APPENDIX 2: CASE STUDY: HAITI

This appendix contains processes and procedures used to develop a site hazard and retaining wall mitigation program in Haiti following the January 2010 earthquake.
A2.1 FORENSIC STUDY

The following information describes the state of the practice study conducted following the January 2010 earthquake in Port-au-Prince, Haiti.

- **Retaining Wall Materials and Construction Practice:** The trained eye becomes aware very quickly that there is one predominant wall type in the Port-au-Prince area, a random rubble stone masonry gravity wall system. This type of construction can be observed throughout the area in a variety of settings, including retaining walls, foundations, parapet walls, boundary fences, and structural walls.

  This wall system is generally constructed to heights of up to 4.0 meters, with a rectangular cross section. In the majority of observed cases, the thickness of the retaining wall is approximately 0.40 meters, regardless of the associated wall height. There are some cases, mainly along major transportation routes, in which retaining walls are constructed up to heights of 10.0 meters. In these cases, the walls are generally constructed with a thickened wall base, resulting in a trapezoidal cross section.

  In many observed cases, intermediate reinforced concrete columns were used within the wall system. The columns were generally spaced at approximately 3.0 meter centers and were used in both retention and non-retention cases (i.e. fences). In a few cases, mid-height reinforced concrete beams were also employed within the wall system. The practice of including reinforced concrete columns and beams within stone masonry walls appears to stem from in-fill masonry construction, a standard pre-earthquake construction practice in Haiti. However, little intrinsic strength value is gained from the use of columns and beams as the wall foundation and/or columns are not sufficiently embedded below the ground surface to develop the required resistance to lateral pressures. Typical embedment depths for these walls ranged from 0.6 to 1.0 meters.

  It could be argued that the reinforced concrete elements assist in bonding the individual elements of the wall together and prevent delamination of individual stones or sections of stones. The delamination failure mechanism as a result of seismic loads is common in wythe masonry construction, in which the walls consist of two wythes, and the space between the wythes is filled with concrete, rubble, debris, or mud, as presented in Figure A2.1.
However, wythe construction is not a common masonry technique in Haiti. In fact, its presence, along with the associated delamination failure mechanism, was observed in very few cases. In summary, the addition of reinforced concrete to random rubble stone masonry gravity retaining wall system does little to enhance its strength characteristics.

Materials for the construction of stone masonry structures are readily available. The limestone rock used in these structures is relatively good quality and found in abundance at excavation sites. Rounded river rock is also used in stone masonry structures. The river rock is considered to be more durable, but the angularity of the limestone rock creates a higher strength bond with the mortar. Therefore, angular stones are preferred over rounded river rocks.

Mortar used in stone masonry construction is very similar to mortar used in concrete block masonry construction. The mortar is comprised of a cement and sand mixture, typically mixed at a 1:3 ratio (cement to sand).

• **Retaining Wall Types:** Three wall functions have been identified within the assessment program, as a result of initial field inspections. The three identified wall functions include: foundation walls, integral walls, and site walls. Soil or rock slopes that require the construction of a new retaining wall are included in the site wall function.

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Each category of wall type is further defined by the following:

**Foundation Wall:** A foundation wall, shown in Figure A2.2, is an earth retaining structure which directly supports a structure. In this scenario the structural loads are transferred to the ground mass through the foundation wall. Foundation walls can be further described as fill walls in which soil backfill is placed behind the wall to create a level building pad for construction.

![Figure A2.2. Rubble stone masonry foundation wall, Tissous.](image)

**Integral Wall:** An integral wall, as shown in Figures A2.3 and A2.4, is an earth retaining structure which also serves as a bearing wall for the structure. In many cases, structural connections are made between the integral wall and the roof structure. An integral wall allows the structure to be built into a hillside slope. Integral walls can be further described as a cut wall, which directly support natural ground and is constructed directly against an excavated soil/rock mass.
Figure A2.3. Exterior view of integral wall, Tissous.

Figure A2.4. Interior view of integral wall, Tissous.
Site Wall: A site wall, as presented in Figure A2.5, is an earth retaining structure which directly supports rock or soil, but is not physically connected to a structure.

![Figure A2.5. Rubble stone masonry site wall, Villa Rosa.](image)

Slope: A slope, as presented in Figure A2.6, is a natural or excavated soil/rock mass which requires an earth retaining structure (site wall) to ensure its continued stability. As mentioned previously, slopes are combined with site walls for assessment purposes.

