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DEVELOPMENT OF EXPERT SYSTEM FOR THE SEISMIC VULNERABILITY OF EXISTING MASONRY STRUCTURES

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Abstract: The collapse of unreinforced masonry structures, that are distributed around the earthquake prone areas of the world, is one of the main causes of death in earthquake disasters. Due to improper methods, lack of knowledge for the construction and maintenance, every year thousands of casualties and collapsing masonry houses are reported.

Most of the masonry building structures in Sri Lanka are designed only to bare the gravity loads, as there have no severe earthquake events frequently been affected. Even though, Sri Lanka was believed to have no seismic threats, it is now realized that Sri Lanka can no longer be considered as a country safe from seismic threats following the recent events that occurred in and around the island. Hence the need for evaluating the seismic adequacy of the existing masonry structures has come into focus. For this purpose, an expert system which contains specific knowledge for masonry structures was developed with the collected data from visual inspection survey, numerical calculations and field experiment.

Keywords: Expert System; Seismic Vulnerability; Seismograph; Unreinforced Masonry Buildings

1. Introduction

A developing country like Sri Lanka, majority of residential and public buildings can consider as masonry buildings, especially in rural areas most are adobe masonry buildings. Masonry buildings are popular due to their low cost in construction, construction easiness, and need of less labour skills, eco-friendly and use of locally available materials (Mendis et al. 2014 [1]). In the point of durability masonry buildings have a higher probability of failure under earthquake.

Hence the existing masonry buildings usually associated to a high seismic vulnerability. It causing injuries or even death of their occupants. But due to economic reasons, masonry building construction is still can considered as the best solution for low income housing in developing countries. Due to the week properties of the materials, geometry, foundations, connections between walls – roofs- floors, stiffness of the horizontal diaphragms or the building condition, gravity load-bearing walls, low flexibility of the floors, high mass of the masonry walls, existing masonry buildings are poor in seismic performance. Furthermore, "non-structural" elements (eg. partition walls) and their connection to the load-bearing walls can also be a reason for poor performance of these buildings.

Recent geological studies found convincing evidence for a long suspected geological phenomenon that the Indo-Australian plate is indeed splitting as shown in Figure 1. It is creating an intra-plate just about 400-500km from the southwest coast of Sri Lanka. Hence there is a potential of increasing seismic activities in Sri Lanka and need to consider the design requirement (Pradeep et al. [2]).

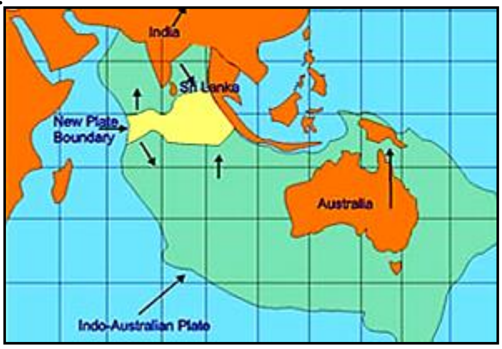

Fig 1: The Indo-Australian seismic plate and the splitting path

Other than that there are several incidents that local residents have complained about low-scale tremor occurred within last two decades and many damaged houses, especially in Hali-Ela, Haputhale, Badulla, Nuwaraeliya, Ampara, Damana, Mahiyangana areas in Sri Lanka (Panagoda. [3]), (Silva. [4]).

It is observed that the damage caused by such earthquakes tend to be very high due to lack of preparedness against them special on building and relevant infrastructure (Pradeep et al. [2]). It is very much essential to study to control the effects of the earthquake since the most of the building structures in Sri Lanka have not designed to bare the earthquake forces.

Though the newly constructed buildings in Colombo area adopted to earthquake building designs, local people in other rural areas build their masonry buildings without considering the seismic resistance. In the case of urban rehabilitation programme this attention may become critical for the designing of future disaster mitigate plan. It is considered being a timely requirement to assess the performance levels of masonry buildings for different return period earthquakes which happens without any advance notification.

