PRIORITIZED POST-EARTHQUAKE RESPONSE

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Abstract

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Prioritized Post-Earthquake Response (PPR) is an integrated system combining state-of-the-art sensor technology and networking with advanced non-linear analysis, to create a real-time network for authorities and communities. It is a highly efficient and cost-effective preparedness tool that enhances community resilience in the immediate aftermath of a seismic event. The PPR Network is comprised of four principal elements: assignment of building damage thresholds; local ground motion measurement; data access and user action.

Damage thresholds are assigned to each building in the network based on the type and age of construction, prominent seismic performance features and the local governing hazard type. To make this process efficient, a database of building damage thresholds has been developed based on the results of extensive non-linear dynamic analysis.

A specialized network of ground motion sensors is deployed that measure the severity of local ground motion; each sensor is connected to adjacent buildings that share the same type of soils. The sensors record peak ground motion that, in combination with the building thresholds, predict the expected level of damage in each building.

Information can be accessed on-line using the "PPR Responder", a tool that incorporates a database of all "connected" buildings in the network. Immediately after an event, the Responder automatically generates a prioritized building damage report for use by local government and by the occupants of each connected building. In the circumstance when no network connection is available, each sensor in the network can be accessed locally to obtain the measured shaking level.

From a community-wide perspective, the information provided by the network can be used for both pre-event planning and post-event response and real-time allocation of resources. From an individual building perspective, PPR will assist building occupants in making the critical *Stay-Leave* decision immediately following the main shock. All building occupants will need to decide independently of local government.

Proper training of the users is a critical component of the PPR Network to maximize its benefit, both for access of the information and to enhance capabilities for pre- and post- event actions. Regular training in the use of the PPR Network will lay the groundwork for self-reliance and community resilience in the immediate aftermath of the seismic event.

Membership in the PPR Network is broadly based and embraces a wide diversity of building owners including government buildings, first responder buildings, schools and residential wood frame houses. Twenty sensors are currently in place across the Greater Victoria area, in Western Canada.

1. Introduction

Prioritized Post-Earthquake Response (PPR) is an integrated system combining state-of-the-art sensor technology and networking with advanced non-linear analysis, for pre-event public education and to provide immediate, on-the-ground information for authorities and communities to optimize response. PPR is designed to be highly efficient and cost-effective and is comprised of four principal elements:

- Assignment of building damage thresholds
- Local ground motion measurement
- Remote and local data access
- Trained user action

At its essence PPR works on an individual building level; the assignment of thresholds is for specific buildings. However, it is not needed to have sensors in every building; just as with traditional seismic networks only a few are actually needed for a group of buildings. It is useful to group buildings according to similar soils, since for practical purposes they will have the same shaking level. We can describe a group of buildings on a single type of soil as a community.

PPR builds from the post-earthquake evaluation practices as defined in the Seismic Retrofit Guidelines [1], Volume 10. These guidelines use a Performance Based methodology developed in British Columbia, Canada for retrofit of public school buildings. To make the process more efficient for designers, the guidelines incorporate a series of common structural prototypes (lateral deformation resisting systems); for each prototype static and quasi-static tests were performed to develop a set of backbone performance curves, and then a large set of incremental dynamic analyses was performed for each prototype to obtain drift values to increasingly scaled earthquake records. These results are combined probabilistically into a database to estimate performance and aid in design.

For the evaluation guidelines, a set of 4 damage states are defined using different drift levels for each prototype. These are a critical component of the evaluation process, since they provide the common basis of determining whether a structure would be green, yellow or red tagged. It is possible to do this due to the nature of the performance based guidelines. These damage states are as follows:

- DS1: minor damage (cracks in drywall etc); simple repairs. Green tag.
- DS2: heavier damage but repairable with reasonable effort. Green tag.
- DS3: heavy damage only repairable with closure of the building. Yellow tag.
- DS4: near total damage; demolition may be necessary. Red tag.

