II. CURRENT STATUS OF HCAI INSTRUMENTATION

The 1971 San Fernando earthquake[1] in southern California resulted in the collapse of several hospital buildings, including four buildings at the San Fernando U.S. Department of Veterans Affairs (VA) Hospital (Figure 1), and caused significant damage to the Olive View Hospital (Figure 2).

Figure 1. The 1971 San Fernando earthquake in southern California resulted in the collapse of Building-1 and -2 at the San Fernando VA Hospital and loss of 49 lives. (Source: USGS earthquake photo archive, available online at https://library.usgs.gov/photo/#/?category1=earthquakes&collection2=san%20fernando%20earthquake,%20february%201971)

[1] *http://earthquake.usgs.gov/earthquakes/states/events/1971_02_09.php*

Figure 2. The 1971 San Fernando earthquake resulted in partly detached staircase and severely damaged buildings at the Olive View Hospital. (Source: USGS earthquake photo archive, available online at https://library.usgs.gov/photo/#/?category1=earthquakes&collection2=san%20fernando%20earthquake,%20february%201971)

After the 1971 disaster, California legislation passed the 1972 Seismic Safety Act. The Hospital Seismic Safety Act (HSSA) as originally proposed called for the immediate strengthening or replacement of all hospital buildings that did not meet the modern standards. However, it was quickly realized that this was an economic impossibility. The proposed law was

changed to apply only to new hospital buildings and existing hospital buildings undergoing substantial structural remodel or expansion and, therefore, all hospitals licensed at the time were "grandfathered" in – that is, they were not required to meet the new statewide standards. The intent was to bring any building whose useful life was being extended by a modernization program up to the modern seismic standards.

In Northridge Earthquake of January 1994, several of these older hospitals sustained significant damage. Hospitals built in accordance with the standards of the Seismic Safety Act resisted the Northridge earthquake with minimal structural damage, while several facilities built prior to the act experienced major structural damage and had to be evacuated. It must be noted that certain nonstructural components of the hospitals did incur damage, even in facilities built in accordance with the structural provisions of the Seismic Safety Act.

An important goal of hospitals is to be able to continue to operate and serve the patient community after a major earthquake. However, the building itself may have been damaged and, consequently, may pose a hazard to patients and staff. It is critical that hospital management have the tools and information necessary to make a rapid decision whether to evacuate or not. Early assessment of the integrity of the hospital buildings affected by the quake is valuable in this decision-making process. For resilience and sustainability of the California's hospitals, it is also necessary to assess their structural condition periodically to facilitate necessary repairs and retrofitting measures.

In response to these needs the HCAI for a long time has supported and continues to support hospital instrumentation in collaboration with the California Strong Motion Instrumentation Program (CSMIP) of the California Geological Survey, Department of Conservation (https://www.conservation.ca.gov/cgs/smip). The instruments record motions in the hospital buildings when earthquakes occur and are useful in understanding the behavior of those hospital buildings structures due to the earthquake motions. The earthquake records can also provide the basic source data to improve understanding of the behavior and potential for damage of such structures under the forces generated and imposed by catastrophic earthquakes. As a result of this understanding, design and construction practices can be modified so that future earthquake damage is minimized and the objective of maintaining continuous operation may be met.

The CSMIP has been instrumental in performing installation, maintenance, and data recovery for strong motion instrumentation in hospitals through an interagency agreement (IAA) with the HCAI since 1984. As of today, close to 90 hospital buildings across the state have been instrumented under this IAA (Table 1). Each year, HCAI provides funding for instrumentation of several hospital buildings. Most hospital buildings are instrumented with accelerometers. Figure 3 shows their locations overlaid on the most recent national seismic hazard map of California. Majority of the instrumented hospital buildings are in regions of high or very high seismic hazard.

