
ANÁLISIS DE RIESGO PARA EL SECTOR RESIDENCIAL COSTARRICENSE POR ZONA SÍSMICA

Reporte Técnico

ENERO, 2017

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Resumen Ejecutivo

Este estudio utiliza los modelos de amenaza, exposición y vulnerabilidad del sector residencial derivados por Calderón y Silva (2016) para Costa Rica, con el fin de estimar índices de riesgo económico según la zonificación sísmica del país propuesta en el Código Sísmico de Costa Rica, edición 2010.

La metodología empleada es la de simulación de eventos estocásticos. Los índices derivados son la Pérdida Anual Promedio, la Máxima Pérdida Probable para los periodos de retorno de 50, 100, 200, 250 y 2000 años y los factores de daño para el portafolio inmobiliario residencial de cada zona.

De acuerdo con los resultados obtenidos, la Pérdida Anual Promedio es de 0.18%, 0.14% y 0.18% para las Zonas Sísmicas II, III y IV, atribuyendo el índice menor en la Zona III al mejor desempeño del sector residencial debido a la mejor calidad constructiva, en relación con las otras dos zonas. Los Factores de Daño obtenidos para el periodo de 200 años son de 2.80%, 3.00% y 3.89% correspondientes a las Zonas II, III y IV, atribuyendo el incremento de los mismos en conformidad con la cercanía con la zona de mayor amenaza ubicada en la costa pacífica.

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Marco Teórico

En esta sección se describe de forma breve y simple la metodología utilizada para derivar los índices de riesgo para el sector residencial por zona sísmica. Para encontrar una descripción técnica completa de la metodología de evaluación de riesgo por medios probabilísticos favor referirse a la investigación realizada por Calderón y Silva (2016) sobre el Análisis Probabilístico de Riesgo Sísmico para Costa Rica.

Metodología de Riesgo basado en Eventos Estocásticos

La evaluación de riesgo mediante el uso de eventos estocásticos permite derivar índices de riesgo homogéneos para portafolios de bienes a gran escala (regional y nacional) que se encuentran bajo amenaza sísmica. La metodología requiere de tres componentes primarios para derivar métricas de riesgo que son: un modelo probabilístico de amenaza sísmica, un modelo de exposición para el inventario bajo amenaza y un modelo de vulnerabilidad de dicho inventario ante la amenaza.

El análisis mediante eventos estocásticos comprende la simulación de un gran número de eventos sísmicos cuyas características, como ubicación, régimen tectónico, magnitud y profundidad están completamente definidas. Dicha simulación está basada en el modelo de amenaza sísmica, es decir, los eventos son generados aleatoriamente, pero sus características están dictadas por el mejor conocimiento sobre la sismicidad del país disponible al día de hoy. Véase por ejemplo en la siguiente figura, uno de los sets de eventos estocásticos generados por Calderón y Silva (2016) para el análisis de riesgo residencial de Costa Rica.

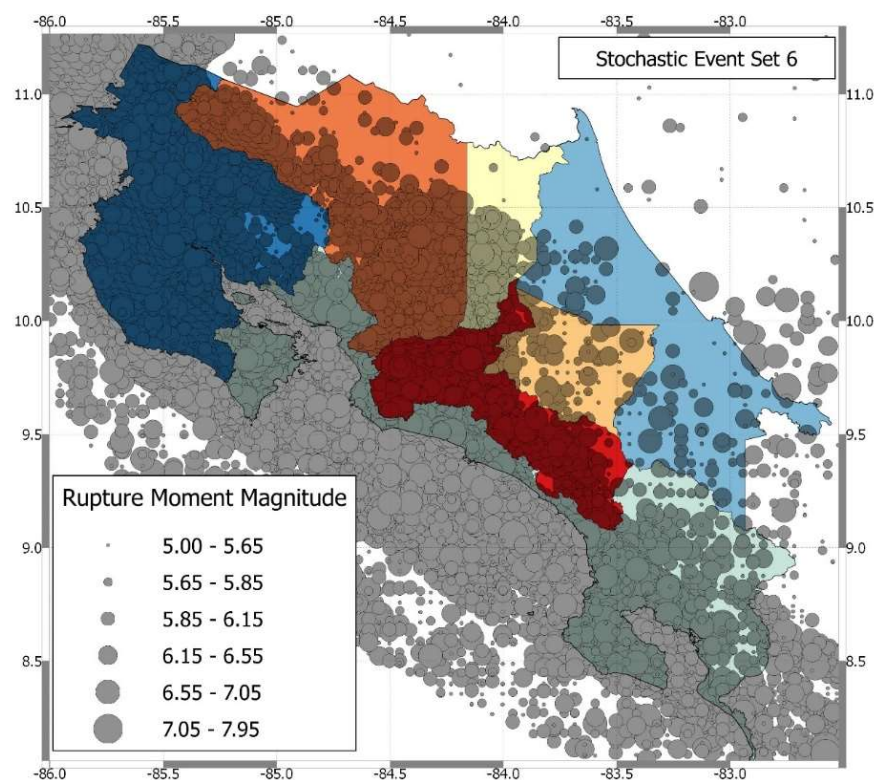


Ilustración 1: Un set de eventos estocásticos para el análisis de riesgo del sector residencial costarricense. Tomado de Calderón y Silva (2016). Cada punto del mapa representa un evento sísmico con características definidas.

Para cada evento sísmico generado se calcula el daño y la pérdida que ocasiona al portafolio en análisis y a dicha pérdida se le asigna un periodo de retorno. El número de eventos estocásticos debe ser suficientemente grande, ya que el propósito de este tipo de análisis es capturar todos los tipos posibles de eventos sísmicos que pueden suceder. Cuando se realiza de forma correcta, el análisis es capaz de capturar los sismos de intensidad baja de gran recurrencia que ocasionan pérdidas mínimas, hasta los eventos de gran intensidad ubicados cerca de zonas urbanas, cuya recurrencia es muy baja, pero tienen el potencial de causar pérdidas catastróficas.

Es posible visualizar de forma gráfica cada pérdida del análisis con su respectivo periodo de retorno. **A este tipo de gráfico se le conoce como Curvas de Excedencia, Curvas de PML, o Curvas de Máxima Pérdida Probable.** Tómese como ejemplo la siguiente gráfica de la investigación de Calderón y Silva. Cada punto en la curva representa un sismo, cuya pérdida puede verse en el eje vertical y cuyo periodo de retorno puede verse en el eje horizontal.

Los otros índices de riesgo que se derivan son los la Pérdida Anual Promedio y los Factores de Daño. La **Pérdida Anual Promedio es la suma de todas las pérdidas registradas, divididas entre el número de años que se consideraron en la simulación de eventos estocásticos.** Este es uno de los índices de riesgo más utilizados ya que es un promedio que muestra de forma homogénea y comparable el nivel de riesgo a cualquier escala. Mientras que los **Factores de Daño, son el resultado de dividir una pérdida entre el valor del inventario.** Estos pueden derivarse para pérdidas asociadas a cualquier periodo de retorno, por ejemplo 200 años, o pueden derivarse usando como referencia la pérdida anual promedio, en cuyo caso el factor queda anualizado.

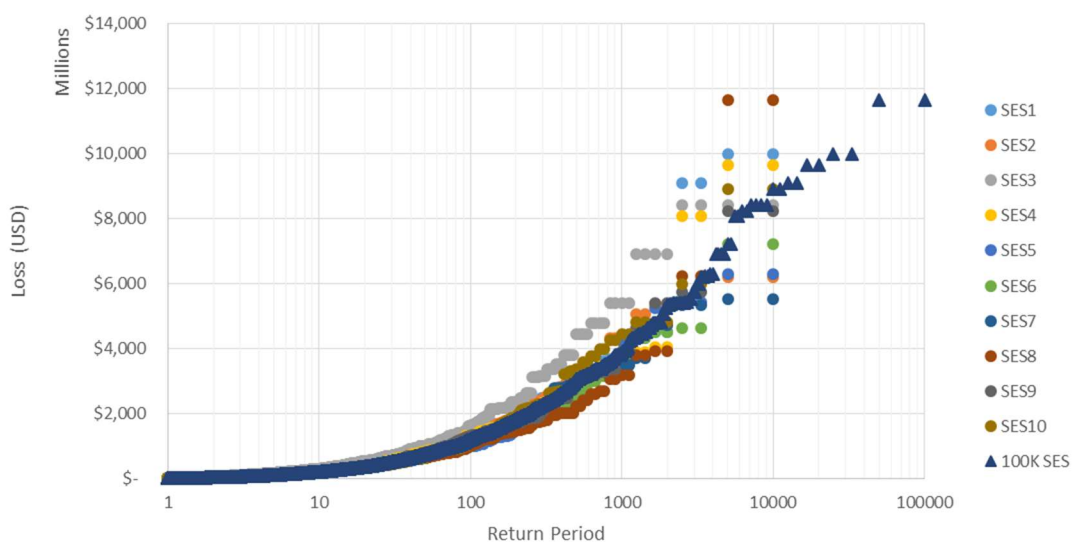


Ilustración 2: Curva de Máxima Pérdida Probable para el sector residencial de Costa Rica. Tomada de Calderón y Silva, 2016.

Para derivar los índices de riesgo en este reporte se utilizaron los mismos modelos de amenaza, exposición y vulnerabilidad desarrollados y empleados por Calderón y Silva, en la plataforma de uso libre (open-source) OpenQuake de la fundación Global Earthquake Model. Sin embargo, en este reporte, el análisis estocástico se repitió desagregado en las tres zonas sísmicas de Costa Rica, definidas por el Código Sísmico del 2010. **Nótese que las tres zonas están definidas como Zona II, Zona III y Zona IV. La Zona I es una**

zona de baja amenaza sísmica no tomada en consideración en este estudio ya que no aplica para el territorio nacional a nivel distrital.

Modelo de Amenaza Sísmica para Costa Rica

El modelo de amenaza determina de forma probabilística la intensidad de la sacudida sísmica esperada en el territorio nacional, basándose en el mejor conocimiento existente (sismos registrados, funciones de atenuación, fuentes sismológicas, etc.) sobre nuestros regímenes tectónicos. Al igual que la investigación a nivel nacional de Calderón y Silva (2016), para derivar los índices de riesgo a nivel de zona sísmica se utiliza como modelo de amenaza el desarrollado por Climent et al. (2008) bajo la coordinación de NORSAR, que comprende toda la región Centro Americana, titulado RESIS II. Para más información técnica sobre el modelo favor refiérase a la publicación "*Evaluación de la amenaza sísmica para Costa Rica*". *Reporte para Costa Rica del Proyecto RESIS II*, Climent et al (2008).

Cabe destacar en este reporte que el modelo es el más reciente y completo disponible en escala nacional. El mismo fue reproducido dentro de la plataforma abierta OpenQuake. La siguiente figura muestra el mapa de amenaza obtenido por Calderón y Silva para la evaluación de riesgo residencial, usado como referencia en este reporte.

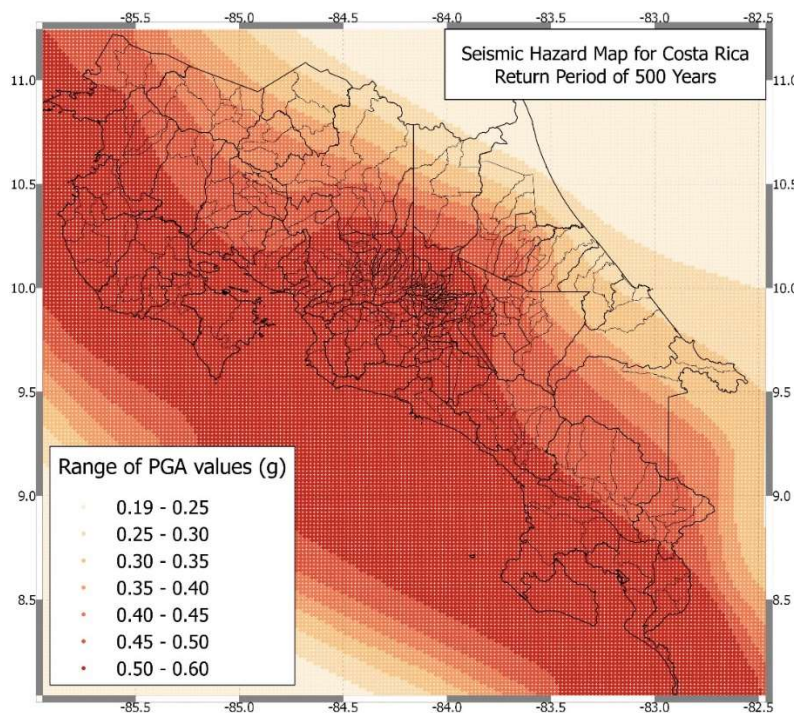


Ilustración 3: Mapa de amenaza sísmica para Costa Rica, en términos de la aceleración pico del terreno para un periodo de retorno de 500 años.

Por último debe mencionarse que las ondas sísmicas pueden experimentar amplificaciones en presencia de suelos blandos. Una pobre estimación de los efectos que produce el suelo en las ondas sísmicas induce errores significativos en las evaluaciones de riesgo sísmico (Silva et al. 2014), por tanto el modelo de riesgo de RESIS II fue complementado por Calderón y Silva con un modelo de efectos de sitio, desarrollado por los mismos usando la metodología simplificada de Wald y Allen (2007).

Modelo de Exposición del Portafolio Residencial

El modelo de exposición contiene todos los bienes para los cuales se requiere determinar el riesgo sísmico, sus características estructurales y su valor monetario. El modelo de exposición utilizado para derivar el riesgo por zona sísmica es el mismo desarrollado por Calderón y Silva (2016). El mismo comprende todas las estructuras residenciales de Costa Rica registradas en los censos de población y vivienda disponibles desde 1973 hasta el 2011. El modelo contiene más **de 1,180,000 estructuras residenciales, clasificadas en 10 tipologías estructurales diferentes, definidas bajo cinco atributos estructurales que son: el material de construcción, el sistema estructural, la altura, el año de construcción y condición** (buen estado, mal estado). Adicional a los atributos estructurales, cada tipología tiene un costo de reemplazo definido basado en los costos de construcción en Costa Rica.

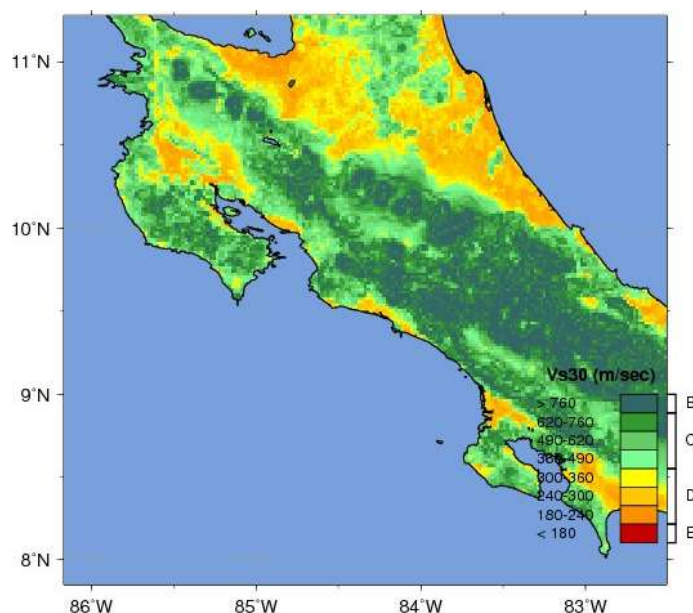


Ilustración 4: Mapa de amenaza sísmica para Costa Rica, en términos de la aceleración pico del terreno para un periodo de retorno de 475 años.

Tipologías Estructurales

Las 10 tipologías estructurales usadas en el análisis de riesgo se presentan en la Tabla 1, con una breve descripción, su valor económico y el porcentaje que representa dentro del portafolio residencial. **El portafolio residencial completo tiene un valor estimado de \$76,000 Millones de USD, del cual más del 70% está concentrado en las tipologías de mampostería reforzada, de baja altura y en buen estado.**

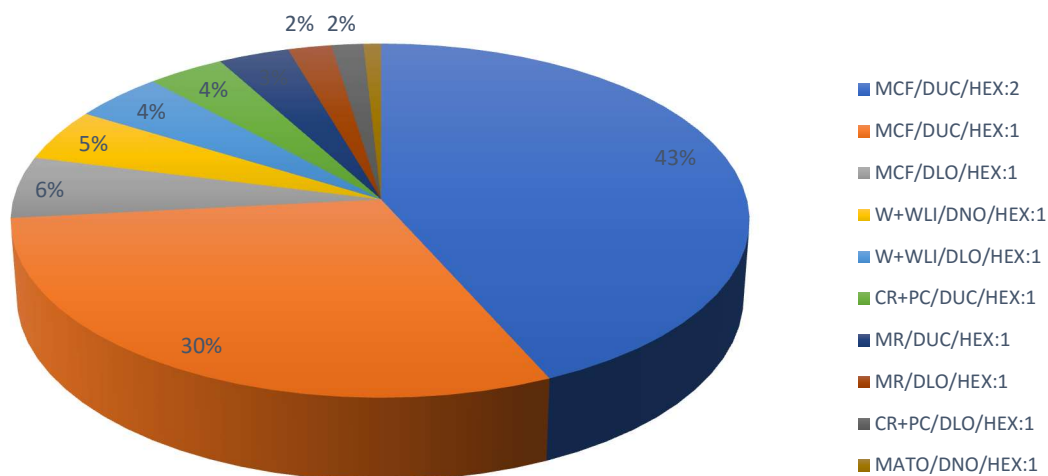
Resolución

El modelo está elaborado en la escala administrativa más pequeña de Costa Rica, que es el distrito. Esto significa que se cuenta con las características del sector residencial para los 472 distritos registrados al 2011 y los índices de riesgo pueden determinarse a dicho nivel. Para obtener resultados a nivel de zona sísmica se mantuvo esta resolución, pero haciendo series de eventos estocásticos por separado para los grupos de distritos que componen cada zona sísmica. El mapa en la Ilustración 5 muestra el modelo de exposición residencial por Zona Sísmica definida en el Código Sísmico de Costa Rica 2010 (CSCR-10).

Para conocer más detalles sobre la metodología utilizada en la elaboración del modelo de exposición favor refiérase a la investigación de Calderón y Silva, 2016.

Tabla 1: Características y valor del sector residencial de Costa Rica.

Tipología	Código	Valor Total
Mampostería -Confinada / Buen Estado /2 pisos	MCF/DUC/HEX:2	\$ 32,864,191,166
Mampostería -Confinada / Buen Estado /1 piso	MCF/DUC/HEX:1	\$ 22,763,456,800
Mampostería -Confinada / Mal Estado. /1 piso	MCF/DLO/HEX:1	\$ 4,272,123,265
Madera/Mal Estado./1 piso	W+WLI/DNO/HEX:1	\$ 3,620,321,252
Madera/Buen Estado./1 piso	W+WLI/DLO/HEX:1	\$ 3,371,394,656
Prefabricado/Buen Estado/1 piso	CR+PC/DUC/HEX:1	\$ 2,878,738,937
Mampostería-Integral / Buen Estado/1 piso	MR/DUC/HEX:1	\$ 2,639,992,017
Mampostería-Integral / Mal Estado/1 piso	MR/DLO/HEX:1	\$ 1,621,705,905
Prefabricado/Mal Estado./1 piso	CR+PC/DLO/HEX:1	\$ 1,184,399,639
Material Informal / Mal Estado / 1 piso	MATO/DNO/HEX:1	\$ 654,325,758
Valor del Portafolio	Todo	\$ 75,870,649,395



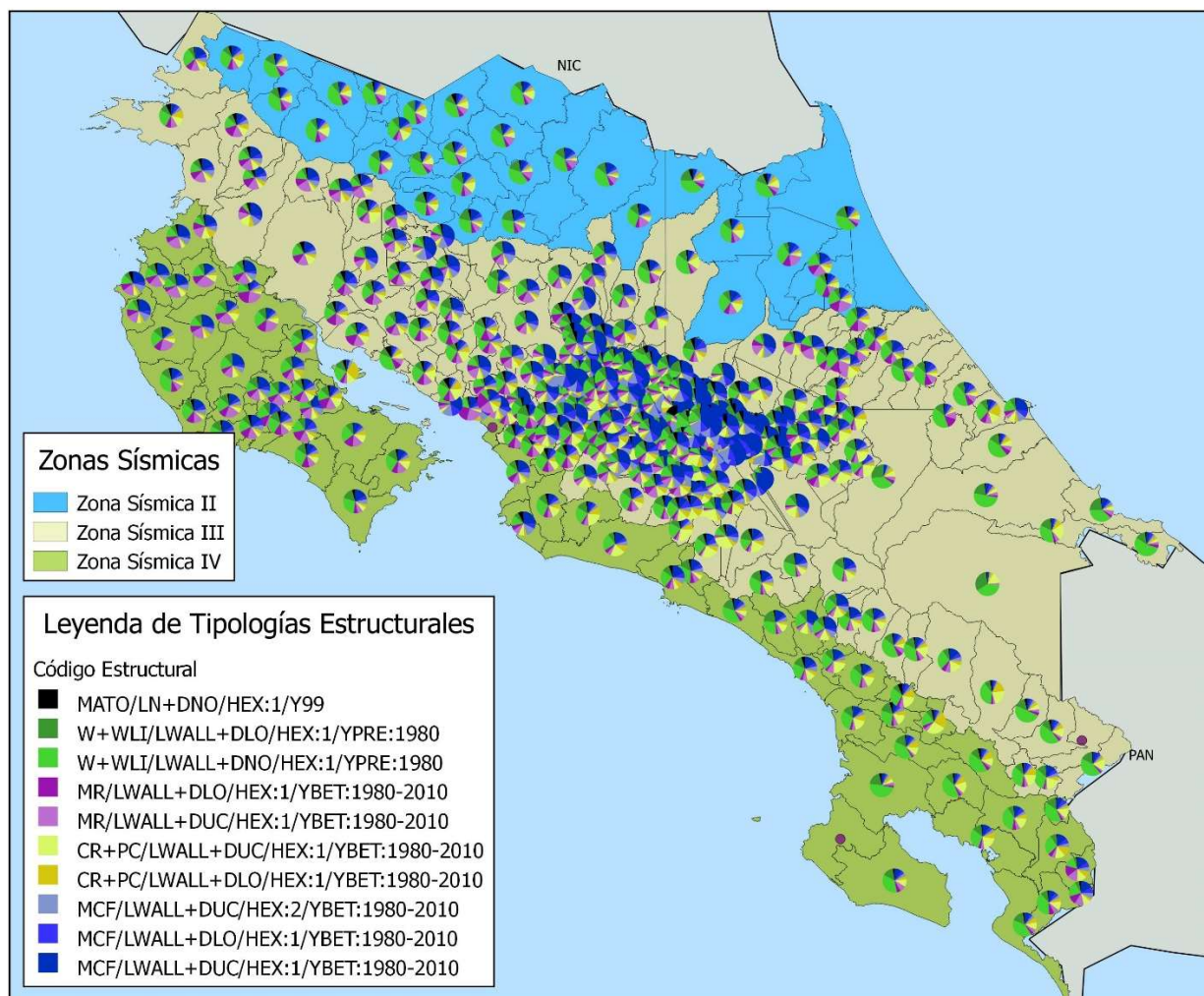


Ilustración 5: Modelo de Exposición Residencial por Zona Sísmica Definida en el Código Sísmico de Costa Rica 2010.

Modelo de Vulnerabilidad del Sector Residencial

El modelo de vulnerabilidad es la herramienta que ayuda a establecer cuál es la pérdida económica que sufre el portafolio en cada evento sísmico. Para este reporte el modelo utilizado para la estimación de los índices de riesgo es el mismo compilado por Calderón y Silva, 2016. Este comprende un catálogo de funciones de fragilidad y vulnerabilidad desarrolladas específicamente para las tipologías residenciales más pobladas de Costa Rica (Calderón y Silva) y América Latina (Villar et al, 2016). En total son 20 funciones, 10 de fragilidad y 10 de vulnerabilidad, las cuales se presentan en los Anexos de este documento. Para conocer más detalles sobre cómo se desarrollaron los modelos de vulnerabilidad, favor referirse a la investigación de Calderón y Silva (2016).

Análisis de Riesgo para Zona II del CSCR-10

Características de la Zona

La Zona Sísmica II está compuesta por los distritos que se muestran en la siguiente tabla:

Tabla 2: Distritos de la Zona Sísmica II

Zona Sísmica II	
Aguas Claras	Los Chiles
Bijagua	Monterrey
Buenavista	Pital
Caño Negro	Pocosol
Cariari	Puerto Viejo
Colorado	Rita
Cote	Roxana
Cureña	San Jorge
Cutris	San José o Pizote
Delicias	San Rafael
Dos Ríos	Santa Cecilia
Duacaré	Upala
El Amparo	Venado
Katira	Yolillal
La Garita	Llanuras del Gaspar

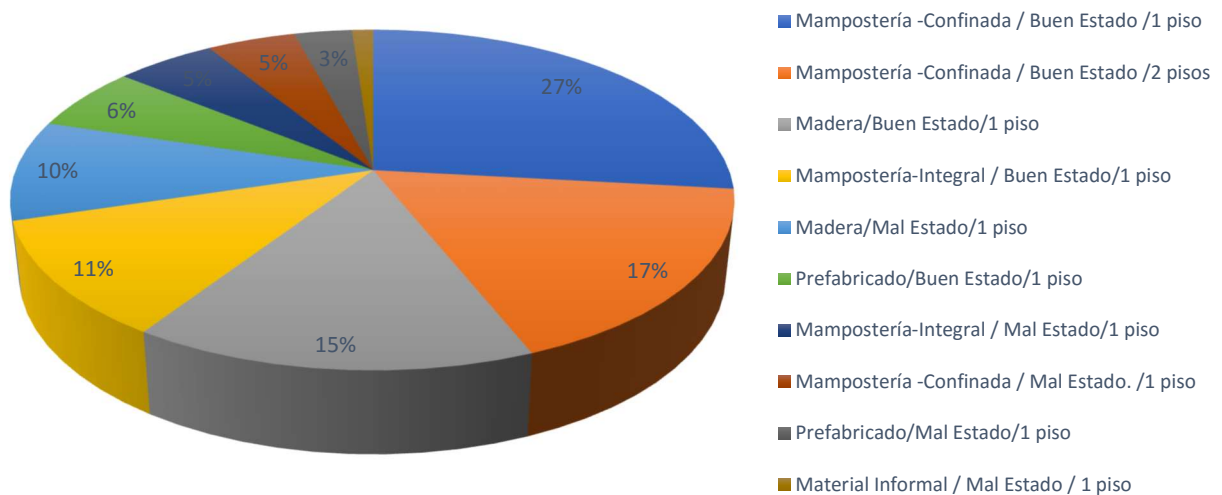
La Zona Sísmica II, que es la de más baja intensidad sísmica, también es la menos poblada de Costa Rica. De acuerdo con el modelo de exposición, **esta zona posee cerca de 65,701 estructuras residenciales, con un valor aproximado de \$2,633 Millones de USD. Esto representa un 5.6% de la infraestructura y un 3.47% del valor de todo el portafolio nacional.**

Tal y como se muestra en la Tabla 3, en esta zona la mayoría de las estructuras están en buen estado. Las tipologías de mejor desempeño, como la mampostería confinada reforzada, tienen una mucho menor participación que en las otras dos zonas del país (menos del 50%). Mientras que el resto del inventario se divide de forma homogénea entre las tipologías de prefabricado, mampostería integral y madera. Por

último, los tugurios y la construcción informal tienen una participación cercana al 1% en el valor del portafolio.

Tabla 3: Características estructurales y económicas del sector residencial en la Zona Sísmica II.

Tipología Estructural	Código	Valor
Mampostería -Confinada / Buen Estado /1 piso	MCF/LWALL+DUC/HEX:2/YBET:1980-2010	\$ 704,721,412
Mampostería -Confinada / Buen Estado /2 pisos	MCF/LWALL+DUC/HEX:1/YBET:1980-2010	\$ 452,154,048
Madera/Buen Estado/1 piso	W+WLI/LWALL+DNO/HEX:1/YPRE:1980	\$ 402,900,165
Mampostería-Integral / Buen Estado/1 piso	MR/LWALL+DUC/HEX:1/YBET:1980-2010	\$ 291,056,152
Madera/Mal Estado/1 piso	W+WLI/LWALL+DLO/HEX:1/YPRE:1980	\$ 250,564,725
Prefabricado/Buen Estado/1 piso	CR+PC/LWALL+DUC/HEX:1/YBET:1980-2010	\$ 160,044,127
Mampostería-Integral / Mal Estado/1 piso	MR/LWALL+DLO/HEX:1/YBET:1980-2010	\$ 139,028,714
Mampostería -Confinada / Mal Estado. /1 piso	MCF/LWALL+DLO/HEX:1/YBET:1980-2010	\$ 123,133,475
Prefabricado/Mal Estado/1 piso	CR+PC/LWALL+DLO/HEX:1/YBET:1980-2010	\$ 80,482,493
Material Informal / Mal Estado / 1 piso	MATO/LN+DNO/HEX:1/Y99	\$ 29,225,175
Total		\$ 2,633,310,484



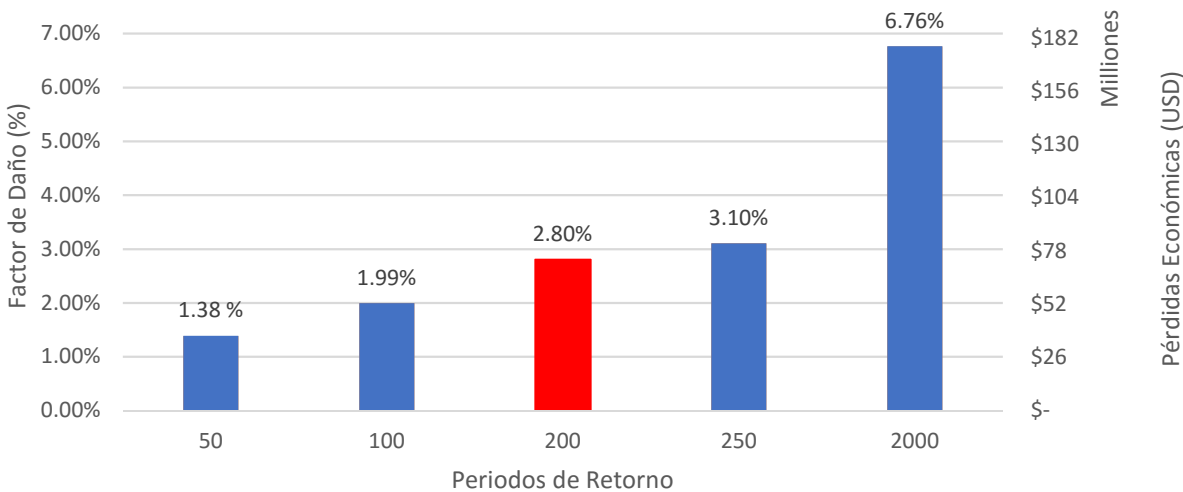
Pérdida Anual Promedio y Factor de Daño Anual

Para la Zona Sísmica II se simularon 50,000 años de actividad sísmica para la generación de eventos estocásticos. Al sumar todas las pérdidas registradas y dividir las por este número de años **se obtiene una Pérdida Anual Promedio de \$4.65 Millones de USD, equivalente a un factor de daño anualizado de 0.18%.**

Pérdidas y Factores de Daño para Periodos de Retorno de 50, 100, 200, 250 y 2000 años

El análisis estocástico permite estimar las pérdidas asociadas a todos los eventos sísmicos simulados. De especial interés en la evaluación del riesgo son los periodos de retorno asociados a los 50, 200 y 500 años. Los factores de daño se obtienen al dividir cada pérdida entre el valor del inventario. En la siguiente ilustración se muestran los resultados obtenidos para la Zona Sísmica II.

