Towards Creating Earthquake-Safe Communities: Seismic Retrofit of an Adobe School Building in Rural Peru Using Geomesh

V. Cedillos & B. Tucker
GeoHazards International, USA

M. Blondet, J. Carpio, J. Quispe, S. Rondon & S. Santa Cruz
Pontificia Universidad Católica del Perú, Peru

M. Bussmann, G. Deierlein & E. Miranda
Stanford University, USA

M. Sanchez
Estrategia, Peru

15 WCEE
LISBOA 2012

SUMMARY
In Peru, many rural communities face significant seismic risk, from a combination of high seismic hazard and the vulnerability of traditional adobe buildings common to these regions. This paper describes a pilot project to mitigate the seismic risk in a community, through the seismic retrofit of an adobe school building in Chocos, a small village in the Andean cordillera. The primary objectives of this pilot project were to: (i) investigate prior knowledge of seismic hazard and risk; (ii) increase, through educational programs, the awareness of seismic risk and the knowledge of earthquake-resistant construction; (iii) carry out a seismic retrofit project to demonstrate the concepts of prevention as opposed to repair and reconstruction after damaging earthquakes; and (iv) promote the spread of seismic risk awareness and knowledge of good construction. The retrofit design and trainings are summarized and presented along with lessons learned.

Keywords: Adobe, Retrofit, Schools, Developing Countries

1. INTRODUCTION

This paper is a summary of the project, “Improving Earthquake Safety in Rural Peru” that was conducted, from November 2010 until end of 2011, by GeoHazards International (GHI), Stanford University, Pontificia Universidad Católica del Perú (PUCP) and Estrategia. The objective of this project was to promote seismic safety for a vulnerable community in rural Peru. For this, the authors aspired to conduct a pilot project to retrofit a school building, emphasizing local training and promoting diffusion of accessible earthquake-resistant technology and methods throughout the selected community and nearby villages.

2. BACKGROUND

Peru has a history of high seismic activity. Over the last century, the country has been affected by numerous major seismic events (i.e. Lima 1940, Ancash 1970 and Pisco 2007) and in the past 50 years, significant school damage has been recorded in at least seven earthquakes (Lee 1967; Silgado 1968; EERI 1970, 1974; Zegarra 1974; Muñoz 1997). The 2007 M8.0 Pisco earthquake, which destroyed houses, schools and hospitals, is the most recent reminder of the seismic hazard and building vulnerability that result in the region’s high seismic risk.

Past earthquakes in Peru have resulted in major changes to the building code and better design and construction of new structures. For instance, during the 1996 Chimbote earthquake many new schools were significantly damaged; as a result, the building code was revised in 1997 to address prior vulnerabilities in the standard school design. These measures were important and essential for the safety of students, but unfortunately, were not sufficient. Although post-earthquake observations and studies have shown that the 1997 building code is adequate for the anticipated ground motions, the number of schools following this new design only accounts for 5% of the total school building stock (Blondet 2009). School buildings built before 1997, as well as many schools built in rural areas (outside the range of typical building code enforcement), remain vulnerable to earthquake shaking. The vulnerability of rural schools is particularly alarming. According to Peru's National Institute of Statistics and Informatics (INEI) in 2009, 34% of Peruvian school buildings are made of adobe—a heavy, brittle construction material known to experience sudden and catastrophic collapse even in small to moderate earthquakes—and in rural areas this percentage increases to over 50%. Unreinforced earth construction is not limited to schools—in rural regions, because adobe is locally produced and inexpensive, it is very common in residential construction, resulting in a further increased vulnerability of these communities.

