Review:

# Summary Report of the SATREPS Project on Earthquake and Tsunami Disaster Mitigation Technology in Peru

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[Received July 30, 2014; accepted September 7, 2014]

**One of the SATREPS projects on earthquake and tsunami disaster mitigation technology in Peru has been promoted since March 2010 for a five-year period. The project focuses on five research fields, i.e., seismic motion and geotechnical, tsunamis, buildings, damage assessment, and disaster mitigation planning. Collaborative research has been carried out through joint experiments, observations, field surveys, computer simulations, seminars and workshops. With the Lima metropolitan area and the city of Tacna set as case study sites, two mega-thrust earthquakes have been simulated and their effects and countermeasures investigated. The simulation results have been validated by observation data and have been implemented in government policy. Young Peruvian engineers and scientists have also received training and education. This paper summarizes the progress and outcomes of the SATREPS project for earthquake and tsunami disaster mitigation in Peru.**

**Keywords:** earthquake, Tsunami, disaster mitigation, international cooperation, Peru, SATREPS

## 1. Introduction

The Japan Science and Technology Agency (JST) and the Japan International Cooperation Agency (JICA) initiated an international research program, "the Science and Technology Research Partnership for Sustainable Development (SATREPS)," under their joint sponsorship in 2008. The following four fields, 1) Environment and Energy, 2) Bio-resources, 3) Natural Disaster Prevention, and 4) Infectious Disease Control, were established under the SATREPS framework.

A proposal entitled "Enhancement of Earthquake and Tsunami Disaster Mitigation Technology in Peru" was granted as one of the projects in the field of natural disaster prevention in April 2009. Following the preparatory phase for planning the details of the joint research, the project was formally started after the signing of the Record of Discussion (R/D) in January 2010 and set to continue for a five-year period.

In our previous paper [1], the objectives, research plan, and progress of the project up to the end of 2012 were described. In this summary paper, further progress and outcomes of the project are presented.

## 2. Research Plan and Activities

In this SATREPS project, comprehensive research on earthquake and tsunami disaster mitigation in Peru has been carried out through strong collaboration among researchers from Peru and Japan. The joint research has been carried out by five research groups: **G1**) Strong motion prediction and development of seismic microzonation (Chiba Univ., CISMID, IGP); **G2**) Development of tsunami countermeasures based on numerical simulation (Tohoku Univ., DHN, IGP); **G3**) Enhancement of seismic resistance of buildings based on structural experiments and field investigations (BRI, CISMID, Toyohashi Tech); **G4**) Development of spatial information databases using remote sensing technology and earthquake damage assessment for scenario earthquakes (Tokyo Tech, CISMID, CONIDA); **G5**) Development of earthquake and tsunami disaster mitigation plan and its implementation in society (Chiba Univ., INDECI, CENEPRED, PCM).

**Figure 1** shows research topics and items of the project and the groups in charge of them. The Lima Metropolitan area (including Callao) and the city of Tacna were selected as the two case study areas of the project. Lima, with the population of about eight million, is the capital and largest city in Peru. Tacna is the regional capital city of the Tacna Region, which borders Chile in southern Peru.

