



Pull-down test of the rammed earth walls at Paga Lhakhang in the Kingdom of Bhutan

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Traditional Bhutanese buildings made of rammed earth are vulnerable to earthquakes, and their preservation, maintenance, and rehabilitation has therefore become a problem that has assumed great significance. However, few studies have focused on rammed earth structures, and almost no data from material or full-scale tests is available for the same. In this study, material tests are conducted on rammed earth core samples extracted from the Paga Lhakhang. Pull-down tests are conducted on the four remaining rammed earth walls at the Paga Lhakhang, and the relationships between the results of the pull-down test and the material test are discussed.

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Introduction

Background and objective

In the Kingdom of Bhutan, rammed earth has long been used as a construction material. As such, many structures made of rammed earth exist in the Kingdom of Bhutan. But also rammed earth structures are distributed especially in the Southeast Asia, Southwest Asia, Middle and Near East Africa, and Central and South America (Jaquin & Augarde & Gerrard, 2008, Fodde, 2009). Unfortunately, many of these structures were damaged by earthquakes that occurred on September 21, 2009 (in eastern Bhutan, Magnitude 6.1), and on September 18, 2011 (near the border of India and Nepal, Magnitude 6.9). Bhutanese rammed earth structures are vulnerable to earthquakes, and their preservation, maintenance, and rehabilitation is a problem that has assumed great significance. Toward this end, it is necessary to clarify the mechanical properties and collapse mechanism of rammed earth walls in order to devise seismic reinforcement and restoration plans. However, few studies have focused on Bhutanese rammed earth structures (Aoki et al., 2012, Ezura et al., 2013), and almost no data from material or full-scale tests is available for the same (Jaquin, 2006, Jaquin et al., 2007, Jaquin & Augarde & Legrande, 2008, Illampas et al., 2013).

The Paga Lhakhang, a rammed earth structure, was destroyed by fire on February 29, 2012. Fortunately, an opportunity to investigate the Paga Lhakhang was presented before its reconstruction (Nakamura et al., 2013, Torizawa et al., 2014). This study aims to determine the material properties of a rammed earth structure and to clarify the structural behavior of rammed earth walls.

An experimental study of the Paga Lhakhang was conducted to determine the structural behavior and characteristics of rammed earth structures. Material tests were executed on rammed earth core samples extracted from the Paga Lhakhang to determine the compressive and tensile strength and Young's modulus of rammed earth. Pull-down tests of the four remaining rammed earth walls, one in the in-plane and the remaining three in the out-of-plane directions, were carried out, and the relationships between pull-down load and displacement and their collapse mechanism are clarified. The results of the pull-down test and material test are presented and discussed.

Outline of Paga Lhakhang

Paga Lhakhang is located on a mountain slope facing the Wangchchu River in Chhukha Dzongkhag, southern Bhutan (Fig. 1 (a)). It is believed that Paga Lhakhang was built in the middle of the 18th century by Kuenga Gyamtsho. However, according to a priest there, it was built 400 years ago. For now, the time of construction remains unclear. Paga Lhakhang was burned down by a fire due to a short circuit in the early morning of February 29, 2012. After the fire, only the inside and outside walls remained (Fig. 1 (b)). Details about the building are unavailable because little investigation data could be obtained after the fire. However, the building was considered to have four stories above ground, with a base made of stone, frame made of rammed earth, and floor frame made of wood.



Figure 1. Front view of Paga Lhakhang.

Material test

Outline of test

Material tests were conducted on rammed earth core samples to determine the compressive and tensile strength and Young's modulus. These samples were extracted from the four remaining rammed earth blocks at Paga Lhakhang using a hand core drill machine (DD-120, Hilti Corporation), as shown in Figure 2. 3–7 samples with a diameter and length of 100 mm and 100–200mm, respectively, were obtained from each block. The samples were irregularly shaped owing to processing difficulties. Therefore, they were shaved off and capped with plaster to make them almost flat on both the top and the bottom surfaces.