3. TOWN AND SCHOOL SELECTION PROCESS

Soon after the project began, the team developed a list of criteria to help select a school and community that would be aligned to the project goals. The criteria included: 1) vulnerability (school construction type, and community resilience); 2) hazards (earthquake, landslide, and flood); 3) community support (labor contribution, and government support); 4) replication potential (similarity of nearby schools, and complexity of intervention); and 5) accessibility (travel time and cost, and year-round accessibility). These criteria were weighted differently, depending on their relevance to the project objectives. Based on the selection criteria, a total of twelve potential communities were visited and rated according to the criteria. The team selected the school in Chocos based on the ratings and a follow-up visit from U.S. and Peruvian team members. The team found Chocos to be a good fit for the project for the following reasons:

The need is high. The community is located in a region of high seismicity (see Fig. 3.1) and has vulnerable structures. The school building is vulnerable due to the construction (adobe) and its users, schoolchildren, are particularly vulnerable. The government does not plan on replacing the school with a more modern design in the near future.

Community was willing to support the project. PUCP had existing ties with the local leaders because after the 2007 Pisco earthquake, Jesus Carpio, PUCP Assistant Professor, in collaboration with Roche, helped build new adobe homes reinforced with geomesh in Chocos. On the scouting trips, the team further developed this relationship with the local leaders and the community was very willing to collaborate. The Vice-Mayor offered to help provide labor, local accommodations for project participants, storage of materials, and material transportation to and from Chocos.

Replication is likely. The school building that was selected is a typical adobe school building, making the retrofit easier to replicate in other similar schools. In particular, another one of the school buildings in the same complex is almost identical to the selected school. This community has also made an effort to replicate a previous project (led by Roche) involving reinforced adobe, demonstrating their awareness of the seismic risk and their willingness to reduce this risk.

The site is accessible most of the year. This is important when considering that some materials need to be transported from Lima or other coastal cities via truck, and that the short project timeline requires deliveries to be possible throughout the anticipated construction schedule.

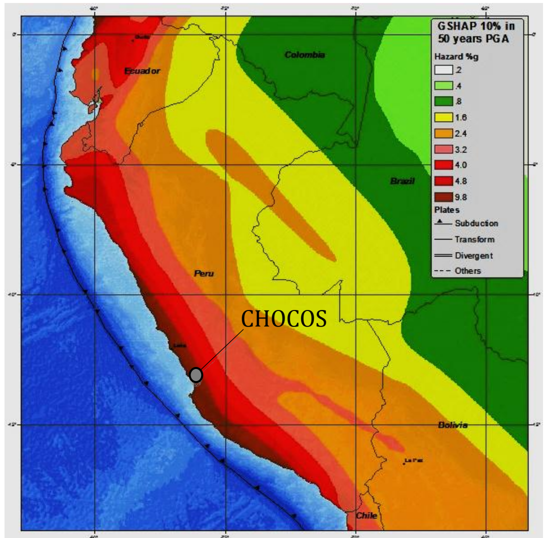

Figure 3.1. Seismic hazard map of Peru (USGS)

4. SCHOOL AND TOWN DESCRIPTION

4.1. Selected Town

The selected school (I.E. 20137 San Cristobal de Chocos) is in the District of Chocos, Province of Yauyos, Department of Lima, and is in the Andean cordillera at an altitude of approximately 2,750m. Two to three hundred people live in Chocos, the majority of them living in one- or two-story adobe buildings. Most residents work in agriculture and do not have fixed incomes. Chocos is surrounded by four other villages that are similar in size, demographic and built environment. This was particularly important, given that one of the project's objectives was to spread seismic awareness throughout the region.

Transportation to and from of Chocos is very limited—public buses arrive and depart about twice a week, the local government owns one truck, only one person owns a private car, and a handful of people own motorcycles. Only one road leads to Chocos off the main highway and this steep and dangerous mountainside dirt road has many switchbacks making transportation of materials and personnel a great challenge.

Chocos has been affected by many earthquakes, most significantly the 2007 Pisco earthquake, which caused moderate damage to many structures (typically severe corner cracking in adobe walls) and even caused several buildings to collapse.

4.2. Selected School

The selected school is one of three primary school buildings of San Cristobal de Chocos de I.E. 20137, which has 74 students and six teachers. The three schoolhouses are one-story adobe buildings with three classrooms in each building. Two of these buildings were constructed in

1954 and the other in 1988 (see Fig. 4.1). Typical adobe walls in the older buildings were 40 centimeters thick, 2.9 meters in height (3.70 meters at highest point in gable walls) and each classroom was approximately seven meters on a side (see Fig. 4.2).

