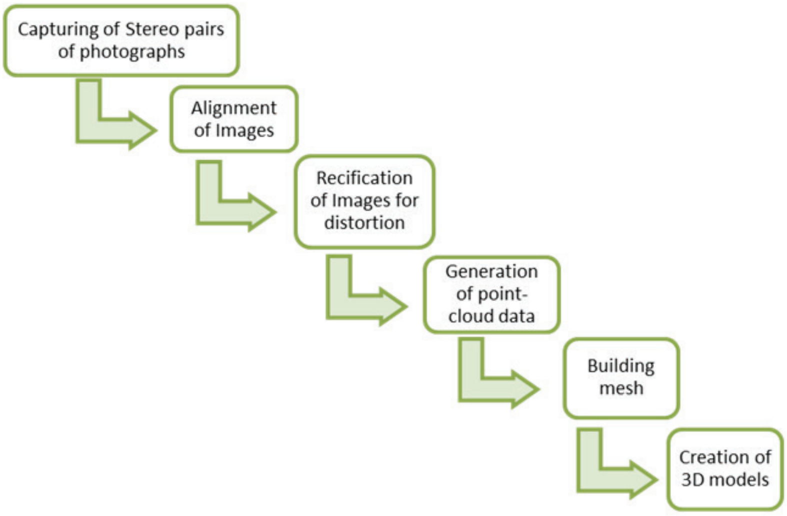


Fig. 2. Process of generating a three-dimensional model from images

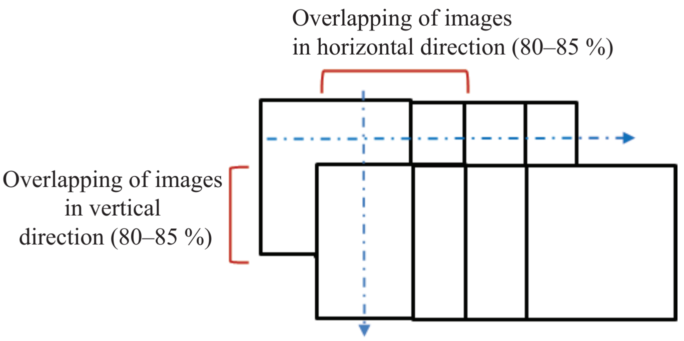
Рис. 2. Процесс генерации трехмерной модели на основе изображений

illustrated in Fig. 3. This overlap is crucial for maintaining continuity and consistency in the photogrammetric process.

Following the capture, the images undergo a meticulous alignment and rectification process. This step is essential as some images may be tilted or scaled inconsistently due to variations in the camera angles or environmental factors during photography. A minimum of four control points is used to accurately align and rectify these images, ensuring that they are correctly oriented and scaled relative to each other. Once the images are rectified, they are processed using specialized photogrammetric software. In this stage, all the photographs are collectively treated as a bundle and undergo a comprehensive adjustment process to correct any distortions. This adjustment is crucial for accurately deriving three-dimensional (3D) coordinates, leading to the generation of high-accuracy point cloud data (Fig. 4).

SITE CHARACTERIZATION — SURFACE WAVE METHOD

Our historical heritage requires special safeguards against natural disasters, especially seismic risk as it is most dangerous for historical buildings due to their vulnerability to seismic response. Also, Trivandrum city falls under Zone III according to the seismic zone classification by the Bureau of Indian Standards [18]. The city