Figure 3 shows an overview of the material test. A compressive strength test and splitting tensile strength test were conducted for rammed earth core specimens according to the Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens (ASTM C39) and the Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens (ASTM C496). The compressive strength test was carried out using a compressive strength testing device (1000 kN) at the Bhutan Standards Bureau, a load cell (KCM-200KNA, Tokyo Sokki Kenkyujo Co., Ltd.), and a digital data logger and switching box (TC-32K and CSW-5A-05, Tokyo Sokki Kenkyujo Co., Ltd.). To determine the average deformation, the displacements at the four corners of rammed earth core samples were measured using displacement transducers (CDP-10MT, Tokyo Sokki Kenkyujo Co., Ltd.). The relationship between the load and the displacement was obtained from the data. The splitting tensile strength test was conducted using a load cell (KCM-20KNA, Tokyo Sokki Kenkyujo Co., Ltd.) because the tensile load is very small.



Figure 2. Rammed earth block.



Figure 3. Overview of compressive strength test.

Results and discussion

Figures 4 and 5 show the example of the compressive fracture mode and the compressive stress and strain relationship, and Figures 6 and 7 show the density and compressive and tensile strength relationship, and compressive strength and Young’s modulus relationship for all samples, respectively. Table 1 summarizes the average results of the compressive and the splitting tensile strength tests. The average values for all samples extracted from each rammed earth block are shown. The compressive strength is estimated considering the scale effect of rammed earth core samples. The density ranges from 1573 to 2033kg/m³ with an average of 1810kg/m³; the compressive strength, from 0.325 to 1.585MPa with an average of 0.845MPa; the tensile strength, from 0.027 to 0.220MPa with an average of 0.101MPa; the ratio of compressive to tensile strength *c/t* for each block, from 7.15 to 11.29 with an average of 8.45; and Young’s modulus, from 48.1 to 320.7MPa with an average of 123.5MPa. As the density increases, the compressive and the tensile strength and Young’s modulus tend to increase. However, the material characteristics of rammed earth differ depending on the construction method, and therefore, the test results vary widely according to the block number.



Figure 4. Compressive fracture mode.

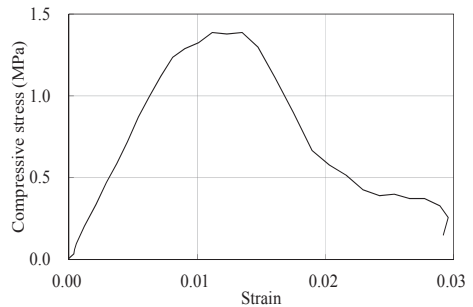


Figure 5. Compressive stress and strain relationship.

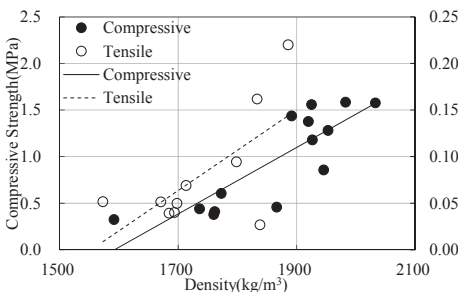


Figure 6. Density and compressive and tensile strength relationship.

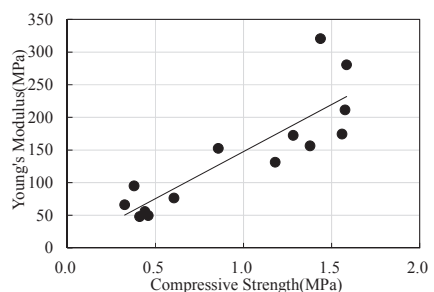


Figure 7. Compressive strength and Young’s modulus relationship.

Table 1. Average results for each block.

