3D Laser Scanning documentation for informing the post-earthquake recovery of heritage settlements

a practical guide

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Preface

Natural and human-induced hazards, particularly earthquakes, endanger human lives, buildings, and infrastructure. The post-earthquake reconstruction of traditional housing and settlements, faces numerous challenges, such as assessing damage in an accurate and appropriate manner, preventing demolition, loss of traditional building knowledge, and tackling the issue of population displacement caused by relocation.

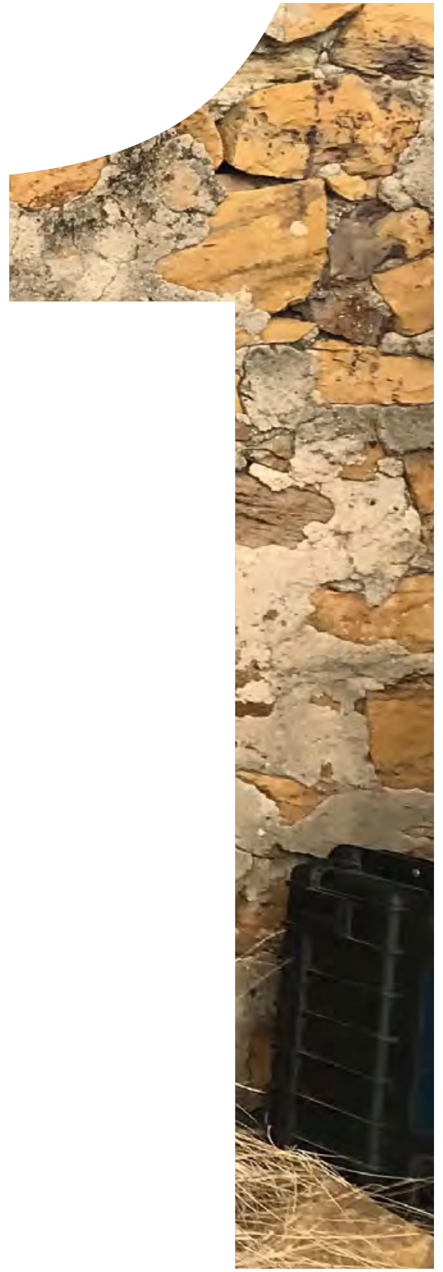
One of the main challenges in heritage contexts is the damage assessment of the structures after an earthquake, which requires specific knowledge and documentation. In this context, accurately and comprehensively recording the built fabric and the ways of life in traditional settlements is key to their conservation and enhancing their historical value. For this, the unprecedented evolution of recording technologies is key due to their capacity to obtain a large amount of measurable data in a limited time.

This guide shows how terrestrial 3D laser scanning (3DLS, also known as LiDAR) and photography can support post-earthquake recovery operations. Understanding post-disaster recovery includes several dimensions – economic, social, and physical – this guide focuses on the documentation of the physical aspects of built heritage, which contribute towards the emotional attachment that communities have had with their places over the years. In this regard, 3DLS and photography allow the accurate recording and documentation of traditional settlements, which is of the greatest importance for a comprehensive assessment of damage and risk. This is due to the visual and metric evidence it gathers, creating a virtual record of a *living heritage* (e.g. the continuously evolving traditional practices of a culture or community, as well as the knowledge systems they make), and offering communities the chance to appreciate their heritage from a new perspective and be empowered by learning about this technology.

In the long term, this tool can support the development of culturally sensitive post-earthquake recovery, which do not infringe on or neglect the traditional way of life and socio-cultural practices. The application of this guidance document before and after seismic events can increase the number of heritage buildings conserved and the quality of their conservation, thereby mitigating risks to these buildings and human lives, and improving public policies.

This guide uses the case study of Bela (Kutch, India) to illustrate the considerations and procedures involved in surveying traditional housing with a terrestrial 3D laser scanner after an earthquake, its primary focus. However, 3DLS, as presented here, is part of a broader and more integral methodology that includes community engagement, social surveys, historical enquiry, and other forms of recording and representation such as photography and videos. 3DLS, as part of this methodology, needs supporting strategies and institutional arrangements for its successful implementation in the recovery of traditional housing and settlements affected by earthquakes in India, and possibly beyond.[1]

1 The methodology and its application to the pilot case of Bela are detailed in a journal article available at **www.3d4heritageindia.com**



1 Introduction

1. Introduction

1.1. Why documentation is important after an earthquake

Traditional housing and settlements are often vulnerable to earthquakes, which can damage or destroy both tangible and intangible heritage values. In a post-earthquake scenario, emergency operations prioritise saving human lives and providing food, medicine, and shelter. Consequently, several years may pass before specific measures are carried out to recover the heritage affected by the disaster, such as in L'Aquila (2009) and Amandola (2016), in Italy, or Pumanque (2010), in Chile (Fig. 1). After the earthquakes in 1993 and 2001 in India, the historic villages of Killari and Adhoi, amongst many others, faced such damage and destruction that many abandoned their homes or had to be relocated to new, culturally incompatible settlements (Jigyasu 2002).

1. A photograph of a house affected by the 2016 earthquake in Amandola, Italy. Wooden reinforcements are holding the structure together.

Although traditional housing tend to attract less attention than more prominent buildings and monuments, they contribute significantly to the historical, architectural and social values that characterise the cultural heritage of communities and their settlements. These humble yet meaningful constructions are the fruit of anonymous, collective efforts (Fig. 2). Therefore, they have value as a group, despite the modesty of their means of construction (Guarda 1988).

Traditional housing and settlements are also carriers of local knowledge which can contribute towards disaster risk reduction: in many cases, such as the Rajbanshi, Gurung and Magar Houses in Nepal (Gautam, Paterno, Bhetwal, & Neupane, 2016) and the Pol Houses of Ahmedabad, the construction techniques of local vernacular housing had developed earthquake-resistant characteristics. But the cumulative damage incurred by multiple earthquakes without adequate repair and maintenance put them at risk of demolition (UNESCO 2001) (Fig. 3). While efforts have been made to improve the building codes to make the new structures more resilient to earthquakes, less attention was paid to existing vernacular buildings, leaving the built fabric of traditional settlements highly vulnerable and prone to replacement (Devilat 2021). Moreover, the contemporary solutions implemented often result in the gradual replacement of the existing structures and the loss of the knowledge of traditional construction techniques developed by the community over the years, alienating them from the recovery process.

2. An adobe house with no damage after the 2010 earthquake in the historical village of Zúñiga, Chile, mainly due to regular maintenance and reinforcement.

3. Photograph of a house in Bela, Gujarat, India.

One of the key reasons for such a loss of tangible and intangible heritage values during the post-earthquake reconstruction is the lack of awareness of the significance of heritage during a crisis, when time is short, and human safety is the priority. The result is visible in numerous cases worldwide: all too often, the post-earthquake reconstruction of these settlements and the relocation of the affected communities lack the necessary cultural sensitivity.

Most earthquake-related actions are implemented after the seismic event. Demolition is often a preferred solution to the retrofitting or strengthening of damaged buildings. Due to a lack of knowledge and available documentation, it often happens that heritage buildings are surveyed because they are unsafe and identified for demolition, instead of recommending the use of that documentation for retrofitting purposes. Ownership issues also create significant confusion in the recovery process, leading to heritage structures that do not gather enough attention or investment. Although nowadays retrofitting is considered to be a safe strategy, two elements are key for addressing these issues. First, to take action at a community level, where different stakeholders can support and help implementation, such as NGOs and local authorities. Second, to document the buildings to facilitate the repair and retrofitting, both as a post-earthquake response and as a risk mitigation measure.

The early introduction of 3D laser scanning documentation can inform timely decision-making regarding the affected structures, but must consider adequate coordination with emergency brigades, relevant authorities and the affected communities, for reasons of overall safety and aid organisation. There is an evident need for recording traditional structures and settlements using innovative methodologies that make use of state-of-the-art techniques such as 3DLS and employ the knowledge obtained to retain the heritage values and integrate them into the recovery process. Moreover, to utilise them to go beyond the post-earthquake response to inform risk mitigation strategies, with the aim of enhancing the number and quality of vernacular buildings conserved, reducing risks to these buildings and human lives, and lead to the improvement of public policies.

An effective methodology for the recovery of earthquake-affected traditional settlements based on 3DLS needs to address the following key considerations:

Holistic. The data collected must provide an accurate understanding from macro to micro-level; ranging from the larger settlement and its surrounding context to the details of individual structures that will help analyse the attributes of the settlement (physical, social, cultural, and economic). To this end, 3DLS technology must be complemented by other surveying methods, such as photography, visual observation, and surveys of the community.

Sustainable. The documentation must meaningfully engage with and involve the local community in the process, transmitting a better visual understanding of its houses' physical and socio-spatial characteristics, neighbourhoods and settlement patterns, invaluable in promoting the long-term physical, social, and economic sustainability of the post-earthquake recovery process.

Resilient. Accurate documentation is necessary for a thorough analysis of the individual structures and neighbourhood clusters, for assessing the extent of the damage caused, for the identification of the physical and social vulnerabilities present, and for the retention of the traditional techniques developed locally over time to withstand earthquakes. This will improve risk communication, as well as *re-construction* processes, by reducing the existing vulnerabilities while retaining the vernacular characteristics of the structures and settlements.

1.2. The aim of this guidance

This guide illustrates how 3DLS documentation can contribute to the holistic, sustainable, and resilient post-earthquake recovery of traditional settlements. It is primarily aimed at professionals and institutions working in disaster risk management, cultural heritage, and other related sectors responsible for post-earthquake recovery. It is specifically targeted at on-site surveyors with a degree of previous expertise/training in using the equipment and related software. It may also be helpful to international and national donor organisations and NGOs, to show the advantages of this form of documentation in post-earthquake scenarios and its potential viability in other types of disaster scenarios.

The document describes the process of using 3DLS to create a record of traditional structures and settlements in regions affected by seismic activity. It outlines the stages of post-processing, the role of data in spatial and structural analysis, the assessment of damage, and the identification of underlying vulnerabilities exacerbating the damage incurred. The analysis of the documentation and records created with 3DLS can help to develop effective post-earthquake recovery guidelines that respect the existing physical and social attributes of affected structures, encouraging the minimisation of demolition in order to uphold their aesthetic and cultural significance.

It is important to note that while this document provides an overview of the 3DLS process for the post-earthquake documentation of traditional buildings and settlements, it does not cover all the technical aspects of documentation. Furthermore, the amount of data collected, the post-processing, and outcomes depend on the team involved in the operation, the equipment and software employed (see Section 2.1.). Various knowledge resources that elaborate on the 3D laser documentation technique should be used to complement the information provided in this guide (e.g. Historic England, 2018).

1.3. The advantages 3DLS offers for post-earthquake documentation

3DLS is a state-of-the-art recording technology that allows the documentation of physical objects and spaces in high-precision, generating three-dimensional coloured digital models, accurate to the millimetre in a short period of time. In contrast, conventional tools for surveys and documentation, such as hand measuring, can be time consuming and may produce inconsistencies in measurements (Devilat 2016).

The data obtained using 3DLS can help governing bodies and other concerned authorities assess the affected areas from macro to micro levels, an invaluable resource for planning new, effective measures. The information resources it offers make it faster and easier to understand the characteristics of a site after an earthquake, accelerating the response of the authorities, who can retrofit, strengthen, and reuse structures as required. This is preferable to the complete demolition and reconstruction of the structures from scratch, which in most cases disturbs the heritage values of a historic site, and the social setup of the area, and entails a heavier carbon footprint.

4. Faro Focus M70 3D scanner, used to scan data in Bela, Gujarat. 3D laser scanners are non-contact devices that capture data as point clouds, or millions of data points with colour information.

5. The scanner in action while scanning the damaged wall of Darbar family temple 5 in Bela, India. This technology provides a basis to produce a precise and current image of the affected areas, which can help to identify damage such as structural cracks, bends, distortions, and other phenomena which conventional documentation processes cannot capture at a comparable degree of comprehensiveness and precision in relation to the time invested.

6. 3D view of a Darbar family temple in Bela, India, captured in only a couple of hours on-site (building number 5 as referenced in image 23, page 47). 3DLS is a powerful tool for understanding the vulnerabilities of structures at risk or that have already been damaged by earthquakes. In addition to providing a complete record for assessing the built aspects of a building or site, 3DLS is a high-speed, user-friendly tool that can generate a precise, visual model of three-dimensional spaces and show the relationship between internal and external areas, further helping users understand the social setting of the site being documented, e.g. sociocultural practices or its function.

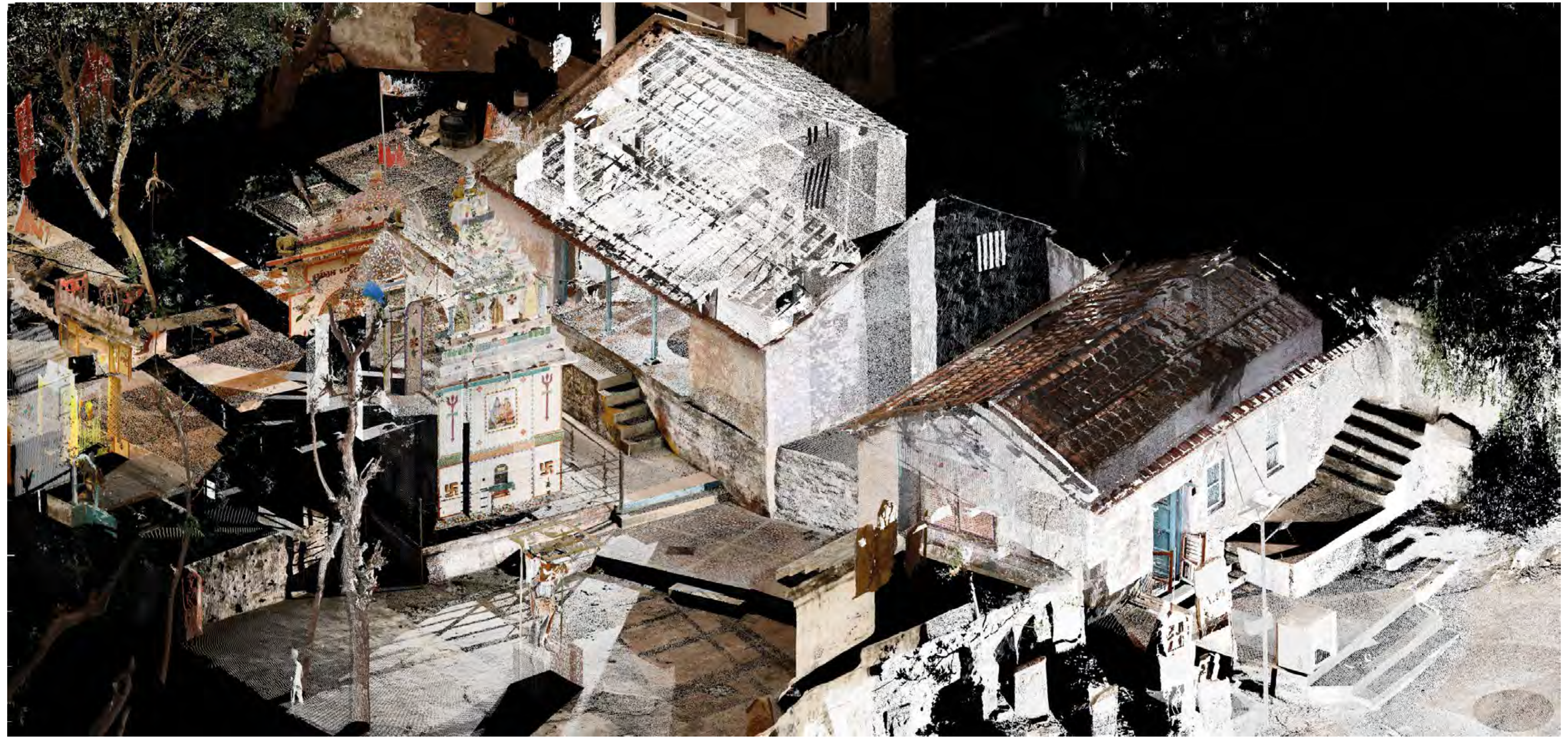
The advantages of this documentation technique can be summarised as follows:

- **It provides three-dimensional real-time documentation** of the studied building/area/settlement compatible with a range of software, many of which are open source.
- **3D laser scanners can collect data from inaccessible areas,** and drones can also be used to enhance data gathering possibilities.
- **The time required for data collection and processing is shorter** than conventional alternatives. The speed of 3DLS shows it is an economically viable method in the long term.
- **Models obtained from the captured data are extremely precise and detailed** compared to conventional documentation techniques (Devilat 2013). This allows more accurate identification and appreciation of the damage, which means better recovery strategies can be devised.
- **3DLS data is compatible with other forms of technology** used for documentation and can be converted into 3D meshes, working drawings, 3D prints, and geotags.
- Depending on the amount of data scanned, **different kinds of information can be gathered about the context** (e.g. public space and landscape surrounding the buildings, material culture), which can lead to the identification of other relevant aspects (e.g. vulnerabilities or patterns of use), and contribute to a more holistic understanding of the site.
- **If used in relation to other sources of information, the data allows comparative analyses** between structures that withstood damage well and those which did not, to identify the factors affecting the resistance of the structures to the event (e.g. building techniques used, quality of materials and execution, structural design).
- Where buildings have partially collapsed, **3DLS can use digital data to virtually fill in gaps in the structure.** This can be used for design interventions, or partial reconstruction for the purposes of conservation, or even simply as a virtual record.
- **It can open new avenues for modernising outdated disaster management policies** (written when only manual documentary methodologies were available) and promote affected communities access to the benefits 3DLS technology provides.
- **It may reduce the carbon footprint of new construction work** by making repair and conservation easier and more effective, thus more attractive than before, compared to demolition and replacement, which are common after earthquakes. Favouring restoration and conservation also promotes the reuse and recycling of on-site resources and materials, with the opportunity to use local skills to revive traditional building practices.

