The fault rupturing the surface on a road in Mashiki Town

The Kumamoto Earthquake Investigation: A Preliminary Report

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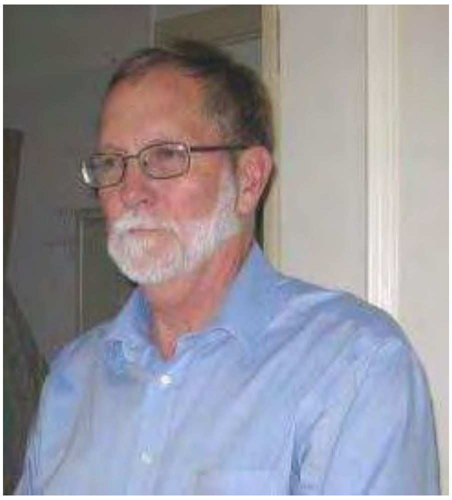

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Forward

Accompanying US Earthquake Engineers to the Mashiki Area

Takanao Nishimoto

On April 18 I visited a small village called Shimo-Otari in Mashiki-cho, the most affected area from the Kumamoto Earthquake with US Risk analysts.

The village was the place where I saw the damage from an earthquake with my bare eyes for the first time in my life. It is sitting on the narrow valley on the south side of a hill on which Aso-Kumamoto airport is located. Houses in the valley are mostly typical old Japanese houses with heavy tiles. A family standing by a completely fallen down wooden warehouse told us that it survived the first shake but the second Shindo-7 shake on the 16th gave the last blow. A new landslide at one of the cliffs along the small river in the village prevented us from driving down to the center of Mashiki-cho that first day

Early next morning, we started the investigation from the same village again with two US earthquake engineers and a Japanese geologist. Downstream of the small river where its dike was heavy damaged was an elementary school which looked not affected by the earthquake. After we identified ourselves and explained the purpose of the visit, the teachers and the principal welcomed the strangers amid the efforts to restore the fallen down shelves, pictures, etc. inside the school. The principal guided us to the locations about which he was most concerned to know if the building damage was critical.

Then the next a half hour was an eye-opening experience for me.

The experienced US earthquake engineer quickly walked through the elementary school buildings with the principal, checking the cracks on the walls and floors explaining to the principal why he did not see them critical. The principal, who seemed very happy with the investigation results from the expert, asked specifically to check the safety of the bridge crossing the nearby river because it is the only evacuation path for people living on the school side of the small river to the opposite side, and the only access path for school children to come to the school. The expert did not take more than a minute to come to the conclusion that the bridge has no problem with bolts fixing steel beams to bridge columns.

It was a bit of a surprise and a shock to me when the expert later said that he was ashamed to see no inspectors dispatched by the local municipal office to check these public facilities aftermath of this big earthquake, which is common in the US.

Then we reached the central part of Mashiki-cho where most severe damage was reported. A US earthquake engineer who has witnessed the earthquake sites in Japan since 1978, including the Miyagi-Oki Earthquake, pointed out that this Kumamoto earthquake can be characterized as one with the strongest acceleration and all sorts of earthquake associated phenomena such as landslide, settlement, strong ground motion and etc.

Here again, the people suffering from the damage to their property and fear of losing their place to live were quite open to listen and accept the evaluation of their house condition from unexpected foreign experts. Housewives from a public housing complex, who came back to clear the mess inside, were very anxious about if they could return to their home. They looked very relieved with the expert's words.

I witnessed one more case which shows how the US expert is really a practical earthquake engineer. We visited the Mashiki-cho sport center which was being used as a shelter and where Japan Self Defense Forces had set up necessary equipment to provide food and water to the evacuees. After looking at the outside and inside of the center, the US expert asked me to interpret his recommendation to one of the young SDF staff. He demonstrated that a low height concrete wall was little bit tilted. It was just in front of the entrance separating a ramp for wheel chair riders from a ramp for vehicles and he could make it fall down by just pushing the wall. He suggested either bringing it down or putting a rope around the area where the wall could fall down. It was a pleasant scene for me to see the young staff immediately run to report his senior.

There were other occasions where we were welcomed to provide evaluations and suggestions to various sectors including a small airline company, a concrete mixing company, and a private hospital.

On the other hand, we failed to access to large companies such as a motorcycle manufacturer and utility company. The larger an organization becomes, the more difficult it becomes to make a quick decision at the front end in the field.

米国リスク管理専門家の益城地区調査同行記

熊本県で発生した今回の地震による被害を調査する米国のリスク管理専門家に同行して、この4月18日から最も被害の甚大であった益城町地区を訪問した。

最初に益城町区域に入ったのは、熊本空港のある高台から細い曲がりくねった道を南側に下りた下小谷という集落である。谷間に軒を接するように並んだ木造瓦葺の日本家屋のほとんどが被害を受けていた。14日の震度6の余震を耐えた家屋の多くが16日未明の本震で倒壊したということであった。川沿いの道路は背後の古い崩落崖の新たな崩落で塞がれ、下流の益城町の中心には進めなかった。

翌日、新たに参加した地震工学の専門家と再び同じ経路で入り、下小谷の集落から始め、地表に亀裂が現われた益城町南東部、家屋の損壊の激しい寺迫地区、そして熊本市内を見て回った。78年の宮城沖地震以降の日本の地震現場をすべて見て来た米国専門家の目からも、今回の地震はこれまで見た中で最も強い加速度を伴う地震であり、地滑り、沈降、揺れなどが複合した特殊な様相を呈しているとのことであった。

下小谷から益城町中心方向に少し下ったところに津森小学校があり、被害状況を見ようと立ち寄ったところ、校長を始め教員全員が後片付けの途中であった。立ち寄った趣旨を告げると、校長は直ちに先頭に立ち、随所にできた亀裂箇所を案内してくれた。それからの米国専門家の動きは驚くほど迅速であった。次々と亀裂個所を見て回り、被害は表面的なもので構造には問題がないことの証拠を挙げ、補修の方法も推奨した。続いて校舎の南を流れる川に掛かる橋を調べ、橋桁に鉄骨ビームがボルト止めされていることを確認して校長を安心させた。この間僅か30分足らず。半世紀近い震災被害の現地調査経験を持つ者の力というものをまざまざと感じた。体育館や教室に同行して、専門家の矢継ぎ早の質問に答えてくれた若い教員も入って正門で集合写真を撮り、大変感謝されて小学校を後にした。

この米国専門家が後で語ったところでは、カルフォルニアでは州政府が直ちに専門家をこうした公的施設の被害状況調査に派遣するが、日本でこうした支援がなされていないのは遺憾だ、ということであった。

行く先々で会った被災した家屋の前で途方に暮れている市井の人々は、訪問の趣旨を説明すると、突然現れた大柄な白髪の米国人に対して何の抵抗もなく診断を求め、或いは納得し或いは安心していた。

倒壊した家屋が続く道の先に外観上は全く被害を受けていない鉄筋コンクリート製の建造物があった。市営住宅である。家の中はめちゃくちゃになって住めないから避難所にいるが、後片付けに来たという二人の主婦はまた住めるようになるかを大変不安がっていたが、専門家の観察結果を聞いて一安心の様子であった。

発展途上国では金持ちの家が被害を免れ、こうした公的住宅が倒壊する事例が多いが、日本では学校を含め公的施設の耐震がしっかりしているとのことである。

益城町の避難所になっているスポーツセンターで、この専門家がいかに実践的な人間であるかを示す事例があった。このバンカーのような堅牢な鉄筋コンクリート造りの建物の前

では自衛隊が炊き出しをし、おにぎりを長い列に並ぶ被災者に提供していた。その直ぐ傍に高さ1.5メートル、長さ4~5メートル、厚さ20センチぐらいのコンクリート製の壁があり、これは車椅子で施設に入るランプと一般者用の階段へのアプローチとの境をなしている。この壁が地盤沈降で少し傾いていた。専門家は手で押してみて傾くことを確認し、直ちに自衛隊員のひとりを呼び止めて、「引き倒してしまうか、人が近寄れない措置をするよう」助言した。この若い自衛隊員が上官への報告に走ったのは見ていて気持ちがよかった。

熊本空港では空港ビル施設の他、航空燃料貯蔵タンクなどを調査した。このタンクは大手の航空会社の所有物でなかったためか、フェンスの中に案内されつぶさに調べることができた。皮肉だったのは、フェンスの入り口に「対テロ警戒中、立ち入り域禁止」と書かれていたことである。入った本人が何の身元確認もされなかったことを驚いていた。

これらと対照的だったのが操業停止している自動車メーカーの工場を訪問した時の対応であった。前者はアポもなしに守衛所で趣旨を告げたので当然かもしれないが、何かの取材に来たものと広報部門に受け取られ門前払いであった。米国では多くの企業が自然災害被災時の時の被害調査と復旧支援にリスク管理専門家を随時使っているとのことである。

筆者には専門的なことはよく分からないが、今回のような調査の目的は、地震によって被害が出た施設や設備と出なかったものとの詳細な観察結果を観測された地震加速度データと突合せ、そうした件数を積み重ねていくことによって、地震による構造物の被害を予測する解析コードの精度を高めて行くことだそうである。

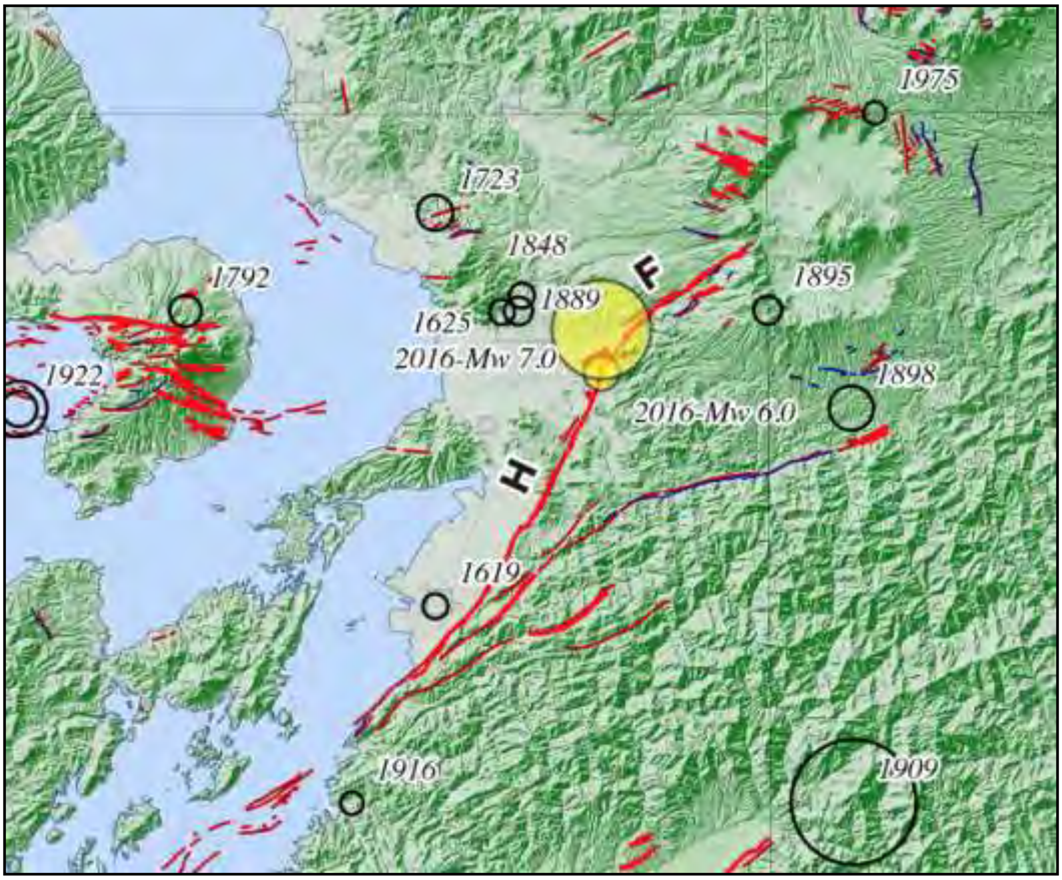
今回の地震は大変浅いところで起きた極めて強い加速度を持つ内陸性地震という特色を持つそうで、こうした調査目的に沿った企業や団体の協力が望まれるとともに、日本においても災害時のリスク管理に当たるこうした専門家を養成する必要を痛感した。

Introduction

Background

At 21:30 on April 14, 2016, an M6.5 earthquake struck along the Furogawa and Hina-gu faults on the island of Kyushu, the southern most main island in the Japan archipelago, about 15km east of Kumomoto City. The strongest ground motion recorded was about 931gal, or about 0.94g, in Mashiki Town.

This proved to be a foreshock[1]. Twenty-eight hours later, in the same area, a stronger M7.0 earthquake occurred with ground motion in Mashiki Town reaching 1165gal, or 1.18g, rupturing the surface in several places. The two earthquakes are shown below in yellow. The historical earthquakes in the area are shown with the dates of occurrence; the circle size indicates the Mw magnitude of the earthquakes.



Date/Time JST	Mw	M	Shindo	gal	Location
4/16/16 at 01:25	7.0	7.3	6.5	1362.1	32.75N, 130.76E
4/14/16 at 21:26	6.0	6.5	6.4	1579.7	32.74N, 130.81E
4/15/16 at 00:03	6.1	6.4	5.7	606.3	32.70N, 130.78E

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[1] A foreshock of 7.3Mw also preceded the main shock, 9.0Mw of the Great Eastern Japan Earthquake.

A note is in order here about the difference between magnitude measurements. Mw is just the seismic moment back-converted to a magnitude using a formula due to Kanamori (1977).

Mw should be the same no matter who measures it, but since the inferred moment can vary depending on the data used and so on it will actually vary a bit.

The Japan Meteorological Agency (JMA) has its own "legacy magnitude" that it still uses. Basically they measure an amplitude from each seismogram, take the logarithm, and apply various corrections. This is what Richter did when he defined magnitudes. There is no reason why Mw and the JMA magnitude should agree for each quake, and they don't.

