

LESSONS LEARNED FROM THE 2021 NIPPES, HAITI, POST-EARTHQUAKE ENGINEERING INSPECTION AND DAMAGE ASSESSMENT

Helene TISCHER¹, Kubilay HICYILMAZ² & Pedro NEGRETTE³

Abstract: *On August 14, 2021, a magnitude 7.2 earthquake occurred near Petit-Trou-de-Nippes, Haiti, roughly 150 kilometres west of Port-au-Prince. Arup collaborated with a health sector INGO, Médecins sans Frontières to do a post-earthquake damage assessment of their local assets in Haiti. This paper provides a summary of the 2-week assignment, as well as the lessons learned in the particular context of an emergency response organization. Buildings at 18 locations in Port-au-Prince, Les Cayes and Port-à-Piment were visually inspected using visual damage assessment (ATC 20) and rapid visual seismic assessment (FEMA 154) procedures. Overall, the buildings inspected presented little to no damage. It is to note that little to no damage was observed in Port-au-Prince in general, given the distance to the epicentre. For the other locations, severe and widespread damages were observed to the building stock, but affected buildings were vacated previous to Arup's visit and not included in the evaluation. However, it was observed that local practice includes the cosmetic repair of damage, these buildings potentially having an even worse behaviour in a future event and to be avoided. Visual seismic assessment was carried out following the FEMA 154 procedure which relies on visual identification of potential weaknesses. All buildings evaluated scored lower than the usual cut off score of 2.0 indicating that all of them would benefit from additional evaluation to determine their expected seismic performance. None of the fit out, or contents of any of the buildings appeared to have been purposely detailed for seismic requirements for non-structural. Conclusions and recommendations had to be adapted to the urgent and temporary nature of the services provided by the NGO, assuring a seismic risk reduction was achieved balanced with other risk factors, time constraints and monetary limitations of the organization.*

Introduction

Arup and Médecins sans Frontières (MSF) collaborated to do a post-earthquake damage assessment field assignment to support MSF's Operational Centre Brussels (OCB) with their work in Haiti in response to the earthquake that struck the southern department of the island and severely impacted some of MSF's facilities. This paper provides a summary of the 2-week assignment carried out by Arup between November 9 and November 24, 2021.

The Earthquake

On August 14, 2021, a magnitude 7.2 earthquake occurred near Petit-Trou-de-Nippes, located in the Tiburon Peninsula, roughly 150 kilometres west of the capital Port-au-Prince. According to the Modified Mercalli Intensity (MMI), very strong to severe effects were felt close to the epicentre (VII to VIII), up to Les Cayes. In Port-à-Piment, the earthquake was felt as strong to very strong (VI to VII). Finally, in Port-au-Prince, shaking could be described as light to moderate (IV to V). Figure 1 shows the MMI of the earthquake with the three locations of interest highlighted. Note that MMI

¹ Associate, Arup, Montreal, Canada, helene.tischer@arup.com

² Director, Arup, Glasgow, Scotland, United Kingdom

³ Structural Engineer, Arup, Amsterdam, Netherlands

is a composite measure of the demand and the vulnerability, and as such higher MMI scores are possible as the building vulnerability increases.

