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TEST FACILITY TO STUDY TRADITIONAL COMPOSITE MASONRY STRUCTURES IN BHUTAN – AN OUTCOME OF SATREPS

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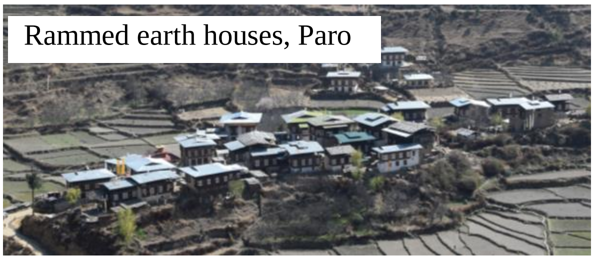
Abstract

Present-Day Bhutan as a nation still practices and actively promotes the nation's indigenous construction practices involving rammed earth and stone masonry houses, which constitute almost 70% of the household in the country. However, the past seismic activities in the Bhutan Himalayan region highlighted that these structures show vulnerabilities against the ground shaking. In pursuant to the damages suffered by the traditional houses from the two earthquakes of 2009 and 2011 that affected Bhutan and the recent damages to traditional stone masonry houses in Nepal during the 2015 Gorkha earthquake, necessitated scientific studies to understand and enhance the seismic performance of such buildings. This paper puts a light in the history of how a USD 4.48 million 5-year intensive research project titled "Project for Evaluation and Mitigation of Seismic Risk for Composite Masonry Buildings in Bhutan" under the scheme of Science and Technology Research Partnership for Sustainable Development (SATREPS) was initiated. The project, as its significant outcome, gives a multi-facility state-of-the-art test facility in the South Asian region in the field of structural and seismic engineering. The paper presents the construction process of the test facility on both full-scale static test and shaking table system, from the pre-construction planning to actual execution channeled through task-based approach, encapsulating the unforeseen hindrances and challenges to post-construction analysis. The paper deals in detail the construction management of the first-ever test facility established in Bhutan. An effort has also been made in presenting the situation analysis based on the cost and schedule of the project. The presented information and lessons learned will serve as a guiding principle in the planning and execution of the similar nature of work in Bhutan. In addition to the construction management aspects, this paper presents the details of the test equipment and instrumentations available at the test facility. More importantly, this paper aims to provide first-hand information on the services available in the test facility for researchers, engineers, and related technical personnel in the field of structural engineering. The paper concludes with a brief overview of the test set-up designed for a pilot shaking table test on a 1/6th scaled two-storied traditional rammed earth building.

Keywords: Traditional construction; Structural engineering; Construction management; Test facility; Bhutan

1. Introduction

There is a rich repository of traditional knowledge systems in the field of Bhutanese indigenous construction materials, techniques, and practices, i.e., rammed earth and stone masonry (with mud mortar) houses. These rich traditions have been passed down from generation to generation through oral transmission and hands-on practices. However, there are rare documentation of such practices in written format, and if found, are only limited to religious works of literature. Statistically, most houses in Bhutan are build using indigenous materials and techniques, such as rammed earth and random stone masonry in mud mortar with an integrated timber system. Rammed earth construction is one of the most dominant traditional construction practices and popular in the western part of Bhutan (Fig.1). A massive rammed earth wall combined with timber components are the main features of such construction typology. The basic technique involves the selection and placing of suitable soil in layers inside a formwork, made of wooden boards, and then hardened by ramming. Stone masonry with mud mortar construction is popular in the eastern region of Bhutan.



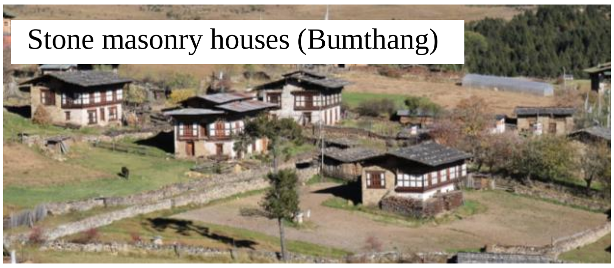


Fig. 1 – Cluster of rammed earth houses (left) in Esuna village, Paro and stone masonry houses (right) in Shingkhar village, Bumthang

1.1 History of earthquakes

The Himalayan region of Bhutan remains secluded from major seismic studies and attributed lack of information(s) underlined that no great earthquakes occurred in this segment of Himalaya (apparent seismic gap). On the contrary, several major earthquakes (M>8) were documented both geologically and historically in the central and eastern Himalaya: in western Nepal (A.D. 1505, ~M8.7), in Bihar-Nepal (1934, M8.1), in Assam (1950, ~M8.4), and near the Shillong plateau (1897, ~M8.1) [1]. However, the findings of the 1714 A.D earthquake reclassifies the apparent seismic gap to a former information gap and imply that the entire Himalayan arc has a high level of earthquake potential [2].

