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TRAINING IN EARTHQUAKE-RESISTANT ADOBE BRICK CONSTRUCTION IN THE PERUVIAN ANDES

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Abstract

In Peru, almost 9 million people live in rural areas in self-built earthen houses essentially because it is cheap, and earthen houses are thermally comfortable. However, their seismic performance is very poor because earthen walls are heavy, weak and brittle, and thus they suffer significant damage or collapse during an earthquake, usually with tragic loss of life.

Researchers at the Pontificia Universidad Católica del Perú (PUCP) have developed several reinforcement techniques for earthen dwellings, in an effort to improve their structural safety. None of these techniques have, however, been adopted by the rural communities where building with earth is prevalent, mainly due to their high cost and the lack of technological sharing of knowledge among the potential builders. Most rural communities therefore live under unacceptable seismic risk conditions. The development of tools and training programs that allow the dissemination of earthquake-resistant earthen construction to mitigate this problem is therefore a most pressing issue.

The PUCP is currently undertaking a pilot project to train a community on the construction of seismically safe adobe houses. This project is being developed at the district of Pullo, a small rural community in the Peruvian Andes where more than 80% of its inhabitants live in adobe houses, with over 50% of them living in poverty or extreme poverty conditions. The project consists on working with the people of the community, helping them improve their housing conditions by acquiring the ability to do so on their own. In addition, a simple low-cost reinforcement is proposed (nylon ropes) in order to increase acceptance among the population and the training program is divided into three phases to ease the learning process.

This paper presents first the communication and training tools developed during the project: a portable shaking table to demonstrate the effectiveness of the nylon-rope mesh seismic reinforcement in reduced scale adobe house models; and an updated construction manual for seismic resistant adobe construction. Finally, the paper describes the social experience of training the Pullo community, the difficulties and successes the project has had, and the conclusions it reached. The results attained are expected to serve as reference for future training programs targeting rural communities under similar high seismic risk conditions.

Keywords: adobe, awareness, education, safe housing, technology transfer

1. Introduction

Peru is a highly seismic country where the combination of severe earthquakes and non-reinforced earthen construction has caused great human and economic losses throughout the years. In 1970, earthen buildings in the Ancash region collapsed and caused the death of over 40 000 people after a 7.9 Mw earthquake [1]; in 1996, over 75% of adobe dwellings in the province of Nazca were damaged by a 7.7 Mw earthquake [2]; in 2001, thousands of earthen buildings in the regions of Arequipa, Ayacucho, Moquegua and Tacna collapsed after an 8.2 Mw earthquake [3]; and in 2007, around 95 thousand adobe households in the provinces of Pisco, Cañete and Chincha were damaged by an 8.0 Mw earthquake [4]. Furthermore, damage reports show most fatal casualties are due to the collapse of non-reinforced earthen dwellings, thus showing their extremely high seismic vulnerability [1, 5].

Despite the high seismic vulnerability of non-reinforced earthen buildings, around 40% of all dwellings in Peru are made of adobe (sun-dried mud bricks) or rammed earth [6] because earth is the only affordable construction material available for most low-income families. Besides, adobe construction does not require skilled labor, and this ensures its dissemination in rural areas where technical assistance is not easily available [5]. However, earth, as a construction material, can only withstand compressive stresses, and so earthen walls cannot withstand the tensile stresses generated during an earthquake and begin to crack [7]. This structural behavior develops into a brittle failure in which parts of the walls fall apart during additional shaking and cause a complete a collapse of the building, usually with a tragic loss of life (Fig.1 and Fig. 2). Millions of families, especially in poor rural areas, live in unacceptably high seismic risk conditions, and simple, low-cost solutions for them are urgently required.

Figure 1 – Destroyed adobe houses (Huaraz, 1970) (credits: Vargas et al. 2005)

Figure 2 – Collapse of traditional Andean houses (Cusco, 2014) (credits: Newspaper Perú21, 2014)

2. Available technical solutions

Over the past four decades, researchers at PUCP and other institutions have developed several reinforcement techniques to strengthen adobe dwellings against seismic events [8]. Internal cane mesh reinforcement had an excellent response in full-scale shaking table tests [9]; external wire-mesh-and-cement-mortar-reinforcement provides significant additional strength to adobe models under moderate earthquake simulation tests [10]; and, external polymer mesh reinforced models showed good dynamic response during earthquake simulation tests, with collapse prevented even during very strong shaking [11]. However, cane is not available in all seismic regions nor it can be found in the large amounts required for massive (re)construction programs, and wire mesh and cement mortar or polymer mesh are prohibitively expensive for the inhabitants of rural earthen houses [12].