This paper provides an overview of the PPR process with respect to an example community.

2. Representative Community

PPR is designed to be used by the community in its planning and response; as described above this requires assignment of damage thresholds for all buildings in the community and a network of sensors that provides the shaking relevant to those buildings. A regional PPR network would be divided up into a series of separate soil polygons, each of which features approximately uniform soil. As an example, a soil polygon could be considered to be 10 sq km, be situated on firm soil and would include the following types of buildings:

Municipal hall: officials in charge of policy making and budgetary decisions

Firehall: tasked with primary coordination of emergency response

School: will act as a community meeting point and shelter after an event

Offices: employs a large number of residents

Residential buildings: single homes and apartment buildings

The traditional emergency response for this community at the authority level would be to respond to reports on the ground as they come in with respect to damage and fire, and if trained personnel are available they would make visual inspections of the critical buildings (particularly the school if it is to be used as a shelter). Residents who are unsure about the safety of their homes will head to the shelters. Building owners with more complex structures will need to wait for engineering inspectors to perform the inspection before they are allowed to reoccupy and resume business operations (this could be several months).

3. Damage Thresholds

Damage thresholds for each building are obtained using non-linear incremental dynamic analysis [2]. A suite of ground motions is selected [3] and applied to a prototype model representing the lateral deformation resisting system for a particular structure. The maximum building drift is computed from each ground motion at increasing levels of application. The set of PPR thresholds are computed based on the prototype exceeding certain drift values. The specific values are taken as the spectral acceleration at 1 second period (Sa(1.0)) from the record that was applied at that drift level . Two threshold values are computed: at the onset of potential damage (Resilience Threshold: Yellow) and at the onset of heavy damage (Total Damage Threshold: red). The PPR thresholds are related to the damage states as described above in the following way:

- DS1/DS2: PPR Green
- DS3: PPR Yellow
- DS4: PPR Red

Fig. 1 shows an example of the PPR thresholds in graphical form. In this example, spectral acceleration (Sa(1.0)) for the Resilience threshold (yellow) is 20%g and the Total Damage Threshold (red) is 30%g. Comparing that to the shown code values of 24%g and 43%g, this structure would be deficient at both levels.

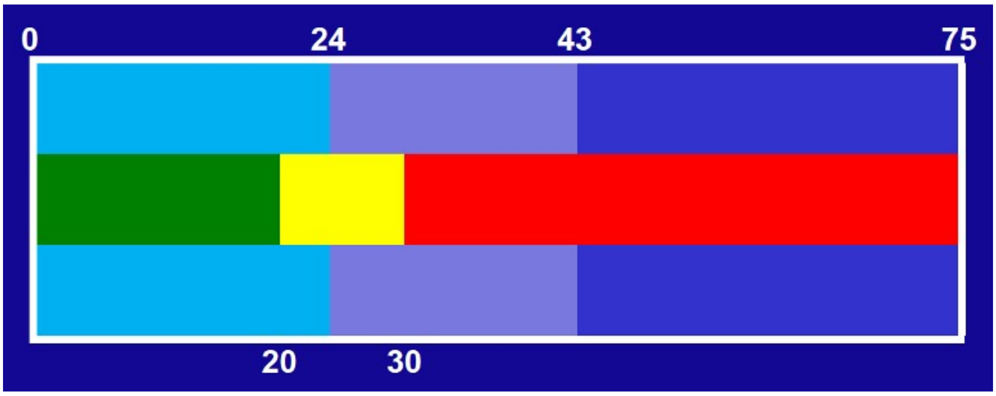

Fig. 1 - Example of PPR Thresholds: Computed values (bottom) vs Code values (top) – Sa(1.0s) accelerations

It is not practical, and not strictly necessary, to perform a detailed analysis on every building in the community. Alternatively, to make this process more efficient, a database of building damage thresholds is developed based on the results of non-linear dynamic analysis on common building types. Then, damage thresholds are then assigned to each building in the network based on the type and age of construction, prominent seismic performance features and the local governing hazard type.