![Figure A2.6. Slope which requires the construction of retaining wall, Tissous.](image)
• **Technical Evaluation:** To better understand how the existing stock of random rubble stone masonry walls perform in static and seismic loading conditions, a technical evaluation was completed. In general, these walls withstood the seismic loads imposed by the January 2010 earthquake with little deformation or damage. There were reports of localized wall failures, but these were primarily attributed to site amplification effects, landslide failures, or poor construction practices.

The predominant wall system in Haiti is a gravity retaining wall. Gravity retaining walls rely entirely on their self-weight to resist overturning and sliding failure mechanisms. These walls are generally constructed without need for reinforcement, as they are proportioned to avoid any tensile stresses from developing within the structure.

### A2.2 Parametric Analysis

Parametric analysis results completed in Haiti revealed that in most soil conditions and for the predominate wall geometry, the critical wall height criterion was 2.0 meters. Therefore, retaining walls with a height less than 2.0 meters were considered stable and not evaluated further in the assessment program based on observed geometry.

Analysis on a variety of wall types and geometries indicate the governing failure mode under seismic loading conditions is overturning. Therefore, mitigation methods have been developed to increase the overturning resistance of the walls. Increasing the overturning resistance of a gravity wall system requires an increase in the wall mass. In most cases this can be accomplished by increasing the width of the wall with the addition of a buttress. However, the simple addition of a buttress is complicated in densely population neighborhoods. In many cases, there is simply not sufficient available area to increase the width of existing retaining walls without significantly encroaching on adjacent properties or structures. Therefore, an additional mitigation measure is required, which provides restraint to the top of the wall without adding significant width to the existing structure.

### A2.3 Mitigation Details

The technical concepts exhibited in the mitigation details presented in this appendix can be applied to a variety of retaining wall construction materials, including earth (adobe), masonry (stone, brick, block), and dry stack (stone, block). However, the specific dimensions and design variables presented in the details have been uniquely designed for a given soil condition and seismic setting and may not be appropriate for
other applications. These mitigation details were developed primarily to provide additional resistance to the governing failure modes of overturning and sliding, as determined by back-analysis.

- **Void Fill:** In some cases, weak or weathered mortar or stone has caused individual stones to fall out of the wall mass, creating a void. The void is simply filled by creating a mortar bed and placing stones and mortar within the void. Stones should be of similar size as those used in original construction. Figure A2.7 presents a photo of a foundation wall requiring a void fill.

![Figure A2.7. Distressed wall requiring void fill, Villa Rosa.](image)

- **Surface Bond Overlay:** Over time, mortar and stone at the face of retaining walls become weathered. This weathered stone and mortar is at risk of weakening to a point where it compromises the integrity of the entire wall system. To prevent further weathering and to increase the strength at the face of the wall, a surface bond overlay is recommended.

  The overlay consists of a 75 mm thickness of mortar placed or thrown onto the face of the wall. The thickness of the overlay has been increased over more traditional block overlays to account for the irregularities and horizontal projection of stones at the wall face. A wire mesh is used to increase the strength of the overlay and assist with bonding the mortar to the wall face.

  A surface bond overlay of an integral wall can provide for a more pleasant interior living space when compared to the finish of a rubble
stone masonry wall. Figure A2.8 shows a photo of an integral wall requiring a surface bond overlay.

![Figure A2.8. Photo. Wall requiring surface bond overlay, Villa Rosa.](image_url)

- **Reinforced Overlay:** The reinforced overlay was born out of the fact that many retaining walls need additional lateral restraint at the top of the wall to prevent overturning failures. The reinforced overlay provides the desired lateral restraint with the added benefit of not adding significant width to walls, a necessity in the densely populated neighborhoods surrounding Port-au-Prince.

The reinforced overlay concept is very similar to the overlay concept developed for block walls under the structural retrofit guidelines. A 75 mm. thick concrete overlay with reinforcing bars is placed on the face of the retaining wall. At the top of the retaining wall, the reinforcing bars are bent and passed through the bottom block of the exterior wall as the overlay transitions into a slab on the floor of the structure. The reinforcing bars, at a given distance behind the face of the wall, are turned down into a trench below the slab, which serves as a deadman anchor. The deadman anchor provides the necessary lateral restraint to the top of the wall to prevent overturning failures during seismic loading events. Figure A2.9 presents a photo of a foundation wall that requires a reinforced overlay.
Buttress and New Retaining Wall: A buttress added to the face of an existing retaining wall will provide the necessary mass to prevent overturning and sliding failures. The buttress can only be constructed if sufficient width exists in front of the wall to avoid impacts with adjacent properties and structures.