Figure 4.1. Primary school (prior to retrofit) in Chocos. The photos are of two adjacent school buildings constructed in 1954. The building on the right was selected for the retrofit project.

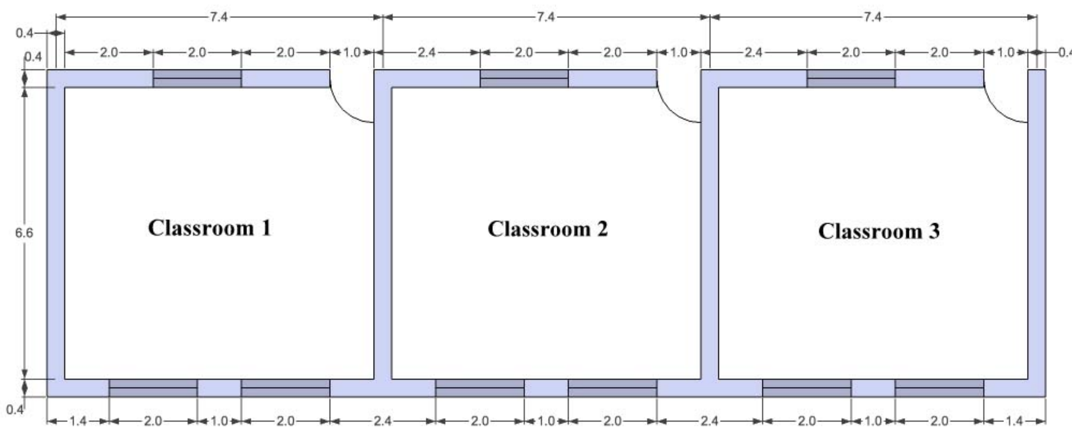

Figure 4.2. Floor plan of existing school building selected for the project. All dimensions in meters.

5. RETROFIT DESIGN

The retrofit design included the following elements:

New interior and exterior footings. These concrete elements, placed next to existing foundations, anchored the new mesh panels on the inside and outside of the existing walls (see Fig. 5.1).

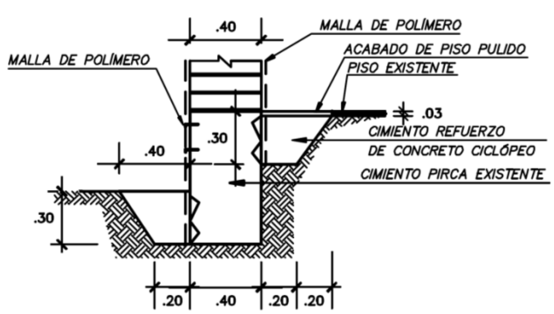

Figure 5.1. Typical retrofit foundation section, showing existing and new foundations.

New wall buttresses. Buttresses, made of new adobe blocks, were built and toothed into the existing wall at spacings prescribed by the Peruvian adobe building code for new buildings, providing additional out-of-plane stiffness to the adobe walls. (Norma Peruana E.080)

Reduction in window opening sizes. Additionally, in order to comply with code requirements for new adobe buildings, the design specified filling in windows such that total opening length did not exceed a maximum fraction of total wall length. See Fig. 5.2. (Norma Peruana E.080)