For the buildings in the generic community above, the following would be examples of thresholds:

Table 1: Sample Building Damage Thresholds

Building	**Era**	**Notes**	**PPR Threshold [%g]**	
			Resilience	**Total Damage**
Municipal Hall	1950's	Governed by URM parapet walls	15	20
Firehall	2000's	Post-Disaster Building	60	85
School	1980's	Partially Retrofitted	40	50
Offices	1970's	Original Construction, Concrete Shearwalls	40	45
Residential Buildings	1910's 2000's	Cripple wall governs Contemporary house	15 50	20 65

4. Sensor Network

PPR requires a specialized network of sensors that will immediately provide information on the severity of local ground motion. As described above, it is not necessary to have sensors in every building; a single soil polygon (area of uniform soil type) will typically require one or two sensors depending on its size. These sensors will provide the data for all buildings within that soil polygon. Each sensor will record peak ground motion that, in combination with the building thresholds, predict the expected level of damage in each building.

The sensors used in the network utilize the concept of an 'internet accelerometer' [4] which is an all-in-one device, including accelerometer, digitizer, recorder and communication (Fig. 2). This allows for ease of installation and maintenance at lower cost, which is necessary to build a dense network. The specifications of the sensor include:

- ANSS Class B Accelerometer
- Low power consumption (0.2A) requiring 5V via USB
- External UPS to provide 24hr of backup power
- Self noise is 60μg RMS in 50Hz (analog 90dB)
- On-board of data storage for 30 days in miniSEED format

The sensor processes the data on-board in real-time, calculating the SDOF response at 1.0 second period due to the measured earthquake in each orthogonal horizontal direction. It then reports the maximum of the two values as the shaking level for use in PPR. The data can be read remotely (via the PPRresponder website; see Section 5) or locally by connecting to a digital display. The displays connect to each sensor using ethernet and can be located next to the sensor or in another part of the building (which is useful if the sensor is in the basement and the display is on the first floor, for example).

In the case of the generic example, two sensors are installed within the soil polygon. Ideally the sensors would be located roughly equidistant to all structures within the soil polygon; in practice however, this is usually determined by the buildings which are accessible to act as hosts (provide installation points, power and network access). Typically, the starting point for a community would be through either the local government (ie the municipal hall); the authorities (firehall) or through the schools. In some cases sensors would be installed in private homes or business. Fig. 3 shows an example map of the community, showing the sensors and how they relate to a fictional soil polygon.