a) plan for capturing stereo photographs

b) horizontal overlap between successive photographs

c) overlap between photographs taken in a vertical direction

Fig. 3. Geometry of photographs configured to produce stereo pairs

Рис. 3. Геометрия фотографий, сконфигурированных для получения стереопар

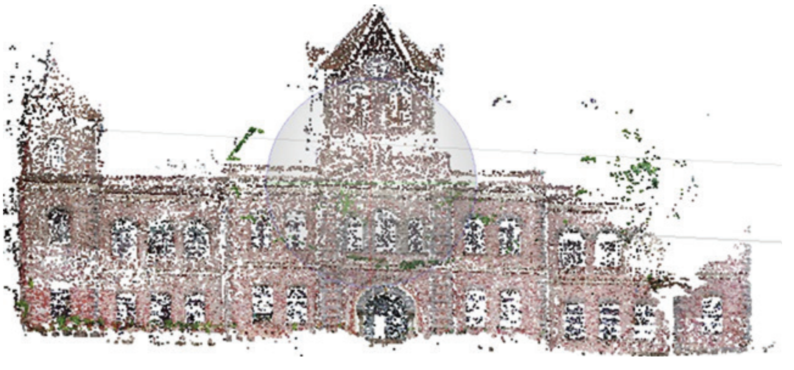


Fig. 4. Point cloud data generated after bundle adjustments

Рис. 4. Данные облака точек, полученные после корректировки

faces susceptibility to moderate earthquakes primarily because of rapid urbanization and the proliferation of buildings. Hence, characterizing the subsoil properties mainly shear wave velocity is crucial as it is an important parameter used to evaluate near-surface stiffness which is a vital property for studies in earthquake geotechnics. The most widely used surface wave methods for near-surface characterization and measurement of shear wave velocity (*Vs*) are Spectral Analysis of Surface Waves (SASW) and Multichannel Analysis of Surface Waves (MASW) tests. The MASW is a more efficient method for characterizing the shallow subsurface properties [9, 13]. This method is based on the analysis of the dispersive properties of Rayleigh waves to estimate the *Vs* of the near-surface deposits.

Multichannel Analysis of Surface Waves Tests

In the present study, the active MASW tests with a linear array of receivers are conducted at selected locations in the study area to estimate the *Vs* profiles. The entire procedure of the MASW test consists of three steps: (i) Acquiring multichannel field records (or shot gathers), (ii) Extracting dispersion curves (one from each field record), and (iii) Inverting the dispersion curves to obtain the one-dimensional (1D) *Vs* profiles (one profile from one curve) [9, 10]. Test locations were carefully chosen to ensure minimal surface interruptions, such as buildings, blocks, or ditches, which could affect data quality. The test locations are spread out uniformly covering the entire study area for extracting reliable subsurface information.

The MASW test setup includes a source, receiver, and an acquisition system as depicted in Fig. 5. The motion is generated when an 8 kg sledgehammer (source) hits against the metal base plate. The motion is generated when an 8 kg sledgehammer (source) hits against the metal base plate. The corresponding signals are detected simultaneously by 4.5 Hz frequency geophones arranged in a linear array at equal spacing. The signals captured by these geophones were transmitted to a 24-channel Geode, where they were recorded and stored in a portable computer as wiggle plots (Fig. 6). An illustration of the field experimental setup, along with the raw data captured during the tests, is presented in Fig. 6.

The successful capture of the ground roll in seismic recordings highly depends upon the proper arrangement of the test setup in the field and the selection of appropriate acquisition parameters [19–21]. Table 1 lists the general MASW acquisition parameters adopted