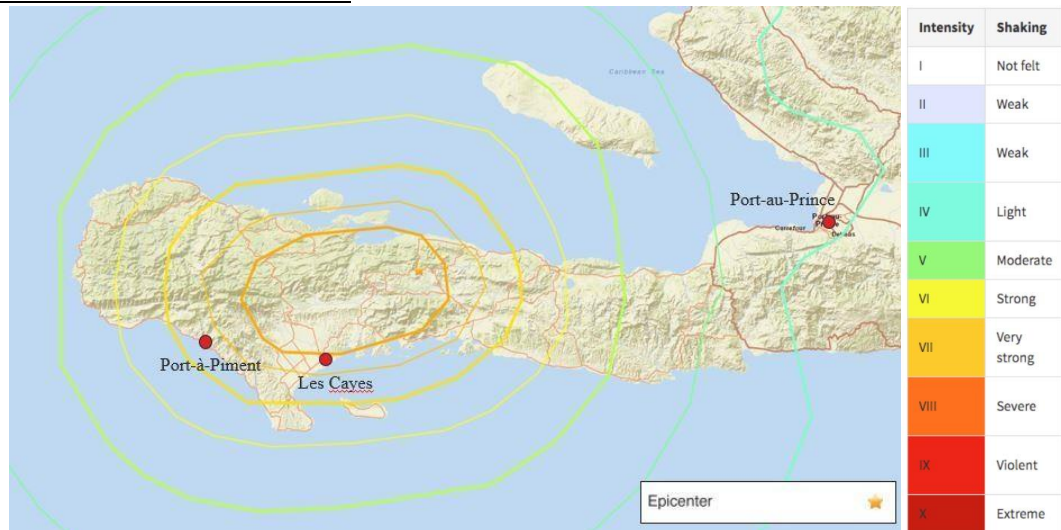


Figure 1. MMI of the Nippes earthquake, modified from USGS (2021).

The impacts of the earthquake were devastating with over 2,000 fatalities and close to 10,000 injuries reported. In terms of building losses, near 84,000 buildings were damaged and around 54,000 destroyed (1,250 schools and 79 health care facilities included).

The earthquake had an impact on many of the MSF activities in the affected area. In Port-àPiment, the earthquake severely damaged a public hospital where MSF had provided sexual and reproductive health care for years. Medical services were initially moved outside to tented areas, and MSF then renovated its logistical base to provide space for MSF and hospital staff to treat patients. In addition, the guesthouse suffered a catastrophic failure with the first level completely collapsing, see Figure 2. Given that the earthquake happened on a Saturday morning, staff members were in the building at the time. Luckily and remarkably, there were no fatalities or serious injuries.

One hospital in Les Cayes was badly damaged in the earthquake. By the time of our visit, MSF in collaboration with hospital staff, were managing paediatric and neonatal care in hospital tents. MSF rapidly built and equipped a delivery room and provided tents for pre- and postpartum care after the earthquake.



Figure 2. Collapsed MSF guesthouse in Port-à-Piment, image courtesy of MSF.

Scope

Buildings and facilities to be assessed were identified by MSF, setting as a priority all medical facilities at three locations: Port-au-Prince, Les Cayes and Port-à-Piment, but including other building uses as well.

Table 1 shows a summary of the visited location identification, city of location and type of usage. The locations have been listed according to the itinerary followed during the trip, and information that allows to identify each location precisely has been omitted.

ID	Location	Type
01	Port-au-Prince	Lodgings
02	Port-au-Prince	Hospital
03	Port-à-Piment	Hospital/Warehouse/Offices
04	Port-à-Piment	Offices
05	Port-à-Piment	Lodgings
06	Port-à-Piment	Storage facility
07	Les Cayes	Lodgings
08	Port-au-Prince	Lodgings
09	Port-au-Prince	Lodgings
10	Port-au-Prince	Lodgings
11	Port-au-Prince	Warehouse
12	Port-au-Prince	Offices
13	Port-au-Prince	Lodgings

Table 1. List of visited location sites.

For each of the numbered only locations, the following scope was accomplished:

1. Perform a rapid, visual damage assessment following ATC 20 procedures (ATC 20, 1989).
2. Carry out a seismic assessment on a deficiency-based system supported by high-level hand calculations using appropriate available data as will be able to be captured during the damage assessment for the main buildings. The method of choice was FEMA 154 (FEMA P-154, 2015).
3. Capture as much data as possible to enable a more detailed analysis, to be performed should this be felt warranted for subsequent stages.
4. Advice on surrounding geotechnical hazards based on visual observations that might pose further risk to the buildings. Given that the visits to the building locations were rapid and geotechnical investigations were not performed, this task was limited to capturing the broad surrounding land topography using conventional photos and field descriptions. The information from the field visits was supplemented by a desk study synthesis of publicly

available high-resolution satellite imagery, topographic, geological and hydrogeological information.