The JMA magnitude for the April 16 (local time) Kumamoto quake was 7.3, as opposed to Mw of 7.0 by the USGS (http://www.japantimes.co.jp/news/2016/04/16/national/more-powerful-magnitude-7-3-quake-rocks-kumamoto-kills-dozens-more/#.VyU69iEopMF.)[2]

Curtiss-Wright Nuclear Division, Japan, formed a small earthquake investigation team of experienced earthquake engineers, risk analysts, and geologists to visit Kyushu from the evening of 4/17 until the morning of April 23. The team was made up of some of the same investigators who were on the IAEA Mission to Onagawa after the 3.11 Great Tohoku Earthquake. The team members were:

1. Woody Epstein, Curtiss-Wright Director of Safety and Risk, Asia-pacific, IAEA Mission team member and the investigation leader;
2. Takanao Nishimoto, Curtiss-Wright Senior engineer and Senior Advisor;
3. Peter Yanev, Yanev Assoc., earthquake engineer, and IAEA Mission team member;
4. Sam Swan, Acceptable Risk LLC, earthquake engineer, and IAEA Mission team member;
5. Koji Okumura, geologist from Hiroshima University (and who did the active fault studies with Woody Epstein at Tsuruga, Higashidori, and Shika NPPs)

Our goal was to gather preliminary data about successes and failures of structures, systems, and components (SSCs) which can have a direct bearing on industrial facilities, hospitals, schools, and power plants, including nuclear power, and then write an investigation report.

For the SSCs, we planned to go to key industrial facilities which are still closed for damage checks. Many industrial facilities have similar equipment to nuclear power plants and in Japan these SSCs are classifies as “S” class (safety class) SSCs which can withstand 0.6g. We also intended to visit local sub-stations and switchyards to investigate success and failures.

We had collected and analyzed the strong motion records for the three biggest events on April 14 through April 16[3] (M6.4, M6.5, and M7.3, see the table on page 10). In this way, we can begin to relate failures and successes with the damage indicating parameters from the

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[2] Thanks to Dr. Robert Geller, Tokyo University, Department of Earth and Planetary Science, for the clear explanation.

[3] All dates are Japan Standard Time.

strong motion records. This has rarely been done before and should be of great interest and use around the world[4].

As Peter Rickwood, a member of the Onagawa mission, stresses, any earthquake inquiry investigation is, hopefully, of an independent, open ended nature. A good investigation is not to give the final word on "safe or not", but rather to make sure the truth is reported and to ensure that scientific and social conversations continue in open and transparent ways.

The Report

The structure of this report is different than most earthquake investigation reports. We have decided to allow each team member to write stand alone sections reflecting their expertise, observations, preliminary conclusions, and reflections. Some sections complement each other; some sections may differ in opinions. Some may even contradict each other. We wanted each section to be able to stand alone.

Indeed, these differences reflect and reveal the uncertainties in earthquake engineering and the earth sciences: uncertainties as to why buildings fail or do not during earthquakes; uncertainties about the likelihoods (not probabilities) of earthquake recurrence rates; uncertainties about hazard maps[5]; our incomplete knowledge about existing faults, and faults we did not know even existed[6].

This not to say that each section has a sole author in the broader sense. Being together for 12 to 14 hours a day, engendered lively (and sometimes exhausted) conversations. Koji Okumura enlightened us all about the geotechnic features he was seeing; Peter Yanev explained in detail what to look for when assessing damages; Sam Swan, while collecting data, expounded on our lack of knowledge of when SSCs fail or succeed; Woody Epstein shared his analyses of the strong motion records and used his software to create strong motion records for the group; and Takanao Nishimoto provided cultural, geographic, and historical contexts as he drove us tirelessly around the Kumamoto area, which was plagued with traffic jams caused by road, Shinkansen (bullet train), and other train line closures.

So without further ado, let us proceed to the authors' contributions. And again, please note, that this is only a preliminary report. We hope that you, the reader, will join in this scientific conversation and will make contributions which will be incorporated in subsequent versions of the report, so as to make this a true open source, living document.

Woody Epstein, April 27, 2016
Curtiss-Wright, Nuclear Division

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[4] The IAEA Mission to Onagawa collected success and failure data and does have the strong motion records with which to relate successes and failures of SSCs with the damage indicating parameters. Unfortunately, these data and relations have not been put into a database, nor have they been released to the public.

[5] See Geller, R.J., Mulargia, F., Stark, P.B., 2015. Why we need a new paradigm of earthquake occurrence, in Subduction Dynamics: From Mantle Flow to Mega Disasters, AGU Geophysical Monograph 211, G. Morra et al, Eds., pp. 183-191, or Kagan, Y.Y., Jackson, D.D., Geller, R.J., 2012. Characteristic earthquake model, 1884-2011, RIP. Seismological Research Letters 83, 951-953 and http://www.seismosoc.org/Publications/SRL/SRL_83/srl_83-6_op/.

[6] The Nojima Fault, which caused the Great Hanshin Earthquake, 1995, is an example.

Where Else Could This Happen: The Berkeley Hills, Los Angeles, Portland, Seattle, Vancouver?

Lessons from Japan's Latest Destructive Earthquake for Home and Building Owners:

I observed the effects of the latest big earthquake in Japan (Magnitude 7.0 near Kumamoto, Kyushu on April 17, 2016 within less than 56 hours after I left the comfort of my wood frame house in the Berkeley Hills of California. That was also about 3 days after the earthquake and 4 days after the M6.3 foreshock of April 16 that originally, to all, seemed like the main event.

The small town of Mashiki is a few miles east of the City of Kumamoto, but unfortunately right on top of the Futagawa Fault, the cause of the earthquake. While Kumamoto had moderate (and some spectacular) damage, much of Mashiki looked like a war zone. A large proportion of its wood frame homes and smaller commercial buildings were in ruins. In some areas, all buildings in view were destroyed; in other areas maybe 20% were affected severely (at least structurally). In total for the area, perhaps 15% of the buildings need to be rebuilt from scratch and more than 30% of the buildings will require expensive repairs.

A view of a residential area at the foot of the hills in the Town of Mashiki. All of the damaged houses are wood-frame construction.

The M6.3 earthquake/foreshock may have been the best thing to happen to Mashiki, and much of the Kumamoto area, in this earthquake sequence. It was strong and destructive enough to put everyone on alert, and to damage somewhat the weakest buildings. So, when the main M7.0 earthquake happened many of these buildings were not occupied – which should help explain the low overall casualty numbers – less than 50 died in the two earthquakes in an area with about a million people.

Another view of a heavily damaged residential area of Mashiki. All of the houses in the photo are wood frame; most are relatively new.

The town and its much bigger neighbor, Kumamoto, remind me of Berkeley and San Francisco. Berkeley is right on top of the Hayward Fault, just like Mashiki is on top of the Futagawa Fault. Both faults are strike-slip faults – in effect they are both faults that cause primarily faulting in the horizontal direction, with some faulting, or slippage, in the vertical direction. Our primary concern with the Hayward fault is a Magnitude 7+ earthquake. That is effectively exactly what happened with Mashiki's Futagawa Fault. The maximum horizontal slip in Mashiki was about 2m (6+ feet) and the maximum vertical slip (uplift) was about 0.7m (2.25 ft). That is, more or less, what we expect on a similar earthquake in the East Bay somewhere from Richmond south to Hollister. If the earthquake is centered on Berkeley for example, then we have something like a worst-case scenario from Richmond south to Fremont (but not for Silicon Valley).

Faulting, along the Futagawa fault through a hilly residential area of Mashiki. At this location the fault has offset a retaining wall about 4 feet (1.2m). Houses founded right on top of the fault were typically completely destroyed. Nearby wood frame houses, not directly on the fault, had various degrees of structural damage – from light to extreme, including many collapses.

Before I discuss what happens to the East Bay with such an earthquake centered on Berkeley, I would like to mention similar scenarios are likely in other areas along the Pacific coast, from San Diego to Portland to Seattle to Vancouver. In the LA area, a similar earthquake can happen on the Santa Monica Fault, on the Hollywood Fault, on the Newport-Inglewood Fault, and on many more. In the San Francisco Bay Area, such earthquakes can be postulated for the San Andreas Fault from San Jose all the way up past Marin County, for example. Similarly sized earthquakes, with somewhat different fault characteristics, can happen right below Portland (on the Portland Hills Fault), right below Puget Sound on the Tacoma Fault or the Seattle Fault, and in the Vancouver Area (the Lower Mainland) below Vancouver and underneath Victoria on Vancouver Island. Since earthquakes on primarily vertical faults (called thrust faults) are, typically, more damaging to structures and infrastructure than faults like the Futagawa and Hayward Faults, the example of Mashiki will suffice for now.

The number one reason engineers, geologists, scientists, sociologists, and others go to earthquakes is to observe and to learn what actually happens – both the positive and the negative. The positive would be successful performance of buildings (no damage to minor damage); the negative would be surprising new damage or other unexpected results (based on prior experience and analyses).

On the left is a practically undamaged house not far away from a severely damaged house (on the right). The difference in performance here is primarily due to the lack of bracing in the garage in the house on the right. Note the unbroken window on the second floor.

I have been going to earthquake sites since 1971 and the M6.5 San Fernando, Los Angeles Area earthquake. Since those first impressions and new experiences in the San Fernando Valley, I have gone to more than 50 earthquakes around the world and sent teams to another 50+. Many of these were in Japan; more were along our shores of the Pacific. Unfortunately, what I saw surprised me. It exceeded my expectations of what can happen to reasonably modern buildings in the hills and nearby areas of all of the regions of the West Coast listed above. The damage caused by the shaking combined with the ground failures in and around the hills was much more than I have seen before, or expected to see anywhere.

Another house with too many openings (windows) and not enough walls on the ground floor. Note the relatively undamaged houses behind and on the right of the collapsed house.

Other severely damaged houses in Mashiki. Most of the damage that occurred was due to too many windows and not enough strength in the lower floor walls. That additional strength can be easily provided with the bracing provided by a few morewell-nailed plywood sheets.

Most of the buildings that failed were made of wood, just like most of the residential inventory along the Pacific Coast. Some were concrete buildings. My team colleagues and I did not observe any failed steel framed buildings.

Many of the failed houses and smaller buildings had heavy tile roofs, much like the tile roofs popular in Southern California and prevalent on older, Mission Style buildings throughout California. These were often also older buildings, built to outdated codes, such as those along the West Coast predating the 1950s – examples would include older houses with wood framing and exterior and interior stucco and plaster walls.

But, many of the failed buildings were new to relatively new, and built to modern Japanese standards, which tend to exceed the requirements of our codes along the West Coast when it comes to earthquakes.

As shown in the photographs below, much of the damage was due to what seemed to be localized failures of the ground beneath the houses and other buildings. Those failures included localized, small landslide like slumps, and lots of ground settlement (or compaction) caused by the shaking of the ground itself during the earthquake. What was really surprising is the extent of the damage caused by this combination of very strong shaking near to the fault and minor ground failures around and under the buildings. I have seen a lot of damage from both shaking and ground failures (such as landslides), but never quite this much. Not nearly this much!

Much of the damage to houses in the hills was also due to ground failures around the house foundations. That was caused by minor local land sliding and/or the slumping of inadequately compacted fills around the houses. These types of fills are necessary to create level pads for the house foundations, as is the common practice along the West Coast of the US and Canada. What was surprising in Mashiki was the extent of such failures. The likely cause of this unusually high damage is the very strong shaking in the immediate vicinity of the fault.

The worst damage occurred exactly where I expected it. That was in the flat ground just before the ground started sloping upwards to become hills. That is the interface between the relatively soft flat ground (just like in Berkeley west of the University campus). The severe damage extends up into the hills for a few hundred yards (meters) and dies down beyond that. This concentration of damage is partially due to the way the earthquake waves are reflected and refracted at the interface within a few hundred yards in either direction. Again, I have observed this many times before, but the observed (and recorded nearby) shaking in this case seems much more severe.

Damage to a house in the hills above Mashiki primarily caused by local ground failure, either due to minor landsliding or inadequate compaction of fill in the construction of a level building site. The building is leaning to the right; the main ground movement is to the left and downhill.

The other hill areas, like the Berkeley hills, typically have numerous landslide areas and areas with slowly creeping surface soil, which can suddenly slide in a major rainstorm or in a stronger earthquake. Many of these areas were built-up in the past, before the more stringent recent codes. What the Kumamoto earthquake shows us is that damage to houses in the hills, and near the causative fault, can be much more extensive than most of us realize.

In conclusion, this earthquake demonstrates that damage to reasonably well built houses near faults, and particularly houses near the base of hills (upslope as well as in the flat) in the general proximity of faults can be much more severe than generally expected. Houses and other small buildings near faults, and particularly built in the hills near faults, should be expected to suffer proportionally more damage. This earthquake should be a warning both to homeowners and their insurers. This applies to Japan, as well as to the entire Pacific Coast of North America.

Earthquake Geology of the April 14 and 16, 2016 Kumamoto Earthquakes

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[This is a preliminary report based on limited information as of April 28, 2016 and shall be revised and corrected. Click HERE for new version.]

1. Overview

A Mw 7.0 earthquake hit west central Kyushu island in west Japan at 01:25 JST on April 16, 2016. Reportedly 49 were killed, 1 are missing and more than thousand are injured as of April 27. 28 hours before, at 21:26 JST on April 14 another Mw 6.1 had shook the same region severely. Intense ground shaking by two successive earthquakes caused structural damages in an extensive area. The shakings by a large number of aftershocks force 90,000 people to evacuate from their homes no matter the homes were damaged or not. And the extensive damages to infrastructures make their lives more difficult.

Previously mapped and evaluated Futagawa and Hinagu fault zones are the sources of these two earthquakes. The Futagawa fault zone, the northeastern portion of the two fault zones runs about 30 km ENE-WSW. The longest section of the NE portion is called Futagwa fault. The SWS-NEN trending Hinagu fault merges with the Futagawa near its west termination (F and H in figure 1). The Futagawa fault is the source of the Mw 7.0 with 2 m+ right-lateral strike-slip at the surface. The Mw 6.1 ruptured about 15 km long northernmost section of the Hinagu fault without surface ruptures. Minor surface ruptures appeared in this section during the Mw 7.0.

2. Tectonics

The earthquake occurred on the south margin of the Central Kyushu rift. Central Kyushu is the only area of volcanic extensional tectonics in Japan, where EW compression is predominant. Unzen volcano in west of Kumamoto, Aso volcano, and Beppu-Haneyama graben in east are within this NS extending volcanic graben. In southwest, the graben is believed to continue down to the Okinawa trough, the active back-arc spreading center behind the Ryukyu island arc. In northeast, the graben terminates in Beppu bay and the active tectonics shift to strike-slip of the Quaternary Median tectonic line (figure 1).

In west of the Quaternary Median tectonic line, there is a continuous boudary between Mesozoic subduction-related sediments in south and the Neogene volcanics and sediments in north. The Median tectonic line in Shikoku is a very active Quaternary transform, but the activity is replaced with normal faulting on shore Kyushu in most part of the graben. So, the geologic boudary along the south margin of the grabe is mostly inactive except for the Futagawa fault.