Table 1. List of instrumented hospital buildings under the HCAI jurisdiction

No	Facility Name	Building Name	Number of Sensors
1	El Centro Regional Medical Center	North Wing	5
2	El Centro Regional Medical Center	Lab Building	7
3	UC San Diego Health La Jolla - Jacobs Medical Center & Sulpizio Cardiovascular Center	Main Hospital	12
4	Scripps Memorial Hospital - La Jolla	Transition Tower (& 5A)	12
5	Sharp Memorial Hospital	South Tower	15
6	UC San Diego Health La Jolla - Jacobs Medical Center & Sulpizio Cardiovascular Center	Bed Tower	24
7	UC San Diego Health Hillcrest - Hillcrest Medical Center	Main Hospital Building	12
8	Hemet Global Medical Center	Tower I	10
9	Desert Regional Medical Center	East Tower	13
10	John F. Kennedy Memorial Hospital	West/South Wing	8
11	Riverside University Health System - Medical Center	Ancillary Building	15
12	Hoag Memorial Hospital Presbyterian	East Wing	27
13	Kaiser Foundation Hospital - Orange County - Irvine	Main Building	15
14	Palomar Medical Center	Hospital	12
15	Palomar Medical Center	Central Plant	6
16	Hoag Memorial Hospital Presbyterian	Inpatient Tower - 1974	18
17	Southwest Healthcare System	Women's Center and Emergency Room	9
18	Orange County Global Medical Center	Administration	6
19	Riverside Community Hospital	Building B	12
20	Providence Little Company of Mary Medical Center Torrance	Original Hospital	21
21	Providence Little Company of Mary Medical Center San Pedro	Central Wing Tower	12
22	Providence Little Company of Mary Medical Center San Pedro	West Wing & Entrance Canopy	12
23	PIH Health Hospital - Downey	Original Nursing Tower	12
24	Martin Luther King, Jr. Community Hospital	Trauma Center	21
25	Kaiser Foundation Hospital - Ontario	Main Hospital	15
26	Redlands Community Hospital	Radiology Addition	9
27	Community Hospital of San Bernardino	North Hospital	12
28	Arrowhead Regional Medical Center	Diagnostic & Treatment Bldg.	8
29	Arrowhead Regional Medical Center	Nursing Tower	19
30	Arrowhead Regional Medical Center	Central Plant	3
31	Adventist Health Simi Valley	Main Hospital Building	12
32	Providence Saint John's Health Center	North Pavilion Inpatient Tower	24
33	LAC+USC Medical Center	Inpatient Tower	12
34	LAC+USC Medical Center	New Diagnostic and Treatment	20

35	Keck Hospital of USC		
36	Henry Mayo Newhall Hospital	Main Hospital - Original Building	12
37	Children's Hospital Los Angeles	Anderson Pavilion	12
38	Palmdale Regional Medical Center	Main Building	16
39	LAC/Olive View-UCLA Medical Center	Main Hospital Building	13
40	Keck Hospital of USC	Main Hospital	24
41	Antelope Valley Hospital	Hospital Tower Addition	12
42	Encino Hospital Medical Center	Main Tower / Basement / Mech Bldg	12
43	Hollywood Presbyterian Medical Center	South Wing	12
44	Hollywood Presbyterian Medical Center	D & T Tower	15
45	Good Samaritan Hospital	Main Hospital	15
46	Community Memorial Hospital - San Buenaventura	New 6 Story Hospital Tower - West	24
47	Ventura County Medical Center	Hospital Replacement Wing	24
48	Ventura County Medical Center	Fainer Wing - Building 304	12
49	Santa Barbara Cottage Hospital	Centennial Wing (Building I) (Arlington Pavilion)	9
50	St John’s Regional Medical Center	Patient Tower	17
51	Marian Regional Medical Center	New Hospital Expansion	12
52	Kern Medical Center	Wing D	11
53	Tenet Health Central Coast Twin Cities Community Hospital	Main Hospital	9
54	George L. Mee Memorial Hospital	New Hospital	10
55	Natividad Medical Center	Acute Care (Building 500)	15
56	Mammoth Hospital	New Wing	10
57	St. Louise Regional Hospital	Hospital Building Area A	10
58	Kaiser Foundation Hospital-Santa Clara	Hospital - Phase I	18
59	Kaiser Foundation Hospital - Fremont	Hospital Patient Wing North	3
60	Kaiser Foundation Hospital - Fremont	Hospital North	12
61	Santa Clara Valley Medical Center	West Wing K Nursing (6006)	15
62	Santa Clara Valley Medical Center	Replacement Bed Building (Sobrato Pavilion) (6011)	20
63	O'Connor Hospital	Replacement Facility	16
64	Washington Hospital	Main Building	21
65	Stanford Health Care	Diagnostic Treatment Center	12
66	Kaiser Foundation Hospital - Walnut Creek	Phase II Hospital	16
67	UCSF Medical Center	Long Hospital	16
68	Mills-Peninsula Medical Center	New Hospital	24
69	Alameda Hospital	South Wing	12
70	Eden Medical Center	Replacement Hospital	19
71	Alta Bates Summit Medical Center-Alta Bates Campus	1985 Building	12