At the end of the mission, introductory training to MSF staff about aspects to consider when selecting facilities from an earthquake engineering point of view was given. Selected staff was also present at all visits to allow for capacity building inside the organization.

Seismological and geotechnical information

Seismicity and local soil class

Publicly available microzonation studies both for Port-au-Prince (MTPTC, 2013) and Les Cayes (Jeudy, 2014) were used to determine the short and long period spectral acceleration values at the studied sites. While less precise than site-specific geotechnical studies, these give a good idea of the local site conditions. No site-specific information was found for Port-à-Piment, and assumptions were made as suggested by FEMA 154 on the soil type.

Table 2 summarizes the findings, with S_s being the short period (0.2 seconds) and S_1 the long period (1.0 seconds) spectral acceleration values. Values presented in the table below are compatible with US codes.

ID	Location [3]	Soil Type	S_s [g]	S_1 [g]
01	Port-au-Prince	B	1.03	0.39
02	Port-au-Prince	D	1.55	0.55
03	Port-à-Piment	D	0.95	0.65
04	Port-à-Piment	D	0.95	0.65
05	Port-à-Piment	D	0.95	0.65
06	Port-à-Piment	D	0.95	0.65
07	Les Cayes	D	0.72	0.32
08	Port-au-Prince	A	1.2	0.42
09	Port-au-Prince	B	1.03	0.39
10	Port-au-Prince	C	1.55	0.55
11	Port-au-Prince	C	1.55	0.55
12	Port-au-Prince	C	1.72	0.42
13	Port-au-Prince	A	1.2	0.42

Table 2. Spectral accelerations and Soil type.

The soil type plays an important role in the determination of the seismic acceleration a building will be exposed to, and differences can be significant even in the same city (compare ID01 to ID02, for example, with a difference of 150% for short periods, which are relevant to low-rise buildings). From a seismic perspective, buildings founded on firm ground are thus very much preferred.

Geotechnical Hazards

Buildings can be exposed to several geotechnical hazards during an earthquake. The ones that are relevant for the context of this study are:

- Liquefaction: when loose, sandy soil is saturated, it can lose all its bearing capacity when shaken during an earthquake. Buildings can sink into the ground or topple over. This phenomenon has been observed in coastal regions in Haiti.
- Soil movement: steep slopes can become unstable during earthquakes, especially in areas with water-soaked soils as the water reduces the ability of the soil to carry vertical and horizontal loads. Buildings built on top of vulnerable slopes or close to it are exposed to catastrophic consequences due to slope stability failures.

Care was taken during the site visit to document any evidence of damages potentially related to these hazards and attributable to the August 2021 earthquake, as well as hazards that could pose a risk in future events.

The only site visited with clear evidence of geotechnical failures was ID07 at Les Cayes. While some evidence of liquefaction might have already been washed away or been repaired at the time of the visit, observations on the type of damages observed and the surrounding terrain, seem to indicate that liquefaction did indeed play a role building's response in the 2021 earthquake.

The risk of liquefaction at the visited locations in Port-au-Prince according to the city's liquefaction hazard map (MTPTC, 2013), is likely null or low as all of them are relatively far away from the coast where the risk increases due to the presence of anthropic and alluvial deposits. For the other two localities, the risk goes from high, in the visited locations of Les Cayes, to low in Port-à-Piment.

While no damage attributable to soil movement was observed, several buildings visited in Port-au-Prince are located on steep hills, although the slopes are usually protected by retaining walls, which themselves need to be seismically stable. In terms of soil movements, the risk is considered as negligible in Les Cayes and medium in Port-à-Piment, given that they are mostly located on flat terrain.

Typical Construction Typologies

Based on our observations and complemented with previous Arup findings after the 2010 earthquake (Hicyilmaz *et al.*, 2010), a limited number of building typologies could be identified for the structures currently being occupied by MSF. These are described below, together with some considerations.