The Futagawa-Hinagu fault zone is driven both by the EW compression derived from Philippine Sea plate subduction and by the N-S extension of the Central Kyushu rift. The slip is right-lateral strike-slip with south-side-up normal separation. That means the WSW-ENE strike Futagawa fault is dipping NWN and the NEN-SWS strike Hinagu fault is dipping WNW. The dips are within 60 to 80 degrees. On both faults, right-lateral strike-slip is predominant, but the uplift of the Kyushu mountains in south is due to the normal component of the fault movement.

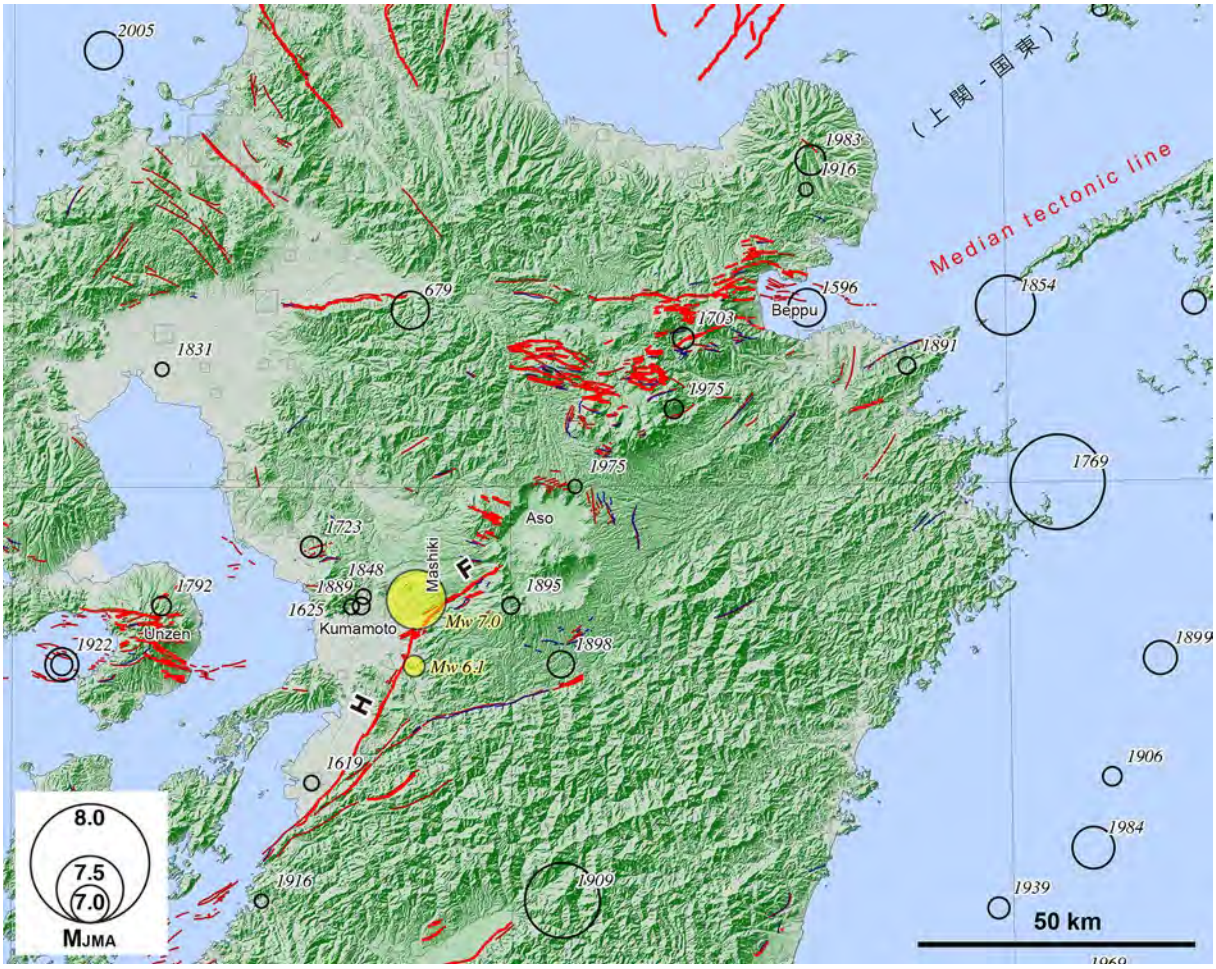


Figure 1 Quaternary faults and earthquakes in Northern Kyushu
Quaternary faults: Nakata and Imaizumi eds. (2002), Research Group for Active Faults of Japan (1995)
Historic earthquakes: Usami (1996)

3. Earthquakes

The April 14 Mw 6.1 recorded the highest JMA intensity scale of 7 at Mashiki JMA (Japan Meteorological Agency) station. The KiK-net (Strong-motion Seismograph Network of the National Research Institute for Earth Science and Disaster Prevention: NIED) maximum peak ground acceleration at Mashiki (KMMH16) was 1580 cm/s^2 in the area of the JMA intensity scale of 7.
http://www.j-risq.bosai.go.jp/report/static/R/20160414212642/0131/00001/R-20160414212642-0131-00001-REPORT_EN.html
http://www.kyoshin.bosai.go.jp/kyoshin/topics/html20160414212621/main_20160414212621.html
http://www.fnet.bosai.go.jp/event/tdmt.php?_id=20160414122500&LANG=en

The Mw 6.1 ruptured the deeper part of the northernmost section of the Hinagu fault. Strong ground motion took place in north and northwest of the epicenter or respectively in Mashiki town and Kumamoto city. The intensity 7 at Mashiki may be due to the directivity effect of the northward rupture propagation on the Hinagu fault. The radiation of strong seismic wave perpendicular to the WNW dipping Hinagu fault plane may be the cause of the strong shaking in Kumamoto.

The Mw 7.0 earthquakes on April 16 occurred during the aftershock sequence of a Mw 6.1 earthquake at 21:26 JST on April 14, 2015. Therefore the Mw 7.0 "aftershock" on April 16 was

immediately redefined as a "mainshock" after the occurrence and the Mw 6.1 "main-shock" was redefined as a "foreshock". The Mashiki JMA station again recorded intensity 7. The Mashiki KiK-net station KMMH16 recorded 1320 cm/s^2 this time, a little smaller than during the Mw 6.1.
http://www.j-risq.bosai.go.jp/report/static/R/20160416012514/0424/00002/R-20160416012514-0424-00002-REPORT_EN.html
http://www.kyoshin.bosai.go.jp/kyoshin/topics/html20160416012405/main_20160416012405.html
http://www.fnet.bosai.go.jp/event/tdmt.php?_id=20160415162400&LANG=en

The main-shock caused extensive structural damages along the Futagawa fault and further east and further west of the fault. The shaking was again the most intensive at Mashiki town. Many houses that were already damaged by the Mw 6.1 collapsed during the Mw 7.0. The extremely strong shaking may be due to the directivity effect of the up-dip propagation of the rupture on the Futagawa fault under Mashiki town, which is located between the epicenter in north and the surface fault in south. Both the epicenter and the fault are two kilometers away from the Mashiki town in opposite directions. The fault plane dips 60° (by GSI: http://www.gsi.go.jp/common/000139798.pdf) to 84° (f-net moment tensor: http://www.fnet.bosai.go.jp/event/tdmt.php?_id=20160415162400&LANG=en) NWN and hypocenter depth is 14 km. The ground acceleration spectra of NIED's KiK-net show significantly larger acceleration at 0.5 to 1.0 Hz by the Mw 7.0 than by the Mw 6.1. Though the peak ground acceleration is smaller by the Mw 7.0, this larger acceleration at 0.5 to 1.0 Hz might account for the heavier damages to Mashiki town by the Mw 7.0.

The rupture propagated toward ENE along the strike of the Futagawa fault. At the end of the rupture is the Minami-Aso village, where 14 were killed and many slope failures occurred. The source fault terminates in the east bank of the Shirakawa barranca where the fault intersects with the Aso caldera rim. In this area, topographic relief is much larger than in other source region for the 300--700 m high caldera walls, 100--150 m deep barranca gorge, and steeply eroded edifices or the central cone volcanoes in east. The steep slopes failed at many locations by the shaking of the mainshock, probably intensified by directivity effects. The Late Quaternary sediments filling the Aso Caldera (95000 years old) also amplified the ground motion to cause many structural damages.

4. Crustal movement and surface faulting

The Geospatial Information Authority of Japan (GSI) published the GEONET (GNSS Earth Observation Network System) observation and model, and SAR (Synthetic Aperture Radar) interferometry results using the ALOS-2 (Daichi-2) satellite together with a lot of low-altitude air-photos and UAV movies.
http://www.gsi.go.jp/BOUSAI/H27-kumamoto-earthquake-index.html
Mw 6.1 foreshock
http://www.gsi.go.jp/common/000139760.png
Mw 7.0 mainshock:
http://www.gsi.go.jp/common/000139809.png
http://www.gsi.go.jp/common/000139905.pdf

The SAR interferometry results clearly demonstrate how faulting occurred and how the surface was deformed. The deformation by the Mw 6.1 is broad and as small as 10 to 20 cm over 10 km wide areas. There was no surface rupture. After the Mw 7.0 more than 10 fringe cycles appeared along the Futagawa fault corresponding to up to 2 m strike-slip offset at the surface on the fault. Along the northernmost

Hinagu fault, the sharp line cutting through frings coincides with the observation of ~25 cm offset by Tohoku University geologists (http://irides.tohoku.ac.jp/irides-news/20160417/289).

According to the preliminary reports from the field and the author's own survey, up to 2.0 m consistent right-lateral strike-slip is observed on the Futagawa fault. The vertical component is usually up to 0.5 m south-side-up, but up to 0.2 m north-side-up deformation is also observed. The offset along the northernmost Hinagu fault is also right-lateral strike-slip. In addition to the slip along the master strands, a 5 km long branch fault of up to 1.2 m right-lateral strike-slip appeared in the east of and under Mashiki town (Kumahara et al.: http://jsaf.info/jishin/items/docs/20160420164714.pdf). There also appeared a conjugate fault with left-lateral strike-slip. These branch faults appeared on modern alluvial plain and there was no remnant of previous slips. The field report of Geological Survey of Japan by Shirahama et al. (http://g-ever.org/updates/?p=334) shows many offset features in the central section of the Futagawa fault. Geospatial Information Authority of Japan (GSI) report (http://www.gsi.go.jp/common/000139911.pdf) based on UAV survey (https://www.youtube.com/watch?v=bS6ftodIHeI&feature=youtu.be) shows the surface rupture near the ENE termination of the Mw 7.0 fault inside the Aso caldera just east of the barranca. The 5 km section of the ENE termination has not been mapped previously.

Most of the Mw 7.0 surface rupture appeared along the previously mapped ~30 km strands of the Futagawa and Hinagu fault. However, the occurrence of the branch faults, south-side down dip-slip, as well as the unmapped termination section presented much more complicated faulting took place in longer than expected source fault.

5. Soil condition in Kumamoto--Mashiki area

Kumamoto city and Mashiki town are located north of Kumamoto alluvial plain (Heiya). Look at the area in the seamless geologic map by the Geological Survey of Japan at https://gbank.gsj.jp/seamless/seamless2015/2d/index.html?lang=en. Kumamoto Heiya is a Holocene alluvial plain (unit 1). The alluvial plain, especially in its southern and eastern parts are mostly too wet for developing and used as paddy fields. Northern half of Kumamoto city and Mashiki town are located north of the plain on Pleistocene fluvial terraces (170 and 171) and on early Late Pleistocene pyroclastic flow (95 and 83). The Futagawa fault cuts the lava plateau (83) and continues along the boundary between the Kumamoto Heiya (1) and Cretaceous rocks. The Hinagu fault in south juxtaposes alluvial plain (1) with bedrocks and run north through bedrocks to merge with the Futagawa fault.

According to Ishizaka et al. (1975: The Quaternary Research [Tokyo], vol. 34: https://www.jstage.jst.go.jp/article/jaqua1957/34/5/34_5_335/_pdf), the Kumamoto Heiya is an area of active subsidence at a rate of 0.90 mm/yr near the coast and 0.45 mm/yr in south of Kumamoto city. With this subsidence rate, 900 m to 450 m sediments are to be accumulated in a million years under the Kumamoto plain. It is very likely this zone of subsidence continues toward east along the Futagawa fault in south and Mashiki town in north.

In the J-SHIS Japan Seismic Hazard Map (http://www.j-shis.bosai.go.jp/map/?lang=en) large site amplification is expected in Kumamoto plain and intensity 6+ to 7 is forecasted in case of Futagawa-Hinagu fault zone earthquake. The Kyushu Express way (right green line) got severe damage on this alluvial plain and is closed now. An express way bridge in the middle of the plain barely survived from collapsing with structural damages. However, the eastern part of the plain is so wet for developing there were no house to be damaged.

Mashiki town, where the severest structural damages took place, is located across the plain from the unit 100 isolated volcanic hill in the geologic map. The center of the town is on the south-facing slope above 11 m high alluvial plain and below 40 to 50 meter high upland consists of Late Quaternary sediments and pyroclastic flows. Subsurface geology is not known yet, but there should be a few hundred meters of sediments that were laid down in pace with the subsidence in south. The sediments may be deposited above south facing bed rock slope as there are hill of Cretaceous rocks several kilometers north.

The KiK-net 1580 cm/s^2 and 1328 cm/s^2 peak ground acceleration, as well as intensity 7 were recorded on the flat top of the upland away from the slope and the alluvial plain. The very strong ground shaking here even destroyed rather new houses on the flat top of the upland where no amplification by surface soil is expected. Therefore the effect of the deeper subsurface sediments and structures on the ground shaking are to be investigated. The significant thickness of Late Quaternary sediments as well as the shape of the basin may have affected the ground shaking on the Mashiki upland.

The author also observed a lot of gravitational slides and lateral spreading on the south-facing slope and on the slopes along incising creeks. There are many collapsed houses owing to this geotechnical causes in addition to the vibration effects. At the foot of the slope, a river runs along the boundary between the upland and the alluvial lowland. The river erodes the upland and fill its course with soft sedmients. There is no clear erosional scarp along the bank, but the sediments of the upland should contact with the alluvial sediment with buried scarps. This situation may be the cause of lateral spreading and sliding in the lower part of the slope. 8 fatalities by the Mw 6.1 foreshocks were reported along the foot of the scarp.