Fig. 2 - PPR Sensor mounted on a foundation wall

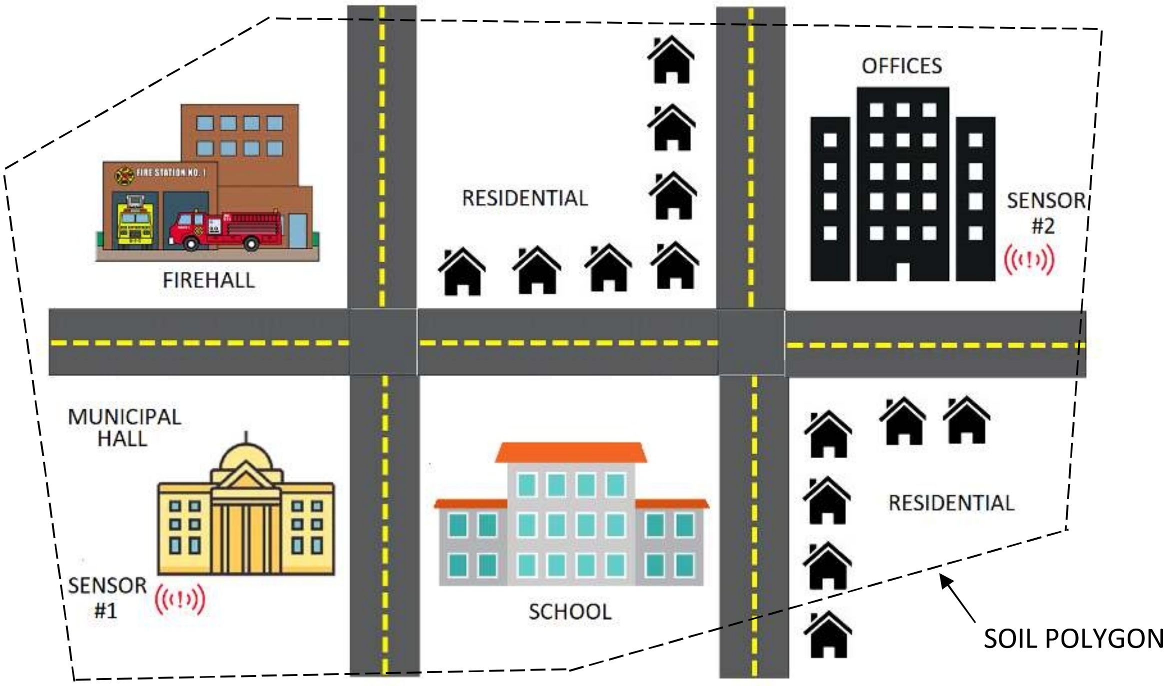

Fig. 3 - Overview of Generic Community and Sensor Locations

5. PPR Responder Tool

The central user access portal is the "PPR Responder", an online tool that incorporates a database of all connected buildings with the live data from the sensors. The tool has features for:

- Facility analysis: for a given building, the results from the database can be extracted related to a given hazard type. Results are plotted for resilience and life safety levels.
- Scenario analysis: this takes the facility analysis further to include multiple buildings; the user can select specific buildings, or an entire set. The results show the expected distribution of damage. This is beneficial for authorities in the resource planning phases.
- Live analysis: the live analysis connects the results in the database to the actual on-the-ground data from the sensors. Immediately after an event, the Responder generates a prioritized building damage report for use by local government and by the occupants of each connected building.

An example of the facility analysis tool is shown in Fig. 4. The PPR rating for the building is shown on the top left; the code hazard demand is shown in the top right. By computing ratios of the two, the 'seismic performance results' for both resilience and life safety can be plotted (bottom left). These results can be used to describe the performance of the building, and a description of classification and ranges are provided in the table on the figure (lower right). This example building has good performance for resilience level, and a slightly deficient performance at the life safety level. If a building is less than 75% of code level, and particularly less than 50% in terms of life safety, this would inform the owner that action is required.