Ilustración 6: Pérdidas y Factores de Daño para diferentes Periodos de Retorno para la Zona II



Análisis de Riesgo para Zona III del CSCR-10

Características de la Zona

La Zona Sísmica III está compuesta por los distritos que se muestran en la siguiente tabla:

Tabla 4: Distritos de la Zona Sísmica III

Acapulco	Espíritu Santo	Orotina.	San Lorenzo
Aguacaliente o San Francisco	Esquipulas	Pacayas	San Luis
Aguas Zarcas	Florencia	Pacuarito	San Marcos
Alajuela	Florida	Palmares	San Mateo
Alajuelita	Frailes	Palmichal	San Miguel
Alegría	Garita	Palmira	San Nicolás
Alfaro	Germania	Palmitos	San Pablo
Ángeles	Granadilla	Pará	San Pedro
Anselmo Llorente	Gravilias	Paracito	San Rafael
Arancibia	Grecia	Paraíso	San Rafael Abajo
Arenal	Grifo Alto	Páramo	San Rafael Arriba
Aserri	Guácima	Patalillo	San Ramón
Atenas	Guacimal	Patarrá	San Roque

Bagaces	Guácimo	Patio de Agua	San Sebastián
Barbacoas	Guadalupe	Pavas	San Vicente
Barranca	Guadalupe o Arenilla	Pavones	San Vito
Barrantes	Guaitil	Pejibaye	Sánchez
Barva	Guápiles	Peñas Blancas	Santa Ana
Batán	Guayabo	Peralta	Santa Bárbara
Bebedero	Hacienda Vieja	Picagres	Santa Cruz
Biolley	Hatillo	Piedades	Santa Elena
Bolívar	Heredia	Piedades Norte	Santa Eulalia
Brasil	Hospital	Piedades Sur	Santa Lucía
Bratsi	Ipís	Piedras Negras	Santa María
Brisas	Jardín	Pitahaya	Santa Rosa
Brunka	Jesús	Pittier	Santa Teresita
Buenavista	Jesús María	Pocora	Santiago
Buenos Aires	Jiménez	Porozal	Santo Domingo
Cachí	Juan Viñas	Potrero Cerrado	Santo Tomás
Cahuita	La Asunción	Potrero Grande	Sarapiquí
Cajón	La Ceiba	Pozos	Sarchí Norte
Calle Blancos	La Cruz	Puente de Piedra	Sarchí Sur
Cañas	La Fortuna	Puntarenas	Sierra
Cañas Dulces	La Granja	Purabá	Siquirres
Candelaria	La Isabel	Purral	Sixaola
Candellarita	La Palmera	Quebrada Grande	Tabarcia
Cangrejal	La Ribera	Quebradilla	Tacares
Capellades	La Suiza	Quesada	Tambor
Carmen	La Tigra	Rancho Redondo	Tapesco
Carrandi	La Trinidad	Rincón Sabanilla	Tarbaca
Carrillos	La Unión	Río Azul	Tayutic
Carrizal	La Virgen	Río Blanco	Telire
Cascajal	Laguna	Río Cuarto	Tierra Blanca
Catedral	Las Horquetas	Río Jiménez	Tierras Morenas
Cervantes	Las Juntas	Río Naranjo	Tilarán
Chacarita	Legua	Río Nuevo	Tirrases
Chirripó	León XIII	Río Segundo	Tobosi
Chomes	Líbano	Rivas	Toro Amarillo
Cinco Esquinas	Liberia	Rodríguez	Tres Equis
Cipreses	Limón	Rosario	Tres Ríos
Cirrí Sur	Limoncito	Sabalito	Tronadora
Colima	Llano Bonito	Sabana Redonda	Tucurrique
Colón	Llano Grande	Sabanilla	Tuis

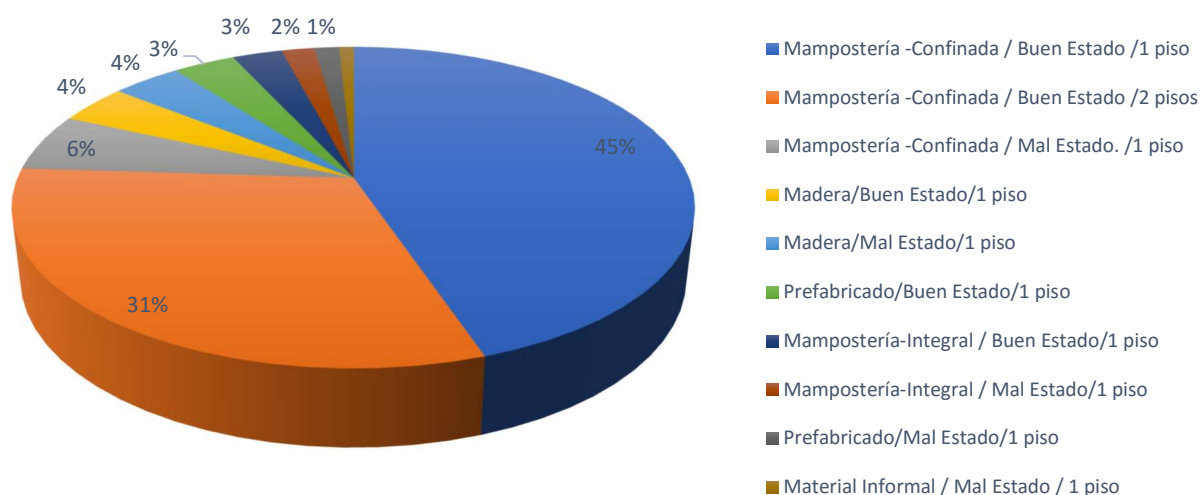
Colorado	Llanos de Santa Lucía	Sabanillas	Tures
Concepción	Llorente	Salitral	Turrialba
Copey	Los Guido	Salitrillos	Turrúcares
Corralillo	Macacona	San Andrés	Ulloa
Cot	Manzanillo	San Antonio	Uruca
Coyolar	Mata de Plátano	San Carlos	Valle La Estrella
Curridabat	Mata Redonda	San Cristóbal	Varablanca
Curubandé	Matama	San Diego	Venecia
Damas	Matina	San Felipe	Volcán
Desamparaditos	Mayorga	San Francisco	Volio
Desamparados	Merced	San Francisco de Dos Ríos	Vuelta de Jorco
Desmonte	Mercedes	San Gabriel	Zapotal
Dulce Nombre	Mercedes Sur	San Ignacio	Zapote
Dulce Nombre de Jesús	Miramar	San Isidro	Zaragoza
El Cairo	Mogote	San Jerónimo	Zarcero
El General	Monte Verde	San Joaquín	
El Mastate	Monterrey	San José	
El Roble	Nacascolo	San José de la Montaña	
El Rosario	Naranjo	San Josecito	
El Tejar	Occidental	San Juan	
Escazú	Oriental	San Juan de Dios	
Escobal	Orosi	San Juan Grande	

La Zona Sísmica III es la región de amenaza intermedia del país. En esta región se concentra la mayoría de la población y por ende, la mayor cantidad del inventario residencial. De acuerdo con el modelo de exposición, **posee más de 982,300 estructuras residenciales, con un valor aproximado de \$66,390 Millones de USD, esto equivale a un 83% de la infraestructura y 87.5% del valor de todo el inventario nacional.** Esto hace que esta zona sea la que mejor representa la realidad constructiva y el desempeño del sector residencial del Costa Rica.

Tal y como se muestra en la Tabla 5, en esta zona más de un 75% del valor del inventario está concentrado en las tipologías de mejor desempeño estructural, que son las estructuras de mampostería confinada reforzada. El cuarto restante esta homogéneamente dividido entre la mampostería integral, el prefabricado y la madera, de los cuales una parte importante se presenta en buen estado. Acá también la tipología que representa la construcción informal y los tugurios tiene una participación de 1% en el valor del portafolio.

Tabla 5: Características estructurales y económicas del sector residencial en la Zona Sísmica III.

Tipología Estructural	Código	Valor
Mampostería -Confinada / Buen Estado /1 piso	MCF/LWALL+DUC/HEX:2/YBET:1980-2010	\$ 29,739,167,739
Mampostería -Confinada / Buen Estado /2 pisos	MCF/LWALL+DUC/HEX:1/YBET:1980-2010	\$ 20,724,504,170
Mampostería -Confinada / Mal Estado. /1 piso	MCF/LWALL+DLO/HEX:1/YBET:1980-2010	\$ 3,833,202,825
Madera/Buen Estado/1 piso	W+WLI/LWALL+DNO/HEX:1/YPRE:1980	\$ 2,618,290,540
Madera/Mal Estado/1 piso	W+WLI/LWALL+DLO/HEX:1/YPRE:1980	\$ 2,574,009,952
Prefabricado/Buen Estado/1 piso	CR+PC/LWALL+DUC/HEX:1/YBET:1980-2010	\$ 2,322,443,967
Mampostería-Integral / Buen Estado/1 piso	MR/LWALL+DUC/HEX:1/YBET:1980-2010	\$ 1,864,014,834
Mampostería-Integral / Mal Estado/1 piso	MR/LWALL+DLO/HEX:1/YBET:1980-2010	\$ 1,239,203,247
Prefabricado/Mal Estado/1 piso	CR+PC/LWALL+DLO/HEX:1/YBET:1980-2010	\$ 916,982,730
Material Informal / Mal Estado / 1 piso	MATO/LN+DNO/HEX:1/Y99	\$ 558,447,174
Total		\$ 66,390,267,176



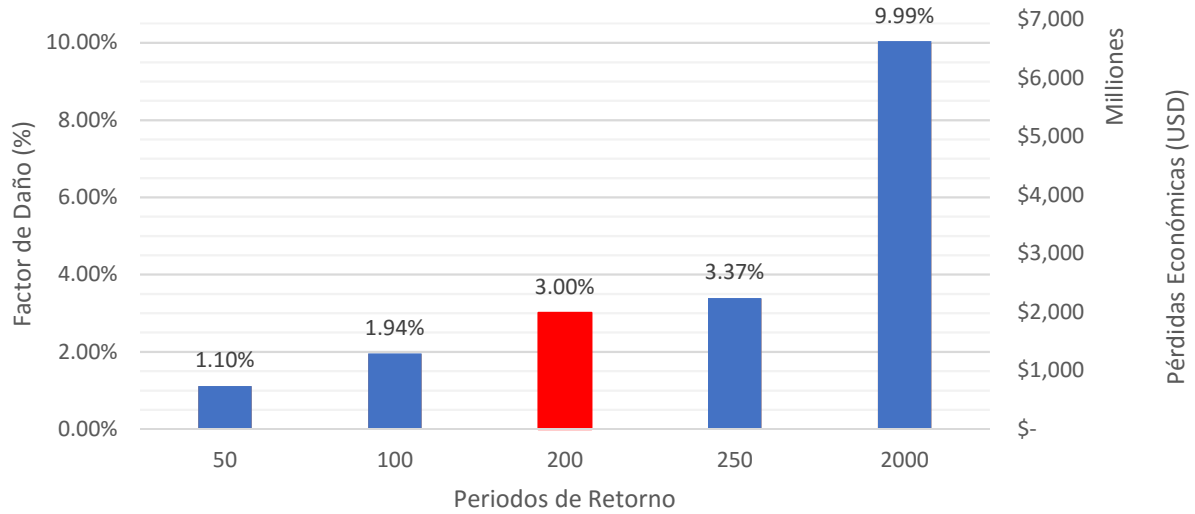
Pérdida Anual Promedio y Factor de Daño Anual

Para la Zona Sísmica III se simularon 50,000 años de actividad sísmica para la generación de eventos estocásticos. Al sumar todas las pérdidas registradas y dividir las por este número de años **se obtiene una Pérdida Anual Promedio de \$96.25 Millones de USD, equivalente a un factor de daño anualizado de 0.14%.**

Pérdidas y Factores de Daños para Periodos de Retorno de 50, 100, 200, 250 y 2000 años

Los factores de daño se obtienen al dividir cada pérdida entre el valor del inventario. En la siguiente ilustración se muestran los resultados obtenidos para la Zona Sísmica III.

Ilustración 7: Pérdidas y Factores de Daño para diferentes Periodos de Retorno para la Zona III



Análisis de Riesgo para Zona IV del CSCR-10

Características de la Zona

La Zona Sísmica IV está compuesta por los distritos que se muestran en la siguiente tabla:

Tabla 6: Distritos de la Zona Sísmica IV

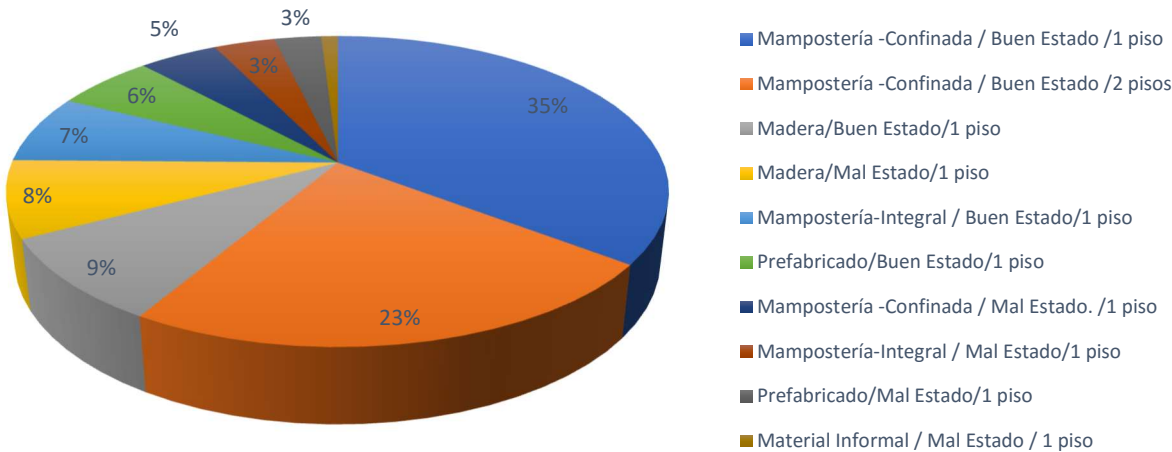
Aguabuena	Corredor	Palmar	San Juan de Mata
Bahía Ballena	Cuajiniquil	Palmira	San Pablo
Barú	Daniel Flores	Paquera	Santa Cruz
Bejuco	Diriá	Parrita	Santa Rita
Belén	Filadelfia	Pavón	Sardinal
Belén de Nosarita	Golfito	Pejibaye	Savegre
Bolsón	Guaycará	Piedras Blancas	Sierpe
Boruca	Hojancha	Pilas	Tamarindo
Cabo Velas	Huacas	Platanares	Tárcoles
Canoas	Jacó	Porvenir	Tempate
Carara	La Cuesta	Puente Carrillo	Veintisiete de Abril
Carmona	Laurel	Puerto Cortés	Zapotal
Cartagena	Lepanto	Puerto Jiménez	
Chánguena	Mansión	Quebrada Honda	
Chira	Monte Romo	Quepos	
Chires	Naranjito	Sámara	
Cóbano	Nicoya	San Antonio	
Colinas	Nosara	San Isidro de El General	

La Zona Sísmica IV es la región de amenaza más alta del país debido a su cercanía a la zona de subducción entre las Placas de Cocos y Caribe. De acuerdo con el modelo de exposición, **posee más de 137,500 estructuras residenciales, con un valor aproximado de \$6,847 Millones de USD, esto equivale a un 12% de la infraestructura y 9% del valor de todo el inventario nacional.**

Tal y como se muestra en la Tabla 7, la zona IV tiene un portafolio similar al de la Zona II, donde el estado de las estructuras es bueno pero las tipologías de buen desempeño ante sismos, como lo son la mampostería confinada reforzada son menos utilizadas que en el Valle Central. Por consiguiente, aquí también las estructuras de madera, prefabricado y mampostería integral tienen una mayor participación en el valor del portafolio. Por último, el porcentaje que corresponde a la construcción informal y los tugurios se mantiene en un 1%.

Tabla 7: Características estructurales y económicas del sector residencial en la Zona Sísmica IV.

Tipología Estructural	Código	Valor
Mampostería -Confinada / Buen Estado /1 piso	MCF/LWALL+DUC/HEX:2/YBET:1980-2010	\$ 2,420,302,015
Mampostería -Confinada / Buen Estado /2 pisos	MCF/LWALL+DUC/HEX:1/YBET:1980-2010	\$ 1,586,798,582
Madera/Buen Estado/1 piso	W+WLI/LWALL+DNO/HEX:1/YPRE:1980	\$ 599,130,547
Madera/Mal Estado/1 piso	W+WLI/LWALL+DLO/HEX:1/YPRE:1980	\$ 546,819,980
Mampostería-Integral / Buen Estado/1 piso	MR/LWALL+DUC/HEX:1/YBET:1980-2010	\$ 484,921,031
Prefabricado/Buen Estado/1 piso	CR+PC/LWALL+DUC/HEX:1/YBET:1980-2010	\$ 396,250,844
Mampostería -Confinada / Mal Estado. /1 piso	MCF/LWALL+DLO/HEX:1/YBET:1980-2010	\$ 315,786,965
Mampostería-Integral / Mal Estado/1 piso	MR/LWALL+DLO/HEX:1/YBET:1980-2010	\$ 243,473,945
Prefabricado/Mal Estado/1 piso	CR+PC/LWALL+DLO/HEX:1/YBET:1980-2010	\$ 186,934,417
Material Informal / Mal Estado / 1 piso	MATO/LN+DNO/HEX:1/Y99	\$ 66,653,409
Total		\$ 6,847,071,735

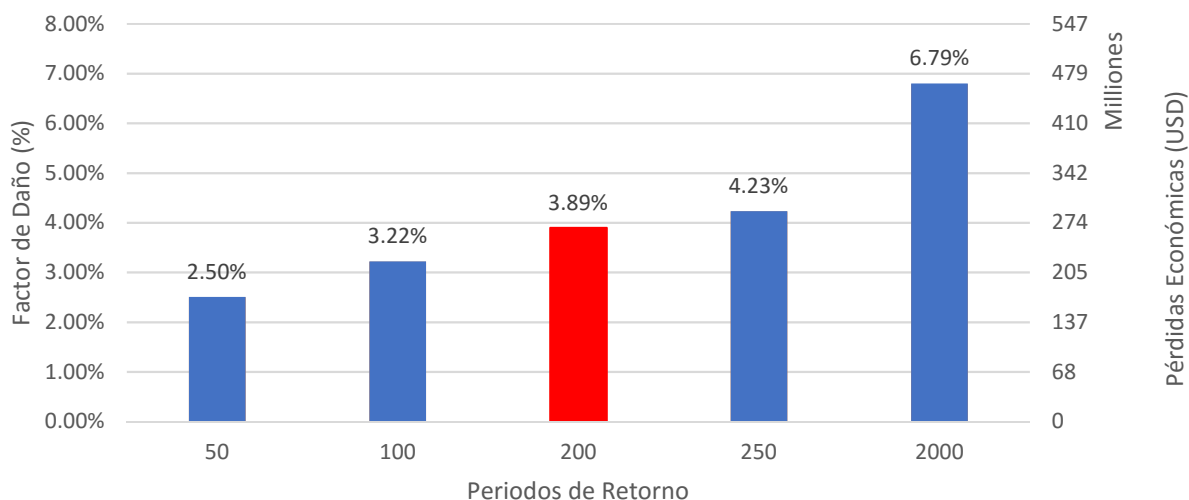


Pérdida Anual Promedio y Factor de Daño Anual

Para la Zona Sísmica IV se simularon 50,000 años de actividad sísmica para la generación de eventos estocásticos. Al sumar todas las pérdidas registradas y dividir las por este número de años **se obtiene una Pérdida Anual Promedio de \$12.23 Millones de USD, equivalente a un factor de daño anualizado de 0.18%.**

Pérdidas y Factores de Daños para Periodos de Retorno de 50, 100, 200, 250 y 2000 años
 Los factores de daño se obtienen al dividir cada pérdida entre el valor del inventario. En la siguiente ilustración se muestran los resultados obtenidos para la Zona Sísmica IV.

Ilustración 8: Pérdidas y Factores de Daño para diferentes Periodos de Retorno para la Zona IV



Comentarios

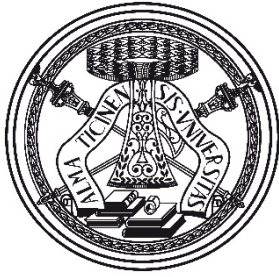
Los índices de riesgo que se presenta en este informe son el resultado de la combinación de los 3 componentes fundamentales de amenaza, exposición y vulnerabilidad. En otras palabras, las variables que afectan los índices son diversas, por consiguiente, vale la pena comentar brevemente cómo se relacionan e influyen los resultados.

Tómese por ejemplo los Factores de Daño. Puede observarse que, para Costa Rica, habiendo obtenido factores para el periodo de 200 años de 2.80% ,3.00% y 3.89% correspondientes a las Zonas II, III y IV, los índices crecen en función de la amenaza. Esto es parcialmente cierto porque la amenaza en Costa Rica aumenta en la región del pacífico debido a la presencia de una zona de subducción de placas. Sin embargo, estos factores están influenciados también por variables como el tipo de suelo, el régimen tectónico y la calidad de la construcción, que varían con cada distrito. Por consiguiente, es posible encontrar casos en los cuales los índices de riesgo no muestren proporcionalidad con la amenaza de la zona. Para último caso tómese las pérdidas promedio anuales. Se determinó que los factores de pérdida anualizados son del 0.18%, 0.14% y 0.18% para las Zonas II, III y IV. En este índice las Zona III muestra un factor anualizado menor porque en una ventana de tiempo extensa (50,000 años), el sector residencial del Valle Central tiene un mejor desempeño y resistencia ante sismos debido a la calidad constructiva, en comparación al de las Zonas II y IV, a pesar de ser una zona de amenaza intermedia. Por otro lado, las Zonas II y IV tienen índices anualizados comparables debido a que la construcción, de desempeño relativamente menor en la zona del Caribe, se ve compensada por niveles de amenaza inferiores a los encontrados en la zona del Pacífico.

Cada índice de riesgo tiene un significado y uso diferente. La pérdida y los factores de daños anualizados, conocidos como la Pérdida Anual Promedio y el Factor de Pérdida Anual Promedio, son índices de riesgo homogéneo que sirven como indicadores del desempeño a muy largo plazo del portafolio ante eventos sísmicos. Usualmente se usan para determinar las zonas, regiones o edificios que requieren de análisis de riesgo más detallados porque muestran este tipo de índices en niveles elevados. También son muy útiles para comparar de forma imparcial el riesgo entre diferentes zonas dentro de un mismo estudio. Por otro lado, las pérdidas y factores de daño asociados a periodos de retorno, por ejemplo, para 50, 200 y 500 años, sirve para determinar cuál es la máxima pérdida probable previsible en eventos particularmente catastróficos, de ciertas características definidas. El periodo de retorno de 50 años representa el evento sísmico probable que puede suceder dentro de la vida útil del portafolio, mientras que los 200 y 500 años representan eventos menos probables pero posibles, dentro de lo razonable, que pueden darse dentro de la vida útil del portafolio. Este tipo de índices son particularmente útiles para análisis financieros, estudios de transferencia del riesgo y medidas de preparación ante desastres.

Por último, puede observarse comparando los resultados globales que hay una leve diferencia (6%) entre los índices globales de riesgo estimados en este estudio, y los encontrados en la investigación de Calderón y Silva 2016. Esto se debe más que todo a la diferencia en la cantidad de eventos estocásticos utilizados. Para este estudio se empleó una ventana de tiempo de 50,000 años, mientras que el estudio previamente mencionada utiliza una ventana de 100,000 años. Esta reducción se llevó a cabo para disminuir los recursos computacionales y de tiempo necesarios para producir los resultados, considerado que los mismos siguen siendo representativos de los obtenidos en el estudio original.

Anexos



Probabilistic Earthquake Loss Assessment for Costa Rica

A Dissertation Submitted in Partial Fulfilment of the Requirements
for the Master Degree in

Earthquake Engineering &/or Engineering Seismology

By

Alejandro Calderón Carpio

Supervisor: Dr. Vitor Silva

February 28th 2016

Istituto Universitario di Studi Superiori di Pavia
Università degli Studi di Pavia

The dissertation entitled “Probabilistic Earthquake Loss Assessment for Costa Rica”, by Alejandro Calderon, has been approved in partial fulfilment of the requirements for the Master Degree in Earthquake Engineering.

Vitor Silva_____

ABSTRACT

This study reviews the current state on seismic risk assessment for Costa Rica and proposes exposure and vulnerability models. These models were combined with an existing hazard model to perform seismic risk assessment at a national scale for the residential building stock in the country. For the exposure model, information from six different governmental and private entities was gathered and analyzed in order to quantify and characterize the building stock. In terms of vulnerability, a complete analytical catalogue is proposed by developing functions for the most common building classes and complementing them with models developed for risk assessment in the South American Region. The most complete national hazard model was replicated using the OpenQuake-engine and complemented with a proposed site model in order to account for ground motion amplification due to soft soils. Risk assessment is achieved by means of probabilistic event-based analysis and the average annual loss ratios and average annual losses are estimated at a national scale, as well as disaggregated per building class and administrative regions. A Probable Maximum Loss Curve was generated using a stochastic event set with 100,000 years of events in order to provide additional financial indicators.

Keywords: risk assessment, exposure, structural vulnerability, seismic hazard, Costa Rica.

ACKNOWLEDGEMENTS

This study depended heavily on the support from several national governmental and private institutions. I would like to acknowledge the participation of the following professionals as local collaborators:

From the National Institute of Geography (IGN), Jonathan Jimenez.

From the Costa Rica Central Bank (BCCR), Elvia Campos Villalobos.

From the Costa Rican Chamber of Construction (C.C.C), Andrea Gonzáles Méndez.

From the Federate Board of Engineers and Architects of Costa Rica (CFIA), the engineer Marcial Rivera.

From the National Institute of Statistics and Census (INEC), Mayra Moreira and Rocío Portilla.

From the University of Costa Rica (UCR), the engineers Rolando Castillo and William Vargas.

From the private sector, the engineer Jorge Ruiz Munguía.

I also extend thanks to all the professionals in the Global Earthquake Model Foundation, who developed and maintain of the software used for the risk assessment. For their outstanding support, help and guidance, my special gratitude to:

Vitor Silva

Catalina Yepes-Estrada

Anirudh Rao

Daniela Rodrigues

Mabé Villar

Luis Rodriguez

Catarina Costa

Daniel Saborío

Alonso Gonzalez

Mehmetcan Atakul

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1 REVISION OF CURRENT STUDIES ON SEISMIC HAZARD AND RISK FOR COSTA RICA

1.1 Introduction

Due to its location alongside the Pacific Ring of fire and the subduction interaction between the tectonic boundaries of the Caribbean and Cocos plates, Costa Rica possesses high seismic activity of intermediate magnitude (M_w from 5 to 7.9). These earthquakes have shown their destructive potential during the last four decades. Events from 1988 to 2009 have left losses estimated to be greater than \$650 Million USD, which account for 36% of the losses registered from natural disasters [MIDEPLAN, 2010].

Aware of the need to understand the risk derived from earthquakes, historically two governmental institutions have worked on seismic risk assessment in Costa Rica: the National Institute of Insurances (INS) and the National Commission of Emergencies (CNE). During the seventies, the INS hired local and international experts to determine the cost of earthquake premiums for the country [Sauter and Shah, 1978]. The project developed the three main components required to assess risk. It determined seismic hazard through probabilistic means. The main structural typologies in the country were identified and characterized according to seismic performance and a set of vulnerability functions were developed, presenting structural damage as a function of seismic Modified Mercalli Intensity.

Despite this early effort to understand earthquake risk in the country, at present the hazard, exposure and building vulnerability have significantly changed since the seventies. Moreover, hazard is the only area of knowledge that has been updated and reevaluated at a regional scale. Even though Costa Rican construction practices are quite different now, vulnerability and exposure have focused mostly on local study cases in areas of vital importance. In terms of a national scale exposure and vulnerability models there is a lot of room for study and research.

Aiming to contribute to modern risk assessment for the country, the main objective of this investigation is to perform seismic risk analysis for Costa Rica's residential building stock and propose a seismic risk profile for the country. To achieve this, exposure and vulnerability models were developed and proposed at a national scale, using the most updated available data on housing and construction. An existing hazard model was complemented with a site model developed to account for motion amplification due to soil conditions. All the risk components were proposed consistent with the standards developed by the Global Earthquake Model

Foundation. Assessment is done through an event-based analysis. The results include estimation of average annual economic losses and the elaboration of a Probable Maximum Loss Curve.

To place this study in context, the first chapter presents a short introduction on the current state of seismic risk assessment in the country. It is followed by the development of the exposure map at a national scale, a set of vulnerability functions and the evaluation of a seismic hazard model already implemented in the OpenQuake-engine. These three datasets were combined to derive several risk metrics. The last chapter of the dissertation focuses on the main conclusions found for each model and final remarks on the determined risk indicators.

1.2 Seismic Hazard Studies

Seismic hazard is the most studied risk component required to assess physical risk in the case of Costa Rica. The first formal study on seismic hazard assessment was performed by Mortgat et al. [1977] at the John A. Blume Earthquake Engineering Center of the University of Stanford. Despite the lack of quality acceleration records and well-developed attenuation relationships for the region, seismic data from Nicaraguan and Costa Rican historical catalogues was used, while line and area sources were created for a region slightly larger than the country. Using a probabilistic approach, maps of iso-acceleration were created for return periods of 50, 100, 500 and 1000 years for the national territory. The first results indicated a maximum peak ground acceleration (PGA) for the country's capital of 0.31 g for a return period (RP) of 500 years. The relevance of this study went beyond hazard assessment, since it introduced concepts of structural design objectives, design philosophy and acceptable risk that served as basis for the Costa Rican Seismic Code of 1984.

On 1994, in a joint project with NORSAR, the University of Costa Rica and the Costa Rican Institute of Electricity, Laporte et al. [1994] used a more complete regional seismic catalogue together with an attenuation model developed specifically for the region's tectonic regime [Climent et al., 1994]. By means of probabilistic assessment, the project produced hazard maps for return periods of 50, 100, 500 and 1000 years. The maximum peak ground acceleration (PGA) for San José was then estimated to be about 0.37 g, for a return period of 500 years. This study became the hazard reference for the Costa Rican Seismic Code of 2002.

Later on, funded by the Norwegian government, another NORSAR project, RESIS II [Climent et al., 2008] produced an updated map of seismic hazard for the entire Central American region, using the most recent information about the seismicity on the region. This study is the reference for hazard for the current Costa Rican Seismic Code of 2010. Although a further revision of the procedure implemented to develop hazard is discussed on a later chapter, this study determined by means of classical probabilistic seismic hazard analysis, maps for return periods of 500, 1000 and 2500 years. Results obtained for a return period of 500 years indicated a maximum peak ground acceleration in Costa Rica in the central volcanic chain of about 0.51 g, which decreases on parallel zones towards the Caribbean coast to values below 0.31 g, as presented in Figure 1-1 and Figure 1-2.