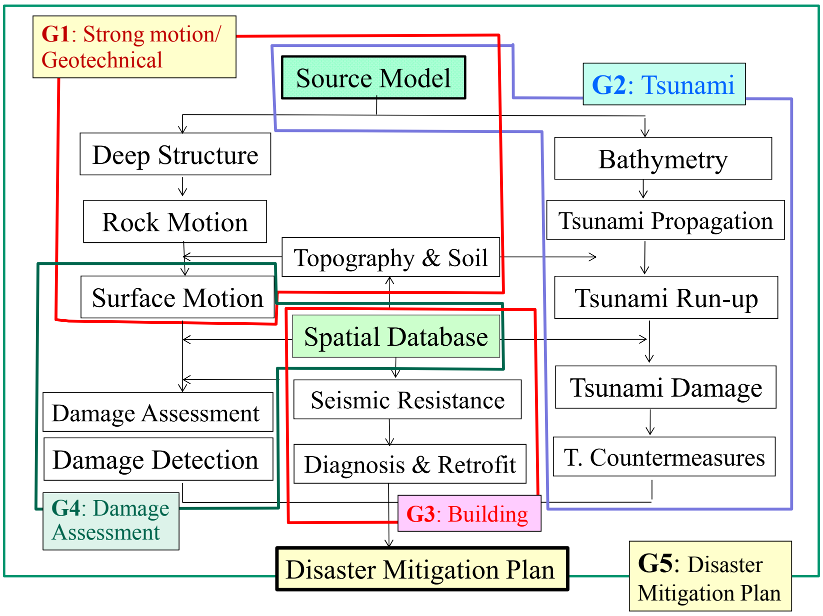


**Fig. 1.** Structure of research topics in the Peru project and the five groups in charge.

Scenario earthquake events for damage assessment were determined based on recent studies [2, 3]. The two major historical earthquakes shown in **Fig. 2** were selected for this purpose because the recurrences of the two events are expected to be the most damaging for Peru. The first event is the 1746 Lima-Callao earthquake ($M_w$8.6), which completely destroyed the city of Lima and caused about 6,000 deaths. The second event is the 1868 southern Peru (Arica) earthquake ($M_w$8.8), which produced large tsunamis along the coasts of Peru and Chile. The earthquake almost completely destroyed the Arica, Tacna, Moquegua and Arequipa areas, causing about 25,000 deaths. The recurrence of these mega-earthquakes is anticipated along the Pacific coasts of Peru and Chile [4].

Group 1 studies seismic motion and geotechnical aspects through seismic and microtremor observations at the case study sites. Together with existing geological data and newly conducted borehole surveys, the soil amplification characteristics have been investigated [5–7].

Group 2 studies tsunami modeling, numerical simulation, damage assessment, and evacuation plan. First, tsunami source and propagation models were examined for the 2001 Atico earthquake [8] and the 2007 Pisco earthquake [9]. After confirming the numerical methods, tsunami propagation simulation [10, 11], damage analysis [12], and evacuation simulation [13] for the 1746 Lima-Callao earthquake were carried out.

Group 3 studies seismic resistance and the retrofitting of buildings in Peru. Using new structural and material testing systems introduced to the structural laboratory of CISMID, loading tests were conducted for a typical structural system in Peru [14, 15]. A database of seismic experiments for masonry structures was also created [16, 17], and seismic vulnerability evaluation for historical buildings was carried out [18].

Group 4 assesses seismic damage to buildings in the case study sites for the scenario earthquakes. First, building inventory data were created in Lima and Tacna from census data, satellite images, and land-use and digital elevation maps [19]. Earthquake damage detection methods from satellite optical and Synthetic Aperture Radar (SAR) images were developed [20], and damage assessment for the scenario earthquakes was carried out [21].

Integrating all the output from the other research groups, Group 5 proposes a strategic plan for disaster mitigation. A computer simulation model was developed [22] that aims to forecast the seismic vulnerability of the Lima Metropolitan area for the next twenty-years under different disaster mitigation measures incorporated in urban development projects.

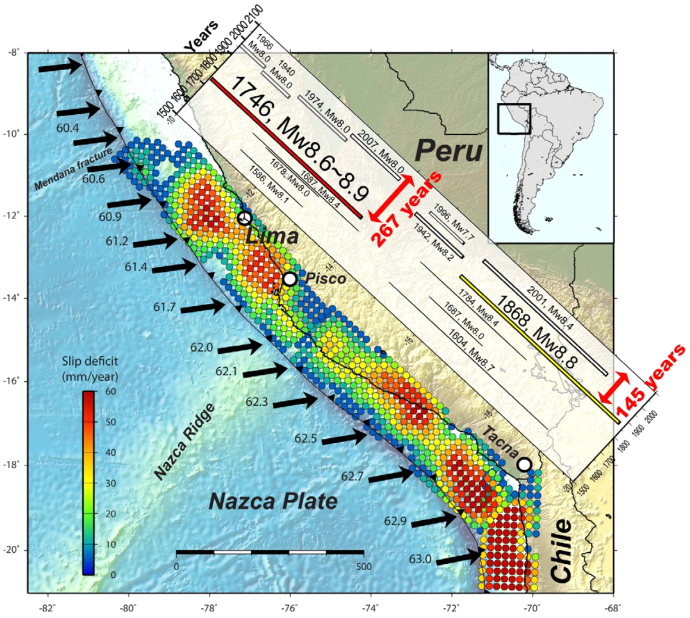


**Fig. 2.** Slip deficit in Peru and northern Chile obtained from geodetic measurements and historical earthquakes along the Nazca subduction zone in Peru [3].

