The Community Seismic Network and Quake-Catcher Network: enabling structural health monitoring through instrumentation by community participants

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ABSTRACT

A new type of seismic network is in development that takes advantage of community volunteers to install low-cost accelerometers in houses and buildings. The Community Seismic Network and Quake-Catcher Network are examples of this, in which observational-based structural monitoring is carried out using records from one to tens of stations in a single building. We have deployed about one hundred accelerometers in a number of buildings ranging between five and 23 stories in the Los Angeles region. In addition to a USB-connected device which connects to the host's computer, we have developed a stand-alone sensor-plug-computer device that directly connects to the internet via Ethernet or wifi. In the case of the Community Seismic Network, the sensors report both continuous data and anomalies in local acceleration to a cloud computing service consisting of data centers geographically distributed across the continent. Visualization models of the instrumented buildings' dynamic linear response have been constructed using Google SketchUp and an associated plug-in to matlab with recorded shaking data. When data are available from only one to a very limited number of accelerometers in high rises, the buildings are represented as simple shear beam or prismatic Timoshenko beam models with soil-structure interaction. Small-magnitude earthquake records are used to identify the first set of horizontal vibrational frequencies. These frequencies are then used to compute the response on every floor of the building, constrained by the observed data. These tools are resulting in networking standards that will enable data sharing among entire communities, facility managers, and emergency response groups.

Keywords: CSN, QCN, cloud services, structural health monitoring

1. INTRODUCTION

The Community Seismic Network (CSN) and Quake-Catcher Network (QCN) are dense networks of low-cost ($50) accelerometers that are deployed by community volunteers in their homes in California. In addition, many accelerometers are installed in public spaces associated with civic services (e.g., city libraries), publicly-operated utilities (power and water companies), university campuses, and business offices. In addition to the standard USB device which connects to the host's computer, we have developed a stand-alone sensor that directly connects to the internet via Ethernet or wifi. This bypasses security concerns that some companies have with the USB-connected devices, and allows for 24/7 monitoring at sites that would otherwise shut down their computers after working hours. Each sensor's host computer or dedicated processor runs a client application that reads in the continuous acceleration time series and executes an event-detection algorithm on the time series. This is to detect earthquake or other shaking source events that cause a vibration response in the buildings or ground.

In the case of CSN, the data are sent to a cloud service where the data are fused, and the event-detection is executed on the entire dataset in order to decide whether alert information should be issued [1]. CSN uses the Google App Engine cloud service, and also forwards the data to an archive at Caltech for use by project scientists and engineers. The advantage of the cloud service structure is that it provides massive parallelism and redundancy during times of disaster that could affect hardware. The cloud computing system consists of data centers with servers geographically distributed around North America. This makes it a more resilient system in the event that a natural disaster such as a strong earthquake affects infrastructure in the location of the sensors and traditional archives that may be in close proximity to the sensors. The disadvantage is the dependence on the organization or company that developed and maintains the data centers.

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The CSN uses the “geocell” system of showing locations of sensors and detections. Geocells are latitude-longitude boxes that can be varied in size; at their smallest they are about one small city block squared. They are defined by physically connected regions that can contain multiple client sensors. The number of detections based on standard trigger algorithms is counted within each geocell and if the number exceeds a predetermined threshold, an event is declared. The advantage of using geocells is that the thresholds can be modified to maximize detection probability, minimize the number of false alarms, and to keep the exact locations of sensors private. The exact location of any one sensor is not shown to the public since the smallest scale that can be resolved in publicly available products is at the scale of a geocell. Each sensor has no knowledge of any other sensors and communicates individually and directly with the cloud. Geocells are used to spatially aggregate subsets of CSN sensors in order to provide geographic location and multiple event detection constraints on the determination of a significant event. For a geocell that is about ½ km long, multiple acceleration observations from sensors distributed throughout the geocell would show coherent waveform characteristics, depending on the wavelength of interest. Similarly, a geocell that contains multiple sensors from within one or two buildings could show consistent characteristics based on coherent building response to a vibration event. Geocells can also be defined such that temporal variations or patterns associated with a shaking event (e.g., a wave propagating throughout a small region or up a tall building), can be resolved within that spatial scale. They are defined large enough, however, that electrical, mechanical or unknown sources of vibrational noise in any one individual sensor can be distinguished by using the presence (or absence) of coherent characteristics in multiple nearby sensors.