Researchers at the PUCP have recently investigated the nylon-rope mesh reinforcement technique as a simple low-cost alternative to mitigate the high seismic vulnerability of adobe dwellings in rural areas. In 2013, an experimental program demonstrated that a previously damaged full-scale adobe model could be repaired via a mud injection combined with an external mesh made with nylon strings (Fig. 3) [13, 14]. During the program, the reinforcement procedure consisted of covering the walls with a mesh made of horizontal and vertical ropes tightened with turnbuckles; the mesh on both faces of each wall were later joined together with thinner ropes (crossties). Later, the structural behavior of the repaired and reinforced model was considered excellent during a sequence of unidirectional earthquake motions of increasing intensity. The nylon-rope mesh worked to maintain structural integrity and stability, and prevented the partial collapse of wall portions that had separated during the shaking [13, 14].

Figure 3 – Full-scale adobe model reinforced with nylon-rope mesh (credits: Blondet et al. 2013)

Figure 4 – Proposed knot used to tighten nylon ropes (credits: Mattsson, 2015)

The nylon-rope mesh reinforcement technique is simple and low-cost. The reinforcement procedure is considered simple enough to be learned without any previous technical knowledge in construction, and unlike non-reinforced adobe construction, it does not require extra machinery. Furthermore, nylon ropes are cheap and widely available at local stores, both in rural and urban areas, unlike most natural or industrialized reinforcement materials. Besides, since turnbuckles are relatively expensive and unknown in rural areas, they can be replaced with simple knots (Fig. 4) as a low-cost alternative to tighten the ropes [15]. The nylon-rope mesh therefore holds great potential for seismic reinforcement in low-cost earthen dwellings in seismic areas [13, 14], and it may serve to mitigate the extremely high seismic risk in which millions of families live in the Peruvian Andes.

3. Communication and educational tools

The application of technical solutions provides the structural safety needed to prevent the collapse of earthen buildings, thus, protecting human life [12]. However, the availability of technical solutions does not suffice because they have yet to reach the people who live in vulnerable earthen homes, especially in rural areas. Whole communities are still building houses with the traditional, non-reinforced adobe-construction technique, leaving them exposed to an extremely high seismic risk [16]. Therefore, two communication and educational tools have been developed in order to bridge the communication gap between academia and earthquake-prone communities, and thus disseminate the nylon-rope mesh seismic reinforcement among Andean rural dwellers.

3.1 Portable shaking table demonstrations

The demonstration equipment is a portable shaking table developed to perform dynamic tests on reduced scale adobe housing models [17]. The portable shaking table is a man-powered mechanical device with a removable 1300 mm x 600 mm platform, which allows the parallel test of two reduced-scale adobe housing models (one reinforced, the other one non-reinforced), each with a 400 mm x 240 mm rectangular base. Both models were made with 40 mm x 40 mm x 10 mm adobe bricks, have an average height of 210 mm, and an average weight of 13.5 kg. In addition, the floor plans of both models are equal and include one centered door on the front wall and one centered window on each lateral wall. Non-reinforced models represent traditional Andean adobe houses, and so they only have door and window lintels, whereas reinforced models also have a reduced-scale wooden crown beam and nylon threads covering the walls.

The portable shaking table aims to raise awareness of the high seismic vulnerability of non-reinforced adobe dwellings, and to raise confidence on reinforced adobe construction in rural communities [18]. During demonstration sessions, non-reinforced and reinforced models can be tested simultaneously, with the differences in their seismic performance easily observed (Fig. 5). The non-reinforced adobe model collapses just like traditional Andean adobe houses during an earthquake, whereas the reinforced model does not collapse even though it can suffer moderate or severe damage. Disregarding the magnitude of the damage, the nylon-thread mesh prevents the collapse of the reinforced model just like the nylon-rope mesh did in the experimental program, thus showing the effectiveness of the nylon-rope mesh in protecting adobe houses inhabitants from earthquakes.

Figure 5 – Differences in the seismic performance of reduced-scale adobe models

3.2 Illustrated construction manual

The construction manual is a technical document that describes in detail how to reinforce an adobe house with nylon ropes. Each step in the construction process is described using a familiar, simple language, and is clearly illustrated with easy-to-follow drawings. Furthermore, the manual presents three types of houses, each with a different number of rooms, which can be built by residents according to their economic status and possibilities, and shows their construction plans in detail. The first option is a two-bedroom house with a 29 m2 floor area; the second option is a three-bedroom house with 42 m2 of floor area; and, the last one is a four-bedroom house with 54 m2 of floor area. This educational tool is mainly meant for masons and rural area residents where informal adobe construction prevails and technical assistance is not easily available.

