DEVELOPMENT OF PARAMETERS FOR USE IN SEISMIC RECOVERY ESTIMATION OF RESIDENTIAL BUILDINGS IN LIMA, PERU

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ABSTRACT :

Lima, Peru is located in an area of intense seismic activity and earthquakes have devastated the city several times in its history. Recent census data also indicates high-growth in residential building since 1993 subjecting an ever-greater number of inhabitants to seismic risk. For effective earthquake planning, it is essential to consider the need for the development of parameters for use in seismic recovery estimation of typical residential buildings in Lima. A survey of builders and other construction professionals working in the metropolitan area of Lima is conducted to determine estimated prices and practice for local construction and repair methods for residential buildings. It is shown how this data can be used to provide a clearly defined damage scale that relates level of damage to seismic losses/recovery. A methodology is also presented as to how this scale could be best integrated with seismological and building vulnerability studies to form a completed seismic recovery estimation model, which would be of benefit to earthquake planning professionals.

KEYWORDS: Damage, confined masonry, loss estimation, Peru

1. INTRODUCTION

Lima, Peru is situated in an area of very high seismicity and seismic risk (Tavera and Buforn 1998; GSHAP 2008). The seismicity of this part of the World has recently been put in to renewed focus by the lethal Pisco earthquake of 15th August 2007 (IGP 2008a). Indeed, Lima itself is a city that in its history has been devastated multiple times by earthquakes (Tavera and Buforn 1998). Additionally, according to a recent 2005 census (INEI, 2008b) Greater Lima has a population of 7.77 million inhabitants (6954517 in the metropolitan area of Lima and 810568 in Callao). There is therefore a high exposure to the seismic risk. However, for the potential consequences of such seismic risk to be fully appreciated the vulnerability of the building stock should also be considered.

Confined masonry is a construction composed of brick walls ‘confined’ by reinforced concrete posts or columns. These walls support reinforced concrete floors which themselves are formed by a series of reinforced concrete beams separated by hollow ‘roof’ bricks. Further details about this form of construction can be found from Blondet (2005) and from Loaiza and Blondet (2002a,b). Details regarding the increased adoption in Lima of confined masonry buildings between 1993 and 2005 can be inferred from recent censuses (INEI 2008a,b) and knowledge of local construction practice. Almost half of all housing units in 2005 (see Table 1) were independent houses of confined masonry. This figure rises to at least 64.8% when apartments in buildings are added, making confined masonry a fundamental component of Lima’s building inventory. Additionally, between 1993 and 2005 within the Greater Lima are there was a 78.5% to almost 100% increase in independent houses and apartments in buildings using this construction method. This can be compared to the almost 40% increase in total housing units during the period; a significant increase in itself. Confined masonry construction is therefore becoming ever more dominant in Lima.

Table 1 Increase in Lima’s confined masonry buildings stock (adapted from INEI 2008a,b)

Housing unit type	Wall and roof material	Quantity (2005)		
		Lima (Metropolitan area)	Callao	Greater Lima
Independent house	Brick (or concrete block) wall and reinforced concrete roof – inferred to be ‘confined masonry’ in most cases	764485	88304	852789
% of Total		49.9%	49.8%	49.9%
% change from 1993		78.0%	82.2%	78.5%
Apartment in building		242790	12458	255248
% of Total		15.8%	7.0%	14.9%
% change from 1993		103.6%	39.2%	99.1%
Total	Any	1532410	177326	1709736
% change from 1993	Any	38.6%	46.0%	39.3%

2. RESEARCH NEED

A variety of organizations might be involved in the field of preparing for and mitigating against earthquake effects to the urban environment. Examples include: local, regional and national government; governmental bodies such as ‘civil defense’; ‘civil society’ organizations including those concerned with building safety; international governmental and non-governmental aid organizations; seismic research institutions; and other entities involved in specialist aspects of earthquake mitigation, for example, the insurance industry. To reduce risk, it is important for such organizations to be able to fully understand the ‘real’ consequences of earthquake-induced damage. With regard to buildings, two such consequences are ‘cost’ and ‘recovery time’. By understanding such consequences more fully, better appreciation of the implications of such economic and societal costs will be developed, leading to enhanced policy-making and mitigation. This may result in, for example, improved building design or control construction quality for new buildings or strengthening or insurance for existing buildings.