A retaining wall detail was completed to guide construction of buttresses and new retaining walls. The geometry of the wall included in the detail will provide a stable retaining wall under static and seismic loading conditions for most soils that may be encountered in the Port-au-Prince area. The base width of the wall is 50 percent of the wall height. This results in a widened wall base and a trapezoidal cross section.

For buttress construction, the final wall geometry should be constructed to the standards of the retaining wall detail, including the section of the existing wall.

In many observed cases, homeowners had simply excavated into hillside slopes to create a level building site, but had failed to construct a retaining wall. The near vertical slopes were excavated primarily in weathered siltstone, conglomerate, or cemented alluvial material. These slopes appear to be stable in dry conditions, but as evidenced during the rainy season, are susceptible to erosion, which can lead to significant ground loss. Retaining walls are required to support each of the soil types commonly found in the Port-au-Prince area.
area. The only exception is the limestone bedrock that is located near range fronts. This material is resistant to localized erosion and has the ability to stand vertical without additional support.

Drainage is a critical element in retaining wall design. The retaining wall detail includes a drainage system which will not allow significant water pressures to develop behind the retaining wall.

Figure A2.10 presents a photo of an excavated slope that requires a retaining wall.

![Figure A2.10. Site which requires construction of retaining wall, Tissous.](image)

- **Gabion Erosion Protection:** Due to the number of localized drainages present in the Port-au-Prince area, coupled with the high susceptibility of erosion that most soils in the same area have, construction adjacent to ravines is almost inevitable. New construction within or immediately adjacent to ravines is not recommended and should be avoided. However, retrofit programs may include structures whose foundations are threatened by ravine instability. In these cases, gabion erosion protection can protect foundation walls by preventing further erosion or instability issues.

Gabion baskets are simply wire mesh baskets that are filled with durable rock. Baskets are laced together with wire. Gabion erosion protection is completed by constructing gabion baskets adjacent to and on top of one another within the required protection area. The bottom layer of baskets should be embedded a minimum of 0.6 meters below the ground surface to prevent the structure from being
undermined. Gabion baskets are commonly available in two sizes in Haiti, 4 meters long or 2 meters long. The width and height dimensions for both types of baskets are 1 meter.

Gabion baskets can be used as earth retention structures; however, stone masonry walls are preferred in this application.

Figure A2.11 presents a photo of a foundation wall that could benefit from gabion erosion protection.

Figure A2.11. Foundation wall adjacent to stream channel requiring gabion erosion protection, Villa Rosa.

A2.4 MITIGATION DETAILS DECISION TREE

A summary of the decision tree used in Haiti is captured in the following subsections, but can be conservatively applied to retaining walls throughout the world. The decision tree is presented in Figure A2.12.

- **Repair Solutions:** Any wall, regardless of type or height, that exhibits signs of deterioration or disrepair is eligible for mitigation measures that are focused on the repair of these walls. These mitigation measures include void fills or surface bond overlays. The void fill detail is prescribed for walls that have lost individual stones or mortar and would benefit from a simple patch. The surface bond overlay is meant for walls that exhibit moderate or severe weathering of the stones, mortar, or both and could benefit from a protective layer of mortar at the wall face.
- **Foundation Walls:** Based on analysis of observed wall conditions in the field, foundation walls greater than the critical wall height, as determined in the technical evaluation phase of the forensic study, require additional lateral support to prevent an overturning failure during seismic loading conditions. The availability of a constructible area in front of the wall is a major consideration in determining the mitigation strategy for foundation walls. A buttress should be employed as a mitigation strategy if sufficient width is available to accommodate its construction. However, if there is minimal width in front of the foundation wall, a reinforced overlay is recommended.

- **Integral Walls:** Integral walls which are sufficiently restrained from lateral movement by the roof structure or shear walls require no additional support or mitigation. In many cases, structural retrofit measures require the addition of shear walls/columns or a ring beam to integral walls. If these additional measures are completed per retrofit guidelines, then no additional support is required. This is another added benefit of completing the structural and site hazard assessments in conjunction with one another, as integral walls may actually benefit from planned structural improvements. However, if these additional structural measures are not planned they may need to be included in structural retrofit plans to ensure the stability of the integral wall.