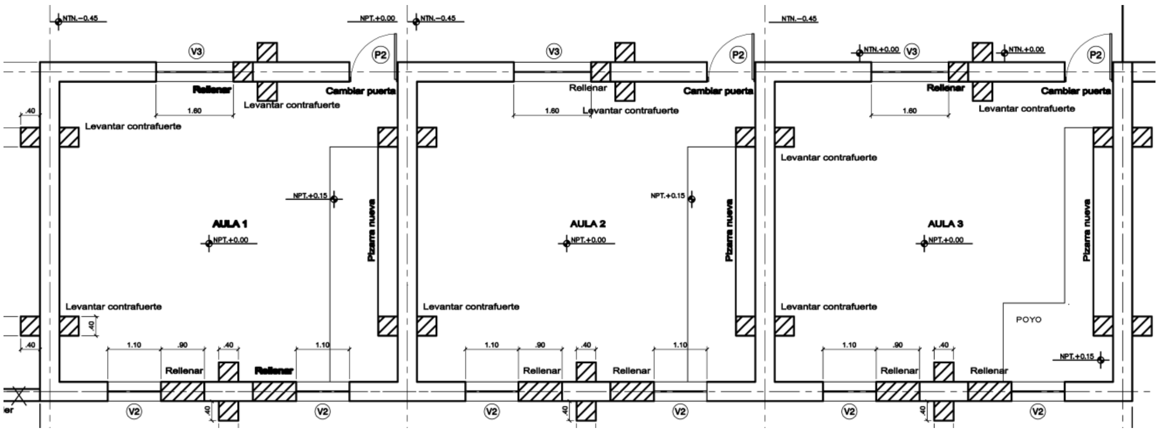

Figure 5.2. Floor plan showing buttresses and filled in areas at existing window openings.

Mesh applied on both sides of walls. In order to prevent a brittle collapse mechanism due to out-of-plane action in walls, mesh was applied to both sides of the wall and tied through the wall with plastic ribbons at regular spacings. This mesh was designed to serve as tension reinforcing in the event of severe deflection under lateral out-of-plane loads, and ultimately as a confining safety net in the event that the adobe within would become damaged and unstable. The school retrofit design was based on techniques extensively studied and tested at PUCP involving reinforcement of adobe walls with wire mesh or geomesh (a heavy plastic mesh commonly used in slope stabilization and other geotechnical applications). Both were considered; geomesh, which has showed ductile response in shaking table tests, was selected as the better option for this project.

Ring beam at tops of walls. A ring beam at the top of the walls was essential both to anchor the tops of the mesh panels and to tie the walls together, allowing the walls to act as a unit under lateral loads. Both wood and reinforced concrete beams were considered; a concrete beam was selected due to its superior strength and stiffness, which were needed given the long wall spans.

The proposed retrofit design was checked against a design acceleration of 0.5g, conservatively exceeding the minimum acceleration requirements of the Peruvian adobe code (Norma Peruana E.080). Strength-based design checks were performed through the entire load path: beginning with inertial forces developed within the adobe walls (in-plane and out-of-plane), then resolving these forces into tension in the mesh, and finally collecting these tension forces into the ring beam and foundations. A note on performance targets: throughout the design, this retrofit was intended to protect life safety under moderate and severe seismic events. Adobe buildings are brittle and can undergo severe damage even in small earthquakes; it is expected that some repairs will be necessary after these events. The goal of this design is simply to allow those inside, children and teachers, to evacuate safely in an event that would otherwise cause sudden collapse.

In addition to the necessary structural aspects of the retrofit, several additional architectural features were included in the construction. This was done to make the school more appealing to the villagers and to help promote a well constructed building as something to desire. These features included a new roof structure, drainage system, ramps, repainted walls, and new doors, windows, blackboards and lights for each room.

6. TRAININGS

6.1. Strategy

A key goal of this pilot project was to promote diffusion of seismic awareness and knowledge of proper adobe retrofit techniques throughout the village of Chocos and nearby villages. The idea was to develop both the demand for safer buildings and the supply of trained builders for these efforts to go beyond strengthening a single school. It was therefore crucial that trainings lead homeowners to value strengthened adobe structures (the demand) and also that they empower local people with the skills required to make their buildings safer (the supply). The materials developed and the trainings themselves were designed with this in mind.