Limitations and challenges

As with any documentation technology, there are limitations:

- 3DLS is more expensive than other 3D documentation techniques, such as photogrammetry. Access to the equipment is one of the main barriers to its wide-scale use. Collaboration agreements with manufacturers of 3DLS equipment and academic institutions can be helpful in solving this issue.
- Although 3DLS is highly accurate, reflective surfaces, such as mirrors, glass, or polished metal, can result in misleading or incomplete data, and noise. To avoid issues, they can be covered during the data capture. If not, the 3D model obtained can be cleaned of those imprecisions. Complementary documentation techniques, such as photography, can be employed to fill any data gaps (Fig. 7).
- Similarly, as 3DLS only records visible surfaces, it can only contribute in this context if complemented with other tools as part of a more comprehensive methodology, such as visual observation, questionnaire surveys, and dialogue with community stakeholders and other relevant groups.
- 3DLS equipment factors such as heat, dust and unavoidable obstructions. Moving objects, such as stray animals or passing traffic, can affect the quality of the data collection. Careful planning is advisable to eliminate or avoid these kinds of issues.
- 3DLS equipment runs on power, and charged batteries are necessary for the duration of the operation. Given the risk of power disruptions in post-earthquake scenarios, prior planning is recommended to avoid leaving the equipment without power.
- 3DLS is state-of-the-art technology, and advanced specific skills are needed (from the on-site capture to post-processing and output development) to obtain an output of the quality required for post-disaster recovery work. These skills are not widely available and require specialist training. Furthermore, adequate, timely data processing demands high-spec systems. Collaboration with 3DLS equipment manufacturers and academic institutions may help solve this issue.



7. 3D image of temple 18 in Bela indicating data gaps. The limitations mentioned can be tackled by following the recommendations given, the expertise of surveyors, the specific aims and the latest advances in the technology's software and hardware. However, understanding the advantages and limitations of 3DLS, it is recommended to complement it with other forms of documentation of the built environment, such as photography, photogrammetry, and short videos – a fast and easy way of documenting spaces, materials, and activities.

1.4. Planning and resources

Expanding from the last point, external 3D laser scanning services providers can be expensive. The equipment and software required are costly, and specific knowledge and skills are needed. Thus, the longer-term aim of introducing 3D laser scanning technology for documenting built heritage in pre-and post-earthquake situations at a governmental level is a progressive strategy (Devilat 2021).

The applicability of this tool lies in institutional support, adequate training and resources, which is why an organisational arrangement is key for enabling it. Partnerships between academia, local NGOs, industry and governmental institutions can be a way to facilitate access to the equipment and the implementation of 3D laser scanning technology.[2]

Understanding the challenge this implies, a set of considerations, recommendations and funding options within current public policies were identified in the form of a Policy Brief,[3] contextualising the possibilities of the proposed framework in present heritage and disaster risk management policies at an institutional and governmental level in Gujarat, potentially useful at a national level. It includes general aspects of strategies and institutional arrangements to support the use of 3D laser scanning technology for the post-earthquake recovery of traditional houses and settlements.

2 The institutional arrangement of this research project, from which this guide is one of the outcomes, replicated successfully the partnership proposed: 1) an international partnership between academic institutions focused on heritage conservation (the Centre for Architecture, Urbanism and Global Heritage at Nottingham Trent University in the UK, the Center for Heritage Conservation at CEPT Research and Development Foundation in India, and the International Centre for the Study of the Preservation and Restoration of Cultural Property ICCROM in Italy); 2) a local NGO (Hunnarshala Foundation in Kutch, Gujarat, India); 3) and, in the project's second stage, involving the Gujarat Institute of Disaster Management (GIDM), an autonomous society advising the Government of Gujarat.

3 A Policy Brief, containing a set of recommendations for institutional arrangements, funding schemes and overall strategies for Gujarat gives context to this Practical Guide, available at **www.3d4heritageindia.com**. NTU, GIDM, CHC CRDF & Hunnarshala Foundation. 2022. *A framework for earthquake assessment, reconstruction and risk mitigation of buildings in historical settlements of Gujarat using advanced recording technologies.*

2 The documentation process

2. The documentation process

2.1 Equipment

- **Terrestrial 3D laser scanner:** Specific features vary according to the manufacturer (Fig. 8).
- **Drone:** to obtain aerial information in the form of photographs and videos (Fig. 9).
- **Photo cameras:** to obtain photographic records.
- **Sound recording equipment:** to record interviews.
- **Additional devices** such as mobile phones may also be used, e.g. photography, recording, or geotagging.

It is recommended to use a Total Station and/or a Global Navigation Satellite System as a control system when surveying if different data sets need to be combined, as it allows georeferencing them. In the case of Bela, the 3D pointcloud from the terrestrial scanner and the drone photography were not combined in one model. They were used manually for visual analysis and damage assessment purposes, so this equipment was not required.

8. 3D laser scanner used in the data capture of Bela. Model: Faro Focus M70.

9. Drone used in the data capture of Bela. Model: DJI Mavic Air 2.

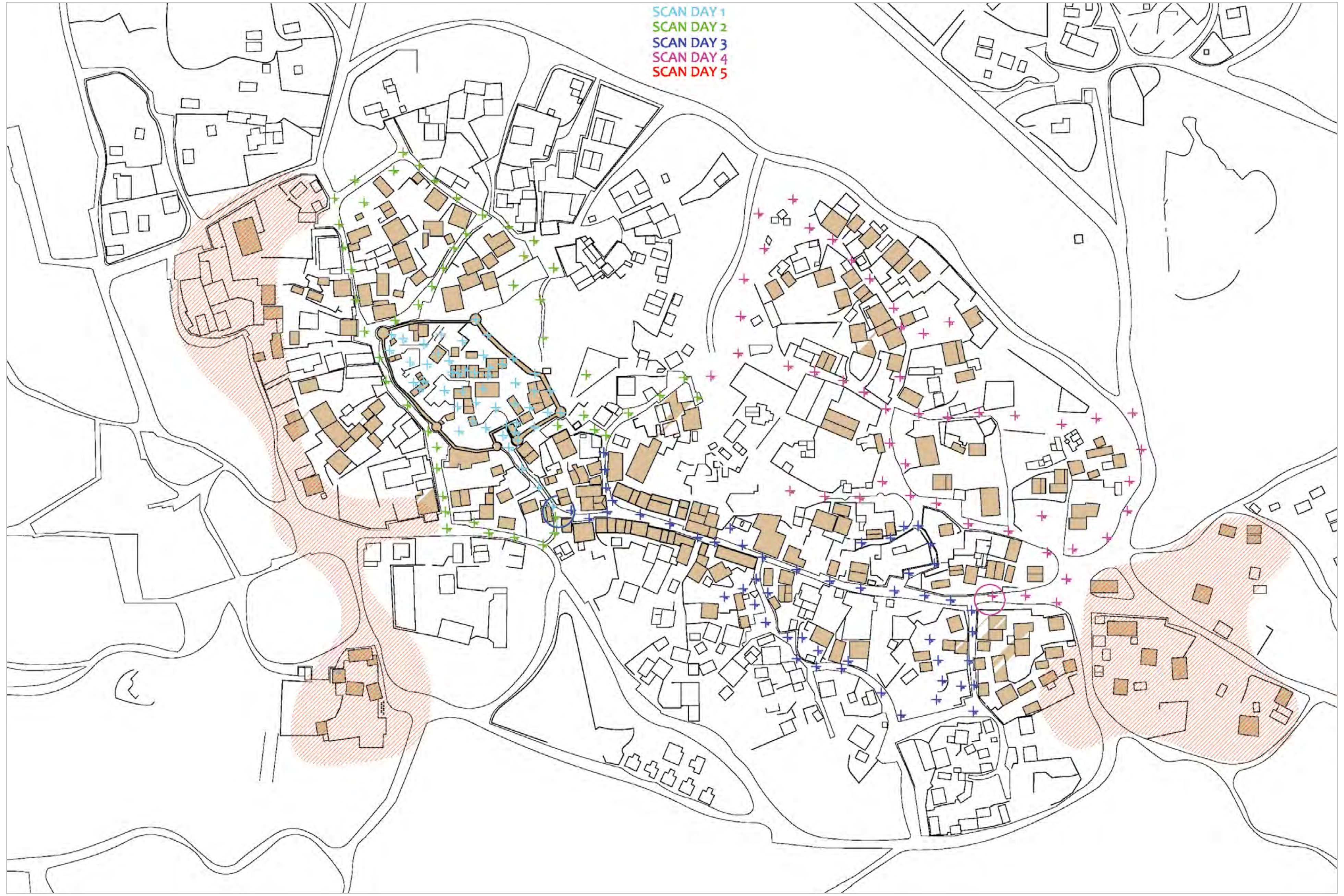
2.2. Preparatory Works

Offsite:

- **Develop a preliminary context** of the settlement to justify the study, which is to be complemented with data collected on-site.
- **Use existing maps** to identify the building or settlement to be documented (Fig. 10).
- **Plan daily scans** when documenting more extensive areas to cover the entire site sequentially; this will help link the scans accurately later (Fig. 11).
- **Set up an on-site team with different responsibilities,** e.g. social surveys, 3DLS, photography, leaving at least two persons for the 3DLS process. It is advisable that part of the team goes to the location in advance to explain the work to be done to local communities and stakeholders.
- **Obtain official permissions for access and operation,** signed by the concerned institutions or authorities. This will facilitate entry to the buildings and sites, and help establish confidence and credibility at the level of community leaders.
- **Obtain the consent of building owners or managers** for any buildings for which interior scans are planned.
- **Ensure you have a working data storage solution,** e.g. web platforms, accessible to partners operating remotely. In case of lack of internet connectivity due to network failures at the site, other alternatives should be prepared in advance, e.g. hard drives for temporary data storage.
- **Organise the work considering existing guidance for surveying heritage structures,** i.e. ICOMOS (1996), Historic England (2018) when applicable.

10. Understanding the site from existing google maps to get an idea of the village profile and a potential area to focus on. Here the example of Bela in Gujarat, India, located in the district of Kutch, northwest of the State of Gujarat, India. One of India's most seismic areas, it was affected by the Bhuj earthquake (7.6 Mw) in January 2001. Bela was once a trade hub due to its strategic placement on the pre-independence trade routes. It is characterised by a coherent built fabric of continuous facades and porticoes. The traditional houses are constructed mainly with stone, mud mortar, tile roofs a wooden support system. Although most buildings were damaged during the 2001 earthquake, very few collapsed.

11. Example of a graphic map identifying clusters for on-site reference and tentative laser scanning points and sequential routes for Bela as a guidance for the on-site data capture.



On-Site:

- **Clearly define aims and objectives.** The team may have to adapt to unplanned changes in the situation and conditions on-site without compromising the aims and objectives of the operation.
- **Consult with the community at every step,** explaining the process and receiving their suggestions, especially when obtaining authorisations. Efforts should be made to understand the social context of the place and engage with every social group, including women and children. This integration will, in turn, facilitate the data collection process and develop interest in safeguarding build heritage, especially when involving younger generations.
- **Adhere to the plan in scanning sessions,** but changes may be necessary if unexpected challenges arise. Adapt considering the usage of the scanned spaces and challenging conditions, such as heat, excessive sun or pedestrian-animal activity, etc. (Fig. 12). Excessive human activity creates noise in the data, leading to delays in post-processing. While the scan is in progress, restrict access to and movement in the area for best results.
- **Take structural damage and debris into account.** After earthquakes, always check for debris and damage to structures. Avoid causing further damage to the site by employing safe spots for scanning. Complement the data capture with photographs, drawings, and observations, identifying elements that could be reused in rebuilding.
- Whenever appropriate, **work with the local community to safely clear out any potential obstructions to scans** (e.g. parked vehicles or rubbish bins) **and cover any reflective surfaces.** Operators must always be mindful of safety for all people involved in the situation as well as the damaged structures, so the scanning process is developed safely and without further affecting the place. Any alterations to the site for the purposes of scanning must be carefully assessed. Scaffolding or other emergency supports to buildings should not be removed. If these cover targeted areas, use complementary documentation methods, such as hand measurements, drawing and photography.
- **Conduct scans uniformly** for large sites and, in the case of specific subjects, ensure sufficient overlap between scans to facilitate the registration process. Overlapped areas captured between the scans are necessary to connect and assemble the final model, or targets need to be used.
- **Complement scans with photography and field notes to:** a) provide for missing visual data and better understanding of buildings, especially drone photography if available; b) capture particular details such as joineries, brick layout, etc.; c) develop a local source material palette for scanned structures, i.e. different types of stone, wood, mortars, roofing materials, etc.
- **Check the data** on a computer at the end of the day or after each scanning session to ensure there are no gaps, e.g. data gaps where there should be a roof, corner, or niche. Such gaps would lead to an incomplete final model. However, incomplete models can be sufficient for the purposes of post-earthquake damage assessment, as specific spaces might not be required. Always be mindful of the objectives of the documentation process since more data captured implies more time on-site and post-processing afterwards. A careful balance is required.
- **Back up any SD cards** used at the end of each day to minimise the risk of data loss. It is recommended to back up the data on the card on an external drive and use a new SD card for each scanning session.

12. In hot climatic conditions such as the case of Bela, scanning early in the morning or late in the evening is safer for both the equipment and the operators. In Bela, the equipment worked at the limit of its heat tolerance at almost all times. The intermediate heat hours were used to charge batteries, communicate with families, backup data, etc. Night-time scans are viable if colour information is not required. Waiting for the sun and the temperatures to rise may be advisable in cold climates. Newer models of scanners feature increased temperature ranges than older ones.

2.3. Ethical concerns

3DLS documents the spatial attributes of a settlement only. It should be complemented by social surveys and photographic documentation to show the significance of the site and the importance of documenting. The community needs to be informed and prepared for the scanning operation so that they can be participants in the process and be able to give informed consent concerning the structures to be accessed and documented.

- **Any action taken at a disaster-affected site must have a *people-centred approach.*** Interventions to protect cultural heritage must be executed in conjunction with humanitarian relief and recovery (Tandon 2018).
- **Give due consideration to the current psychological state of affected communities,** which will be impacted after an earthquake. When integrating social surveys into the documentation process, seek the assistance of social workers to reduce the risk of triggering an adverse reaction of the respondents, who could be under considerable stress.
- **Any team coming to the site must respect the unique character and diversity present at the site, its community, and their greater context.** Avoid generic or insensitive solutions to the local context (Fig. 13).
- **Community engagement** should complement the 3D survey of the built fabric, to explain the work to be carried out and obtain the necessary information for an integral understanding of the studied sites. It should, ideally, start taking place before the survey to make way for it from a logistics point of view (access) and prepare the ground for people's understanding and acceptance of the process and for obtaining their permissions. This is especially relevant since the 3D laser scanner technology has a precision of millimetres and captures everything on sight, posing an ethical challenge to make that understandable in advance to those whose houses will be interiorly scanned.
- **Ensure the team knows exactly who to interview and what to record** to minimise any hindrance to relief work and maximise efficiency.
- **Collect data as objectively as possible,** and complement scans with visual observations and interviews.
- **All actions should be monitored very carefully to avoid damage to the site.** Special consideration should be given to the safety of the scanning team, as well as the community. For instance, if a section of a building is inaccessible or potentially dangerous, discuss the possibility of getting that data safely, e.g. around the corners or aerially with a drone.

13. Leaflet used for engaging with local people in Bela. The leaflet detailed 3D images of houses captured for a previous project in Ahmedabad (See Case Study 4.5.2.), to exemplify the work to be done and obtain informed consent. The leaflet worked as a synthesised participant information sheet. It was translated to the local language (Gujarati), as well as the applicable consent form, which was aimed at owners or caretakers of buildings to be scanned interiorly. The leaflet was handed to any community member approaching the team, and contained all relevant information and contact details. All direct verbal interactions between the team and local people were also in the local language. Consent was obtained mainly in oral form and recorded, as local people were weary of signing written documents. The majority of the people engaging with the documentation process were happy for the village to be of interest and helped when possible.

- **Data dissemination should also follow ethical principles making sure the local communities understand and accept its purposes and terms, for the benefit of heritage conservation and the greater public interest.** Aspects of privacy and other rights should be considered and cultural sensitivities respected, thus all data should be reviewed by the community members before they are made publicly available (Fig. 14). See the work by Santana, Awad and Barazetti (2020) for further reference on this point and wider aspects related to digital workflows in heritage documentation.

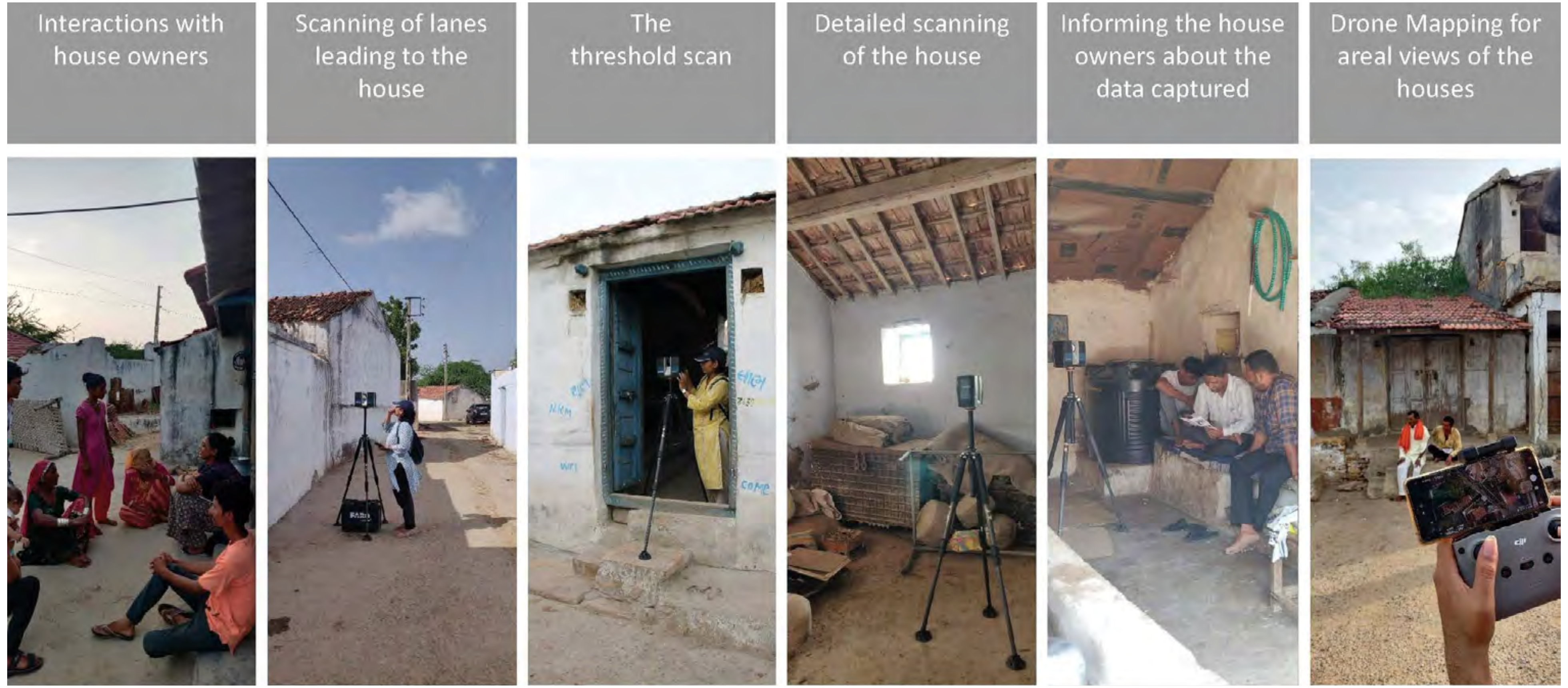
14. Workshop and Exhibition "Digital Bela: architectural heritage in a new light", held in Bela on the 17th and 18th of November 2021. As the technology and its possible outputs were strange to most people, a workshop and exhibition was developed six months after scanning on-site to show images, videos and architectural projections obtained from the captured data to community members, for them to understand its potential for earthquake-related prevention and recovery. Booklets compiling the plans, sections and images of each individual structure based on the 3D scan data were given to the owners and carers of those buildings, for them to understand the resulting record and approve its use.