Due to those reasons the seismic vulnerability and risk assessment of existing masonry buildings are truly essential. Developing a computer based assessment method (expert system) with past earthquake damage history & repair thereof, construction practices being adopted, building typology, seismic zoning of the area, building samples, detailed survey of selected buildings, quantitative and qualitative analysis will help to assess the seismic capacity or the seismic vulnerability of existing masonry buildings. This expert system will unable to select required seismic retrofitting, and identify the particular weaknesses and deficiencies to be corrected after scoring for the serious of field questionnaires as a qualitative measurement.

2. Objectives

Objective of the current study is focusing on survey and analysis of seismic vulnerability of existing masonry structures in South-East region in Sri Lanka and develop an expert system for enhancing the seismic safety of buildings.

3. Methodology

3.1 Selection of building type

In order to estimate seismic vulnerability of existing building stocks on a wide spread area as historical, engineered structure, non-engineer structure, residential, public and many. It is imperative to make suitable path for selection of building samples, analysis and determine the risk levels.

This expert system work with residential, school and hospital masonry buildings since those are the most damaged structures during the post-earthquakes and can easily upgrade with low cost retrofitting methods to enhance the existing seismic vulnerability level.

3.2 Selection of area

It is clearly identified that the Colombo area is most critical as in the history records. But today so many constructions and projects in that area have consider the seismic effect and most of all the designing are done with respect to seismic resistance by providing deep pile foundations, shear walls, hydraulic dampers and more earthquake effect control methods.

Hence Colombo area is not considered to the field investigations and data collection. But there are other areas which also record the low-scale tremor and many damaged houses during past years, especially in Nuwaraeliya, Haputhale, Hali- Ela, Bandarawela, Badulla, Mahiyanganaya, Ampara, and Damana (South-East area of the Sri Lanka). Those areas were selected as the source for the data collection of the existing performance of the masonry buildings.

3.3 Qualitative approach

As the first phase; visual observation survey data take in to account for measure the seismic vulnerability of masonry buildings in selected area. The visual inspection survey method is designed to be implemented the overall quality, safety of the existing structure without performing any structural calculations.

Fig 2: Observed failures of masonry structures - visual observation survey- South East Sri Lanka

The visual inspection and the qualitative expert system combination is expected to take around 30 minutes for inspect, data collect and decision making process in each building at site.

Walkover surveys were carried out in Ampara, Bandarawela, Badulla, Mahiyanganaya area to collect the visual inspection data sheet. In here a particular building was assessed and scored under several sections including seismic parameters which are more important in the resistance for any seismic attack. Those parameters are divided into general detail, masonry details, non-structural component details and ground characteristics as mentioned in the Table 1.

Table 1: Scoring system parameters for the visual inspection survey

General Information (Existing condition)	Masonry details of the Building	Non-structural Components details	Ground Characteristics
Type of the building, No of stories, Year built, Total floor Area, Maintains frequency, No of occupies, No of rooms, Visual construction quality, Number of access ways, Open space availability, Adjacency, Existing crack pattern	Foundation Type, Wall Type, Mortar Type, Thickness of wall, Irregularities, Sloping site, Out-of-plane, Short column, Plan Irregularities, Finishing, Load path, Building frame structure, Column type, Horizontal bands, Doors and windows	Parapets, Chimneys, Equipment & Furnishings	Soil Type, Geologic Hazards

After completing visual inspection survey; those data used to identify the existing seismic hazard level of those masonry structures. For that a particular scoring system was developed. A special scoring system have developed and programmed in excel sheet with the aid of past experiment and literature. In here a checklist uses to calculate the safety compliance level of masonry structure. Seismic vulnerability and safety compliance of an existing building is evaluated by answering checklist. User can fill in the checklists of only those hazards which are relevant to selected masonry structure at a particular place.