## 3. Strong Motion and Geotechnical Issues

### 3.1. Source Model Scenarios and Strong Ground Motion for a Future Mega-Earthquake in Lima

A methodology based on a model of Inter-Seismic Coupling (ISC) distribution in subduction margins as well as information on historical earthquakes was developed in order to estimate the slip distribution of future mega-thrust earthquakes in the central Andes region [3]. The results of ISC indicate the existence of two strongly coupled regions, the first one off the shore of Lima and the second one off the shore of Pisco (**Fig. 2**). Broadband source models suitable for strong motion simulation were also constructed. A set of 12 broadband slip sources and 9 different locations of rupture starting points were also calculated.

The domain of the strong motion simulation spans a 50 km × 55 km area covering the entire Lima metropolitan region. The EW, NS, and UD components of strong ground motion at 169 grid points spaced every 5 km were calculated for a seismic bedrock condition ($V_s = 3,454$ m/s) and for all the scenarios. Then seismic bedrock waveforms were convoluted by soil transfer functions at every grid point [23], to obtain accelerograms at an engineering bedrock condition ($V_s \sim 0.4$ km/s). Finally, PGA (**Fig. 3**) and PGV ground motion maps for Lima were calculated by including shallow site amplifications at a grid interval of 250 m by means of an empirical relationship between the average S wave velocity for the shallowest 10 m of soil (AVS10) and ground motion amplifications with respect to the engineering bedrock [7].

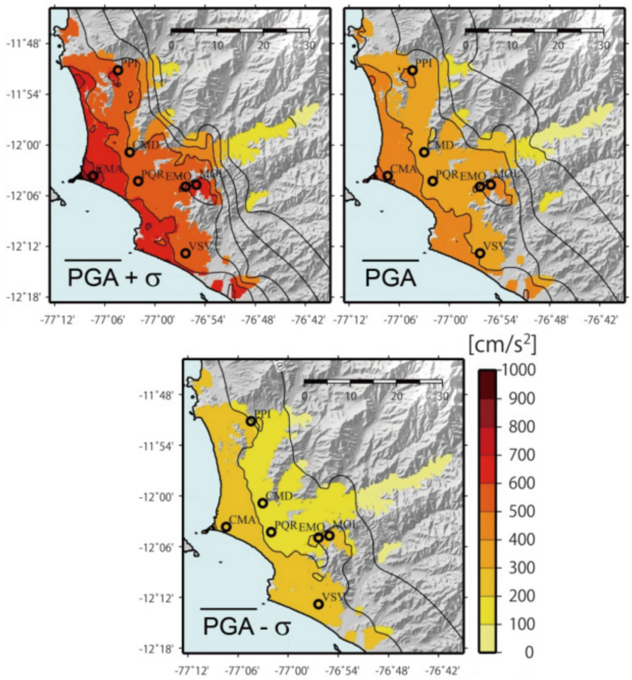


**Fig. 3.** Average PGA distributions for all scenarios, as well as the ground motion values one standard deviation from the mean.

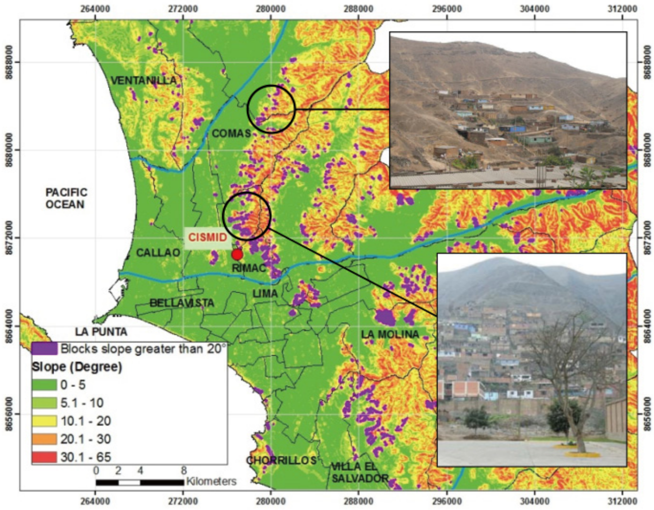


**Fig. 4.** Distribution of populated slopes in Lima that have an inclination greater than 20 degrees.

### 3.2. Dynamic Response of a Typical Populated Slope in Lima

Over the last fifty years, Lima has experienced a very complex urbanization process resulting in encroachment into rocky Andean foothills close to the historical center (**Fig. 4**). A populated slope located in the district of Independencia was chosen as the target area.

