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THE COST-EFFECTIVENESS OF A PUBLIC CALIFORNIAN EARTHQUAKE EARLY WARNING SYSTEM

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Abstract

The RMS catastrophe earthquake model has been used to assess the cost-effectiveness of a public Californian earthquake early warning system. Taking a thirty year time frame, there is a reasonable expectation that the safety investment would be warranted by the number of lives saved and the reduced fire loss following earthquake. Significant additional early warning benefits also accrue to a number of corporate stakeholders. Given the balance between societal and corporate benefits, it would be equitable if the private sector supported this investment in public safety.

Keywords: earthquake; early; warning; cost; California

1. **Introduction**

The concept of an earthquake early warning system for California dates back to the Hayward Fault earthquake of October 21, 1868. An astute physician, Dr. J.D. Cooper, figured out that telegraph cables could transmit an earthquake warning. This was a remarkably prescient observation, for earthquake science barely existed in 1868, and the telegraph had only reached California fifteen years before. Furthermore, with 30 fatalities, the death rate was only about 1:10,000, so this was far from being a humanitarian disaster.

A warning system would never have actually been viable before the modern digital era. But progressively the seismological challenges in issuing reliable and timely earthquake warnings in California have been resolved, so that a public earthquake early warning system (EEWS) could at last become operational 150 years after Dr. Cooper's vision. But how cost-effective would such a system be? This is an important question, not just in California but elsewhere in seismic zones around the world lacking EEWS. The relative cost-effectiveness of retrofitting seismically vulnerable buildings and implementing EEWS matters when policy-makers have to decide on seismic safety resource allocation. Indeed, progress in EEWS acceptance is slowed by concerns that this initiative would detract to a greater or lesser extent from engineering efforts to mitigate earthquake risk to vulnerable buildings.

With its headquarters in Newark, close to the southern end of the Hayward Fault, RMS not only has the earthquake risk management expertise to address this question, it is itself a potential safety beneficiary of such a system. A magnitude 7.0 rupture of the Hayward Fault starting at the northern end is a plausible scenario for a recurrence of the 1868 event. If an EEWS were operational, RMS staff would have up to ten seconds to find an office desk to duck under, cover and hold.

There is a strong political consensus in California for a public EEWS. This was re-affirmed soon after the South Napa earthquake of August 24, 2014 at a Berkeley symposium on earthquake early warning. In the previous year, the California State Legislature had passed an earthquake early warning system bill. The installation of a public EEWS for California and the Pacific Northwest would cost $38 million, and the annual running costs would be $16.1 million.

2. Investment to avoid accidental death

Public safety has its own socio-economic and geographical context. What is affordable in one region may be extravagant in another. California has the highest GDP of any state in America, and has a population of almost 40 million. In some affluent zip codes, the price of a modest mansion would pay the annual cost of EEWS operation. California is earthquake country. Seismic motion is the only natural hazard to which all Californians are exposed, and earthquake safety is a state priority.

In the 21st century, Dr. Cooper's successors in medicine have carried California to the international forefront of clinical treatment and research into healthy aging. In California, the psychology of wellbeing has been pioneered, and life expectancy is amongst the highest in the United States. To improve life expectancy further, there is a strong willingness to invest to reduce the incidence of accidental death.

Almost half of U.S. home fires start in the kitchen. Mitigation of this fire following earthquake risk is one of the potential EEWS benefits: warning time may allow some ignition sources to be controlled. There are several thousand house fire deaths each year in the United States. As of 2011, residential fire sprinklers have been required in all new one-and two-family dwellings and townhouses in California. The cost-effectiveness of such a home safety measure was earlier demonstrated in a report produced for the U.S. Fire Administration [1]. For deciding on U.S. investment to reduce fatality risk, this study used the median figure of $7.94 million in 2005 dollars. This amounts to $10 million in 2015 dollars, and is the figure adopted here.

The equivalent figure for terrorism is much greater [2]. Since 9/11, the investment by the Department of Homeland Security to reduce U.S. terrorism fatalities is counted in billions of dollars. This includes resilience measures in California that have dual function in reducing risk from both terrorism and earthquakes. In as much as the earthquake risk exceeds the terrorism risk in California, this implies a substantial value accorded to earthquake safety.

For a public EEWS, the potential to save a significant number of lives is crucial if it is to be cost-effective. This potential is not self-evident, and cannot be assessed quantitatively without an elaborate computer model of earthquake casualties, having a fine geographical resolution with state-wide California exposure information on the population at risk.