The grade of building seismic vulnerability is depending on its final score level. A basic vulnerability score will select by user for each parameter with respect to the site observations (Figure 3). Modification of these basic scores to the issue importance level existence of different types of efficiencies. A final structural score, S, is determined for a given building by adding all the weighted modified scores in each selective sections with respect to structural hazard level. The final score that indicates the relative seismic vulnerability of a building within a group to identify the buildings requiring further study and can have a damage probability interpretation.

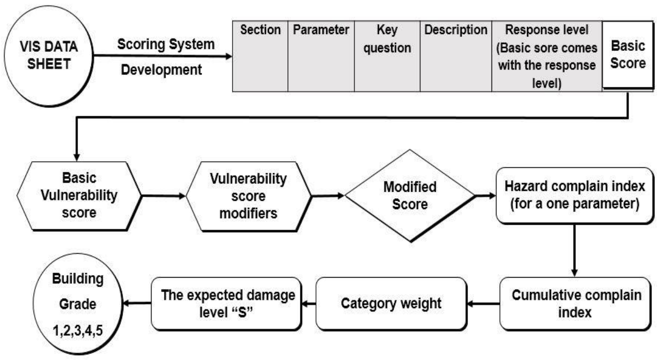

Fig 3: The scoring system flow diagram

Final results of the score level can conclude with graphical interpretation as in Figure 4.

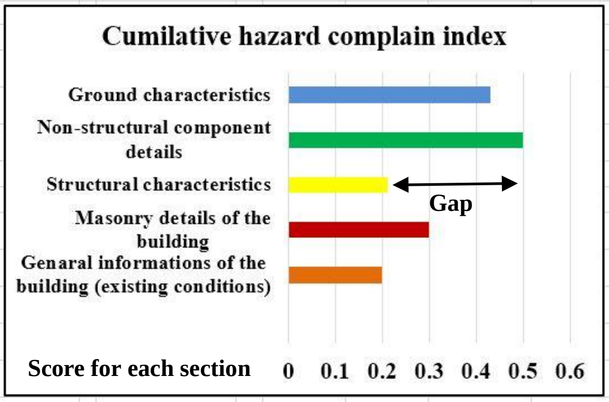

Fig 4: Summery of the seismic vulnerability results.

By referring and comparing the score and gap between them in each sections of masonry building; user can identify the critical conditions in term of seismic resistance and selecting suitable retrofitting method.

Based on literature information, the "cut-off" score for structural grading system was selected. This cut-off score decides the risk level of the particular masonry structure. Above survey data used to validate this cut-off mark and develop a grading system accordance with the score level as grade 1 to grade 5.

The damage classifications based on the European Macro Seismic Scale (EMS-98). Typical building types in walkover survey areas are defined and compared to the standard construction types of the EMS-98. EMS-98 intensity scale denotes how strongly an earthquake affects a specific place or structure. Modern EMS-98 scales introduced both qualitative and quantitative approach to seismic damage level. The flexibility that EMS-98 offers for use outside of the European region urge current version of the scale for global application. (Maqsood et al. [5]). Since the visual detection of the building damages are basic for the building classification; EMS-98 selected only as the basis for building classification.

Vulnerability classification was modified and an appropriate vulnerability class for the Sri Lankan building stock was defined with probable ranges by taking into account the local construction practices.

This procedure utilises a method of grading system that requires the evaluator to identify the primary structural lateral load-resisting system, and identify building qualities that modify the seismic performance expected for this lateral load resisting system. These results can also be used to determine the necessity of retrofitting buildings where more comprehensive vulnerability assessment may not be feasible.

3.4 Quantitative approach

Developing the expert system tool with quantitative approach is essential to get more accurate results for the inspection and provide accurate instructions to recommend the best retrofitting method. For that building deformation data under the seismic load have to be investigated. Hence it is proposed to build a model masonry house and identify its behaviour, crack propagation during a seismic load.