In order to assess these 'real' consequences, three aspects of seismic risk assessment should be considered: seismic hazard, vulnerability of building type to the hazard, and cost/recovery time due to building damage. Few complete seismic risk assessments have been undertaken to date with respect to confined masonry buildings (Tavera 2001). Instead, seismic hazard in Peru has been researched by several bodies, notably the Peruvian Geophysics Institute (IGP 2008b). Some studies investigating the vulnerability of confined masonry buildings have also been conducted, for example, Blondet and Cesar (2001), although further research is required. On the other hand, it is argued that there is a general need for research into the 'real' consequences of earthquake-induced damage (Hill and Rossetto 2008a,b) and this piece of research therefore focuses on the subsequent issue of the relationships between damage (as assessed by a vulnerability study) and the consequent building 'cost' and 'recovery time'. Such relationships are often expressed through damage scales, and important characteristics of damage scales to seismic loss estimation have been identified elsewhere (Hill and Rossetto 2008a,b). Analysis of post-earthquake data is typically used as input for seismic loss estimation studies. Post-earthquake data concerning cost of repair or replacement of buildings damaged in earthquakes is limited by a number of factors: infrequent damaging earthquakes resulting in insufficient data, data at a macro-level or in differing formats, out-of-date data and propriety control. In the case of confined masonry buildings in Lima which have been subject to a limited quantity of heavily damaging earthquakes, such empirical data is even further limited. Furthermore, the level of refinement of data tends not to allow a component-based cost assessment to be carried out. Collection of new construction cost data lends itself to this component-level approach, providing current data in the format required for a study and not requiring any prior earthquake damage. It is therefore pertinent to propose an alternative but complementary method for calculating recovery cost and time, which will also improve precision of the damage-recovery relationships, in particular where advanced analytical modeling of vulnerability which can capture component-level damage has been undertaken.

To propose such a method, it was necessary to undertake a survey of builders in Lima, Peru, to ascertain current costs and construction time for confined masonry buildings. The following sections describe the research carried-out, the method that could allow its use in seismic loss estimation, and how such a method can be linked to a vulnerability study.

3. CONFINED MASONRY CONSTRUCTION SURVEY

A construction cost survey was undertaken in the metropolitan apart of Lima between August 2007 and March 2008. The research is on-going. The survey sample is considered self-selecting and was conducted through hand distribution of the questionnaires to builders. Self-employed builders rather than construction contractors were selected since it is generally accepted that they currently constitute the greater share of the housing industry and would be consequently crucial to a reconstruction effort. An initial pilot-survey determined that the most appropriate form for the Spanish-language questionnaire would be no-greater than 1 page in length and ideally would ask questions in a form that is frequently understood by builders, hence the questionnaire has similarities with a classical builders' estimate for work. Questions were asked on minimum, maximum, and probable price and length of different construction phases including demolition and site clearing. The reason that questions were presented in this manner is that the local market in advanced reinforced concrete repairs such as carbon fiber jacketing or epoxy injection are nascent. It was therefore judged that in a post-earthquake environment, the most common form of repair would actually be replacement. Nonetheless, a specific masonry strengthening repair method question was also included. Although the lower response rate to that question (see this section) might indicate limited understanding of the technique, the construction techniques used are sufficiently similar to those used for the main construction to remain relevant. In order to provide builders with an experience more in keeping to their usual practice, questions were also presented with quantities. Subsequently it has been determined that this might not be necessary. The structural-component related questions (in English) and construction units are given in Table 4.