2.4. Data capture on-site

Despite having previous planning on what to scan, once on-site in post-earthquake emergencies, the 3D laser scanning would come at a second stage when the post-earthquake humanitarian needs are addressed, and after realising a visual in-situ assessment of the village/town. This will complement or adapt any previous planning by identifying areas with damage or partial destruction to be scanned, ruling out visibly unaffected or totally destroyed areas and buildings, as well as open spaces. Time and resources available are also criteria in this decision-making, as well as available hardware's processing capabilities. Large data sets integrating several scans are more challenging to handle and time-consuming to work with, whilst having smaller clusters of scans can be more manageable and efficient for immediate post-earthquake damage and risk assessment, as long as the clusters correspond to single buildings or structural entities. Having more scans for connecting clusters across the scanned village would be less important in this case than covering more affected buildings.

Once there is a clear definition of what to scan:

- **Align and level the scanner tripod** according to scanner readings to keep it straight
- **Specify scan resolutions** suitable to the dimensions of the area or object to be scanned, with a sufficient density of scanned points.
- Depending on the complexity of the project, model and software of 3DLS used, **consider using target points** to facilitate scan registration.
- **Determine whether a colour scan is needed.** Black and white scans are significantly faster than colour scans. Employing black and white scans can speed up the process, e.g. if used to capture data connecting larger sets of scans. While the visual outcome is not as rich as with coloured scans, black and white scans still capture the metric information needed for most technical aspects to be assessed.
- **Be prepared to adapt to on-site contingencies and new situations,** even if this means modifying the original plan. Organise tasks accordingly, e.g. interviews can take place in interior spaces when it is too hot for scanning.
- **Identify what is required for a structural analysis.** e.g. try to get the data of the joints between walls and roofs from the interior and exterior of the buildings.
- **Complement with other sources of information,** such as drone mapping (Fig. 15).
- **Keep a log** of any irregularities or incidents which may arise during scans (e.g. bad weather, interferences, reflective surfaces). Make sure the scan number is also included in the log.
- **Always follow the manufacturer's recommendations and instructions** when using a laser scanner. For example, do not expose the equipment to temperatures above the recommended limit. Ascertain whether your scanner model is waterproof and may be used in mild rainy weather.
- **Allow for pauses or swap scanning teams** during the process, especially under challenging conditions, such as extreme heat.
- **Data backup daily** on-site.



15. Key actions of on-site data capture at Bela in June 2021. For the 3DLS documentation of Bela, the research team was divided into two groups. The first was responsible for community interactions and interviews, identifying individual buildings to document (criteria: building techniques, additions or alterations, damage, typology). The second was responsible for digital documentation through 3DLS, complemented with photography, videos and drone photography, covering the main public spaces and buildings following the first team's selection. There was an effort to engage with the communities as much as possible in the documentation process, e.g. children were often asked to play the role of field soldiers to temporarily stop moving vehicles and animals while scans were in progress. Particularly during oral interviews, the team kept in mind the community's social principles, such as wearing appropriate clothing and reciprocating positively to their hospitality.

2.5. Data post-processing

- Create a copy of the original data as a backup before importing it.
- When importing data to the post-processing software, specify the desired level for the automatic data filter.
- If applicable, input information on the weather conditions, debris or temporary objects (e.g. people, vehicles) needing removal. Keep in mind that removing things from a completed scan is time-consuming and must be carried out manually. This increases the cost of the scanning process unnecessarily. Usually, such elements do not hinder the analysis of the building for repair and *re-construction.*

2.5.1. Data Registration

Registration is the process of combining individual scans into a more extensive dataset using designated software, which can be done on-site or after the data capture (Fig. 16). If the number of scans is large, the required computer specifications for data post-processing will also be higher (e.g., RAM, processor speed). It is advisable to find **a balance between what data is required and how it will be joined together, so the 3D resulting point cloud is usable in the software and hardware available.**

2.5.2. Exportation, visualisation and delivery

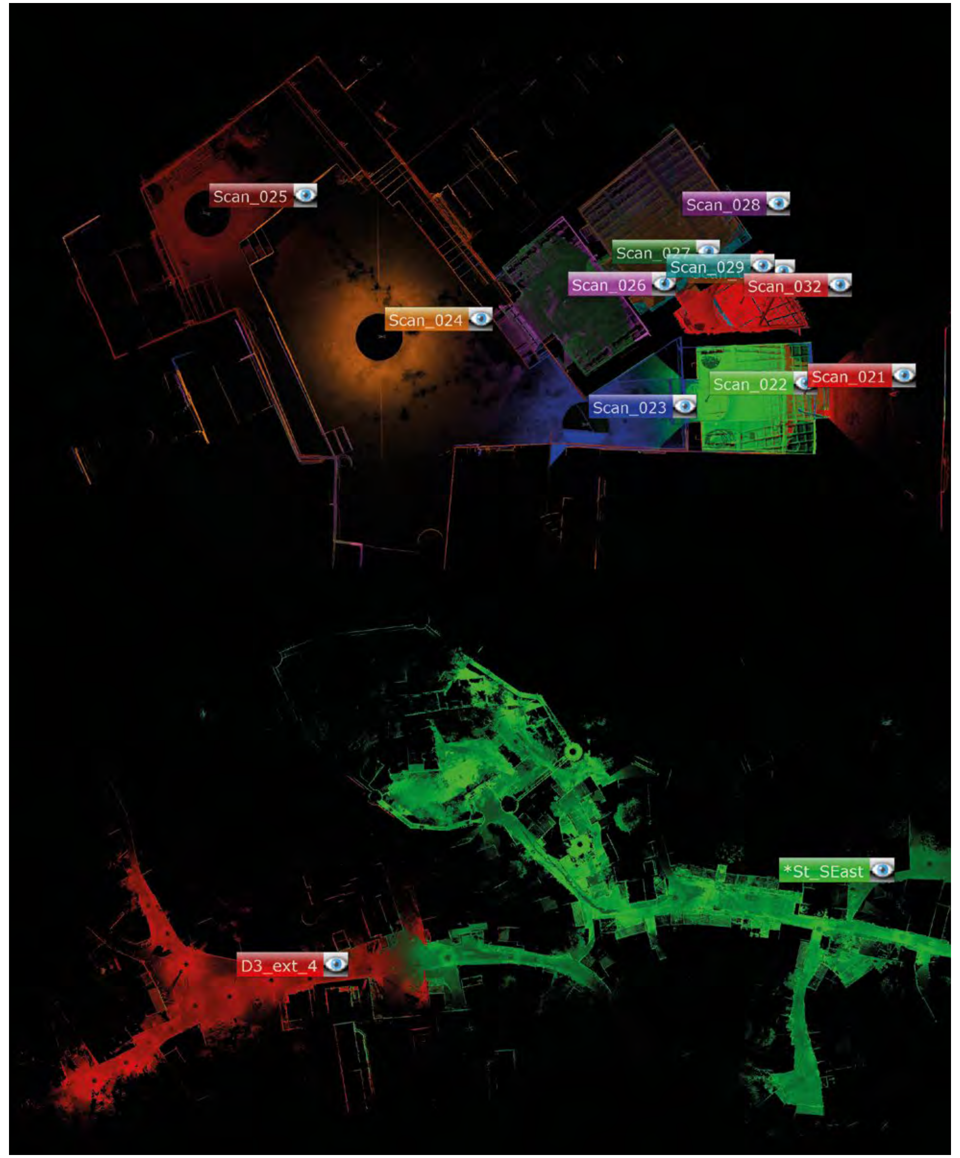
Once a 3D model combining the scans is ready, it can be visualised and exported to different formats according to the specific requirements of the case in question (Figs. 17 and 18). Heritage Building Information Modelling (HBIM) and Artificial Intelligence (AI) applied to the analysis of point cloud data, are emerging fields that could significantly enhance and optimise post processing and complement the direct observation and human analysis of point clouds in the future.

2.5.3. Data accessibility, preservation and update

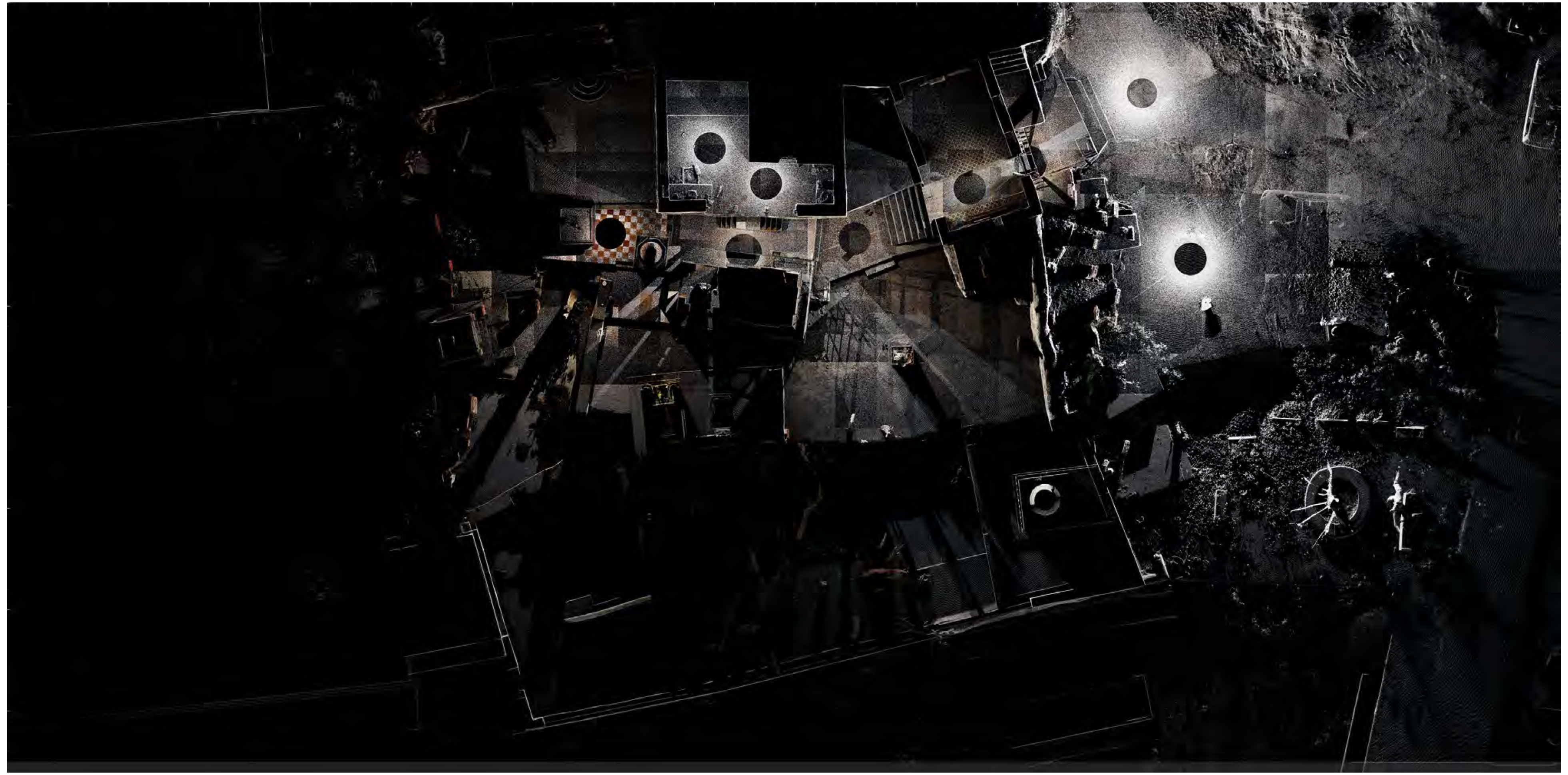
- Make 3D documentation accessible, so it can be of use to communities, academics, NGOs, local governments and other relevant stakeholders. For example, the data can be of relevance to governmental institutions to be sensitised about heritage importance, but also to be empowered to use it for risk management and emergency processes. Similarly, the data can help empower the communities, who are the ultimate custodians and bearers of tangible and intangible culture, to articulate their culture's value and the benefits they can accrue from such assets through sharing the 3D documentation.[4]

4 The supporting data for this research project [10.17631/RD-2022-0002-DCAT] is available at http://irep.ntu.ac.uk/id/eprint/45904/. Specific authors are indicated for each data set.

- It is key to understand the data usability over time, generating files that can last, e.g. file formats compatible with open-source software and keeping the data archived and accessible at perpetuity using online platforms for example. See the work by Moore, Rountrey and Kettler (2022) for a comprehensive account on data capture, post-processing and preservation protocols.
- For the benefit of heritage conservation, the data capture can become a process over time, where follow-up field trips at regular intervals can serve to complete missing parts or capture damage evolution.

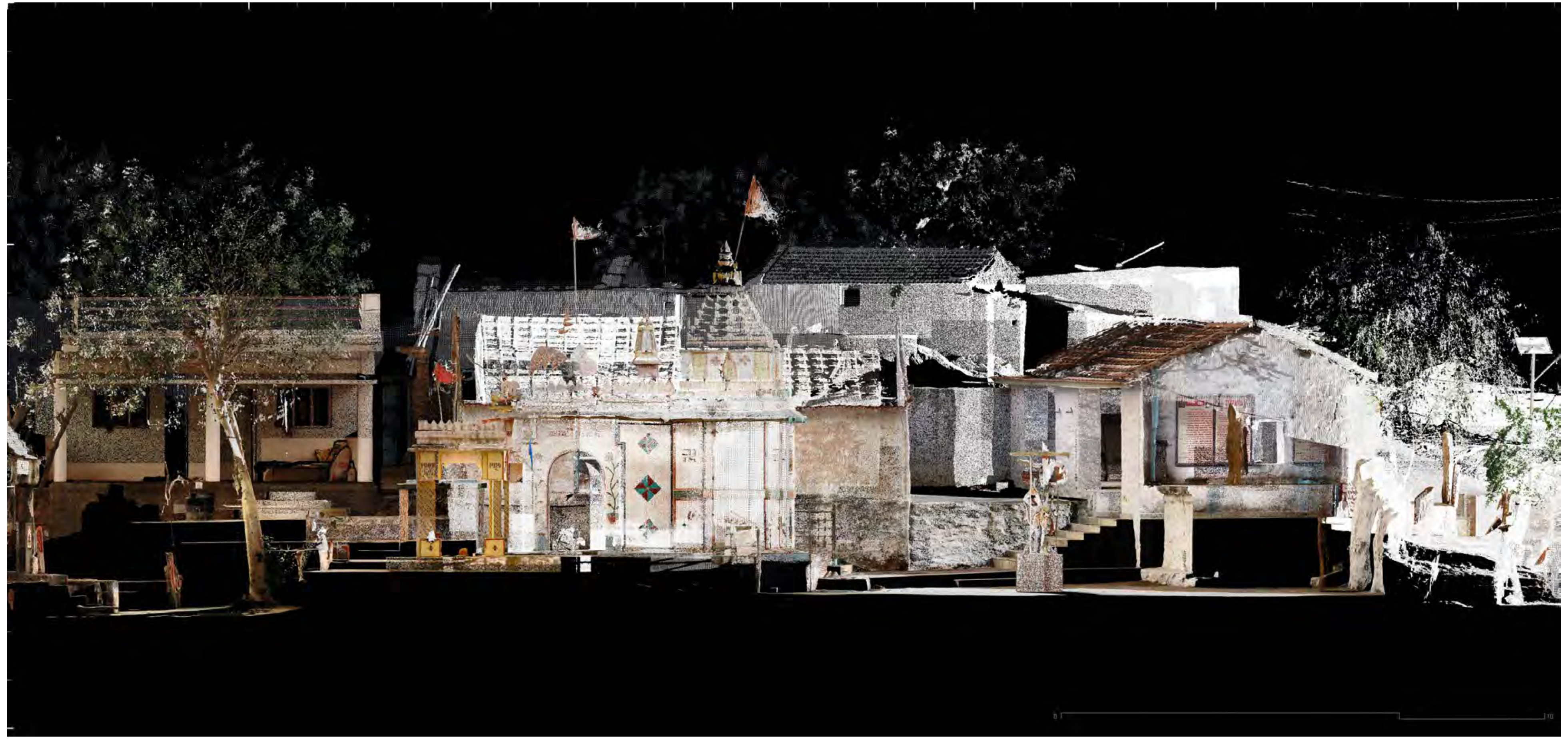


16. Registration process of scans using Faro Scene software for the data set of Bela, India.



17. Plan of temple 18 in Bela, rendered using the 3DLS Dta obtained on-site at Bela, Gujarat. The 3D scan model can also be sectioned to obtain measured architectural projections, such as plans, sections and elevations.

2. The documentation process



18. Section of the same temple, remdered from the 3D data of Bela. The 3D point cloud, images, and technical projections obtained can be used to interpret and analyse the information using appropriate software in 3D and 2D formats.