For model such kind of environment the best place is the rock blasting site. In the case of earthquake, the frequency of waves will be less and its amplitude will be more in long period of time. However, in blasting, the frequency will be high and amplitude will lower in short time period. Hence the blasting and earthquake difference in the type of vibration.

But in the rock blasting the damage occurs which depends on the received structural vibration as same as in an earthquake. In both cases the energy dissipation is mostly done in ground vibration. Since Sri Lanka not frequently affect to earthquakes with high magnitudes; it is limited to select similar vibration source in actual environmental condition.

Due to those reasons a scaled model house was built near to rock blasting site and observed the crack pattern propagation and the strengthening efficiency with mesh type retrofitting technique for validate the results in expert system.

Before build up a model house it is necessary to ensure that the particular rock blasting release sufficient vibration level to record any crack pattern or can compare with the earthquake magnitudes. According to the experimental study, a wall panel experienced a structural separation from the foundation by a significant cracking at a PPV (Peak Practical velocity) of 30.2mm/s (Wickramasinghe et al. 2011 [6]).

The motion of ground particle usually occurs in horizontal, vertical and transverse direction. When vibration occurs each particle has velocity and that maximum velocity referred to as PPV (Ranasinghe et al. 2012 [7]). In most cases, the PPV is closely linked to the potential to damage structures rather than the acceleration or displacement. (Wickramasinghe et al. 2011 [6]).

To ensure the selected rock quarry is sufficient to have the adequate vibration level (PPV) the seismograph (Blastmate III) was set up at the different locations of the site.

A transducer was fixed on the surface soil using ground spikes, pointing the arrow located in the top of the standard transducer in the direction of source vibration.

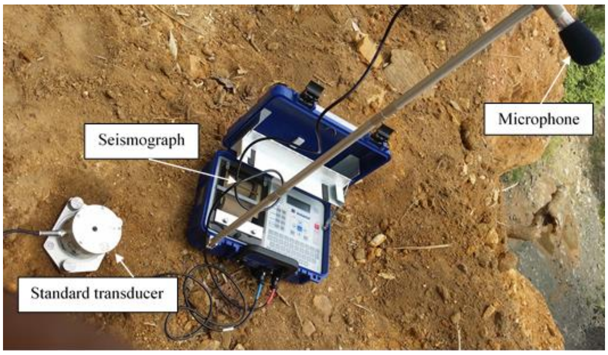

Fig 5: Measuring ground vibration induced by rock blasting

The response spectrum was obtained and it is analysed to identified the critical PPV value. The results are displayed in the Figure 6.

According to the results; PPV values for vertical direction 68.7 mm/s, for longitudinal direction 39.2mm/s and for transverse direction 36.2mm/s. So these results confirmed that the vibration level exceed the limit of 30.2mm/s and the location, the distance form source is suitable to build up the model house.

	Tran	Vert	Long	
PPV	36.2	68.7	39.2	mm/s
ZC Freq	>100	85	85	Hz
Time (Rel. to Trig)	0.008	0.013	0.013	sec
Peak Acceleration	1.94	3.87	2.56	g
Peak Displacement	0.172	0.104	0.212	mm
Sensor Check	Disabled	Disabled	Disabled	
Frequency	***	***	***	Hz
Overswing Ratio	***	***	***	

Peak Vector Sum 81.2 mm/s at 0.013 sec

Fig 6: The experimental results of vibration level at the rock blasting site

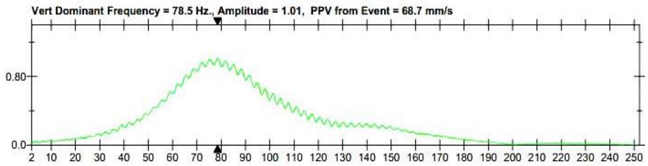

Fig 7: FFT report generated for the vertical direction vibration

Figure 7 shows the frequency spectrum of the vibration in vertical direction. Frequency spectrum shows that the maximum energy of the vibration in vertical direction. These observations confirmed the site suitability for the model house.