4. CONSTRUCTION SURVEY RESULTS

Whilst over 50 responses were received, initial results from a selection of up to 28 respondents are provided herein. Figures 1 and 2 present the results in terms of the median probable value which in this case has been normalized to the value of R_T from the example in Table 4 (i.e. model new 3-storey building) and is defined in Table 2. All phases have between 25 and 28 responses except phases 7 and 8 which have 8 and 4 responses respectively. It can be seen that, for example, phase 1 (trench foundation) costs 102 Peruvian Nuevos Soles, S/., (0.164x623) and takes 0.25 days per meter length (0.312x0.789), whilst phase 10 (reinforced concrete floor construction; non-ground floor) has a typical cost of S/. 149 (0.239x623) and takes 0.15 days per square meter (0.187x0.789). The cost values exclude sales tax.

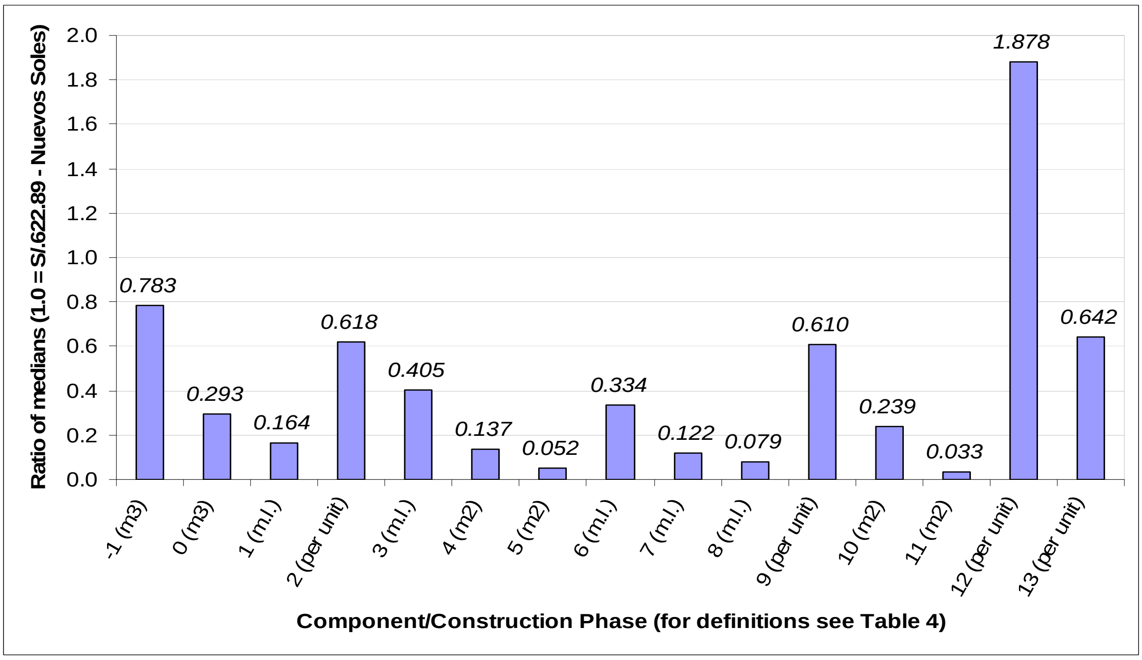

Figure 1 Ratio of probable component cost medians (normalized to R_T from Table 4 example)