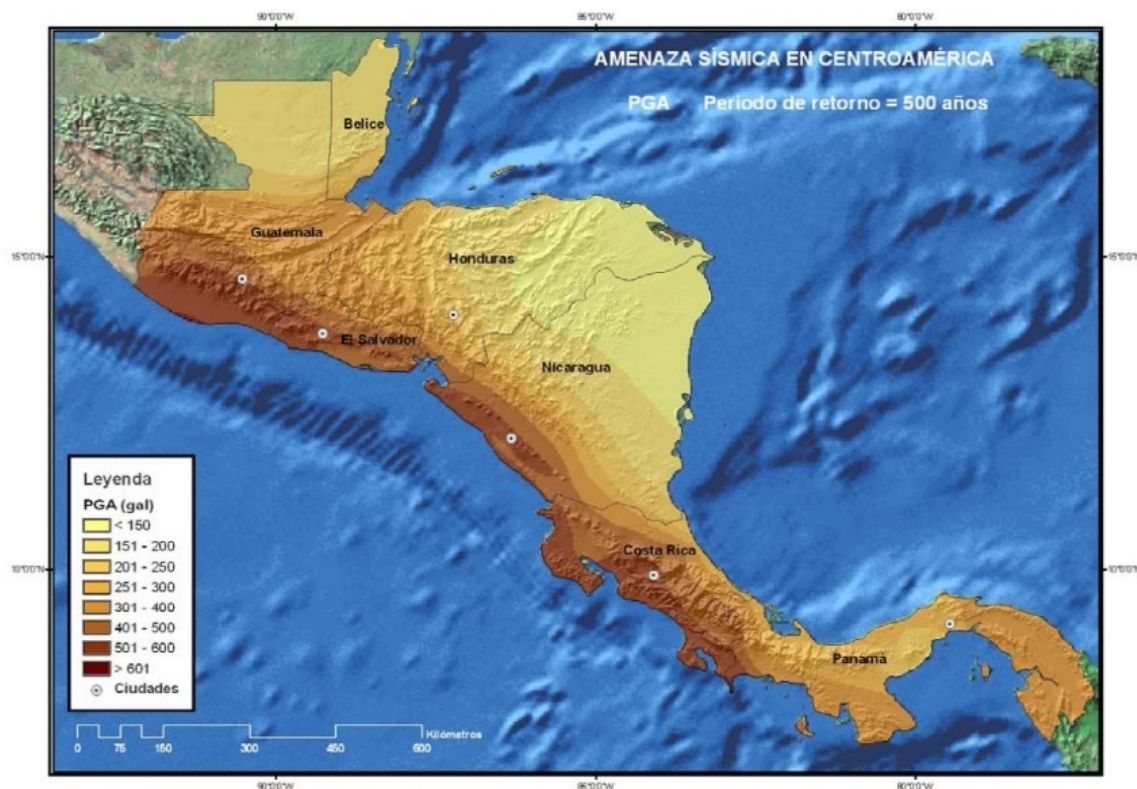


Figure 1-1: PGA hazard map for Central America for a RP of 500 years [Climent et al. 2008].

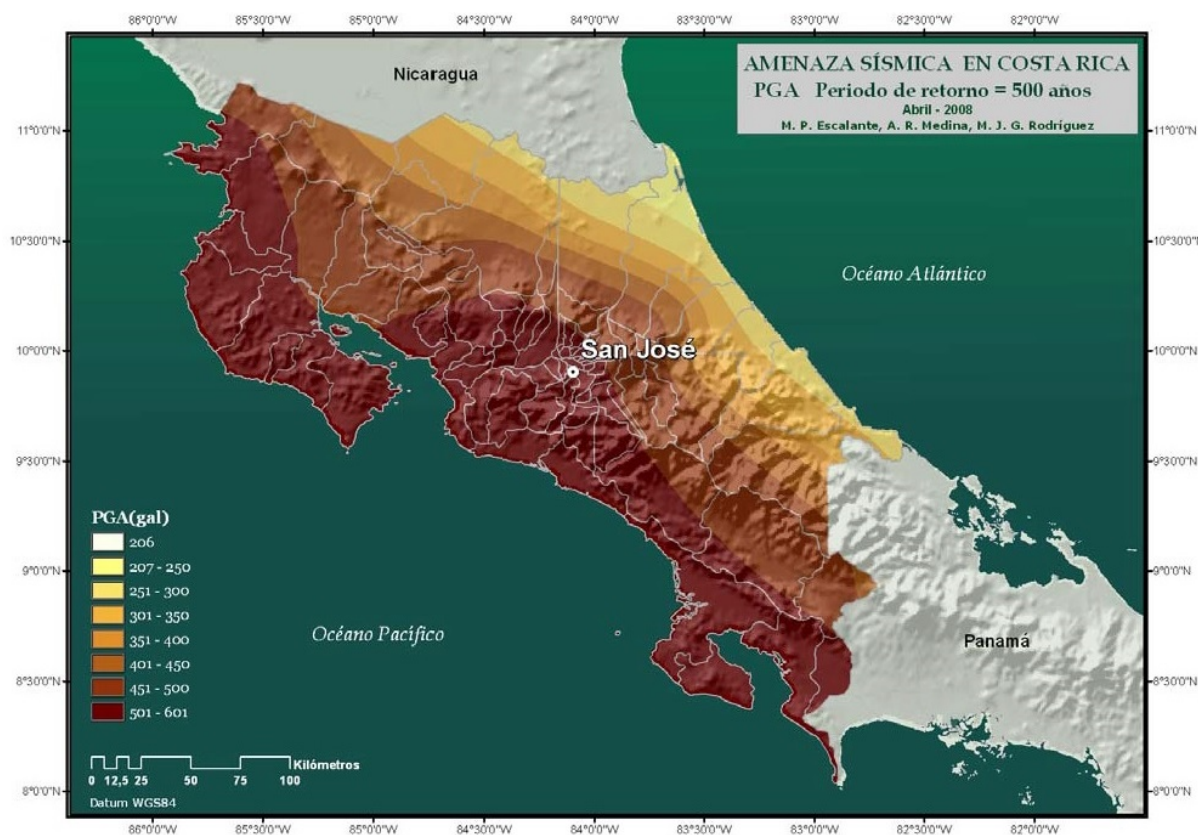


Figure 1-2: Hazard map for Costa Rica. PGA values for a return period of 500 years [Climent et al. 2008].

1.3 Risk Assessment Studies

Although during the last decade the interest on risk studies increased significantly, the most relevant work on physical risk assessment for Costa Rica was carried out by Sauter and Shah [1978]. The project was performed for the National Institute of Insurances (INS) during the late seventies and aimed to determine a method for estimating earthquake insurance premiums in Costa Rica. The researchers revised the national building stock and determined that structural type and age of construction were enough structural attributes to make a reliable vulnerability assessment for the country. A set of vulnerability models were developed using such data, where the percentage of damage for each structural typology could be known for a continuous range of Modified Mercalli Intensity values. The curves, which recognized the level of seismic design within typologies, are presented in Figure 1-3. These results served for several vulnerability and risk assessment studies that came on the following decades.

More recently, Montoya [2002] elaborated an earthquake risk assessment for the country's old capital, Cartago City. The study aimed to develop and test a methodology for providing inputs to correctly assess earthquake risk, since it is unclear which vulnerability-relevant data is being gathered by the local governments. By reviewing the legal framework used in the country to register information of construction development, the study concludes that structural types, building height, number of floors and foundation types are attributes not reliably captured at present. It also suggests improvements to cadastral registration and points the effectiveness of using remote sensing combined with field observations in order to build a proper database.

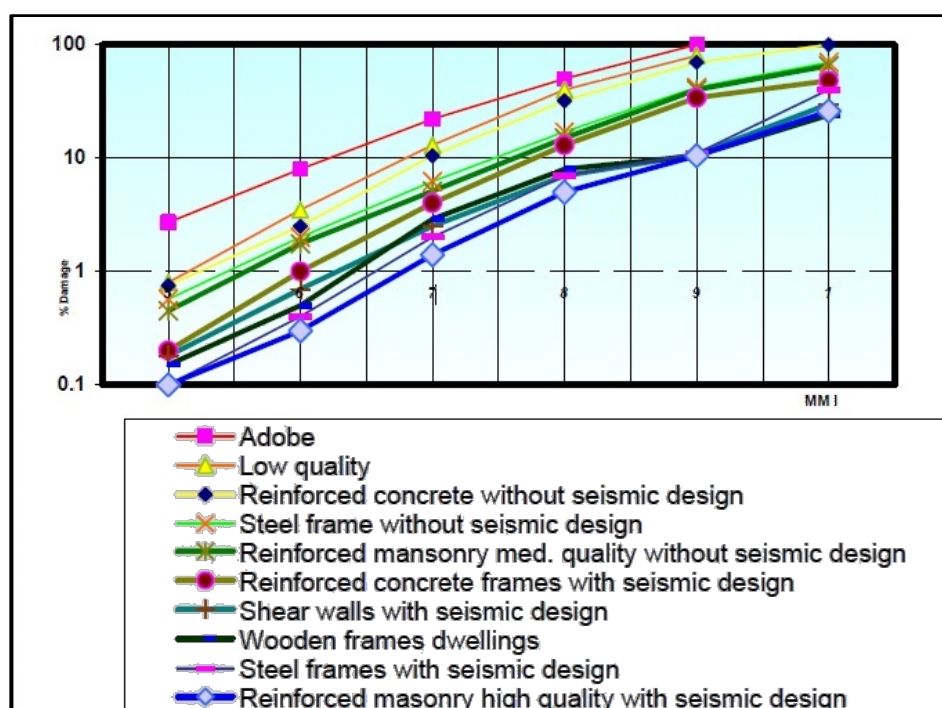


Figure 1-3: Vulnerability curves for Costa Rica developed by Sauter [1978], adapted from Lamadrid [2002].

Later on Lamadrid [2002] and Montoya et al. [2003] performed hazard, vulnerability and risk analyses, respectively, for another city in the Cartago province, Turrialba. The studies developed hazard maps and a database of the elements under flood and earthquake risk. A digital parcel map of the entire city was constructed using GIS tools, as presented in Figure 1-4.

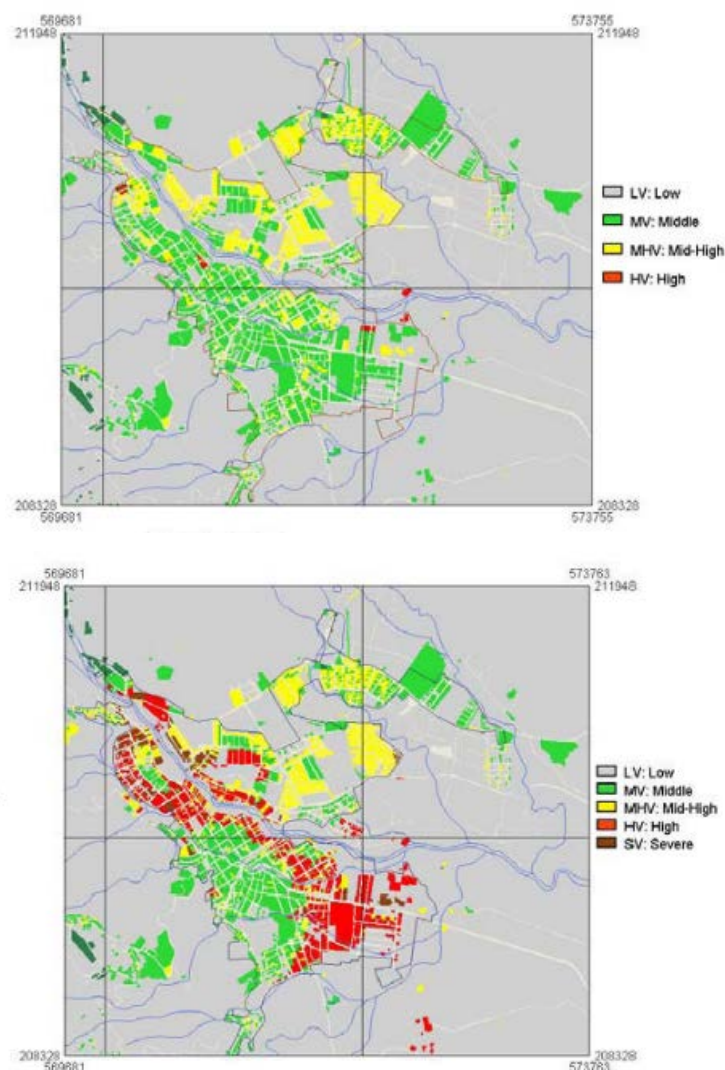


Figure 1-4: Risk maps created using GIS tools, for the City of Turrialba. Return period of 50 years on the top, 150 years on the bottom.

Climent et al. [2003], under the Regional Action Program of UNESCO Capacity Building for Natural Disaster Reduction for Central America, made another case study for the city of Cañas, in Guanacaste Province. The project used a deterministic hazard approach, identifying the city's vulnerability classes using Sauter and Shah [1989] building classification. Earthquake vulnerability maps like the one presented in Figure 1-5 were produced for two MMI intensity scenarios.

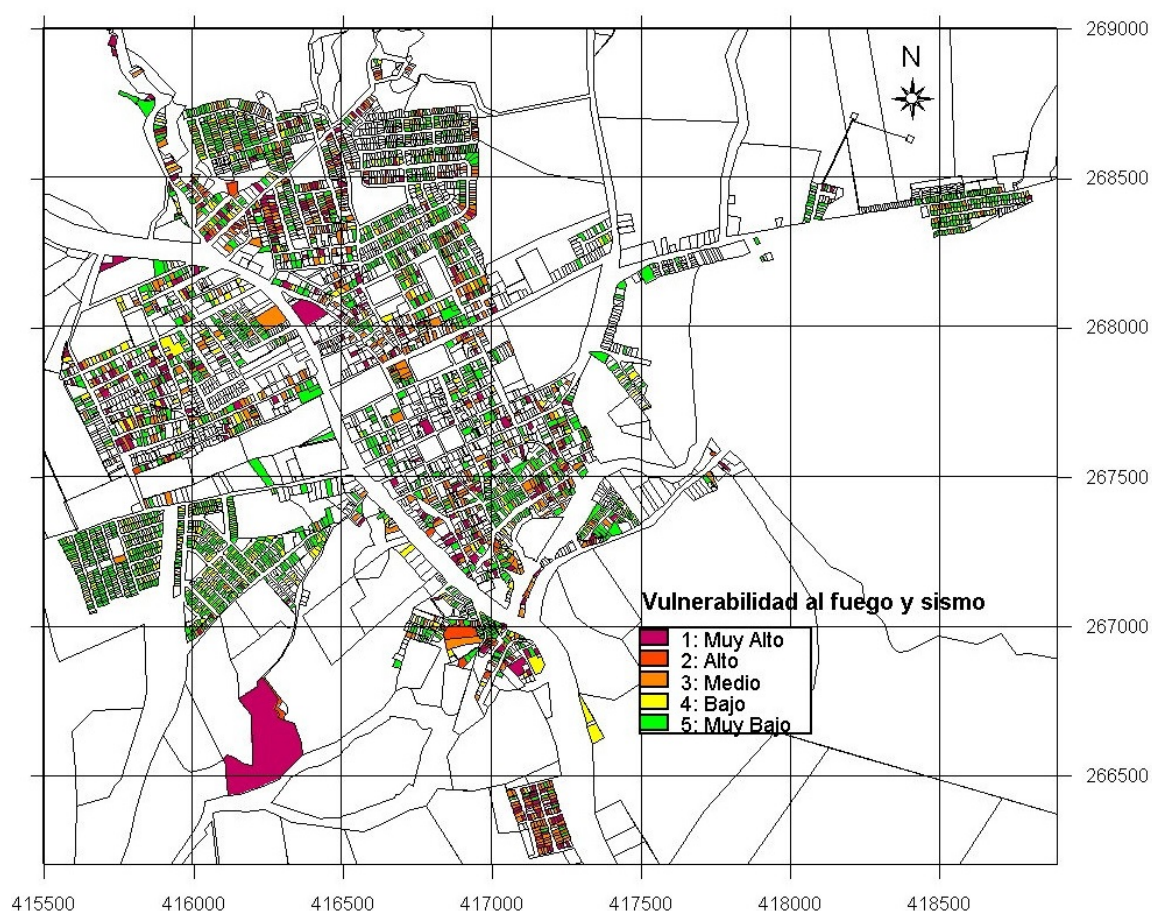


Figure 1-5: Seismic vulnerability for the city of Cañas Climent et al. [2003]

Salas [2003] worked on risk assessment for the San José Metropolitan Area (AMSJ), presented in Figure 1-6. Focused on the determination of an urban risk index based on probable life loss, the GESI [2000] methodology was used to assess physical risk, with the fragility curves suggested by the Federal Emergency Management Agency (FEMA) [2003]. Physical vulnerability was measured from structure expected damage and collapse probabilities, whereas social vulnerability was identified by means of social indicators, like the Social Risk Index (IRS) and the Unsatisfied Basic Needs Index (NBI). The latter study also included identification of soft soils within the AMSJ, and used PGA results from Rojas et al. [2000] to produce seismic hazard maps for a return period of 500 years. The study concluded that on a district scale, 12,080 expected human losses are reached for an annual exceedance probability of 0.2%. Other important results indicate direct spatial correlation between the most vulnerable structural typologies and the lowest indicators of social development. Distribution of expected damage showed that the capital districts of Pavas, La Urúca, San Felipe, Hatillo, San Sebastián, Desamparados and Patarrá, are significantly vulnerable.

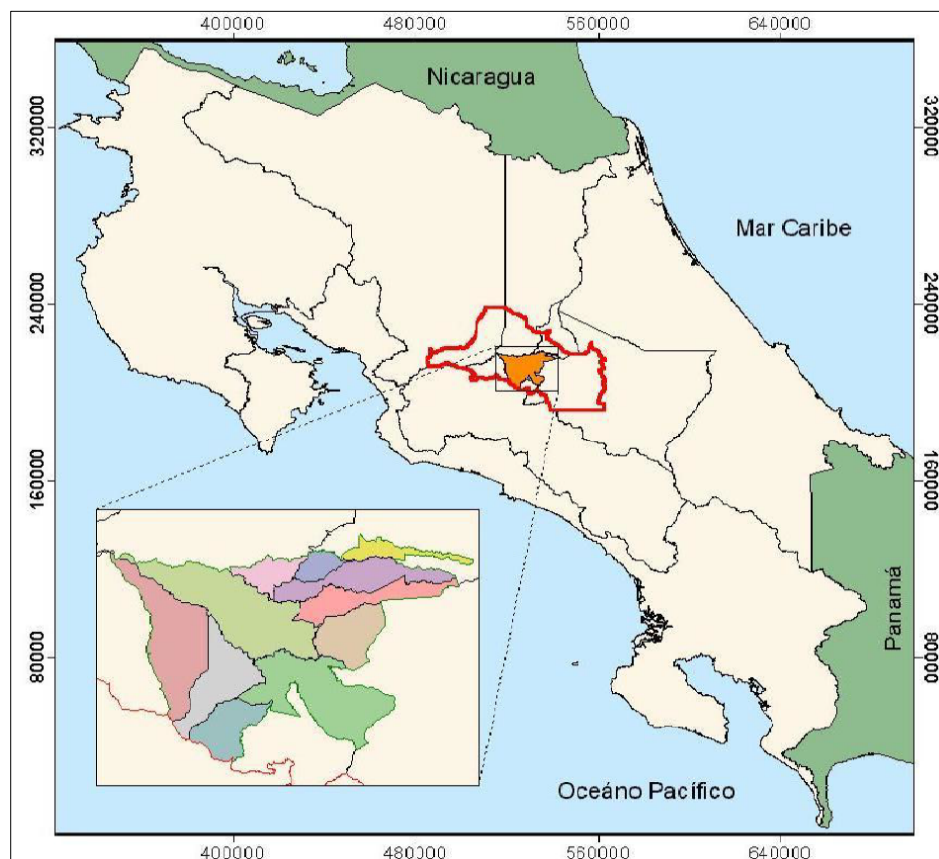


Figure 1-6: Study area of the residential stock risk assessment from Salas research [Salas, 2003].

1.4 Remarks on Previous Studies

The results of the hazard studies are directly applicable to this investigation. Specifically, the project RESIS II which covered Central America on a regional scale, makes it particularly useful for national level risk assessment.

The risk studies, with the exception of Sauter and Shah [1978], were performed using different assessment methodologies, focusing on a specific region of the country and not on a national scale, within a time frame that ranges from 1970 to 2003. These studies are therefore used as a reference for the development of the exposure and vulnerability models in this study. Quantitative comparison of results is not possible due to the differences previously mentioned.

1.5 Limitations

The studies mentioned in this chapter are presented due to their relevance on the topic of this investigation, their availability within its time frame and their influence on the results of the risk assessment. However, the amount of studies done for Costa Rica, in a national and international context, is not limited to the references on this chapter.

2 DEVELOPMENT OF AN EXPOSURE MODEL AT A NATIONAL SCALE

2.1 Introduction

The exposure model presented within this chapter aims to develop a dataset featuring the spatial distribution, building classification and replacement cost of the residential building stock in Costa Rica, which are fundamental to reliably evaluate physical vulnerability and economic losses. This chapter presents the procedure implemented to determine a representative number of building macro-classes. It focuses on further classification of all the known dwellings into its final fully defined building taxonomies. With the complete classification of the dwellings, then conversion from dwellings to buildings and the replacement cost assignment is explained. Important results and remarks on the model are presented at the end of the chapter.

2.2 Building Class Identification and Mapping Scheme

2.2.1 Tools for identification and methodology

The optimal tool for building class and structural attributes identification would be a national cadaster database, containing all the buildings and their relevant structural attributes. However, in Costa Rica such database does not currently exist. Thus, the main tools used for building class identification are the National Census from 1973 to 2011 provided by the National Institute of Statistics and Census (INEC).

Using the official census has three main advantages. First, the census capture both formal and informal construction, which allows for risk assessment in regions with low social development indexes. Second, it is performed to the smallest administrative level, the district, which makes risk assessment on a national scale possible. Third, the census inquiry captures dwelling attributes using more than 45 variables, thus allowing appropriate building class identification.

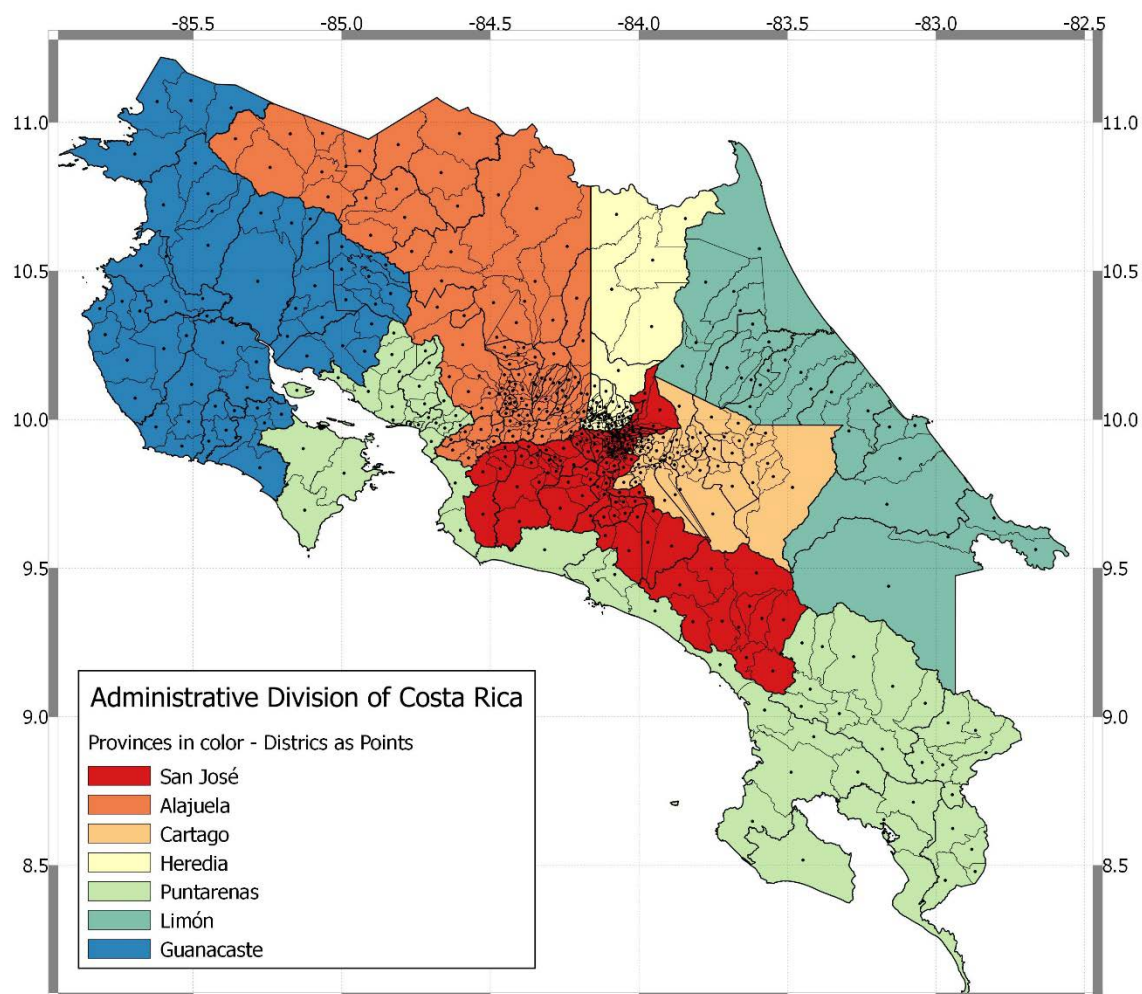


Figure 2-1: National census allows for risk assessment at a national scale, for the smallest administrative level. Each point on map represents a site for risk assessment, in this case the district centroids.

As explained in the following sections, census data was complemented with construction permits granted during the 2003 to 2010 period provided by the Federate Board of Engineers and Architects (CFIA), construction statistics from the Costa Rican Chamber of Construction and the National Enquiry of Homes (ENAH) from the INEC. The methodology used in this investigation to identify building classes is based on the work proposed by Yepes et al. [2016] for the South American Risk Assessment (SARA) project, supported by the GEM Foundation [GEM, 2016]. The final taxonomy definition is based on the GEM Building Taxonomy [Brzey et al., 2013].

2.2.2 Lateral Load Resisting System

The Costa Rican National Census do not specifically capture the lateral load resisting system (LLRS). Instead, it registers the exterior wall construction material of a dwelling. It is possible therefore to make an estimation of the main structural macro classes studying the exterior wall material variable, and further subdivide the macro classes using additional variables like dwelling and floor type.

An example of this procedure is provided using the dwelling presented in Figure 2-2. Even though the census registers the use of concrete masonry blocks as construction material for the individual house dwelling type, the use of an earthen floor is a poverty indicator that suggests low quality construction practices. Therefore, this structure falls into the unreinforced masonry building class. Applying this procedure, sixteen building macro classes were identified on the initial stage of the model.



Figure 2-2: Unreinforced masonry structure, identified using three census variables. Photograph source: <http://goo.gl/dKTdx0>.

2.2.3 Date of construction

An approximate date of construction can be derived for the identified structural systems studying construction trends in Costa Rica from 1973 to 2011. For example, comparison of the number of masonry dwellings registered in the year of 2011 with the year 1973 as presented in Figure 2-3, suggests that currently more than 80% of the masonry structures were constructed after the seventies. This is an indicator of having seismic provisions since design codes were introduced on that decade. Another example can be found for the precast concrete structures, which were basically non-existent prior to the eighties and now constitute the third most used structural system in the country. Therefore, further classification of macro classes was achieved by differentiating buildings constructed before and after 1980, in which the first have much less expected ductile behavior than the latter.

Identification of the date of construction was not possible for the building classes that belong to informal construction, like the load resisting systems made of waste materials, the unreinforced masonry and the natural wood pole and beam structures used by the indigenous population. However, no relevant time-dependent variations in the structural characteristics of these building classes is expected.

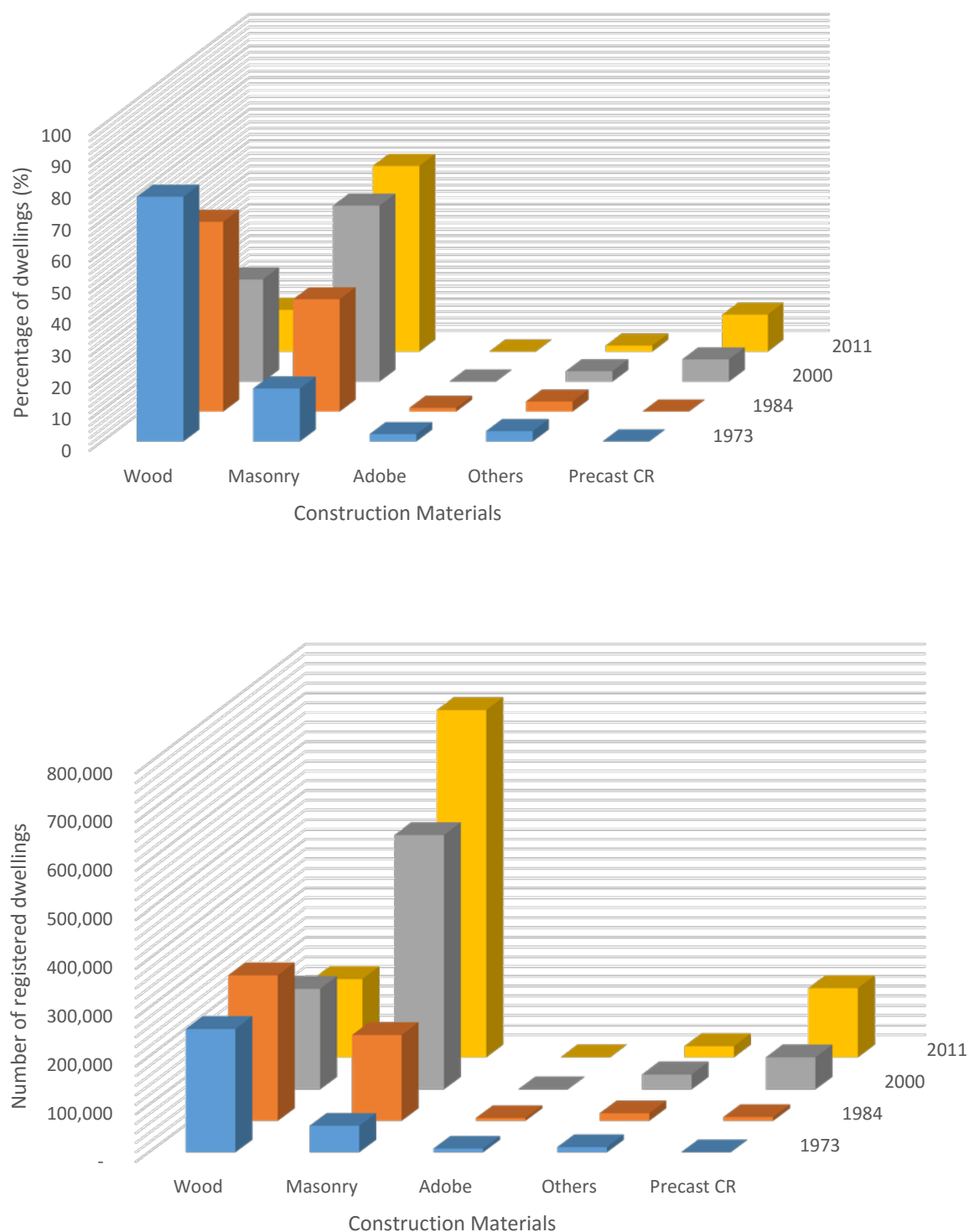


Figure 2-3: Trends on construction materials used on dwellings from 1973 to 2011 on Costa Rica. Top: Percentage of dwellings according to construction materials. Bottom: Absolute number of dwellings according to construction materials.