First, with the objective of evaluating the variation in dynamic properties along the chosen populated slope, seven microtremor array measurements were conducted in the flat and sloping areas. From the obtained S-wave velocity profiles, it was evident that the distance down to bedrock gradually decreases in the same way the natural period of vibration decreases as one approaches the foot of the slope. In addition, in the sloping part, a top layer was found to have poor static and dynamic properties as a consequence of the earthmoving technique known as "cut and fill" [24].

Second, a finite element model of the slope was generated and solved for plain-strain conditions in the time domain by applying an input motion at the bottom of the model, one of the synthetic accelerograms developed within the framework of this project. The results showed that amplification of the response is evident for surface layers in the flat region, and no larger values were found in the sloping areas of the model.

## 4. Tsunami Issues

The tsunami group aims to contribute to enhancing the resilience of tsunami disaster mitigation efforts in Peru by developing tsunami damage estimation and mitigation technologies. Our activities in Peru consist of following seven elements.

1) Transfer of tsunami numerical model
2) Verification of tsunami numerical model with past events
3) Study of historical tsunamis
4) Tsunami risk assessment along the Peruvian coast and the mapping of tsunami impact
5) Support of the tsunami evacuation plan
6) Public outreach

Throughout this project, the tsunami numerical modeling techniques were transferred to six Peruvian researchers. They learned the basic theory of tsunami physics, the numerical modeling scheme, and tsunami inundation modeling. First, we applied the tsunami inundation model to a past tsunami event (the 2001 southern Peru earthquake, $M_w$8.3), to validate the inundation model [26]. Second, we determined the tsunami source scenario of 1746 ($M_w$9.0) by analyzing historical documents to clarify the tsunami travel time and heights and by analyzing the characteristics of the tsunami witnessed in the town and port of Callao [27]. The tsunami source model was constructed consistent with the witnessed event. Third, we performed tsunami risk assessment to determine the area most at risk. Considering a 50-year probability of occurrence of major earthquakes and potential tsunami exposure (population exposed to tsunami inundation), we determined the Lima-Callao region to be the most at risk in the near future [27].

We further simulated tsunami inundation in Lima to determine the worst-case scenario of tsunami inundation based on twelve possible earthquake scenarios. Integrating the tsunami inundation model results [10], a questionnaire survey, and a multi-agent simulation [13], we evaluated the tsunami evacuation plan in La Punta, Callao [28]. There are twenty evacuation buildings in La Punta, and the performance of each was evaluated in terms of demand and capacity (**Fig. 5**). The results suggested that the spatial allocation of vertical evacuation buildings be improved. Finally, we used all the findings of the project for public outreach, especially in public symposiums and evacuation drills.

Throughout the project, we constructed a procedure for tsunami modeling, model validation, tsunami risk mapping, damage/loss estimation, and loss reduction. This procedure will be applied to other Latin American countries, such as Ecuador and Colombia, where other SATREPS and JICA projects are in progress. We all hope that the outcome of the project will be passed to various stakeholders and institutes to mitigate future tsunami disasters.

## 5. Seismic Resistance of Buildings

While it is common for buildings in urban areas to be reinforced concrete structures, buildings in rural areas in Peru are often adobe and confined masonry structures. Historical monuments are often stone masonry structures as well. Therefore, in order to enhance the seismic resistance of buildings in Peru, it is important to examine the evaluation and retrofitting methods for different types of structures.