Concrete Frame with Unreinforced Hollow Block Masonry Infill with Concrete Slabs

Unreinforced hollow block masonry with concrete slabs is typical for mid- and high-income housing in the country, as well as other small to medium size commercial structures. Buildings of this type can be recognized by the flat concrete slabs, most times used for the floors and the roof and the presence of heavy walls in both directions of the building that clearly carry the gravity load. Most of the time portions of the building are supported by columns.



Figure 3. Example of unreinforced hollow block masonry with concrete slabs.

This system has as advantage that it is an economic type of construction that uses readily available local materials. It has demonstrated mixed behaviour during past seismic events, depending on the correct execution of basic guiding principles. Some fundamentals to consider in relationship with this system are:

1. It is important for the unreinforced masonry walls to be confined by columns and beams at all extremities and around all floor and window openings (beams should be present at sill, lintel and roof level). This does not appear to be common practice in Haiti, where columns and beams might be completely missing or only present at some corners of interior wall ends.
2. The layout needs to be balanced and simple in both principal directions. Spans should be relatively short and evenly spaced. There should be walls on all sides of the building and in both directions, and a combination of masonry walls in one sector and columns in another is to be avoided. There should be at least one wall without openings at each principal direction.
3. While virtually impossible to determine after construction is complete, it is important that the rebar detailing and spacing be in line with requirements for seismic zones: closely spaced seismic ties, with 135-degree bent hooks, are needed to assure good seismic performance of such buildings. The quality of the concrete plays a role. It is important to use the right prime materials, respect the proportions between sand, gravel, cement and water, and follow the right procedures for mixing, placing, proper formation of formwork such that the cement paste does not leak out and finally curing the concrete.

4. A critical factor is the order in which the structure is constructed: the walls need to be erected before the columns and beams to assure that the system performs well under earthquake.
5. Additive construction, where stories are added over time once resources become available, is common in Haiti. This practice is not recommended because of several reasons, such as the increase in seismic and gravity loads to the system at the ground floor, that it probably has not been designed to. Column starter bars might also be exposed to the elements over long periods of time, potentially rusting.
6. Flat roofs are prone to water infiltrations, so it is important for them to be watertight. Water can lead to the rebar rusting and the concrete to degrade.

Unreinforced Hollow Block Masonry with a Light Roof

Small, one-storey construction oftentimes uses unreinforced hollow block masonry, typically concrete, with a light steel or wood roof structure covered with corrugated galvanized iron roofing. This type of construction is widely spread along the country as it is cheap and therefore accessible to people with limited resources and was found at MSF facilities for several of the smaller, auxiliary structures. Key points to consider for this type of construction are:

1. Points 1 to 4 of the previous typology are applicable: walls should be confined by columns and beams; the layout needs to be balanced and simple in both principal directions and rebar detailing and spacing needs to be appropriate for seismic regions.
2. Masonry walls should be interlocked at the corners to prevent the walls to overturn in the event of an earthquake.
3. The light roof should be properly attached to the masonry structure. Care should be given to create a positive (tension) connection between the walls and the diaphragm to provide out of plane restraint to the walls.



Figure 4. Example of unreinforced hollow block masonry with light roof.

Other Types

There are several other systems that were found on site, less common in nature, including:

- Single story steel structures with a light roof;
- A concrete shear wall structure;
- Concrete frame buildings;
- Prefabricated or custom systems;
- Modified or unmodified shipping containers;

These systems will need to follow some minimum rules to resist earthquakes, like appropriate detailing, connections, and support to the ground.

Materials and Construction Quality

Material and construction quality were observed to be generally poor. We had opportunity to learn about local practices in Port-à-Piment. The main observations made were:

- Concrete quality is very poor:
 - Sand is usually taken from the river and is not cleaned before use. Sharp sand appropriate for construction is rarely seen or used.
 - River stones are commonly used instead of graded gravel as coarse aggregate. The rounded shape of river stones is not appropriate for concrete.