3

3DLS for post-earthquake analysis

3. 3DLS for post-earthquake analysis

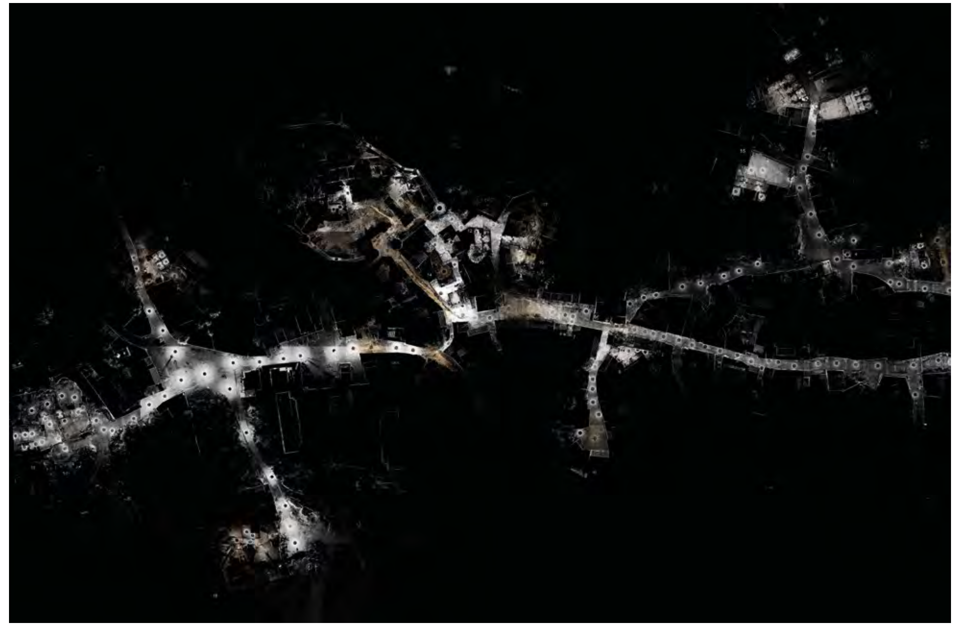
A 3DLS survey of a large area can be used for developing strategies at three interrelated scales:

- **The settlement level.** For an overview of the settlement, to understand its layout, extension, and the general features of the structures (Fig. 19).
- **The neighbourhood cluster level.** For a clear illustration of the morphology, use of open spaces, and access points (Fig. 20).
- **The building level.** For a detailed examination of individual buildings: the traditional techniques employed, as well as any building elements, alterations, and damage (Fig. 21).

Combining the architectural, cultural and historical dimensions through 3D laser scanning (3DLS) and photography (terrestrial and aerial) for the accurate and comprehensive recording and documentation of heritage settlements in a short period compared to traditional drawing techniques such as hand-measured surveys, informs and supports post-earthquake *re-construction* and risk management of heritage settlements in seismic areas by:

- **Understanding local characteristics and vernacular practice.** Knowledge of the building materials, techniques, morphology, use of spaces, and relationship to natural features, is useful when planning repairs, restorations, retrofitting, and/or reconstruction operations on traditional housing and settlements.
- **Identifying any transformations, additions, and alterations.** By investigating the changes that have been made to the house, neighbourhood, or settlement, it is possible to reveal the needs of the occupants and the community, which are key in planning an effective recovery process. Knowing what changes have been made also allows the identification and eventual resolution of any vulnerabilities which may have been created or aggravated by such modifications.
- **Assessing damage and risk.** The data collected in the scan can reveal and visualise the damage of the built fabric. Knowledge of the physical state of the structures is crucial for repair, restoration, or retrofitting actions to be carried out. These actions can improve buildings' resistance to earthquakes.

While the data collection and some assessments could be done as immediate post-earthquake actions, this section exemplifies mid and long-term post-earthquake analysis using the case study of Bela, affected by the Gujarat earthquake in 2001 of 7.7 Mw magnitude. Applying these technologies in an emergency situation would require sensible adaptation to the context, the definition of priorities and institutional arrangements of the data collected as part of a wider framework (See Policy Brief referenced on page 21).



19. Plan of Bela rendered from all the scans obtained on-site.

20. Zoom in on that plan, focusing on the Darbar neighbourhood at Bela.

21. Zoom in on that plan, focusing on houses 1 and 2 in the Darbar area at Bela.

3.1. Analysing characteristics

3DLS, together with visual recording and oral interviews, can be used for mid and long-term analysis, to extract physical evidence and scale representations of the following aspects of traditional houses and settlements, leading to a culturally sensitive *re-construction*:

- **The spatial arrangement of the settlement,** its topography, as well as the function and purpose of its constituent parts, particularly for the settlement's inhabitants (Fig. 22).
- **The site's morphology** in terms of the relationship between built and open spaces.
- **The function of public and private spaces.**
- **The interior arrangements.**
- **Access points.**
- **Traditional building materials and techniques,** tackling local environmental conditions, such as thick mud walls to resist the hot climate or gable roofs to ease runoff from heavy rainfall.

22. Bela's aerial view rendered from the 3DLS data obtained in June 2021. The historic area of Bela was scanned in 5 days, spending 7 hours per day, obtaining 325 scans in total.

The following images have been rendered from the 3DLS data. The black circles correspond to all the positions where the 3D laser scanner was placed, and the black areas correspond to those where no scan data is available.

This has been used to generate a working plan that can serve to guide the post-earthquake actions according to the level of damage of each structure. The working plan combining different sources of information (Fig. 23) helped in understanding not only the physical characteristics of built and open spaces but also their connectivity with the rest of the settlement (Fig. 24). This can further inform the planning of recovery strategies such as defining appropriate intervention actions of the buildings, e.g. repair, retrofit or rebuild; or to create a mitigation and risk assessment plan at the level of the settlement, including spatial relevant information such as community refuge points or escape routes.

23. Plan of Bela rendered from the 3DLS data indicating the 18 buildings interiorly scanned. The 3D scan data was used as an accurate medium to further validate the CAD drawing made during the preparatory work in Bela, based on the Google Earth aerial view. Building numbers identified on this image are used to reference all the cases shown throughout this guide.

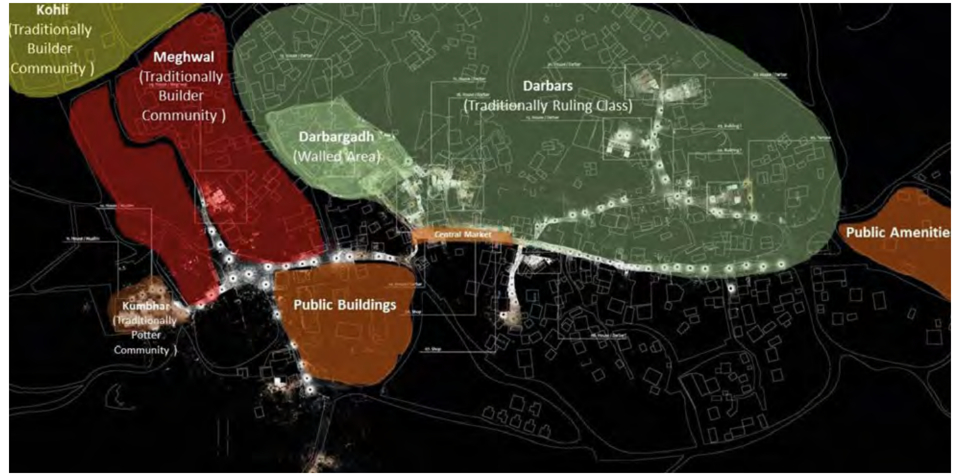
24. Section through the center of Bela showing the topographic profile.

25. Zoom of the section on Fig. 24, looking at the elevation of the Market Square showing the public sitting areas.

Local interviews and photographic records also helped understand Bela's social dynamics at micro and macro levels (Fig. 27). Such information is crucial not only during earthquakes but also in the preparation phase so that the existing link between the physical and social structures of the settlement can be respected.

General observations, together with 3DLS data, showed that most constructions were single-storied (Fig. 28), sandstone buildings, with mud or cement mortar (Fig. 29), and sloping, clay-tiled roofs supported by wooden beams. When the walls were exposed (Fig. 30), the scans captured the detail of the stone masonry building technique.

26. Public seating area at the Central Market Square where men congregate in Bela, Gujarat.



27. Socio-spatial structure of the Bela settlement mapped based on the 3DLS data. Identifying socio-cultural, religious and/or caste boundaries is relevant as engagement activities with the local community need to be adapted to that specific context.

28. Single-storey house in Bela with plastered wall.

29. Community members building stone walls with cement mortar.

30. Section and axonometric of building 3 in Bela, rendered from the 3DLS data, revealing the detail of the stone masonry used in constructions. Refer to plan in Figure 23 for the building's location.

Figure 31. Axonometric view of house number 9 in Bela, rendered from the 3DLS data captured in June 2021.

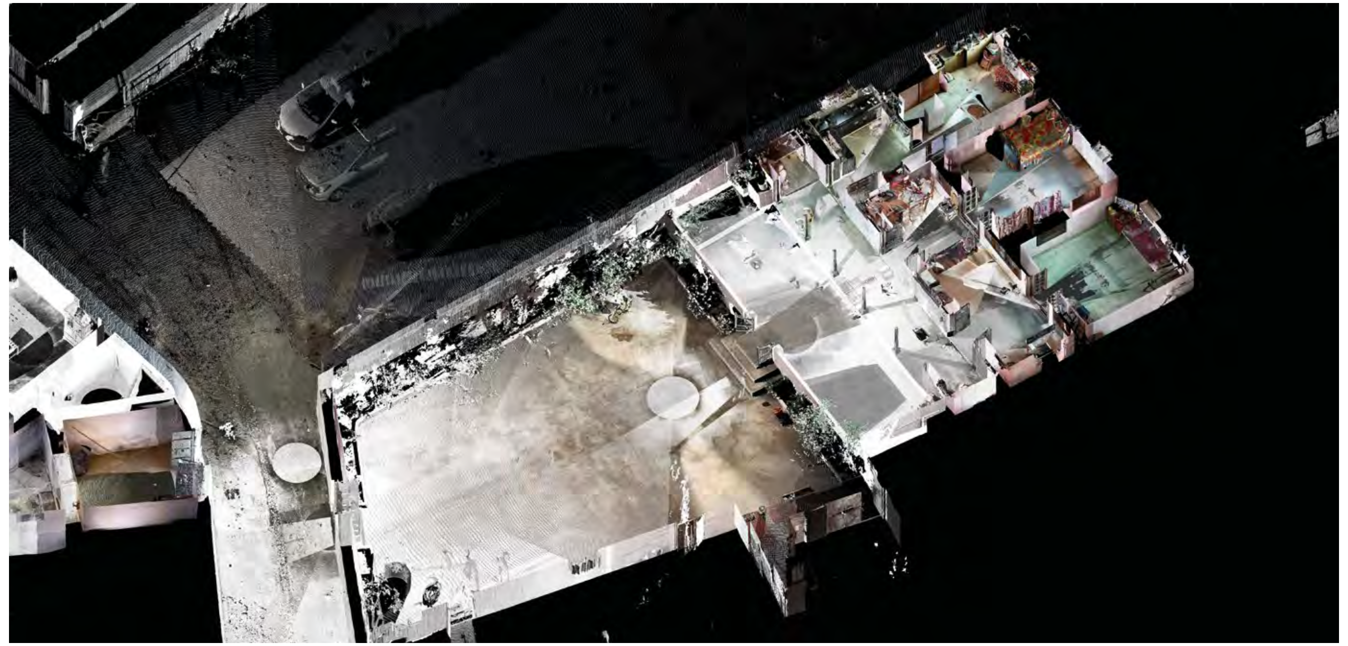


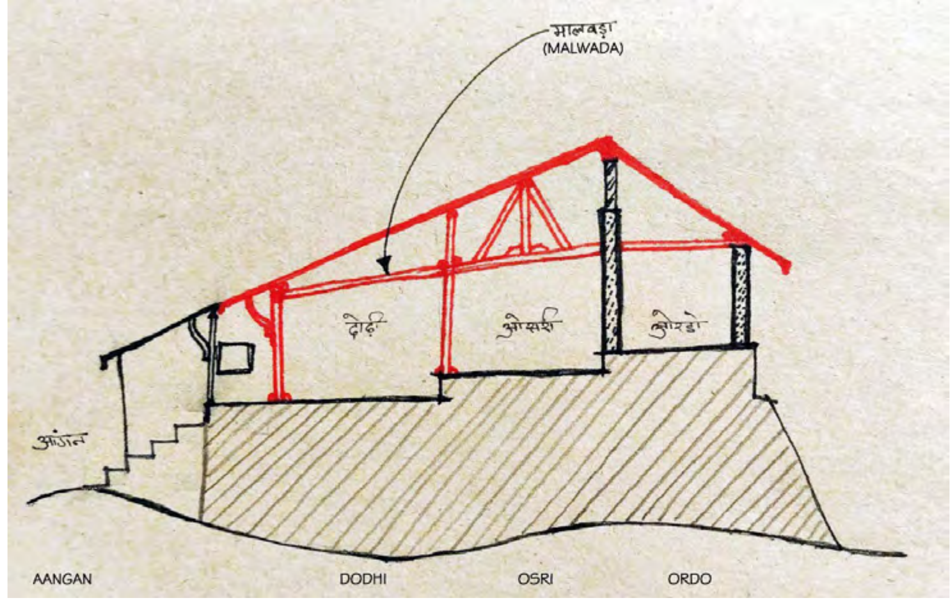
Figure 32. Axonometric view of house number 2 in Bela, rendered from the 3DLS data captured in June 2021.

3D Laser scan data can serve as a basis to analyse architectural typologies and visualise complementary data. For example, through on-site observation and interviews by our team, it was inferred that House number 9 (Fig. 31) belonged to a less privileged household, whereas House number 2 (Fig. 32) was newer and belonged to a comparatively more privileged one. Both are stone structures framed with timber and have sloped roofs.

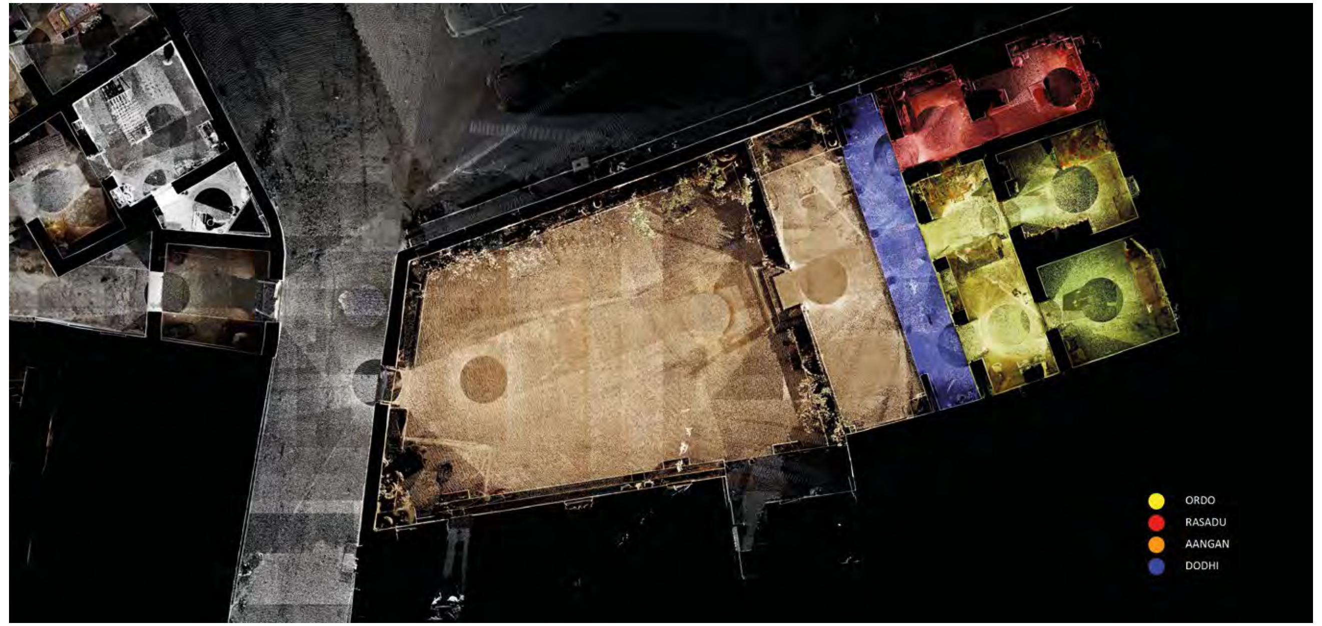
Both kinds of buildings are constructed on a plinth, the height of which mainly depends on economic status, though the terrain and conditions of the site can also be factors. Dwellings are structured as a sequence of spaces developing from public to private that can be appreciated as increasing degrees of enclosure, going hand in hand with the floor levels going up.

33. Plan of house number 9 in Bela rendered from the 3DLS data captured, illustrating the internal spatial arrangements.

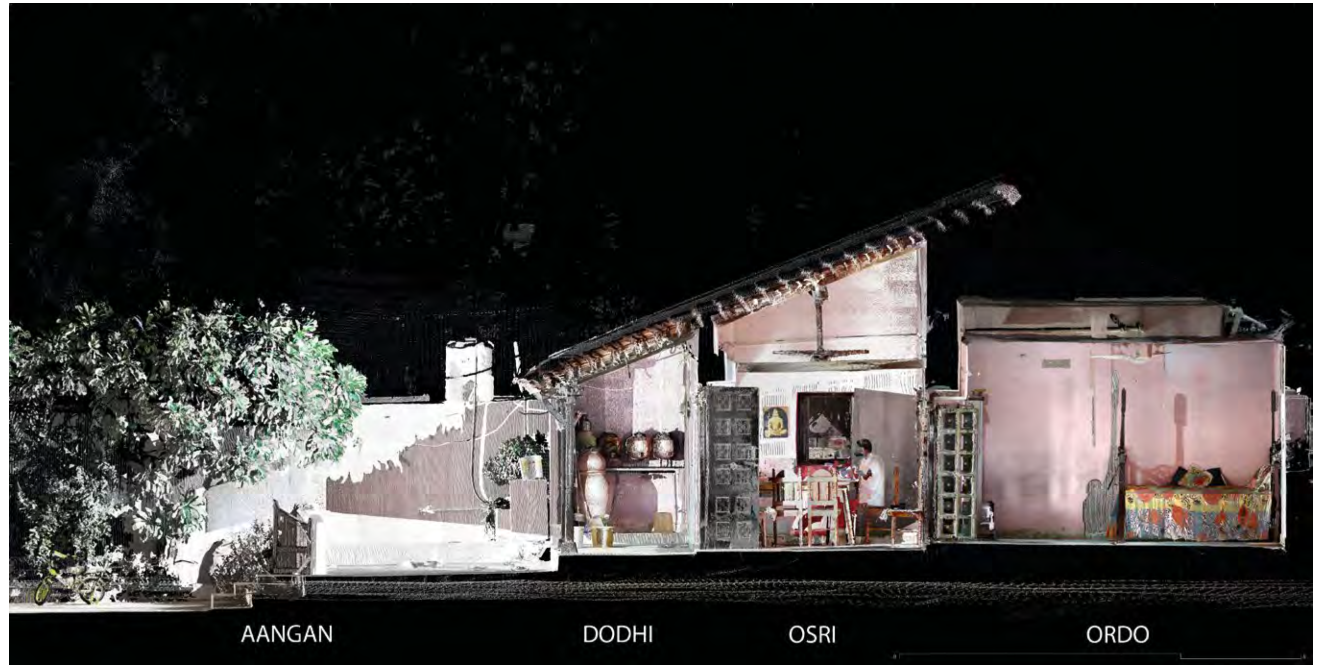
Number 2, belonging to a more privileged household, stands on a higher plinth and has more levels than Number 9. The main rooms, or *ordo*, are situated at the very top level, usually facing the house's main entrance. All the spaces open to a semi-public corridor, typically partially open, known as the *osri*. Households of lower economic status often have rooms instead of an *osri*, which is the case in building number 9. In both houses, the *dodhi* is a more public, shaded corridor mainly used when carrying out domestic chores. The kitchen, or *rasadu*, is a separate unit, usually located on one side of the house, depending on the space available. The presence of toilet units within the grounds of a residence is a relatively new addition in most places and is separate from the main block (Figs. 37-43). The information discussed here integrates 3DLS data and survey discussion with local people.