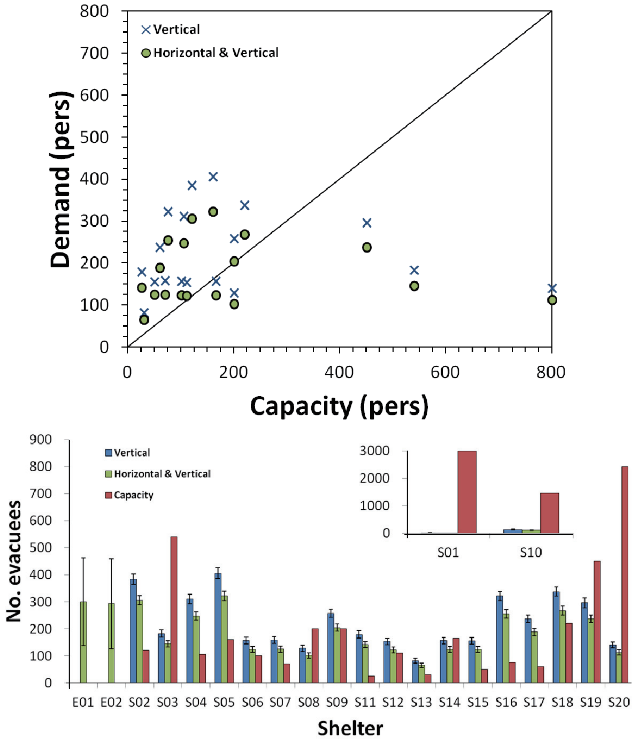


**Fig. 5.** Demand and capacity of vertical evacuation shelters in La Punta [13].

### 5.1. Development of Seismic Database for Masonry Structures

Masonry structures, including confined masonry and adobe structures, are widely used as houses in developing countries, including in Peru. However, the mechanical characteristics of these structures, such as member strength and deformation capacity, have not been sufficiently studied enough. Therefore, to develop seismic evaluation and retrofitting techniques, a seismic database of mechanical characteristics of masonry structures was created based on experimental data collected from various research sources such as research papers, original test data, etc. [16, 17].

### 5.2. Development of Seismic Evaluation and Retrofitting Techniques

To understand the real behavior of buildings in Peru, a seismic monitoring system has been implemented in several buildings in Lima (**Fig. 6**). The observed records are automatically transmitted through the Internet to servers in Peru and Japan. Also, the nonlinear behavior of typical structures in Peru, such as low ductile walls and confined masonry walls, were tested using the new hydraulic loading system installed in CISMID (**Fig. 7**) under the support

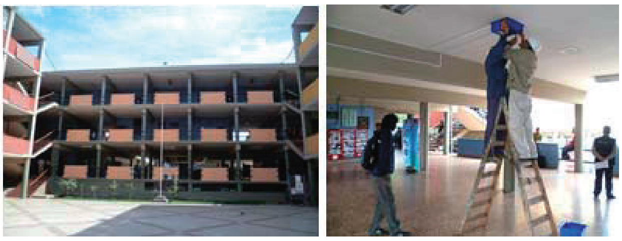


**Fig. 6.** Seismic monitoring system of buildings in Lima.

**Fig. 7.** Structural tests using a new loading system.

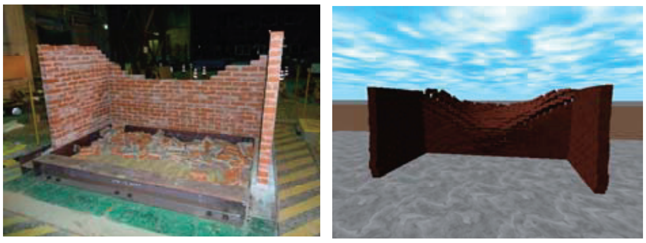


**Fig. 8.** Shaking-table test and analysis of out-of-place failure of masonry walls.

(a) No retrofit (b) Full retrofit (c) Partial retrofit

**Fig. 9.** Retrofit of low ductile walls using carbon fiber sheets.

**Fig. 10.** Microtremor measurement of an adobe building.

of JST and JICA [14, 15]. The mechanism of out-of-plane failure of masonry walls was examined through shaking-table tests, and the test results were simulated using the discrete element method, as shown in **Fig. 8** [29]. Furthermore, an experimental study done on the flexural behavior of reinforced concrete walls was conducted [30], and a reasonable retrofitting technique using carbon fiber sheets (CFS) was proposed for low ductile walls in order to improve their flexural capacity. Performance was verified through structural tests, as shown in **Fig. 9** [31].

### 5.3. Enforcement of Seismic Resistance of Historical Buildings

Site investigation and microtremor measurement were conducted to investigate historical buildings in Peru and to develop enforcement techniques for preserving their historical value (**Fig. 10**). The techniques were verified through structural element tests and a numerical analysis for buildings.