The QCN sensors in buildings are connected to netbooks with continuous data streaming in real-time via the Berkeley Open Infrastructure for Network Computing (BOINC) software program to a server at Stanford University [2]. The current QCN architecture includes two QCN ‘projects’; one project records continuous data and another records only triggered data around times of strong ground motion. A QCN station or sensor-node is connected to either the continuous or triggered QCN project. Both projects use a simple short-term-average over long-term-average triggering scheme to determine when significant ground accelerations occur, and package and send waveform data and derived parameters such as peak ground acceleration to the central QCN server. The basic analysis currently done by the station uses only a fraction (1-5%) of the computing capabilities of the desktop, netbook, or plug computer that is monitoring the sensor. Therefore, each QCN sensor-node has additional processing power that can be exploited for more than just the current event detection and data streaming.

In the case of both CSN and QCN, maps of peak accelerations are produced for events within seconds of the onset of the shaking. These maps are produced primarily for local earthquakes with $M>2.5$ with detection distance increasing with increasing magnitude. The maps have also been generated for other shaking events that were detected by the sensors such as strong thunderstorms, windstorms, and the firing of a historic cannon for special events on the Caltech campus.

Thus far CSN or QCN engineers, seismologists, staff and students have instrumented nine buildings, each with between 2 and 13 accelerometers. The instrumented buildings include the reinforced concrete Millikan Library building on the Caltech campus and the steel-frame Factor building on the UCLA campus. Near downtown Los Angeles, six buildings between 5 and 14 stories tall have been instrumented by CSN and QCN. A 23-story steel-frame office building in downtown Los Angeles was also instrumented. See Table 1 for all buildings in California instrumented by CSN and QCN.

Ideally, one would use floor-by-floor structural drawings with section call-out information to construct accurate, realistic finite-element models of our buildings for dynamic analysis using earthquake data for validation. In most cases, however, such details are not available, and even if they were, construction and validation of such models is a time-consuming process. In order to carry out useful numerical estimates of building response, a simple approximate building model has been developed where the building is considered as an elastic continuum of the appropriate elastic properties (Young’s modulus, shear modulus, and average density) [3]. If the geometric form of the building is prismatic we can determine its eigenfrequencies and mode shapes using analytic expressions derived for a Timoshenko beam which considers both the shearing and bending of the building [3,4,5]. If the dimensions of the beam are known, then the mode shapes can be uniquely determined by knowing the eigenfrequencies of the first two modes. Because many buildings tend to rock on their foundation, we have also included a rotational and translational spring at the base of our Timoshenko beam. In this case, knowing the first two eigenfrequencies of the building allows us to estimate the mode shapes of a bending, shearing, and rocking building. If vibration data is available from many locations in a building, then the mode shapes can be determined directly by filtering the records to the eigenfrequencies. If acceleration records are available only from one location in the building, we can still estimate the vibrations of the building using elastic models of the building. While such a model is simple, we have verified that we can use eigenfrequencies alone to derive approximate mode shapes observed in several densely instrumented buildings.

Table 1. Buildings instrumented by CSN and QCN in southern California.

Building type	# Stories	# sensors in building
Steel-frame (Factor Bldg.)	15 (+ 2 basements)	6
Steel-frame with bracings	5 (+ basement)	5
Steel-frame	23	2
Reinforced concrete with shear walls (Millikan Library)	9 (+ basement)	13
Concrete (cast in place) with shear walls	12 (+ basement)	6
Concrete (cast in place) with shear walls; with concrete seismic retrofit	14 (+ basement)	6
Concrete (cast in place)	11	5
Concrete	5 (+ basement)	5
Concrete	5 (+ basement)	2

2. TIMOSHENKO BEAM MODELING

2.1 Application to 12-story concrete building

In this paper, we apply the prismatic Timoshenko beam model with soil-structure interaction (SSI) to approximate the dynamic linear elastic behavior of the 12-story concrete-shear wall building near downtown Los Angeles that has been instrumented with six CSN accelerometers. The closed form response solution with complete vibration modes derived by [3] is applied to the 12-story building. The building properties, including mode shapes, are computed knowing the ratios of the frequencies of the first two normal modes in the two orthogonal horizontal directions. The natural frequencies of the first two vibrational modes of a building have been identified by spectral analysis of data from a single seismometer installed in the building on the 9th floor.