The team also made efforts to convey a positive message and feeling of empowerment when discussing seismic vulnerabilities, considering the negative associations that most villagers have with earthquakes. For example, the trainings covered not only the problems with earthquakes (e.g. the catastrophic behavior of adobe structures), but also the solutions (i.e. actions villagers themselves can take to prevent this behavior). Additionally, to improve the relevance of the trainings, the team used common and simple vocabulary, and explained technical terminology (i.e. out-of-plane wall failure) using situations relevant to the villagers (i.e. adobe blocks falling into a home or onto the street).

6.2. Training Materials

Various training materials were developed and used in Chocos. These included:

Adobe Blocks Video. This easy-to-follow video showed two structures identical in configuration (a house and a school) modeled with small wood blocks. One is “strengthened” using a net that represents geomesh and a wood ring beam. The structures are set on a table that is shaken to simulate an earthquake and the results are as expected—the structure without strengthening completely collapses while the other has some damage, but remains standing. The purpose of this video was not to demonstrate accurately the actual physical behavior of an adobe structure during an earthquake, but rather to illustrate in a very simple manner the danger of an unreinforced adobe building and the importance and effectiveness of strengthening these structures.

Motivational Video. This video shows several Peruvians, whose homes collapsed during the 2007 Pisco earthquake, rebuilding their adobe homes using geomesh. This was developed to motivate and empower people by example—that is, villagers of similar backgrounds building adobe structures with geomesh.

Typical Building Vulnerabilities Videos. Short videos were developed to illustrate three common building vulnerabilities observed in the town—large windows, high wall slenderness ratio (height to thickness), and long unbraced horizontal wall spans. The videos showed two structures modeled by wood blocks, one being more vulnerable than the other (i.e. one representing a wall with a large window and the other with a small window). Both structures were set on a table that was shaken to simulate an earthquake. In each of the examples, the more vulnerable structure (the wall with a larger window, the more slender wall, and the wall with a longer horizontal span) failed much faster. These videos were used to help villagers understand in a purely visual manner why certain structural characteristics are particularly dangerous in earthquakes.

6.3. Training Sessions

Three main audiences were targeted during the trainings:

Children. Training for children mostly involved "movie nights," which consisted of projecting an animated children's film for the entire village. Before and after the movie, some of the training videos that were developed were shown to promote seismic awareness. The team also held short training sessions for schoolchildren to promote earthquake awareness and preparedness.

Homeowners. These trainings focused on empowering homeowners, including both males and females, to identify vulnerabilities in buildings around their community and to work together to develop strategies for reducing their earthquake risk. A community mapping exercise was conducted where the participants walked through the town and identified vulnerabilities in their community. At the end of the exercise, the participants gathered and developed a summary of the most crucial vulnerabilities in their community along with ideas on how to address them.

Construction Workers. In addition to the trainings for homeowners, villagers working on the school retrofit attended trainings of a more technical nature. These trainings consisted of two parts: the first focused on understanding the danger of adobe buildings and identifying vulnerabilities of adobe structures. The participants, led by the project team, walked around the village and identified vulnerabilities of adobe buildings in their community. The second part focused on solutions to the problems with adobe buildings; in this session, the participants again walked around the village and discussed ways to fix the vulnerabilities that they had previously identified. The participants then went to the school, prior to the start of retrofit construction, and identified its vulnerabilities and developed ideas on how to address them. This process was carried out for the construction workers to fully understand why each part of the retrofit was essential in making the school safer, and resulted in an improved sense of community buy-in to the technical process of the retrofit.

7. IMPLEMENTATION

Following the training modules, a local workforce of approximately 15-20 villagers, supervised on site by project team members, carried out construction.

7.1. Construction Sequence

Below is the construction sequence by task, each with an approximate number of workers and days required. Tasks that did not require a full workforce were performed simultaneously.

Demolition. (10 workers, 5 days) Workers removed the existing roof, roof structure, stucco, doors and windows, and exposed existing adobe. Workers also carefully removed partial or full adobe blocks as required to tooth in new masonry at buttresses and windows (described below).