## 6. Geospatial Data Development and Damage Assessment

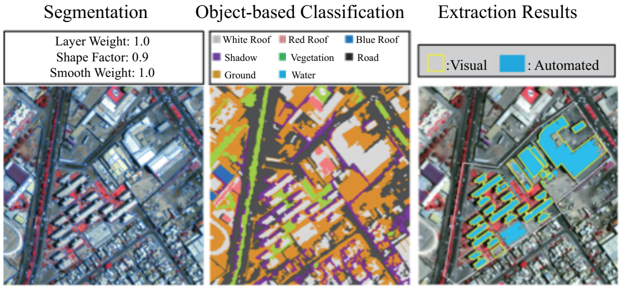
The tasks of Group 4 are 1) the construction of geospatial data for damage assessment, 2) quick damage detection for recovery planning, and 3) building damage assessment due to scenario earthquakes using advanced remote sensing technologies.

### 6.1. Construction of Geospatial Data

We constructed the following geospatial data using various satellite images: 1) Digital Surface Model (DSM), 2) Urban Development Map, and 3) Building Inventory for the Lima metropolitan area. A DSM with 5 m spatial resolution was constructed based on the fusion of the data from ALOS-PRISM and IKONOS images [19]. The data can be used for evaluation of topographic features, estimation of building heights, and assessment of slope stability.

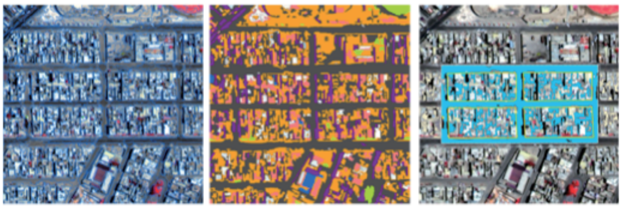
In order to grasp the regional characteristics of urbanization history, an urban development map was constructed using differentials of Landsat time-series images taken at three different times, such as in 1987, 1998, and 2006 [19]. The results showed rapid development in the suburbs of Lima.

A building inventory was constructed from a combination of the census data, the field survey data, and the DSM from satellite images. The procedure for the construction of the data and the results for Lima can be found elsewhere in this volume [21]. For Tacna, building inventory data were also constructed. **Fig. 11** shows the distributions of buildings in Tacna detected through an object-based analysis [32] from WorldView-2 satellite images.



(a) Large building area

(b) Low-density residential area



(c) High-density residential area

**Fig. 11.** Result of segmentation (left), object-based classification (center), and extracted regions and building outline made manually (right) for three areas in Tacna [32].

## 6.2. Quick Damage Detection

Quick damage detection after earthquakes is vital to efficient recovery planning. A method that uses the difference and correlation of the backscattering intensity for pre- and post-earthquake synthetic aperture radar (SAR) data was developed to estimate the severe damage ratio, based on the dataset of ALOS-PALSAR images for the 2007 Peru earthquake and the detailed field survey data for the city of Pisco [20]. The visual damage interpretation was carried out building by building using QuickBird high-resolution satellite images. Compared with field survey data, the results of the damage inspection showed that about 70% of the collapsed buildings of in the entire city were detected [33]. The co-seismic surface deformation due to the 2007 Pisco earthquake derived using an interferometric SAR (InSAR) technique is shown in **Fig. 12**. These satellite data analysis techniques were transferred to Peruvian research institutes through the seminar held in August 2013.

## 6.3. Building Damage Assessment

Building damage assessment was conducted by combining the results of the ground motion simulation done by Group 1, the fragility curves, and the inventory data of buildings. The effects of seismic retrofit of poorly constructed buildings were also assessed. By introducing retrofit, the number of households that would suffer from severe damage was reduced from 430,000 to 200,000.