This particular building was built in 1968 and has12 floors plus a basement. It is concrete (cast in place) with shear walls. The building has six accelerometers installed internally, recording continuous acceleration time series data at 50 sps since June, 2012. Each seismometer consists of a three-component Phidget (accelerometer plus ADC board) and a processor. The Phidgets are each connected to a SheevaPlug plug computer manufactured by GlobalScale Technologies. The SheevaPlugs have 1.2 GHz ARM-compatible processors running Linux, and Gigabit Ethernet connectivity. The Phidgets are plugged in as a peripheral to the SheevaPlug's USB port and the data are sent via the Google AppEngine to the data archive. The seismometers are located in the basement, 3rd floor, 6th floor, 9th floor, and two on opposite sides of the 11th floor of the building.

Shortly after installation, a local earthquake was recorded by this and other CSN-instrumented and QCN-instrumented buildings. On August 8, 2012 at 06:23:34 UTC, an M=4.5 earthquake occurred near Yorba Linda in southern California. Another M4.5 event followed at 16:33:57 UTC nearby on the same day. The CSN detected and recorded data on both earthquakes on its sensors throughout Los Angeles and surrounding areas. The earthquake was recorded by the 12-story building on all floors with sensors with good signal-to-noise ratios and are used in the Timoshenko beam model and waveform predictions based on analysis of data from only a single seismometer.

Following the approach derived in [3] based on [4,5], the 12-story building was modeled as an equivalent prismatic Timoshenko beam with SSI. The dimensions of the building are 23 by 24 meters and its height is 48 m; thus its aspect ratio (L/d) = 2.1 where L=height and d=depth (which is almost the same as the width), We use the acceleration time series recorded in the building to determine the first two natural frequencies, f_1 and f_2, of the building in each orthogonal horizontal direction. The accelerometers are oriented such that the horizontal measurement axes are parallel and perpendicular to the primary load-bearing walls. These frequencies are estimated from the spectra of the August 8, 2012 Yorba Linda earthquake accelerations. From the 9th floor sensor, f_1 =1.04 Hz and f_2=3.56 Hz in the NS direction, and f_1 =1.17 Hz and f_2=3.87 Hz in the EW direction. The frequency ratios f_2/f_1 (=3.3-3.4) are similar for both directions, which means that the shear stiffness relates in the same way to the bending stiffness for both directions.

SSI is simulated with a translational spring with stiffness K_T and a rotational spring with stiffness K_R incorporated in the base of the building model. K_T and K_R are estimated from the soil properties [6]. We estimated the soil P-wave velocity V_p, S-wave velocity V_s, and density ρ_{soil} using standard values for soil conditions characterized by firm-packed sedimentary layers. This particular building site is located on the edge of a large sedimentary basin that underlies much of the central and southern parts of the city of Los Angeles. The soil properties are characterized by Poisson's ratio υ, soil shear modulus, G_{soil}, soil translational spring stiffness K_T, soil rotational spring stiffness K_R, and equivalent foundation radius $r_0 = \sqrt{(cross\text{-}sectional\ area\ of\ building/\pi)}$ [3]. The density of the building $\rho_{building}$ is approximated from the structural type of the building. Note that choice of value for $\rho_{building}$ only affects the absolute value of the natural frequency output from the Timoshenko beam model, but not the natural frequency ratios. The effective shear modulus of the building is calculated using $G^* = \rho_{building}\ (4Lf_1)^2$, where f_1 is determined from the waveform data. Finally, stiffness ratio $r = shear\ stiffness/flexural\ stiffness = 12kG^*L^2/E^*d^2$, is determined through an inverse problem using the measured or estimated values shown in Table 2. The output of the model is a partial differential equation of the Timoshenko beam model from which additional parameters such as the effective Young's modulus of the building, E^*, can then be calculated. Once the model is determined, it can be used to construct mode shapes and to predict values for higher modal frequencies. If these higher modes are also observable in the time series data, they provide additional constraints on the model accuracy.

Table 2. Timoshenko beam modeling parameters for the NS and EW directions of the 12-story concrete building near downtown Los Angeles.