72	UCSF Medical Center at Mission Bay	UCSF Benioff Children's Hospital	18
73	Priscilla Chan And Mark Zuckerberg San Francisco General Hospital and Trauma Center	Replacement Hospital	24
74	Kaiser Foundation Hospital - Oakland/Richmond	Hospital	18
75	Lucile Packard Children's Hospital Stanford	New LPCH Expansion Building	21
76	Stanford Health Care	New Stanford Hospital	36
77	California Pacific Medical Center - Van Ness Campus	New Acute Care Hospital	24
78	California Pacific Medical Center - Mission Bernal Campus	New Hospital	16
79	Kaiser Foundation Hospital - San Francisco	North Wing	18
80	Marinhealth Medical Center	06 - West Wing	12
81	Northbay Medical Center	Phase 1 Replacement Building	12
82	Novato Community Hospital	Hospital	12
83	Kaiser Foundation Hospital - Santa Rosa	Hospital	13
84	St. Joseph Hospital	Phase III Addition Building	11
85	Sutter Coast Hospital	Hospital Building	10
86	Huntington Memorial Hospital	West Tower	3
87	Kaiser Foundation Hospital - Los Angeles	LAMC Hospital - Phase I	3
88	Adventist Health White Memorial	Specialty Care Tower	3
89	Kaiser Foundation Hospital - Downey	Main Building	3