The main character in the construction manual is "José", which represents a typical Andean resident who uses adobe bricks as construction material. It is believed that this allows a more profound identification in the people being trained, thus leading to a better understanding and appropriation of the new technology [17]. The construction manual also includes “Maria”, the main character’s wife, who has an active role in the construction process. This inclusion references the active role women have during the whole construction process, from adding straw when making adobe bricks, to knotting the nylon ropes when placing seismic reinforcement on the walls.

The illustrated construction manual includes all of the information required in order to build an earthquake-resistant adobe brick house reinforced using the nylon-rope mesh technique. It includes risk factors, recommended location for a house, soil-selection criteria, proper adobe-brick making process, foundations and plinth, reinforcement procedures and proper roof structures. This document is a full, step-by-step illustrated guide for dwellers, mason and technicians (Fig 6).

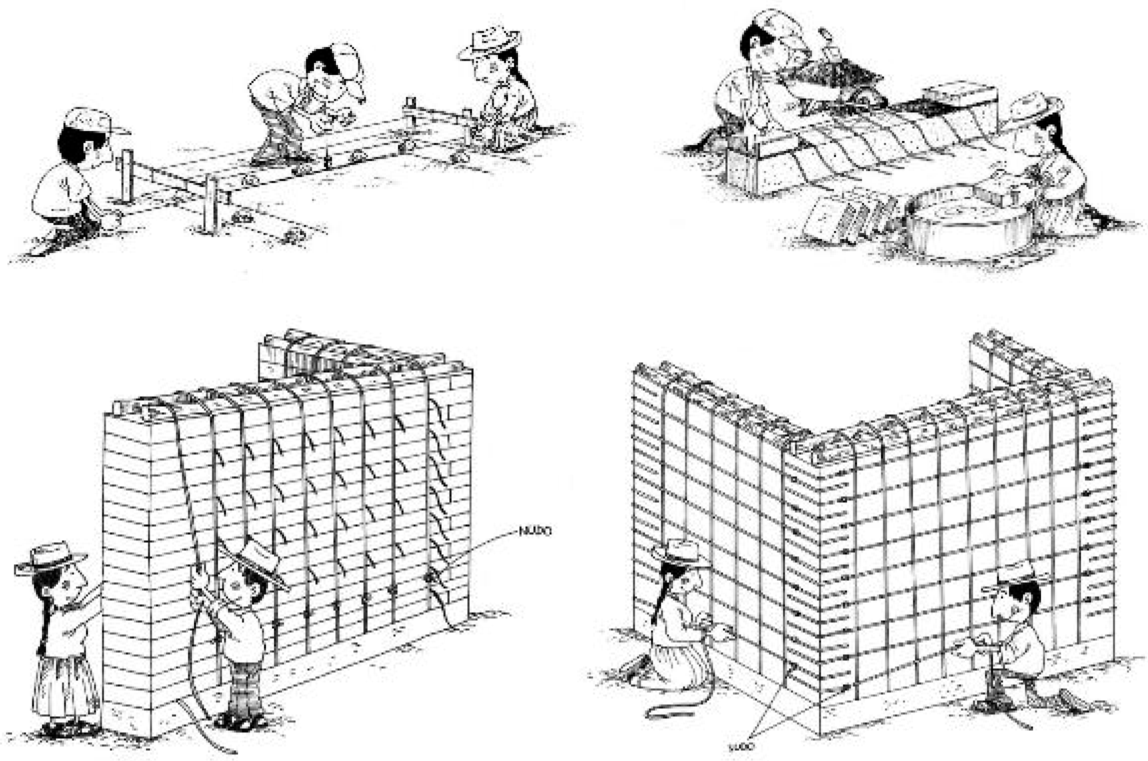

Fig. 6 – Sample illustrations from the construction manual

4. The PUCP Training Project

The technology-transfer initiative or educational campaign described in this article is part of a broader project of the Academic Direction of Social Responsibility of the PUCP (DARS-PUCP) that aims to develop risk-management capabilities for Andean communities. The initiative is based on the experience acquired in a small-scale reconstruction program developed by PUCP and CARE-Peru (a nongovernmental organization (NGO) that specializes in development) after the August 2007 Pisco earthquake [4]. This work is interdisciplinary and it brought together partners in engineering, psychology, anthropology, history, and communications, and its goal was having seismic reinforcement accepted by homeowners and residents in Andean communities.