Detailed earthquake casualty risk analysis is required, taking due account of three factors that curtail the safety benefits of EEWS. First, there is a blind zone around the earthquake epicenter within which warning time is eroded by the time for the nearest station to record a seismic signal, and the time delay in data processing and telemetry. Secondly, there is already a high standard of earthquake construction and retrofit in California which reduces the extent of future earthquake damage: citizens of California are safer indoors now than in the 20th century. Thirdly, those who find themselves trapped in collapsed buildings are unlikely to have been helped by any early warning.

3. Duck, cover, and hold

Earthquake engineers recommend for those indoors when an earthquake is perceived the Duck-Cover-Hold strategy: move no more than a few steps to a safe place, such as under a sturdy table, then drop down onto hands and knees to avoid falling; cover your head and neck under the table or with your arms and hands; and then hold on.

A century of U.S. experience has shown that taking shelter under sturdy furniture during earthquakes is far more effective at protecting lives than running outside. The outsides of buildings pose many additional hazards that may fall on people trying to run outside. Many of the 120 fatalities from the March 1933 Long Beach earthquake occurred when people ran outside of buildings only to be killed by falling debris from collapsing walls. Seventy years later, in the San Simeon earthquake of December 2003, two people died attempting to exit a collapsing unreinforced masonry building. Those who remained in the same building were subsequently rescued.

It may not be possible to execute the Duck-Cover-Hold strategy. At the precise moment of ground shaking, an occupant of a building may be on a staircase, in a corridor or hallway, in a bathroom or other room with no large sturdy table to crawl under - or simply in the wrong room at the wrong time, e.g. room with a fragile table top, store room, library, garage, wine cellar etc.. Two people were crushed when buried under books, model trains and other collectibles during the 1994 Northridge earthquake [3]. Contemporary photographic records of overturned bookcases and detached air conditioning ducts confirm the sound sense of seeking a safe shelter during the 1989 Loma Prieta earthquake.

Especially for older people, the risk of falling would be high if they tried to reach their safe place whilst the ground is moving. In the Loma Prieta earthquake, more than half of hospitalizations in Santa Cruz County were attributable to falls. Of these, the elderly were the most frequent fall victims [4]. During the Northridge earthquake, those over 60 had six times the risk of a more serious earthquake-related injury, and those who fell had five times the risk compared with those struck or cut by objects [5].

The population of California is ageing. The California Department of Finance projects that in 25 years' time there would be ten million people aged 65 and over. On average, one in three U.S. adults aged 65 and older falls each year [6]. Of those who fall, 20% to 30% suffer moderate to severe injuries that make it hard for them to get around or live independently, and increase their risk of early death. Even if the proximate cause of death may be respiratory failure, in reality a bad fall may be the original cause.

4. Better shelter with EEWS

Particularly the elderly, and others with mobility restrictions, need time to find shelter in an earthquake. The time challenge in reaching a preferred safe place is eased by an earthquake early warning. In the Loma Prieta earthquake, 60% of those injured during the period of shaking were trying to evacuate or move to a safer place in the building. The additional EEWS seconds might be used to find a safer place than one that just happens to be closer. A safer place could be a sturdier, larger table. Where there are multiple occupants of an apartment or home, several tables in different rooms may be needed. A safer place might also be in a room where the damage consequences of a ceiling collapse are lower. Extra time also helps to avoid back strain in getting under a table, which was a problem faced by about 10% in the Loma Prieta earthquake [7].

Assuming a future projected California EEWS inter-station distance of 20km, warning times at varying epicentral distances have been estimated [8]. The area close to the epicenter is called the blind zone, where no early warning is achievable. However, as the distance increases from 25km to 50km, 75km and 100km, the warning times lengthen progressively from 1 to 8, 15, and 22 seconds.

One second would only allow an occupant time to find a safe place a few steps away. But Japanese tests have shown that even a single second of warning may have a human stabilizing effect. In 8 seconds, a safe place could be found in the same room; in 15 seconds, a safe place could be found in an adjacent room; in 22 seconds a safer place could be found further away on the same floor level. These timings should be adequate for most people, even those with some mobility impairment. With increasing number of seconds of earthquake warning, proportionately more occupants should manage to find their preferred safe place without falling and injuring themselves.