Fig. 5. MASW test setup — Equipments

Рис. 5. Установка для многоканального анализа поверхностных волн — оборудование

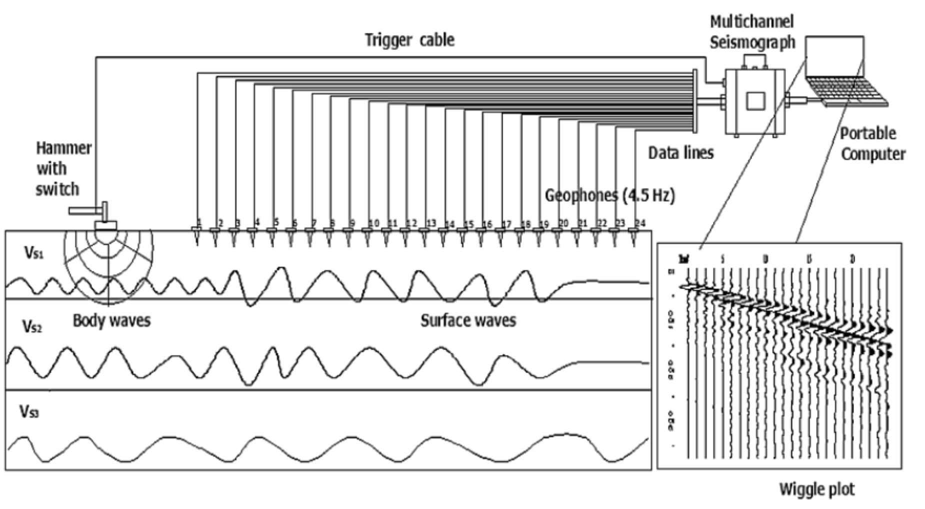


Fig. 6. Schematic diagram of MASW experiment setup

Рис. 6. Схема экспериментальной установки многоканального анализа поверхностных волн

Table 1. Field data acquisition parameters of MASW test

Табл. 1. Параметры сбора полевых данных для многоканального анализа поверхностных волн

Parameter Spread configuration	Setting Linear
Spread length	12 m
Geophone interval	0.5 to 1 m
Total number of geophones	12 to 24
Geophone type	4.5 Hz vertical geophones, with base plates for surveys on paved ground
Shot locations	Nine. One shot at off-ends from the middle and both end at a distance equaling geophone interval, One shot at off-ends at both ends at a distance of 1, 2 and 5 m from the first geophone
Source-offset	0.5 m perpendicular to the survey line
Source equipment	Sledgehammer (8 kg) and strike plate
Trigger	Hammer switch taped to sledgehammer handle and connected to seismograph trigger port and manual triggering in some cases
Specimen interval	0.125 ms
Record length	2 s
Stacking	3 Stacks at each shot

Fig. 7. MASW test setup in front and side of the PMG office building

Рис. 7. Испытательная установка многоканального анализа поверхностных волн спереди и сбоку от офисного здания главного почтового управления

during this survey. At each location, the test is repeated with shots at the beginning, middle, and end of the receiver array line, ensuring the consistency and reliability of the acquired field data. It should be noted that three sets of data were stacked to improve the Signal/Noise (S/N) ratio of the data. Also, the geophones located far from the source were set to the highest gain to improve the strength of the signal. The MASW survey conducted to obtain the shear wave velocity profile in front and side of the PMG office building is shown in Fig. 7.

A specimen waveform of the acquired data i.e. wiggle plot with the shot location at –0.5 m away from the first geophone is shown in Fig 8. Each of these waveforms indicates a connected channel/Geophone and their distance from the first geophone is marked as the ordinate label. Since this waveform corresponds to the shot position 1, it can be seen that the first geophone has received the first arrival initially and the time taken by the waves to reach the other geophones can be observed from the arrival of the first breaks in the subsequent geophone readings. The collected data are then stacked to improve the S/N ratio. The signals are then filtered to remove any ambient noise. These signals are then transformed into the frequency–phase velocity domain to obtain the dispersion curve. Fig. 9 shows the dispersion curve generated from the waveform data obtained (as shown in Fig. 8). This curve reveals the dominant phase velocities versus frequency and is an indicator of the variation of the body wave velocities with the depth. Further, on applying inversion techniques, the variation of the shear wave veloc-