- Cement is expensive and probably not used in the right quantities.
- Mixes seem to contain too much sand.
- Concrete is mixed by hand.
- Appropriate placing, vibrating and curing is questionable.
- Formwork is often leaky meaning that vital cement paste often leaks out of the forms removing strength from the concrete that is being cured.
- Materials not properly stockpiled and protected from the weather.
- Quality of concrete blocks is variable, certainly because of similar reasons as exposed for the concrete. Blocks are shown to break through handling on site.
- Rebar is used sparingly; detailing in general is not appropriate for seismic regions.
- Incremental construction is used extensively, adding stories to existing buildings when more resources become available. It is unlikely that the additional loads imposed through such a practice to the ground floor have been considered in the original design.
- Seismic damage is not so much repaired as covered up superficially with mortar and paint.

While some of the same problems will certainly be encountered in Port-au-Prince and other bigger cities, at least at these locations the appropriate building materials, as for example crushed gravel, are readily available. As such, it is expected that better quality materials and construction are found there.

Damage Assessment

Methodology

To conduct the damage assessment the ATC 20 methodology was used. This methodology relies on forms that can be filled out by visual observation of the building only and its goal is to quickly assess damage suffered by buildings during an earthquake. It is to note that the goal of the assessment is to determine if the structure has lost a significant amount of its load-bearing capacity due to the earthquake, and not to identify its inherent seismic resistance characteristics that could make it vulnerable/resilient to earthquake loading.

The main steps to complete the damage assessment following this methodology are as follows:

1. Observation of the exterior of the building and surroundings.
2. If building deemed safe to enter, observation of the interior of the building.
3. Identify main building characteristics and damages. Pictures are taken as support.
4. Fill out forms, identify label of building.

This procedure was followed for each one of the main buildings located at the numbered locations, using the rapid assessment form (ATC 20-2).

Results

All buildings received an “green” classification according to the damages observed, meaning that the inspection did not reveal damages severe enough to restrict access to the building or its use. In fact, most of the buildings did not show any damage that could be attributed to the earthquake. Some additional observations are:

- The shaking in Port-au-Prince was not strong enough to produce any visible damage we could detect, either at MSF facilities or in general.
- Damages were more widespread in Port-à-Piment and Les Cayes for the general building stock. Although only a moderate proportion of buildings observed showed damage (around 5 to 15%), it was serious in nature, with severely damaged and collapsed buildings observed. It was noted that local practice is to cosmetically by covering up cracks and even more severe damage. We observed evidence of such repairs at several locations in Port-à-Piment noting that these are not structural repairs and certainly not seismic retrofits.
- The ID04 building was being finished to be occupied during our visit. New wall and roof finishes, and new flooring was installed, and any potential damages or degradation was already repaired. MSF staff who had inspected the building previously confirmed that the front façade wall on the ground floor was damaged and completely replaced. They stated that there were no other damages.
- Damages were observed at the beams of one of the buildings at ID03, but these were attributed to structural damage and not the earthquake. Cracks at both ends of beams were typical, potentially indicating a shear weakness.
- ID07 was the building that showed most damages, and these appear to be mostly related to poor ground conditions. In general, there were cracks observed on the walls at the front

of the building (although some clearly not recent) and on the ground. Note that damages were not considered extensive enough to warrant a restriction in the use of the building. This building was only temporarily occupied by MSF.

Seismic Assessment

Methodology

Seismic assessment was carried out following the FEMA 154 procedure. The practical steps to complete this assessment are similar to what is described for the damage assessment, with the focus being not on observed damages but on observed potential weaknesses. The required information was collected in parallel to the information required for the damage assessment.

The FEMA 154 is a methodology that was developed to quickly screen large building stocks to identify buildings that are potentially hazardous. These buildings should then be further screened by a design professional experienced with seismic design to determine if they are indeed seismically vulnerable.