The most intense ground shaking at Mashiki town is presumably due to the effects of seismic wave radiation and of rupture directivity both for the Mw 6.1 and the Mw 7.0. The failure of slopes and possible lateral spreading are the additional cause to the shaking of the severest structural damages. Some researchers claim the branch fault in east and under the town is the cause of the localized damages. It is not likely because the ruptures in the sediments and shallow bedrocks generate neither strong ground motion nor directivity effect. There is no significant concentration of damages by shaking along the master strand of the Futagawa fault. This is clear and strong evidence that ruptures at and near surface have nothing to do with strong vibratory motions.

In Kumamoto city, moderate structural damages took place extensively. The southern half of the city has expanded into the Kumamoto Plain above hundreds of meter thick sediments. The northern half of the city is on Late Pleistocene terraces on Quaternary volcanics. Thick soft sediments and rocks may have amplified the ground motion. Detailed investigation on the soil condition and damages should be carried out to understand seismic risks in the cities on soft sediments.

6. Past earthquakes and earthquake forecast

No historic earthquake larger than M 6.5 was recorded in the source area (figure 1). In Kumamoto, M 6.0 to M 6.5 earthquake occurred every 50 to 100 years. These earthquakes killed 10s of people and damaged Kumamoto castle repeatedly. So, the 2016 shaking in Kumamoto is not an unusual event. Earthquakes larger than M 7.0 were inferred only by paleoseismological excavations on the Futagawa-Hinagu fault zone.

HERP, the Headquarter for Earthquake Research Promotion of the government of Japan, had evaluated long-term seismic potential of the Futagawa-Hinagu fault zone in 2002 and revised it in 2013. The seismic risks of the Futagawa-Hinagu fault zone was evaluated by rather limited geologic information of recurring earthquakes. For the Futagawa segment of the fault zone, an earthquake around M 7.0 with 2 m surface offset on a 19 km long rupture was forecasted. A M 6.8 earthquake was forecasted for the 16 km segment of northernmost section of the Hinagu fault, on which the Mw 6.1 occurred at depth and surface ruptured during the Mw 7.1.

The conditional probability of the earthquake in 30 years was estimated as 0 to 0.9 %. This estimate is based on two past earthquakes in paleoseismological excavations. The timing of the two events are 2200 to 6900 years before present and 23000 to 26000 years before present. One or more events were supposed to have been missing in the geologic records. Assuming 2 or 3 events since 26000 years ago, recurrence interval was estimated as 8100 to 26000 years. The large uncertainty and long interval made the probability less than 1 %. But 0.9 % 30-year probability is rather high for slow-moving intra-plate faults in Japan and the highest possible ratio between the elapsed time and the recurrence time was 0.9 at the highest.

Figure 2 Surface rupture at Shimojin (N32.49519° E 130.84871°)
The rupture offsets the southeast corner of a paddy by 1.2 m right-lateral strike-slip (east edge of the paddy) and 0.4 m south-side-up. The slope to the left is a fault scarp of the Futagawa fault. It seems farmers cut into the scarp to make the paddy wider and the scarp steeper. The fault passes just in front on left hand side of the upper-right house. The house is almost intact.

An Overview of the Kumamoto Earthquake Sequence

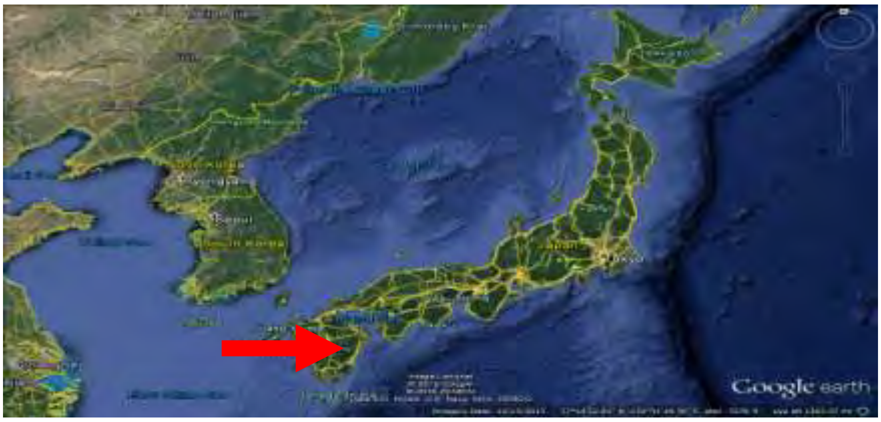
Sam Swan, PE, Acceptable Risk LLC, Berkeley, California

The main shock of the Magnitude 7.0 Kumamoto earthquake sequence occurred at 1:25 early Saturday morning (local time) on April 16, 2016. The main shock was preceded by a magnitude 6.5 earthquake at 9:26 in the evening on Thursday April 14. Damage from the initial earthquake alone was sufficient to attract world news coverage. The sequence of a moderate-magnitude-followed-by-large-magnitude earthquake illustrates the chance that any damaging earthquake may in fact be a foreshock, followed within a day or two by a much larger event. Earthquake history indicates this happens perhaps 10% of the time.

The earthquake sequence was centered in the western central section of Kyushu, the southernmost main island of Japan. The earthquake was caused by a right-lateral-strike-slip movement on the Futagawa-Hinagu Fault, which extends about 100 kilometers from the volcanic caldera of Mount Aso in the northeast to the Yatsushiro Sea in the southwest near the City of Kumamoto. The Magnitude 7.0 main shock appears to result from a shallow rupture over about 30 kilometers of the Futagawa fault (*Dr. Koji Okumura, Hiroshima University*). The fault rupture was centered in the small town of Mashiki east of the City of Kumamoto. The fault broke the ground surface creating horizontal offsets approaching 2 meters in roadways along the trace and passing through several homes.

The combination of earthquakes caused severe damage in residential areas near the fault's surface trace. Ground motion was recorded at dozens of instrument stations on Kyushu. The five strong motion recordings nearest the fault trace measured between 0.50g and 1.4g peak horizontal ground acceleration (1.0 g = the force of gravity). In the small area of most severe damage, effects would be considered as high as Intensity Nine to Ten (MMI IX - X) on the conventional Modified Mercalli Intensity Scale or intensity 7 on the Japan Meteorological Agency Scale, commonly called Shindo..

A small team of engineers was organized by the Curtis-Wright Nuclear Division of Tokyo. The team arrived in the earthquake-affected area of Kyushu on Monday, April 18, two days after the main shock of early Saturday morning. The engineering team spent five days in the damaged area surrounding the City of Kumamoto. This brief post-earthquake study was intended to capture general effects from the earthquake sequence through first-hand observations immediately following the event.



The surface trace of the fault on the southern side of the Mashiki Valley created offsets in roadways and retaining walls and in a few homes. The photo looks west along the Futogawa fault toward Kumamoto.

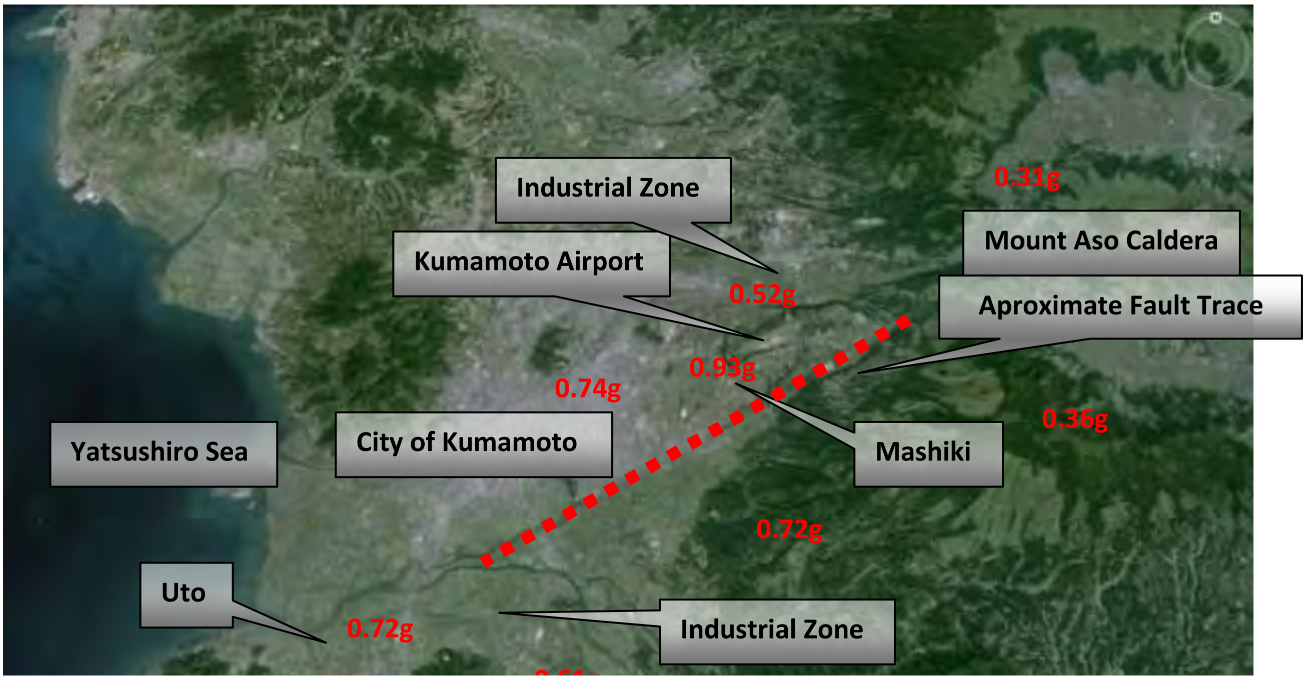
General Observations

The most severe damage from the earthquake sequence was concentrated in a band approximately 3 kilometers east-west by 1 kilometer north-south along the north side of the valley that contains the residential area of Mashiki . This zone of severest damage overlays the Futagawa fault plane which dips to the north from the surface rupture. Severe damage appeared to rest on shallow alluvial soil atop volcanic rock at the base of the low hills that bound the north side of the valley. This region was of course also the focus of media coverage due to extensive collapse of homes and small commercial buildings.

The area includes a combination of one and two-storey recent and older structures that would represent a typical suburban area in any developed country including the United States. Building codes in Japan include provisions for earthquake load that are comparable to high seismicity areas of the United States. Major upgrade of the Japanese code in 1981 might be considered the time line between older more vulnerable construction and more recent earthquake-resistant construction. Homes and commercial buildings in Mashiki are generally wood-frame structures with stucco or pre-fabricated siding. Homes typically are topped by tile roofs, which of course are a factor in earthquake damage due to their mass. Commercial buildings and residential apartment buildings are primarily reinforced concrete frame, with a few steel fame or concrete shear wall structures.

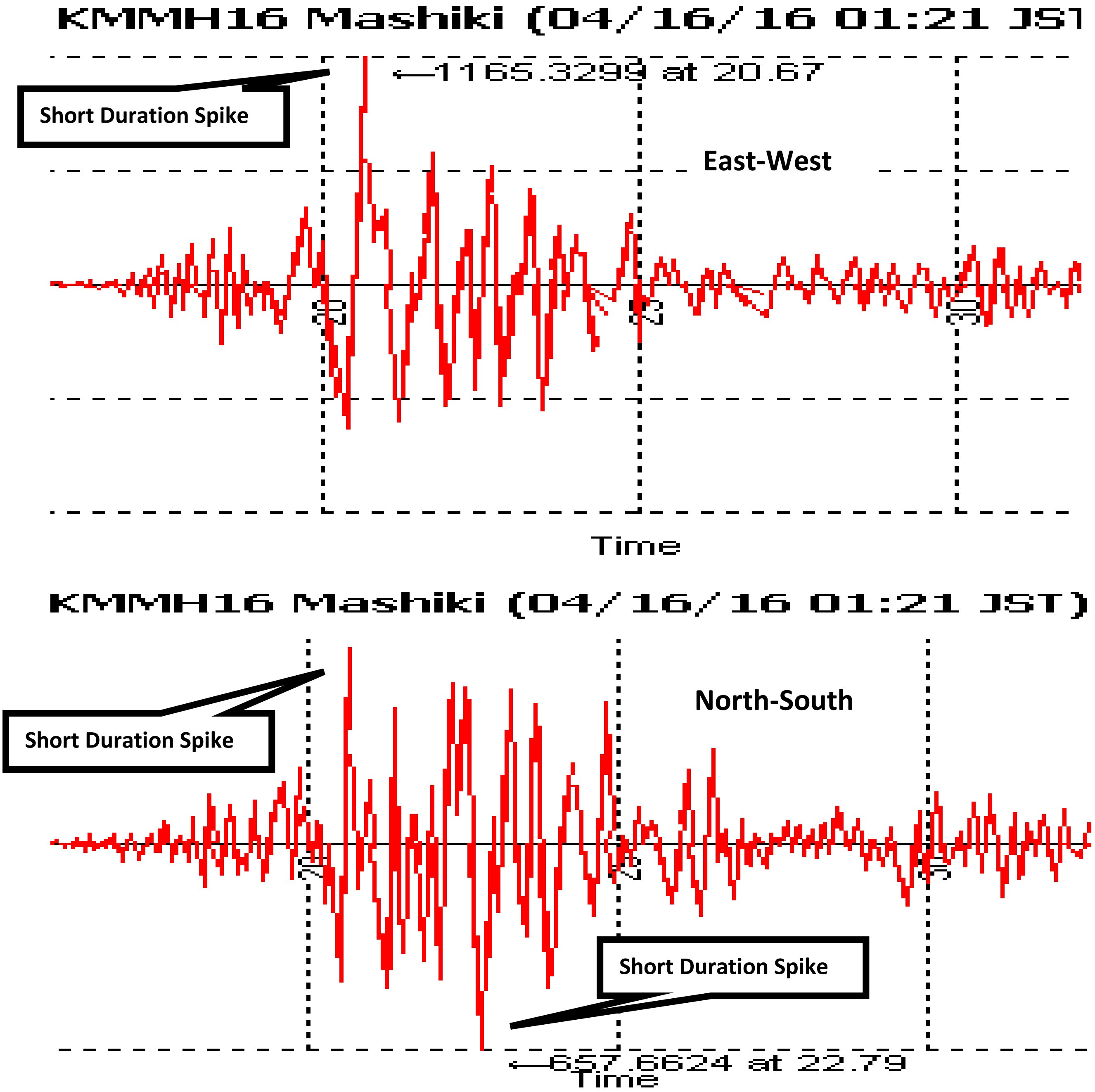
As expected partial or total collapse tended to occur in older structures although not without exception for newer structures. As a rough estimate perhaps 10% of the housing and commercial buildings in the heavily damaged Mashiki residential area were a total loss, suffering partial or total collapse. Perhaps 50% of the structures in the area are salvageable but will require serious repair.