By enabling more people to find shelter, EEWS should be effective at preventing some critical injuries and deaths that might be categorized as avoidable, given the prevailing seismic building codes. Such deaths include those resulting from falls, blows, cuts and impacts from falling and overturning objects, as well as from some trauma injuries. The EEWS payoff depends on reducing the number of severe trauma injuries, categorized in the 1994 Northridge earthquake as blunt force, crushing and piercing trauma [9].

For collapsed buildings, securing even the optimum shelter inside is assumed to be of no avail since occupants would be crushed or asphyxiated. EEWS mitigation of earthquake fatalities comes from those buildings that have not collapsed, but are severely or moderately damaged, so there is a prospect of rescue or recovery. For earthquakes of magnitude 7 and higher, there may be a substantial number of such buildings beyond the EEWS blind zone in regions which are exposed to substantial levels of ground shaking of Intensity VIII or more. However, for lesser magnitude 6 events, there would be far fewer such buildings beyond the blind zone, and so less opportunity for EEWS to save lives.

5. Fault rupture hazard scenarios

The standard time period for long-term earthquake fault rupture forecasting is thirty years. This has an economics link with the typical duration of a home mortgage, and is also a suitable time frame to consider economic EEWS cost-effectiveness for an active seismic region, since it allows the multi-decadal time-dependence of seismic hazard to be explicitly incorporated.

The most recent thirty year forecasts for California have been published under the acronym UCERF3 [10]. This third Uniform California Earthquake Rupture Forecast has been developed by the 2014 Working Group on California Earthquake Probabilities (WGCEP), and provides consensus estimates of the magnitude, location and likelihood of potentially damaging earthquake ruptures in the greater California region. Uncertainties in 30-year rupture likelihoods are quantified using an elaborate logic-tree of alternative model input values. The main active faults considered are mapped below.

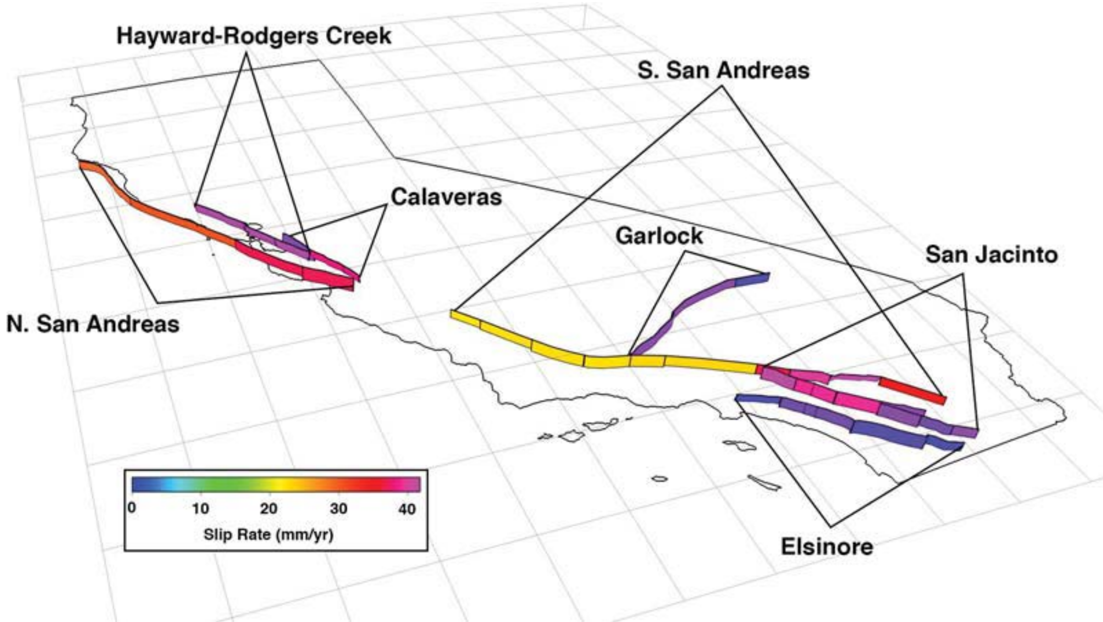

Fig. 1 Main active faults in California [from [10] Field et al. (2015)]

Three key fault rupture scenarios for California casualty risk, which feature prominently in the annals of California earthquake history in the years 1857, 1906, 1868 are:

[A] M7.9 earthquake on the South San Andreas Fault

[B] M7.9 earthquake on the North San Andreas Fault

[C] M7.0 earthquake on the Hayward Fault

For each of these four generic scenarios, RMS has used an adapted form of its California earthquake casualty model to perform half a million random realizations of potential EEWS reductions in the number of fatalities and serious injuries. These simulations account for the progressively longer warning times at increasing epicentral distances, thus allowing proportionately more building occupants to find secure shelter to duck-cover-hold. In a building that has been damaged but has not collapsed, those with such secure shelter have a better chance of avoiding serious injury or death than those who fail to find such shelter.