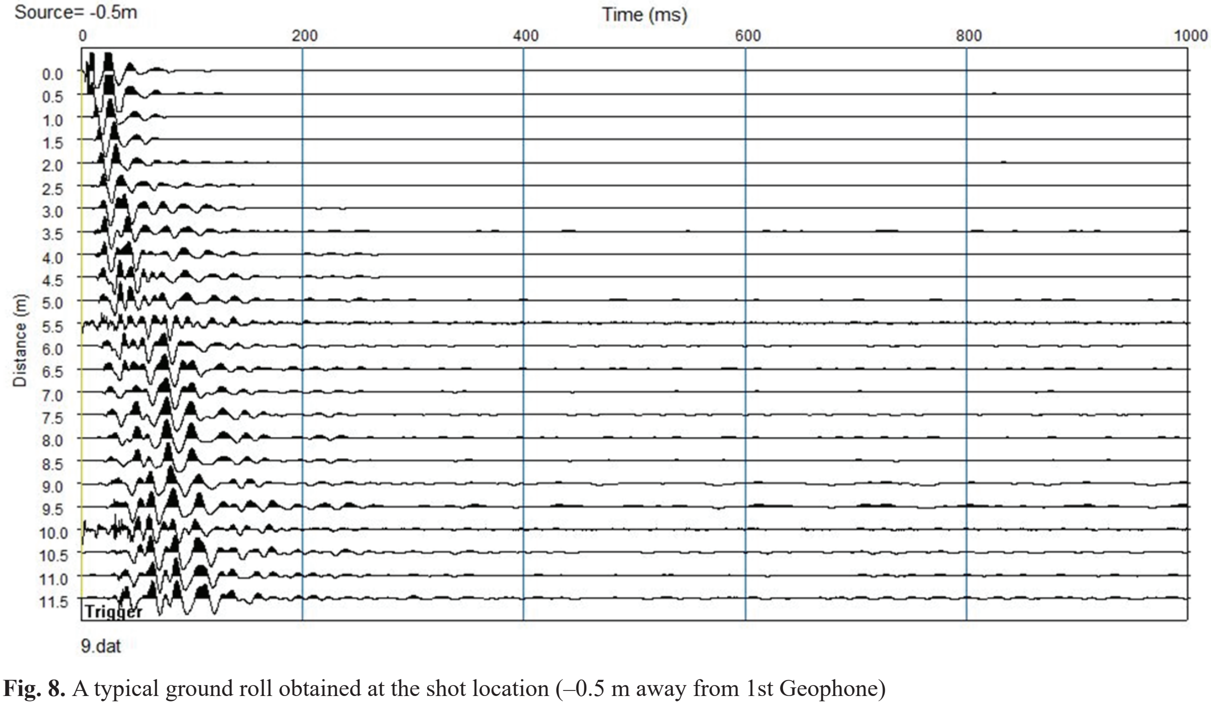


Fig. 8. A typical ground roll obtained at the shot location (–0.5 m away from 1st Geophone)

Рис. 8. Типичные поверхностные волны, полученные на месте съемки (–0,5 м от 1-го сейсмометра)

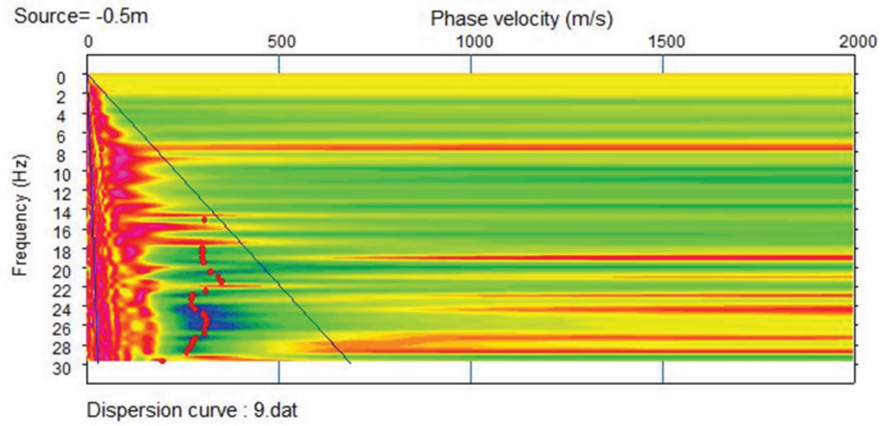


Fig. 9. A dispersion curve after filtering

Рис. 9. Кривая дисперсии после фильтрации

ity across the soil layers is obtained by comparing with theoretical dispersion curves iteratively. Thus, a 1D shear wave velocity profile is obtained for each shot gathered which is placed at the middle and both ends of the receiver spread for different geophone intervals.