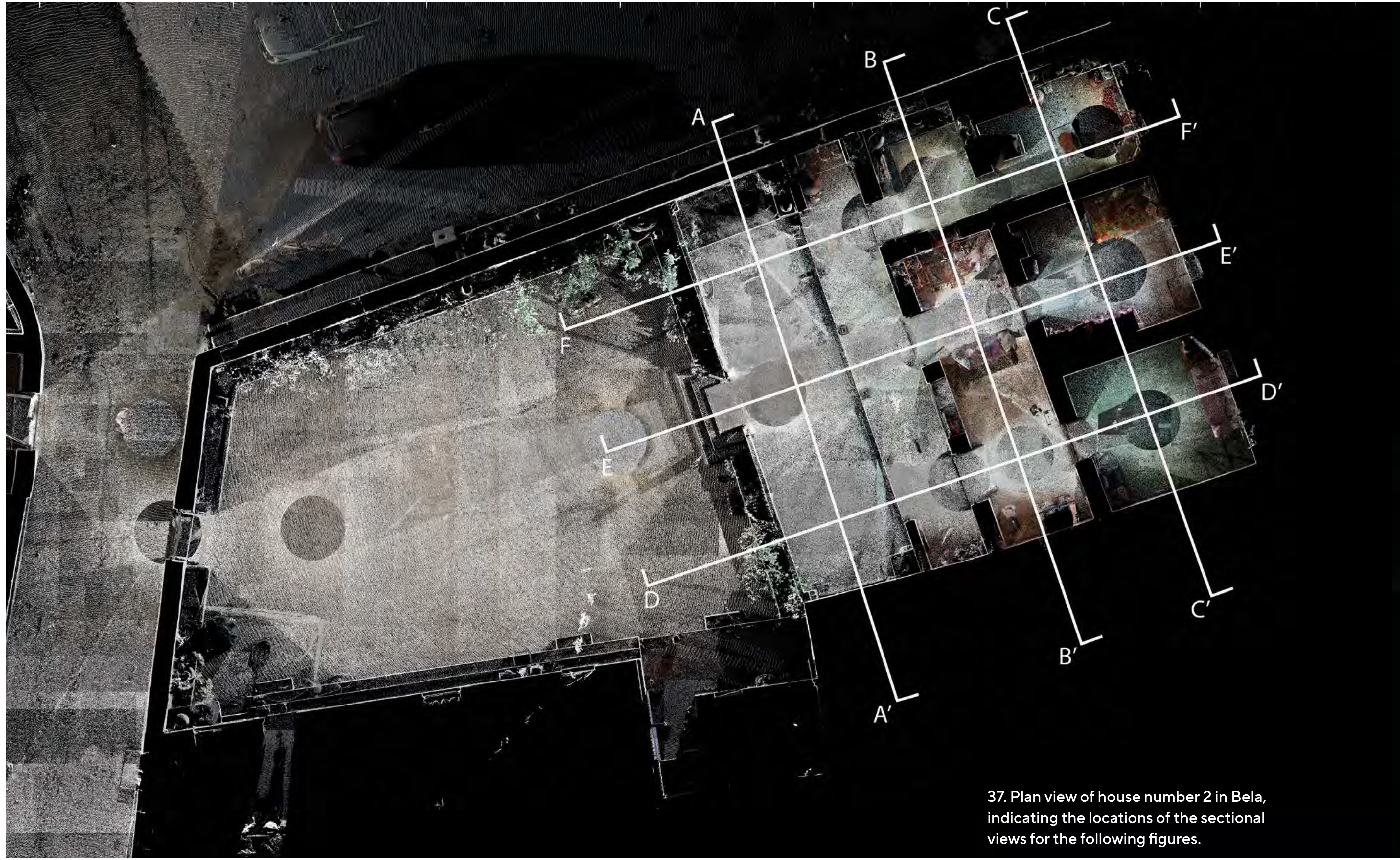
34. Schematic internal layout of building number 2 in Bela illustrating the internal spatial arrangements.



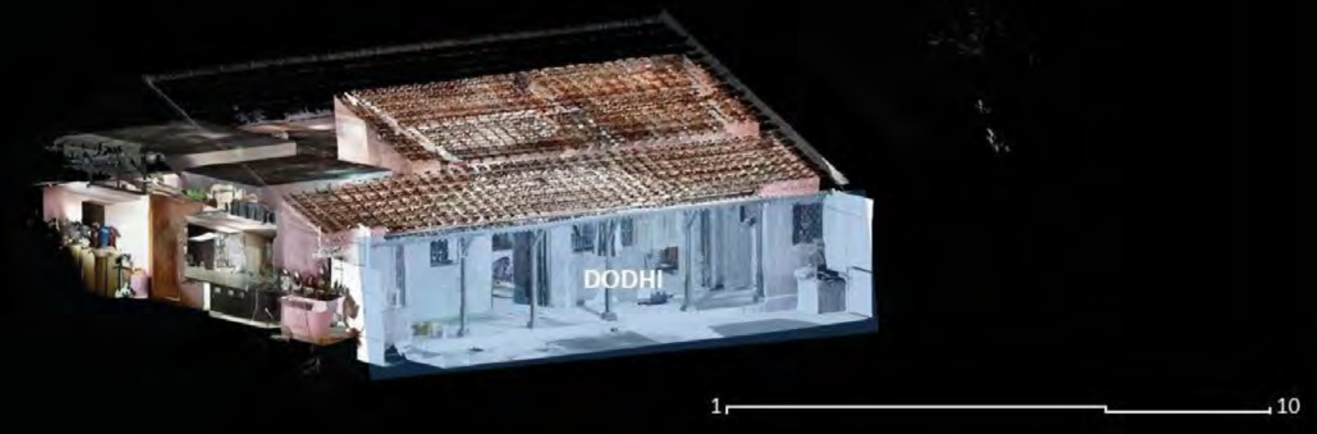
35. Plan of house number 2 in Bela rendered from the 3DLS data captured, illustrating the internal spatial arrangements.



36. Section of house number 2 in Bela rendered from the 3DLS data, illustrating the internal spatial arrangements.



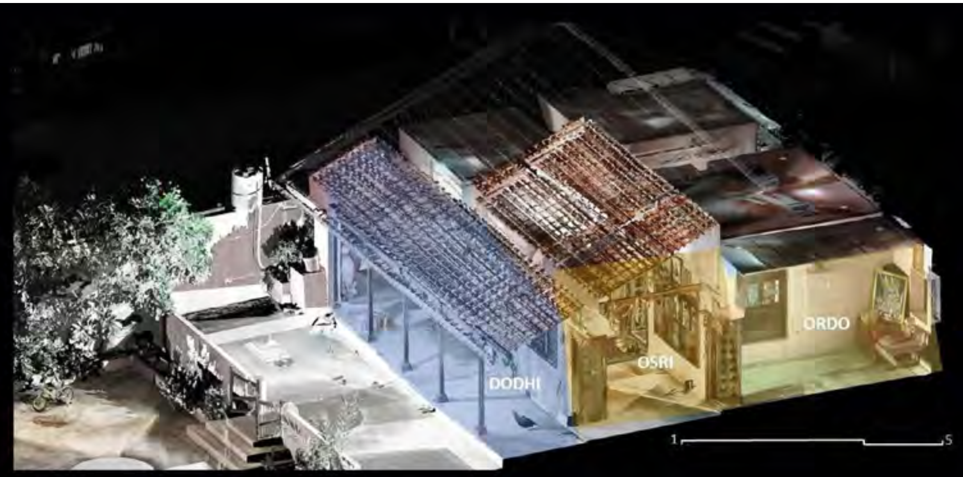
37. Plan view of house number 2 in Bela, indicating the locations of the sectional views for the following figures.



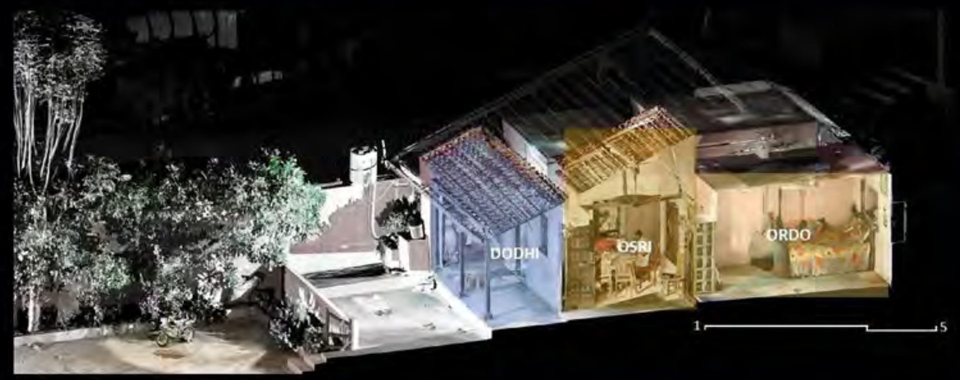
38. Axonometric sectional view of section AA′ showing the 'dodhi' area in building number 2.

39. Axonometric sectional view of section BB′ showing the 'osri' area in building number 2.

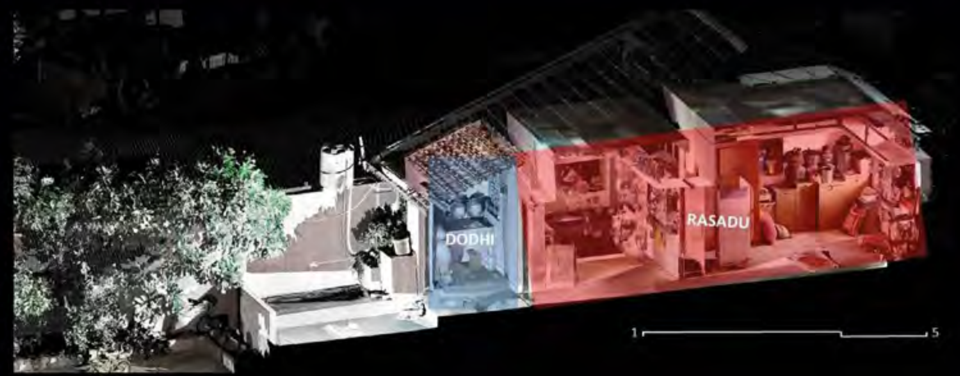
40. Axonometric sectional view of section CC′ showing the 'ordo' area in building number 2.



41. Axonometric sectional view of section DD' showing the different rooms, roof structure and furniture layout in building number 2.

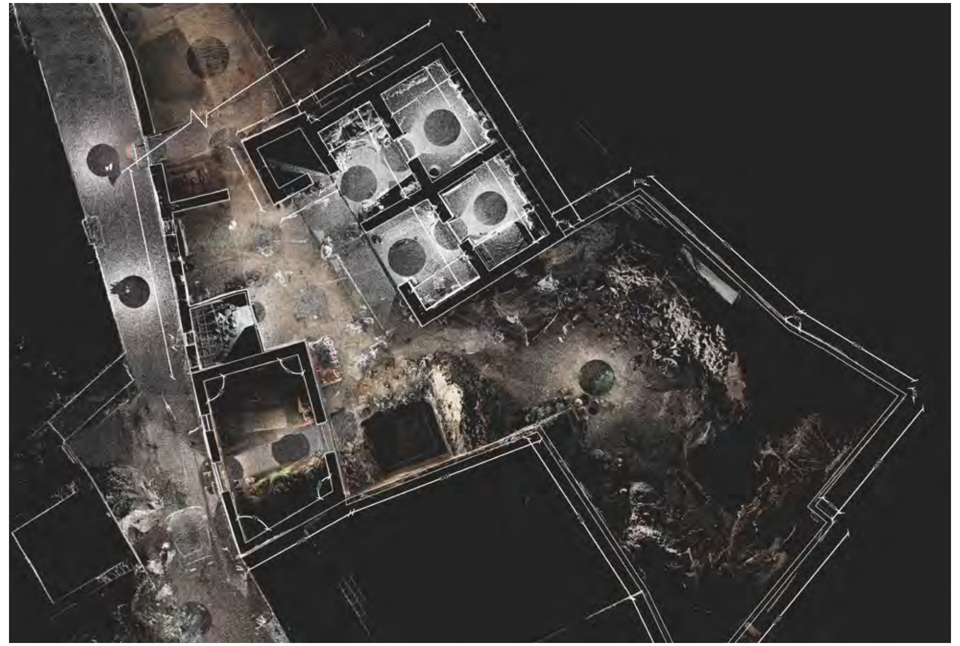


42. Axonometric sectional view of section EE' showing the different rooms, roof structure and furniture layout in building number 2.



43. Axonometric sectional view of section FF' showing the 'rasadu' and the arrangement of utensils and internal vegetation in building number 2.

The 3D point cloud can be exported to software such as AutoCAD for line-drawing analysis, with precise dimensions, as has been done in the case of the Number 9 building in Fig. 45. It can also be exported to Revit software for HBIM analysis.



44. Line drawings extracted from scanned data from building number 9, illustrating spatial dimensions.

45. Furniture layout drawn in AutoCAD over the 3DLS plan of house 9.

3.2. Identification and analysis of transformations in traditional constructions

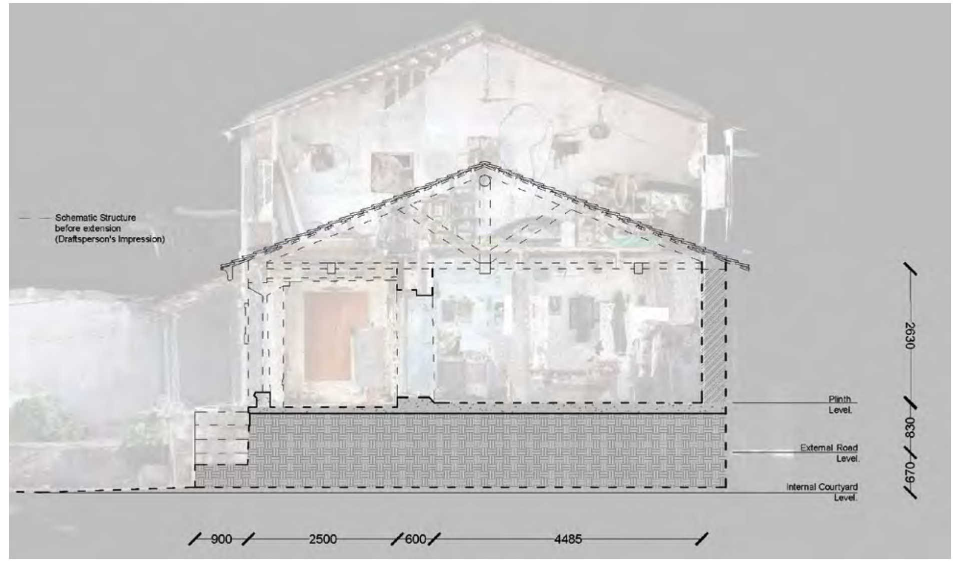
Traditional settlements undergo changes due to the changing needs of the community, access to new building materials, disasters, or migration. While 3DLS can provide measurable data to identify and analyse such changes, interviews are more effective in discovering their causes, as they offer insights into the experiences of the people living through the changes and, consequently, are a valuable resource for recovery planning.

These methods allow the analysis of various aspects of changes affecting houses and settlements, which, in turn, constitute important clues to determining the needs and vulnerabilities of the site and its inhabitants.

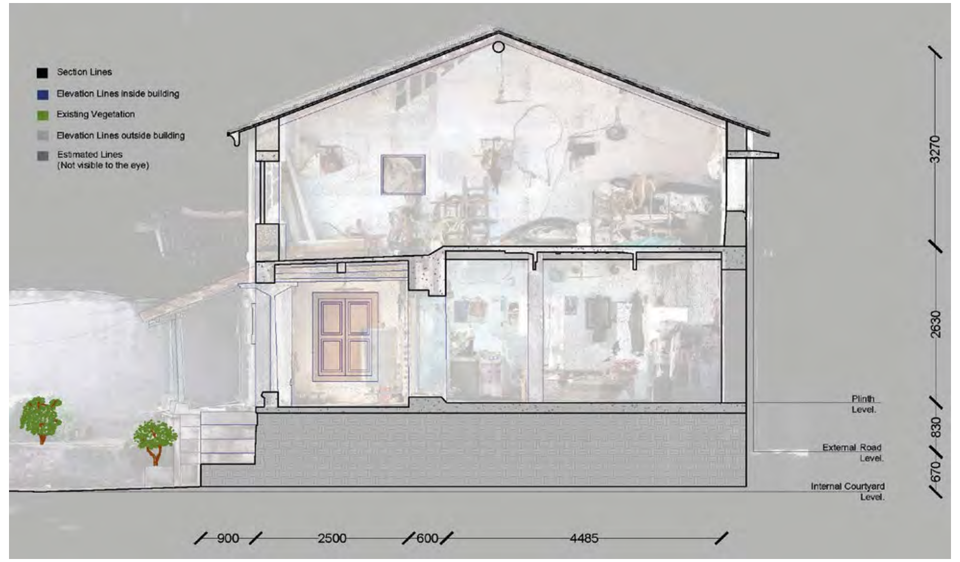
- Changes to the site over time, in relation to archival data, if available.
- Additions and alterations made by communities due to their changing needs, e.g. starting a family.
- Changes in the building materials employed due to external causes, e.g. access to newer materials.
- The use of non-local, non-traditional building techniques or materials due to the unavailability of local materials or the loss of traditional knowledge.
- The alteration of spaces due to changes in customs and practices.
- The effects of changing living patterns, e.g. post-disaster migration or rehabilitation.