For [A]: a repetition of the 1857 Fort Tejon earthquake at 8.20 am, EEWS might save the lives of about a hundred people indoors. For [B]: a repetition of the 1906 San Francisco earthquake at 5.12 am, EEWS might only save the lives of about twenty people indoors, because of the blind zone covering San Francisco, and the early hour. A rupture initiating far north of San Francisco would enhance the EEWS risk mitigation benefit. For [C]: a repetition of the 1868 Hayward earthquake at 7.53 am, but with a rupture initiating at the northern end, EEWS might save the lives of about eighty people indoors. This saving would be reduced if the rupture started further south.

A fourth significant fault rupture scenario for California casualty risk is [D]: a magnitude 7.5 earthquake on the San Jacinto Fault. At 2pm EEWS might save the lives of about a hundred people indoors. A fifth fault rupture scenario for California casualty risk is [E]: a magnitude 7.0 earthquake on the Calaveras Fault. At 2pm EEWS might save the lives of about ten people indoors.

Taking a risk-averse stance on the uncertainties in the 30-year rupture hazard probabilities for the main faults and in their rupture locations, the expected number of lives saved in California through EEWS would be expected to exceed fifty over the next thirty years. The overall casualty risk mitigation, including the reduction of several hundred serious injuries inside buildings and some outside, and considering the demographics of an ageing and increasing population, would thus justify an investment of $500 million over thirty years, which would pay the annual EEWS operational costs.

As a historical benchmark, there have been just over two hundred earthquake deaths in California over the past 60 years. This is a comparatively modest figure for a seismic region, which reflects California's high professional stature in earthquake engineering, and the progressive drive towards enhancing seismic safety, which gains impetus with lessons learned from every major event. The proportion of these several hundred deaths that might have been avoided through EEWS is likely to have been under half. But note should be made of the dynamical seismological argument that the forthcoming half century in California may well be more active than the last.

Beyond California, the EEWS is scheduled also to cover the Pacific North West. The key disaster scenarios for Oregon and Washington are a M9 rupture of the whole offshore Cascadia Subduction Zone, and smaller M8 ruptures of the southern section of this Zone. Based on these great earthquake scenarios, there is a clear justification for the Pacific North West EEWS. The regional quality of earthquake construction in the Pacific North West is generally lower, which amplifies the warning safety benefit, and the state capitals of Portland and Seattle could receive substantial warning of impending prolonged shaking from a great offshore earthquake. Sea-floor sensors near the Cascadia Subduction Zone would warn both of ground shaking as well as tsunamis.

6. Fire following earthquake

Unlike seismic retrofit, EEWS would not reduce building damage from ground shaking. However, EEWS does have some property protection capability: it can mitigate the loss from fire following earthquake. Scawthorn [11] has noted that the size of the fire following earthquake loss is difficult to accurately assess, but best estimates suggest a major earthquake in urban California will result in tens of billions of dollars in fire loss. Based on the latest UCERF3 forecasts, there is a very high likelihood of such a major urban Californian earthquake occurring during a thirty year time period.

One of the classic EEWS applications is for the automatic opening of fire station doors so that fire engines can respond to emergency calls without any delay from damaged door jamming. Apart from this benefit for fire suppression, the number of ignitions could be meaningfully reduced through EEWS. There are numerous types of ignition, ranging from overturned heat sources, to electrical short-circuits, to chemical spillage, and contact friction. In the Northridge earthquake, electrical short-circuits and sparking were the most common source of ignition. EEWS would have made no difference to these ignitions. However, about 20% of ignitions were attributable to a gas appliance flame, match/lighter, and other sources that potentially might have been amenable to manual control if there had been some warning time [12]. Prior earthquake preparedness in factories, offices and homes could include identifying and rehearsing rapid actions that could lower the risk of uncontrolled ignition.