RESULTS

Point cloud data generated through close-range photogrammetry provides a precise spatial representation of a structure, capturing intricate architectural details with high accuracy. This data serves as a digital documentation of the building, identifying each object within the complex and detailed layers. Subsequent processing of the point cloud data allows for the automatic extraction of individual building elements, which are then used for detailed modeling. By employing meshing techniques that connect points to form continuous surfaces, a detailed 3D model of the built heritage is created (as shown in Fig. 10). This model offers an accurate digital replica of

Fig. 10. 3D model of the Post Master General (PMG) office created from the point cloud data

Рис. 10. 3D-модель офиса главного почтового управления, созданная на основе данных облака точек

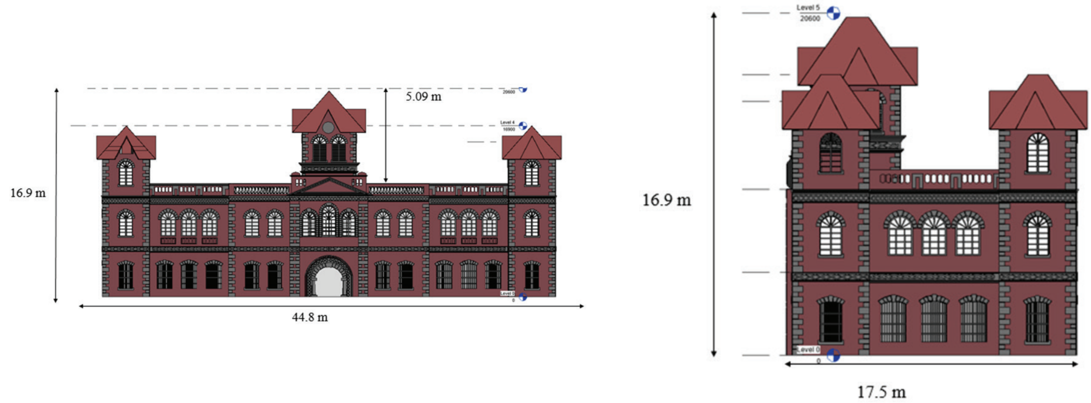


Fig. 11. Geometric measurements from the 3D model

Рис. 11. Геометрические измерения по 3D-модели

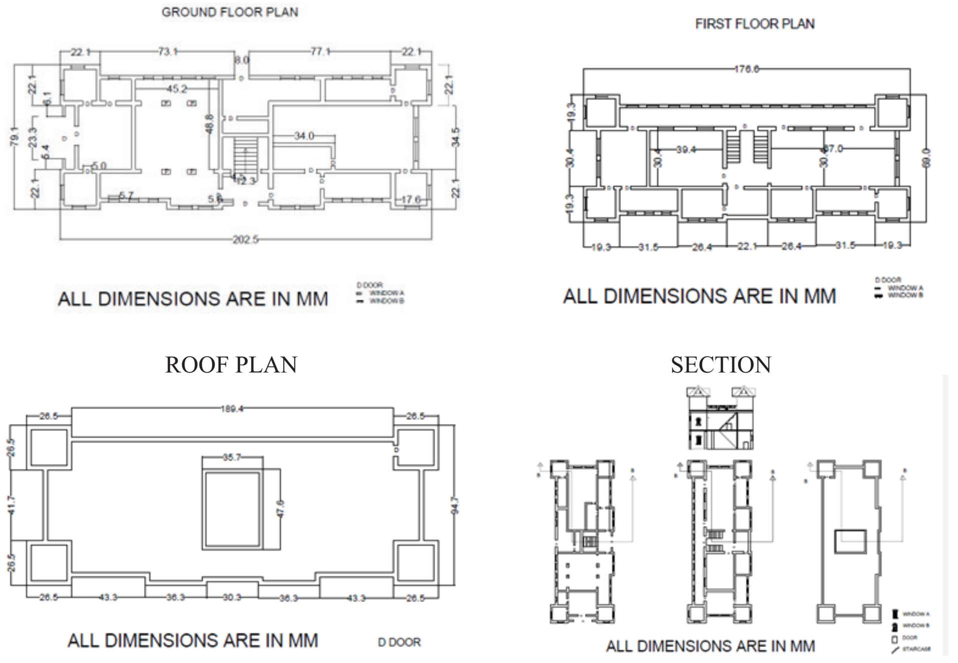


Fig. 12. Floor plans and Sections extracted from the 3D model

Рис. 12. Поэтажные планы и сечения, полученные на основе 3D-модели

the structure, enabling geometric evaluation (see Fig. 11), and preserving its architectural and cultural significance for future analysis and conservation efforts.