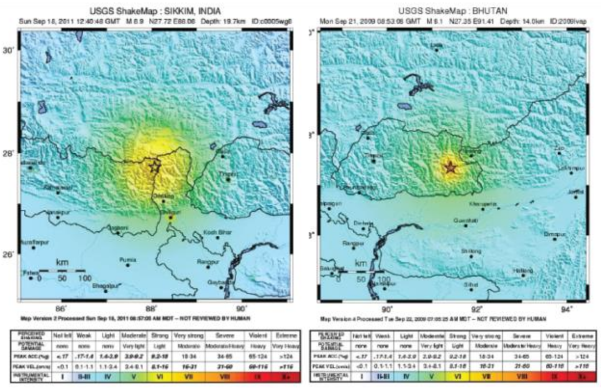
Moreover, Bhutan has witnessed the seismic event (earthquake of a magnitude not exceeding M7) in the last decades. The recent seismic events that have occurred in this region also show a high probability of another strong earthquake to occur close to the Bhutan Himalayan region.

1.2 Challenges for Bhutan

According to the National Statistics Bureau (NSB) of Bhutan, 66% of households in the country, especially 83% of households in rural areas, live in such traditional buildings. These traditional buildings represent not only the unique architecture of Bhutan but also expresses the social and economic viability of the community. The sustenance of this community-based practice using indigenous materials and techniques to build traditional houses is an integral part of the unique cultural landscape of Bhutan.

With the increasing socio-economic development and rapid urbanization, the local population prefers to replace traditional construction practices by modern construction practices (such as reinforced concrete buildings). The observation of the poor structural performance of such houses during the last two earthquakes of September 2009 and September 2011 earthquakes, as illustrated in Fig.2, further triggered the public to believe that such traditional masonry structures do not perform well against the earthquake. From the statistics based on the National Recovery and Reconstruction Plan (NRRP) documents, the 2009 Narang Earthquake affected 4950 rural homes, and the 2011 Sikkim Earthquake affected 6,977 rural households in

20 Dzongkhag. Proper investigations are required to clear the misconception about the poor seismic performance of traditional houses during the last two earthquakes. The poor performance entails to critical factors such as typology and age of the house, quality of construction, amongst other aspects. Scientific and engineering experimental research and studies on such types of constructions (masonry structures) are limited and require much attention globally. At a national level, the Royal Government of Bhutan places high importance on the preservation and promotion of indigenous construction practices, and one such attempt is to study the traditional Bhutanese houses [3-6]. These experiments reported in the literature are limited to pull-down tests with the use of excavators in the absence of proper testing facilities and financial constraints.



(a)

(b)

Fig. 2 – (a) 2009 and 2011 earthquakes [http://earthquakes.usgs.gov/] (b) Damages suffered by traditional houses.

1.3 Initiation of Science and Technology Research Partnership for Sustainable Development (SATREPS) project

A systematic and thorough scientific research to evaluate the load-bearing masonry structures is necessary to make a judgment on the safety of such structures, especially for the least developed countries. Such types of houses are understood to be vulnerable to seismic activity, but we need to consider the affordability and social aspect of such communities. Aside from typical dwelling houses, there is much need for seismic evaluation, and judgment for many of the large scale heritage structures which are of similar construction in nature, which represents the unique heritage of the place. In an attempt to understand the traditional material and techniques, through the lens of engineering-based approach, the Royal Government of Bhutan has been seeking technical and financial supports from developing partners. One such significant initiative found in Bhutan is the "Project for Evaluation and Mitigation of Seismic Risk for Composite Masonry Buildings in Bhutan" under the scheme of Science and Technology Research Partnership for Sustainable Development (SATREPS).

This particular five years (April 2017 to March 2022) intensive research project exemplifies the continued effort made by the concerned local governmental Bhutanese organization in collaboration with Japanese institutes. This SATREPS project provided the rare opportunity to develop the concept of the test facility in Bhutan, not only to realize the overarching set objective but to sustain and facilitate future research works. The allotted budget for the project is USD 4.48 million (USD 2.80 million funded by Japan International Cooperation Agency (JICA) and USD 1.68 million by Japan Science and Technology Agency (JST)) and partly funded by RGoB. The overall goal of the project is to disseminate the seismic technology for disaster mitigation of the composite masonry buildings through:

- Evaluation of the seismic risk of composite masonry buildings
- The development of seismic technology for constructing and strengthening such buildings
- Enhance the dissemination mechanism for seismic technology.

Although this SATREPS project deals with several aspects of evaluation and mitigation of seismic risks, the present paper primarily focuses on the details of the test facility, which is one of the primary outcomes of the project. The paper deals in-detail the construction management of the first-ever test facility established in Bhutan. More importantly, this paper aims to provide first-hand information on the services available in the test facility for researchers, engineers, and related technical personnel in the field of structural engineering.