46. House 1 showing upper floor added to an existing single-storey building.

47. Elevation of house 1 from the interior courtyard, showing the upper floor and its positioning, rendered from the 3D scanned data.



49. Schematic interpreted section of house 1 before adding the upper floor, drawn on AutoCAD from data acquired through 3DLS.



50. Section of house 1 with line drawing on AutoCAD analysing the existing structural system from the 3D point cloud data.

48. Plan of house 1 from the interior courtyard, showing the upper floor that was rebuilt after the 2001 earthquake.

In the case of Bela, communities increased their built space due to an average increase in family size. Due to the availability of land, most communities, especially the more privileged, choose to construct new buildings, often using non-traditional materials, such as brick or concrete, following traditional designs. For example, when interviewed, the owner of house 1 explained that the residential complex it belonged to was one of the oldest quarters in Bela. The entire complex was composed of single-storey units. The building in question was expanded with the construction of a second storey, in stone and timber. After the Bhuj earthquake in 2001, the most recent destructive in the region, the upper floor of the building collapsed entirely. Instead of traditional materials, the new storey (Figs. 46-50) was rebuilt using modern, non-traditional materials, e.g. stone and fired bricks with cement mortar, and Reinforced Cement Concrete (RCC) slabs. Currently, the space is used for storage.

By analysing the 3DLS scan with an AutoCAD line drawing (Figs. 49-50), the upper floor is seen to be at risk in the event of an earthquake, due to the heterogeneity of materials used and the inadequate structural support provided by the thin slab constituting the floor of the upper storey. In Bela, as in many similar cases, no technical support was provided (or sought) on adequately fitting a new structure made with new materials in the old building. The whole construction is thus potentially vulnerable now. Moreover, it also poses a danger to the central courtyard space, a potential assembly point, which could have provided refuge during an earthquake.

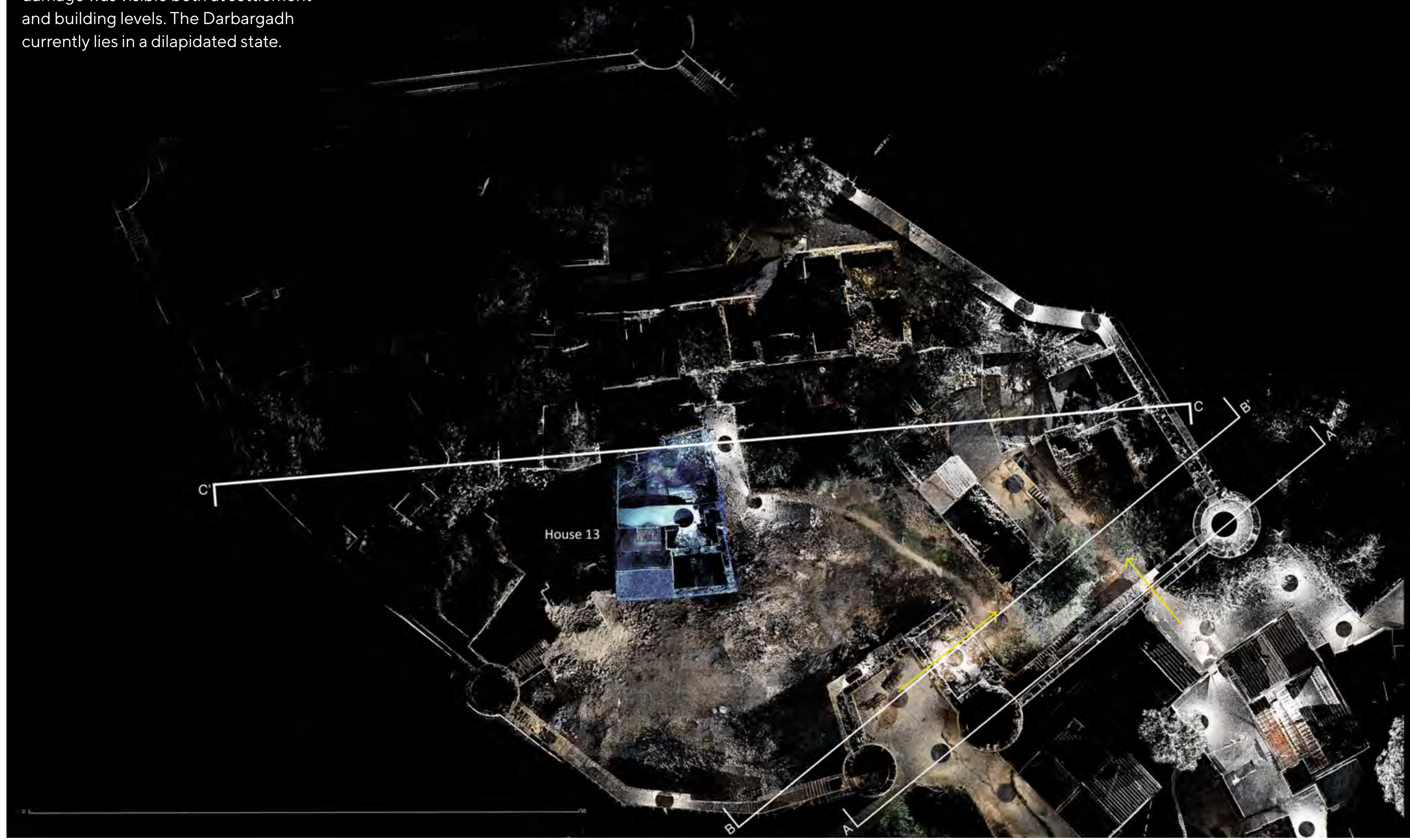
3.3. Earthquake damage assessment and risk

3DLS can be used as a basis to analyse different aspects relevant to the understanding of risk and damage in post-earthquake scenarios. Recently, there has been a rapid growth of research reporting successful experiences in the use of 3D laser scanning records for the structural (even automated) assessment and management of buildings, including architectural heritage, as well as infrastructure in general (Riveiro and Lindenbergh 2020). For example, it can be used to:

- Detect the type of damage, e.g. breakage, cracks, wall bends, sinking plinths.
- Gather measurable data to study the impact and magnitude of the damage in buildings.
- Detect internal damage, e.g. water seepage, and intrusive vegetation growth.
- Identify physical attributes, which could make the site more vulnerable, e.g. heterogeneous use of materials, uncontrolled expansions of buildings, or external features, such as trees or lamp posts.
- Identify patterns in the damage suffered after an earthquake, e.g. collapsed roofs, broken tiles or wall deviations.
- Measure the rubble present after an earthquake to plan its management and potential reuse.

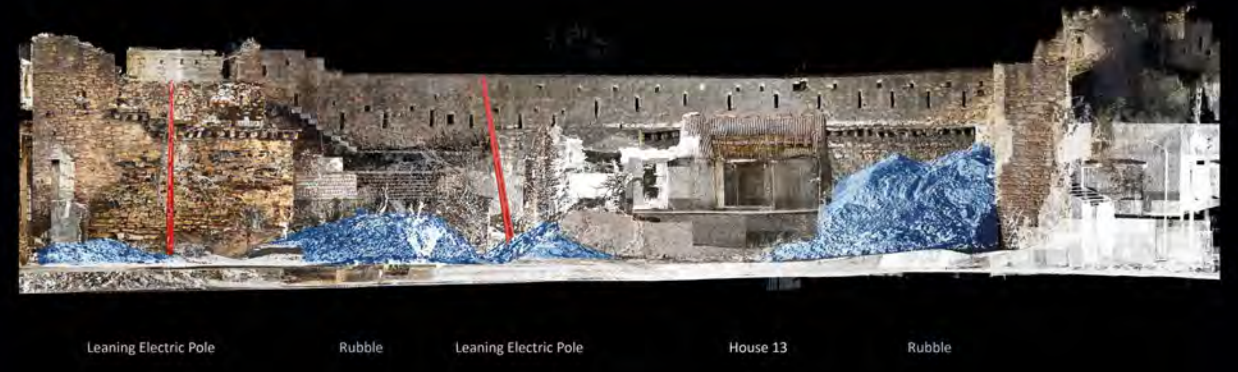
3. 3DLS for post-earthquake analysis

51. Plan of the Darbargadh (Fortress) extracted from 3D scanned data, indicating section lines. In Bela, the damage was visible both at settlement and building levels. The Darbargadh currently lies in a dilapidated state.

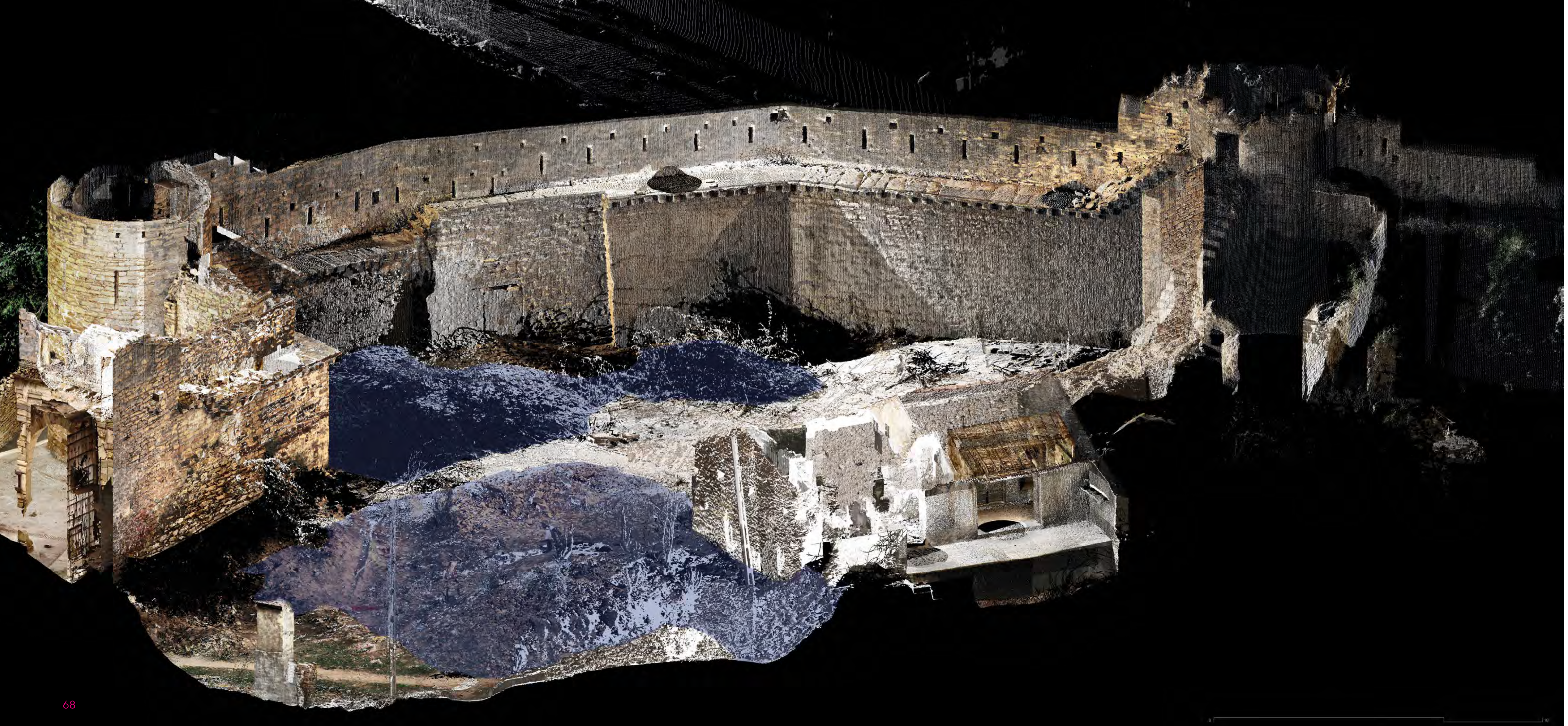


52. Section AA′ showing access points in the Darbargadh derived from the 3D scanned data.

53. Section BB′ showing the vegetation in Darbargadh derived from the 3D scanned data.



54. Section CC showing house 13 surrounded by rubble and vulnerable objects.



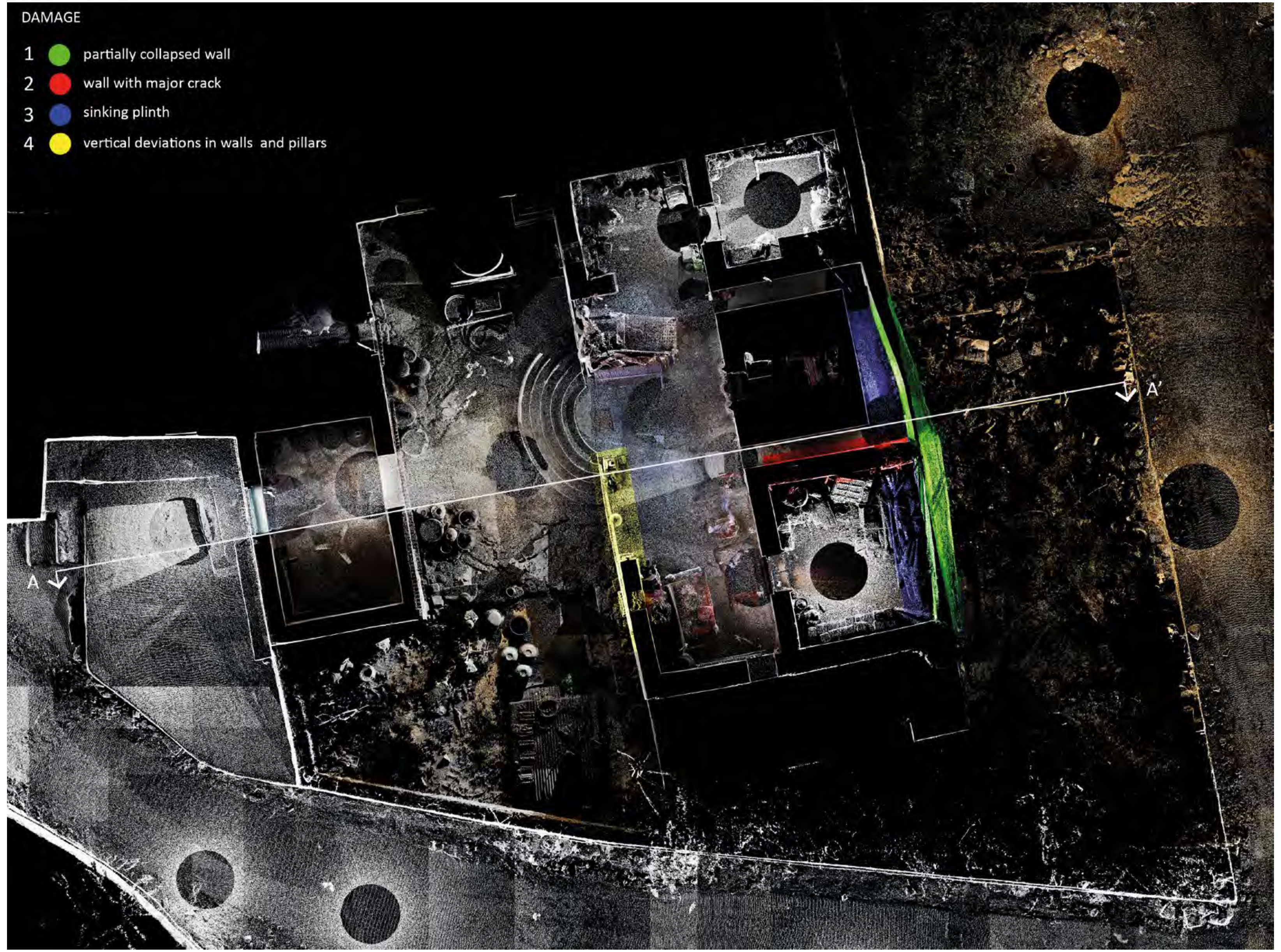
55. 3D view of building 13, with a partially collapsed roof and walls inside the Fortress in Bela. The surrounding rubble is marked in blue. The image was rendered from the 3D scanned data, using the same line profile as in section CC'.

56. Photographic record of building 13 in Bela, with surrounding debris as marked in the previous figures. Photograph taken in the opposite direction of image 55, showing the back of the building.

57. Top views of building 13 inside the Darbargadh in Bela. India. In a post-earthquake scenario, aerial drone photography and video capture are the most relevant records to complement the terrestrial 3D laser scan data. They can help damage assessment even when buildings are physically inaccessible. It is an excellent complement to the 3D laser scanner that only captures data from the ground level, especially when there is no access to higher points to cover rooftops, treetops or inaccessible open spaces.