The developed model enables the extraction of 2D drawings, such as plans and sections (as shown in Fig. 12, 13), and the creation of walk-through models that detail the assets and construction methods. This process leads to the generation of digital datasets that are essential for monitoring and maintaining the heritage building.

As a result of MASW tests conducted at the study area, the shear wave velocity profile is estimated characterizing the subsurface of the PMG office building site.

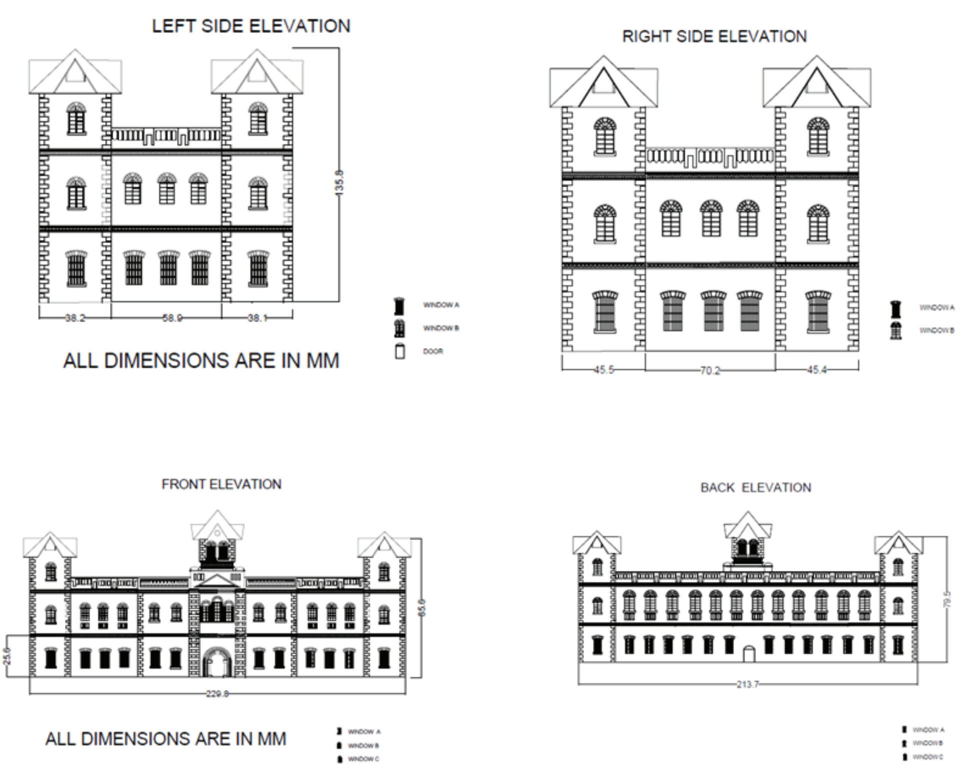


Fig. 13. Elevations extracted from the 3D model

Рис. 13. Фасады, полученные на основе 3D-модели

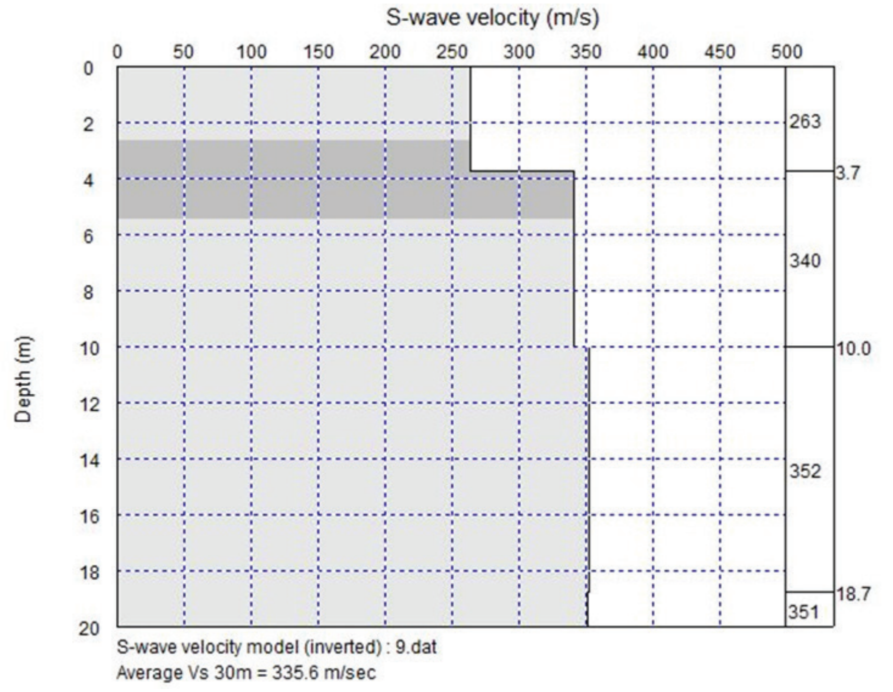


Fig. 14. A typical shear wave velocity profile in the study area

Рис. 14. Стандартный профиль скорости поперечной волны в районе исследования

Table 2. NEHRP site classification for seismic design based on *Vs* ranges

Табл. 2. Классификация площадок национальной программы по снижению опасности землетрясений для сейсмического проектирования на основе диапазонов *Vs*

Site Class	S-Velocity (*Vs*) (ft/sec)	S-Velocity (*Vs*) (m/s)
A (Hard Rock)	>5,000	>1,500
B (Rock)	2,500–5,000	760–1,500
C (Very Dense Soil and Soft Rock)	1,200–2,500	360–760
D (Stiff Soil)	600–1,200	180–360
E (Soft Clay Soil)	<600	<180
F (Soils Requiring Site-Specific Evaluations)	<600, and meeting some additional conditions	<180, and meeting some additional conditions

The typical 1D shear wave velocity profiles estimated from the data obtained corresponding to Fig. 8 are shown in Fig. 14.

It can be observed that the average shear wave velocity of the study area is between 300 to 350 m/s indicating the presence of stiff soil in the site and belongs to site class D as per the NEHRP (National Earthquake Hazard Reduction Programme) site classification [22] (Table 2). The depths corresponding to this range are identified from *Vs* profiles indicating the effective depth of penetration of the waves is up to 5 m indicating the presence of shallow foundations at the site.