Effects to one- and two-storey wood frame housing resulted from a combination of strong ground shaking and soil failure including landslide, soil slumping and settlement. The area of severe damage includes a ground motion recording on the ridge atop the low hills bounding the north side of the Mashiki Valley. The record averaged 0.93g (acceleration of gravity) in the two horizontal directions. The area of most severe damage in Mashiki could be rated as high as Intensity Nine to Ten based on effects. This area was surrounded by a much larger area perhaps 10 kilometers east-west by 5 kilometers north-south that would be rated Intensity Eight (MMI VIII). This area of moderate to serious damage extended approximately from the Kumamoto Airport in the northeast to the edge of the urban area of Kumamoto in the southwest. A larger area of perhaps 30 kilometers east-west by 20 kilometers north-south would be rated Intensity Seven. The experience for modern construction in developed countries like Japan, with stringent seismic provisions in building codes, is that Intensity Seven (MMI VII) is the threshold of damage to structures and contents. This area of Intensity Seven or greater effects extended from the hills bounding the Aso Caldera in the northeast to the coastline in the southwest. This region included the City of Kumamoto and the industrial areas to the northeast and south. Soil conditions obviously had a significant effect on the level of ground shaking and subsequent damage. Thus pockets of higher or lower shaking would be included in the general regions outlined above. The map below illustrates the areas included in the engineering team’s investigations and strong motion records in the region from the main shock of April 16.



The general region affected by the earthquake is illustrated by the satellite image (courtesy Google-earth) showing the approximate location of the fault rupture and the measured peak ground accelerations (average of horizontal components). The peak ground accelerations are courtesy of the USGS web site and Woody Epstein of Curtis-Wright, Tokyo.

The strong motion record above the heavily damaged Mashiki residential area recorded over 1.0g in the east-west direction. This peak ground acceleration however is observed from the acceleration time history as a short duration spike. The amplitude exceeds the more realistic measured acceleration of about 0.50g for less than 0.1 second. This short duration of peak acceleration would have minimal energy content and hence a minor contribution to damage in the area.



The peak ground accelerations recorded by the Mashiki strong motion instrument are spikes in the measured horizontal acceleration, with durations of less than 0.1 second, lacking serious energy content compared to the longer duration acceleration cycles of less amplitude.

The general observation regarding earthquake effects is that damage was sporadic, indicating variation of soil conditions and ground motion over distances on the order of a city block. Sections of homes with only minor cracking would be followed by several structures totally collapsed. Of course observations from the street will not always reveal serious structural damage hidden by only minor distress in the non-structural cladding.

The zone of serious structural damage faded as the city of Kumumoto was entered from the east. With some exceptions damage in Kumamoto itself was sporadic and minor to moderate, with shear cracks in plaster or concrete and broken plate glass observed only occasionally in the downtown business district.

The most serious damage was concentrated on the north side of the Mashiki Valley where the soft soil meets the volcanic rock of the hills. As an estimate roughly 10% of all homes and small business structures were a total loss through partial or total collapse.

Collapse of homes was often attributable to soft first stories containing garages where large door openings provided no restraint against lateral loads.

Soil slumping or spreading caused some collapses, as with this home that tilted toward the nearby stream bed.

The strong motion instrument nearest the area of heavy damage is located in a small concrete shed in a park atop the ridge bounding the north side of Mashiki Valley. The instrument recorded a peak of 1.18g in the east-west direction, averaging 0.93g horizontal.

Serious damage was sporadic in the newer homes of the residential area on the hilltop near the Mashiki strong motion instrument. Close inspection however revealed that most homes required some level of repair. Damage became more extreme proceeding down the hill into the older district atop softer soil.

As the city of Kumamoto was entered going from Mashiki east-to-west, visible damage in buildings declined becoming sporadic. Serious affects such as loss of this masonry siding from a steel-frame building represented less than 1% of structures.

Nearing the center of Kumamoto visible damage in buildings became difficult to find, although serious structural problems are occasionally hidden by undamaged exterior fixtures. The photo shows a typical view across a range of building ages and sizes from the main east-west traffic artery.

One of the few notable exceptions of serious building damage was the soft storey collapse of the Mitsubishi dealership show room in south central Kumamoto. Lack of adequate ties around vertical rebar in the concrete columns appeared to be the root cause. The photo was taken just before the team was asked to leave by the Mitsubishi sales manager.

The universal indicator of earthquake damage in central Kumamoto were the piles of damaged furniture, appliances and collapsed perishables stacked in front of every large apartment complex, indicating the degree of damage to unrestrained internal fixtures.

Lifelines

The area that experiences serious structural damage in an earthquake is normally surrounded by a much larger area that experiences interruption in critical utilities or lifelines. **Electric power** is the utility service upon which all others depend. The Island of Kyushu is served by the Kyushu Electric Company. Power generation in the Kyushu system includes a combination of coal, oil and gas-fired thermal plants, two nuclear plants -- Genkai (shut down) in the north and Sendai (operating) in the south -- and a mixture of small hydroelectric, wind and solar plants throughout the island. The urban area of Kumamoto includes little local generating capacity. Instead power is supplied to the city over the island's network of 220 and 500 kilovolt transmission lines. Two major electrical substations are the primary suppliers to the region, located on the north-south 500-kilovolt line near the town of Kikuchi northeast of Kumamoto and near Misato to the southeast.

Regional power blackouts are a normal occurrence in strong earthquakes even if the power grid suffers little actual damage. On Saturday the day of the early morning main shock, Kyushu Electric reported loss of power to approximately 165,000 customers in the greater Kumamoto region (*Nikkei Asian Review*). Because the major substations are located away from the region of most severe shaking, restoration of power was relatively rapid. All but isolated pockets of service were restored by Tuesday, when 6500 customers were reported by Kyushu Electric as still without power. A factor in rapid power restoration was the fact that the major generating plants were well away from the earthquake. As examples the Genkai and Sendai nuclear plants, located more than 100 kilometers to the north and south respectively, measured very low shaking in their on-site recorders. Sendai in the south is one of only three nuclear plants that have restarted since the Magnitude 9.0 Tohoku earthquake and tsunami of 2011. Shaking measured at Sendai did not reach the trigger point for scramming the reactor and shutting down the plant.

Electric power to the greater Kumamoto area is supplied over 220 and 500 kilovolt transmission lines into major substations such as this one near Kukuchi. The photo shows the entry of 500-kV lines dropping into the steel truss frame with cables dropping to the tall ceramic insulators of circuit breakers.

High voltage power is stepped down to distribution levels in substations throughout the greater Kumamoto region. Rapid power restoration in the area may be partially attributed to good anchorage of equipment and the shorter ceramic insulators for distribution voltage.

Loss of **telecommunication** is normally the most disruptive effect of a major earthquake. Even if telecom receiving antennas and switching centers are undamaged, telecom normally overloads in any disaster due to the sudden traffic volume. Telecom systems are not immediately affected by loss of regional AC power, as phone systems operate on DC power from in-station batteries. However batteries discharge within about a day if AC power is not available for recharge. The 2011 Tohoku Earthquake created an incentive in the major telecom companies in Japan to improve options for emergency service. Following the initial shock in Kumamoto on Thursday, April 14, the three major service providers for Kyushu, Softbank, NTT Docomo and KIDDI, set up temporary Wi-Fi hot spots around the affected area (*Japan Times*). The temporary hot spots allowed free cell phone access to anyone within range. Similarly Line Corporation provided a free access for texting (“short messages, please”) as an alternative to voice communication. Much of the telecom traffic volume following a disaster is simply messages out-of-area to friends or family providing updates of “OK or not-OK”. Cell and internet connections appeared to be normal in the region within two days of the earthquake when this engineering team arrived.

Restoration of potable **wate**r normally takes longer than electric power as water storage tanks and buried water pipelines are susceptible to damage, and pump stations require power to re-pressurize the system. Water supply is not only necessary for life support and sanitation, but is usually required to maintain air conditioning for larger facilities. Most large buildings use evaporative cooling towers as their ultimate heat sink. Critical facilities such as telecom switching centers will often depend on water supply to cooling towers to control the high heat loads of their electronics within operating temperature ranges.

As the heavily shaken area was visited in the immediate days following the earthquake, water was noticed leaking into streets from broken mains in the heavily damaged area of Mashiki. Repair of failed water lines requires first location of the break, isolating the damaged section of line, excavation, line repair, re-pressurizing the line to ensure the leak is repaired, then replacement of surface covering. Water service was initially lost to over 400,000 customers in the Kumamoto region (*Japan Times*). After bypassing damaged pipelines, service had been restored to all but about 90,000 customers by Tuesday three days after the earthquake. Restoration of water service to the heavily damaged area in the Mashiki Valley was likely to take more than a week.

Water supply for greater Kumamoto is stored in uphill reservoirs such as this 500,000 gallon concrete tank overlooking the town of Uto. As reservoirs happened to be located primarily outside the heavily shaken areas, water service was restored to all but the Mashiki Valley within a few days.

Rupture of underground water mains delays restoration in soft soil areas subject to severe shaking. The photo shows water seeping from a break on the fault trace on the north side of the Mashiki Valley.

Like water systems **gas** service is susceptible to damage in buried pipelines. Gas pipelines normally have a better earthquake performance than water lines as buried gas lines are usually welded steel. However gas service is typically shut off over the earthquake affected area to avoid ignition from leaks. Gas was shut off in the Kumamoto region following the initial earthquake (*Nikkei Asian Review*). Gas service was expected to require more than a week for restoration in the heavily shaken Mashiki Valley as testing for leaks is a necessary precaution.

The most universal effect of any major earthquake is disruption of **transportation**, especially in urban areas. Rail service to central Kyushu was shut down for several days following the earthquake, due in part to a derailed Shinkansen (bullet train) near Kumamoto. Kumamoto Airport northeast of the City closed, due in part to non-structural damage within the terminals. A few flights were resumed to the airport on Tuesday and Wednesday. The airport generally escaped significant structural damage based on the brief tour by this engineering team. Restoration within the terminals focused on repairing isolated areas of ceiling damage and cleanup of fallen merchandise in food and shopping marts. Concrete shear walls in the buildings' core suffered shear cracking, but far short of serious structural damage.

The main north-south Kyushu Expressway was closed south of the town of Tamana due to damage at bridges and overpasses. Traffic detoured on two-lane peripheral highways, causing delays of hours. Only the fact that the mountainous and agricultural area of central Kyushu has only a moderate population density allowed traffic to move at all.

Traffic arteries were closed following the earthquakes due to bridge and overpass damage including failure in columns (upper photo) and slumping where bridges meet abutments (lower photo). Closures divert traffic to alternative routes creating major delays that affect the population far beyond the area of earthquake damage.

Industry

The industrial area northeast of Kumamoto includes several dozen large firms for manufacture of vehicles, electronic components and pharmaceuticals. Kyushu has in fact been termed Japan's "Silicon Island". Access to the major manufacturing firms could not be arranged for this engineering team in the immediate days following the earthquake. However general status updates were provided from the larger firms such as Sony, Mitsubishi, Ebara, Honda, Toyota and Renesas Electronics. It appeared that even if damage to structures and equipment was minor, operations would be suspended in the plants at least for the week following the earthquake (*Japan Times*). Plant staff is often allowed several days to deal with effects in their homes and render assistance to friends and family. Most of the larger firms reported at least minor damage in structures and internal systems as a general description released to the media. The effect of even short-term shutdown of the larger firms near Kumamoto interrupted the supply chain of critical parts in downstream manufacturing operations throughout the world. As an example Toyota reported partial suspension of manufacturing due to loss of certain parts supplied from Kumamoto. The modern procedure of "just-in-time" delivery presents an obvious vulnerability to supply chain interruption on a world market.

The engineering team was able to visit a few smaller sites as a sample of the earthquake effects on industrial construction. Local industrial sites were selected where the team could gain access in areas where damage seemed concentrated or where the facilities themselves suffered damage.

The aviation fuel tank farm adjacent to Kumamoto Airport provided a sample of steel vessels, piping, pumps, power supplies and control systems, including the buried fuel distribution piping to the aircraft fuel taps at the terminal gates. Aviation fuel is stored in to two steel tanks each of about 300,000 gallons (1.1 million liters). The tanks rest unanchored on concrete pads with peripheral asphalt rings to drain rainwater away from the tank base. Rocking of one tank shattered the asphalt surrounding the base. Otherwise the two vessels were undamaged as was the piping, pumps, power supplies and control system downstream. Aviation fuel was therefore available to support the gradual re-opening of the airport in the week following the earthquake sequence.

Kumamoto Airport experienced only minor damage to internal fixtures plus minor cracking in interior concrete shear walls. The airport re-opened gradually with flights starting on Tuesday three days following the earthquake sequence.

The aviation fuel facility serving Kumamoto Airport stores fuel in two welded unanchored steel tanks of about 300,000 gallons capacity each. Rocking of one tank shattered the asphalt ring around the base for water drainage, but the tanks were otherwise undamaged and able to provide fuel as the airport re-opened.

The engineering team was able to visit two cement distribution plants where damage occurred in steel silos. A distribution plant on the southwest side of Kumamoto was under repair six days after the earthquake due to settlement in the foundation of a cement silo. The silos are supported on braced steel posts atop concrete pedestals embedded in the soil. Settlement beneath one pedestal tilted a silo, causing uplift on the opposite side. At the time of the team visit a crane was in place lifting the tilted vessel back into level alignment.

A more serious example of silo damage was observed a few kilometers away at a distribution plant on the southeast side of Kumamoto. At this site two steel-post-mounted silos collapsed. The silos were reported as full of cement at the time. Collapse of the vessels occurred due to failure not at the base but in flanged joints in the silo support framing. The bolted connections in the flanges appeared to have corroded over time. Toppling occurred in the two larger vessels, with the adjacent three smaller remaining upright and intact.

Brief visits were made to agricultural storage facilities in the area south of Kumamoto near the town of Uto. This area is near the junction of the Futagawa and Hinagu faults and assumed near the southwestern end of the fault rupture from the Magnitude 7.0 event. Line-ups of storage silos with attached pneumatic conveyor ducting were observed to be intact, although details of the blowers that convey product through the ducting were not collected. Nearby distribution plants for pressurized gas such as nitrogen and nitrous oxide were also in operation with no apparent breach of pressure vessels or piping.