2. Experimental test facility – Research Institute for Traditional Structures (RITS)

The approach for the design of the test facility caters to future expansions as deemed necessary, keeping in view the continuum up-gradation of local technical capacities and observing the constant technological advancement. The current form of this test facility can cater to basic material testing to quasi-static tests on real sized specimens and dynamic testing of reduced-scaled prototypes. The test facility will play a crucial role in understanding the load-carrying capacity and seismic responses of buildings in Bhutan.

2.1 Test facility location, its major components, pre-construction planning, and project timeline

The test facility is located within the premises of the Department of Culture (DoC) at Kawajangsa, Thimphu. The major structural components of the state-of-art test facility include two reaction walls and two strong floor systems, one strong floor with underground access, as illustrated in Fig.3. The test facility has the capacity to conduct three full-scale static tests at the same time. The reaction walls have the lateral load-carrying capacity of 2000kN (lateral design load) at the height of 5 meters. The facility also houses the shaking table in between the two reaction walls. Table 1 shows the material specification used for the construction. An enclosed shear wall on four sides and seven shear walls of 300mm thick supports the strong floor-1 of slab thickness 1200mm at the underground level. This part of the test facility has underground access, and the whole system is laid with a mat foundation base slab of 800mm thick.

After the design phase, the Japan International Cooperation System (JICS) have made tender for construction works, with technical assistance from NCU and DoC. Following the tendering process, the work was awarded to a local construction firm, M/s Tashi Deling Construction and Consultancy firm based on the firm's capacity and quoted price through a competitive bidding process. The total cost of construction of the test facility was USD 387,226.27. Table 2 shows the timeline of the construction process with significant events.

Table 1 – Details of material specifications

Material specification	Details
Concrete grade	M20
Steel reinforcement grade	Fe 500
Reinforcement diameter (mm)	10, 12, 16, 20, 25, 28

Table 2 – Project timeline

Major event detail	Date
The signing of the contractual works	Dec 07, 2017
Place of a work order to the contractor	Dec 13, 2017
Salang Tendrel (Groundbreaking ceremony inaugurated by Queen mother of Bhutan)	Dec 26, 2017
Expected completion date	Jul 15, 2018
Actual completion date	Dec 20, 2018

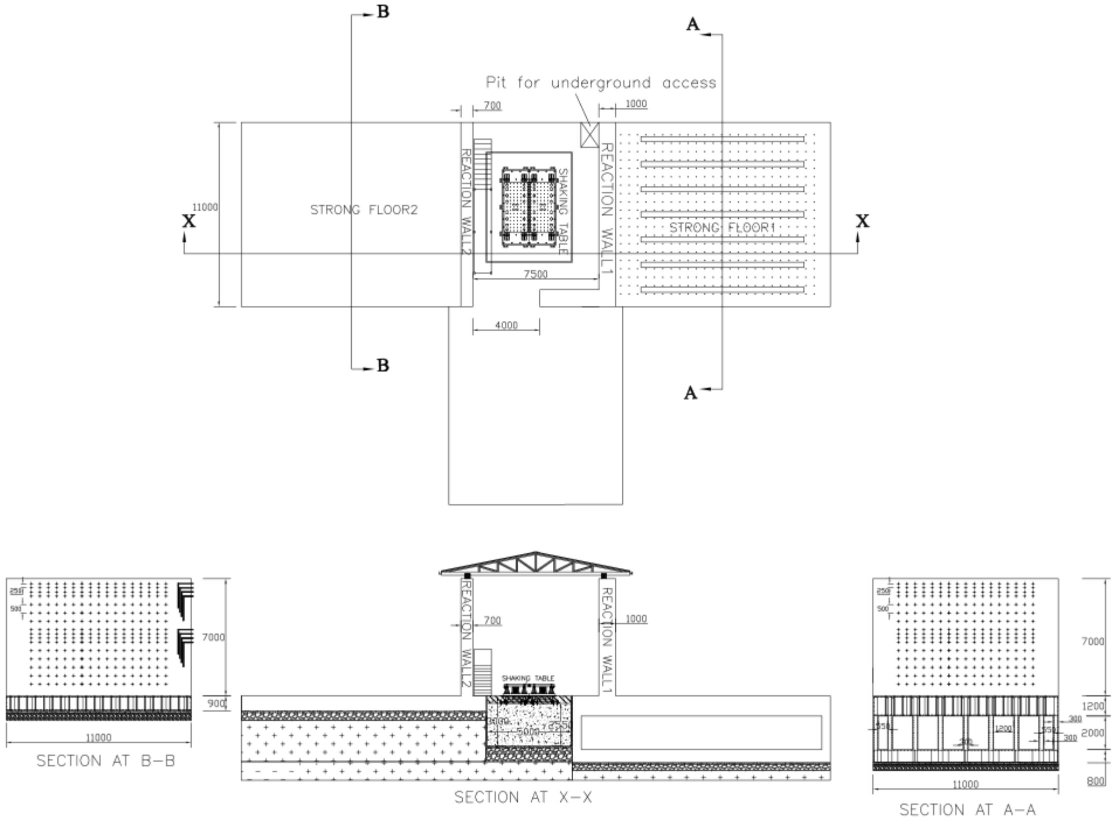


Fig. 3 – Details of the test facility (All dimensions in mm)