The central idea in this initiative is that people should not be mere recipients of external aid, but agents of their own development by acquiring the skills required to lead the life they want [19]. In this project, this means that people living in adobe brick dwellings should learn how to build earthquake-resistant houses on their own. The program therefore trains community members in the construction of safer adobe houses using a simple low-cost reinforcement technique. It is expected that the skills acquired will allow community members to continue improving their housing conditions once the project is over, thus enhancing their quality of life in an ongoing and sustainable way. There is the additional prospect that trained community members may also use the skills acquired to earn income as technicians in construction projects.

The technology-transfer initiative is divided into three phases in order to increase the acceptance of the nylon-rope mesh reinforcement technique, ease the transfer of technology, and develop a platform where trained people can work on similar projects:

Phase One: Educational familiarizing workshops that include field demonstrations using a portable shaking table and scaled models. Its main goals are to educate community members in the high seismic vulnerability of their dwellings, and to show the value of building earthquake-resistant adobe brick houses.

Phase Two: Training workshops that teach community members how to build an improved earthquake-resistant adobe house using a simple low-cost reinforcement technique through an illustrated construction manual. The main objectives are to train community members in practical skills, and to provide a reference document for future construction.

Phase Three: Assessment based on identifying improvements for future training programs. The project's success is assessed by the application of this technique beyond the structures built during training (e.g., the number of independently built or reinforced houses). Another potential assessment outcome is the extent in which local governments have developed similar training programs.

5. Technology-Transfer Experience in the Andean Community of Pullo

5.1 The Andean community of Pullo

Pullo is a small rural community in the Ayacucho region of the Peruvian Andes (Fig. 7). Earthquakes are relatively common in this area because it lies near the boundary between the Nazca and the South American tectonic plates. In August 2014, a 6.6 earthquake on the Richter scale injured around 100 people, adversely affected 55 houses, and rendered 30 of these structures uninhabitable [20]. After this event, Cáritas, a local NGO, asked the DARS-PUCP for relief aid and earthquake-resistant construction training, and in response Pullo was offered to be part of the PUCP training project.

Figure 7 – Geographical location and main square of the Andean community of Pullo

In Pullo, over 80% of the houses are made of traditional adobe [6] and built without technical assistance or seismic reinforcement criteria [21]. Typical adobe houses are one- or two-stories high and have "C" or "L" floorplans with a yard or farmland area behind the house. The bathroom and kitchen are built separate from the main building and rooms are unconnected from each other. Therefore, the living room, each bedroom and any other rooms in the house have an external door connected to the yard, a balcony or a staircase (Fig. 8). Foundations are made of stone and mud mortar forming a "pirca" 0.50-0.80 m high; some houses also have a stone and mud mortar plinth. Each floor has a height ranging between 2.40 and 3.10 m, but the highest point in a two-story house can be 7.0 m. Roofs are built with eucalyptus logs, highly available in the area, spaced 0.60-0.80 m, rest directly over the non-reinforced walls, and are covered with woven straw or woven cane, mud mortar and straw to settled clay tiles.

Dwellers know empirically that non-reinforced adobe houses have very poor seismic performance despite their excellent thermal and acoustic properties (Fig. 9). Sadly, however, over 30% of the rural population lacks access to industrialized construction materials and over 60% live in conditions of poverty or extreme poverty, without access to utilities like water and electricity [6]. For many families, adobe bricks therefore are the only affordable and available building material. Furthermore, a lack of awareness of construction techniques prevents homeowners from investing additional time and money on seismic reinforcement, or repair existing damages [12]. As a result, the damage observed corresponds to lack of seismic-resistant building techniques during construction (the absence of collar beams and the excessive thickness of mortar joints) and insufficient maintenance throughout time [21].

Figure 8 – A typical two-story adobe house in Pullo

Figure 9 – A damaged and inhabited adobe brick house in Pullo

5.2 Educational workshops

Phase One of the PUCP training program in earthquake-resistant construction in the district of Pullo consisted of two educational workshops carried out in May and September 2015. The educational workshops had an interdisciplinary approach, so three civil engineers, one psychologist, and one communications professional traveled to the community. Advertising was used to promote the educational workshop: Group interviews were conducted with community leaders; personal and group invitations were made to residents of all genders and ages; and, general announcements were made using the city hall megaphone. However, attendance was free and voluntary as participants did not receive any form of compensation. The educational methodology was planned to be highly interactive and both workshops had a two-hour length according to resident's time and date availability.

As an introduction to the familiarizing educational part of each workshop, participants were shown a video from the 1970 earthquake in northern Peru. The team made open questions (e.g., "How did you feel watching the video?") that allowed community members to express their thoughts—and fears—regarding earthquakes and how they perceived their adobe houses. Participants confirmed the need for safer housing in Pullo both times. They considered adobe a brittle material, but the only one they could afford, and thus feared losing their households and their lives to earthquakes.