Historical experience in California, such as from both the Loma Prieta and Northridge earthquakes, shows that many ignitions happen well outside the EEWS blind zone. For the M7.8 Southern California Shakeout scenario [13], approximately 1600 ignitions have been simulated, more than half of which are outside the EEWS blind zone, and a quarter are gas-related. For this scenario, the burnt area has value of $40 billion, so that the average fire loss per ignition is $25 million. If just 1% of the ignitions might be averted through EEWS ignition control, then the fire loss saving would be about $400 million. This scenario has about a 10% chance of occurrence in thirty years, so that the expected saving in fire loss from this single California disaster scenario alone is $40 million, which would pay for the EEWS installation costs.

7. EEWS stakeholder survey

Apart from its societal impact in reducing the toll of deaths and serious injuries, as well as fire following earthquake property loss, a public EEWS would have additional significant safety and commercial value for a diverse range of regional stakeholders. For a number of stakeholders, advance warning of a possible power outage may enable a precautionary response to be initiated.

For most stakeholders, the expense of a private EEWS may not be commercially justifiable, given the many more common risks which need to be addressed. However, it would be cost-effective for these stakeholders to contribute collectively in keeping with their sense of corporate social responsibility to the community at large, including their own customers, staff and indeed families. Some of the major stakeholders in EEWS are listed below by industry.

7.1 Hospitals and Clinics

One of the significant EEWS benefits is heightened situation awareness. Even a few seconds of early warning should be of value to highly skilled professionals, such as surgeons, working with safety-critical precision instruments. Laser eye surgery is one of the most delicate and intricate surgical operations; the proportion of patients who experience a significant complication is about 1:100. Major earthquakes are infrequent, and the chance of a patient being unlucky enough to experience notable earthquake shaking during surgery is extremely small, about 1:100,000. This lies well within the error noise of surgical practice. Nevertheless, EEWS would enable surgeons to relieve patient anxiety over an earthquake occurring at a critical moment during an operation.

7.2 Retirement Communities and Nursing Homes

Each year, a typical U.S. nursing home with 100 residents reports 100 to 200 falls; many are unreported. Because of the frailty of the elderly, and their heightened vulnerability and propensity to decline in health sharply after falling, nursing homes and retirement communities should do whatever is possible to protect their residents from destabilizing sudden ground movement. Accordingly, they should especially value EEWS for providing crucial warning time for residents to find safe shelter. With entrance fees to some California retirement communities being as high as $1 million, due diligence over the safety of residents should extend to supporting the provision of hazard warning.

7.3 Hospitality Industry

Corporations that provide hospitality for their paying guests have an obligation to ensure safety and security. EEWS availability should be especially welcomed by high-end hotels, clubs and spas with an exclusive clientele, whose safety, comfort and convenience are paramount. Halting elevators to avoid guests being trapped between floors is a service that the larger hotels in California should provide. One of the celebrities shaken by the 1906 San Francisco earthquake whilst sleeping in a luxury city hotel was the Italian tenor, Enrico Caruso. The potential future liability costs of earthquake injuries to distinguished guests should encourage prestige Californian hotels to support a public EEWS.

7.4 Entertainment Industry

Amusement Parks

Fatal falls from Ferris wheels are very rare, but tragedies do happen: a girl fell to her death from a New Jersey Ferris wheel in 2011. Falls are possible because riders on Ferris wheels are rarely restrained with metal bars or seat belts. Unlike a roller coaster, there are no designed physical forces that would throw a rider off. But every few decades, a large regional earthquake might turn a Ferris wheel trip into a dangerous thrill ride. However, a few seconds of earthquake warning would allow riders the opportunity to brace themselves for unexpected lateral movement. Safety is the first priority for the American amusement park industry, which has an annual revenue over $12 billion. Attendance is price-elastic, so business success depends on public confidence in safety, and it would be in their collective interest for California amusement parks to support a public EEWS.

Film Studios

The cost of injuries is especially high for film studios. Even a modest cosmetic injury could prevent a film star from appearing on screen for months. Body parts may be insured for tens of millions of dollars. Given that a large earthquake could shake all the stars in Hollywood, the aggregate risk would be hundreds of millions of dollars. It would thus be cost-effective for the film studios to contribute towards EEWS in California.