2.2.4 Building height

Building height is directly captured by the national census only for the individual house dwelling types, which range from one to two stories. Since this attribute strongly influences seismic performance, building height can be derived indirectly analyzing data on the construction size of the dwelling. The National Enquiry of Homes, performed by the INEC [2015], captures dwellings construction size and allows for dwelling filtering using census variables. Therefore, once all building classes were separated through their corresponding filters, the distribution of construction area for each one was retrieved as an additional census variable.

Figure 2-4 shows the area distribution of confined masonry. With knowledge of Costa Rican construction practices, it is possible to establish a filtering rule that assigns all dwellings with construction areas of 150 m² or less to a one story height class, ranges from 150 m² to 250 m² can be evenly distributed among one and two-storey classes, and more than 250 m² to two-storey classes alone. By applying these rules on all classes, the height attribute was identified on all building classes, further subdividing the initial sixteen macro classes into twenty two.



Area distribution of MCF-DUC Typology

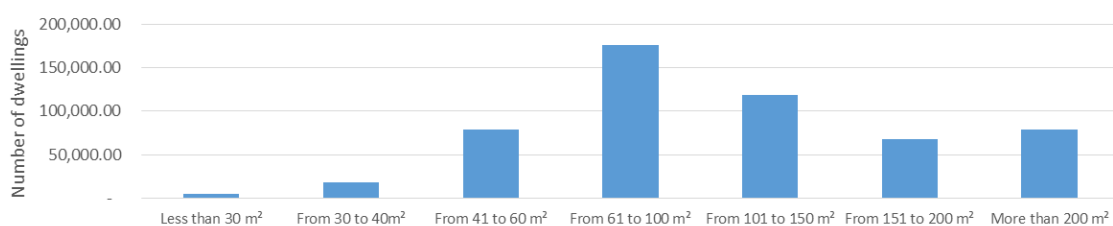


Figure 2-4: Area distribution of dwellings identified as confined masonry using census variables. Top Left: One storey dwelling, 150 m² or less. Top Right: Two-storey dwelling, more than 200 m². Bottom: Area distribution of the confined masonry building macro class. Photo sources: <http://goo.gl/Q0lrBz> and <http://goo.gl/WUcktf>.

2.2.5 Ductility level

It is not possible to predict seismic performance of a building class using census variables alone. However, it is possible to use additional filtering variables in order to differentiate expected seismic performance within each building class. This was done on the building classes where registered structural pathologies (damaged exterior walls, damaged roofs, heavy roofs on light

structures, etc.) could have a significant impact on the dynamic behavior of the structures, like the concrete precast and wood typologies.

Figure 2-5 shows how wooden structures were further classified by expected ductility levels. Light roofed and well-maintained structures are expected to behave much better than neglected structures with heavy shingle clay roofs. This was the final criterion for building taxonomy identification.



Figure 2-5: Further classification of structures using roof weight and wall condition variables to differentiate expected ductility levels. Left: low expected ductility wooden structure due to heavy roof and bad condition of LLRS. Right: high expected ductility wooden structure due to light roof and good condition of LLRS. Photo sources: <http://goo.gl/9uJJLu> and <http://goo.gl/9uJJLu>.

2.2.6 Replacement cost

A replacement cost must be calculated for each building class in order to allow the assessment of economic losses. It must represent the cost of repairing or rebuilding a certain building class in case it collapses and should exclude the price of property or land. In Costa Rica, the price of construction has been widely studied by many governmental and private institutions, like the Federate Board of Engineers and Architects (CFIA), the Ministry of Treasury, the Central Bank and Costa Rican Chamber of Construction.

Using as the main reference the Manual of Real State Assets by the Ministry of Treasury [Ministerio de Hacienda, 2015], an initial construction value per square meter was identified for all building classes. The manual was preferred as the main tool since it assigns value on structures using variables like wall material, roof type, floor type, structure condition and more. Since variables like these were also used in building class identification, the manual allowed for a direct assignation of an initial replacement cost. Once all the building classes had a defined value, further calibration was done using the Index of Construction Costs of the Federate Board of Architects and Engineers [CFIA, 2015] and the Construction Prototypes for the Costa Rican Central Bank [CFIA, 2015]. Since the average area of construction of the dwellings was available from the identification of the height attribute, a final replacement cost was obtained multiplying the cost per square meter by the average size of each building class.

2.3 Mapping Scheme Implementation

The procedure described above must be done for the 1.3 million dwellings found on the 2011 National Census. In order to automate the process of assigning each building class, a mapping scheme was implemented on a python script. The program goes through every dwelling on a census file, captures its geographical location and identifies the relevant variables. Then, it assigns the dwelling to a specific typology if its variables meet the set of rules used to define that taxonomy. The output of the parser contains all the dwellings of the census, classified according to the respective taxonomy they belong to. Revision procedures were performed after classifications to ensure that the initial amount of dwellings of the census equals the amount of dwelling classified under the GEM Building Taxonomy [Brzey, 2013].

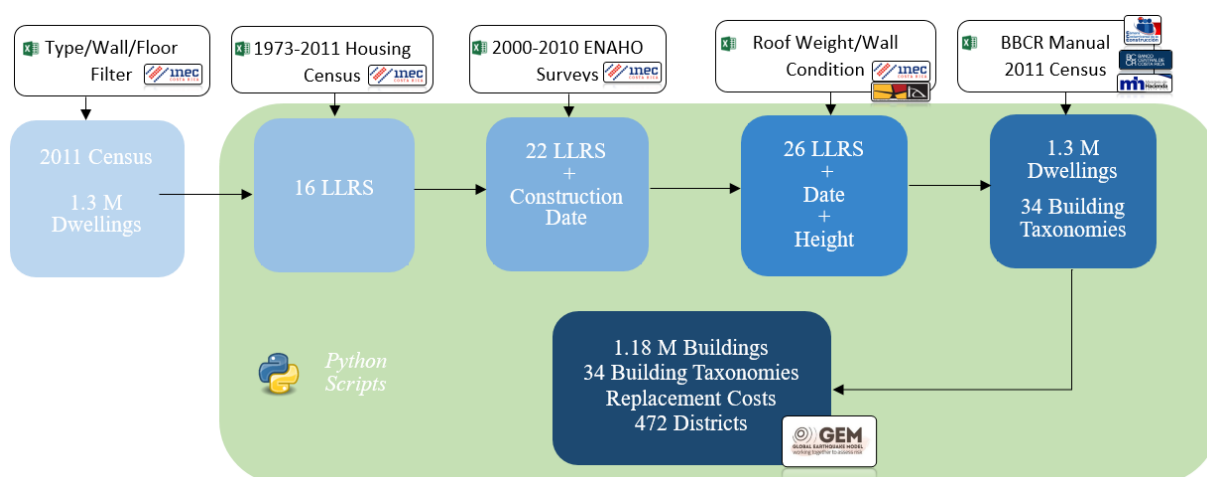


Figure 2-6: Mapping Scheme workflow

Post processing is required in order to transform the number of dwellings into buildings. This is done through a second python script, which applies dwelling to building conversion factors to every dwelling on the output files. In the case of Costa Rica, since the individual house dwelling types on the census directly register number of buildings, conversion factors are only necessary for high-rise typologies (3 storeys or more). The final output is the exposure model, where all the buildings have a defined geographical position, lateral load resisting system, date of construction, height, expected ductility and replacement cost according to the GEM Building Taxonomy [Brzey, 2013].

2.4 Exposure Model at a National Scale

2.4.1 Building Classes

Around 1.3 million dwellings are registered in the 2011 Housing Census, which results in 1.18 million structures after the implementation of the mapping scheme. These buildings are distributed among a total number of 34 building classes, as listed in Table 2-1.

Table 2-1: Identified building classes. L.L.R.S stands for lateral load resisting system.

Material	L.L.R.S	Expected Duc.	Height	Year
Unreinforced Masonry	Wall System	Non-ductile	1-storey	Unknown
Confined Masonry	Wall System	Ductile, high	1-storey	Post 1980
Confined Masonry	Wall System	Ductile, medium	1-storey	Post 1980
Confined Masonry	Wall System	Ductile, high	2-storey	Post 1980
Confined Masonry	Wall System	Ductile, medium	2-storey	Post 1980
Confined Masonry	Wall System	Ductile, high	3 to 6 - storey	Post 1980
Confined Masonry	Wall System	Ductile, medium	3 to 6 - storey	Post 1980
Reinforced Masonry	Wall System	Ductile, high	1-storey	Post 1980
Reinforced Masonry	Wall System	Ductile, medium	1-storey	Post 1980
Concrete Precast	Wall System	Ductile, high	2 to 6 - storey	Post 1980
Concrete Precast	Wall System	Ductile, medium	2 to 6 - storey	Post 1980
Concrete Cast In Place	Dual System	Ductile, high	2 to 6 - storey	Post 1980
Concrete Cast In Place	Dual System	Ductile, medium	2 to 6 - storey	Post 1980
Concrete Cast In Place	Wall System	Ductile, high	6 to 12 - storey	Post 1980
Concrete Cast In Place	Wall System	Ductile, medium	6 to 12 - storey	Post 1980
Concrete Cast In Place	Frame System	Ductile, high	1 to 2 - storey	Post 1980
Concrete Cast In Place	Frame System	Ductile, medium	1 to 2 - storey	Post 1980
Light Wood Sections	Wall System	Ductile, high	1-storey	Pre 1980
Light Wood Sections	Wall System	Ductile, medium	1-storey	Pre 1980
Natural Wood Sections	Pole-Beam System	Ductile, medium	1-storey	Unknown
Light Wood Sections	Wall System	Ductile, high	2-storey	Pre 1980
Light Wood Sections	Wall System	Ductile, medium	2-storey	Pre 1980
Heavy Wood Sections	Wall System	Ductile, high	1-storey	Post 1980
Heavy Wood Sections	Wall System	Ductile, high	2-storey	Post 1980
Precast Concrete	Wall System	Ductile, high	1-storey	Post 1980
Precast Concrete	Wall System	Ductile, low	1-storey	Post 1980
Concrete Cast In Place	Frame System	Ductile, high	2 to 6 - storey	Post 1980
Concrete Cast In Place	Frame System	Ductile, medium	2 to 6 - storey	Post 1980
Steel Cold Formed	Frame System	Ductile, low	1-storey	Post 1980
Steel Cold Formed	Frame System	Ductile, medium	1-storey	Post 1980
Steel Hot Rolled	Frame System	Ductile, high	1 to 2 - storey	Post 1980
Light Wood Sections	Frame System	Ductile, low	1-storey	Pre 1980
Waste Materials	Unknown	Non-ductile	1-storey	Unknown
Adobe	Wall System	Non-ductile	1-storey	Pre 1980

2.4.2 Building class distribution

The complete model, in which the respective building class is displayed together with its spatial distribution for the 472 districts is presented in Figure 2-7.

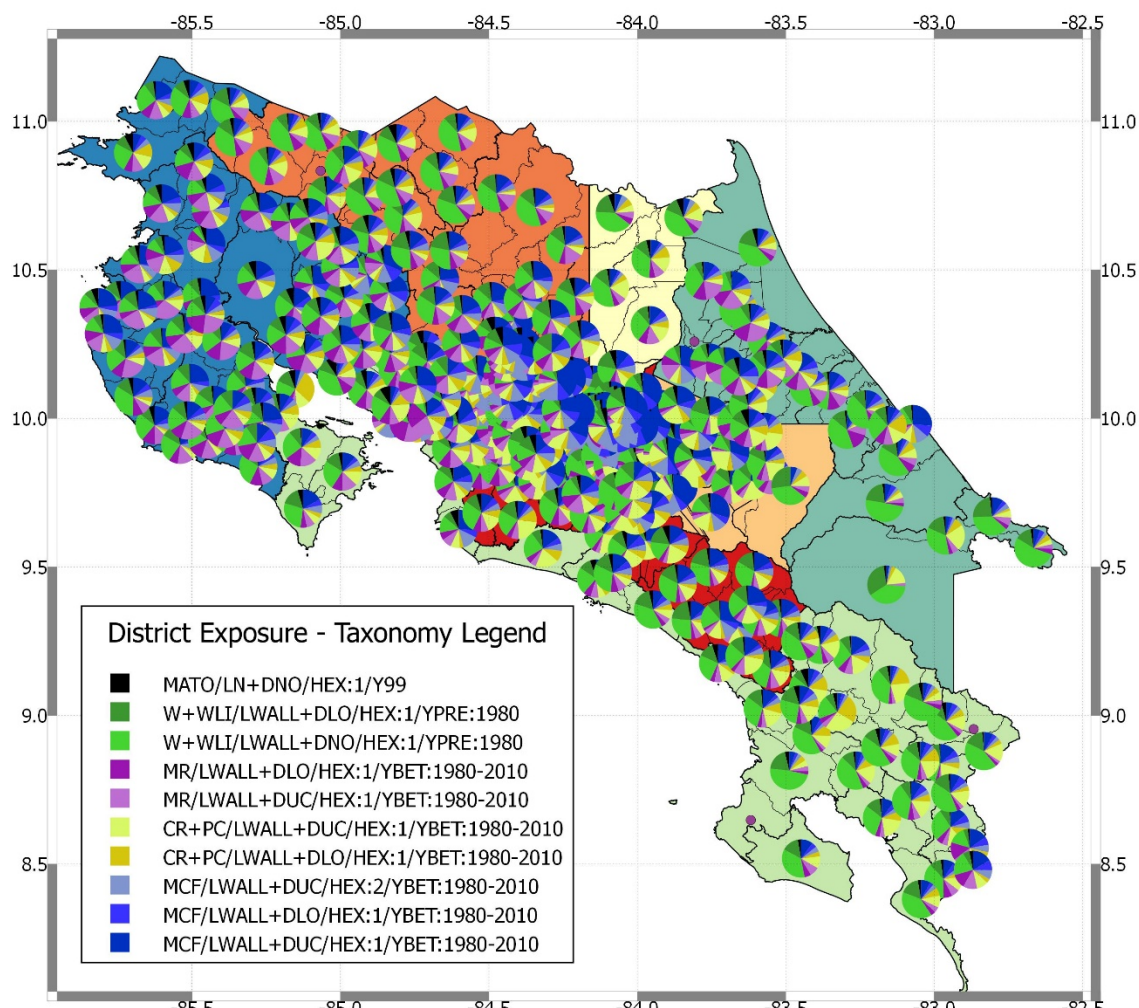
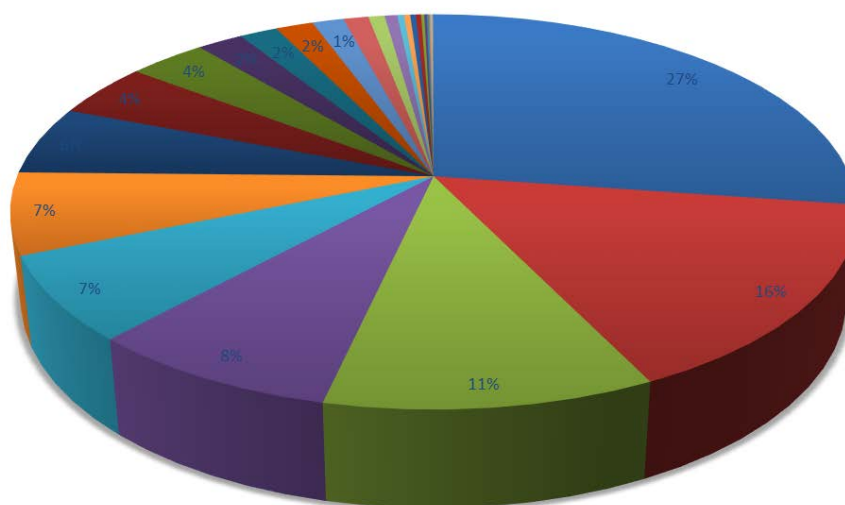


Figure 2-7: Exposure model at district level. The map shows building class distribution for 472 administrative regions registered in 2011. Legend only shows the top 10 building classes.

According to these results, even though 34 building classes were identified, more than 92% of the buildings in Costa Rica belong to the typologies presented in Table 2-2.

Table 2-2: Top 10 Building Taxonomies in Costa Rica and their respective percentage of use, adding up to 92% of the buildings in the country.



Material	L.L.R.S	Expected Duc.	Height	Year	Percentage
■ Confined Masonry	Wall System	Ductile, high	1-storey	Post 1980	27%
■ Wood	Wall System	Ductile, medium	1-storey	Pre 1980	16%
■ Confined Masonry	Wall System	Ductile, high	2-storey	Post 1980	11%
■ Precast Concrete	Wall System	Ductile, high	1-storey	Post 1980	8%
■ Confined Masonry	Wall System	Ductile, medium	1-storey	Post 1980	7%
■ Wood	Wall System	Ductile, high	1-storey	Pre 1980	7%
■ Reinforced Masonry	Wall System	Ductile, high	1-storey	Post 1980	6%
■ Reinforced Masonry	Wall System	Ductile, medium	1-storey	Post 1980	4%
■ Precast Concrete	Wall System	Ductile, low	1-storey	Post 1980	4%
■ Waste Materials	Unknown	Non-ductile	1-storey	Unknown	2%

Among the taxonomies least used for residential purposes are the steel, adobe, bahareque, high quality laminated wood houses and the wood structures used by the indigenous population.

2.4.3 Simplified exposure model

In order to perform physical risk analysis, it is necessary to associate each building class with a vulnerability function. According to Table 2-1, a total of 34 vulnerability functions should be used for the risk assessment in Costa Rica. However, the collection or derivation of analytical models is a time consuming process, and as explained before, 92% of the buildings in Costa Rica fall only into 10 classes. This makes it possible to perform a simplification of the exposure model, which is composed of the top 10 building classes, but still includes the assets from the remaining typologies distributed among them. By doing this simplification, risk analysis

becomes possible since only 10 vulnerability functions are required. Figure 2-8 shows the simplified version of the exposure model, which is still done at districts level, but is presented aggregated for provinces for visual clarity on the map.

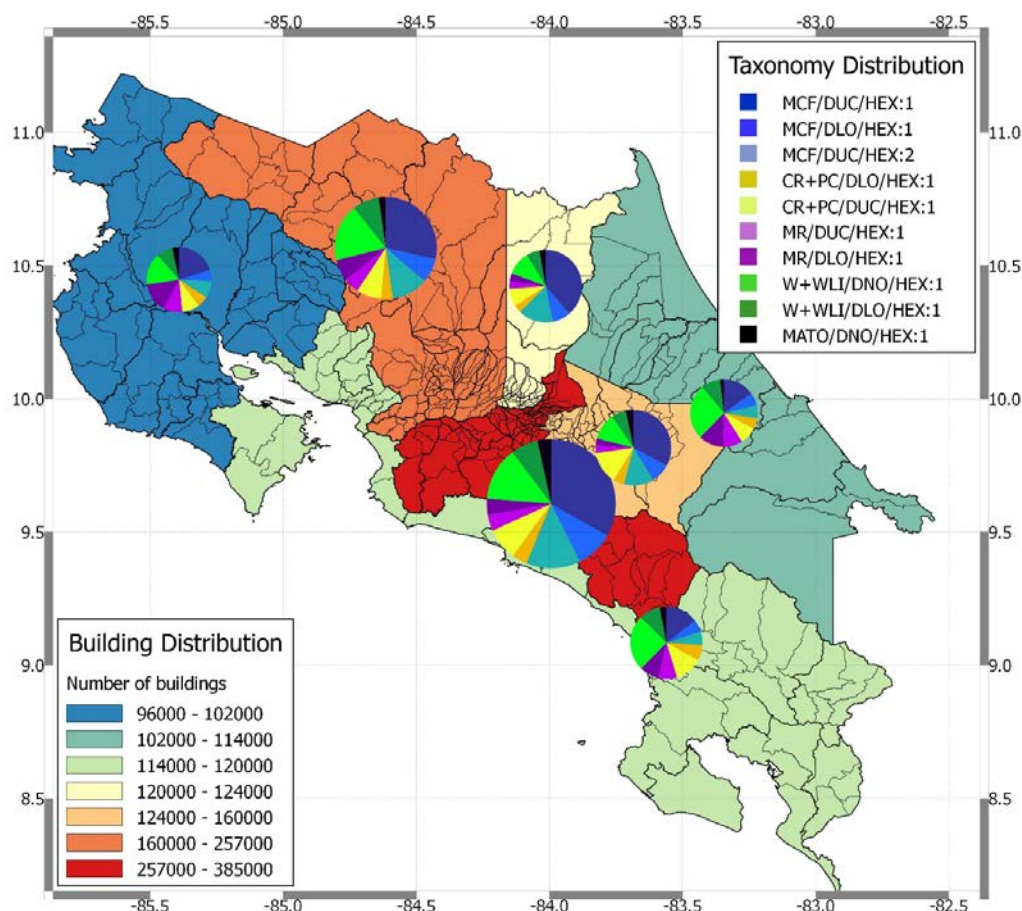


Figure 2-8: Simplified Exposure Model. Building classes are aggregated by province for visual clarity.

2.5 Remarks on the Exposure Model

The map on Figure 2-8 shows that provinces comprising the Great Metropolitan Area of Costa Rica, which are San José, Alajuela, Cartago and Heredia, have more than 50% of the buildings on confined masonry typologies and the highest concentration of low quality construction. The outer provinces of Limón, Guanacaste and Puntarenas, have much less confined masonry but much more reinforced masonry, wood and precast concrete buildings.

Good correlation of the results with reality is found on specific attribute definition. For example, the capitol districts of San Rafael de Escazú, San Pedro and La Merced exhibit the greatest concentration of high-rise buildings, like cast in place concrete of more than 6 storeys. Districts with low indices of social development in the Central Valley, like Los Guido and León Trece, present significant number of structures of low quality construction. The districts in the Talamanca Region, like Telire and Valle de la Estrella, show the biggest concentration of wood building classes, which is expected since they are located in the tropical rainforest where wood is the most accessible construction material.

As a general conclusion, census data and results from the exposure model presented in Figure 2-9 suggest that high rise building classes in Costa Rica still account for less than 5% of all the residential buildings in the country. Most homes are structures between one or two-storey, constructed post 1980 with seismic provisions and have ductile lateral load resisting systems, which directly contributes to lower risk indices in a region of elevated seismic hazard. This seems to be in accordance with the overall good performance of the residential stock has shown during the earthquakes occurred over the past four decades.

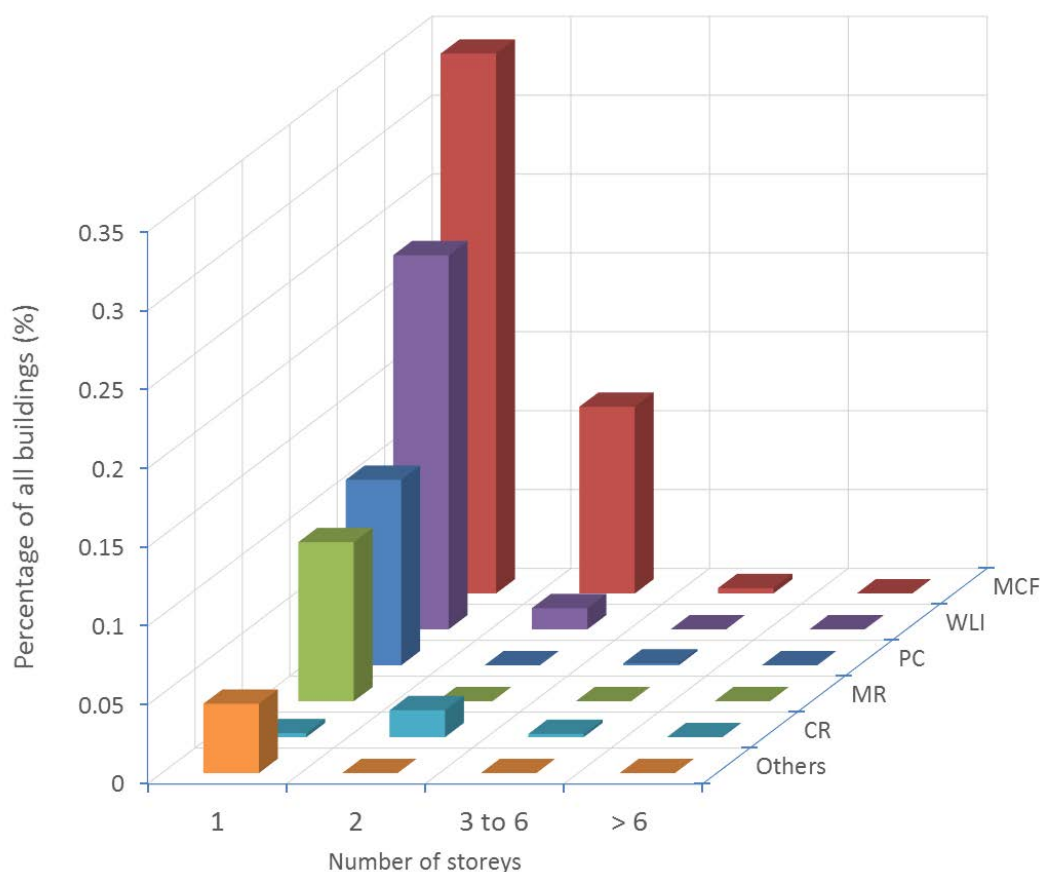


Figure 2-9: Height distribution per structural macro classes in Costa Rica. MCF, WLI, PC, MR and CR stand for Confined Masonry, Light Wood Sections, Precast Concrete, Reinforced Masonry and Reinforced Concrete respectively.

2.6 Limitations

A great amount of information was reviewed in order to define each building class. For the most common typologies, like reinforced masonry or precast concrete buildings, a substantial amount of data was successfully gathered from different private and governmental institutions in order to define attributes like the number of dwellings, year, quality of construction and building height. However, in the cases of the taller building classes (4 or more storeys), little to no information is being gathered in order to reliably identify and assign two specific attributes: height and dwelling-to-building conversion factors. Even though this uncertainty affects less than 8% of the known dwellings in the country, these characteristics were handled considering local expert opinion rather than actual data.

3 VULNERABILITY MODELS FOR RISK ASSESSMENT IN COSTA RICA

3.1 Introduction

This chapter covers the development of analytical vulnerability models for four of the most important building classes found in the exposure model. First, the definition of index buildings and components for analysis is explained, followed by the elaboration of structural models and the selection of the damage states. Then, the analysis type and its respective results are used to derive fragility functions for each building class. The selection of existing fragility functions for the remaining classes in order to complete the model is also explained and justified. The chapter concludes with the implementation of a consequence model and derivation of the whole set of vulnerability models for risk assessment in Costa Rica. All the steps were followed in accordance with the methodology present in the Guidelines for Analytical Vulnerability Assessment of low/mid-rise Buildings developed by D'ayala et al. [2014].

3.2 Selection of Models to Develop

The simplified exposure model presented on Figure 2-8 would require 10 vulnerability models for risk analysis. This investigation focused on the development of models for the confined masonry and precast concrete classes.

One and two-storey confined masonry ductile structures were chosen based on their importance on exposure, since they comprise more than 30% of the buildings in Costa Rica. Construction practices, design specifications and material qualities are quite standardized for these typologies, which allows modelling with reliable data for material behavior.

Precast concrete structures also have standardized construction practices and well-known materials because they are produced by a limited number of national manufacturers. It is believed that these structures perform similar to standard quality reinforced masonry houses. However, no experimental data was found on their inelastic behavior or analytical model proposals for the structural components. Therefore a simplified structural model was established for this building class. Two versions were developed, one with a lightweight roof structure and another one with a heavier roof, in order to evaluate the impact that typical shingle clay roofs have on the seismic performance.

3.3 Definition of Index Buildings and Component Selection

A single index building was selected to represent the median or typical case structure on the four building classes. The main reference for construction materials, construction quality, structural component dimensions, geometry and architecture were the Construction Prototypes prepared by the Federate Board of Engineers [CFIA, 2015] for the Costa Rican Central Bank. The prototypes main objective is to estimate the annual GDP on private construction. Each one is elaborated from a quarterly sampling process on projects registered by the CFIA, with a national coverage, and comprises the full characteristics of the construction including costs, architectural, structural, electrical and mechanical specifications of the each building class. The specific prototypes used for reference are presented in Figure 3-1, Figure 3-2 and Figure 3-3. Over 40 structural plans of individual housing buildings were also revised in order to validate standard material quality selection.

The components selected for analytical modelling were the ones considered to have a high vulnerability and contribution to the lateral load resisting system. In all three building classes this was an exterior wall.

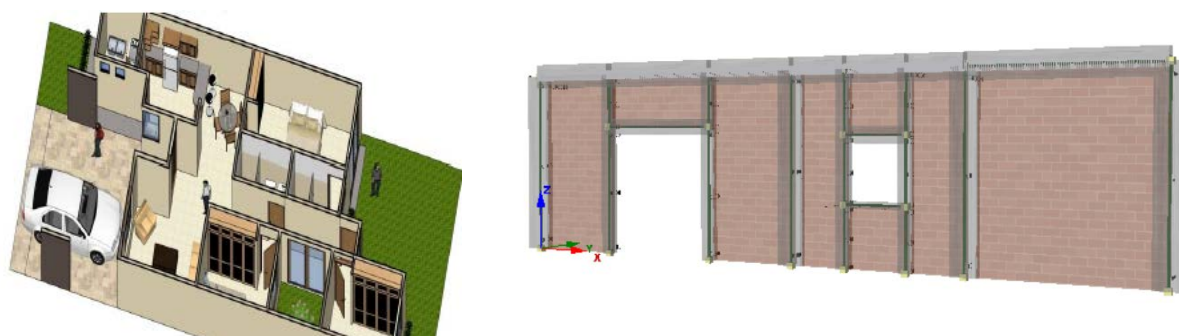


Figure 3-1: (On the left) One-storey reinforced masonry prototype. Source: CFIA Construction Prototypes [2015]. (On the right) Model of the vulnerable component.



Figure 3-2: (On the left) Two-storey reinforced masonry prototype. Source: CFIA Construction Prototypes [2015]. (On the right) Model of the vulnerable component.

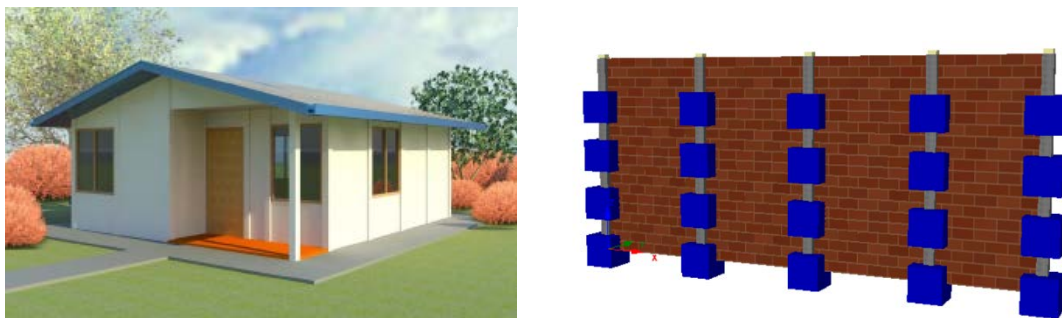


Figure 3-3: (On the left) Precast Concrete Prototype. Source: CFIA Construction Prototypes [2015]. (On the right) Model of the vulnerable component.

3.4 Model Type Selection

3.4.1 Masonry models

Analytical modelling was performed using the computer software developed by Seismosoft Ltd. [2015], SeismoStruct. For the confined masonry structures, the components are represented by strut and tie 2D models first developed by Crisafulli [1997] and implemented by Smyrou et al. [2011]. The inelastic infill panel element allows modelling the inelastic behavior by means of six strut elements, as presented in Figure 3-4. For each direction two diagonal struts carry axial loads from the corner nodes, while two struts capture the shear by activation on the direction of the compression.