CONCLUSION AND DISCUSSION

In this study, an attempt has been made to develop a comprehensive method for documenting and managing the built heritage by assessing its seismic risk. The methodology to construct a three-dimensional model from the images is developed using close-range photogrammetric techniques and advanced software. In addition, surface wave analysis i.e. MASW tests have been carried out at the study area to estimate the shear wave velocity of the soil which is necessary for seismic response analysis. Based on the study presented, the following conclusions are drawn:

1. The developed 3D model with enhanced geometric and parametric information will provide a ‘close a reality’ experience rendering for maximum detailing and visual appeal. The so-developed model will serve as a single source of information in all work phases of restoration and management of heritage buildings. The contributions of our work can also be used in developing digital exhibitions, virtual tours, etc., in the near future to promote digital heritage tourism.

2. Seismic design codes use site classifications to evaluate the seismic demands on structures based on how soil foundations respond to earthquake ground motions. The MASW test results indicate that the *Vs* values

of the soil are in the range of 300 to 350 m/s indicating that the PMG office heritage site belongs to Site D as per the NEHRP standards characterizing the subsurface with stiff soil. This classification will guide engineers in understanding and mitigating seismic risks, ensuring structural resilience in the face of seismic events.

Thus, the developed combined suite of digital documentation and seismic surface wave technique for characterizing seismic velocities of the subsoil for the built heritage will play a key role in sustainable heritage conservation and management against natural hazards such as earthquakes.

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