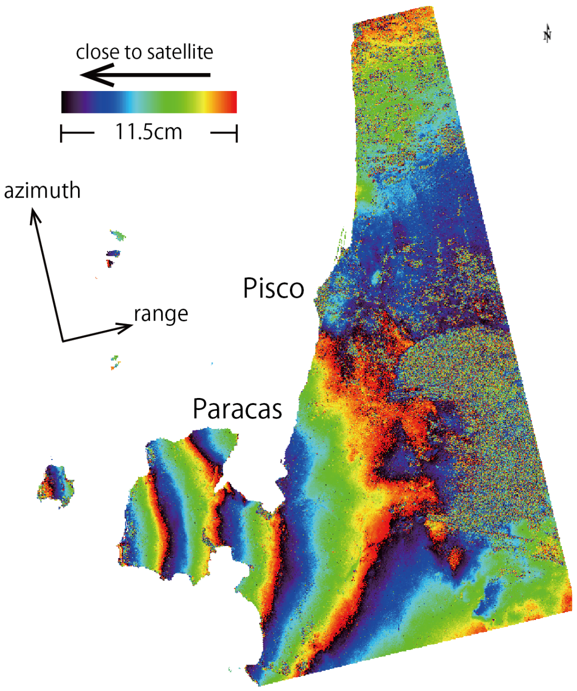


**Fig. 12.** Co-seismic surface deformation due to the 2007 Pisco earthquake calculated by InSAR technique using pre- and post-earthquake PALSAR images.

The procedure for the damage assessment and the results are found elsewhere in this volume [21].

## 7. Disaster Mitigation Plan

When the SATREPS Peru project started, we planned to propose a prototype urban development plan that considered earthquake and tsunami disaster mitigation for the case study areas. However, it was not found to be an easy task because modern urban planning just started in Peru after the 2007 Pisco earthquake. **Fig. 13** shows the land-use and road network plan in the Pisco area [34]. The plan was issued 5 years after the Pisco earthquake. The map was considered to be the first urban development master plan in the country, but it only defined basic land use for the areas currently unused.

Almost at the same time, the first urban development regulation in Peru, “Rules of Territorial and Urban Development,” was issued by Peru’s national government [35]. In the regulation, eleven land use zones were defined in its Article 32 as residential (R), housing-workshop (I1-R), industrial (I), commercial (C), pre-urban (PU), public recreation zones (ZRP), special use (OU), complementary public service, special regulations area (ZRE), monumental zone (ZM), and agricultural zone (ZA). Considering that land use planning is just in its infancy in Peru, we found it difficult to propose a prototype land-use plan that would take natural disaster mitigation into account. Instead, we decided to carry out a simulation study on the effects of disaster mitigation policy.

For the Lima metropolitan area, the SIRAD project [36]

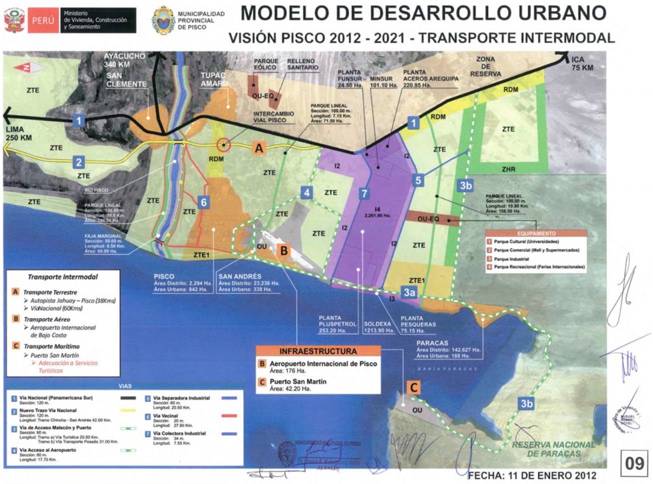


**Fig. 13.** Model of urban development: Vision of Pisco 2012-2021 [34].

for "resources for immediate response and early recovery in the occurrence of earthquake and/or tsunami in Lima and Callo" was implemented by INDECI with the support of the United Nations Development Programme (UNDP) and the European Commission in 2011. Various resource maps were produced in a GIS environment, but they were not available in a digital format to the SATREPS project. We therefore digitized several maps for the purpose of assessing the effects of disaster mitigation policy on urban development in Lima and Callo. The method and results of the simulation are found in Kaji et al. [22].

## 8. Project Management and Outreach Activities

The Peru project workshops were held annually either in Peru or Japan. The first workshop was held in the CISMID conference hall in Lima on March 15 and 16, 2010, followed by the second workshop held at Chiba University on March 9 and 10, 2011. The 2011 Tohoku earthquake occurred on the day after the second workshop, when the participants were on their field trip to Kamakura, about 45 km southwest of Tokyo. The third workshop was held in Tokyo on March 13, 2012, commemorating the 2011 Tohoku earthquake [1].