Block	Sample number	Load	Density (kg/m ³)	Stress (MPa)	c/t	Young's Modulus (MPa)
No. 1	3	Compressive	1892	1.392	7.29	208.8
	2	tensile		0.191		
No. 2	3	Compressive	1692	0.388	8.05	70.3
	4	tensile		0.048		
No. 3	2	Compressive	1920	1.117	11.29	154.5
	1	tensile		0.099		
No. 4	3	Compressive	1736	0.485	7.15	60.2
	3	tensile		0.068		
Average		Compressive	1810	0.845	8.45	123.5
		tensile		0.101		

Pull-down test

Outline of test

It is necessary to clarify the mechanical properties and collapse mechanism of rammed earth walls to devise seismic reinforcement and restoration plans. The collapse mode of rammed earth walls also differs depending on their construction method. Therefore, it is extremely important to clarify the construction methods and structural findings from the pull-down test for rammed earth walls. From the relationship between the pull-down load and the displacement, the collapse mechanism, mechanical properties, and construction methods of the rammed earth walls were clarified.

Test method

The pull-down test on the rammed earth walls at Paga Lhakhang was conducted in the out-of-plane and in-plane directions of the walls shown in Figure 8. The rammed earth walls subjected to the test were designated as Wall-1 to -4. Wall-3 was pulled down in the in-plane direction, and the other walls were pulled down in the out-of-plane direction. The height of Wall-1 was ~6.2m, which was almost from the ground line to the ceiling level of second story, and the width was ~4.1m. The height of Wall-2 was ~5.8m and the width was ~7.4m. The height of Wall-3 was ~6.1m and the width was ~2.3m. The height of Wall-4 was ~11.5m, which was almost from the ground line to the roof level, and the width was ~12.7m. Wall-4 was pulled down at the ceiling level of second story.

We connected the top of the rammed earth wall and the backhoe by a wire (Figs. 9 and 10). As the backhoe moves backward, the wire pulls the rammed earth wall down. During this time, the wire is subjected to tensile force, therefore rammed earth wall is subjected to component forces, which are divided into the compressive force in the vertical direction and the tensile force in the horizontal direction. To reduce the compressive force on the rammed earth wall, to load more pure horizontal force, and to ensure safety when the rammed earth wall collapses, the horizontal distance between the rammed earth wall and the backhoe was set to at least three times the height of the rammed earth wall ($\geq 3h$) (Fig. 9).

To avoid the local failure and to apply a distributed load on the wall, a wooden plate was placed on both the front and the back of the top of the rammed earth wall at the point where we applied the load; a hole was drilled through the wooden plate and the edge of the rammed earth wall for the wire to pass through, thus wrapping the rammed earth wall with the wire (Fig. 11). Wall-4 was pulled with two wires because of wire breakage during the pull-down test. The wire was attached to the forks of the backhoe to pull the rammed earth wall.

The load was measured by a tensile-type load cell (TLP-200KNB, Tokyo Sokki Kenkyujo Co., Ltd.) inserted between the wires, to which shackles (FH-20B, Tokyo Sokki Kenkyujo Co., Ltd.) were attached on both ends and the data was recorded on a smart dynamic strain recorder (DC-104R, Tokyo Sokki Kenkyujo Co., Ltd.). To measure displacement, the string was allowed to move along with the deformation of the rammed earth wall, and the displacement was recorded on video. The relationship between the load and the displacement was obtained by synchronizing the time on the video and the computer used for load measurement.



(a) Wall-1 (out-of-plane).



(b) Wall-2 (out-of-plane).



(c) Wall-3 (in-plane).



(d) Wall-4 (out-of-plane).

Figure 8. Overview of rammed earth walls subjected to pull-down test.