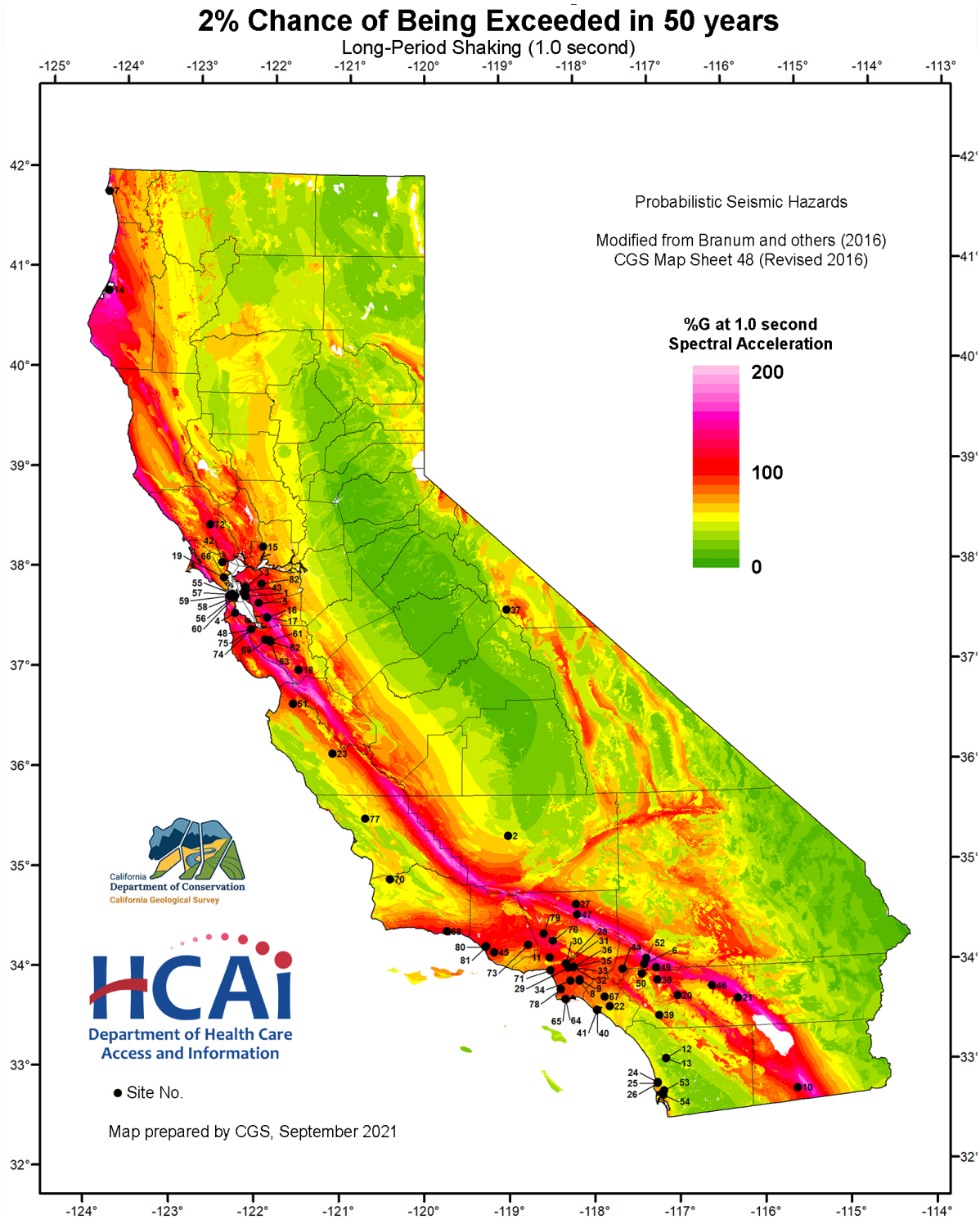

Figure 3. Locations of the instrumented hospital buildings (black dots). The base map is the seismic hazard map of the California. Colors on this map display the levels of horizontal shaking that have a 2 percent probability of exceedance in a 50-year period.

Hospital Buildings with seismic isolation and or passive energy dissipation are required by the California Building Code (CBC) to be instrumented. Different types of applications of such systems will perform differently. Instrumentation provides the opportunity to reveal which type of such systems is more effective than others. HCAI promotes construction of buildings with new and innovative seismic resistant systems with predictable and improved seismic response and behaviour. However, designs of hospitals buildings submitted for review that use such seismic resistance systems (deemed as experimental) may not yet be permitted by the CBC because the building code has not caught up with the latest technology. In those cases, HCAI under the provisions of "alternate means of compliance" permits such systems for hospital construction provided that such buildings are instrumented prior to the issuance of the certificate of occupancy. Examples include structures with Buckling Restrained Braced Frames, Steel Plate Shear Walls, Special Steel Moment Frames with SidePlate connections, new soil stabilization systems that become part of the building foundation, etc. In such cases, the owner is responsible for the cost of the instrumentation and installation with HCAI responsible for the maintenance of the instrumentation and data retrieval through CSMIP.

In addition, the goal of HCAI with the assistance of the HBSB Instrumentation Committee was to select and instrument with a sufficient array of sensors (including a free field) station at least two hospital buildings per year in addition to any buildings required to be instrumented by the CBC. The cost of instrumentation of these buildings selected for instrumentation by the HBSB instrumentation committee is paid for by HCAI. With a greater number of hospital buildings being added to the list of instrumented buildings each year which are either owner funded or HCAI paid, the cost of monitoring and maintenance has reduced that frequency in recent years.

The committee considers a list of candidate hospital buildings that have been selected for instrumentation. The list of candidate hospital buildings has been formulated by the committee based on specific eligibility criteria. Some of eligibility criteria that the Committee considers placing a building on the list of candidate hospital buildings for instrumentation is as follows:

- Proximity to one or more of the many major California faults capable of generating a large earthquake(s) (M>6.5)
- Sites w/ high probability of seismic event(s)
- Type of structural system
- Soil type (soft soil)
- Tall interstory heights
- Adjacency to other buildings (pounding)
- Buildings with projecting wings
- Template Buildings on the same site
- Building system configuration (irregularities)

- Seismically retrofitted buildings
- Buildings reassessed from an SPC-1 level to an SPC-2 through the HAZUS methodology

Each such instrumented building has a well optimized number of sensors placed at critical locations to generate meaningful data that characterizes the response of the subject buildings to help the scientific and engineering community in assessing design/analysis procedures thereby validating the mandates of the HSSA. The number of the accelerometers [typically force-balance accelerometer (FBA) is shown in Figure 4] deployed in each building varies depending on the floor area, the number of stories, and the number of the wings the building has. For instance, the Bed Tower building at the Stanford Hospital in Redwood City, has a dense array of 34 FBA accelerometers and a free-field station equipped with a tri-axial accelerograph (Figure 5).