3. Construction management and detail plan of action for the construction works

3.1 Detail Plan of Action for the construction of the test facility.

The success of the construction work depends on the effectiveness of collaboration between the client and the contractor, with an efficient monitoring system. It also depends on the careful analysis and subsequent forecast of unforeseen conditions. The nature of this particular construction is different from the development of residential and institutional buildings, as found in the country. The construction of this test facility, with different types of structural components, is first of its kind. Thus all the concerned parties made much effort in the preliminary planning and execution, with precautionary measures in place. Fig.4 shows the detail action of plans, one as per the initial plan and second based on the actual timeline of works.

The following sections briefly outline the process of activity and problems faced during the work execution:

Task 1. The contractor executed the initial mobilization of materials, labor, and setting up of the site office as per the initial plan of action. [On time]

Task 2. The excavation works were delayed by two weeks. The work was expected to be completed by the first week of January 2018, but the work extended up to the third week of January. As per the contract documents, the excavation work was supposed to involve medium to hard soil. However, big boulders were found as shown in Fig. 5, which needed heavy-duty excavation works, including rock breaker equipped to excavators and employing heating and thawing techniques. Further, the use of excavators could not be done during the weekdays and the office hours since it caused vibrations to the adjacent office buildings. The change in specification of excavation was subsequently made. The subsequent tasks following excavation work were delayed by two weeks. [Delayed by two weeks].