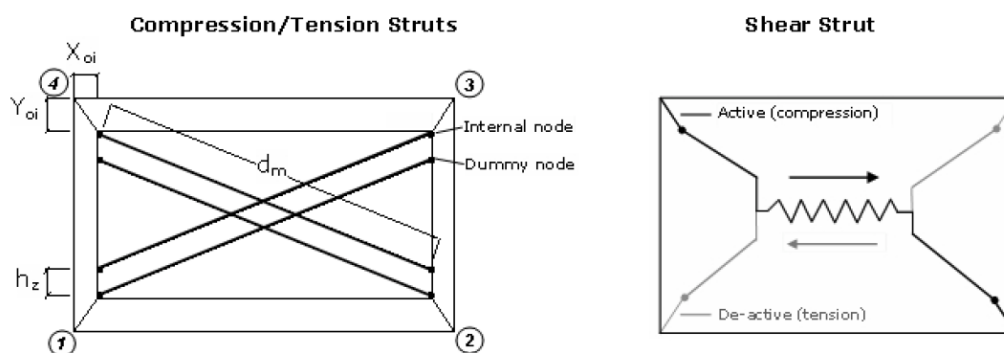


Figure 3-4: Strut and tie model of confined masonry. Source: SeismoStruct User Manual [2014].

Each strut possesses a dedicated hysteresis model whose characteristics are defined according to the material properties of masonry, preferably identified by experimental data. For the axial struts the main data requirements are presented in the left column of Table 3-1. The middle column shows the typical values used on strut and tie models. The column on the right presents the values used in the modelling of Costa Rican confined masonry.

For the shear struts, the main data requirements are presented in the left column of Table 3-2. The middle column shows the typical values used on strut and tie models. The column on the right presents the values used in the modelling of Costa Rican confined masonry.

The initial Young Modulus, compressive and shear bond strength are the main contributors to the strength and lateral stiffness of the panel. Hence the model is very sensitive to these parameters. There is experimental data on the compressive and shear bond strength of the Costa Rican concrete block masonry. According to the course on Advanced Construction Materials imparted in the University of Costa Rica [2014], shear stress resistance can be approximately derived if the compressive resistance of the masonry is known using expression 3.1. The shear bond resistance can also be approximately determined using the compressive resistance of the mortar with the expression 3.2. Both equations were developed by testing on masonry prisms and bed joints of different qualities, for units of kgf/cm².

$$f'm\theta = 0.0669 f'm + 2.9691 \quad (3.1)$$

$$\tau_o = 0.0596 f'mort + 3.2731 \quad (3.2)$$

The production of materials for the concrete masonry is regulated by minimum quality standards in Costa Rica. It is considered that variability of the masonry performance arises from the material quality of the block, mortar bond and grout, as well as construction practices and level of inspection. Based on these factors, masonry is classified in three classes: A, B and C.

Exposure indicates that masonry building classes have a wall lateral load resisting system in good condition and their age of construction is post 1980. This suggests that the building population has seismic provisions and a medium to high quality of mason work. Therefore class B masonry and type S mortar quality parameters were used for the one story and two story wall models.

The concrete frames were modelled using force-based plastic hinge frame elements, with a dedicated hysteretic model for concrete and steel. According to the Costa Rica Seismic Code [2010] provisions, masonry confining elements must be provided at least with established minimum confinement and longitudinal reinforcement. Steel must be ASTM-A706 [ASTM, 2001] compliant and concrete must have at least a 21 MPa of compressive strength after 27 days. Therefore, a standard uniaxial bilinear stress strain model with strain hardening was chosen for the hysteresis of the steel. For the confined concrete, the Mander et al. [1988] model was selected.

Table 3-1: Mean axial strut curve properties for confined masonry hysteretic behavior. Source of typical values is SeismoStruct Manual [2014].

Axial Strut Curve Parameters		Typical values	Used values
Initial Young Modulus (KPa)	E_m	$400f'_m\theta - 1000f'_m\theta$	274400
Compressive strength (KPa)	$f'_m\theta$	theoretical or experimental	686
Tensile strength	f_t	-	0
Ultimate strain (m/m)	ϵ_u	0.001 - 0.005	0.002
Closing Strain (m/m)	ϵ_d	-	0.04
Strut area reduction strain (m/m)	ϵ_1	0 - 0.0003	0.0008
Residual strut area strain (m/m)	ϵ_2	0.0003 - 0.008	0.0015
Starting unload stiffness factor	γ_{un}	0.0006 - 0.016	1.5
Starting reloading factor	α_{re}	1.5 - 2.5	0.2
Strain inflection factor	α_{ch}	0.2 - 0.4	0.7
Complete unloading strain factor	β_a	0.1 - 0.7	1.5
Stress inflection factor	β_{ch}	1.5 - 2.0	0.9
Zero stress stiffness factor	γ_{plu}	0.5 - 0.9	1
Reloading stiffness factor	γ_{pr}	-	1.5
Plastic unloading stiffness factor	ϵ_{x1}	-	3
Repeated cycle strain factor	ϵ_{x2}	-	1.4

Table 3-2: Mean shear strut curve properties for confined masonry hysteretic behaviour. Source of typical values is SeismoStruct Manual [2014].

Shear Strut Curve Parameters		Typical values	Used values
Shear bond strength (KPa)	τ_o	100-1200	745
Friction coefficient	μ	0.1-1.2	0.4
Maximum shear strength (Kpa)	τ_{max}	-	1062
Reduction shear factor	α_s	1.4 - 1.65	1.4

3.4.2 Precast concrete models

The precast concrete wall system is produced by national manufacturers [Productos de Concreto, 2002]. It combines the use of small concrete columns, usually 12 cm by 12 cm, with 3.6 cm thick concrete panels. These elements assemble through male-female connections to create wall partitions that are 2.5 m high. The columns are prestressed and reinforced with a single steel tendon, 7.1 mm in diameter and ASTM A-421 [ASTM, 2015] compliant. Compressive strength of concrete ranges around 31 MPa.

For the modelling of this building class simplified 2D elastic elements were used in combination with discrete plasticity rotational springs. The springs were distributed along the height of the columns and have the trilinear moment curvature relationship, presented in Figure 3-5. It was assumed that these walls are more vulnerable in the out of plane direction, therefore the wall panel contribution of lateral stiffness was not considered in the analysis.

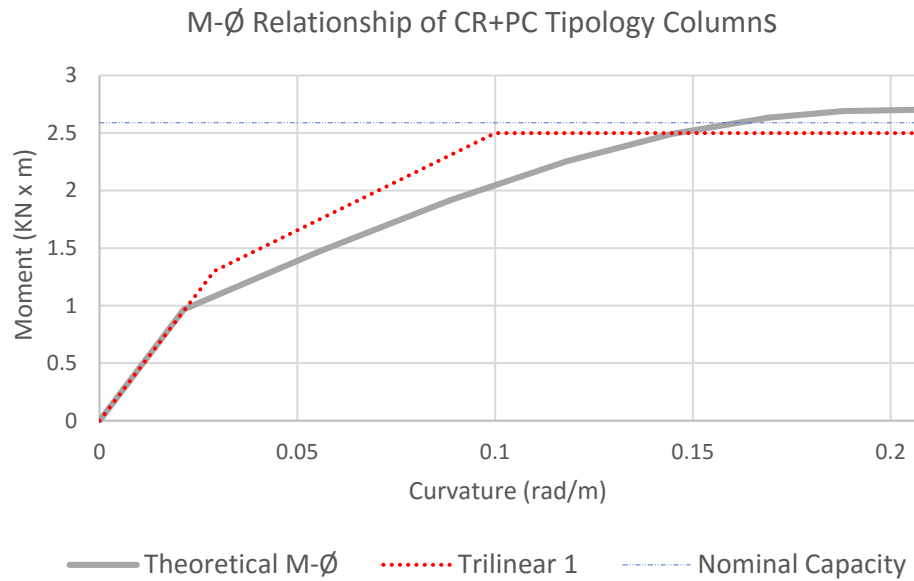


Figure 3-5: Precast column nominal capacity and moment-curvature relationship for plasticity.

3.5 Definition of Damage States

Four damage states have been defined for the fragility assessment. To define when a structure would enter any given damage state, Static Adaptive Pushover Analysis was performed on the models and four damage thresholds were proposed for each one. Inter-storey drift was selected as the engineering demand parameter to be monitored from the pushover response of the structure. The thresholds chosen for each state are the ones proposed by Villar et al. [2016] in the development of a fragility model for South America, presented in Table 3-3. On the table Sd_y is the spectral yield displacement and Sd_u the spectral ultimate displacement of the structure. The capacity curves obtained for the masonry and precast concrete models are presented together with the limit states in Figure 3-6 and Figure 3-7.

Table 3-3: Damage criterion used for thresholds. Taken from Villar et al. [2015]

Damage State	Threshold
Slight	$0.7 Sd_y$
Moderate	$0.75 Sd_y + 0.25 Sd_u$
Extensive	$0.5 (Sd_y + Sd_u)$
Collapse	Sd_u

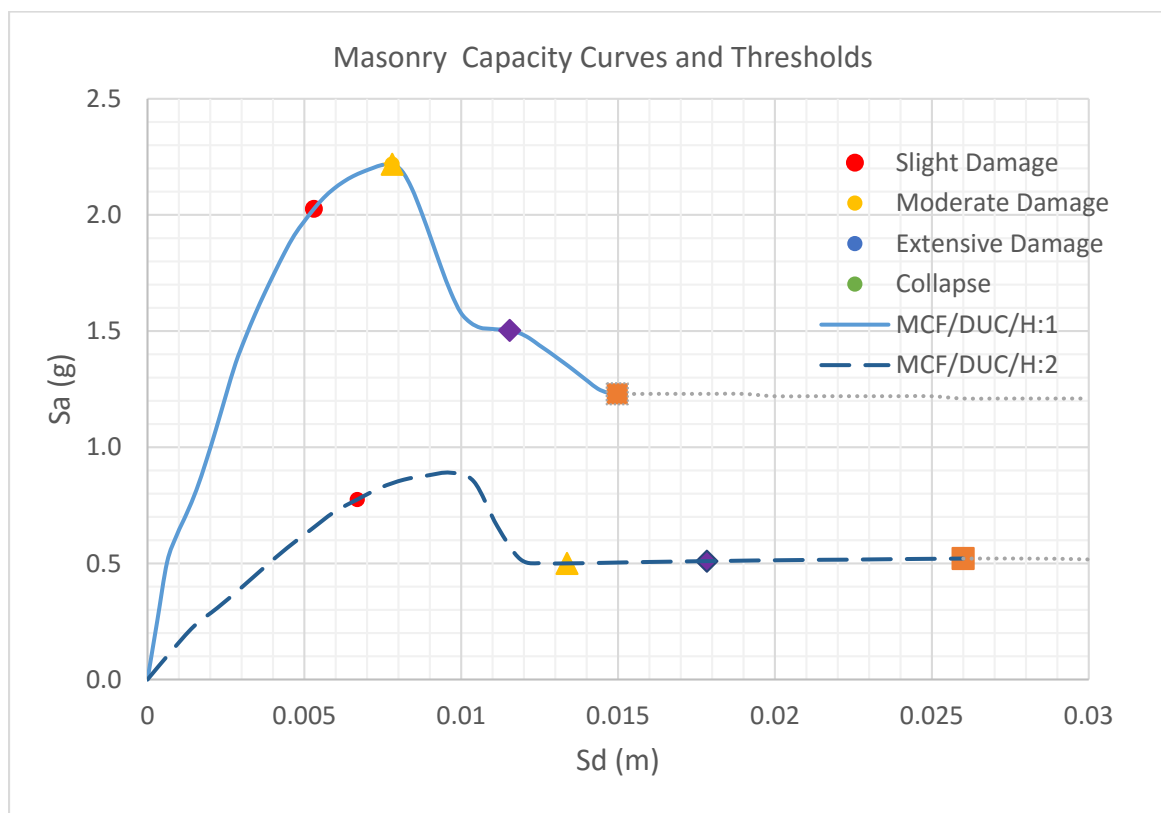


Figure 3-6: Capacity curve of masonry models and thresholds.

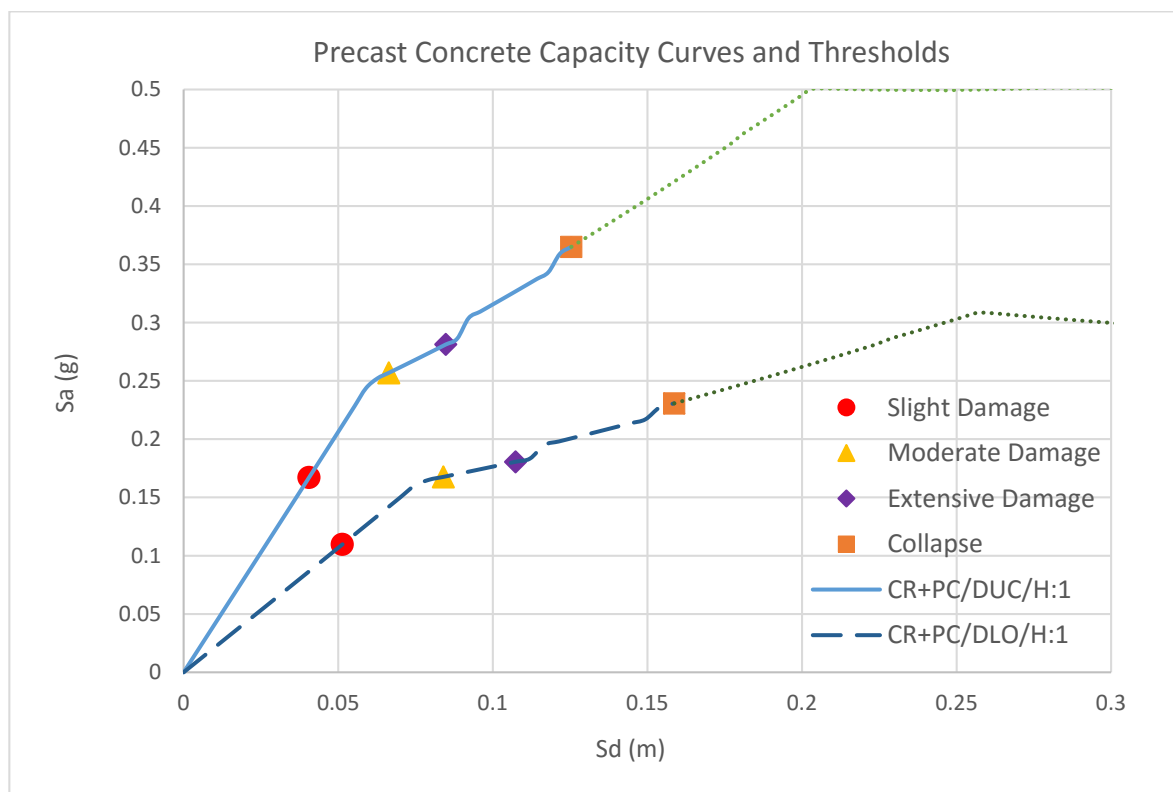


Figure 3-7: Capacity curve for the precast concrete models and thresholds.

3.6 Dynamic Analysis and Fragility Derivation

For the non-linear time history analyses, a Multiple Stripe Analysis (MSA) approach was adopted. Several sets of ground motion records were taken from the PEER (Pacific Earthquake Engineering Research) database, considered to be representative of the tectonic regimes found in Central America. Depending on the model, 8 to 10 sets ground motions were used. Each of these sets contains 30 ground motion records. The maximum interstorey drift on the structures was captured on each iteration and plotted against an increasing intensity measure level, as presented in Figure 3-8 for the one-storey confined masonry building class.

It was possible to derive fragility functions from the MSA results by treating every exceedance of a limit state in a statistical model. For each intensity measure, the probability of the structure reaching a damage level was taken as the fraction of analysis causing drifts that surpassed its limit state. Continuous functions were derived by regression analysis of the set of points obtained in this way. A lognormal distribution was assumed, with logarithmic mean and logarithmic standard deviation determined using the least squares method. Figure 3-9 shows the MSA results and the derived continuous vulnerability model of the one-storey confined masonry building class. Figure 3-10 shows the final continuous functions for the rest of the models.

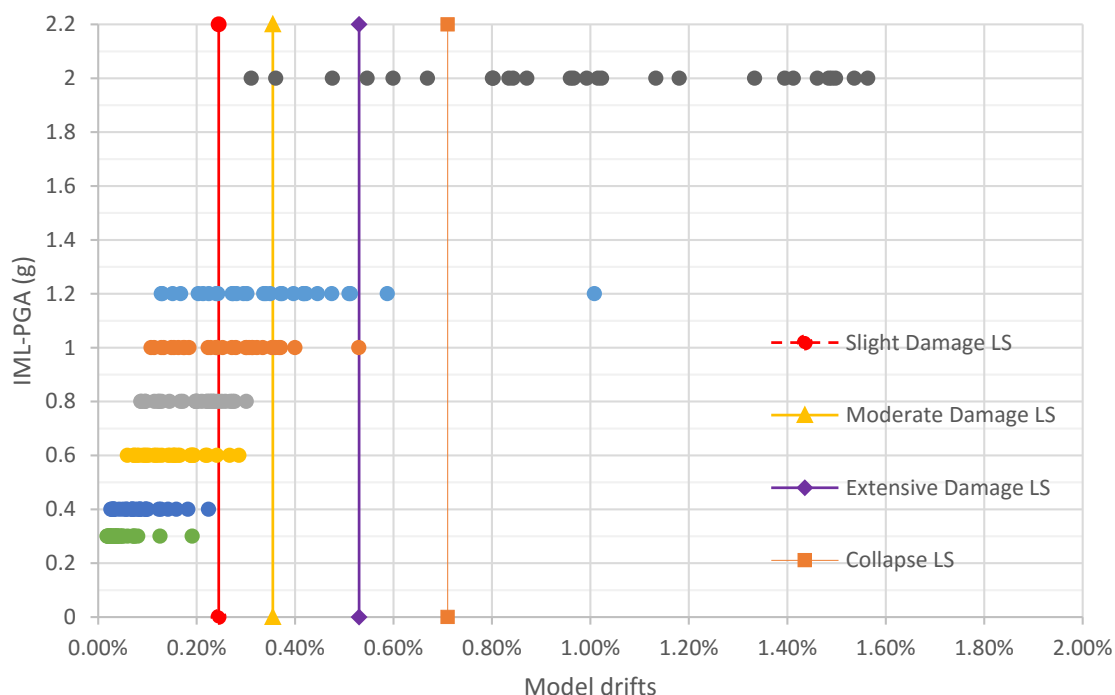


Figure 3-8: MSA results for the confined ductile one storey building class.

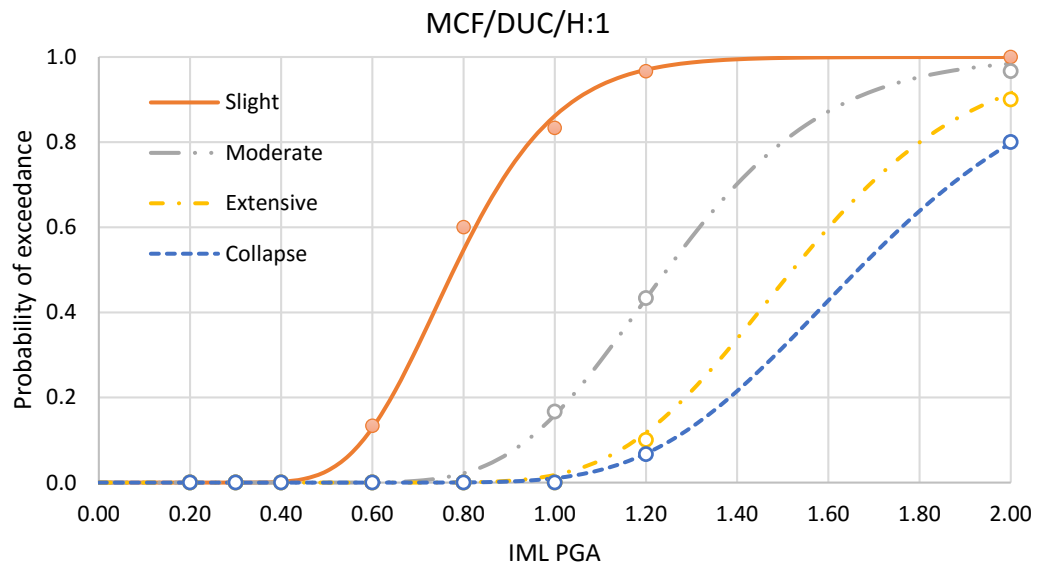


Figure 3-9: Continuous fragility function for the confined ductile one storey building class

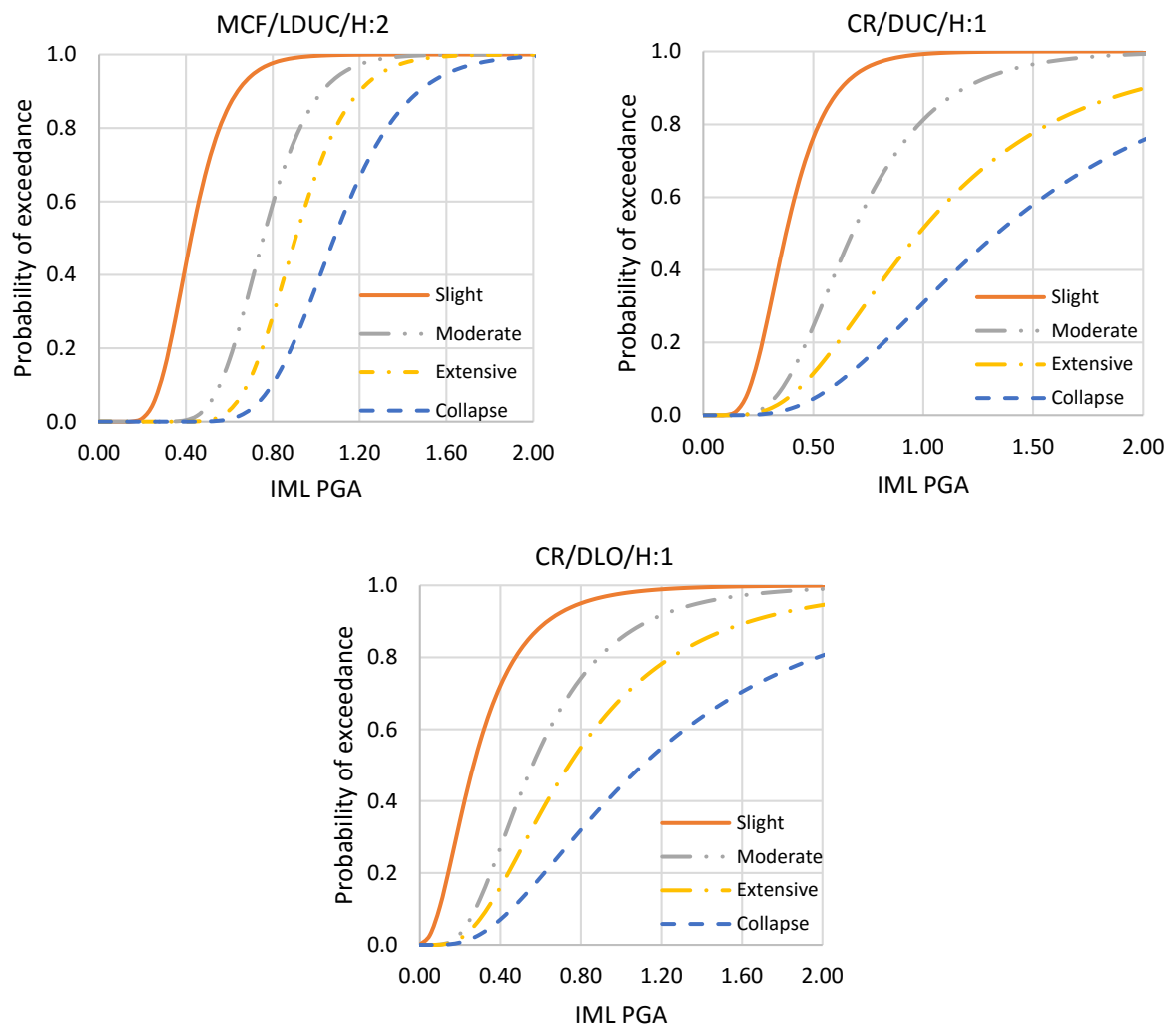


Figure 3-10: Fragility models for the rest of masonry and precast concrete buildings classes.

The development of these fragility functions was performed for the four top building classes. For the remaining building classes found in the exposure model, fragility models developed by Villar et al [2016] were adopted. These functions were proposed and used for the South American Risk Assessment Project supported by the GEM Foundation [2016]. They are considered appropriate for risk assessment in Costa Rica under the assumption that the medium to low quality typologies are not significantly different from the ones found in the Andean countries. Final fragility model assignment and fragility model lognormal parameters are presented in Table 3-4 and Table 3-5 respectively.

Table 3-4: Building classes and corresponding fragility models.

Exposure Model	Assigned Fragility Models	
Taxonomies	Fragility Function	Source
MCF/DUC/HEX:1	MCF/DUC/H:1	Developed for C.R.
MR/DUC/HEX:1		
MCF/DUC/HEX:2	MCF/DUC/H:2	Developed for C.R.
MCF/DLO/HEX:1	MCF/DNO/H:1	SARA Project [GEM Foundation, 2015]
MR/DLO/HEX:1		
W+WLI/DLO/HEX:1	W+WLI/H:1/DUC	
MATO/DNO/HEX:1	UNK	
W+WLI/DNO/HEX:1		
CR+PC/DUC/HEX:1	CR+PC/DUC/H1	Developed for C.R.
CR+PC/DLO/HEX:1	CR+PC/DLO/H1	Developed for C.R.

Table 3-5: Lognormal mean (λ) and standard deviation (ζ) of the fragility functions.

Exposure Model	Fragility Models							
	Slight		Moderate		Extensive		Collapse	
Taxonomies	λ	ζ	λ	ζ	λ	ζ	λ	ζ
MCF/DUC/HEX:1	-0.25	0.21	0.22	0.22	0.42	0.22	0.51	0.22
MR/DUC/HEX:1	-0.25	0.21	0.22	0.22	0.42	0.22	0.51	0.22
MCF/DUC/HEX:2	-0.86	0.21	-0.28	0.24	-0.10	0.24	0.08	0.32
MCF/DLO/HEX:1	-0.81	0.36	-0.02	0.41	0.16	0.41	0.44	0.48
MR/DLO/HEX:1	-0.81	0.36	-0.02	0.41	0.16	0.41	0.44	0.48
W+WLI/DLO/HEX:1	0.12	0.43	1.20	0.74	1.76	0.82	2.88	1.15
MATO/DNO/HEX:1	-0.70	0.35	-0.20	0.42	-0.04	0.42	0.22	0.42
W+WLI/DNO/HEX:1	-0.70	0.35	-0.20	0.42	-0.04	0.42	0.22	0.42
CR+PC/DUC/HEX:1	-0.98	0.40	-0.39	0.44	-0.02	0.56	0.29	0.58
CR+PC/DLO/HEX:1	-1.15	0.55	-0.58	0.60	-0.31	0.62	0.10	0.69

3.7 Damage-to-loss model and vulnerability derivation

The intensity measure level was correlated to physical structural loss through the use of a damage-to-loss model. The final values presented in Table 3-6 are the result of a calibration analysis done for Costa Rica after several risk assessment iterations. These ratios are considered to correlate appropriately with the limit state thresholds and the expected level of physical damage they represent.

Table 3-6: Consequence model for loss estimation.

Consequence Model	
Damage State	Loss Ratio
Slight Damage	0.05
Moderate Damage	0.25
Extensive Damage	0.60
Collapse	1.00

A set of vulnerability functions were developed by combining the derived fragility functions with the cumulative cost of each proposed damaged state.

Vulnerability can be expressed as the product between the resulting losses once a damage state occurs times the probability of a building sustaining that damage state. By summing this probability relation for the four damage states considered, the mean vulnerability of the building class can be obtained, expressed mathematically on Equation 3.3:

$$E(C|im) = \sum_{i=0}^n E(C|ds_i) \times P(ds_i|im) \quad (3.3)$$

On the expression $E(C|im)$ is the mean loss ratio of the building class, while $E(C|ds_i)$ is the loss when a given damage state is reached. $P(ds_i|im)$ is the probability of reaching that damage state under a given intensity measure level. The resulting set of vulnerability functions is presented in Figure 3-11.

3.8 Remarks on fragility models

The development of the fragility models presented herein was an iterative process. For the masonry models, reliable evaluation of the nonlinear behavior required achieving first an acceptable prediction for the capacity of a single squat wall subjected to shear, and then proceed to the elaboration of the more complex 2D models, since no experimental data on inelastic behavior for the Costa Rican masonry was available. The initial nonlinear time history analyses indicated that ground motion records scaled to PGA of 1.0 g were not sufficient to generate the collapses. Therefore, the records had to be linearly scaled in order to capture failure of the structures. In both cases the failure criteria was the shear failure of any of the main infill masonry panels in the model. The final results obtained for the one and two-storey ductile masonry building classes were considered satisfactory based on the expected performance of these classes. According to the obtained fragility models, buildings do not show significant chance of sustaining any damage for PGA values under 0.2 g. In terms of collapse, no failures

occurred for PGA values up to 0.6 g and 1.0 g for the one story and two story structures, respectively. This seems to be in accordance with the performance they should exhibit, since they are assumed to be designed with provisions from the Costa Rican seismic codes. Typical design PGA values in the codes for lateral load estimations range from 0.36 g to 0.42 g, for medium to high seismic hazard zones.

For the precast concrete models, the wall panel-column elements exhibited great flexibility in the out of plane direction. The precast concrete column however did not fail under excessive chord rotations. Therefore, failure criteria had to be based on the expected damage in other structural components under excessive displacement, like the roofing structure. According to the obtained fragility model, these structures have a significant probability of achieving slight damage from PGA values of 0.1g and above. Collapses do not occur for PGA values below 0.25 g and 0.36 g for the low ductility and high ductility models respectively. Since these structures have been identified to be constructed after the eighties, only the high ductility houses seem to perform according to the main of seismic provisions. In this regard, they seemingly perform like medium quality reinforced masonry structures, as it is commonly believed.

3.9 Limitations

The main limitation on the development of vulnerability models is the time available for analytical studies. For this study, a two dimensional simplification of a single index building was implemented for structural analysis, in order to be able to analyze at least three building classes using non-linear structural models. A fourth model was developed by simply changing the roof weight on the structure to quantify the influence of a heavy roof on the precast building taxonomy.

Development of analytical models for the confined masonry required the use of strut and tie models in order to capture the inelastic behavior of these structures. In Costa Rica, the characteristics of the average structural properties of these typologies are very well known, and therefore development of such analytical models is possible. However, the lack of available experimental data on which several model parameters rely on became another important limitation in the procedure.