With few exceptions such as the collapsed cement silos, it appeared that the smaller industrial operations south of Kumamoto were able to quickly recover due to limited damage to their steel construction. The strong motion record nearest the industrial area is located at the Uto city hall. The five-storey city hall structure itself suffered partial collapse due to failure in its concrete columns. The strong motion instrument adjacent to the building recorded a peak ground acceleration of 0.72g as an average of the two horizontal directions. Normally this PGA would be associated with Intensity Nine (MMI IX). However, with the exception of City Hall, damage to nearby homes and commercial buildings was minor, appearing to correspond more to Intensity 7 or 8 (MMI VII – VIII). The generally moderate effects to small industry and residential structures in the Uto area therefore are either a confirmation of the effectiveness of Japan's building codes or an indication that peak ground acceleration and structural damage correlate poorly. Both conclusions may be true.

The most serious damage in the Uto area was partial collapse of the city hall due to failure in the main concrete columns. The Uto strong motion recorder is housed in a small enclosure on the city hall grounds (lower photo).

A cement silo at a distribution plant southwest of Kumamoto was being re-leveled by crane lift six days after the earthquake (upper photo). Drop of one corner of the silo foundation pedestal due to soil settlement (lower photo) lifted the opposite corner.

The two larger silos collapsed at a cement distribution plant southeast of Kumamoto. Overturning appeared to be caused by failure at flanged connections in the framing due in part to corroded bolts. The three smaller silos that remained intact and upright were reported as newer installations.

Storage facilities for the agricultural areas south of Kumamoto remained generally intact and free of major structural damage including the large ducting that pneumatically conveys product to the tops of silos.

Emergency Facilities

The engineering team lacked sufficient time to perform a thorough review of emergency response by the government and non-government organizations in the days immediately following the earthquake. However an overview could be obtained by visits to two example emergency response facilities.

The sports complex in the town of Mashiki was designated as the emergency shelter and supply distribution center for the most heavily damaged area. The complex is located in the center of the Mashiki Valley immediately south of the most heavily damaged residential area. The sports complex itself is a relatively new structure consisting of a two storey concrete shear wall enclosure with interior arenas. The structure itself displayed only minor cracking and spalling in the concrete. Soil settlement and pockets of liquefaction could be observed from permanent waves and offsets in the pavement in front of the complex, and slumping of the soil around the building foundation. When the engineering team visited three days after the earthquake the local population formed a long line for distribution of emergency supplies including food and bottled water. On the order of 100,000 people were reported by the news media as displaced by the earthquake sequence, much of this population from the Mashiki area.

The West Kumamoto Hospital near the town of Uto was visited by the engineering team as a sample emergency response facility in a less heavily damaged area. The hospital is about 2 kilometers east of the Uto city hall record which measured 0.72g peak ground acceleration (average of two horizontal directions). The relatively minor earthquake effects to the hospital and its surroundings indicate that ground motion may have been somewhat less compared to the city hall record location.

The hospital consists of two wings, the older, a two-storey concrete frame structure, opened in the late 1990s; and the newer main facility, a six-storey concrete-shear-wall-and- frame building, opened in 2015. The hospital's main facility thus represents essentially state-of-the-art design for seismic loads in building structures and internal fixtures.

Despite the apparent high ground motion in the general area, damage in the hospital was only superficial. Minor cracking and spalling was observed where pavement or brick curbs met the base of the building. The expansion joint in the new building showed chipped paint and scratched plaster to illustrate that the gap had performed its function to accommodate relative movement between the building sections. Typical damage to non-structural fixtures such as suspended ceilings was described by the hospital management as very minor.

Most importantly the major medical equipment was reported to be undamaged by the hospital facilities manager, allowing the facility to function as an emergency care center. Power was lost following both earthquakes, and remained off through Sunday to be restored on Monday. Following both earthquakes the standby generator on the roof of the main building started automatically for backup power supply.

With emergency power the in-building utilities remained functional with the possible exception of off-site communication. Air conditioning for the main building is provided by roof-mounted heat pumps exhausting through fan-coil heat exchangers. Unlike most large facilities the building therefore does not rely on water for cooling towers as the ultimate heat sink for cooling. The only significant damage to building utility systems was failure of a short run of piping spanning between two of the potable water storage tanks located on pads outside the hospital. The tanks ensure continued water supply for consumption and sanitation if water service should happen to be cut off, from an earthquake for example[7]. Differential rocking of the two water tanks ruptured the pipe interconnection, resulting in a partial drain of the tanks. Partial loss of the water inventory did not affect hospital operation; the failed pipe was quickly repaired.

When the hospital was visited on Friday a week following the initial earthquake, operations appeared to have returned to normal, allowing the facility staff to host the engineering team on their brief tour. The very minor effects to the hospital seem to illustrate the effectiveness of the Japanese building code in protection of critical emergency response centers.

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[7] West Kumamoto Hospital uses under-ground water as a sole source of water. It does not use municipal water.

The Mashiki sports complex is a two-storey concrete shear wall structure designated as the emergency shelter and supply distribution point for the most heavily damaged area. The soft soil at the center of the valley displayed severe settlement, creating permanent waves and offsets in the pavement where the local population lined up for supplies. Pockets of liquefaction were indicated by sand boils as shown at lower right in the lower photo.

The West Kumamoto Hospital near the town of Uto had essentially no structural damage from the earthquakes despite the apparent high ground motion indicated by the nearby record at the Uto city hall. Operations could be continued immediately following the earthquake due in part to standby power and the on-site water supply.

General Observations

The general conclusions of the engineering team from the few days of investigation immediately following the Kumamoto earthquake sequence can be summarized as follows:

- Damage was extreme in the small region of the Mashiki Valley just north of the fault rupture. The apparent combination of high ground acceleration and soil failure, including land-slide, soil settlement and slumping, damaged homes and small businesses to a level rarely observed in developed countries.
- Records of the ground motion from Japan’s extensive system of permanent strong motion stations confirmed the high level of shaking. The five records nearest the fault rupture all exceeded horizontal ground acceleration of 0.50g, with over 1.0g at the record location above Mashiki nearest the worst damage.
- Despite recordings exceeding 1.0g in the horizontal direction, damage to the relatively recent housing construction in the vicinity of the Mashiki record was generally moderate. The time history shows that the peak ground acceleration was a short-duration spike that lacked serious energy content. The more realistic representation of peak amplitude in the record would be in the range of the longer duration cycles peaking at about 0.50g. This observation of peak acceleration corresponding to short duration would likely hold true for

the other strong motion records in the area. Peak acceleration alone typically does not correlate well with damage.

- Effects to structures ranging from homes to high-rises generally illustrated the beneficial effect of building code improvements in Japan, starting around 1981. The severity of ground shaking in Mashiki however did not spare all new construction built-to-code.
- Casualties were high for a developed country, but could have been much higher had the region of extreme shaking and ground failure been centered in the city of Kumamoto itself rather than in the suburban residential area of Mashiki.
- The large industrial area northeast of Kumamoto was also spared extreme shaking. Effects in the industrial area would generally be rated Intensity Seven bordering on Intensity Eight. Intensity Seven shaking normally would not seriously impact modern industrial construction. Rapid recovery of business operations within one or two weeks would be expected.
- The restoration of critical lifelines, including power, water, telecom, fuel, and transportation was helped by the location of critical facilities such as high voltage substations away from the area of most intense shaking. Improvements in emergency response following the earthquake and tsunami of 2011 may have sped lifeline recovery, as illustrated by the rapid emergency Wi-Fi stations set up by service providers immediately following the initial shock.
- The Magnitude 7.0 Kumamoto earthquake illustrates the likely impact on a similar urban or suburban area in a developed country with good seismic provisions in building codes. The earthquake magnitude and the resulting ground shaking in soft soil areas represent the potential of many active faults near urban areas in California, Oregon and Washington.

Example Emergency Response Facility: The West Kumamoto Hospital

The West Kumamoto Hospital was visited by the engineering team as a sample emergency response facility in close proximity to the strong motion record located adjacent to the partially collapsed Uto City Hall. The hospital complex is about 2 kilometers east of the Uto City Hall record which measured 0.72g peak ground acceleration (average of two horizontal directions). The relatively minor earthquake effects to the hospital and its surroundings indicate that ground motion may have been somewhat less compared to the City Hall record location.

The hospital consists of two wings, the older a two-storey concrete frame structure opened in the late 1990s, and the newer main facility a 6-storey concrete-shear-wall-and- frame building opened in 2015. The hospital's main facility thus represents essentially state-of-the-art design for seismic loads in building structures and internal fixtures.

Despite the apparent high ground motion in the general area, damage in the hospital was only superficial. Minor cracking and spalling was observed where pavement or brick curbs met the base of the building. The expansion joint in the new building showed chipped paint and scratched plaster to illustrate that the gap had performed its function to accommodate relative movement between the building sections. Typical damage to non-structural fixture such as suspended ceilings was described by the hospital management as very minor.

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Sunday to be restored on Monday. Following both earthquakes the standby generator on the roof of the main building started automatically for backup power supply.

With emergency power in-building utilities remained functional with the possible exception of off-site communication. Air conditioning for the main building is provided by roof-mounted heat pumps exhausting through fan-coil heat exchangers. Unlike most large facilities the building therefore does not rely on water for cooling towers as the ultimate heat sink for cooling. The only significant damage to building utility systems was failure of a short run of piping spanning between two of the potable water storage tanks located on pads outside the hospital. The tanks ensure continued water supply[8] for consumption and sanitation if water service should happen to be cut off, from an earthquake for example. Differential rocking of the two water tanks ruptured the pipe interconnection, resulting in a partial drain of the tanks. Partial loss of the water inventory did not affect hospital operation; the failed pipe was quickly repaired.

When the hospital was visited on Friday a week following the initial earthquake, operations appeared to have returned to normal, allowing the facility staff to host the engineering team on their brief visit. The very minor effects to the hospital seem to illustrate the effectiveness of the Japanese building code in protection of critical emergency response centers.

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[8] See footnote 7.

Schools in the April 16, 2016 M7.0 Kumamoto Earthquake:

A Lesson from Japan's Latest Destructive Earthquake on How to Strengthen Older Schools and Buildings

Peter Yanev, Yanev Associates, California, USA

April 21, 2016

Once again, I find myself in Japan immediately after a big earthquake. I left California the day after a Magnitude (M) 7.0 earthquake hit Japan's Kyushu Island to join several colleagues in investigating the effects of the earthquake.

I also came to Japan to learn from the successes of Japanese engineers. Older school strengthening programs are one of the great successes of Japan. Our earthquake investigation team did not review the performance of all schools affected by the earthquake, but we were able to observe the performance of several in the area of the strongest and most damaging shaking, including the Mashiki area, just east of the Town of Kumamoto in Kyushu.

The author (in hardhat) with the Tsumori Elementary School principal and staff

The Town of Mashiki straddles the Futagawa Fault, where some of the largest fault displacements in the earthquake were found – nearly 2m (6 ft.) of horizontal displacement and about 0.7m (2+ ft.) of vertical displacement. The town and its region lie along a river, and its buildings, mostly single-family houses and smaller commercial buildings, are built on a river plain and along the hills on both sides. The houses in the Mashiki area experienced the worst damage that I have ever observed to wood-frame buildings – that is not an observation taken lightly, given that I have participated in and managed the investigations of about 120 earthquakes and other natural disasters around the world.

The Tsumori Elementary School in Mashiki, the town most affected by the destructive Kumamoto earthquake. The bridge leading to the school was a major concern for the Principal of the school, as it provides access to the school for many of the students. We did not find any significant damage.

We observed that, generally, there was no visible structural damage to the schools in the area. In the first day of investigations, we looked briefly at two schools and investigated one in detail, the Mashiki Elementary School, which is very close to the fault that ruptured the ground and caused the earthquake. The school is located amidst some of the worst damage because the area experienced some of the strongest shaking. The performance of the school is a great lesson in good engineering and good risk management.

We visited the school on April 19, 2016, five days after the earthquake. We noted that there was no tag on the building(s) indicating that the school had not been officially inspected for safety and restart of operation. We poked around a few minutes, and while taking exterior photographs we were greeted by some of the teaching and maintenance staff. They were curious why we were there and what we were doing. Within a few minutes, we were conducting an unofficial damage and safety assessment of the school with the school principal and several of the teaching staff. It was remarkable that the school had yet not been officially inspected, especially given the results of our impromptu and much-appreciated investigation.

The investigation took about 45 minutes. We visited all of the buildings, many of the classrooms and other rooms, and the auditorium/gym.

The Tsumori Elementary School gym. One quick look at the building, and adequate familiarity with school earthquake strengthening programs in Japan and around the world, was sufficient for me to realize that this school had been strengthened for earthquakes after it was originally built (well before the more recent earthquake code standards). The steel X-braces (behind the second floor windows and inside the gym) are used often in Japan and elsewhere for strengthening.

Of course, the reason we stopped by in the first place was that it was obvious to me that the school was older and had been strengthened (retrofitted) for earthquakes sometime after it was originally built. Such strengthening of schools started around the 1978 Magnitude 7.4 Sendai (Miyagi-Ken-oki), Northern Japan earthquake. That was my first earthquake investigation in Japan, as well as my first visit to Japan and I saw firsthand a number of severely damaged school and university buildings. The earthquake extensively damaged many schools and university buildings in the Sendai area; a few buildings collapsed. Since then, I have investigated many earthquakes in Japan and have visited Japanaround 50 times. I also opened an office in Tokyo for my former company, EQE International, shortly after the 1995 Kobe earthquake and worked on many earthquake-engineering projects throughout the country, including on some of Japan's nuclear power plants following the Magnitude 9.0 mega-earthquake and tsunami of 2011.

Another obvious strengthening detail - note that the two story solid concrete wall has been added to strengthen the original school. It replaced the windows that were there in the original design. This "shear wall," which adds strength, is a common retrofit detail and works well for this type of concrete-frame construction.

This photograph shows one of the most common details used for the strengthening of schools and other buildings throughout the world. It involves inserting new, solid, well-reinforced concrete walls (called shear walls) between existing columns in order to strengthen the buildings. These walls can be added to the exterior, as in this school, or to the interior, which tends to be less architecturally disruptive but also more expensive.

Working with the World Bank, for example, we have used this technique to strengthen over 1,000 such buildings (mostly schools and healthcare buildings that were all collapse hazards) in Istanbul, Turkey since 2006.