The method works by allowing to calculate a score for each building based on the information collected by visual inspection only which gives an indication of the possible behaviour of the buildings. The parameters that will affect a building's score are:

- The seismicity of the location, defined as low, moderate, high and very high. Note that for all visited locations, the seismicity is high.
- The type of soil on which the building is located.
- The type of structure, with 17 different lateral load resisting systems defined in the form.
- The presence of vertical irregularities of the building, defined as sloping site, weak and/or soft storey, setbacks, short columns, split levels or other.
- The presence of plan irregularities, defined as torsion, non-parallel systems, re-entrant corners, diaphragm openings.
- The risk of pounding.
- The redundancy in the system.
- The age of the building.
- Some characteristics of specific building types.

Structural scores typically range from 0 to 7, with higher scores corresponding to better expected performance of the system and lower potential for collapse. While the cut-off score needs to be defined depending on each evaluation campaign's specific needs and characteristics, a final cut off score of 2 is suggested by the guidelines: any building with a score below this number should be studied in more detail.

It is important to understand that this screening method is meant to be the first stage in a multitier evaluation. While the method identifies attributes that could lead to a poor seismic performance, conservative assumptions have been made. At the same time, given the nature of the method, there might be attributes that won't be visible, and a building deemed safe might be hazardous.

Finally, FEMA 154 is not specifically designed for Haiti, and neither the classification nor the scores there contained are necessarily directly applicable given the overall safety and risk context of society in Haiti. The method was still used, given that it allows to identify undesirable traits and get a more scientific understanding of the potential vulnerabilities than what is possible without a well-defined method. Some input requirements can't be established through visual inspection, as for example the seismicity, year of constructions, detailing within reinforced concrete members or base material properties. We established these parameters from desk studies and in the field through collaboration with MSF. Reasonable assumptions were made when needed.

Results

Final scores of all the buildings were below the cut-off score of 2. Most buildings scored 0.3, which was the minimal score allowed by the method. These low scores can be attributed to the high incidence of irregularities at almost every site.

Given the low scores, all buildings would benefit from additional evaluation to determine their expected seismic performance. It is suggested to MSF to further prioritize which buildings to evaluate further considering the time frame the building will be occupied, the exposure (number of people at a specific site, as well as the period the building remains occupied), importance of the building for continued operation, ease of finding a more suitable alternative and a multi-hazard approach that balances the reduction of seismic risk with other manmade or natural hazard MSF will be subjected to on the ground.

Correlation between damage observed and FEMA154 evaluation

A recurrent question from MSF on the ground was if having survived either the 2010 event for Port-au-Prince, or the 2021 event for Les Cayes and Port-à-Piment, would be enough to prove a building to be safe. In general, each earthquake is different and relying on only one event would not be enough to give assurance for future events: the magnitude, direction, duration, and other factors that vary from one event to the next can be quite different and produce different effects on the building. Values used for design are thus derived from multiple events (a minimum of 12 is oftentimes required in construction codes). However, this logic still has some merit, in the sense that buildings that survived certainly have a better seismic design than those who were severely damaged or collapsed.

If the building was not damaged, the significance of the experienced earthquake can be defined by its strength when compared to the design earthquake. Modern building codes use a very rare earthquake for design: it is usually an event has a probability of occurrence of 2% in 50 years. The aim of the design is to provide life safety: it is expected that under this event the building will be damaged, potentially irreparably, but that it is still standing to allow occupants to exit after the event. In case of hospitals and other essential facilities, that need to be functional after an earthquake, an importance factor, usually of 1.5 is applied to the design earthquake forces (a 50% increase compared to a regular building).

Using the peak ground acceleration as the parameter to compare the lived and expected shaking, the findings are summarized in Table 3 below. These are approximate numbers, obtained for publicly available information.

Location	Significant Earthquake	Felt PGA [g]	Design PGA [g]	Ratio
Port-au-Prince	2010 Léogâne	0.50	0.72	69%
Les Cayes	2021 Nippes	0.35	0.42	83%
Port-à-Piment	2021 Nippes	0.20	0.48	42%

Table 3. Comparison of felt and design PGA values.