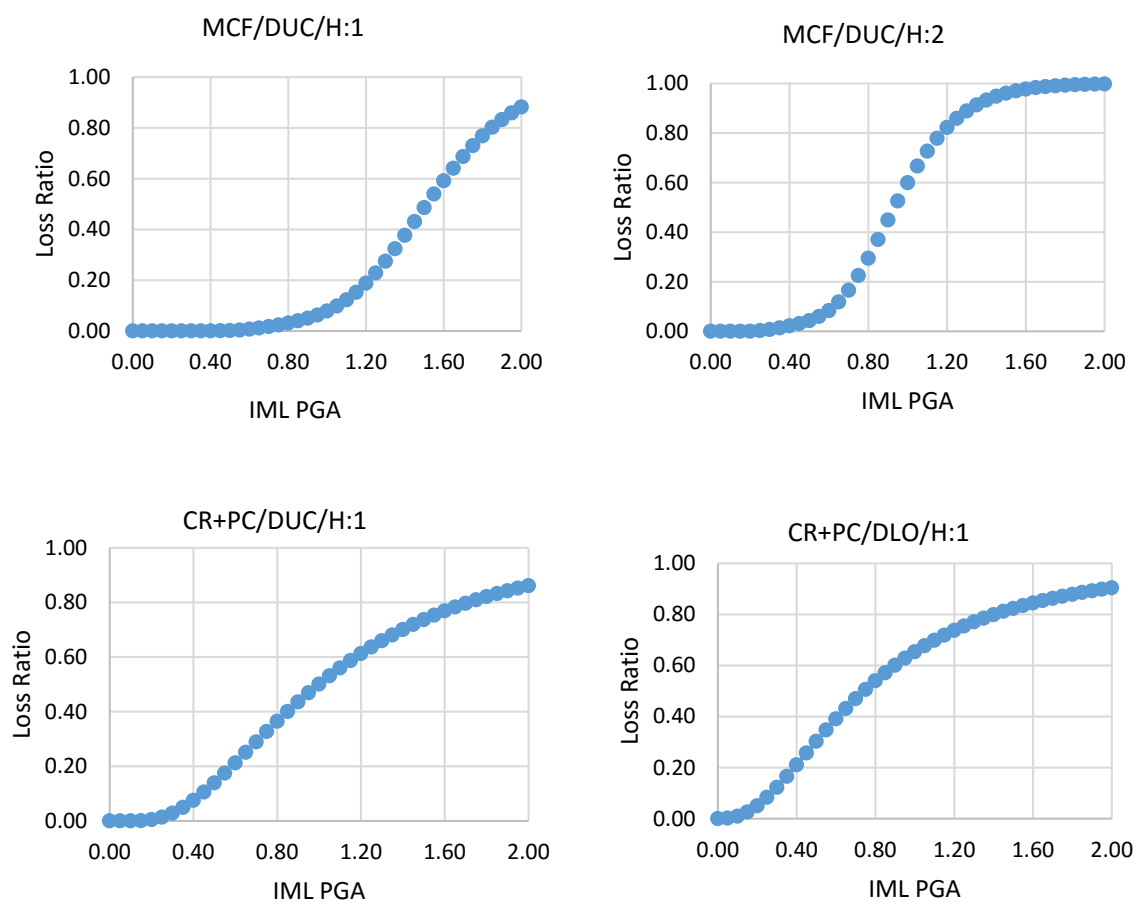


Figure 3-11: Discrete vulnerability curves for the top four building classes in Costa Rica.

4 MODEL IMPLEMENTATION AND RISK ANALYSIS

4.1 Introduction

This chapter briefly explains the implementation of the hazard, vulnerability and exposure models in the OpenQuake-engine [GEM, 2016] used for seismic risk analysis. Focus is given to the seismic hazard and the reproduction of the model proposed in the RESIS II project for Costa Rica. It is complemented with the presentation of a site model to consider seismic amplification due to local soil conditions. A short mention on the exposure and vulnerability inputs for OpenQuake is included. The chapter concludes with the analysis type, methodology and parameters used in the risk calculations for Costa Rica.

4.2 Hazard Implementation

The 2010 RESIS II Seismic Hazard Model for Central America was developed by a team of experts from Costa Rica, Nicaragua, Guatemala, Honduras, El Salvador, Panama, Spain and Norway [Climent et al., 2008]. It was adapted and implemented in the OpenQuake platform so it can directly be used for risk analysis by the GEM Foundation [GEM, 2015].

On the original RESIS II project, hazard was obtained through classical probabilistic analysis methodologies. A single regional catalogue was achieved, updated and complete with 29,700 events of moment magnitude 3.5 and above, and three types of zones (cortical, subduction interplate and subduction intraplate) were established. In terms of attenuation functions, 8 models that best fitted regional data were selected for analysis, concluding that Climent et al. [1994] and Zhao et al. [2006] were the most appropriate for cortical zones, Spudich et al. [1999] for interplate tectonic regimes, and Zhao et al. [2006] together with Spudich et al. [1999] for intraplate zones.

For this study, the implementation of this model performed by the GEM foundation [GEM, 2015] for Central American was filtered to focus computation efforts on the continental territory of Costa Rica. Results obtained for a return period of 500 years, presented in Figure 4-1, indicate that maximum hazard is found on the country's central volcanic chain, with expected PGA of 0.52 g for the capital city of San José. This value decreases on parallel zones towards the Caribbean coast below 0.31 g. The outputs obtained from the OpenQuake-engine exhibit great correlation with the original national hazard model.

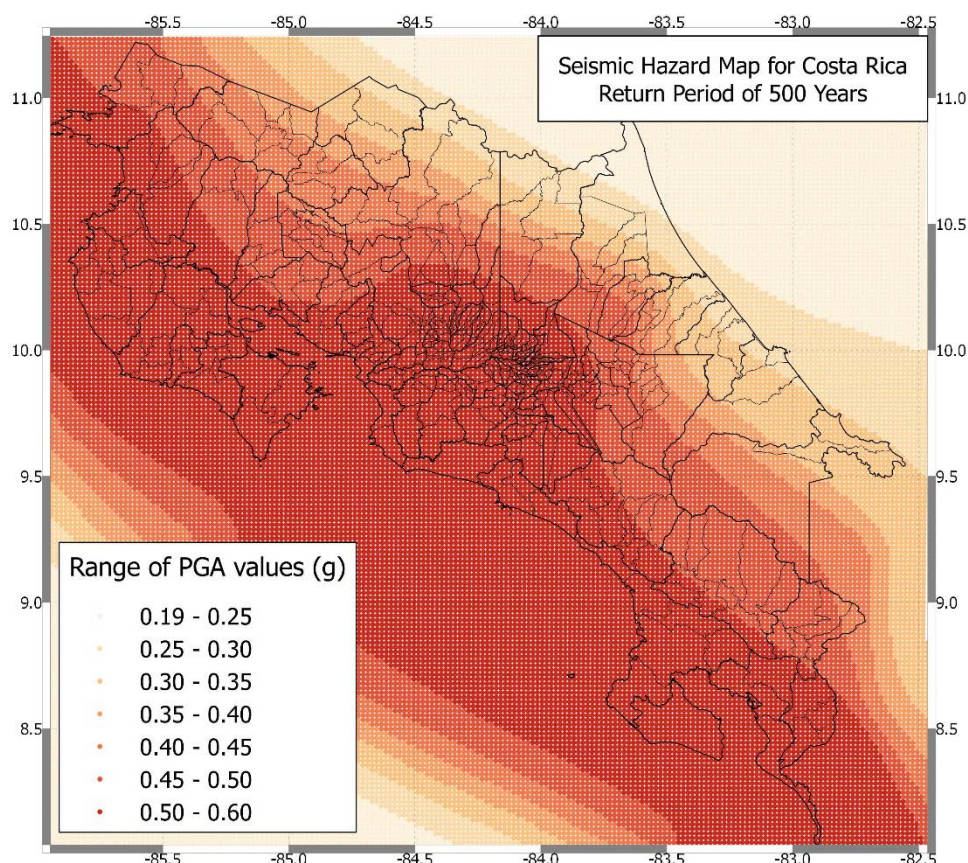


Figure 4-1: Hazard map for a return period of 500 years obtained for Costa Rica.

Poor estimation of site effects can introduce significant errors in seismic risk results [Silva et al. 2014]. To accurately consider seismic amplification due to soil conditions, a site model was implemented using V_{s30} values. The V_{s30} parameter is the average velocity of the shear wave between 0 and 30 meters of ground depth. The OpenQuake-engine is capable of estimating motion amplification from the attenuation models in the sites where V_{s30} data are available. Therefore, a 5km x 5km mesh was created using the USGS Custom V_{s30} mapping tools, containing velocities ranging from 760 m/s to 180 m/s. The parameters, presented in Figure 4-2, are obtained using the simplified methodology proposed by Wald and Allen [2007], which uses medium to high resolution slope topography to obtain proxy V_{s30} values.

4.3 Exposure and Vulnerability Implementation

The exposure and vulnerability models were adapted to be used by OpenQuake using the Input Preparation Toolkit developed by the GEM Foundation [GEM, 2015]. There are a total of 472 sites where risk assessment is performed, with 4702 residential assets. The vulnerability models were imputed as 10 discrete functions with 100 ordinates each. Model inputs were revised using the validation tool of the OpenQuake-engine.

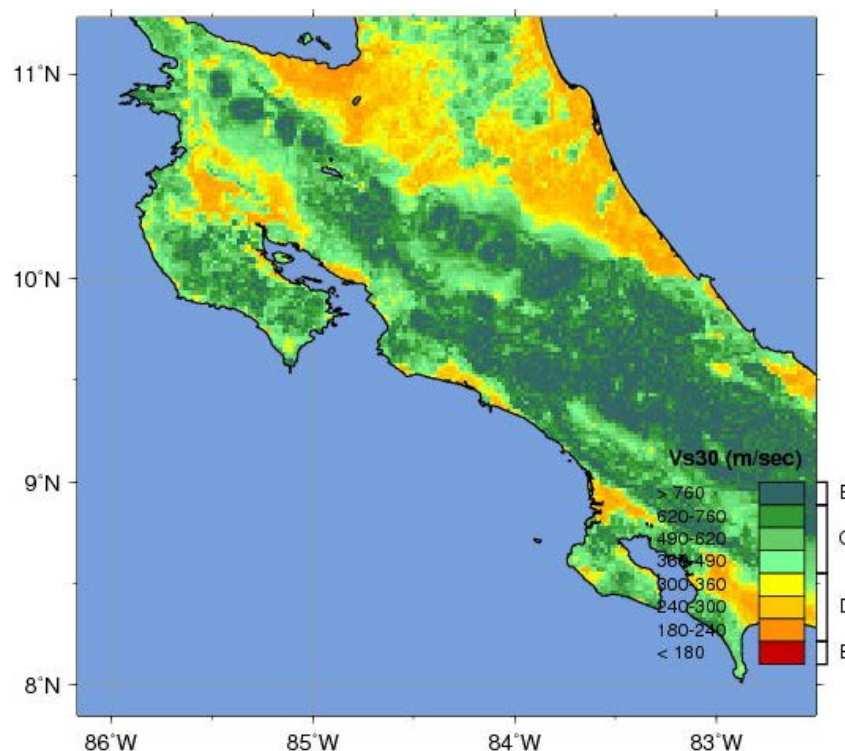


Figure 4-2: Site model for Costa Rica using Vs30 values. Source: USGS Vs30 Mapping Tool.

4.4 Event Based Risk Analysis for Costa Rica

Earthquake loss assessment by means of average annual losses and maximum probable loss requires a probabilistic event-based approach.

The OpenQuake calculator first uses the hazard source model to generate several stochastic event sets. For risk assessment in Costa Rica, a total 100,000 events sets were generated, each with an investigation time of one year. Each event was used to calculate a ground motion field. Then, the vulnerability function assigned to each asset is used to derive the loss ratio based on the mean ratios defined for each intensity measure. The average annual loss is obtained by annualizing the total amount of economic losses registered in the total time span (i.e. 100,000 years) of the analysis. The maximum probable loss curve is built by assuming a Poissonian distribution of the occurrences.

4.5 Remarks on Model Implementation

Concerning the hazard model, results indicate that if a standard PGA value of 0.2 g is used to define the amount of capital stock at risk in Costa Rica, basically the entire residence sector is susceptible to suffer losses. Moreover, according to the site model in Figure 4-2, districts with the biggest concentration of buildings, like the ones comprising the Great Metropolitan Area of the Central Valley and the provincial capital cities of Limón, Puntarenas and Liberia, will be subjected to ground motion amplification due to soft soils. This combination of high seismicity and unfavorable exposure has direct negative impact on the country's potential for economic loss.

4.6 Limitations

The risk analysis takes into account the amount of residential assets estimated to exist in the country using the 2011 National Housing Census [INEC, 2011] and the 472 administrative regions where they were registered by that time. No consideration for the increase in buildings since 2011 to the present date was undertaken in order to exclude additional uncertainties from the risk results.

5 RISK ASSESSMENT FOR COSTA RICA

5.1 Introduction

This chapter contains the results of the seismic risk assessment for Costa Rica. Several outputs are presented and discussed, like annual average loss ratios and annual average economic losses, which are presented disaggregated per building class and aggregated at a district and national scale. It discusses the elaboration of the Probable Maximum Loss Curve for the country in the format of economic losses and associated return periods. A risk profile for the residential stock is proposed with remarks about its final results and their respective uses. The section concludes with a small discussion about potentially insured building classes and their influence in risk assessment.

5.2 Stochastic Event Sets

In order to estimate variability in the results of risk assessment, ten sets of ten thousand stochastic events were produced and analyzed separately. The magnitude for some sets ranged from Moment Magnitude 5.5 to 7.95. Figure 5-1 maps the resulting ruptures from one of the analysis sets. Generation of ruptures and their respective magnitude is evidently larger in the Pacific Coast of the country, where subduction regimes and complex fault sources are located. The amount of events decreases significantly outside the Central Valley and rupture generation is much seldom along the Caribbean Coast. This tendency is evident in all the analysis sets.

For each set, all the ruptures that caused economic losses were sorted by damaged assets, annual rate of exceedance and return period. Estimations of loss ratios and average annual losses are the mean values resulting from the ten analyses. For completeness, the final Probable Maximum Loss Curve takes into account the whole set of analysis and shows expected losses for a return periods up to 100,000 years.

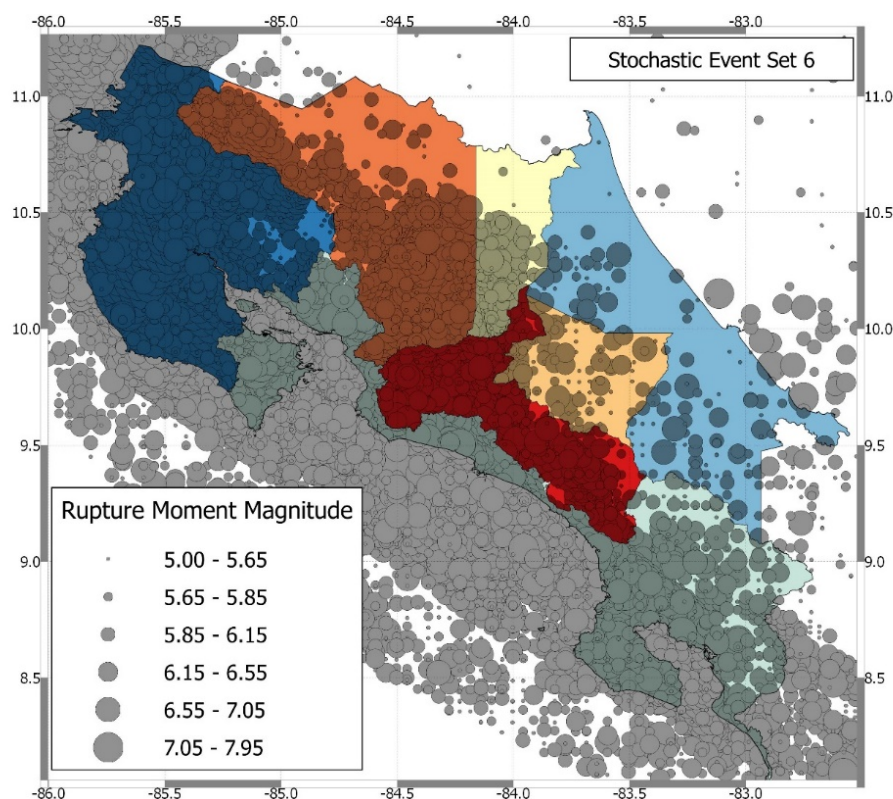


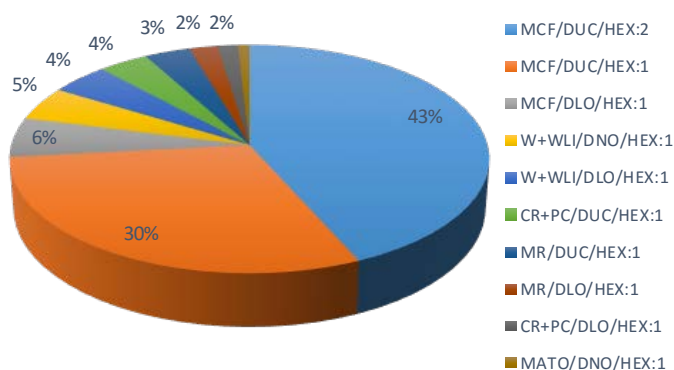
Figure 5-1: One of the stochastic event sets used in event based risk assessment for Costa Rica.

5.3 Average Annual Loss Ratios

Table 5-1 shows the distribution of stock value for the residential assets estimated using national exposure model. According to the results, Costa Rica has a residential capital stock of approximately \$76,000 USD millions. Around 85% of the total stock is comprised of reinforced masonry structures, the rest is evenly distributed among individual houses made of wood and precast concrete, with a minor percentage of value on low quality housing.

Table 5-1: Residential Capital Stock distribution for Costa Rica

Taxonomy	Stock Value
MCF/DUC/HEX:2	\$ 32,864,191,166
MCF/DUC/HEX:1	\$ 22,763,456,800
MCF/DLO/HEX:1	\$ 4,272,123,265
W+WLI/DNO/HEX:1	\$ 3,620,321,252
W+WLI/DLO/HEX:1	\$ 3,371,394,656
CR+PC/DUC/HEX:1	\$ 2,878,738,937
MR/DUC/HEX:1	\$ 2,639,992,017
MR/DLO/HEX:1	\$ 1,621,705,905
CR+PC/DLO/HEX:1	\$ 1,184,399,639
MATO/DNO/HEX:1	\$ 654,325,758
Capital Stock	\$ 75,870,649,395



Once losses have been annualized, it is possible to obtain average annual loss ratios (AAL Ratios) by taking the resulting economic loss reported by the building classes and dividing it by the stock value of each class.

For Costa Rica, the estimated loss ratios are presented disaggregated by taxonomy in Figure 5-2. The calculated values suggest that even though a great share of the capital stock is concentrated in masonry building classes, these actually lost the smallest portion of their value due to earthquakes. Ductile masonry structures that are two-storey high possess the highest loss ratio of all the masonry structures, but nevertheless it is still significantly smaller than the less ductile, low quality wood, waste and precast concrete material taxonomies.

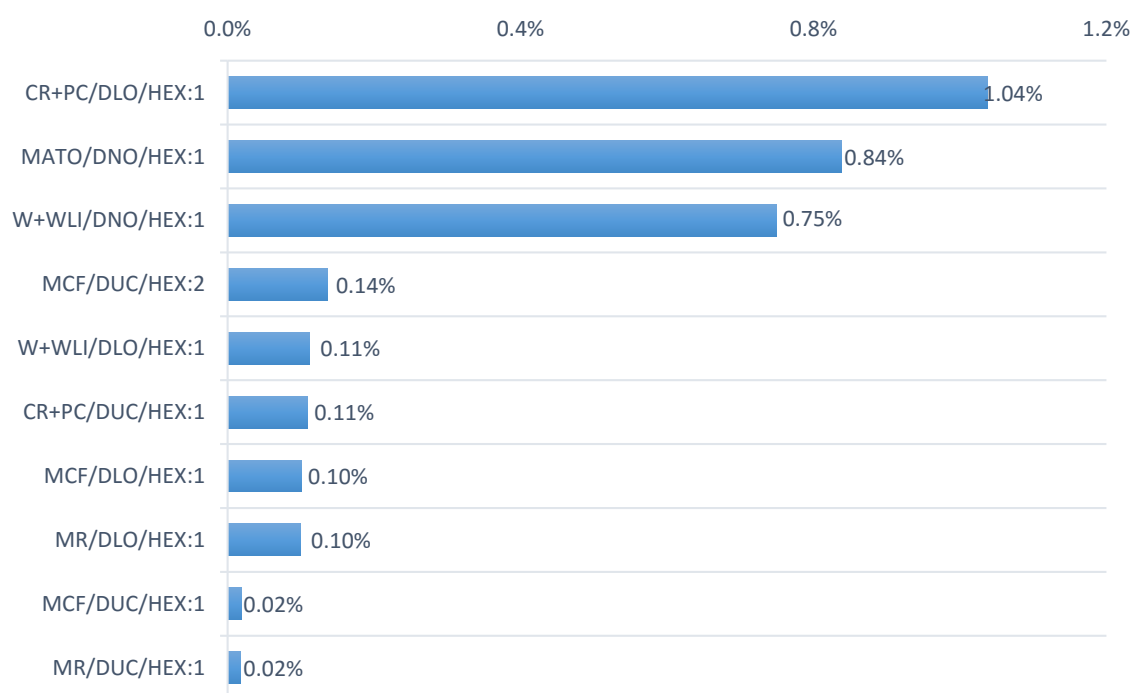


Figure 5-2: AAL Ratios disaggregated by taxonomy.

AAL Ratios are obtained by adding the economic losses reported from the building classes and dividing it by the capital stock value of a district, or the total capital stock value of the country. Average AAL ratios at a district scale were calculated for Costa Rica and are mapped on Figure 5-3. The map shows that districts along the Pacific Coast have the highest loss ratios found on the national territory. Isla de Chiriquí, Parrita, Savegre and Pavones possess estimated loss ratios up to 0.50%, which is significantly large and suggests they have the greatest earthquake vulnerability of the country. Farther northeast loss ratios reduce significantly in most districts present on the Central Valley, with a mean value around 0.12%. Urúca, Cinco Esquinas, San Francisco, Hospital and Los Guido are the most vulnerable districts of the Great Metropolitan Area, with ratios around 0.15% and 0.20%. The closer to the Caribbean Coast, the lower the loss ratio values are. For example, the Port City of Limón has a loss ratio of 0.03%.

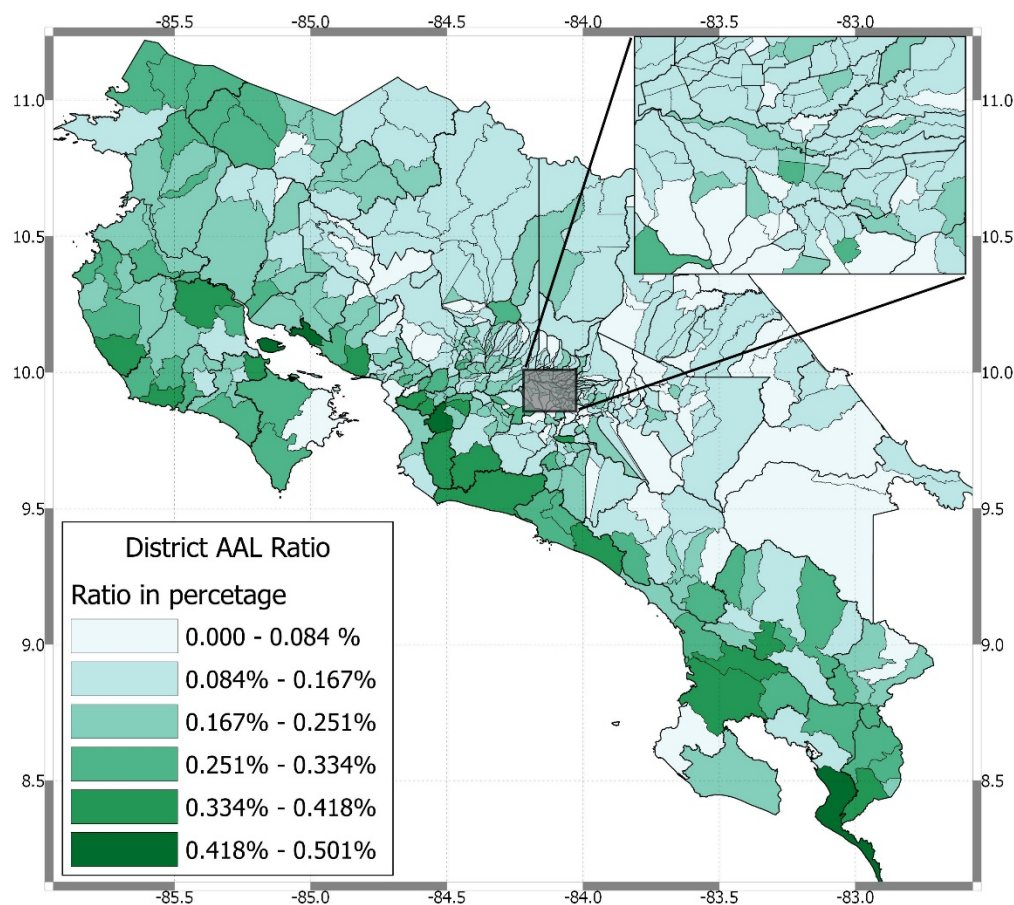


Figure 5-3: Aggregated AAL Ratios at district scale.

When all results from each of the ten sets of risk analysis are taken into account, the national average annual loss ratio varies from 0.131% to 0.145%, for a final mean value of 0.139% as presented in Figure 5-4.

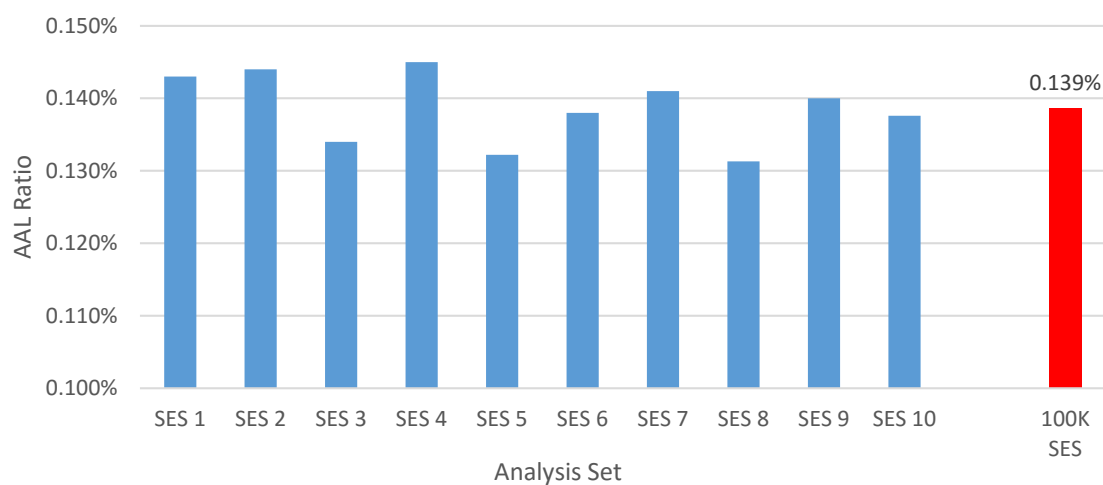


Figure 5-4: Aggregated AAL Ratio estimated for Costa Rica.

5.4 Average Annual Losses

Average Annual Losses in economic terms are significantly different from loss ratios because they are obtained by adding all the losses caused by the ruptures and dividing them by the risk analysis time span. They are not normalized by the stock value in a region, therefore can be taken as direct indicators of the risk of economic loss due to earthquakes.

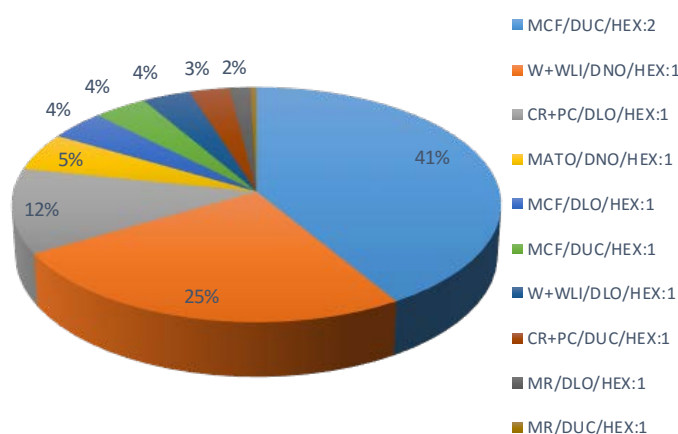
Average annual losses disaggregated by building class are presented in Table 5-2. Results indicate that two-storey ductile masonry buildings account for more than 40% of the annual economic losses. This can be attributed to the combination of a moderate loss ratio with the highest stock value present in the exposure model. The other significant losses are distributed among the building classes of medium to low ductility. These are the wood, precast concrete and waste materials, which possess the three highest loss ratios. Squat and ductile reinforced masonry structures, even though are among the most common building classes, present the smallest economic losses.

Losses reported from each building class within a region can be added to present the aggregated average annual loss at a district scale or a national scale. The AAL per district in Costa Rica are presented in Figure 5-6 and Figure 5-7. As the maps show, the biggest economic loss potential for Costa Rica is mostly concentrated in the Central Valley, specifically in the Great Metropolitan Area. More than 20 districts there report losses greater than \$1 USD Million annually, with San José, Pavas, Alajuela, San Francisco, Urúca, San Sebastián and Desamparados showing values that could go up to \$1.4 USD Million.

However, high risk districts are not exclusively found in the Central Valley. Sites of great commercial value, like the port cities of Limón and Puntarenas, production areas like San Carlos, Naranjo, Nicoya and Turrialba, together with populated cities like Parrita, Quepos, and Santa Cruz, present significant annual losses outside the Great Metropolitan Area. In fact, Liberia, the provincial capital of Guanacaste, is the district with the highest loss estimated, with an average of almost \$2 USD million annually.

Table 5-2: Average Annual Losses for Costa Rica, disaggregated by taxonomy.

Taxonomy	Average Annual Loss
MCF/DUC/HEX:2	\$ 43,529,348
W+WLI/DNO/HEX:1	\$ 26,621,556
CR+PC/DLO/HEX:1	\$ 12,293,099
MATO/DNO/HEX:1	\$ 5,487,343
MCF/DLO/HEX:1	\$ 4,334,010
MCF/DUC/HEX:1	\$ 4,180,641
W+WLI/DLO/HEX:1	\$ 3,744,470
CR+PC/DUC/HEX:1	\$ 3,125,648
MR/DLO/HEX:1	\$ 1,621,095
MR/DUC/HEX:1	\$ 464,335
Aggregated AAL	\$ 105,401,545



When all results from the ten sets of risk analysis are taken into account, the national average annual loss varies from \$99 USD Million to \$111 USD Million, for a final mean value of \$105 USD Million as presented in Figure 5-5.

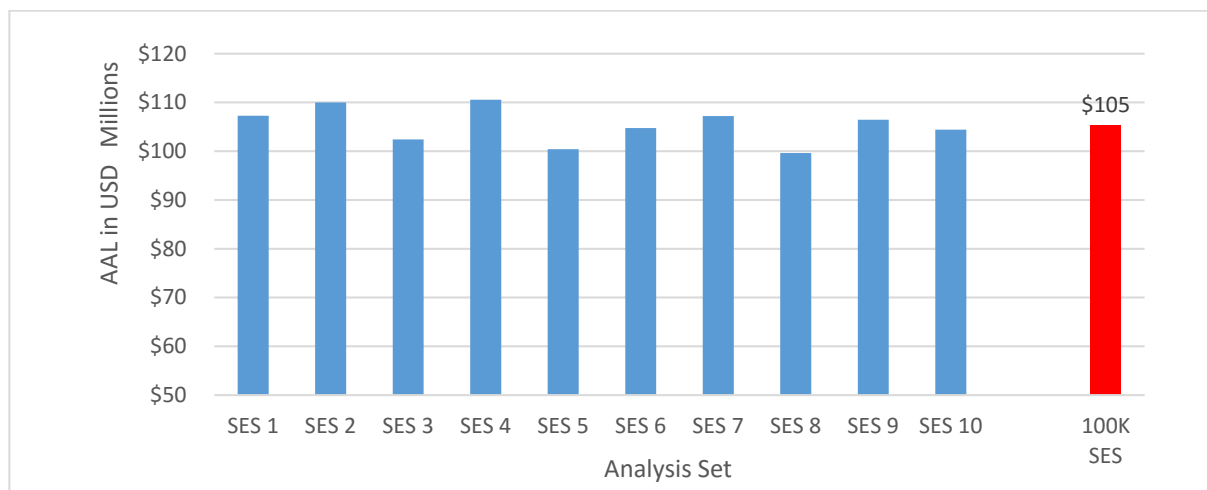


Figure 5-5: Average Annual Losses aggregated at a national scale.