A view of the school from a neighboring house. Contrast the performance of the virtually undamaged school with that of the collapsed house just across the street.

Views of collapsed buildings around the school. The bottom photograph is from inside a classroom, looking at a collapsed small commercial building across the river (also shown in the left photo above).

With the school principal and some of his staff we walked throughout the school looking for and explaining the reasons for the existing damage. Some of this damage, and the lack of it, and some of the interiors and exteriors of the buildings are shown in the pictures below. The Principal showed me some of the damage that was of concern to him. It turned out to be superficial damage that had no effect on the strength of the post-earthquake buildings and the safety of the students and staff. The damage included minor cracking, especially around some of the so-called seismic joints that separate adjacent buildings and are expected to be lightly damaged in a strong earthquake. We also observed fallen pictures and books and other minor furnishings, a bit of ground settlement in the yards around the school, a few fallen ceiling tiles (in the gym) and other light fixtures (yes, they can injure people), the fallen stone monuments surrounding a small shrine on the school grounds (which could have hurt badly someone standing next to them), etc.

Once again, it was remarkable how little was damaged given the size and strength of the earthquake. The damage, or really the lack of it, shows how well we understand the effects of earthquakes on school buildings and how well we can protect our children and their teachers. It also shows that the strengthening of our older schools (those designed to outdated codes, written before the lessons of so many recent earthquakes) dramatically reduces the risk to their occupants. This has now proven to be the case in all recent major earthquakes in Japan, as well as in California and Chile, for example, where society has provided the funding needed to do the required engineering and construction work.

I saw similar performance in many old but strengthened schools in Chile in the M8.8 2010 earthquake, and in Japan in the M9.0 2011 earthquake that caused the major tsunami leading to the destruction of the Fukushima nuclear power plant. (The nuclear accident was actually caused by flooding due to inadequate tsunami walls with respect to the low elevation of the emergency diesel generators, not the earthquake itself). In fact, one of the most memorable sights of that earthquake was an old school near Ishinomaki that had been strengthened. The structure of the school was barely damaged, even after it was shaken by a Magnitude 9 earthquake for several minutes and was then hit by the great tsunami plus a localized fire, likely caused by leaking gas. So, the performance of the Mashiki Elementary School was not surprising to me. I expect good performance of those schools in Japan and elsewhere that have been properly strengthened. I just hope that we continue fixing schools, and other public and private buildings and infrastructure, before the next, inevitable earthquakes occur.

Interior of the virtually undamaged gym. A few lightweight ceiling tiles fell because of inadequate attachment to the structural roof (and ceiling). The debris can be seen in the lower right corner; all the windows are intact.

Additional photos of the practically undamaged interior and exterior of the elementary school.

A fallen office cabinet (that was not anchored or braced) and books in a hall that had not been cleaned up at the time of our visit. As the earthquake occurred at night, the school was not occupied and no injuries occurred.

Another essentially undamaged older school in the earthquake area. Again, note the additional “shear walls” that were added, blocking some of the pre-existing windows. Because of the declining student population, the school is no longer used for teaching. Fortunately, the buildings are now available as emergency shelters for those that lost their homes in the earthquake. Other than life safety for students, one of the primary additional reasons for focusing on strengthening schools is their potential use as emergency shelters following disasters.

The Nishi-Kumamoto Hospital in the April 16, 2016 M7.0 Kumamoto Earthquake:

A Lesson from Japan’s Latest Destructive Earthquake on Hospital Construction in Earthquake Country

Peter Yanev, Yanev Associates, California, USA

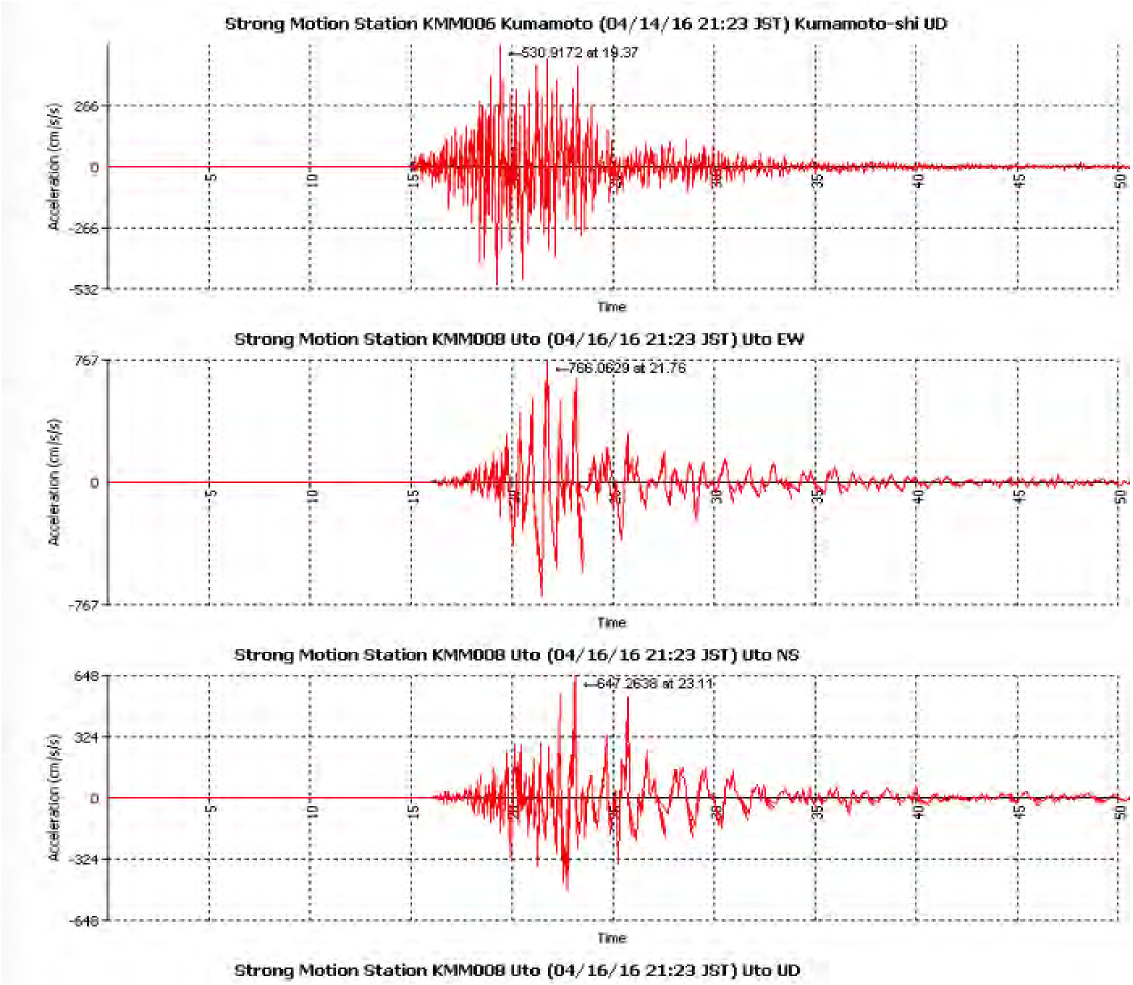
April 24, 2016

On the last day, April 22, of our investigation of the M7.0 Kumamoto, Japan earthquake of April 16, our team visited the Nishi-Kumamoto (West Kumamoto) Hospital. The hospital complex, which is shown below, is between Kumamoto and the Town of Uto.

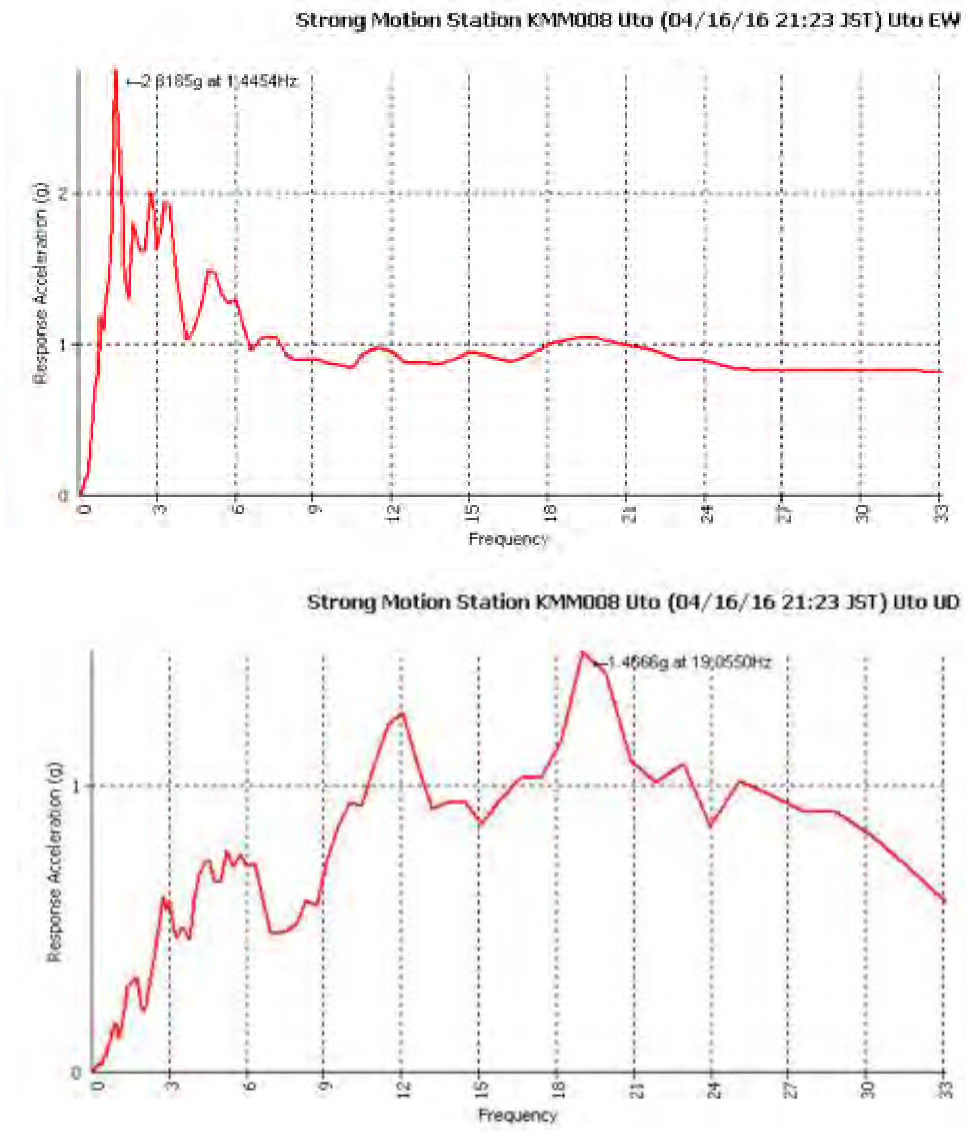
Nishikumamoto Hospital, as seen on Google Maps, consists of several buildings, including an Assisted Living Facility. The main hospital building is in the lower left corner, and is also shown in the photo below.

The hospital is located less than two miles (about 3 km) from Uto City Hall, which was heavily damaged, and in a state of near-collapse. A strong motion instrument (accelerometer) recorded the earthquake ground motion at the City Hall site; the three records from the site are shown below. Their peak accelerations are 0.62g EW, 0.84g NS, and 0.54g UP with an average of 0.73g for the two horizontal components. The three components of the record are shown in the figure below. Another instrument, further to the east in Kumamoto City recorded accelerations of 0.78g EW, 0.66g NS, and 0.43g UD, with an average of 0.72g for the two horizontal components. Thus, the hospital likely experienced similarly high accelerations, with earthquake duration of about 15 to 20 seconds.

The main building of the hospital, built in 2012 showed no visible structural damage. The only significant damage inside the building was minor spalling at seismic (expansion) joints. There was also minor settlement of the ground (and excavation backfills) around the buildings.



The strong motion records from the Uto City Hall site that is about 2 miles (3km) from the hospital. Courtesy of Woody Epstein's software, Shakeman.



The response spectra for the EW and UP components of the Uto City Hall time histories. The site is about 2 miles (3km) from the hospital. Courtesy of Woody Epstein's software, Shakeman.

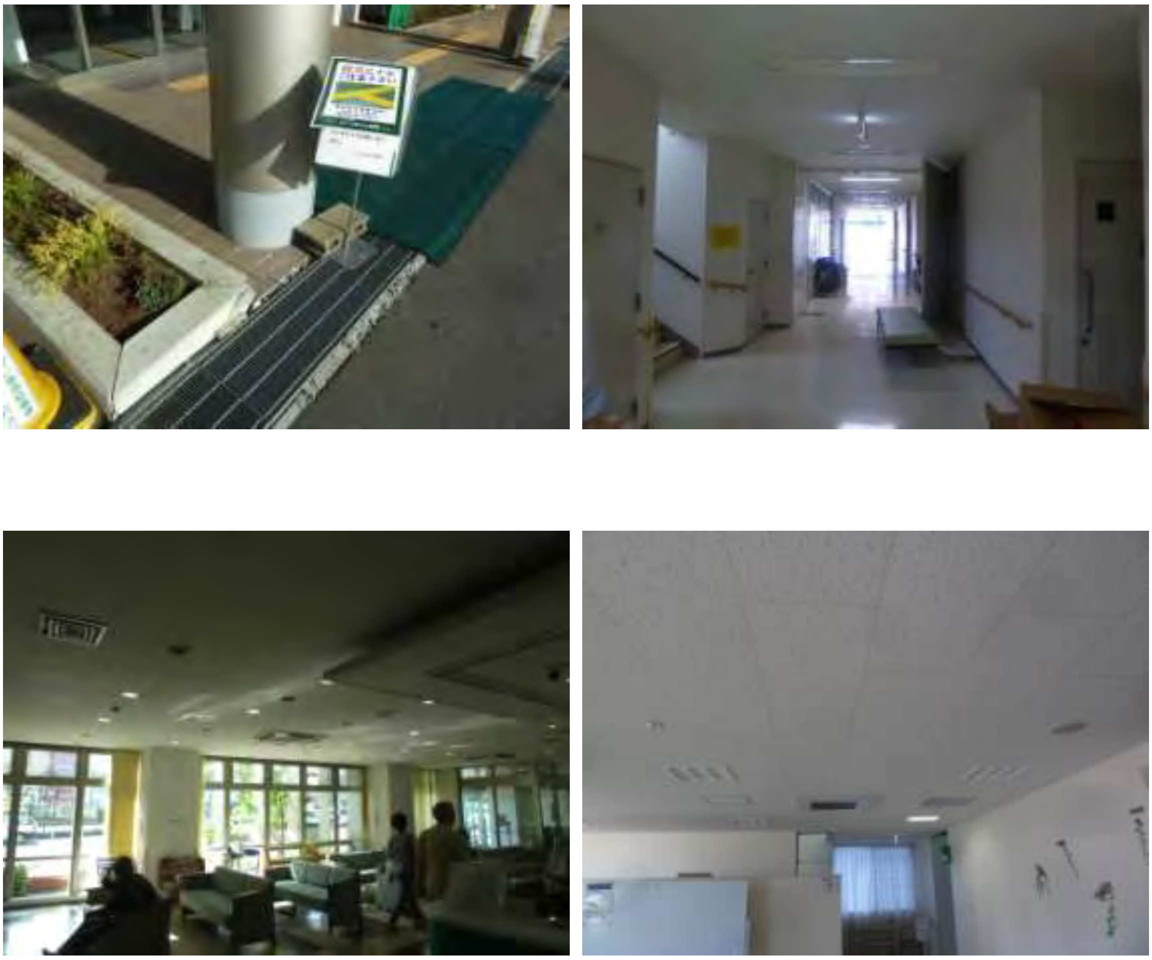
The photographs below show two buildings, the heavily damaged Uto City Hall (where the above time histories were recorded) and another collapsed building in Kumamoto, plus a nearby concrete batch plant. The hospital is between the two damaged buildings and the concrete plant, another indication that the ground motion at the hospital was strong enough to damage and/or collapse older, less well designed and built structures.