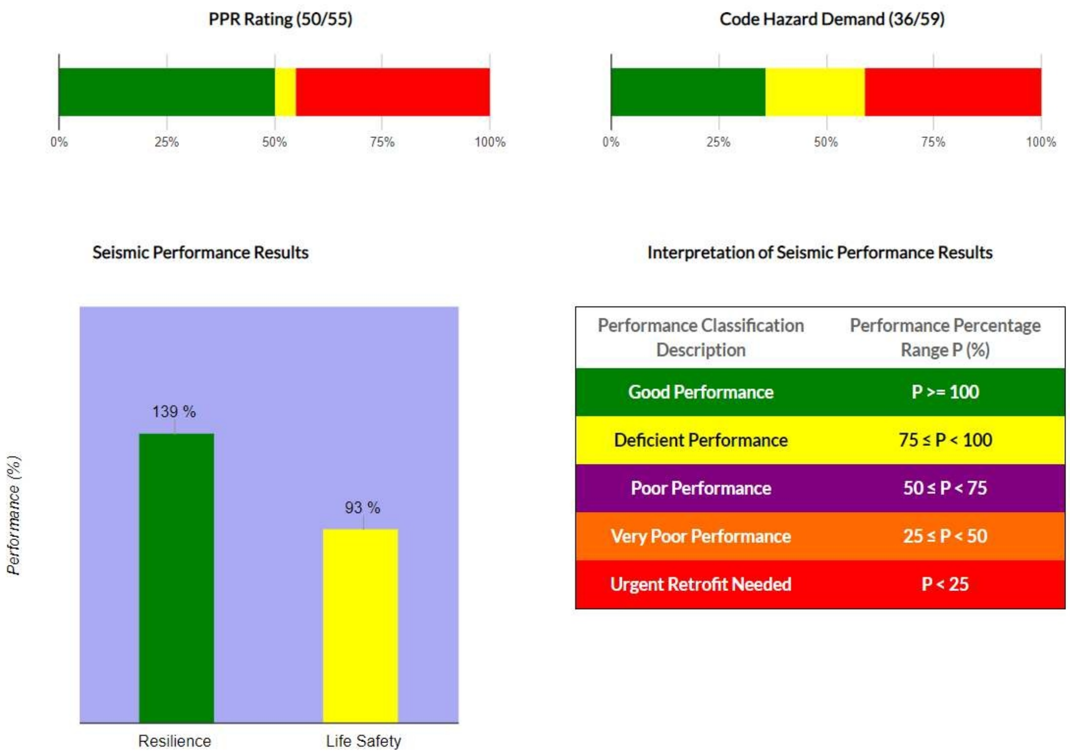

Fig. 4 - PPR Responder Tool – Facility Analysis Example

6. Training

Proper training of the users is a critical component of the PPR Network to maximize its benefit, both for access of the information and to enhance capabilities for pre- and post- event actions. Regular training in the use of the PPR Network will lay the groundwork for self-reliance and community resilience in the immediate aftermath of the seismic event.

The method of training will depend on the type of structure and how it is operated. For the generic community as able:

- Municipal Hall: Typically, engagement and training begins with the higher-level staff, and then work down to operations and security staff. PPR will augment the emergency response plan. Due to the age of the structure, egress routes may be modified to consider falling hazards.
- Firehall: Typically, engagement is with the Fire Chief and/or Deputy Fire Chief. In this type of specialized facility they will have desire to have a PPR plan for the firehall but also for the larger community and known vulnerable buildings. They will have a vested interest in the location and data of all sensors in the local area, and in the number of community participants.
- School: School training is unique because of the nature of the occupants which include staff and students. Schools will not only have detailed response plans but will also have many drills throughout the school year, and PPR will be incorporated. Training may be done directly at the school through the Principals and Vice Principals, or through the school district with maintenance and operations staff. Typically, it will involve those who are involved with the emergency response plan.

- Office Building: Office buildings will often have security personnel on site, and emergency response plans that involve floor wardens in charge of accounting for all occupants. PPR may modify egress routes, and muster points away from the building if falling debris is an issue.
- Residential: For a single-family residential unit, training would focus on understanding what the PPR thresholds mean, what to expect from your own home after an event, where to get the PPR shaking value (if it is not in your own home) and how to make a decision to stay or leave your home. In many cases the training would happen on a larger scale, such as a community event. For multi-unit residential, there may be additional training with respect to exits, occupants needed assistance etc.

7. Functions of PPR

Community Planning (Pre-Event)

A critical aspect of PPR is to aid authorities and residents in pre-event planning. Having every building in a community as part of the network allows the authorities and reponders to have information on what to expect from a distribution of damage point of view. The tools on the PPRResponder website can be used to estimate the distribution of damage based on differenct earthquake scenarios.

Community Response (Post-Event)

When an event occurs, each sensor in the network will record the shaking and compute the PPR values. These will be reported through the PPRresponder tool, and if the network is unavailable, data will be retrieved from each sensor and made available locally (at the sensor site) and reported back to the emergency managers in the community.

The information on the overall shaking coupled with the previously determined PPR thresholds for each building will be used to assist in allocation of resources.