5.5 Probable Maximum Loss Curve

The Probable Maximum Loss (PML) Curve plots all event losses against their associated annual rate of exceedance or return period. Figure 5-8 shows the Probable Maximum Loss Curve for Costa Rica in the latter format.

As the curve indicates, if the analysis sets are treated separately, the estimation of losses for the greater return periods exhibits significant scatter. This can be directly attributed to the rare incidence of great earthquakes, like Mw 7.9 events, that may not be generated by the engine due to a short time span of analysis. Maximum losses for a return period of 10,000 years estimated this way vary from \$6,000 USD Million to almost \$12,000 USD Million. Hence the importance of running a greater number of stochastic event sets. Using an analysis time span of 100,000 years, the scatter is considerably reduced and the curve smoothed to be more representative of the possible economic losses. The complete analysis set, plotted using triangular ordinates, considered more than half a million ruptures for loss estimation.

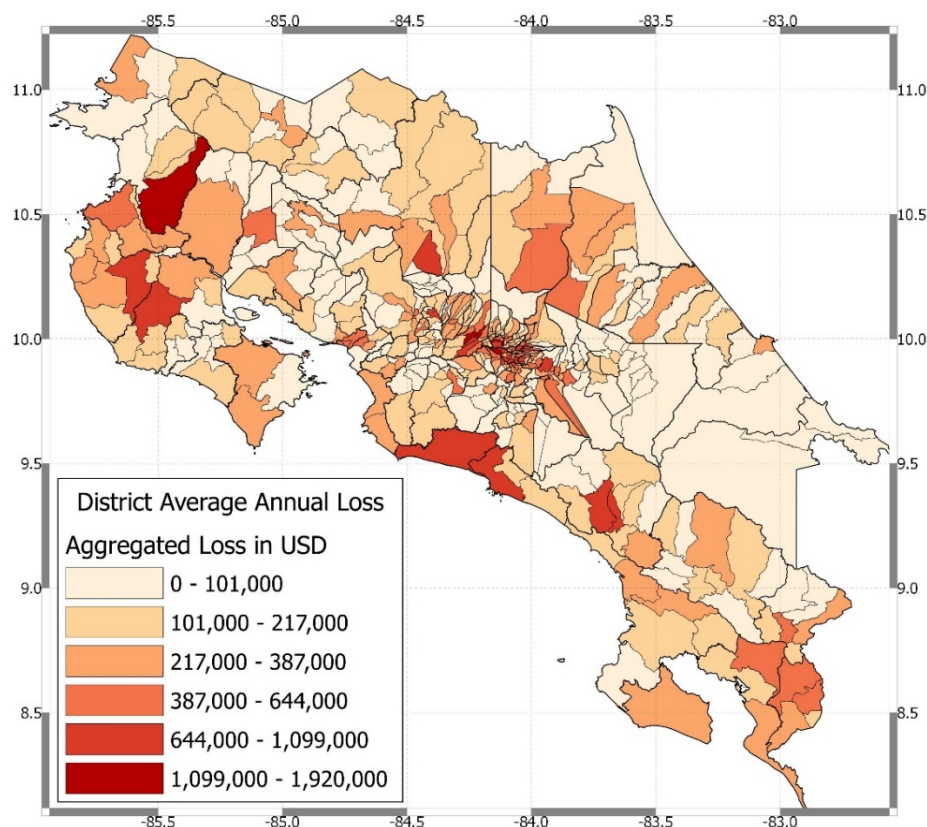


Figure 5-6: Aggregated Average Annual Losses per district in Costa Rica.

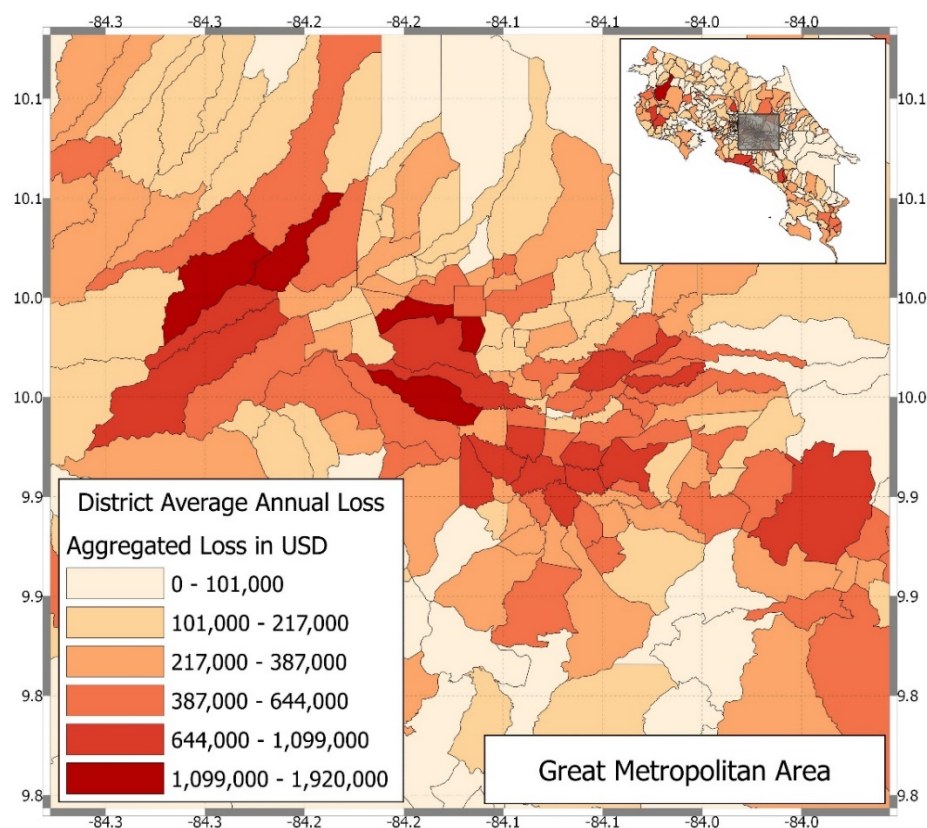


Figure 5-7: Aggregated Average Annual Loss per district in the Great Metropolitan Area.

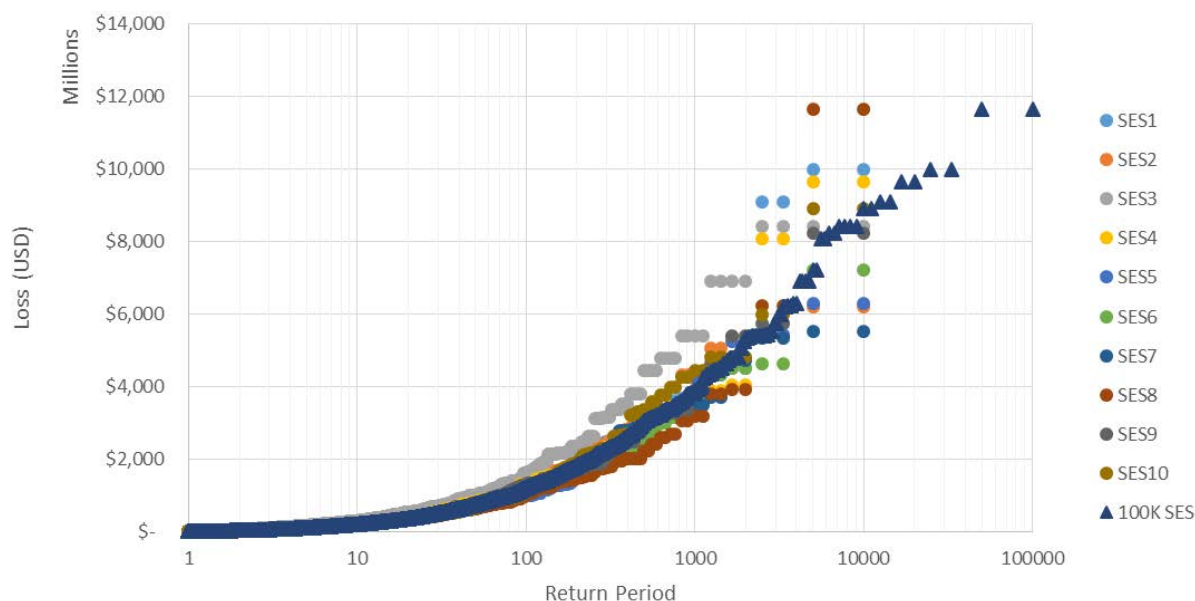


Figure 5-8: Probable Maximum Loss Curve for Costa Rica.

5.6 Costa Rica Risk Profile

With the results obtained from the assessment it is possible to generate a risk profile for the residential assets of Costa Rica. Figure 5-9 presents the proposed risk profile, which contains the main social, risk and financial indicators relevant for risk assessment. This type of data can be used by emergency management and financial agencies to guide decision-making processes towards effective risk reduction.

Referencing the general social and risk indicators, the first noticeable aspect of the profile lies in the fact that due to the relatively high seismic hazard, all the population of the country and its entire capital stock are considered at risk. Moreover, according to the hazard and exposure models, more than 70% of the buildings in the country are located at sites where the expected PGA for a Return Period of 500 years ranges from 0.36g to 0.51g on rock, with a great portion of those buildings lying over soft soils. This combination of factors can be considered as the main driver of earthquake risk in the country. However, exposure results also indicate that low rise, code compliant and relatively ductile building classes are the most common building classes. Therefore this serves as a significant counter, balancing the risk indices.

In terms of risk distribution, the profile shows that the gross of the losses are concentrated in the Great Metropolitan Area of the country. The capital districts of San Jose, Pavas, Alajuela, San Francisco and Curridabat exhibit the biggest lost potential, which can be attributed to high population density. Other regions like Urúca, San Sebastián and Desamparados have a combination of high population density and concentration of medium to low quality typologies. Another driver contributing to elevated risk indices in this region is the spot of medium soft soils found in the Central Valley. However, there is a strip of districts along the southern part of the country where losses are also particularly high. Liberia, Santa Cruz, Parrita, Quepos, San Isidro Del General, Canoas, Guaicará and Corredor are zones that register losses comparable to the mean found in the Central Valley, even though population in some of them is significantly

lower. Here, moderate to high-risk indices are the product of a higher exposure to seismic hazard combined with the effects of soft soils and lower quality construction. Along the north Caribbean Coast and the tropical rainforest in the east, losses are much smaller. Districts like Limón, Sarapiquí and Guapiles show appreciable risk levels mainly because they are heavily populated centers.

Referencing the magnitude of the losses, a total mean of \$105 USD million annually is the final estimation. The number is obtained for the residential building stock and is not an indicator of losses in industrial, commerce or infrastructure sectors. Still the amount is significantly high. To put it in context, according the Ministry of Treasury [Ministerio de Hacienda, 2015], in the year 2015 the budget for road infrastructure development and maintenance will be close to \$450 USD million. In other words, if the loss estimation is correct within the order of magnitude, the country could potentially lose yearly due to earthquakes more than a fifth of the sources directed to construct and maintain lifelines.

Validation of the average annual loss could be performed by doing deterministic earthquake scenarios for historical earthquakes with the most reliable recorded losses. This is outside of the scope of this investigation, however it may prove to be challenging. Historical events, like the 1991 and 2009 earthquakes have reported economic losses within the range of \$100 and \$515 USD million, respectively [MIDEPLAN, 2010]. However, these estimations seem conservative. The 1991 Bocas Del Toro earthquake alone noticeably damaged roads, railroads, bridges, ports, aqueducts, leaving also close to 7,500 people homeless. The reported \$243 USD million in losses seems significantly low. Other important events like the 1983 and 2012 earthquakes reported collapsed buildings and deaths but no official economic losses, which seems to be an inconsistency in the records. Nevertheless, the losses that are officially reported, presented in Table 5-3, suggest that the estimated annual average is reasonable.

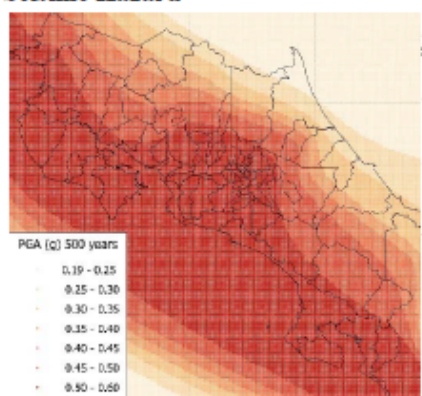
Table 5-3: Official loss report from historical earthquakes by the Ministry of National Planning and Economic Policies of Costa Rica [MIDEPLAN, 2010].

Event	Year	Mw	Economic Loss
Alajuela	1990	6.1	\$ 3,438,295
Limón	1991	7.6	\$ 243,965,698
Los Santos	1991	4.9	-
Turrialba	1993	-	\$ 950,248
Damas	2004	6.2	\$ 5,021,556
Cinchona	2009	6.1	\$ 405,842,989
Nicoya	2012	7.6	-

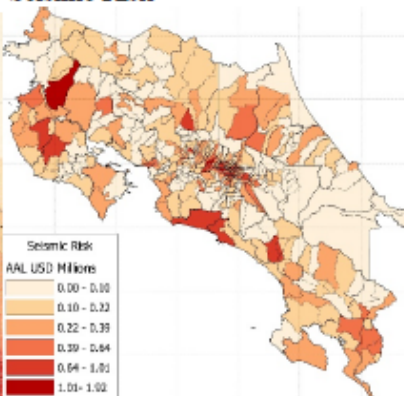
Earthquake Risk Profile for Costa Rica

The deadliest earthquake in the history of Costa Rica was the 1910 Cartago earthquake, which left a dead toll of 1000. After a relatively low seismicity period, significant events have occurred again in 1983, 1990, 1991, 1999, 2004, 2009 and 2012. Particularly damaging, the Bocas del Toro and Cinchona earthquakes caused more than \$600 USD million in economic losses.

Seismic Hazard



Seismic Risk



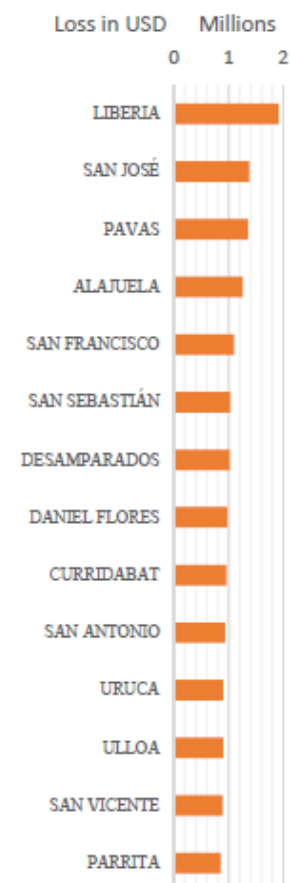
Social Indicators

Population (mil.):	4.94
GDP (USD mil.):	49,620
Capital Stock (USD mil.):	75,870
Life Expectancy (years):	78.20
GINI Index:	49.20
Gross Savings (USD mil.):	9,205

Risk Indicators

Population at risk (mil.):	4.94
Property at risk (USD mil.):	75,870
AAL Economic (USD mil.):	105
AAL Ratio (percent):	0.14
Max. Economic Loss (USD mil.):	8,180
Probable Max. Loss (USD mil.):	1,839

Top 15 districts at risk



Financial Indicators

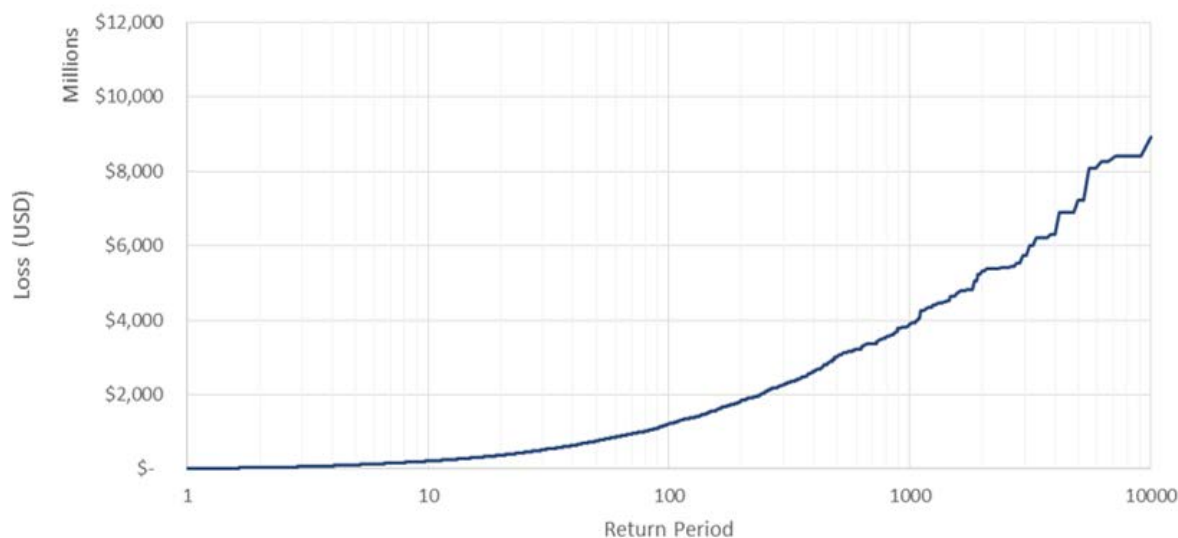


Figure 5-9: Proposed Risk Profile for Costa Rica.

Besides presenting graphically the losses associated to all the ruptures included in the analysis, the Probable Maximum Loss Curve presented in the profile is a tool for evaluation of financial risk. For example, the return period of 200 years has particular relevance because modern regulations require insurers to have financial resilience for this frequency level [European Commission, 2007]. Hence the loss associated to this return period becomes the reference of sufficient economic solvency for insurers. According to the risk assessment for Costa Rica, the mean value of loss for the 200 years return period is \$1,839 USD million, close to 4% of its yearly gross domestic product. The costliest event generated in this study was located in the Central Valley of Costa Rica, with a magnitude of 7.9 (Mw). An earthquake of this kind has an estimated loss of \$8,180 USD million, which is approximately 16% of the national domestic product.

5.7 Potentially Insured Assets

These results were estimated considering damage to all assets in the exposure model, which was developed at a national scale. This means they include losses on the building classes that are not likely to be insured, like the low quality light wood, precast concrete and waste material building classes. However, according to the previously discussed loss disaggregation, around 40% of the losses come from these types of structures. Therefore, if risk assessment was performed considering only the potentially insured residential assets, the average annual losses, the maximum probable loss and maximum loss would be considerably lower. For example, simply assuming that 100% of the potentially insured buildings pay earthquake premiums, and removing all low quality typologies from the previously discussed results, the change in the average annual losses, presented in Table 5-4, is significant. The Probable Maximum Loss Curve would also present significant changes.

Table 5-4: Number of potentially insured buildings, value and resulting losses.

Taxonomy	Insured Buildings	Insured Value	AAL	AAL Ratio
CR+PC/DUC/HEX:1	108,307	\$ 2,878,738,937	\$ 3,125,648	0.11%
MCF/DLO/HEX:1	92,534	\$ 4,272,123,265	\$ 4,334,010	0.10%
MCF/DUC/HEX:1	334,573	\$ 22,763,456,800	\$ 4,180,641	0.02%
MCF/DUC/HEX:2	137,496	\$ 32,864,191,166	\$ 44,829,348	0.14%
MR/DUC/HEX:1	77,307	\$ 2,639,992,017	\$ 464,335	0.02%
Grand Total	750,217	\$ 65,418,502,185	\$ 56,933,983	0.09%

5.8 Limitations

Validation of the results of risk assessment could be achieved performing deterministic scenarios replicating historical events, for which losses have been recorded. This however is outside the scope of the present study. The official losses from historical events presented in this chapter serve to reference the frequency and damage of events within the last four decades in Costa Rica.

6 CONCLUSIONS

This study proposed national scale exposure and vulnerability models for risk assessment in Costa Rica. For the hazard model, the RESIS II project proposed for the Central American region [Climent et al., 2008] was considered to be the best representation of earthquake hazard available and was therefore employed in the risk analyses.

The exposure model was elaborated using the National Housing Censuses from 1973 to 2011 as the main tool. The main limitation found during the process was the reduced amount of available information on high-rise construction in Costa Rica. However, according to the census and the proposed dwelling to building conversion, less than 5% of the structures belong to these typologies. The main structural attributes determined for the buildings were the construction materials, lateral load resisting system, height, size, date of construction, expected ductility and replacement cost. A total of 1.18 million structures were identified over 34 building classes together with their respective geographical distribution, at the smallest administrative level of Costa Rica, which is the district. Results of exposure indicate that 55% of the buildings in the country are low-rise masonry houses, with seismic provisions and a medium to high expected ductility levels. Around 35% are precast concrete and light wood constructions which are extensively used in governmental housing programs and less than 2% are precarious edifications of waste materials. It was possible to conclude that over 92% of the structures are concentrated in 10 building classes, which allowed for a simplification of the exposure model for more efficient risk assessment. The exposure also concluded that more than 85% of the capital stock value of the country is concentrated in masonry structures. The rest is evenly distributed among individual houses made of wood and precast concrete, with a minor percentage of value on low quality housing.

The vulnerability model proposes four fragility curves for the most common building classes. For their derivation, index buildings were identified and simplified 2D wall element models were produced for structural analysis. Using the SeismoStruct software [Seismosoft, 2015], Static Nonlinear Adaptive Pushover Analysis were performed for the derivation of the capacity curves of each model. The Multiple Stripe Analysis method was used for the nonlinear dynamic analysis. The intensity measure level used was the peak ground acceleration from ground motion records and interstorey drift was selected to be the engineering demand parameter. Four limits states were proposed for damage assessment in the models. The fraction of analysis that resulted in exceedances of the established damage states were treated as the probability of exceeding a limit under given an intensity measure. Continuous fragility models were constructed using least square regression analysis. The rest of the fragility model was taken

from the work of Villar et al. [2016], which proposed a series of curves for risk assessment in South America. Vulnerability was achieved by the implementation of a damage-to-loss model, which was calibrated for Costa Rica by revision and analysis of resulting damage ratios.

The RESIS II source model was complemented with a soil conditions map containing Vs30 data determined through the simplified methodology developed by Wald and Allen [2007] in order to take into account seismic amplification due to soft soils. According to the hazard results, the entire national territory has an expected PGA of 0.2 g on rock or above for a return period of 500 years. Which indicates that the entire residential capital stock of Costa Rica is under earthquake threat. Moreover, careful review of the site and exposure models revealed that the most important populated centers of the country are located in sites with considerable soft soils, like the Central Valley. This was identified as the main potential risk driver in Costa Rica.

Successful implementation of the three models in the OpenQuake-engine was achieved. For the assessment of risk the probabilistic event-based risk calculator was used. Ten runs of 10,000 stochastic events sets (each one with an investigation time of one year) were created and analyzed separately in order to capture potential variability in loss estimations. Results for the average annual loss ratio and average annual losses were taken as the mean value resulting from the ten analyses. These were calculated aggregated at a national scale, as well as disaggregated by building class and district. For the elaboration of the Probable Maximum Loss Curve all the generated events and respective losses were used. More than half million ruptures were computed in the process.

In reference to the loss ratios, it was concluded that the low quality buildings made of waste, wood and precast concrete materials have the highest loss ratios amongst the building classes, ranging from 0.75% to over 1.0%. While the low-rise masonry structures with seismic provisions present values around 0.02%. The two storey masonry structures, which represent 40% of the residential stock value, have a moderate ratio of 0.14%, which is very close to the national estimated AAL ratio of 0.139%.

When the loss ratios are analyzed by region, it was possible to identify that the most vulnerable districts of the country are located along the pacific coast. Isla de Chiriquí, Parrita, Savegre and Pavones possess estimated loss ratios up to 0.50%. On the other hand, in the Central Valley, the loss ratios range between 0.08% and 0.14%. With the particular exception of Urúca, Cinco Esquinas, San Francisco, Hospital and Los Guido, the most populated centers of Costa Rica exhibit low to moderate seismic vulnerability. Much lesser loss ratios are found along the Caribbean Coast.

Despite possessing the smaller loss ratios, more than 50% of the economic losses come from the reinforced masonry building classes. This is attributed to the fact that they comprise 85% of the entire capital stock value. On the same framework, even though less than 25% of the stock value is concentrated on the low quality building classes, it was estimated that the other half of the losses come from damage on these structures.

In terms of risk distribution, the gross of the economic losses were found on the Central Valley of the country. More than 20 districts in the Great Metropolitan Area exhibit an average loss

around \$1 USD million annually, with San José, Pavas, Alajuela, San Francisco, Urúca, San Sebastián and Desamparados showing values that could go up to \$1.4 USD Million. Outside the Central Valley, sites of great commercial value, like the port cities of Limón and Puntarenas, San Carlos, Naranjo, Nicoya, Turrialba, Quepos and Santa Cruz exhibit annual losses comparable to capitol districts. Liberia, the provincial capital of Guanacaste, is the district with the highest loss estimated, with an average of almost \$2 USD million annually. A final estimation of \$105 USD Million was the total aggregated annual loss value at a national scale.

With all the results of the risk assessment at hand, a seismic risk profile for the residential stock of Costa Rica was proposed. The main recognized risk driver for the country was the combination of greatly populated centers in sites that have both, high seismic hazard and seismic amplification due to the presence of soft soils. The highest concentration of risk indices are found on the Great Metropolitan Area. However, a strip of southern districts was identified to have potential losses close to the average found in the Central Valley. The top 10 districts at risk were determined to be Liberia, San José, Pavas, Alajuela, San Francisco, San Sebastian, Desamparados, Daniel Flores, Curridabat, and San Antonio. A maximum probable loss of \$1,839 USD million was determined for a return period of 200 years. This is close to 4% of Costa Rica's yearly gross domestic product. A maximum possible loss of \$8,180 USD million, around 16% of the national domestic product, is associated to a return period of 100,000 years.

Future work on the risk assessment performed herein could include a framework for testing and validating the proposed models. In this regard, the best scenario to be modelled could be the 2009 Cinchona earthquake, which reported highest losses in the present official records [MIDEPLAN, 2010]. Improvement on the exposure model is possible, however further division of the building classes seems to be unpractical and unnecessary given the huge concentration of structures on few widely used building classes. However, calculation factors like the dwelling to building ratio on the high-rise classes could be more precisely determined if additional data on these structures would be available. The vulnerability model has the biggest potential for improvement. More detailed and sophisticated structural models could be developed for the more populated taxonomies, including the medium to low ductility reinforced masonry structures. In terms of hazard, the source model used shows very good correlation with the original national model developed on the RESIS II project for estimated PGA values on rock. Therefore, improvement could rely in revision of the site model used to account for seismic amplification.