Excavation for new foundations. (10 workers, 5 days) Workers cut interior and exterior trenches adjacent to existing walls, taking care not to undermine existing rubble foundations. Trenches needed to be deep enough for sufficient anchorage of mesh panels that would later be attached to walls. In this stage, the team encountered challenges with large boulders in the trenches where new foundations would be placed. In some cases, where the boulders would not allow for sufficient embedment of the mesh panels, the boulders needed to be cut away with a rock saw, which was a labor-intensive and time-consuming process.

Fabrication of new adobe blocks for walls and buttresses. (7 workers, 3 days) To make new blocks, suitable soil was excavated from the hillside, and sand for the adobe mixture was brought in via truck from several kilometers away. Earth was mixed and formed into blocks, and set out to dry in the courtyard near the school. The blocks measured 40cm x 40cm x 10cm, and required approximately two weeks from the date of forming before they were suitably dry for placement.

Perforation of existing walls for mesh ties. (2 workers, 6 days) To secure the mesh to the structure, the existing walls were perforated with small holes through which plastic ties were passed, connecting the interior and exterior mesh panels to one another. Workers used electric drills (battery-operated drills did not have sufficient power) with bits long enough to pass through the existing walls (typically 40cm thick), favoring the mortar joints for hole locations as drilling through the blocks themselves tended to crack the adobe. Workers then passed the plastic ties through these holes, to be left in place until the mesh panels were attached.

Addition of new walls and buttresses. (15 workers, 5 days) To comply with the requirements of Norma Peruana E.080 for maximum allowable window dimensions and unbraced wall lengths, all windows were reduced in size and buttresses were added to brace the existing walls. Window openings were reduced by means of new adobe bricks toothed into the existing walls; similarly, pockets were cut into existing bricks to engage the new buttresses into the existing walls.

Attachment of mesh panels. (10 workers, 4 days) From rolls of mesh 3.0m wide, workers measured and cut panels to fit all faces of the walls, allowing a surplus at the top and bottom for embedment into the new concrete ring beam and new concrete foundations, respectively. Following this, the mesh panels were then tied onto the walls and to one another.

New foundations. (8 workers, 4 days) Once the new mesh panels were in place, the trenches excavated alongside the existing foundations were filled with concrete to anchor the mesh. To avoid the concrete simply pushing the mesh against the existing foundations (which would result in poor anchorage), fist-sized stones were placed in the trench to separate the mesh from the wall and allow for good embedment of the mesh into the concrete mass.

Concrete ring beam. (10 workers, 7 days) A new continuous reinforced concrete beam was constructed at the top of each existing wall. First, some workers assembled rebar cages on the ground, while others built simple wood forms atop the existing walls to form the sides of the ring beam. Next, cages were lifted into the forms and the segments spliced as needed. With the steel reinforcing in place, workers filled the forms with concrete, finished the top surface, and covered the beam with wet concrete sacks for curing. Forms were stripped after two days.

New gable walls. (6 workers, 2 days) Above the ring beam at each of the four transverse walls, the design called for new adobe gable walls to support the longitudinal roof members. Here, mesh panels were embedded into the ring beam that could be folded up around the new gable walls.

New roof construction. (2 workers, 12 days) The new roof design included three new wood roof trusses (one above each classroom) and a series of purlins to which the corrugated plastic roof panels would attach. Some of these panels were translucent, allowing more natural light to reach the classrooms. Because the carpentry involved with this was a longer and more skilled task than the formwork carpentry, the team sub-contracted this work to a local carpenter.

Stucco. (8 workers, 6 days) After the overhead work was complete, workers could safely return to working on the walls. To protect the plastic ties from rapid degradation in sunlight, and to give the school a finished appearance, several coats of mud stucco were applied to the walls.

Site work. (6 workers, 3 days) The workers accomplished several tasks to improve the existing site outside the building. Ramps were constructed (rather than stairs to allow to for fast evacuation) because the existing courtyard elevation was below the elevation of the classroom floors. The workers also filled in foundation trenches where the top of the new concrete footings did not come all the way up to existing grade or the top of the existing footing.