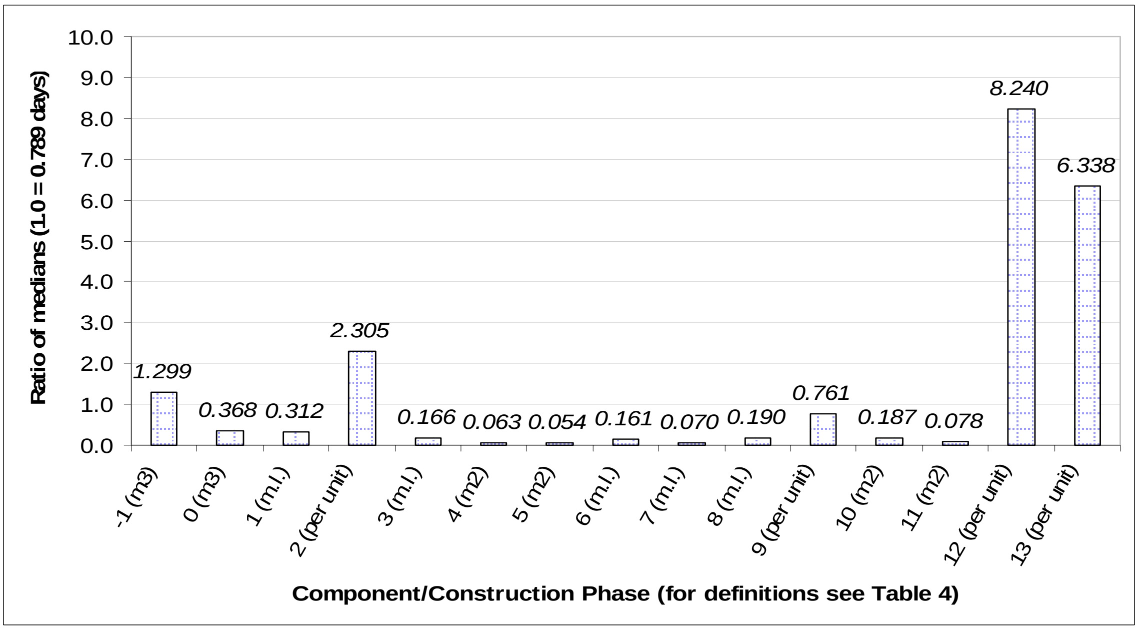

Figure 2 Ratio of probable component duration medians (normalized to R_T from Table 4 example)

5. ALTERNATIVE METHOD FOR DERIVING RECOVERY RATIOS

The results of the construction cost survey are used here to outline an alternative method for deriving recovery ratios (cost and time). This method would be particularly suited to advanced analytical vulnerability methods, such as 3D finite element analysis, that can capture information at the structural component level. In essence, the methodology consists of determining the quantity of component damage to various structural components and deciding which and how much construction replacement (as a repair) would be used or whether the building requires demolition and complete replacement. The cost/time ratio is determined through summing the required quantities. The methodology can therefore be expressed mathematically, see Table 2.

Table 2 Recovery ratio equations

$$RR\left|DS_i\right| = R_{DS\,i} / R_T \quad \text{(from Equation 1.1)}$$

with

$$R_T(m^2) = \chi R_1 + \delta R_2 + \varepsilon R_3 + \varphi R_4 + \psi R_5 + \gamma R_6 + \eta R_7 + \lambda R_9 + \mu R_{10} + \nu R_{11} + \omega R_{12} + \rho R_{13}$$

and

$$R_{DS\,i}(m^2) = \alpha_1 R_{-1} + \beta_1 R_0 + \chi_1 R_1 + \delta_1 R_2 + \varepsilon_1 R_3 + \varphi_1 R_4 + \psi_1 R_5 + \gamma_1 R_6 + \eta_1 R_7 + \kappa_1 R_8 + \lambda_1 R_9 + \mu_1 R_{10} + \nu_1 R_{11} + \omega_1 R_{12} + \rho_1 R_{13}$$

where $\alpha, \beta, \chi, \delta, \varepsilon, \varphi, \psi, \gamma, \eta, \kappa, \lambda, \mu, \nu, \omega, and\, \rho$ are constants determined from the inventory study (see example in section 6) and where $\alpha_1, \beta_1, \chi_1, \delta_1, \varepsilon_1, \varphi_1, \psi_1, \gamma_1, \eta_1, \kappa_1, \lambda_1, \mu_1, \nu_1, \omega_1, and\, \rho_1$ are constants determined from the damage quantities found during the vulnerability study and are the ratio of the damage to the relevant stage normalized to $1m^2$ of floor area. These parameters should assigned values for each damage state. R values can be taken from data such as that in Figures 1 and 2

6. EXAMPLE

In order to use this method, it will be necessary to firstly determine certain parameters from the inventory assessment, providing the numerical values of the parameters α to ω in Table 2. As an example, consider Figure 3 which is a plan for a confined masonry 3-storey building in Lima (located on an 8x20m plot). Table 3 presents some of the key quantities for the foundation and ground floor of the building. These key quantities relate to: total constructed floor area, stairwell area, masonry walls, columns, pad foundations, trench foundations and ground beams. In general, these values should then be normalized to a square meter of floor area, as indicated in the table.