Figure 4. Typical force balanced accelerometers used in hospital buildings' seismic instrumentation.

These sensors are strategically located in the building to measure the building's translational motions. The measured quantity is the acceleration of the translational degrees of freedom. Each hospital building is instrumented in a similar way: the accelerometers are deployed permanently at the locations where the maximum response is expected, usually at the edges of the buildings. Each building is often equipped with a triaxial accelerometer located on the lowest floor, which provides the input ground motion in three orthogonal directions.

The goal of such instrumentation deployment is to record floor accelerations and to compute the relative displacement between adjacent floors (interstory drift), as well as the overall building roof displacement, floor torsion, building rocking, the travel-time of transmitted shear waves between consecutive floors, and the building's modal parameters (for example, vibration periods, mode shapes, and modal damping values). Other accelerometers located away from the building record free-field ground shaking (see Figure 5), providing ground shaking motion without interference of the structure.

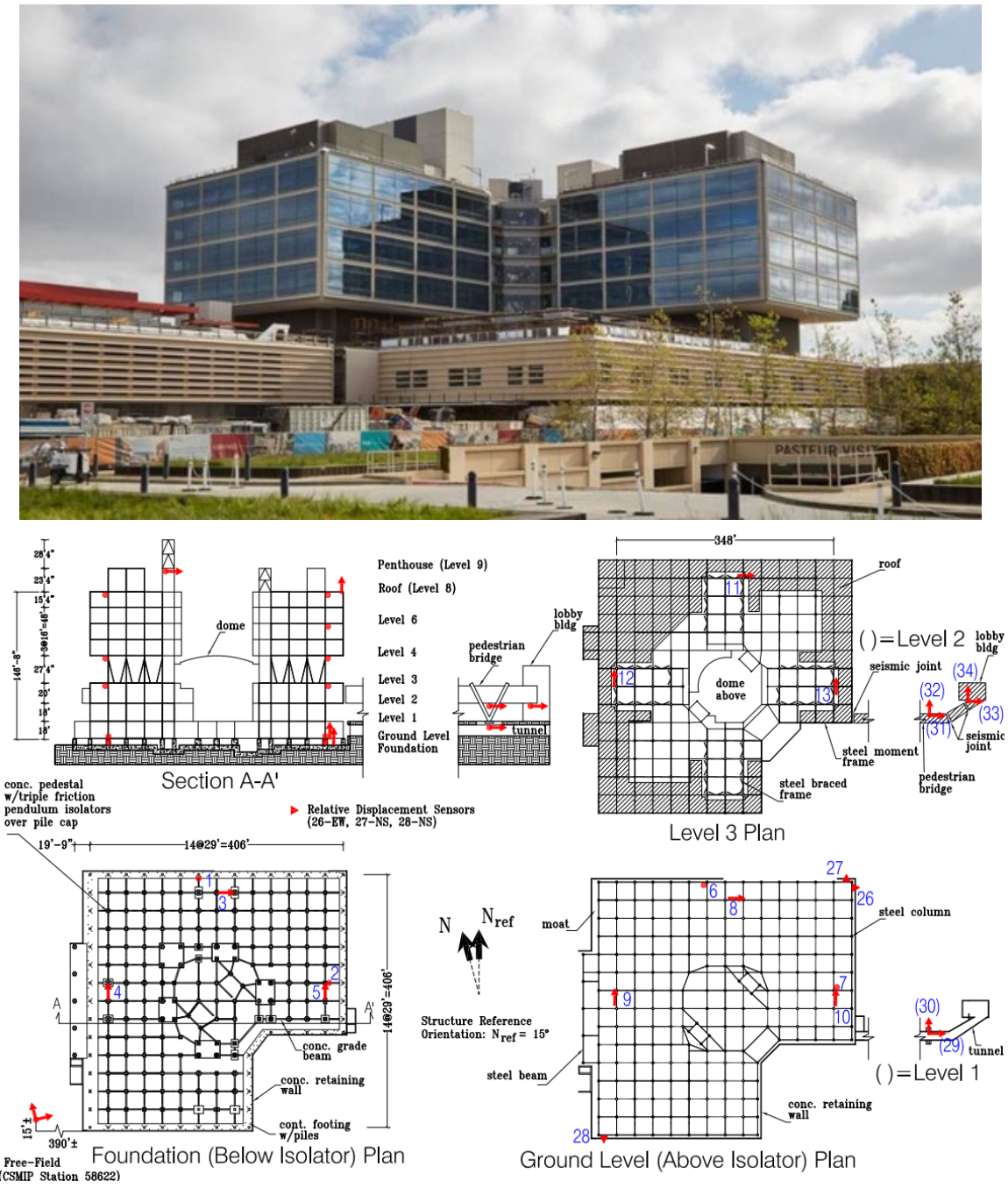

Figure 5. Photo (top) and sensor lay out diagram (bottom) of the seven-story hospital building in Stanford Medical Campus. Red arrows in the schematic diagram show the locations and indicate the directional sensitivity of the strong-motion sensors (accelerometers). The sensors are connected to a central data acquisition system in the building (Photo source: https://med.stanford.edu/news/all-news/2019/05/new-stanford-hospital-nearing-completion.html; sensor layout source: https://www.strongmotioncenter.org/NCESMD/photos/CGS/bldlayouts/bld58623.pdf)

Why the need for a Separate Inventory of Instrumented Hospital Buildings?

California hospital buildings are different than other less essential occupancy buildings in the state. The California hospital buildings are separated into two major classifications: Pre-Act buildings and Post-Act buildings. Pre-Act buildings were permitted prior to March 7, 1973 and are not in compliance with the HSSA. Post Act buildings were permitted and constructed after March 7, 1973 and are in compliance with the requirements of the HSSA. Post-Act buildings possess higher strength and stiffness than typical buildings built in the same era under the requirements of the model code enforceable at that time. The response of hospital buildings will be very different than nonhospital building of the same era even though they are built of the same material, structural system engineering methodologies etc.