The fourth workshop was held in Lima on March 14, 2013 (**Fig. 14**), followed by a public symposium on March 15, 2013 (**Fig. 15**). The fifth (last) project workshop was held in Tokyo on March 6, 2014 (**Fig. 16**). In the annual workshops, we discussed the progress of the project and its schedule for the coming fiscal year.

One important aspect of the Peru project is the joint research activities carried out by Japanese and Peruvian engineers/scientists. **Fig. 17** shows some scenes from activities in Peru, such as (a) spectroradiometer field observation in Tacna, (b) a remote-sensing image analysis seminar and training session at CONIDA, and (c) a tsunami evacuation drill in La Punta.

**Fig. 14.** Participants in the fourth workshop on March 14, 2013 at CISMID in Lima, Peru.

**Fig. 15.** Public symposium on March 15, 2013 at the Sonesta Hotel in Lima.

**Fig. 16.** Participants in the fifth workshop on March 6, 2014 in Tamachi, Tokyo, Japan.

The project also invited young Peruvian researchers for human resources development. Six doctoral students from National University of Engineering (UNI) were selected for Japanese Government Scholarships by MEXT; two have completed their Ph.D courses and four are now studying at Japanese universities.

The Joint Coordinating Committee (JCC) was organized soon after the start of the project. JCC provides oversight on the project and meets annually as well as on an as-needed basis in order to approve its annual work plan, to review progress, and to exchange opinions on the project. The first JCC meeting was held in September 2011; it then met annually in August 2012, 2013, and 2014. The final project review meeting was conducted in Lima together with the fourth JCC, following the project evaluation procedure of JICA.

One of the prospective goals of this project has been knowledge transfer to other Pacific-rim countries, especially to neighboring Latin American nations. In accordance with this objective, together with the SATREPS

(a) (b) (c)

**Fig. 17.** Joint activities in Peru; (a) spectroradiometer field observation in Tacna, (b) remote-sensing image analysis seminar and training at CONIDA, and (c) tsunami evacuation drill in La Punta.

**Fig. 18.** Group photo of "the International Symposium on Earthquake and Tsunami Disaster Mitigation in Latin America" on March 7, 2014 in Shinagawa, Tokyo.

Chile project, we organized the International Symposium on Earthquake and Tsunami Disaster Mitigation in Latin America, which was held on March 7, 2014 in Tokyo. 25 researchers from Peru, Chile, Colombia, Ecuador, Mexico, Nicaragua, and El Salvador, as well as the project members and sponsors from Japan, participated in the symposium. There were 135 participants in all, including Ambassadors to Japan from Peru, Chile, Ecuador, and Nicaragua as well as representatives from Colombia (**Fig. 18**). The symposium was quite successful in terms of understanding and future research collaboration in the field of natural disaster mitigation in Latin American countries and Japan.

## 9. Conclusion

Following the introductory paper [1] on the project, this paper has summarized the further progress and outcomes of the SATREPS project, "Enhancement of Earthquake and Tsunami Disaster Mitigation Technology in Peru." The project has been promoted by five research groups: seismic motion and geotechnical, tsunamis, buildings, spatial information database and damage assessment, and disaster mitigation planning.

The project started in March 2010 and will end in March 2015. The collaborative research has been promoted though joint experiments, observations, field surveys, computer simulations, seminars, and workshops. With the Lima metropolitan area and city of Tacna were selected as case study sites, two mega-thrust earthquakes were simulated and their effects and countermeasures were investigated. The simulated results were validated by observation data and implemented in government policy. Training and education were also given to young engineers and scientists. We hope that the project contributes to the enhancement of earthquake and tsunami disaster mitigation technology in Peru and neighboring Latin America countries.

**Acknowledgements**

This research is supported by the Japan International Corporation Agency (JICA) and the Japan Science and Technology Agency (JST) under the framework of SATREPS program.

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**Academic Societies & Scientific Organizations:**

- Japan Society of Civil Engineers (JSCE)
- American Society of Civil Engineering (ASCE)
- Seismological Society of America (SSA)
- Earthquake Engineering Research Institute, USA (EERI)