Individual Response: Stay-Leave Decision

From an individual building perspective, PPR will assist building occupants in making the critical *Stay-Leave* decision immediately following the main shock. All building occupants will need to decide independently of local government. This decision will be made mostly after the event, but critical planning should be done in advance, in order to make the decision more clear. This is one of the advantages of PPR in its ability to assess the potential dangers in a given building and its expected performance.

8. Example Scenarios

For the purposes of discussion, it is useful to examine two example scenarios: for a moderate earthquake and a large earthquake. In many cases the benefit of PPR becomes most obvious in the case of a smaller or moderate event, when shaking is significant, with widespread visible damage, but uncertainty about the actual safety of buildings.

Moderate Event

Consider a moderate subduction event with a return period of 500 years, and a maximum Sa(1.0) of 17%g; the event occurs in the daytime with most people away from their homes. The shaking is felt across the region, and some small damage is observed. In the case of our example community, some damage is seen in the older houses with cripple walls and for structures with URM (as in the parapets on the Municipal Hall). Some damage is seen in drywall and unsecured non-structural elements are displaced.

Most of the population will observe the drop, cover and hold on response to the initial shaking. In some cases the shaking may be minor and the occupants will not respond, nor feel that they need to trigger the emergency response. For the others, and for each of the buildings as described above, they will observe the following PPR response:

- Municipal Hall: After the shaking, the occupants will check the PPR value from the sensor (the display will be located in a conspicuous location near an exit). Upon seeing that the value is slightly above the yellow threshold, they will trigger the response to evacuate the building. However, the designated wardens will first check the exits to ensure that no failure of the URM parapets has occurred. Upon an overall visual inspection, the building warden can make the decision whether to re-enter the building.
- Fire hall: After the shaking, the occupants will obtain the PPR value either from the website or from the personnel at the Municipal hall or office (a plan will be in place to have communication via radio between these parties). Upon confirmation of the low shaking value compared to their own facility, they will focus their response on immediate response needs (known fires etc) and then turn to the PPR reports which will indicate the vulnerable buildings compared to the known shaking.
- School: After the shaking, the school administrators will immediately follow their response procedures, often which will involve evacuation. They will obtain the shaking values, either via the website or by radio or other pre-planned method. A decision will be made to re-enter the building since the shaking is much less than the PPR threshold of 40%.
- Office: After the shaking, the building officials will immediately enforce the emergency response procedures. They will obtain the shaking values directly from the sensor or the website, and make a decision to re-enter the building since the shaking is less than the PPR threshold.
- Residential: During the shaking, some of the residents will be home, while most will not. Those who are home will feel the shaking directly. They will first check the PPR levels on the website, and if that is not possible, they will head towards the location of the nearest sensor to obtain the value. Those in older homes and particular those with cripple walls will feel the shaking more strongly, and may see some significant damage to siding and doorways.
- Residents who are away from home (at work etc) will check the website to see what the shaking level is. In many cases they will be well aware of the thresholds assigned to their home, but those values will be available on the website. For those that have lower thresholds, they may attempt to get to their houses immediately and check on pets or loved ones. Those that can see that their homes are likely undamaged would be free to focus on other tasks in the short term. This has advantages as it keeps people working and off the roads which are needed for emergency personnel.

Severe Event

Consider a severe event with a return period of 1000 years, and a maximum Sa(1.0) of 42%g. The event occurs during the daytime when most of the population is away from their homes. The shaking is felt strongly across the region, and significant damage is widespread. In the case of our example community, damage is seen in many structures, some partial collapses have occurred (including to the URM and cripple walls) and significant damage to external and internal cladding (drywall and siding) and unsecured non-structural elements is observed.

Most of the population will observe the drop, cover and hold on response to the initial shaking. For each of the buildings as described above, they will observe the following PPR response:

- Municipal Hall: After the shaking, the occupants will check the PPR value from the sensor (the display will be located in a conspicuous location near an exit). The values will have exceeded the thresholds for both the parapets and for the upper storey, and they will trigger the response to evacuate the building. As part of the evacuation plan, some of the exits may be closed off due to risk of external failing debris. The designated wardens will check the approved exits for safety. The occupants will not be allowed to re-enter the building until a qualified engineer has performed the inspection and allowed reoccupation.