Many Pre-Act buildings have been reclassified, through the FEMA Hazards U.S (HAZUS) methodology which is a loss estimation tool, from posing a significant risk of collapse and a danger to the public (SPC-1), to buildings that do not significantly jeopardize life, but may not be repairable or functional following strong ground motion (SPC-2). However, this HAZUS methodology is mostly untested in a strong seismic event; the need for seismic instrumentation becomes obvious. Select buildings with voluntary seismic improvements for some not all seismic vulnerabilities and eligible for reclassification through HAZUS have been instrumented.

Because of the infrequent and unpredictable nature of when and where an earthquake will occur, it is therefore important to instrument some of these buildings where the seismic performance is unknown, so that valuable information useful to develop earthquake protective technology is not lost.

While the inventory of number of hospital buildings in the California has grown, this inventory is skewed towards newer hospital buildings and buildings with Seismic Force Resisting Systems with higher seismic resistance to strong ground shaking.

HCAI has statutory authority (HSSA, Section 130025) and responsibilities in the event of a seismic event, or other natural or manmade calamity to activate its emergency response center and mobilize a specialized team of authorized representatives to examine the hospital building structure(s) or systems affected by such an event.

Having the appropriate strong motion information along with detailed structural system information helps focus the HCAI team with post-earthquake assessment on what to look for and the recommendations to make to the hospital owner for a detailed post-earthquake evaluation report for both structural and non-structural performance. As the strength of the building is enhanced for reduced drifts, the demands on the non-structural components and systems increase, and seismic floor acceleration data coupled with post-earthquake reconnaissance will be very valuable in seismic hazard mitigation efforts.

Conclusion

The HSSA requires hospitals to be in substantial compliance with the HSSA by January 1, 2030 and all general acute care hospitals must be able to remain operational beyond

that point in time. The hospital seismic instrumentation program is monitoring the pulse and health of the HSSA. The hospital instrumentation program will give the capability to the earthquake engineering community to quantitatively validate the performance of per-and post Act buildings as well as predictions of risk analysis tools such as HAZUS and PACT.