A plain brick masonry structure was chosen as test house. The test house was designed as the 1:4 scaled structure of actual masonry house. Walls were built up with English bond brickwork. Since the rock blasting site continuously blast per four days, the adequate strength of masonry mortar has to be achieved in short period. In that case sample mortar cubes were casted with high early strength admixture. Masonry blocks were casted as set with three cubes as 1:4:0.01, 1:4:0.25 and 1:4:0.5 cement: sand: admixture

The compressive strength of cubes was tested (Table 2) in 2 days,3 days and 5 days.

Table 2: Compressive test results for masonry mortar.

Day	Load (N per mm²)			
	Controller	01 mix	02 mix	03 mix
Day 2	6.84	8.72	wet	wet
Day 3	7.36	9.36	0.72	0.64
Day 5	7.86	9.92	2.4	1.1

According to the BS5628-1:2005 page 11; M4 compressive strength class 1:4 cement: sand mortar masonry should achieve 4 N/mm² at 28days. It is identified that the mix 01, 1:4:0.01 (cement: sand: admixture) was achieved the limitation early strength even after two days. So that proportion selected for all the masonry works in model house.

Before brickwork, bricks soaked in water. Mortar of compounding ratio; early-strength admixture with cement 1 and sand 4, was used as bond for bricks. The compressive strengths were 0.15MPa of brick, 0.8MPa of mortar, approximately. Wooden lintels were installed on openings. Weight of test house slab was about 30 kg. walls covered with white wall filler layer to clearly identify the crack lines.

For measuring the vibration level and observed the crack propagation; Three transducer was fixed on the three different locations of the masonry house (Figure 8).

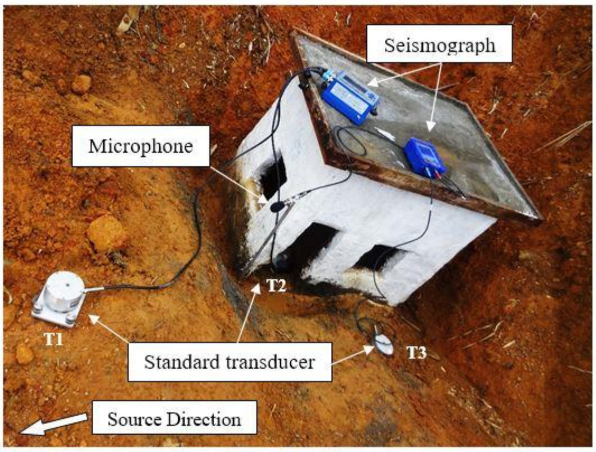

Fig 8: The experimental set up of seismometers

The response spectrum was obtained and it is analysed to identified the critical PPV values and FFT values to confirm that the vibration level exceeded the required PPV as Wickramasinghe et al. 2011 [6].

Small hair cracks were visible on the opening corners and the bottom level of the model house (Figure 9).

Fig 9: Observed crack lines after blasting

Crack width was measured by using standard crack gauge and most of the cracks are recorded as 0.1mm, 0.15mm. Major cracks clearly identified near the doors and windows openings. Other than that a linear crack line propagates through the bottom wall level where the bricks connected to the foundation. Diagonal crack appeared from the top and bottom of window openings.

Hence it was conformed that the openings are more vulnerable to collapse in seismic attack. As these finding have to applicable to Sri Lankan condition; Cost effective retrofitting techniques selected for strengthening the opening areas of masonry building. By comparing different techniques, the mesh type retrofitting was the best. It is cost effective, can easily apply, locally available, even can use to existing buildings without many disturbances to the structure.

To idealised a proper retrofitting techniques to reduce the crack propagating at corners and openings; another ferrocement retrofitted modal masonry house was built in the same place (Figure 10).