- **Site Walls and Slopes:** The nature and competency of retained soils is a significant consideration in the design of retrofit solutions for site walls and slopes. Additional mitigation measures are not required for site walls or slopes, if adjacent soils are standing vertical or near vertical and are competent (i.e. resistant to erosion). If there is any question as to the competency of the rock, a retaining wall should be recommended.

In the case of site walls, the addition of a buttress would be a suitable mitigation measure. The final geometry of the retaining wall with a buttress would be constructed per the retaining wall detail, inclusive of the geometry of the existing wall. In the case of excavated or unstable slopes, the construction of a new retaining wall is recommended.

- **Gabion Erosion Protection:** Gabion erosion protection is not included in the decision tree, as its use should only be considered in special cases. As has been mentioned previously, gabions provide an excellent means of erosion protection along stream channels and ravines. However, construction adjacent to ravines or stream channels is not recommended and should not be encouraged.
Figure A2.12. Retaining Wall Mitigation Decision Tree.
PLACE A 2.00 CM THICK LAYER OF MORTAR IN THE CAVITY BEFORE LAYING ROCKS

REMOVE DEGRADED MORTAR, LOOSE MATERIAL, AND OTHER DEBRIS BEFORE REPLACING ANY ROCKS

REPLACE THE ROCKS WITH RECOVERED MATERIAL, OR WITH NEW ONES OF A SIMILAR SIZE AS THE EXISTING
USE CHICKEN WIRE MESH AS REINFORCEMENT ATTACHED WITH #2 STEEL HOOKS

HOMOGENEOUS LAYER OF CEMENT PLASTER ON ONE SIDE OF RETAINING WALL WITH A MINIMUM THICKNESS OF 5.00 CM

-NOTE: SEE MTPTC REGULATIONS FOR CEMENT PLASTER MIX PROPORTIONS AND APPLICATION
DETAIL STRUCTURAL DECOUVERTE

PROJET

DATE

MUR DE SOUTENEMENT

SANS ECHELLE

RETAINING WALL

OVERLAY RETROFIT DETAIL

(E) WALL

(1) #3 @ 60 cm BOTH WAYS

(E) SLAB

BREAK (E) SLAB TO CONSTRUCT AN ANCHORING TRENCH

SPACERS

(1) #3 @ 60CM, BOTH WAYS

H + 0.5 m

0.3 m

(2) #3

H

(1) #3 @ 60CM, BOTH WAYS

(E) MASONRY FOUNDATION

0.30

75 mm

75 mm

0.3H

D10.3

PROJECT

DATE

SCALE : NO SCALE
AVOID CONTINUOUS VERTICAL OR HORIZONTAL JOINTS

PVC Ø 100 MM WEEP DRAINS @ 1.5M, 2% SLOPE FORWARD

NOTE: H MAX = 4.00 m

DEPTH PER SOIL TYPE
0.30 m IN ROCK
0.50 m IN SAND
1.00 m IN CLAY

35 % MAX.
TYPICAL ASSEMBLED GABION BASKET

GABION BASKET NOMINAL SIZES AND CAPACITY

<table>
<thead>
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<th>SIDE CODE LETTER</th>
<th>SIZE IN METERS</th>
<th>DIAPHRAGM PARTITIONS</th>
<th>CAPACITY(H)</th>
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</thead>
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<td>1</td>
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</tr>
<tr>
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<td>3</td>
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<td>C</td>
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<td>1, 1</td>
<td>1, 1</td>
</tr>
</tbody>
</table>

CONTINUOUS LACING WIRE TO NEXT DOUBLE HALF HITCH

SINGLE HALF HITCH

STEEL WIRE Ø 2.2 mm

CONTINUOUS LACING WIRE TO NEXT SINGLE HALF HITCH

SELVAGE WIRE

DOUBLE HALF HITCH

ALTERNATE SINGLE AND DOUBLE HALF HITCHES AS SHOWN

LOOP TWO MESHES AT EACH END OF STIFFENER

PLACE STIFFENERS @ 30cm SPACING HORIZONTALLY AND VERTICALLY

STIFFENERS

DIAPHRAGMS

ALL END GABION CELLS

ALL INTERIOR GABION CELLS

TYPICAL SIFFENERS

TYPICAL INSTALLATION GABION BASKETS