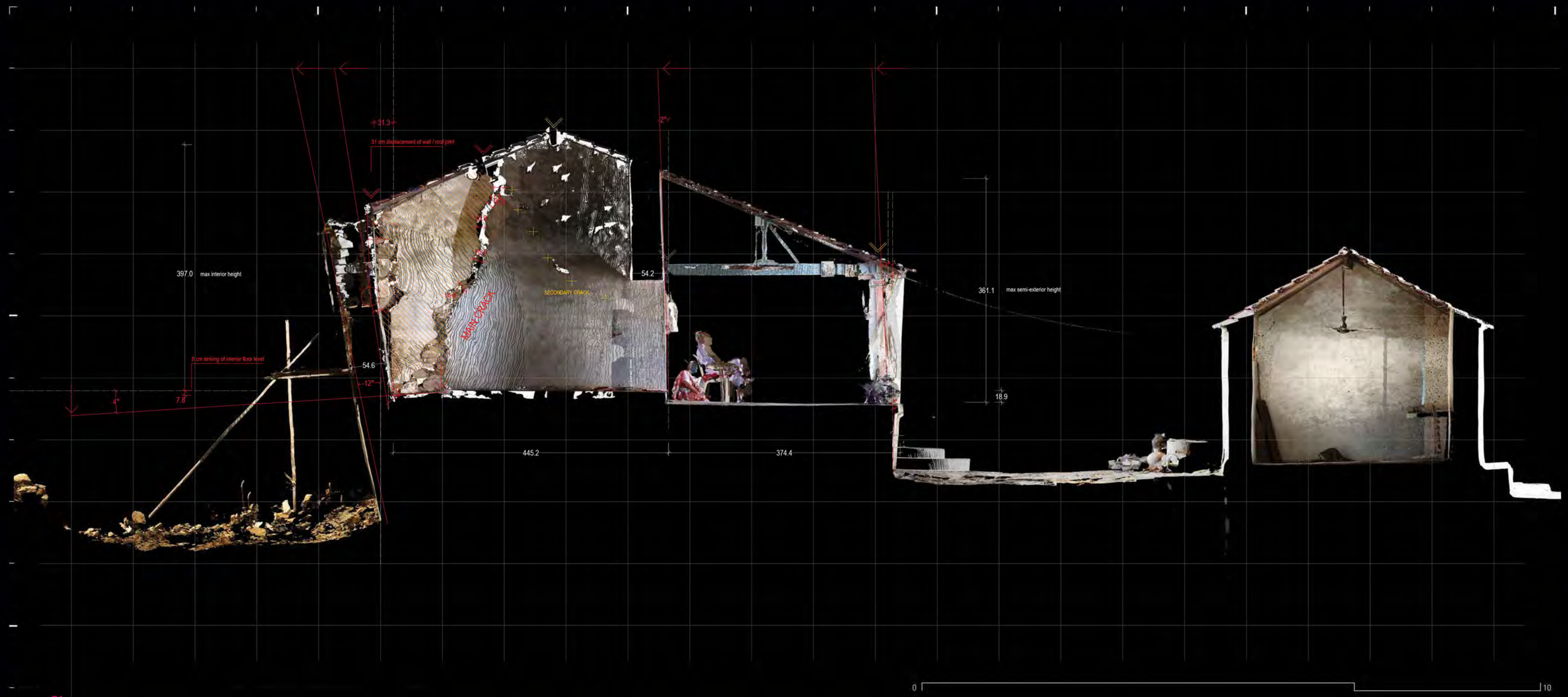
As seen in the figures 51-57, plans and sections generated with 3DLS data accurately represent and measure spatial conditions like debris spread; vulnerable and/or hazardous objects, such as leaning electric poles; access points; and potentially damaging vegetation. In this instance, a fire hazard was identified in the significant number of dry branches. All this information can be used to develop retrofitting strategies for damaged buildings after an earthquake (see *Case Study 1: Advanced recording technologies for post-earthquake-damage assessment and re-construction in Chilean vernacular settlements*), as well as planning evacuation routes and motivating concrete actions to reduce risks.

At the building level, a community temple in Bela, henceforth Building 5, showed evidence of extensive damage and allowed studying the extent and typology of damage (Figs. 58-64). According to the residents, cracks formed during the 2001 earthquake grew larger and deeper over the years, especially along the circumambulatory pathway (Fig. 60). Due to a lack of maintenance over the years, a void (labelled *Damage 1*) formed on the eastern wall. At the time of the 3D laser survey, the gap was under repair, hence the scaffolding on the east side of the temple. The plinth of the structure was also revealed to have sunk, especially at the eastern end (labelled *Damage 3*).



58. Plan of Building 5 rendered from the 3DLS data of June 2021 with damage identified in colour.

59. East elevation of temple 5 rendered from the 3DLS data in June 2021, showing the partially collapsed wall (damage 1).

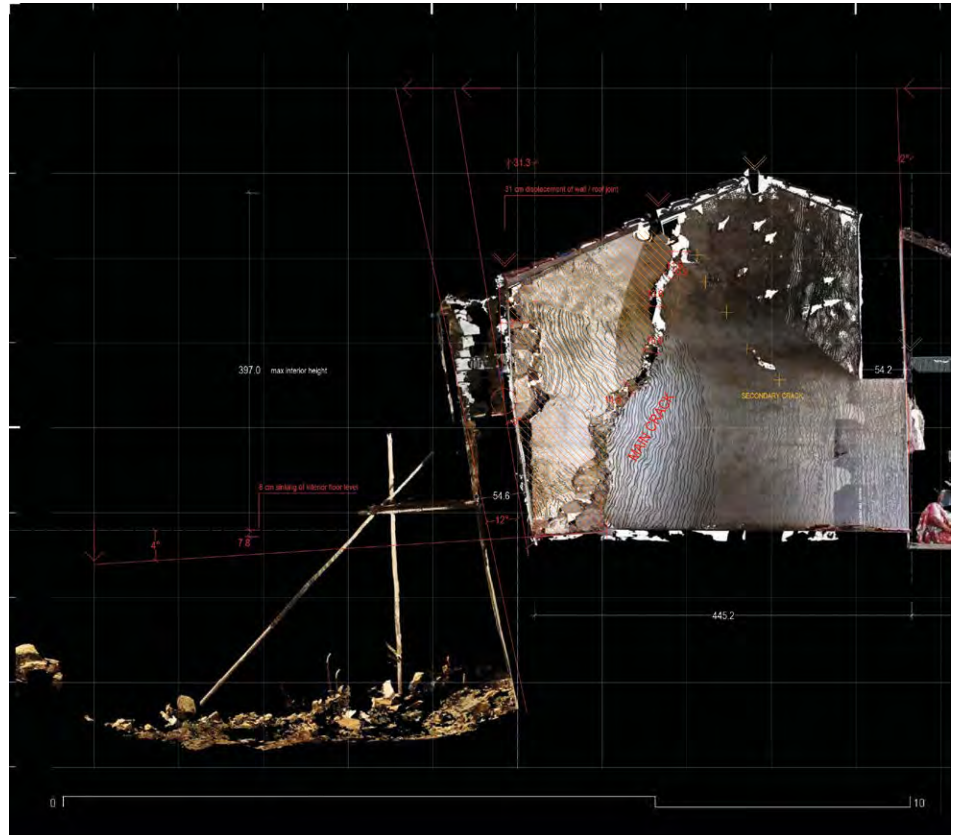


60. Analysis of the cross-section AA′ from the LiDAR data of the temple 5 in Bela, Gujarat. The possibility of generating this type of building profile is also helpful to be analysed in specific structural software.

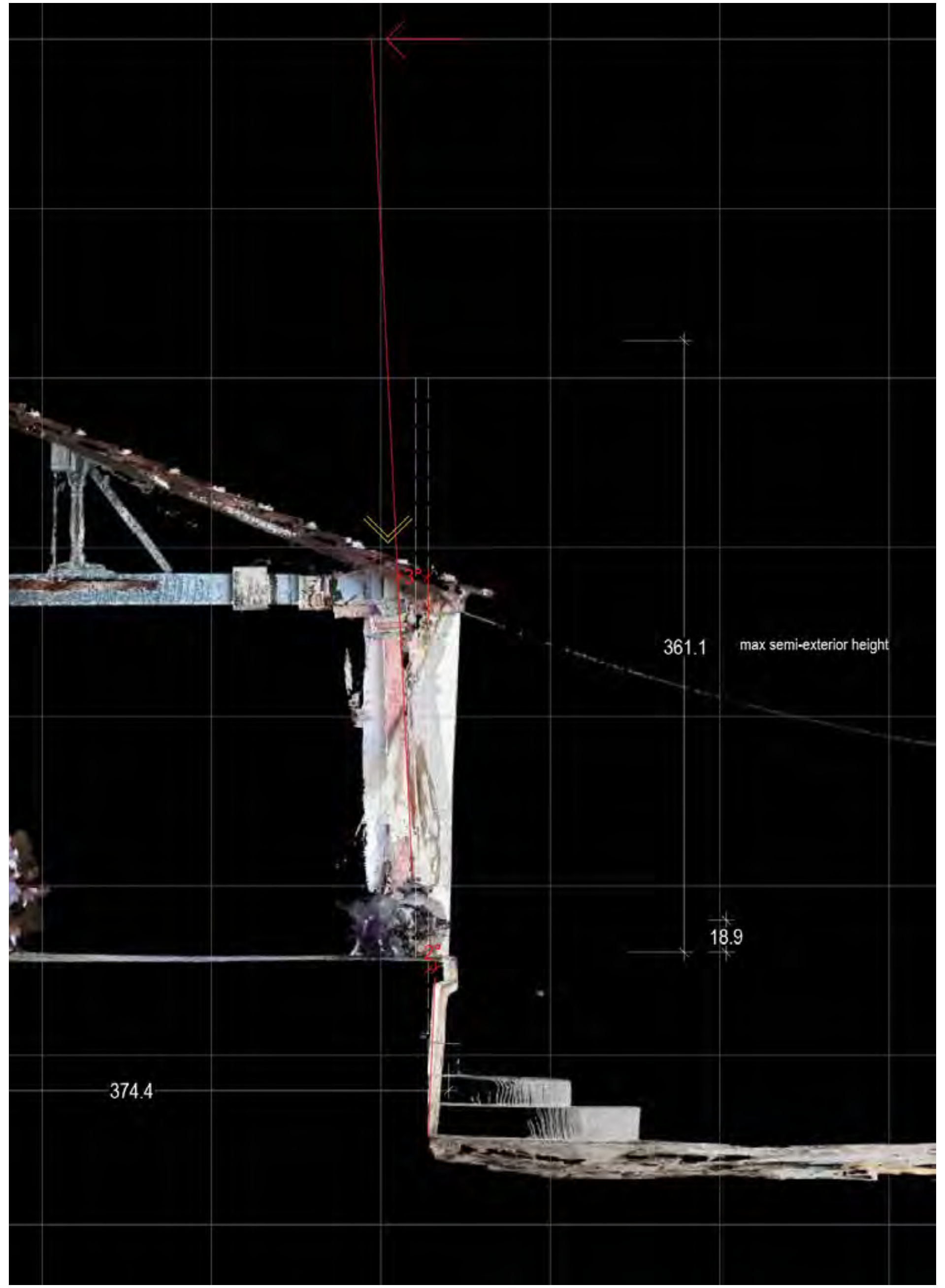
61. Section AA', showing the extent of damage 2 (wall cracks and deviation).

The information gathered from the 3DLS should be further analysed by trained engineers to guide the building's structural assessments and repair, informing the overall recovery process.

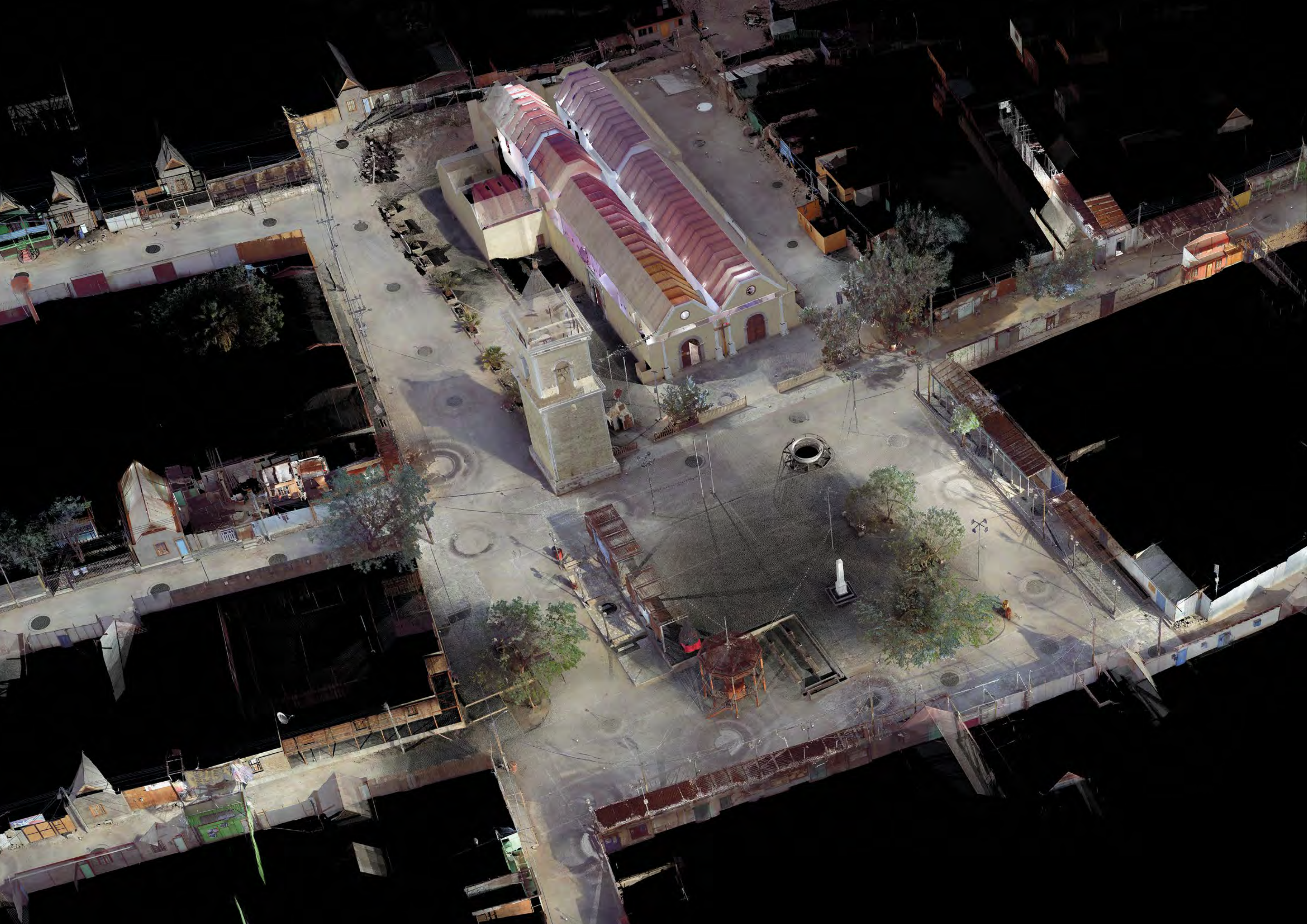
62. Internal view of Damage 2 (wall cracks) and portion of damage 1 (collapsed wall). Photographs can also serve as evidence of damage, but without accurate metric information as with 3DLS.



63. Zoom damage 3, sinking plinth.



64. Zoom damage 4, vertical deviations in walls and pillars.



4

End matter

4. End matter

4.1. Acknowledgements

This guidance document is one of the outcomes of the research project: "A sustainable *re-construction* method for seismic-prone heritage areas of India based on advanced recording technologies" (www.3D4Heritageindia.com),[5] based at the Centre for Architecture, Urbanism and Global Heritage in Nottingham Trent University (NTU) and funded by the UKRI Arts and Humanities Research Council (AHRC) and the Department for Digital, Culture, Media and Sport (DCMS). Project Reference: AH/V00638X/1.

The research team comprises Dr Bernadette Devilat as Principal Investigator; Professor M. Gamal Abdelmonem as Co-Investigator and Dr Felipe Lanuza as Research Fellow from the Centre for Architecture Urbanism and Global Heritage NTU. In India, the team is composed of Dr Jigna Desai as Co-Investigator, Mrudula Mane as Research Associate, and Zeus Pithawalla as Research Assistant from the Centre for Heritage Conservation (CHC), CEPT Research and Development Foundation (CRDF) in Ahmedabad; and the Hunnarshala Foundation (in particular Aditya Singh) supporting with community participation and providing key networks and local knowledge in Kutch, Gujarat. From the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM) in Rome, Dr Rohit Jigyasu is Co-Investigator and Sukrit Sen is Research Associate.

5 In the future, the project's website will be accessible permanently under this address: https://3D4heritageindia.wordpress.com/

The on-site scanning in Bela, India, was done as part of this project in 2021 by Mrudula Mane and Zeus Pithawalla, with the support of Dr Jigna Desai (CHC CRDF), Aditya Singh and Tanvi Choudhari (Hunnarshala Foundation); and Sukrit Sen (ICCROM). Post-processing and visual outcomes were done by Dr Bernadette Devilat and Dr Felipe Lanuza (NTU). An exhibition and community engagement workshop were done in Bela in November 2021, which counted with the support of the same India team, plus Nigar Shaikh (CEPT University) and Komal Pawaskar (Hunnarshala Foundation).

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Declaration of interest: Faro Technologies kindly facilitated access to the 3D laser scanning equipment at a discounted rate in exchange for including the Faro logo on the project's website and outcomes.

4.2. Image credits

Photographs: Bernadette Devilat (Figs. 01 to 03 and 14), Sukrit Sen (Figs. 04, 26, 29), Mrudula Mane (Figs. 05, 12, 15, 28 and 56); and Zeus Pithawalla (Figs. 08, 09, 46 and 62).

Drone photographs: Rishi Khatri, supported by Astha Desai and Zeus Pithawalla (Fig. 57).

Images and technical drawings from 3DLS data: Bernadette Devilat and Felipe Lanuza, using the 3D data obtained on-site by Mrudula Mane and Zeus Pithawalla, supported by Jigna Desai; Aditya Singh and Tanvi Choudhari; and Sukrit Sen (Cover and figures: 06, 07, 16 to 22, 25, 30 to 32, 36, 37, 47, 57, 59).

Diagrams and illustrations: Mrudula Mane (Figs. 10 and 68) and Aditya Singh (Fig. 34).

Plans and leaflet: Felipe Lanuza (Figs. 11 and 13).

Drawings over 3DLS images: Felipe Lanuza, using the 3D data by Bernadette Devilat, Mrudula Mane and Zeus Pithawalla (Figs. 23, 24, 44, and 60, 63 and 64). Also, Figs. 33, 35, 36, 48, 51, 52, 54, and 58 based on the image concept by Sukrit Sen.

Drawings over 3DLS images: Bernadette Devilat, using the 3D data by Felipe Lanuza, Mrudula Mane and Zeus Pithawalla (Fig. 61). Also, Fig. 55 based on the image concept by Sukrit Sen.

Drawings over 3DLS images: Sukrit Sen, using the 3D data by Bernadette Devilat and Felipe Lanuza, obtained on-site by Mrudula Mane and Zeus Pithawalla (Fig. 27, 38 to 45, 49, 50 and 53).

Images and technical drawings from 3DLS data: Bernadette Devilat, using the 3D data obtained on-site in Chile with the help of Diego Ramírez and Felipe Lanuza (Figs. 65-67).

Divider images: Dividers 1 and 2: Sukrit Sen, Dividers 3 and 4: Bernadette Devilat and Felipe Lanuza.

4.3. Glossary of Terms

1) 3D laser scanning: a documentation technology that uses a laser to capture data from the built environment in the form of a point cloud.

2) 3D meshes: a mesh is a geometric data structure formed of continuous surfaces divided into a series of polygons with XYZ values. A point cloud obtained via 3D laser scanning can be processed (and simplified) into meshes to further assess and work with the captured data.