In conclusion, if a building suffered little to no damage in the 2010 earthquake in Port-au-Prince or the 2021 event in Les Cayes, and if the damage suffered was repaired adequately (something that cannot be easily assessed nor assumed based on the observations on the ground), it is plausible that the structure will fair similarly well in a future event with a return period of around 1000 years (rough equivalent to the experienced GPA), although it cannot be said with certainty. For Port-à-Piment, the shaking was significant but not strong enough to be comparable to the design event. No additional considerations have been given in this discussion to higher required performance for health care facilities, which would mean that the experienced earthquakes are far below of the design event, should this required performance be considered.

Finally, it is noted that FEMA154 results are a conservative first step to evaluate large building stocks. The high incidence of irregularities in the studied buildings can explain the low overall values obtained, even by buildings that survived the aforementioned earthquakes. However, a more detailed assessment would be required to determine if these buildings are in fact unsafe for a design earthquake.

Conclusions

Between November 9 and 24, 2021, several MSF facilities located in Haiti were visited, with the main objective to discover any concerning damages after the August 2021 Nippes earthquake and do a rapid visual seismic assessment. This visit was complemented with a desk study to determine relevant seismological and geotechnical characteristics and hazards.

It was concluded that none of the MSF facilities in Port-au-Prince showed damages from August 14, 2021, earthquake as the shaking in Port-au-Prince was insignificant. None of the MSF facilities inspected at other locations appeared to be significantly damaged from August 14, 2021, earthquake either. However, MSF had quickly vacated the buildings severely damaged during the earthquake, with alternative solutions to meet the local population's needs long established at the time of our visit. These heavily damaged buildings were excluded from our assessment.

Some concerns related to the gravity capacity of existing structures were observed during the visit. MSF demonstrated quickly adapted, with solutions for these problems already being implemented by the time the field seismic damage assessment assignment in Haiti was completed.

Visual seismic assessments using FEMA 154 has revealed that none of the facilities being used by MSF in Haiti have passed an initial screening. This means that all the facilities may have seismic deficiencies and are likely vulnerable to future earthquakes. Prioritization of what building to further evaluate would be a sensible next step.

The following more general conclusions were reached, that could be applicable for others operating in seismic active regions:

- We did not observe any deliberate systematic detailing of non-structural components and their attachments. Retaining these elements adequately is a low-cost and simple to implement measure, that will lead to reduced risk of injury or death from failure of these elements, as well as reduced monetary loss and downtime in case of moderate to strong shaking.
- For existing facilities in seismic prone areas identified to have concerning characteristics, a multihazard approach should be used to select facilities warranting further seismic studies and eventual retrofit, or replacement by an alternative installation. Points to consider for decision include, but are not limited to, other man-made or natural hazards, the importance of the installation to the NGO's operations, the occupancy rate, the vulnerability of the users, the length of time the installation will be used, the feasibility of enacting any retrofit should it be necessary, the alternative installations that could be used, the best investment of the available funds, and the risk tolerance inherent to the NGO's operation.
- NGOs should develop and implement site and building selection criteria for seismic prone areas. For rented facilities, moving over time to buildings with fewer characteristics that could make them vulnerable towards earthquake might be the least expensive strategy to reduce the overall risk of the building stock. The requirements should be balanced with other risks, manmade or natural (as for example gang violence, break-in, hurricanes, and flooding).
- When building new facilities, it is important to either validate with the manufacturer that prefabricated systems are approved for their use in high seismic zones or engage with engineers specialized in seismic design to validate either design typologies or particular designs.
- The quick turn over of deployed employees makes it important to clearly document requirements in consolidated design guidance when selecting existing buildings, including quality assurance and construction monitoring guidelines.

Acknowledgements

The authors would like to thank MSF for providing logistics and accommodations during the site visit, as well as for their warm welcome. This work was made possible thanks to the financial support from Arup.

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