Fig 10: Observed crack lines after blasting

After the same experiment procedure, it was observed that no any visually observed crack propagates on the masonry walls after steel mesh retrofitting.

4. Results

The data collected in initial walkover survey used as inputs to the developed expert system. From that obtained results for residential masonry buildings are representing in following.

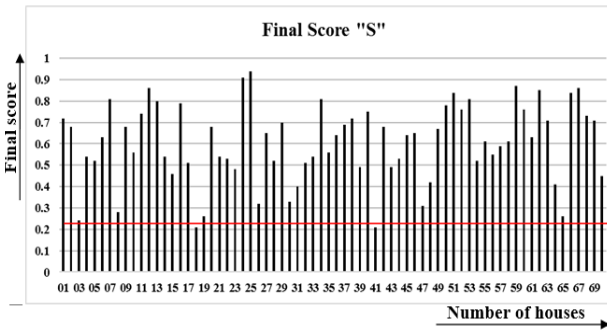

Fig 11: Final score variation for residential masonry buildings

According to the expert system evaluation results. From the field data the S=0.23 score level is found as the cut-off mark. S < 0.23 indicates high vulnerability requiring further evaluation and retrofitting of the building. Structures scored below 0.23 that have to retrofit immediately against the seismic load. Structures scored above 0.23 are classified in to different classes and high score buildings considered as strength enough to earthquakes and minor tremors for the safe evacuation.

It has found that 2 residential structures out of 70 are high seismic vulnerable and required immediate retrofitting (Figure 11). It was identified that 29 houses categorised under grade 2 will experienced moderate damage (Slight structural damage, moderate non- structural damage), cracks in many walls, fall of fairly large pieces of plaster in the presence of considerable earthquake magnitude. These houses can adopt light retrofitting techniques to enhance the seismic load bearing capacity. Grade 3 class masonry houses need special attention on retrofitting while it is indicated 39 houses on it. These houses substantial to heavy damage (moderate structural damage, heavy non- structural damage), large and extensive cracks in most walls with many structural failures.

From the expert system; obtained results for School masonry buildings are representing in following Figure 12.

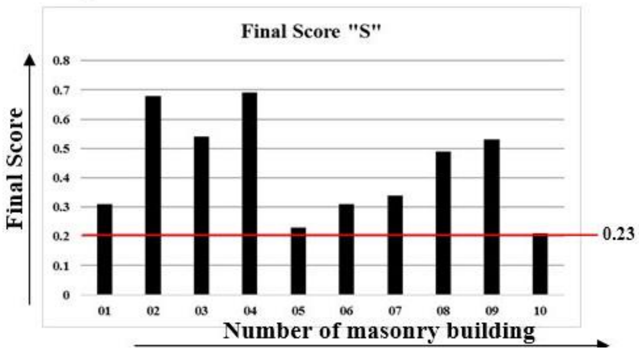

Fig 12: Final score variation for school masonry buildings

According to the results most of the hospital masonry buildings in selected area are categorised under grade 3 and need special attention on retrofitting. Hence it is confirmed that most of the masonry structures are not strength enough to bear seismic loads.

5. Conclusions

In this study, a tool kit called expert system was developed with the field data of South-East region in Sri Lanka and experiment data to survey and analysis of seismic vulnerability of existing masonry structures. It was found that the most masonry structures are in danger with seismic load. Unreinforced masonry structures have huge possibility to falling under earthquake if the proper strengthen have not done. By using this expert system user can identify the existing risk level and have recommendations to upgrade the structure to have effective evacuation period in an earthquake.

It was confirmed that openings are diagonally cracked with seismic loading and the crack developing in opening areas can minimized by providing steel type mesh retrofitting band.

The expert system methodology permits easy and rapid reassessment of the risk level of buildings already surveyed based on availability of new knowledge that may become available in future due to scientific or technological advancements.

Acknowledgement

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