3) 3D printing: making three-dimensional solid objects from a digital file using a 3D printer.

4) Axonometric view: a type of orthographic projection of a three-dimensional object rotated on one or more of its axes, to convey a three-dimensional visualisation and understanding of it, keeping its geometric properties (opposite to the use of perspective). 3D laser scan data of a building can be rendered in axonometric views for its visualisation, measurement and assessment, as well as in perspectival mode to resemble the visual perception of the captured object.

5) CAD: Computer-Aided Drawing.

6) Carbon footprint: the amount of carbon dioxide and other carbon compounds emitted due to certain activities, such as construction or the use of fossil fuel transportation.

7) Circumambulatory pathway: the path surrounding a sacred object or space, usually found around shrines.

8) Computer specifications: technical descriptions of the computer's components and capabilities such as processor speed, model, manufacturer, etc.

9) Conventional survey and/or documentation techniques/tools /methods: generally used or having been extensively used over the past for documenting buildings for one or more of the following purposes: assessment, representation, study, conservation, and intervention.

10) Disaster risk management: applying policies and strategies to prevent or reduce disaster risks and/or losses, contributing to the resilience of affected settlements and communities.

11) *Re-construction*: to build again, as a step forward, respectful towards the past but adaptable to ever-changing social, cultural and physical contexts. It refers to a comprehensive methodology for a wider long-term conservation strategy of housing in heritage areas that includes risk mitigation, planning and post-earthquake response. It makes a distinction with reconstruction—understood as current responses and strategies of replication 'as before' (Devilat 2021).

12) Registration process: to connect each individual scan to generate a digital point cloud that replicates the geometric properties of the documented site/object. It is made through specific software corresponding to the equipment used in the data capture.

13) Social setup: an aspect of a settlement that pertains to the human environment among which events occur and among which characters live or interact.

14) Total station: a surveying instrument used for measuring land, infrastructure and buildings, which integrates electromagnetic distance measuring and an electronic theodolite.

15) Heritage values: the meanings and values that individuals or groups of people bestow on heritage, including collections, buildings, archaeological sites, landscapes and intangible expressions of culture, such as traditions (Díaz-Andreu, 2017).

16) Vernacular Heritage: buildings and settlements built with traditional ways and methods developed over the years in response to their specific needs, locally available resources, and their surrounding environment. According to Devilat et al. (2021) vernacular built environments are vital for sustaining particular ways of living and the cultural heritage of usually vulnerable inhabitants.

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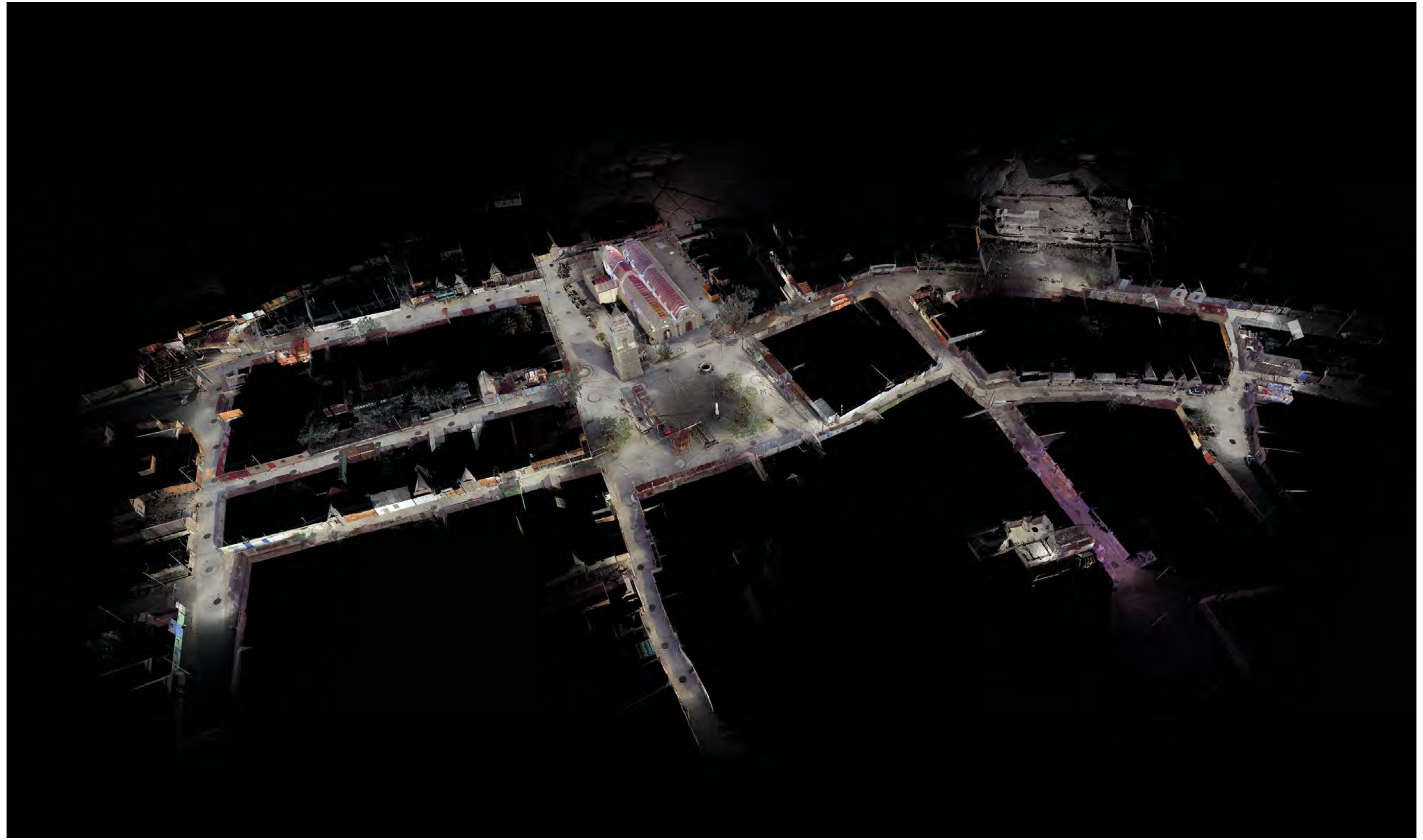
4.5. Case studies

4.5.1. Advanced recording technologies for post-earthquake-damage assessment and *re-construction* in Chilean vernacular settlements

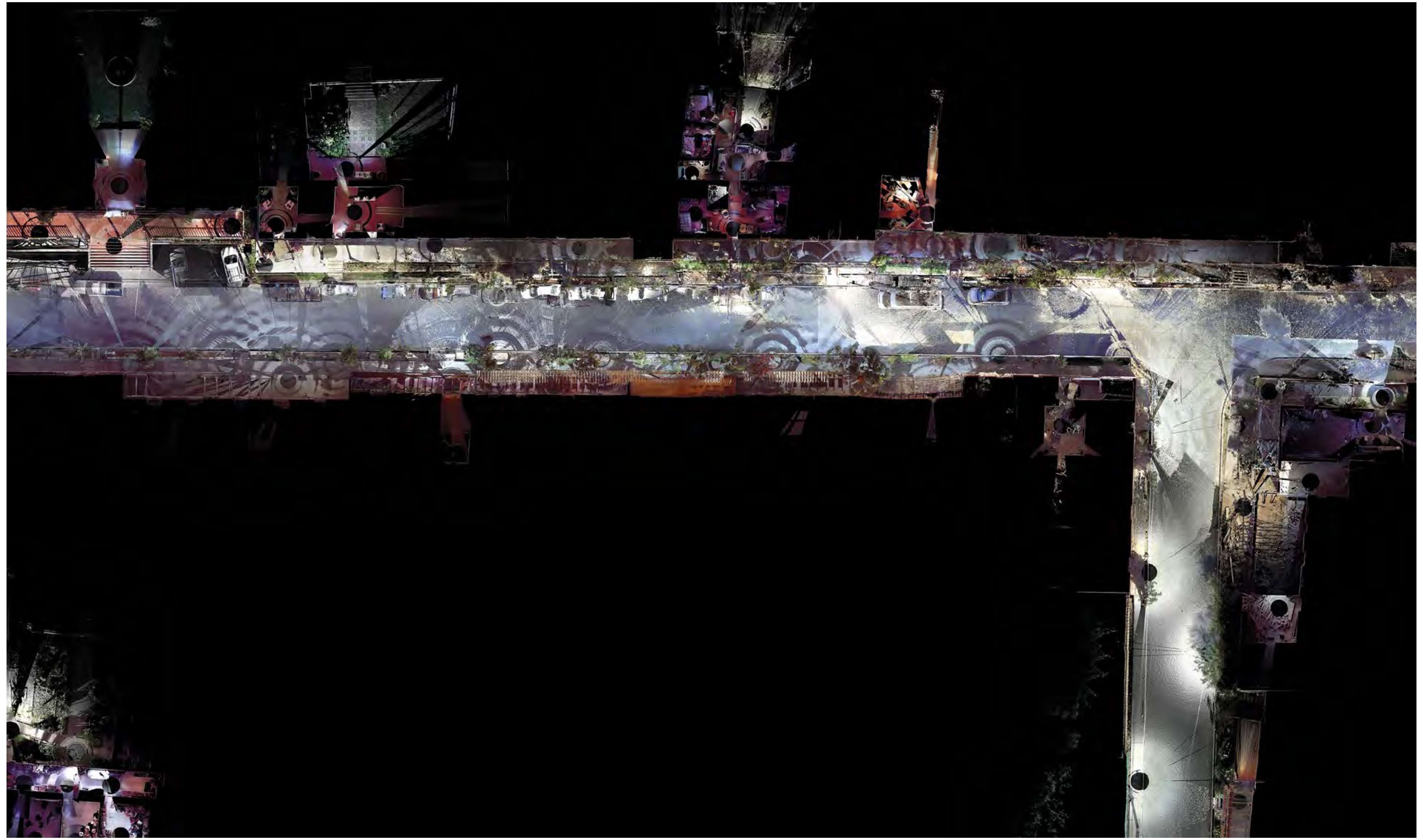
This case study shows the first time advanced recording technologies were studied for the *re-construction* of seismic heritage areas in Chile by Dr Bernadette Devilat. Heritage settlements in Chile are built using mainly vernacular building techniques such as adobe and quincha. Despite earthquakes occurring regularly, specific approaches for housing in heritage settlements are only created after the destruction, making them insufficient to avoid large-scale damage and disruption; where one of the critical challenges is the documentation of structures pre and post-earthquakes with the aim of reusing as much as possible instead of complete replacement. This is part of what she proposed as *re-construction*, an alternative vision to the previous reconstruction approaches mainly based on uncritical replication.

By using 3DLS to document the heritage settlements of San Lorenzo de Tarapacá (Fig. 65), Zúñiga and Lolol, affected by the 2005 and 2010 earthquakes, she introduced an in-depth understanding of contextual information of the villages, recording each one in just three days on-site. This was an experiment to see how much data could be captured in a short period, to resemble a post-earthquake emergency situation, with some extra days for collecting complementary social information through questionnaires. Based on the resulting comprehensive and measurable 3DLS data of what was available in each site, Devilat proposed design strategies to promote reparation and reuse of damaged vernacular dwellings, discussed the implications of heritage reconstruction with analysis throughout different periods of time and use, and argued for the introduction of the technology institutionally. This informs a more inclusive and sustainable method for risk mitigation, *re-construction* and emergency actions, taken forward in the research project in India—with similar challenges to avoid the displacement of local people.

Taking just one of the three settlements as an example, over a span of three days, a total of 195 scans and almost 6 billion points were captured in the public area designated as a *Typical Zone* in Lolol (Figs. 66 and 67). Using the processed 3DLS and social data, and according to the level of damage to each house, a series of strategies were developed to inform interventions and future designs. The interventions proposed solutions for the reuse and repair of affected dwellings; a way forward that respects the past whilst adapting to ever-changing social, cultural and physical contexts. They were grouped in two phases: first, securing safe inhabitation through emergency shelters and supports; and second, addressing *re-construction* as a way of retrofitting the affected dwelling, using the post-earthquake 3D record.



65. Aerial view of San Lorenzo de Tarapacá, Chile from the terrestrial 3D-laser-scanning obtained on-site in 2013, showing damage constructions and governmental reconstruction after the 2005 earthquake.



66. Partial portion of the plan of Lolol, Chile, rendered from the 2013 3D laser scans obtained in three days on-site.

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The consolidated data allowed to understand people's ways of living, which could help design spaces aiming to not disrupt their living patterns during the design of these strategies. The developed solutions were site-specific but the procedure is replicable for similar sites that need to undergo post-earthquake recovery and proves to be fast and sustainable due to working with the remains instead of building anew.

Acknowledgements: The on-site scanning of Lolol, Chile was done in 2013 by Bernadette Devilat and Felipe Lanuza, as part of the fieldwork of her PhD research titled: '*Re-construction* and record: exploring alternatives for heritage areas after earthquakes in Chile' at the Bartlett School of Architecture, University College London (UCL), supervised by Professors Stephen Gage and Camillo Boano. That doctoral research was finished in 2018 and was funded by the National Agency for Research and Development (ANID), Scholarship Program Doctorado Becas Chile 2009-72100578. There was no connection with Faro Technologies at that time. With thanks to Diego Ramírez for facilitating the 3D laser scanning equipment in Chile.

67. View of a dwelling affected by the 2010 earthquake in Lolol, Chile, with proposed storage-walls for materials and rubble to be re-used designed over the 3DLS data obtained on-site.

4.5.2. Documenting as training: Two Heritage Houses in the Walled City of Ahmedabad

Efforts need to be made to build the capacity of professionals in the Disaster Risk Management and Heritage sectors, and in academic institutions, to use this technology and make it more accessible economically and in terms of expertise. 'Surveying heritage buildings in Ahmedabad, India: Empowering local action and skills for heritage conservation' was a parallel project implemented alongside the 3D laser scanning in Bela in which a partnership between academia and industry (FARO, the manufacturer of the 3D laser scanner used) was set. It aimed to install local capacities for recording and surveying heritage buildings; a knowledge transfer to improve maintenance and tackle deterioration. This was done through a series of training activities done by Dr Devilat from NTU for students and staff of CEPT University and the Center for Heritage Conservation (CHC) CEPT Research and Development Foundation (CRDF) in Ahmedabad. The data captured included two houses listed as Grade III heritage buildings, located within the UNESCO World Heritage Site of the Walled City of Ahmedabad. By giving access to the equipment, software, and training to the local team in India, they were able to carry out the 3DLS survey in Bela, as the UK team was not able to travel due to COVID-19-related risks and restrictions. The post-processing was done by the UK team.

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With thanks to Jinagya Awas Trust in Ahmedabad for facilitating access to the buildings.

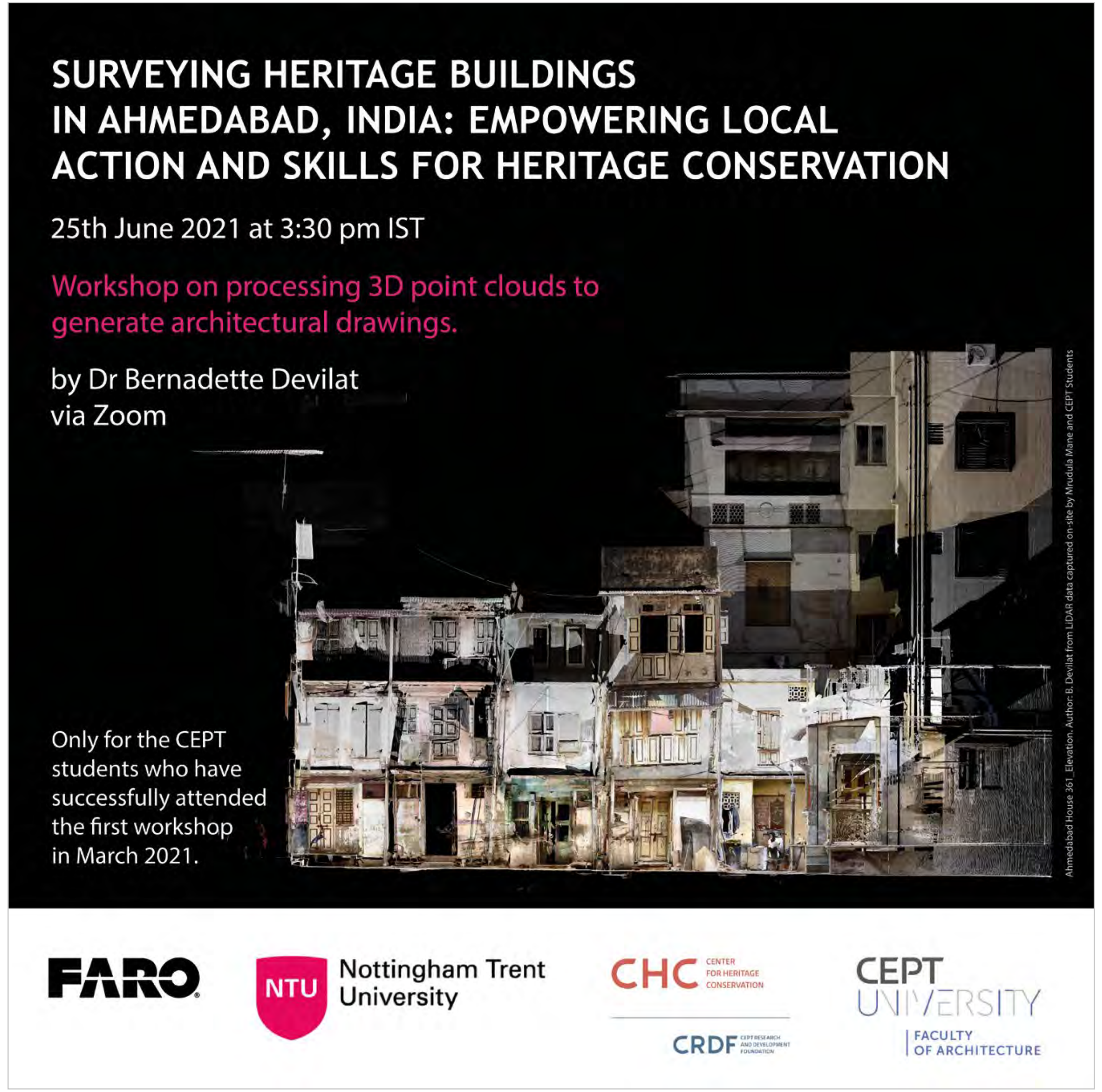

Figure 68: Poster of the second student workshop.

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