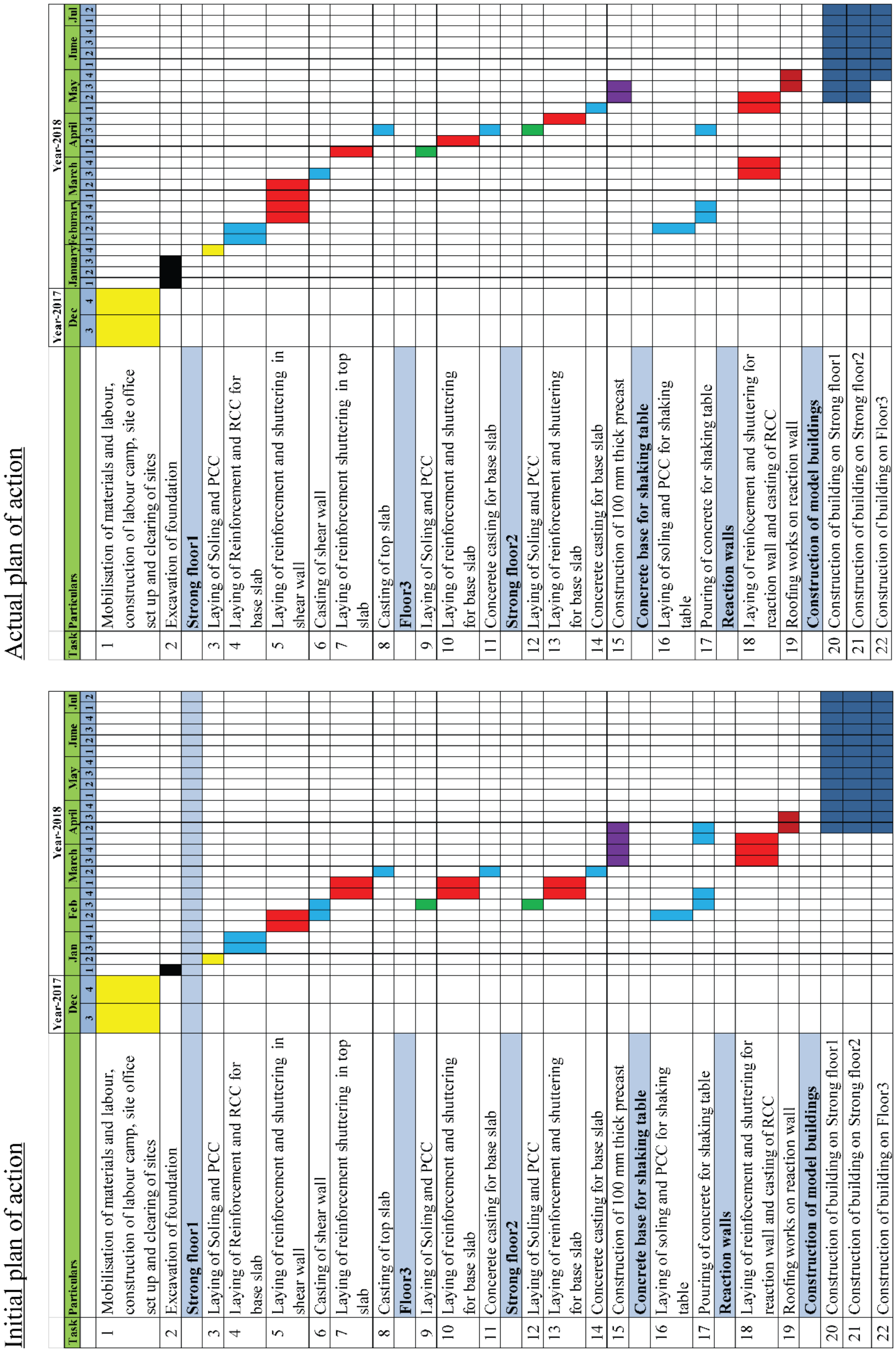


Fig. 4 – Plan of action and schedule of works for the test facility-
Initial plan of action (left) and Actual plan of action (right)

Tasks 3 and 4. The laying of soling and PCC below the Strong floor-1 followed by the setting of reinforcement and RCC for the base slab, as illustrated in Fig. 6a and b were executed within the stipulated time. The tasks were delayed by two weeks due to the preceding task. [Delayed by two weeks]

Task 5. The reinforcement laying for the shear walls (Fig. 6c) initially stipulated to last two weeks was extended to 4 weeks. The complexity of reinforcement laying and preparation for shuttering works attributed to the delay of work, thus creating four weeks of delay in the overall timeline of work. [Delayed by four weeks]

Task 6. The concrete casting for the shear walls (Fig. 6d) was completed within a week, as stipulated. [Delayed by four weeks]

Tasks 7 and 8. The laying of reinforcement and casting of concrete for the top slab of Strong floor-1, as shown in Fig. 6e got extended by a week. The preparation for shuttering works and placement and fixing of Poly-vinyl pipes for provisional holes located within the top slab also contributed to the delay of works. [Delayed by five weeks]

Tasks 9-11. Tasks 9-11 for floor-3 (Fig. 7a) were completed within three weeks instead of four weeks as per the initial plan of action. The tasks were supposed to start at the end of February but could only begin at the start of April due to extra effort required for completion of Task 7 and 8. [Delayed by five weeks]

Tasks 12-15. These tasks on Strong floor-2 (Fig. 7b) started after the end of Task 10. The reason for the delay was similar to the reason stated for the preceding set of tasks. [Delayed by five weeks]

Task 16. The task for soling and PCC for the shaking table was completed as per the initial plan of action. The timely completion of this task was critical as the procurement and installation of shaking table equipment is dependent on this factor. [On time]

Task 17. The concreting works for the shaking table foundation were divided into two different phases. The first phase was pouring the base concrete of 2.55 m deep and 5 m wide (Fig. 8a), and the second phase was to pour concrete over the shaking table steel anchorage frame (Fig. 8b). [On time]

Task 18. The delay in the execution of Tasks 3-15 of the strong floors impacted the reinforcement laying tasks for reaction walls. Further, the non-availability of reinforcing bars of 28 mm diameter attributed to the delay. The 28mm diameter rebars are rarely used for the construction of buildings in Bhutan. Therefore the production of such specification of rebar also conforms to the quantity requirement (demand) of the proponent. [Delayed by five weeks]

Task 19. Delay in preceding tasks caused a delay in the roofing works. [Delayed by five weeks]

Task 20-22. The construction of three full-scale houses started after completion of Task 8, 11, and 14 representing respective base slabs. The construction process was also significantly delayed due to the heavy monsoon starting from June till August. [Delayed by four weeks]

3.2 Post construction situation analysis:

The significant weightage compared to all the activities was seen in the reinforcement and reinforced concrete works, as shown in Fig. 9. The consumption of reinforcement was approximately about 200MT in total, out of which the utilization of 28mm diameter reinforcement contributes to approximately about 100MT. Other civil works were limited to excavation, stone soiling, plain cement concrete, plastering, shuttering, and roofing works. Thus, this projection may be non-applicable to the construction of residential and commercial buildings where other civil works may attribute to a significant increase in the cost of the work.