Miscellaneous closeout. (12 workers, 2 days) In the days before the opening ceremony, workers painted the school and installed new lights, windows, and chalkboards, and cleared the site of equipment, materials, and construction debris. The opening was held on August 14, 2011.

7.2. Construction as a Training Tool

To aid in the transfer of this retrofit technology, the team used the entire construction process as a training tool for the workers to learn about the requirements of a successful retrofit. Team members filmed each structurally essential construction activity with a worker explaining the importance of that specific activity; these short interviews were compiled into a video, with an accompanying checklist, for homeowners around the community. The purpose of this video was to promote diffusion of this technology into the surrounding community, and to inform homeowners, via the voices of fellow community members, of the essential requirements for a good retrofit – making them into smart consumers of home retrofits using this technology. The requirements selected for this checklist and video were: 1) repair damaged walls; 2) connect geomesh to the walls; 3) ensure that the geomesh is anchored into the new foundations; 4) ensure that the geomesh is anchored into the new ring beam; 5) tie the geomesh overlaps; 6) connect the roof to the ring beam; and, 7) cover the geomesh with mortar to protect it from the sun.

7.3. Efforts to Engage Government

For the official opening ceremony of the renovated school building, in which the town was recognized for its participation in and contribution to the project, the team visited nearby towns to extend formal invitations to mayors and city council members, to promote the diffusion of this technology to adjacent communities. The team also invited members of the Ministry of Housing, Construction and Health from Lima, in order to bring awareness of this project, and the retrofit technology, to the national level.

8. OUTCOMES AND LESSONS LEARNED

Various challenges emerged as the project unfolded, some that were particular to the actual implementation of the project and others that were specific to the diffusion of this earthquake-resistant technology throughout Chocos and other nearby villages. Implementation challenges included working with limited and unreliable construction equipment—the concrete mixer breaking down, not having access to adequate rock-cutting blades to clear the area for the new footings and an unreliable power supply for the power drills. Acquiring the construction equipment and material itself was also a challenge—access to much of the equipment (levels, drills) and material (geomesh, cement, steel reinforcement, timber) involved between a four and seven hour drive, to either San Vicente de Cañete or Lima, making transport costs high. Therefore it was crucial to limit the number of trips and ensure that enough, but not an excess of material was ordered.

Looking ahead at diffusion, it is expected that the high costs of transportation materials and equipment, along with the high cost of geomesh itself, will make it difficult for local people to replicate this earthquake-resistant technology without some external financial help. Government programs that currently focus on housing improvement—including safe cook stoves, thermal heating, and access to potable water—could help with this issue, although including seismic safety in these programs would be a complex intervention. Even if the community had enough financial resources to reinforce their own adobe structures, other problems exist, such as adequate water supply, that the community might consider more pressing and therefore could take precedence. Retrofit work itself has many high-level technical challenges, including first determining whether a structure is suitable for a retrofit or if it should be rebuilt for either financial or structural reasons. Although many of the adobe structures in Chocos and surrounding communities are fairly similar, any variation causes difficulty in replicating one specific retrofit design.

These challenges and lessons learned highlight the crucial need to continue exploring strategies—involving technical, social and political aspects—that would significantly reduce the seismic risk in such vulnerable and impoverished communities.

AKCNOWLEDGEMENT

This project was conceived of as a memorial to the late Mr. Satoru Ohya, a generous donor to and founding member of the Board of Trustees of GeoHazards International. Throughout his later life, Mr. Ohya passionately and generously supported a wide variety of efforts to improve earthquake safety in developing countries, particularly school earthquake safety. The seed funding for this project in Chocos came from the GeoHazards International Satoru Ohya Memorial Fund, comprised of donations from friends and admirers of Mr. Ohya. These funds were augmented by additional generous contributions from the Swiss Reinsurance Company Ltd, and the Thornton Tomasetti Foundation. Student and faculty participation was supported by the John A. Blume Earthquake Engineering Center, Engineers for a Sustainable World, Stanford University and the Pontificia Universidad Católica del Perú.

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