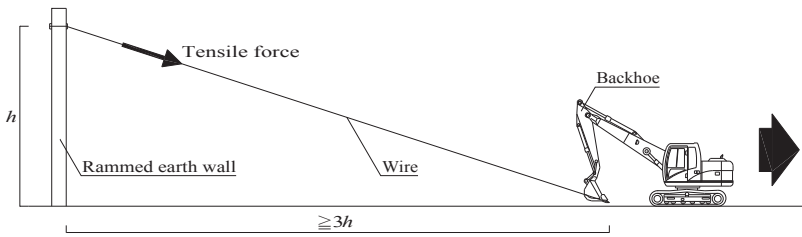


Figure 9. Schematic of pull-down test.



Figure 10. Overview of pull-down test.



Figure 11. Wooden plate.

Results and discussion

Figure 12 shows the collapse modes of Wall-1 to -4 and the load–displacement curves are shown in Figure 13. Wall-1 collapsed by the section loss of the rammed earth and restriction effect of the wooden member included inside the orthogonal rammed earth wall. Wall-2 and -4 collapsed by the section loss of the rammed earth caused by joists at the floor level of Paga Lhaxhang. Wall-3 collapsed by sliding at the section loss of the rammed earth. The rammed earth walls showed very small deformation before the maximum load, and then, they suddenly collapsed after the maximum load.

The tensile stress of the rammed earth wall is estimated from the equilibrium of forces (Fig. 14). The compressive stress by self-weight is calculated as follows:

$$\sigma_{N1} = -\frac{W}{bD} = -\frac{bDh\rho}{bD} = -h\rho \quad (1)$$

where W = weight of upper part of destroyed wall; b = wall thickness; D = wall length; h = distance between top of wall and destroyed section of wall; ρ = density of rammed earth; and σ_{N1} = compressive stress generated by self-weight.

The vertical compressive stress by the component force of the diagonal pulling force is calculated as follows:

$$\sigma_{N2} = -\frac{P \sin \theta}{bD} = -\frac{Pa}{bD\sqrt{a^2 + L^2}} \quad (2)$$

where P = tensile force on wire; θ = angle between wire and ground level; a = distance from ground to destroyed section; L = horizontal distance from wall to backhoe; σ_{N2} = compressive stress generated by component force of diagonal pulling force P ; f = distance from ground to bottom of wall; and H = wall height.

The tensile stress by moment is calculated as follows:

$$\sigma_M = \frac{M}{Z} = \frac{6P \cos \theta \cdot h''}{b^2D} = \frac{6PLh''}{b^2D\sqrt{a^2 + L^2}} \quad (3)$$

where M = moment generated on destroyed section by diagonal pulling force P ; H = distance from top of wall to wire hole; h'' = distance from wire hole to destroyed section; Z = section modulus of wall; and σ_M = tensile stress generated by moment M .

The tensile stress of rammed earth f_t is calculated as follows:

$$f_t = \sigma_{N1} + \sigma_{N2} + \sigma_M = -h\rho - \frac{Pa}{bD\sqrt{a^2 + L^2}} + \frac{6PLh''}{b^2D\sqrt{a^2 + L^2}} \quad (4)$$

Table 2 summarizes the calculation results of each stress on the rammed earth walls. The tensile stress of rammed earth ranges from 0.012 to 0.370MPa with an average of 0.162MPa. The tensile stress estimated from the results of pull-down tests is similar to that obtained from the material tests. However, more data is required from the material or full-scale tests of rammed earth because the currently obtained data shows wide variations. In addition, the tensile stress of the rammed earth wall must be estimated in consideration of the restriction effect of the orthogonal wall.



Figure 12. Collapse mode of rammed earth walls.