Fig. 5 – Excavation works (Task 2)

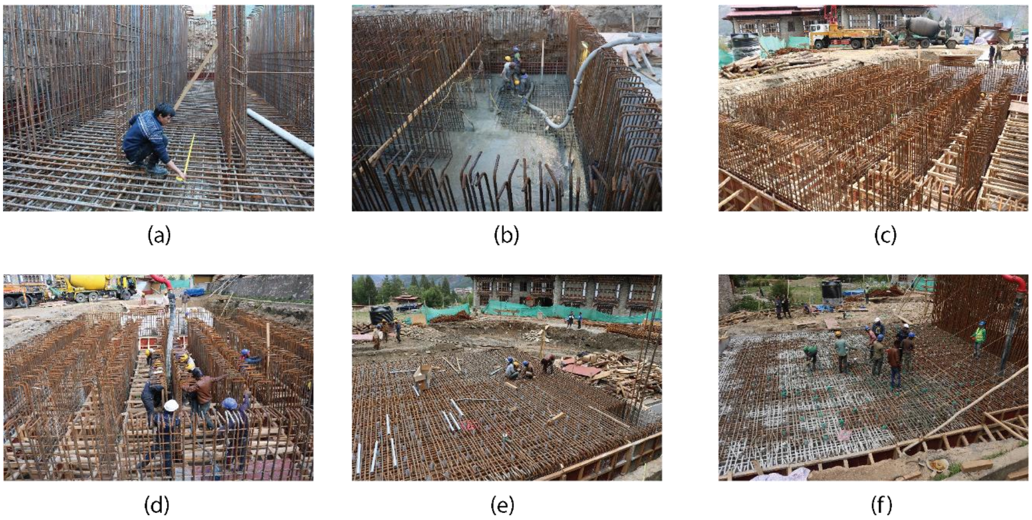


Fig. 6 – Activities for Task 03 to 08: (a) Laying of reinforcement for base-slab, (b) Concreting of base-slab, (c) Fixing of reinforcement and shuttering for shear wall, (d) Concreting of shear walls, (e) Fixing of reinforcement and PVC pipes for top slab, (f) Concreting of top slab

Fig. 7 – Tasks 09 to 15: (a) Reinforcement and concreting works for floor-3, (b) Reinforcement and concreting works for floor-2

Fig. 8 – Concrete pouring for shaking table base (Task 17): (a) Fixing shuttering and concreting works for phase-1, (b) Complete concrete work for phase-2

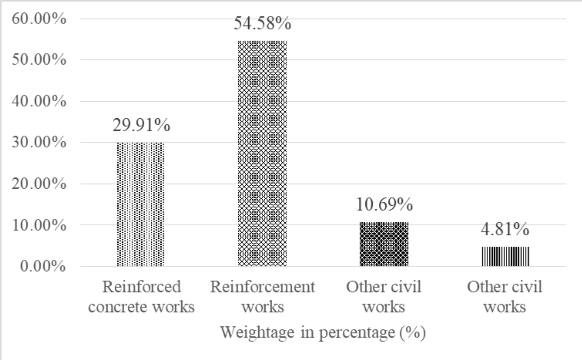


Fig. 9 –Weightage for different activities in percentage (%)

Lessons learned: During the construction phase, many challenges imposed on delays and hindrances. The requirement of changes in the specification, due to the nature of excavation works, market non-availability of reinforcement, difficulty in fabrication of built-up sections, were carefully made. However, these unforeseen activities resulted in delays in the workflow of the project, as detailed above. It is thus necessary to study the ground conditions and the availability of technical skills of the workforce, and material production schemes, amongst others. Further, there were delays experienced due to harsh weather conditions, heavy snowfall in December through February, and torrential monsoon from June through August.

Another crucial factor was the consideration required for weather conditions and corresponding human behavior. The weather had an adverse impact on the construction process of the full-scale building model of stone masonry with mud mortar (Task 21). The Thimphu city experiences heavy rainfall in June through August, and possible water seepage from the ground caused the failure of one of the constructed wall. There were no human casualties, but this resulted in a delay in time and loss of materials. This incident occurred when the construction was about to reach the first-floor level. The whole building had to be reconstructed from the ground floor to have the desired construction method as required for experimental studies. Extra precautionary measures were put in place as an aftermath of the unfortunate incident to avoid such events, particularly in the case of stone masonry building built with mud mortar. It is imperative to consider the harsh winter season from December till February, which hinders the concreting works. More so, it is not preferable to undertake any concreting tasks and also the unavailability of workers during this period.

4. Test equipment and instrumentations

4.1 Static jack system

Two 1000kN and two 500kN capacity hydraulically operated static jacks are available at the facility to perform the full-scale static test [7]. Both types of static jacks have a stroke of ± 200mm. Table 3 shows the details of the hydraulic jacks. The jack systems require manual operation (handling) using hydraulic pumps. The following sections will discuss a brief overview of the test setup designed for the pilot full-scale static test.