- Fire hall: After the shaking, the occupants will obtain the PPR value either from the website or from the personnel at the Municipal hall or office (a plan will be in place to have communication via radio between these parties). Upon confirmation that the shaking value is below the yellow level for their own facility, they will focus their response on immediate response needs (known fires etc) and then turn to the PPR reports which will indicate the vulnerable buildings compared to the known shaking. For this case it is critical to have as many of the residential units enrolled in the PPR program to determine the appropriate response.
- School: After the shaking, the school administrators will immediately follow their response procedures, often which will involve evacuation. They will obtain the shaking values, either via the website or by radio or other pre-planned method. A staff with training in rapid damage assessment (ATC-20 or equivalent) may perform an assessment and determine if it is safe to re-enter. In some cases, different parts of the school (library, classroom, gymnasium etc) may have different thresholds, and a decision may be made to not re-enter certain blocks, or move all students to a single block (such as the gymnasium) until they can be picked up by parents. This would be of particular importance in case of inclement weather (rain, snow, cold, etc).
- Office: After the shaking, the building officials will immediately enforce the emergency response procedures. They will obtain the shaking values directly from the sensor or the website, and evacuate. A staff with training in rapid damage assessment (ATC-20 or equivalent) may perform an assessment and determine if it is safe to re-enter. In most cases the staff will not re-enter the building and wait for a qualified engineer to perform the inspection.
- Residential: During the shaking, some of the residents will be home, and some will not. Those who are home will feel the shaking directly. They will first check the PPR levels on the website, and if that is not possible they will head towards the location of the nearest sensor to get the value. Those in older homes and particular those with cripple walls will feel the shaking more strongly, and may see some significant damage to siding and doorways. In some cases partial collapses will occur. Many homes will see damage to drywall, fixtures and other non-structural elements.
- Residents who are away from home (at work etc) will attempt to check the website to see what is the shaking level; it is possible that there will be no or limited network connectivity. In many cases they will be well aware of the thresholds assigned to their home, but those values will be available on the website. For those that have lower thresholds, they may attempt to get to their houses immediately and check on pets or loved ones. Those that can see that their homes are likely undamaged would be free to focus on other tasks in the short term. This has advantages as it keeps people working and off the roads which are needed for emergency personnel.

9. Conclusions

Prioritized Post-Earthquake Response (PPR) is a highly efficient and cost-effective preparedness tool that enhances community resilience in the immediate aftermath of a seismic event. A PPR Network is comprised of four principal elements: assignment of building damage thresholds; local ground motion measurement; data access and user action. The damage thresholds are based on non-linear incremental dynamic analysis, and a database of common construction types has been created to aid in the difficult task of dealing with a large building stock. A specialized sensor network is deployed to provide immediate, on-the-ground data with regards to the shaking level. The data will be available via a webtool, or directly at the sensor location in case of loss of internet. It is an easily scalable tool in terms of buildings and sensors that can be added.

PPR has benefits to both building owners and to authorities, before and after an earthquake event. Prior to the earthquake, PPR will benefit owners by enhancing their post-earthquake planning, using the assessments to better understand what to expect and how they should respond. After an earthquake, when access to building officials and engineers will be limited for many months, it will provide crucial information that will aid in the decision to stay or leave the building. This will be valuable to resumption of business in private and government buildings; and for residents to be able to stay in homes and apartments.

Membership in the PPR Network is broadly based and embraces a wide diversity of building owners including government buildings, first responder buildings, schools and residential wood frame houses. At the time of publishing the network consists of:

- Twenty sensors throughout Vancouver Island, in Western Canada.
- 13 Provincial Government buildings
- A public school, with plans to expand to the entire district,
- A firehall, with plans to expand to the entire community
- 4 residential buildings, each expanding to their respective community.

10. Acknowledgments

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