Input	NS	EW
Frequency ratio f_2/f_1	3.4	3.3
S-wave velocity V_s	150 m/s	
P-wave velocity V_p	300 m/s	
Soil density ρ_{soil}	1586 kg/m^3	
Poisson's ratio υ	0.33	
Building depth d	22.5 m	
Building height L	47.5 m	
Building density $\rho_{building}$	24 kg/m^3	
Equivalent foundation radius r_0	14.71 m	
Soil shear modulus G_{soil}	3.57×10^7 Pa	
Soil translational stiffness K_T	2.58×10^9 N/m	
Soil rotational stiffness K_R	4.52×10^{11} N/m	
Building effective shear modulus G^*	9.44×10^5 Pa	$1.19\text{x}10^6$ Pa
Output		
Stiffness ratio r	7.5	5
Effective Young's modulus E^*	4.75×10^6 Pa	8.49×10^6 Pa

For the 12-story bldg, the natural frequency ratio of the 3rd mode was estimated from the model and found to be 7.23 Hz in the NS direction and 7.55 Hz in the EW direction. Stiffness ratio r=5-7.5 was determined from the ratios of the frequencies. Note that this is a little higher than the value for a pure shear beam with a rigid base model which has as its first three frequencies f_1, $3f_1$, and $5f_1$. An r value of approximately 1 would indicate pure shear beam behavior and a value on the order of 100 indicates significant bending beam behavior. This value for r (=5-7.5) shows that the response of the 12-story building is close to that of a pure shear beam with a small amount of bending, so this type of response is consistent with what is expected of this tall, relatively slender building. The calculated mode shapes are shown in Fig. 1.

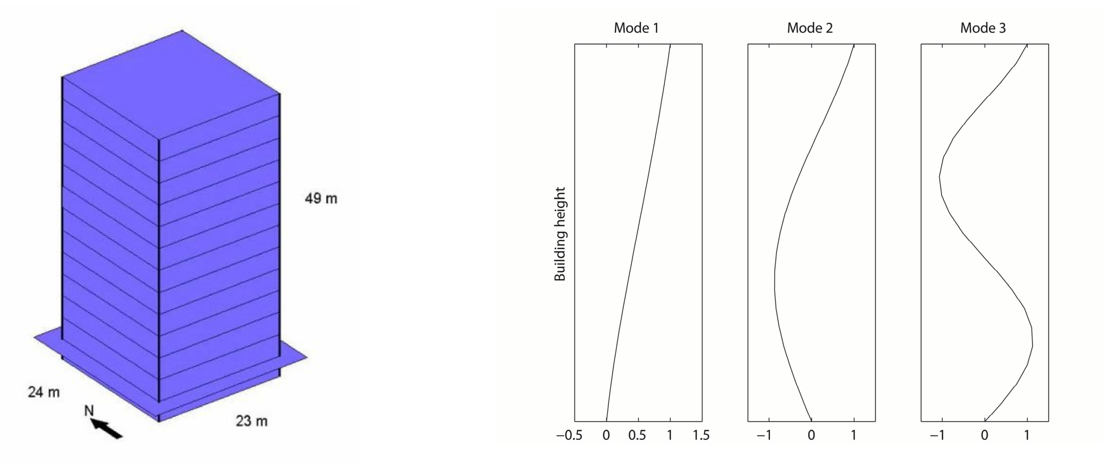

Figure 1. (Left) *SketchUp* visualization model of 12-story concrete building used in analysis. (Right) First three NS translational mode shapes resulting from the Timoshenko beam calculation for the 12-story concrete building.

2.2 Building response prediction

Once the mode shapes are computed, the entire spatial-temporal building vibration response is then approximated by the appropriate modal summation and travelling wave component. Analysis is presented here for the 12-story building which experiences primarily pure shear deformation with a small amount of bending. Using the pre-determined mode shapes presented in the previous section, the approximate total displacement responses of the other floors is computed following the single-station method introduced in [7]. This approach was successfully applied to local earthquake datasets recorded in two buildings: the 17-story steel-frame Factor building which deforms primarily in shear, and the 9-story reinforced concrete Millikan Library building which deforms in shear with a significant component of bending [7].