4.2 Dynamic shaking table system

The test facility also houses 3m × 3m shaking table. Table 4 shows the specifications and schematic drawing of the shaking table. This dynamic shaking table system will help in understanding the relationship between the input earthquake and the consequent response of the structure for verification of the proposed seismic strengthening measures. The facility will also cater to public awareness programs for earthquake-related disaster preparedness and demonstrations to the general public. The installation was completed and successfully launched on March 22, 2019.

Table 3 – Specifications of the static jack systems

Specifications	Hydraulic jacks	
Capacity (kN)	500	1000
Stroke (mm)	± 200mm	± 200mm
Discharge pressure (MPa)	49.26	64.22
Cylinder effective area (cm^2)	101.51	155.71
Oil capacity (litre)	4.10	6.30
Weight (kilograms)	385	745

Table 4 – Specifications of the shaking table

Specifications	Details
Table size	3m × 3m
Stroke	± 150mm
Operating frequency	0.1 50Hz
Peak ground acceleration	0.5*g*
Height limitation	3 m
Weight limitation	10 ton

4.3 Instrumentations

The experimental facility also has an extensive list of instrumentations required for accurate measurements of quantities such as deformations, micro-tremor vibrations, and accelerometers. The displacement transducers (LVDTs) of four different types are available, as detailed in Table 5. The test facility also offers a more sophisticated displacement sensor IL-300 laser displacement transducers. Table 6 lists the available load cells of different types and capacities. The experimental facility also possesses a high-end data-logging system, TML digital dynamic strain-meter Model DS-50A with a 40-channel strain unit, and a 10-channel voltage unit [8].

Table 5 – Specifications of the displacement transducers

Specifications	Quantity
CDP-M Small Displacement transducer (5-100mm)	4.00
TML Displacement transducer (type SPC-50C)	5.00
TML Displacement transducer (type SPC-100C)	5.00
TML Displacement transducer (type SPC-200C)	2.00

Table 6 – Specifications of load cells

Specifications	Quantity
KCM- 20KNA	1.00
KCM-200KNA	1.00
CLU-100A (Capacity- 1MN)	1.00
TLP- 200KNB (capacity-200kN) with FH shackles	1.00

5. Pilot shaking table test

Pilot dynamic tests on two reduce-scaled rammed earth (RE) buildings were carried out in December 2019 using this test facility. The reduce-scaled test specimen is a 1/6th scaled two-storied house with a floor area of 0.9m x 1.35m and height 1.14m. The wall's thickness is 100mm. The form of the specimen represented the typical traditional residential house of Bhutan and was selected based on typology and representative study of traditional houses of Bhutan. Fig.10 shows the schematic view and real picture of the test specimen. Two test specimens were tested at the same instant, one unreinforced and the other retrofitted, as shown in Fig. 11(a) and (b). The retrofitted specimen utilizes a steel mesh-wrap (0.5mm diameter and 15.4mm opening) retrofitting technique with a cover of 10mm cement plaster (1cement:3sand). The instrumentations involved the use of 16 accelerometer sensors (STP-300S), eight sensors on each test specimen. Data logging was done using SignalExpress (National Instruments), and the data sampling rate was set at 200Hz.

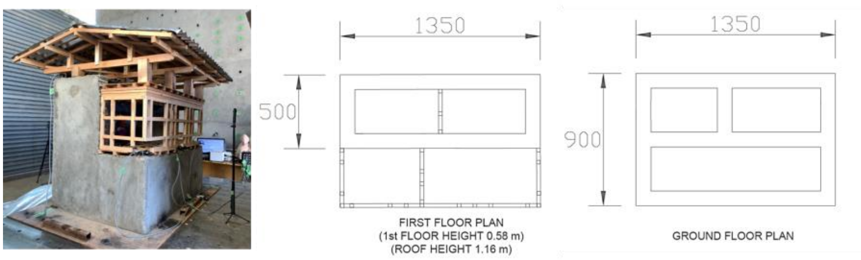


Fig. 10 – 1/6th scaled test specimen details for shaking table tests.

The input ground motion used for the shaking table test involves a series of scaled ground motion of earthquake recorded in Thimphu, Bhutan, on September 12, 2018. The original record is scaled to simulate the 1/6th scaled specimen based on simple model similarity [9] with corresponding scaling factors.

The input ground motions are applied in 8 sequential runs with increasing amplitudes of the target PGAs – 0.2*g*, 0.4*g*, 0.6*g*, 0.8*g*, 1.0*g*, 1.2*g*, 1.4*g*, and 1.6*g*. Fig.11(c) shows the response acceleration spectra for the input ground motion with PGA 0.2*g*. It should be noted that before the actual earthquake loading, the specimens are subjected to white noise with PGA 0.03*g* and frequency from 1Hz to 25Hz. The natural period of vibration for both unreinforced RE and reinforced RE was 0.0625 sec.