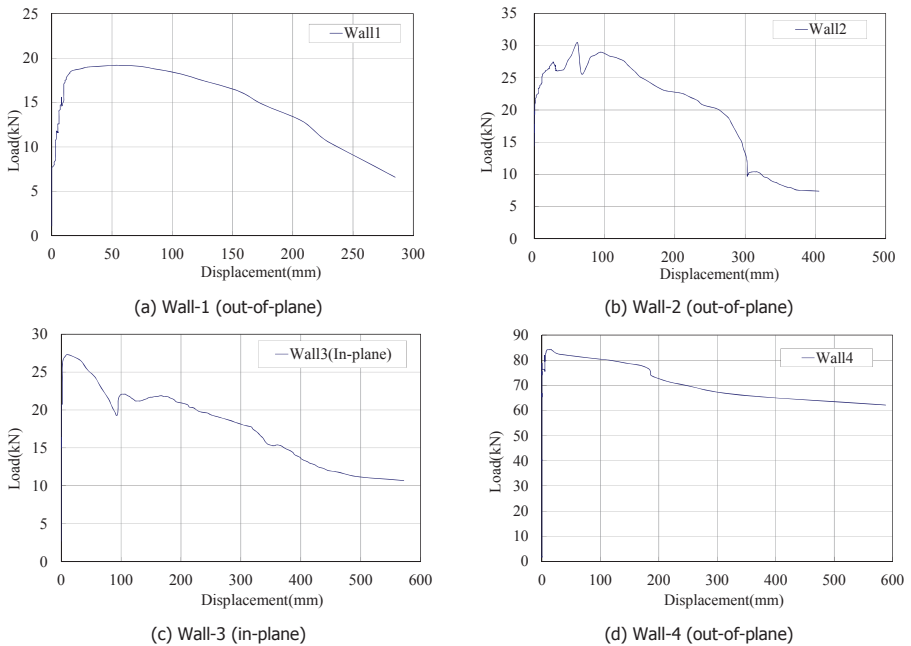


Figure 13. Load-displacement curve.

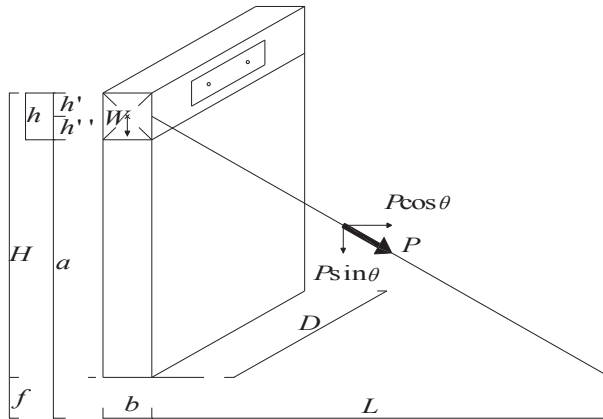


Figure 14. Schematic of force balance.

Table 2. Calculation results of tensile stress.

Stress (MPa)	σ_{N1}	σ_{N2}	σ_M	f_t
Wall-1	-0.017	-0.002	0.031	0.012
Wall-2	-0.052	-0.002	0.122	0.069
Wall-3	-0.049	-0.008	0.428	0.370
Wall-4	-0.112	-0.004	0.314	0.198
Average	-0.058	-0.004	0.224	0.162

Conclusions

In this study, material tests were conducted on rammed earth core samples extracted from the Paga Lhakhang to determine the compressive and the tensile strength and Young’s modulus of rammed earth. Pull-down tests of the four remaining rammed earth walls at the Paga Lhakhang were conducted, and the relationships between the pull-down load and the displacement and their collapse mechanism were clarified. The main findings of this study are as follows:

- 1) The material tests indicate that as the density increases, the compressive and the tensile strength and Young’s Modulus tend to increase;
- 2) The pull-down tests indicate that the rammed earth wall shows very small deformation before the maximum load and then suddenly collapses after the maximum load;
- 3) The pull-down tests indicate that the rammed earth wall collapses in the out-of-plane direction upon section loss of the rammed earth and the connection with the orthogonal rammed earth wall, and it collapses in the in-plane direction by sliding upon section loss of the rammed earth;
- 4) The tensile stress of rammed earth as estimated from the results of pull-down tests is similar to the results of material tests, although they show wide variations.

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