Table 3 Inventory data for example building

Component	Quantity	Quantity per m^2 floor area	Note
Total floor area	108 m^2	1.000 m^2/ m^2	Including stairwell area
Stairwell area	1 unit (10.4 m^2)	0.009 units/m^2 (0.096 m^2/ m^2)	Considered on per floor basis
Masonry wall	66 m length (m.l.)	0.611 m.l/ m^2	2.05m high when ground beam present; 2.4m otherwise; Median: 0.15m wide
Column	25 units	0.231 units/m^2	Median: 0.3x0.3x2.6 (3.8m depth to pad base for ground floor columns)
Pad foundation	14 units	0.130 units/m^2	Median: 1.2 x 1.2 x0.6m deep
Trench foundation	75 m.l.	0.694 m.l/ m^2	Median: 0.6m wide x 0.8m deep
Ground beam	96 m.l.	0.889 m.l/ m^2	Median: 0.35m x 0.15m wide

In a subsequent vulnerability assessment, each damage state should be numerically described in terms of damaged quantities of the parameters, termed α_1 to ω_1 in Table 2. For example, let us consider a 'complete' damage state where a 3-storey confined masonry building requires total demolition and replacement (refer to Table 4). Using R values from Figures 1 and 2, and the equation from Table 2 it is found that the 3-floor model building total cost is S/. 277000 (S/. 855 /m^2) with a cost ratio (CR) of 1.37, and a total time of 403 days (about 19 months; 1.24 days/m^2) with a recovery time ratio (RR_T) of 1.58. Through inclusion of detailed construction components/phases, the procedure therefore offers significant versatility for those conducting vulnerability studies (using advanced analytical methods) to define and incorporate quantifiable damage levels based on component-level replacement.

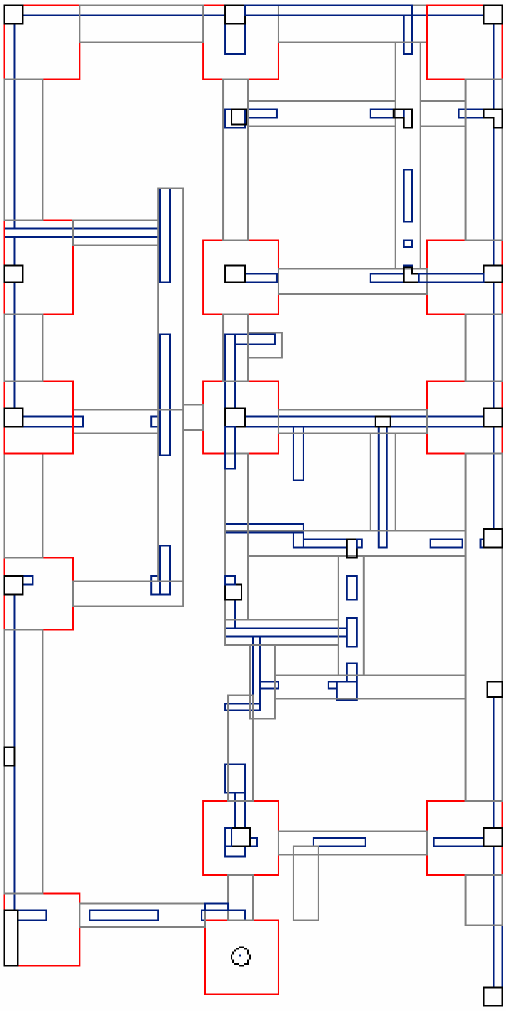

Figure 3 A confined masonry 3-storey building foundation/ground floor structure outline plan (not to scale)