Casinos

Late night poker players at the Napa Valley Casino ran outside, leaving their chips behind, when a local M6.0 earthquake struck at 3.20am on August 24, 2015. In the event of a much larger earthquake occurring at a peak time in the late evening, it would be in the commercial self-interest of the casino management to provide the maximal warning possible for their customers. Not only would everyone be safer, both staff and customers, but this would also reduce the risk of acrimonious disputes over the ownership of chips left on the gambling tables, and winnings entitlements for disrupted games.

7.5 Construction Industry

Especially vulnerable outside are those who work above ground, e.g. construction workers and others who spend time on scaffolding and ladders. EEWS could provide time for workers above ground to find a safer position, and for loads on cranes to be stabilized. In the United States, there are about 50,000 injuries per year from occupational ladder accidents requiring treatment in emergency departments [14]. An additional several dozen injuries suffered in an earthquake during construction hours would not be a substantial risk, but an early earthquake warning would be a deserved additional tier of safety for those doing dangerous jobs on construction sites.

7.6 Manufacturing Industry

California has more manufacturing businesses than any other state. Computer and electronics comprise the state's largest industrial subsector. Although most of the chip manufacturing plants in Silicon Valley have long since moved to Asia, there remains a core of manufacturing plants left in California, which are vulnerable to sudden earthquake ground shaking. Some manufacturing plants could respond adaptively to sensing the initial ground motion, without the need for EEWS. However, other manufacturing plants would experience reduced damage and business interruption if there were a warning from a public EEWS.

7.7 Aviation Industry

Air travel is an important component of transport infrastructure. As with any natural hazard warning, both pilots and air passengers would benefit from a public EEWS. During the Tohoku earthquake of March 11, 2011, one plane at Tokyo Narita airport veered off course as it taxied out to the runway, forcing the pilot to turn back to the terminal, suspecting a mechanical malfunction. Worse than such an episode, the contingency of an earthquake disrupting an airport traffic control system is one that airlines should wish to mitigate through early warning.

7.8 Automobile Industry

EEWS would be a desirable hi-tech safety feature enabling future autonomous vehicles in California to slow down automatically when an earthquake is detected. More conventionally, a public EEWS might reduce accidents from road, bridge or ramp failures. For example, an EEWS might cut the traffic load on an overpass by a few dozen vehicles. If one collapsed, as did the Cypress Freeway in the Loma Prieta earthquake, there might be up to a hundred fewer casualties. Traffic deceleration would also reduce the risk of road junction accidents where the traffic lights are out. It would also mitigate the risk of a car overturning after hitting a street break or obstruction, as happened with fatal consequences in the Northridge earthquake.

7.9 Wine Industry

The South Napa earthquake of August 24, 2014, fortunately occurred at night, so did not cause any injuries in the wine country. Although the M6.0 earthquake was not large enough for EEWS to have been effective, a future daytime M7 Northern California earthquake could demonstrate EEWS utility by mitigating serious injuries at wineries and wine stores from falling wine barrels and bottles. Given that the annual retail value of California wine sales in the U.S. exceeds $20 billion, some wine industry support for EEWS would be affordable and exhibit prudent risk management.

8. Conclusions

A Californian EEWS could reduce significantly the earthquake toll of indoor serious injuries and fatalities, especially for the most dreaded large earthquakes. It would continue the quest to improve seismic safety in California [15]. The safety benefit, along with the fire loss reduction benefit, would warrant the EEWS investment not just for California, but for the West Coast. An investment in EEWS is different from other safety investments in having blanket geographic coverage on the West Coast, rather than enhancing safety in just a few counties. Indeed, for the same annual financial budget of $16 million, greater casualty risk mitigation could be achieved through funding a West Coast EEWS than by increasing the supply of backup emergency healthcare facilities, or through further seismic retrofit to reduce the post-earthquake healthcare demand. EEWS is thus cost-effective in a relative as well as absolute sense. Initiatives to use smartphones as sensors [16] would shrink the blind zone and increase further the cost-effectiveness. Supplementary to improved emergency response and reduced building vulnerability, EEWS makes good economic safety sense. However, EEWS is not, and should not be perceived as a substitute for such important measures.

Beyond life and fire safety, there are numerous regional stakeholders in the private sector who would stand to gain from EEWS operation. Their gain adds to the overall cost-effectiveness of EEWS. Quite apart from business continuity benefits and self-interest to protect key professionals, business leaders and executives, these stakeholders can also serve the broader public interest by contributing to EEWS funding. In the context of corporate social responsibility, support for EEWS would benefit all residents of California, as well as visitors from other states and abroad.

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