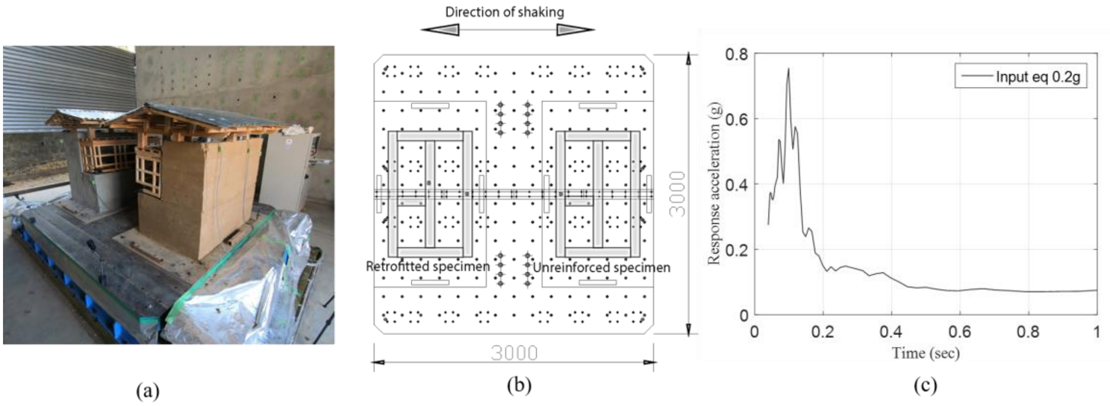


Fig. 11 – (a) Picture of test specimens on shaking table, (b) Test set-up, (c) Response acceleration spectra for the input ground motion PGA 0.2*g* (damping coefficient = 5%).

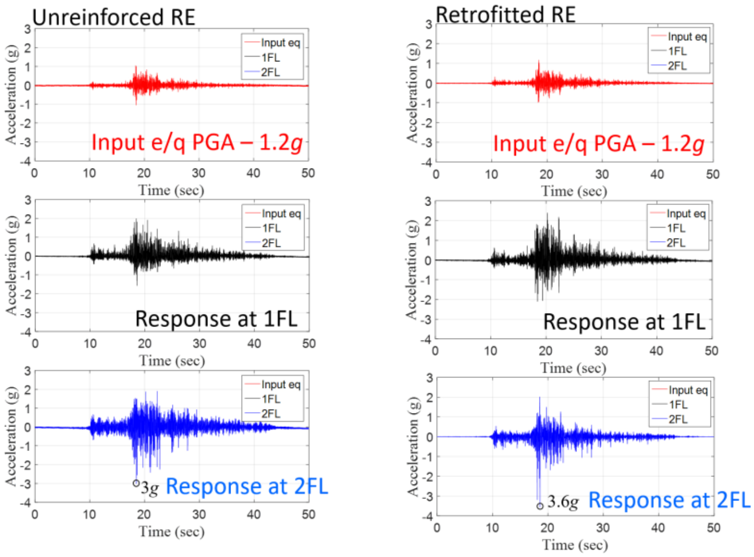


Fig. 12 – Acceleration time-history for unreinforced and retrofitted specimens at PGA 1.0*g*.

Fig. 13 – Damage for unreinforced and retrofitted specimens at PGA 1.0*g*.

Fig.12 shows the acceleration time history records for the two specimens tested at PGA of 1*g*. The acceleration records are presented for the input e/q, response at the first-floor level (1FL), and second-floor level (2FL). The unreinforced RE specimen showed a response acceleration 3 (three) times the ground excitation, and the retrofitted counterpart showed stiffer response with 3.6 times the ground acceleration. The unreinforced RE showed multiple cracks with clear vertical and horizontal cracks at the back wall and was near collapse state (Fig.13). The retrofitted counterpart showed comparatively stable response with limited cracks within the walls, with some plaster spalling near the openings at 1FL and no visible cracks at the back wall.

6. Conclusions

The paper provides first-hand information about the first-ever test facility of Bhutan. The paper reports on the comprehensive construction management dissecting each task relative to conventional construction practices. Various services available within its premises of cutting-edge technology in the field of structural and earthquake engineering are presented. This paper aims to create awareness amongst the local and international researchers and interested individuals, about the efforts of the Royal Government of Bhutan in collaboration with international agencies, in creating various platforms for future research works. The test facility will be a crucial part of the Research Institute for Traditional Structures (RITS). RITS will cater to the establishment of know-how and technologies for a safe and sustainable traditional structure. Further, a pilot shaking table test performed successfully at the test facility is also presented, highlighting the vulnerabilities in existing construction practices in rammed earth and possible strengthening measures.

7. Acknowledgments

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