Table 4 Construction component definitions/units and example constants/assumptions/ratios

Phase number	Component/Phase	Unit	Example quantity[a] for ground floor	Example quantity[a] for 3-floor building
-1	Demolition	m^3	α_1 = 37.4 m^3 per floor[b]	α_1 =112.1 m^3
0	Site clearing	m^3	β_1 = 37.4 m^3 per floor[b]	β_1 =112.1 m^3
1	Concrete trench foundation	m length	χ_1 = 75 m.l.	χ_1 =75 m.l
2	Reinforced concrete (RC) pad foundation	unit	δ_1 = 14 units	δ_1 =14 units
3	RC ground beam	m length	ε_1 = 96 m.l.	ε_1 =96 m.l.
4	False ground floor	m^2	φ_1 = 108 m^2	φ_1 =108 m^2
5	Ground floor finish	m^2	ψ_1 = 108 m^2	ψ_1 =108 m^2
6	Brick masonry wall	m length	γ_1 = 66 m.l.	γ_1 = 198 m.l.
7	Cement render of wall	m length	η_1 = 99 m.l[c]	η_1 =297 m.l.

8	Wall 'mesh' strengthening	m length	$\kappa_1 = 0$	$\kappa_1 = 0$
9	RC Column	unit	$\lambda_1 = 25$ units	$\lambda_1 = 75$ units
10	RC Floor (non-ground/roof)	m^2	$\mu_1 = 108$ m^2	$\mu_1 = 324$ m^2
11	Floor finish (non-ground/roof)	m^2	$\nu_1 = 108$ m^2	$\nu_1 = 324$ m^2
12	RC Stair	unit	$\omega_1 = 1$ unit	$\omega_1 = 3$ units
13	Stair finish	unit	$\rho_1 = 1$ unit	$\rho_1 = 3$ units
Example:				

Vulnerability assessment at damage level, i: For a theoretical damage state where it was found total demolition and replacement is required for a 3-storey building, recovery ratios are given as:

$$R_T(m^2) = S/.\ 622.89\ ;and\ \ 0.789\ \ days$$

$$R_{DS\,i}(m^2) = S/.\ 855\ ;and\ \ 1.24\ \ days$$

$$\therefore CR = 1.37; RR_T = 1.58$$

Notes: [a] Example quantities based on Table 4 values; and
[b] For example, assume building volume equal to (0.2m x floor area) + [(0.3x0.3x2.6)x columns] and (0.15m x walls).
[c] For example, assume render interior on all walls and 50% exterior.

7. CONCLUSION

A construction cost survey provided initial data that has been used to outline an analytical method for deriving recovery ratios (cost/time) for residential buildings in Lima, Peru. This method provides an alternative but complementary approach to existing empirical methods and in conjunction with seismic hazard and component-based building vulnerability studies can form a complete seismic recovery estimation model for earthquake planners. Use of 'real' consequences, such as cost and time, which can be readily understood by all stakeholders (including the public and government), is essential if seismic risk assessments are to satisfactorily influence disaster management and prevention policy-making and therefore reduce risk. This is especially important in a city such as Lima, Peru which has a high seismic risk and exposure.

Recommendations include:

a) Municipal authorities should collect component based information similar to that in Table 3 and publish statistics regularly (e.g. biannually). This data could easily be collected through the existing construction permit process.
b) Suitable civil society or governmental organizations should conduct and publish a regular (e.g. biannual) survey of construction components cost/time in the format of figures 1 and 2, which can be used by those assessing vulnerability to provide precise estimates in terms of 'real' consequences.

ACKNOWLEDGEMENTS

Thanks are given to the numerous builders and construction workers who participated. Thanks also to those assisting in the collection of the filled questionnaire forms. This work is part of a PhD funded by Benfield Group Ltd. and the UK's Engineering and Physical Sciences Research Council (EPSRC) via its CASE for New Academics scheme.

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