The initial vibrating motion of a building due to earthquake forces is modeled by travelling waves which are related to the transient response; all other contemporaneous motion is modeled as resonant modal vibration following the approach presented in [7]. Resonant modal displacement response contains energy primarily at the building's 1st modal frequency, while the travelling wave time series contain energy for the rigid body response from ground excitation (at frequencies lower than the 1st mode frequency) and travelling impulses (at frequencies higher than the 1st mode frequency). We model the total horizontal displacement response $u(t,z)$ at height z in the building as: $u(t,z)=f_1(t)*u(t,z)+ f_2(t)*u(t,z)$ where $f_1(t)*u(t,z)$ is a bandpass filtered displacement dataset around the 1st frequency of the building (i.e., the 1st mode response), and $f_2(t)*u(t,z)$ is the residual response that includes low-frequency rigid body motion from ground excitation and high-frequency travelling waves; $*$ denotes convolution.

For the 12-story building, we estimated the responses on all floors using data from the accelerometer on the 9th floor. The August 8, 2012 M4.5 Yorba Linda earthquake was recorded on five floors (basement, 3, 6, 9 and 11) so we use these data to validate the numerically simulated waveforms. Using data only from the accelerometer on the 9th floor, acceleration time series are estimated for the basement, 3rd floor, 6th floor, 9th floor, and 11th floor. The first mode of vibration is captured by applying a two-pole Butterworth filter for frequencies between 1 and 1.25 Hz. The filtered data are then weighted by the mode shape which determines the relative displacement weights for each floor from this mode. This is added to the travelling wave component, assumed to represent the ground motion effect, also provided by the 9th floor dataset. The result for each floor is then compared with the recorded time series from each floor. Fig. 2 shows that the calculated waveforms match the data remarkably well.