The next part of each workshop focused on eliciting responses to one specific question: "Do you believe construction with adobe can be earthquake resistant?" Since participants unanimously gave a negative answer, the project team showed previously selected technical and motivational videos showing the effectiveness of seismic reinforcement, while adding commentaries and questions for the audience. The final video presented the full-scale adobe model reinforced with the nylon-rope mesh and tested in the full-scale shaking table at PUCP. Some questions from the participants showed their interest (e.g., "How thick do the ropes have to be?") while others were skeptical (e.g. "How are those thin ropes going to protect my house from earthquakes?")

Finally, the portable shaking table was demonstrated in front of each group of participants. These live demonstrations allowed community members to observe up close the expected seismic performance of a non-reinforced adobe house during an earthquake (Fig. 10). Participants identified the non-reinforced model with the seismic behavior of their households during earthquakes, and they also commented on the importance seismic reinforcement has for the enhanced model after each demonstration. Furthermore, at the end of the first workshop over 70% of adult participants signed up for upcoming training sessions, and 80% of the participants returned the following training session after the second educational workshop [22].

Figure 10 – Live portable shaking table demonstrations

5.3 Training workshop

Phase Two of the PUCP training program in earthquake-resistant construction in the district of Pullo comprised one training workshop in September 2015. The training workshop was focused on the development of practical construction skills, thus, two civil engineers and one communications professional traveled to the community. Additional advertising was undertaken in order to promote the workshop: Community leaders received periodic reminders by phone and cellphone, and posters inviting them to come using simple language and images were placed in strategic parts of the community. However, the lack of personnel in the study area made the advertising process harder [22].

As an introduction to the training workshop, participants were shown a poster with detailed graphical information regarding an earthquake-resistant adobe house. The poster suggested they should build away from hazardous soils with proper foundation and plinth; place small centered windows and doors; use collar beams and nylon ropes as seismic reinforcement; and, use plaster to prevent the erosion of adobe bricks, mortar and nylon ropes. In addition, the project team added commentaries and questions for the audience that allowed deeper understanding of the information.

The main part of the workshop focused on the practical training of dwellers in the nylon-rope mesh reinforcement technique. Participants received portions of rope and were taught one chosen tying knot; this exercise served to validate its simplicity as most rural dwellers easily replicated the knot in their first attempt. Participants then had the opportunity to practice placement of the nylon ropes on an existing adobe wall property of the town hall (Fig. 10). The work team explained the reinforcement procedure step by step, instructing participants at the same time to do it on their own. Participants first drilled holes through the mortar joints using manual tools or an electric drill, and then slid the ropes through the holes avoiding mortar joints on the corners; finally, they used the knot they had practiced to tighten the ropes.

Figure 10 – Practical training in the nylon-rope mesh technique

6. Conclusions

Non-reinforced earthen construction should be avoided in seismic areas. However, millions of families already live under extremely high risk conditions, and urgent solutions are required for them. The main challenge is not to develop affordable and more sustainable solutions, but rather to disseminate these alternatives among these communities. Thus, the first step to bridge the communication gap between academia and earthquake-prone communities is the development of educational campaigns aimed to raise awareness in high seismic risk areas. This communication effort is complex and multidimensional. It cannot (and should not) be carried out by the academic community alone. It must involve the government at the central, regional, and local levels; NGOs involved in urban and rural development; the professional engineering, architecture, social science, and communications communities; the educational system starting in elementary school; and the media in all of its forms.

The technology-transfer experience in the Andean community of Pullo reaffirms the importance educational campaigns have in the attainment of a successful dissemination of earthquake resistant construction, as dwellers must trust seismic reinforcement in order to include it in their building practices. The educational workshops succeeded in raising seismic awareness and the local willingness to participate in future training sessions and learn the nylon rope mesh technique. We therefore recommend that future studies and training programs include an educational phase when working with technology transfer in rural communities. More significantly, the team considers the communication and educational tools that we have developed might be applicable in, or adapted to, other seismic areas where people build with earth—specifically in poor areas in Western South America, Central America and southern Asia—in the hope of improving the safety of households for more families.

The research team believes the efforts presented in this article will help mitigate the high seismic risk of the Andean community of Pullo, as its dwellers now have some knowledge of seismic reinforcement criteria. However, Pullo is just one of very many rural communities living in non-reinforced earthen dwellings in seismic areas throughout the world. The dissemination of earthquake-resistant construction among dwellers in order to prevent a tragic loss of life due to seismic events, is thus a pressing issue.

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