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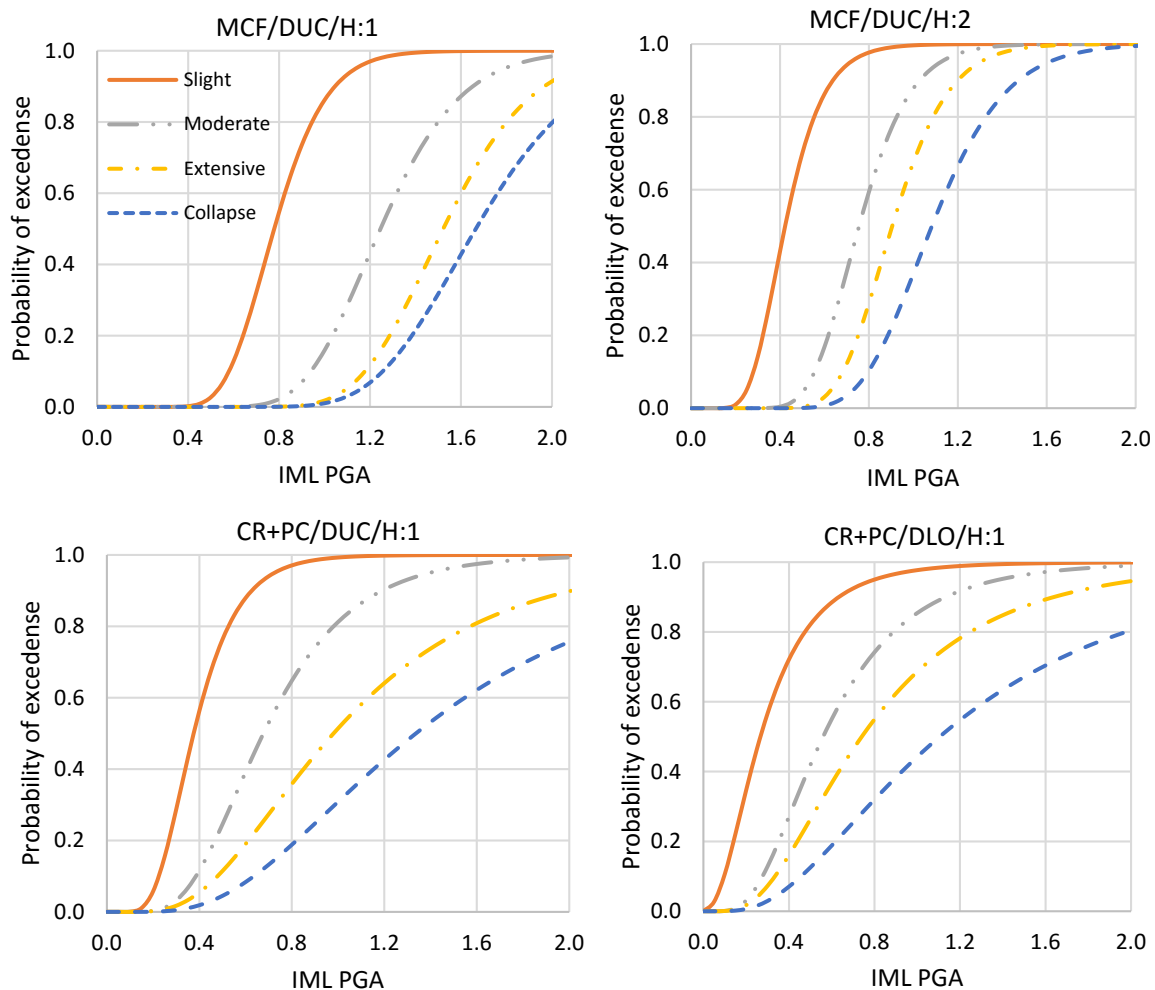
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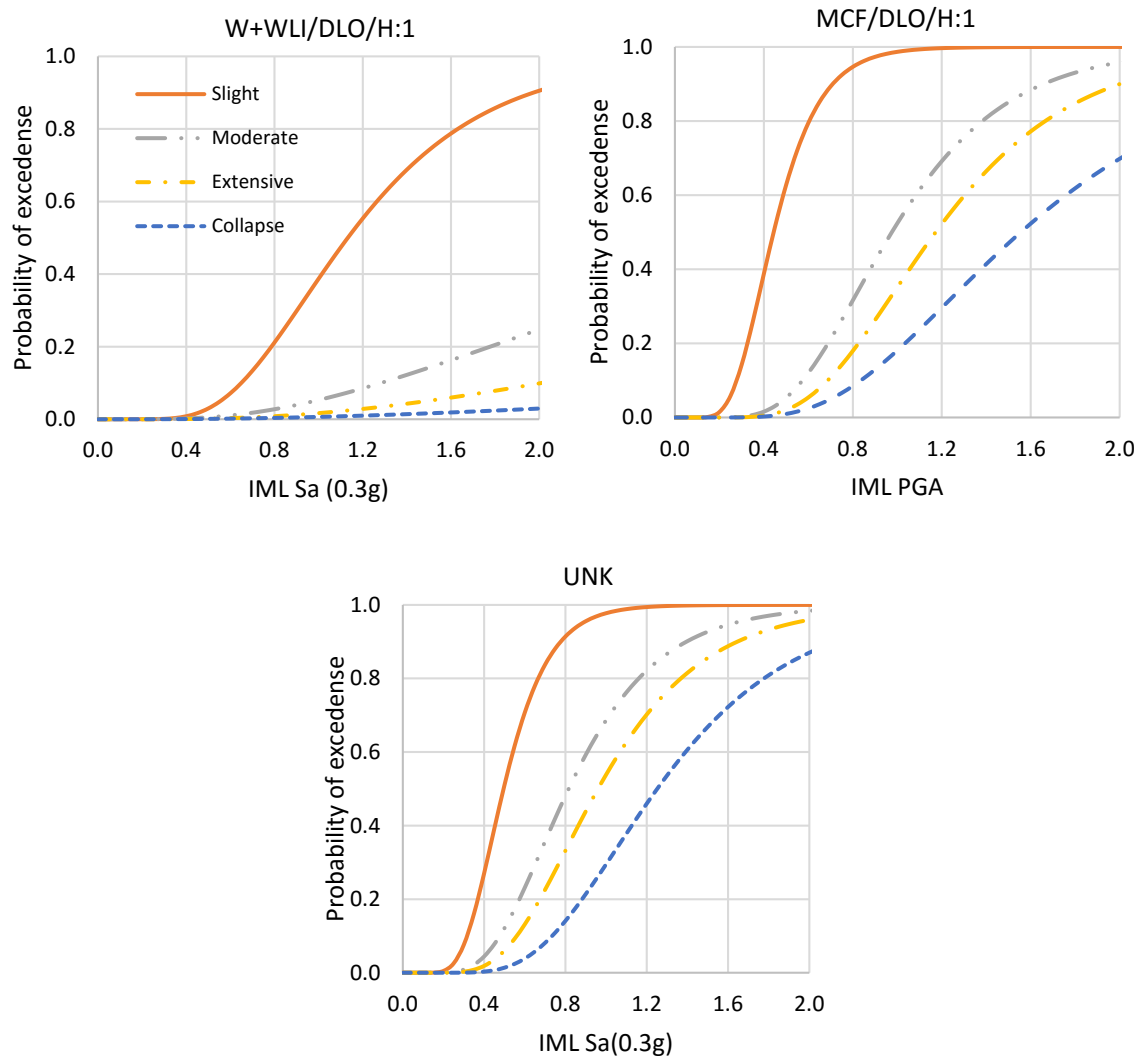
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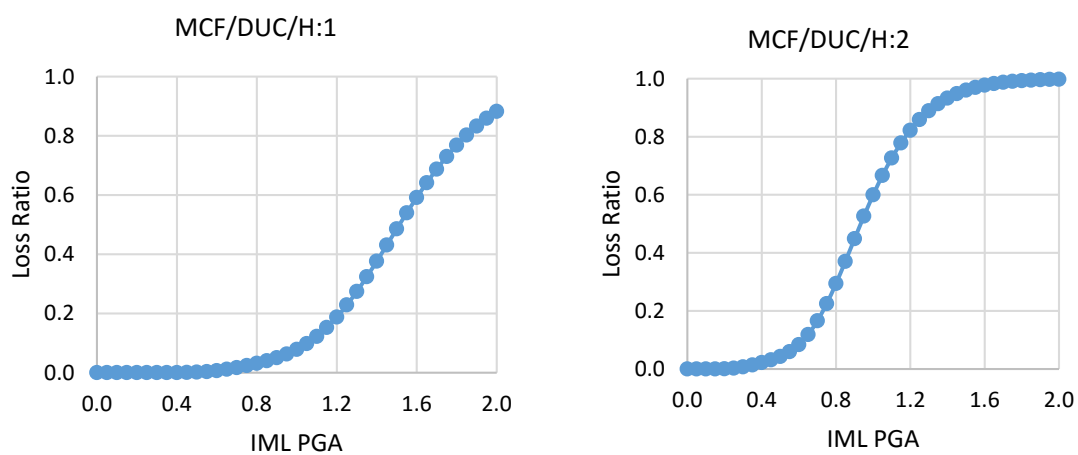
APPENDIX A

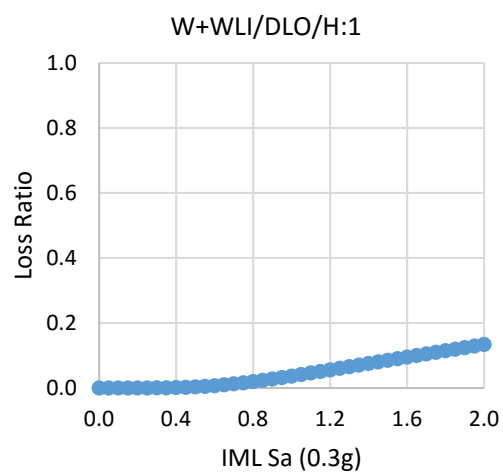
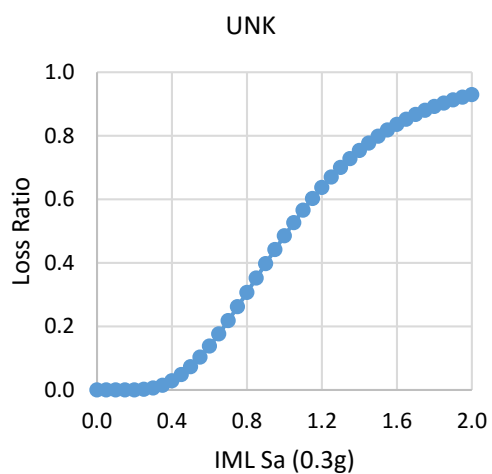
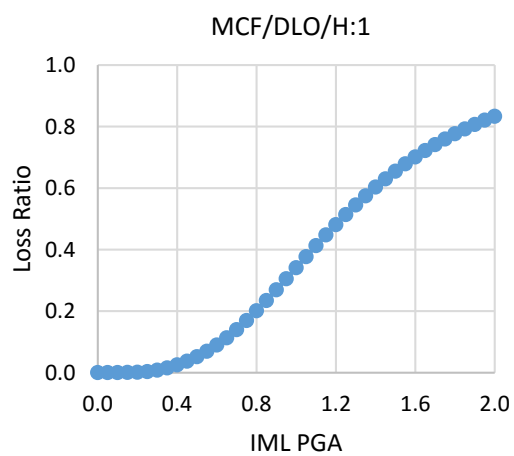
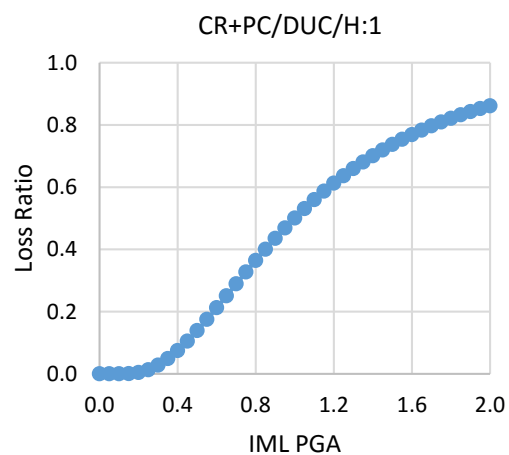
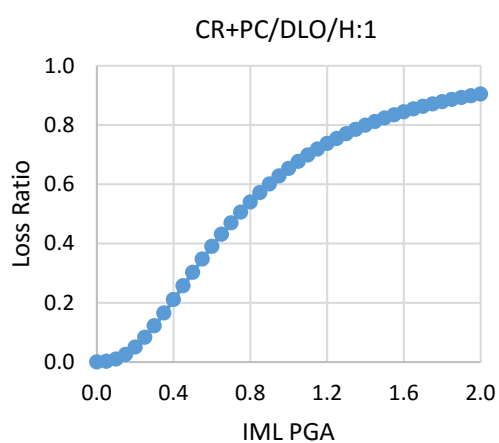
Complete Fragility Catalogue





Complete Vulnerability Catalogue





APPENDIX B

Aggregated and Disaggregated Building Distribution

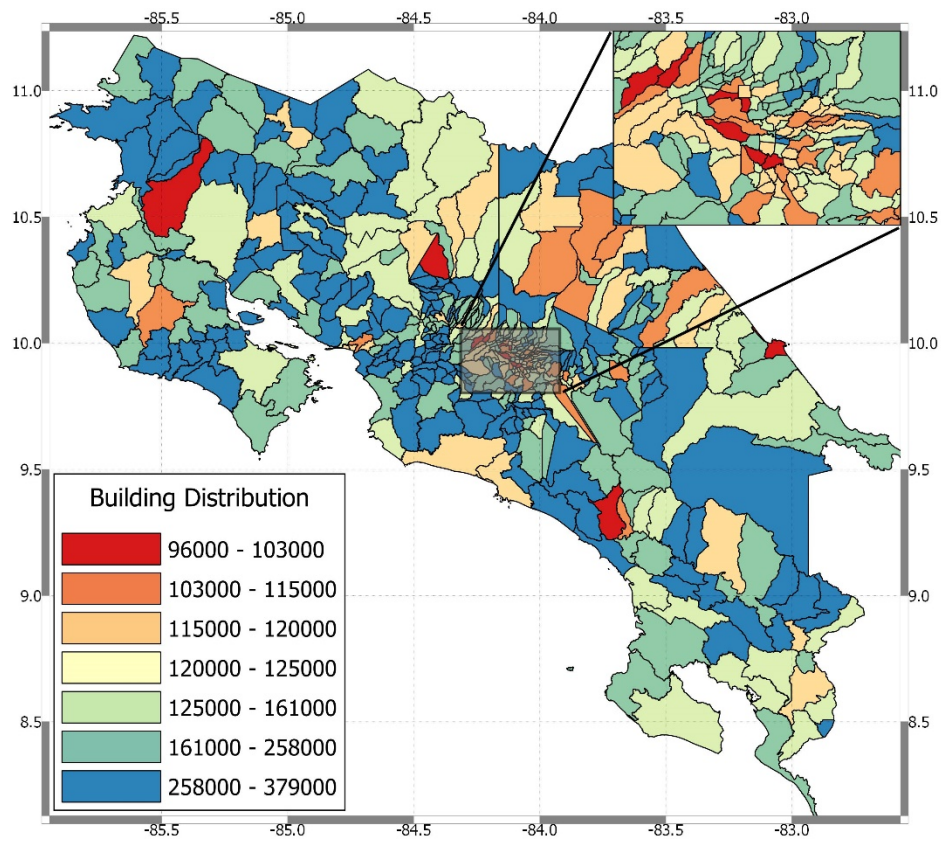


Figure 7-1: Aggregated building distribution at a district scale.

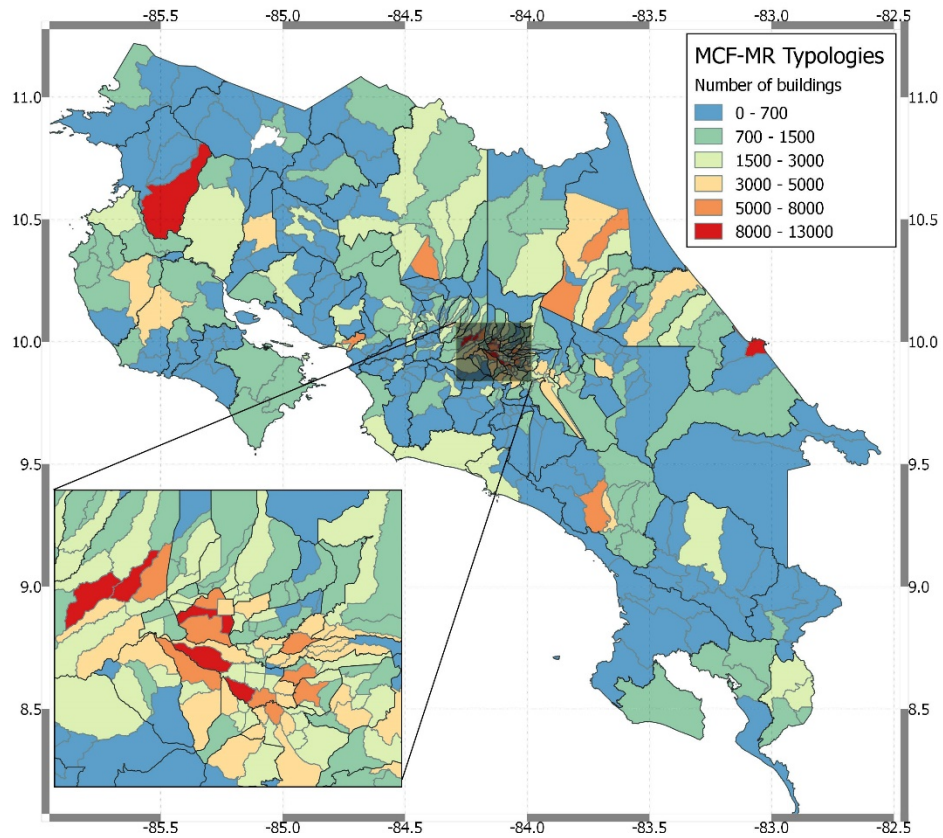


Figure 7-2: Reinforced masonry building distribution at a district scale.

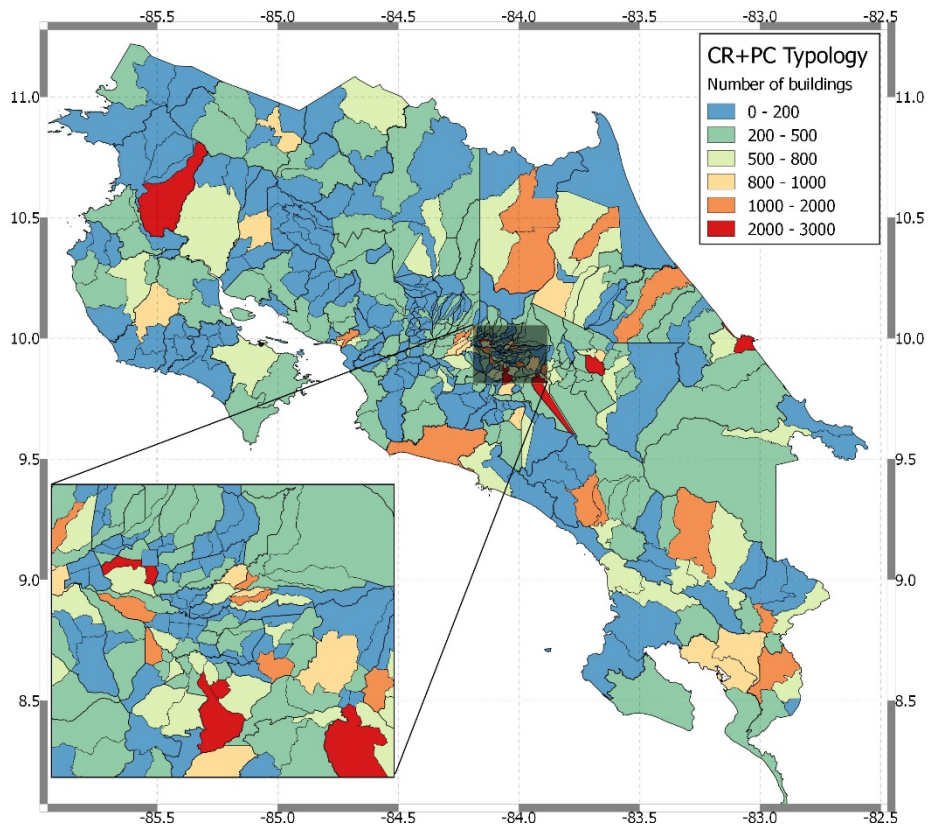


Figure 7-3: Precast concrete building distribution at a district scale..

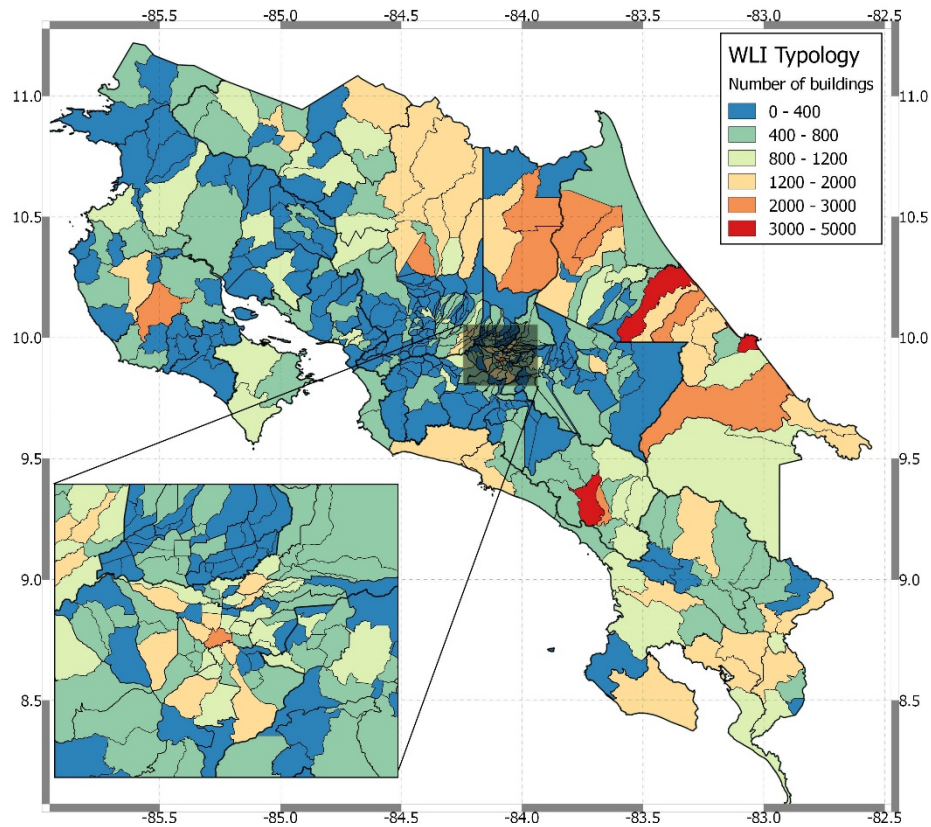


Figure 7-4: Light wood building distribution at a district scale.

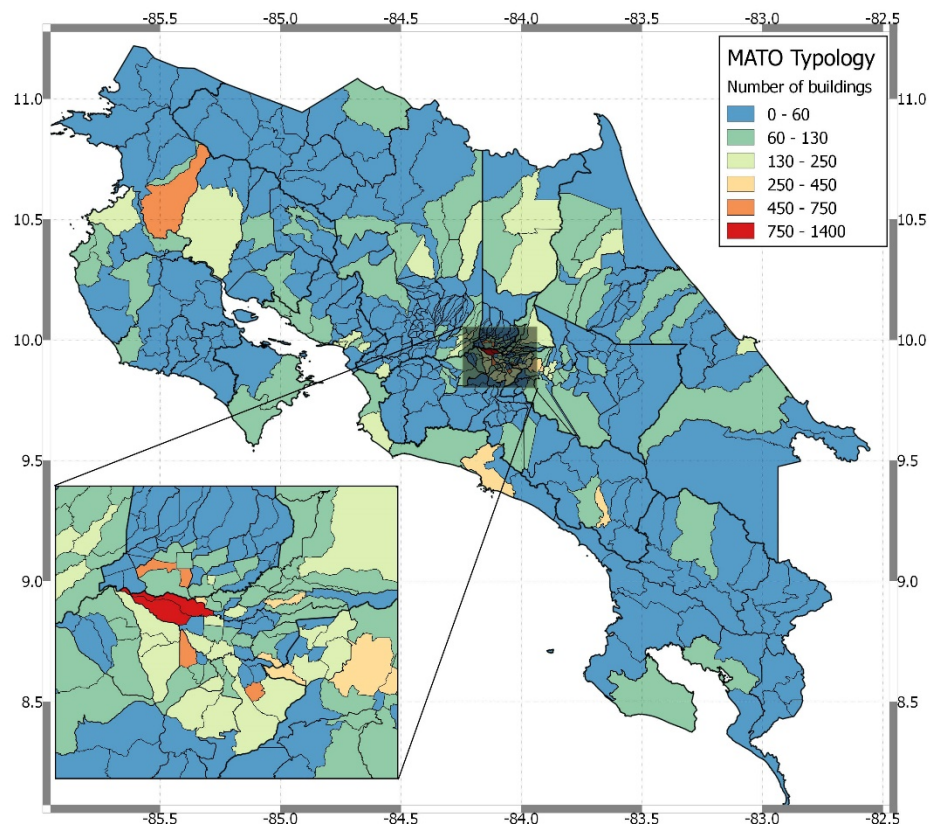


Figure 7-5: Low quality building distribution at district scale.

APPENDIX C

Disaggregated Loss Ratios per Taxonomy

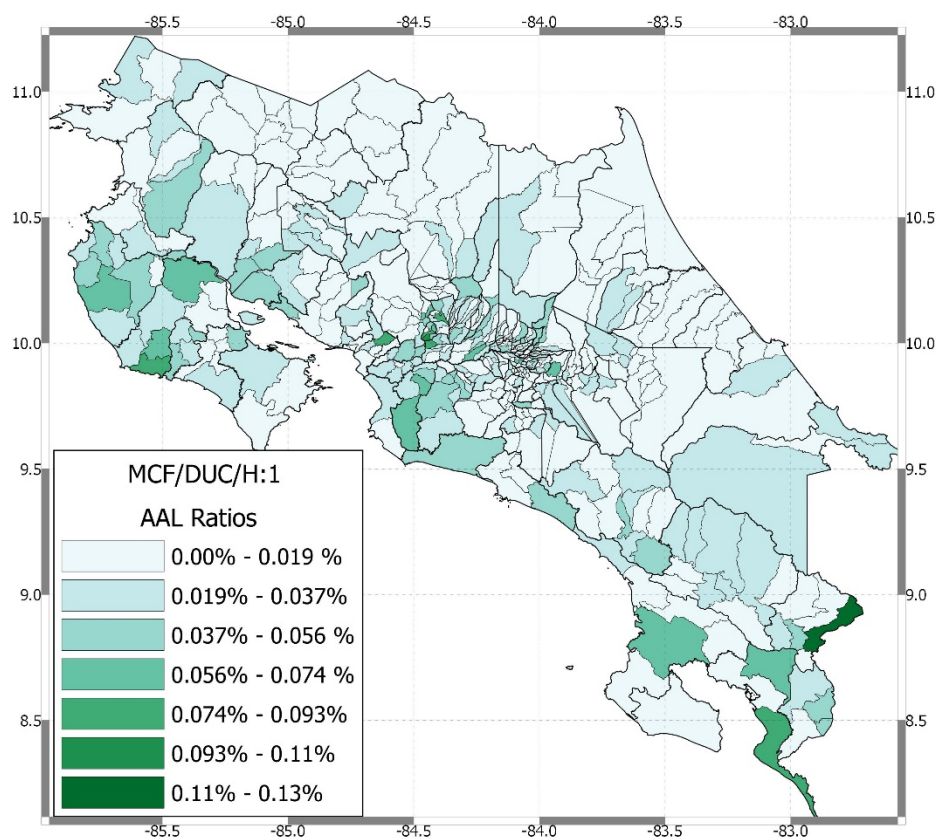


Figure 7-6: Ductile, one storey, confined masonry loss ratio distribution at a district scale.

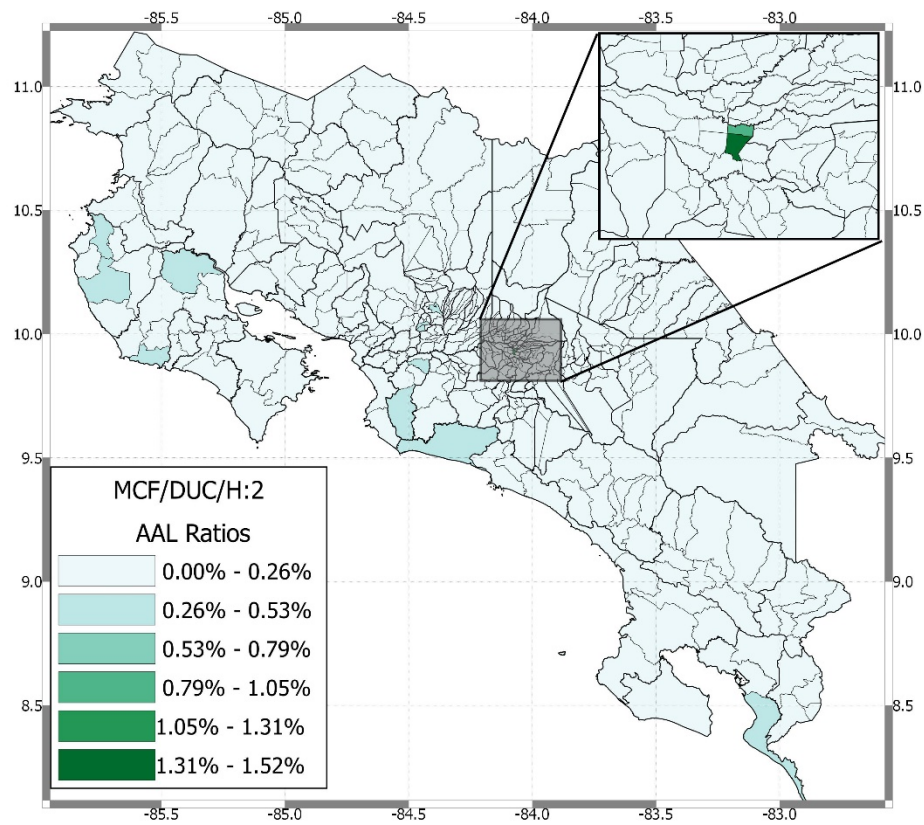


Figure 7-7: Ductile, two storey, confined masonry loss ratio distribution at a district scale.

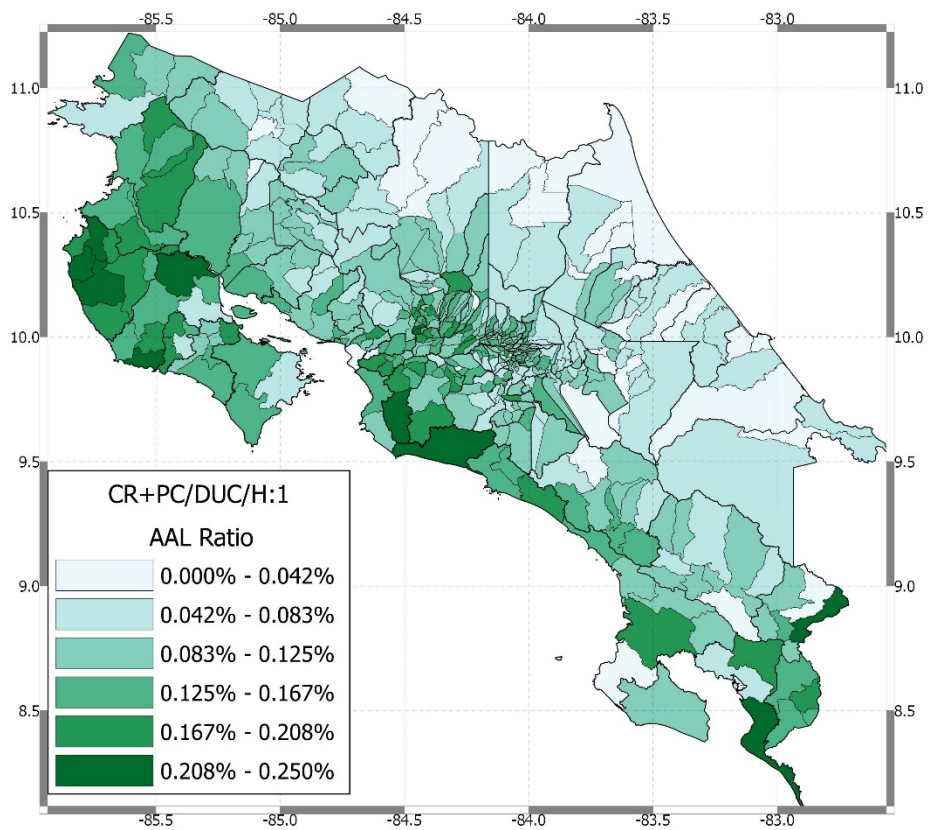


Figure 7-8: Ductile, one storey, precast concrete loss ratio distribution at a district a scale.

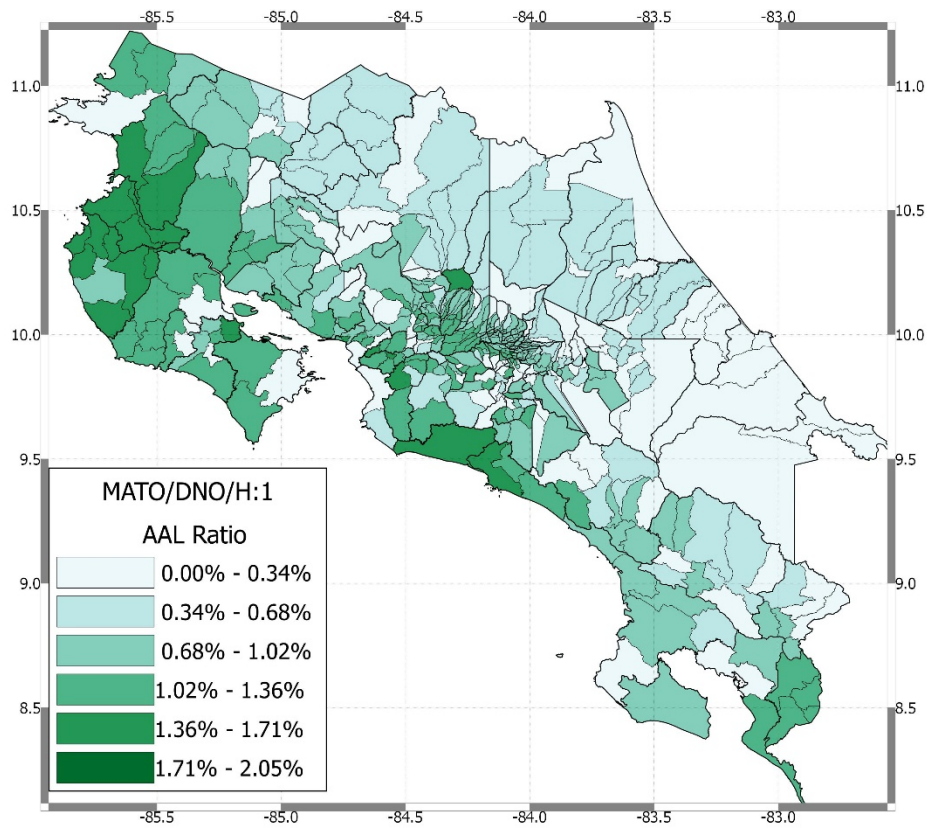


Figure 7-9: Low quality, waste material loss ratio distribution at a district scale.