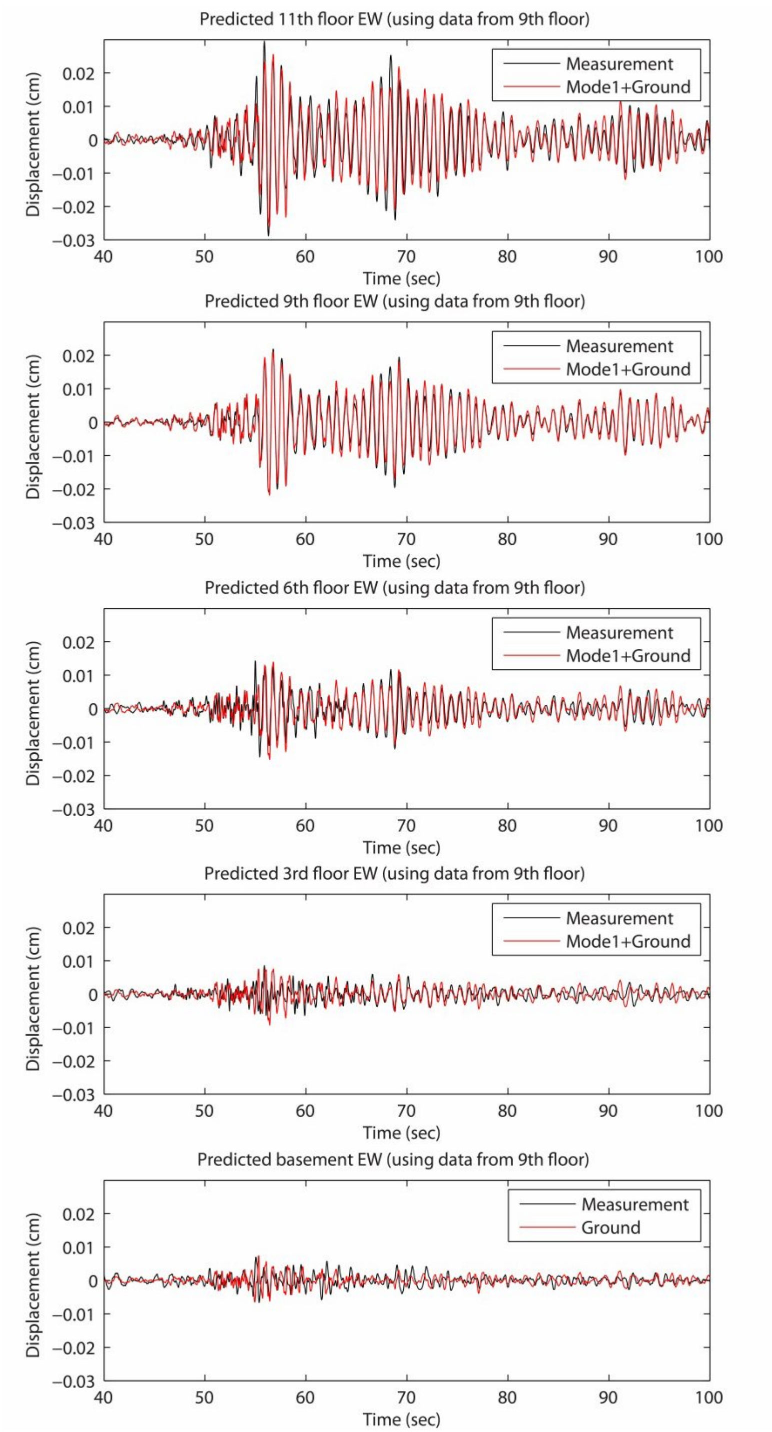

Figure 2. EW displacement predictions using the August 8, 2012 M=4.5 Yorba Linda, CA earthquake waveform recorded by the sensor on the 9th floor. “Measurement”=recorded acceleration time series, “Mode1” = mode 1 contribution with floor weighting provided by mode shape obtained from Timoshenko beam calculation. “Ground” = travelling wave component provided by residual from 9th floor recording after removing the first mode contribution. The travelling wave residual approximates the input ground motion for frequencies above and below the first modal frequency.

3. DISCUSSION

Since building response to this earthquake is linear, the estimated response on all floors should be nearly the same as the observations if no measurement error exists. One source of instrument error, however, are errors in time stamps. Each seismometer has an internal clock that gets time synched with a local NTP time server. In the first few weeks of deployment, however, this time sync did not always occur. Initial comparisons between the Timoshenko beam predicted waveforms and the observations revealed that there were small time errors in the 12-story building dataset. To correct these, we applied a method discussed in [7] and successfully applied to another set of earthquake records from an instrumented 9-story building. We filtered the data for the fundamental frequency and cross correlated each floor's filtered waveform with a master waveform (the 9th floor in this case). In theory this works because all waveforms narrow-bandpass filtered around the fundamental frequency should be perfectly in sync to reflect the building's in-phase response. After computing the cross correlations, the time shifts required to bring the different floors into sync were then applied as a time correction to the raw data.

The travelling wave requires a correction to account for the travel time between the reference floor and floor of interest. If the shear-wave speed is between 300 m/s, as observed for the reinforced concrete Millikan Library building [8] and 160 m/s observed for the steel-frame Factor building [9], then a wave takes about 0.2 s to travel from the ground floor to the top of a 12-story building. Although this time lag is not large, it is within observable measurements on CSN and QCN sensors. The time lag correction is made to the Yorba Linda dataset here by estimating the building shear-wave speed $V_s=4L/T_1$ where L=total height of the building and T_1=fundamental period of the building. Applying this correction individually to each predicted floor results in time corrections between 0.04 s which is only one time point in the 50 sps acceleration time series, and 0.24 s which is within the temporal resolution of the acceleration records. For a much taller building, this correction becomes increasingly important, since for example, a 20-story building might require a minimum of 0.5 s time lag between ground floor and top floor.

4. CONCLUSIONS

It has been shown for an instrumented building that the mode shapes can be estimated knowing only the first two frequencies in either horizontal direction. The approach has been applied to an instrumented 12-story concrete (cast in place) building with shear walls near downtown Los Angeles. The frequencies were identified directly from spectra from August 8, 2012 M=4.5 Yorba Linda, California earthquake acceleration time series. When the basic dimensions and the first two frequencies are input into a prismatic Timoshenko beam model of the building, the model yields mode shapes that have been shown to match well with densely recorded data. Once the mode shapes are known, predictions for acceleration response on every floor can be predicted when only one acceleration record is obtained for the building. This approach uses the observation that the building's response is dominated by the 1st modal response and the residual response which is the travelling wave due to the building's transient response to earthquake forces exciting it at the base. Approximations are more accurate when the single record is obtained from near the top of the building. For the instrumented 12-story building, comparisons of the predictions of responses on other floors using only the record from the 9th floor with actual data from the other floors shows this method to approximate the true response remarkably well.

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