It is possible that the hospital experienced somewhat lower ground motion. That is based on our observations in the general region of the hospital, where damage was not widespread.

Two heavily damaged reinforced concrete buildings in the general region of the hospital, which is roughly equidistant from the two buildings. Both of these buildings are much older and are designed to outdated and, obviously, deficient building codes. The building on top is Uto City Hall. The visible façade damage is due to the failure of precast concrete non-structural façade panels (shown in more detail on the right). The main concrete frame of the building is heavily damaged and near collapse. The recorded ground motions, shown in the previous illustrations, were made on the City Hall site, outside the building. The second two-story building (lower left) had an inadequate soft-story ground floor that collapsed. The photo on the lower right shows collapsed silos at a nearby concrete batch plant (Kumamoto Ryoko Concrete Co.). Two of five silos collapsed. The three newer silos, in the back, designed to higher and more recent design criteria survived without significant damage.

The hospital buildings suffered no significant or visible structural damage. The six-story main building is a 3-year-old shear-wall concrete structure, completed in 2012. The two-story adjacent hospital building was completed in 1989. The ground around the two buildings compacted and settled a little during the earthquake, causing no damage to the structures. The only damage noted on the interior ground floor was minor damage at structural expansion joints (gaps), which were specifically designed to allow adjacent parts of the structures to move and which are expected to suffer minor damage, similar to what happened.

A partial view of one of the two story hospital buildings (left) and the undamaged steel framed and braced parapet on the roof of the 6-story main building.



The most obvious, and inconsequential damage to the hospital was minor settlement around the periphery of buildings. The photo in the upper right shows some settlement at the main entrance to the hospital. The other three photos are of interiors of the main building, including the lobby (lower left). Note that the undamaged ceilings are rigid ceilings and not flexible, suspended ceilings that are typically easily damaged.

The hospital engineer stated that the earthquake caused only minor and insignificant damage to the interior of the hospital, including minor damage to ceilings. We noted that the hospital did not have suspended ceilings anywhere in the areas visited. That is likely a primary reason why the interior perfumed as well as it did.

We were informed that the major medical equipment was not damaged significantly and, coupled with the good performance of the other hospital non-medical equipment, as discussed below, allowed the hospital to function as an emergency center following the earthquake.

Off-site power was lost during the earthquake. The individual hospital buildings rely on their own emergency generators. Both generators started up upon loss of off-site power. One of the diesels, on the roof of the six-floor main building, is shown below.

The emergency diesel, located on the roof of the six-story main building, started up upon loss of off-site power. That, and a second generator in one of the other buildings, provided adequate power to the hospital following the earthquake, until off-site power was restored.

Much of the critical mechanical and electrical equipment of the hospital is on the roof. Some of that equipment is shown in the photographs below. All of the equipment on the roof is bolted or braced; none was damaged. We observed that the bolting and bracing details for the equipment were designed to standard industrial details, not to the much more stringent and expensive details required of hospitals in California, for example.

Some of the equipment on the roof of the six-story main building. None of the equipment was damaged in the earthquake. Our inspection revealed good design details for the anchorages and braces of the equipment, piping, and other systems.

Potable and service water for the hospital is stored in five (or more) tanks at ground level outside the hospital buildings. The tanks were not damaged. Two of the tanks lost water when piping interconnecting the tanks broke due to differential movements of the tanks during the earthquake. The pipes connecting the tanks did not have flexible joints but were rigid and could not accommodate the differential movement. The partial loss of inventory did not affect significantly hospital operations. The broken pipes were repaired quickly.

Two anchored potable water tanks lost contents when the rigid piping that interconnected them failed due to differential tank movement during the earthquake. The repaired lines are shown on the right. A flexible pipe connection between them would have prevented the only significant equipment and systems damage at the hospital.

Other anchored equipment at ground level had no damage, including the two potable water tanks on the left and a diesel generator on the right.

We visited the hospital on Friday, April 22, six days after the M7.0 main earthquake. Everything in the hospital appeared to be normal. Other than the very minor damage described above, the only real indication of an earthquake, or at least the only indication of the concern with aftershocks, was non-essential furniture such as cabinetry and wall decorations. Most of these had been laid down on the floor so that they could not fall and injure or interfere with operations.

Out of concern for further aftershocks, the hospital placed art and other wall mounted objects on the floor (left). Heavy furniture that can overturn, such as the tall cabinet on the right, were also lowered to the floor so that they would not tip over in aftershocks. I have visited many hospitals, and other public buildings along the Pacific West Coast and throughout the world after earthquakes – this thoughtful precaution was a first for me.

Overall, the Nishikumamoto hospital performed admirably during and after the earthquake. It is an excellent example of good engineering without much of the excessive earthquake engineering details required for new and for existing hospitals in California, particularly for the equipment and related systems.

The hospital, and others like it in the affected region, should be studied in much more detail, especially by hospital regulators and code writers in Oregon, Washington, and British Columbia. These are two states and a province that are in the process of developing their own requirements and regulations for the earthquake design of new hospitals and strengthening of older hospitals that are designed to outdated codes.

California regulators and engineers should also study further and apply the positive lessons from this major earthquake in a country that takes earthquakes seriously. That is the only way to control the steady increase in requirements and costs for earthquake protection, much of it based on overly conservative engineering assumptions and computer analyses and not on adequate real-earthquake experience.

The Kumamoto Airport in the M7.0 Kumamoto, Japan Earthquake of April 16, 2016

Peter Yanev

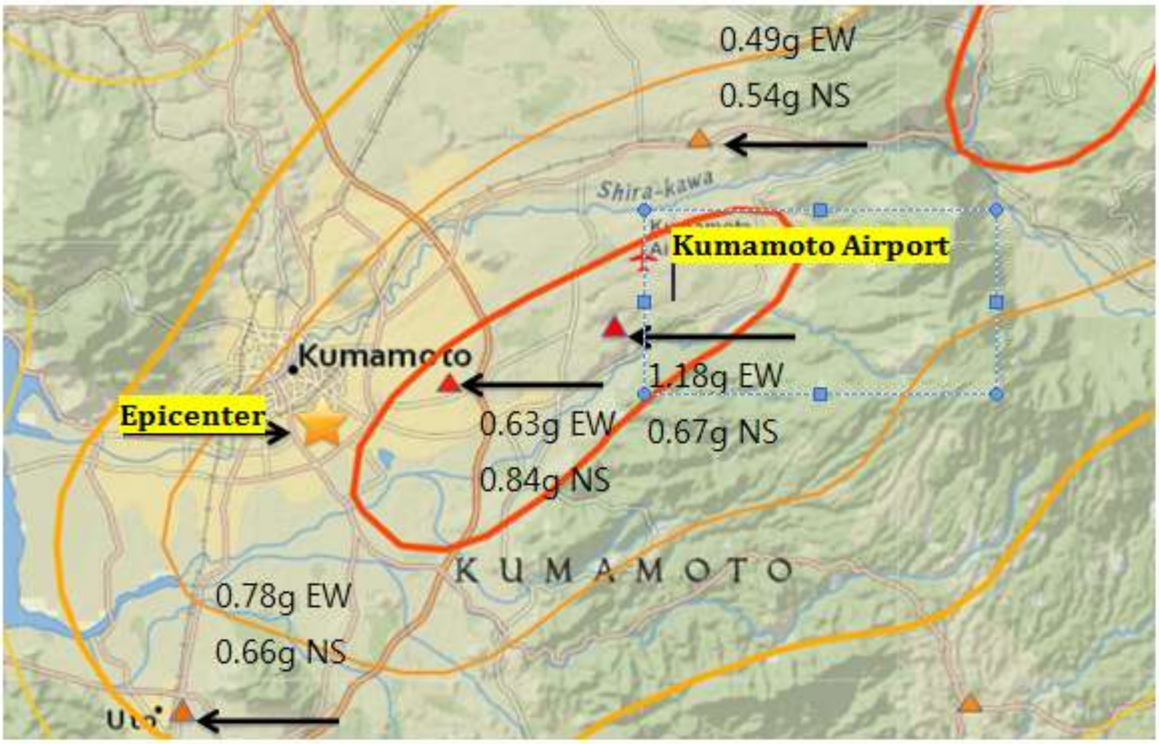
Yanev Associates, California, USA

April 25, 2016

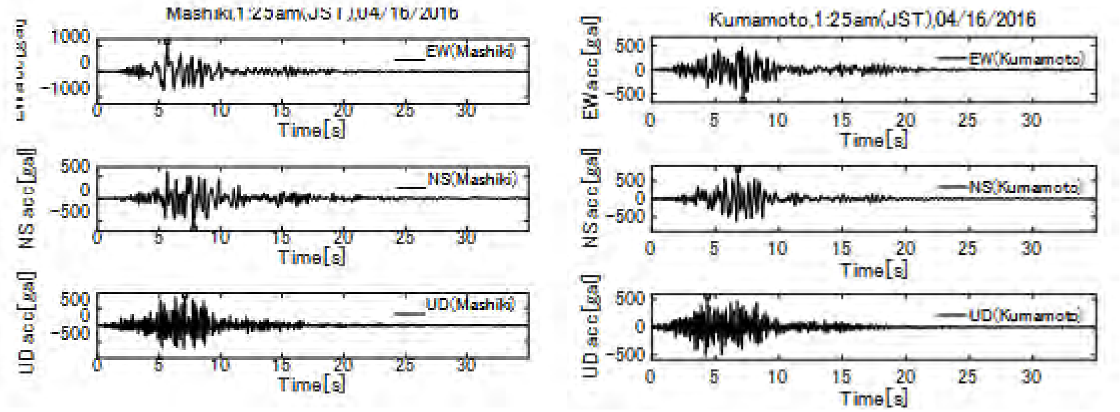
Our engineering and risk management team conducted a rapid investigation of the Kumamoto Airport (also known as Aso Kumamoto Airport) on April 20, four days after the M7.0 Kumamoto, Japan earthquake of April 16, 2016. The airport is located on a plateau of volcanic origin at an elevation of 632 ft. (193 m) west of the City of Kumamoto and north of the Mashiki Town, which suffered some of the worst damage in the earthquake and recorded some of the strongest ground motions. It is about 3 miles (4.5 km) southwest of the airport.

Kumamoto Airport, as seen on Google Maps. Our team conducted a rapid visual evaluation of the effects of the M7.0 earthquake, with emphasis on the terminals and some of the infrastructure to the south of the runway (in the central area of the photo).

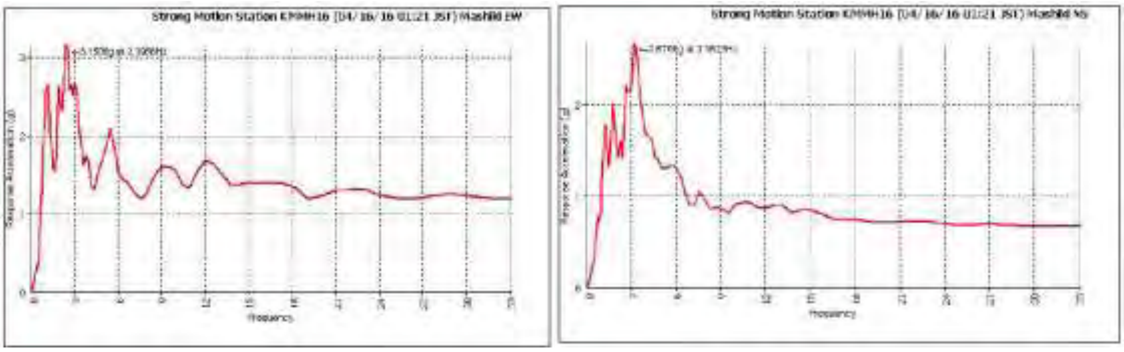
The recorded Mashiki ground motion has peak accelerations of 1.18g in the EW direction, 0.67g in the NS direction, and 0.89g in the vertical direction. These are very strong ground motions and likely the strongest recorded near an airport. The recorded ground motion at Kikuyo, slightly further north of the airport, has peak accelerations of 0.49g EW, 0.54g NS, and 0.40g UD. This information, plus additional records, is summarized in the figure below. The information is superimposed on the USGS intensity map of the earthquake. The time histories and their respective response spectra (Courtesy of the Earthquake Engineering Research Institute (EERI), are also shown below.



Above is the summary of the ground motions recorded nearest to the Kumamoto Airport. The PGAs for the three components of each record are shown. The map also shows the intensities of the earthquake estimated by the USGS. The area within the red contour is MMI IX; the area within the wider orange contour is MMI VIII. The airport is in MMI IX.



The recorded time histories at Mashiki, left, and Kumamoto, right. Courtesy EERI.



The 5% damping response spectra for the Mashiki EW and NS records. Courtesy of Woody Epstein's software, Shakeman.

Our team investigated the effects of the earthquake on April 22, 6 days after the M7.0 earthquake. The airport's main, newer Domestic Terminal was operating, whereas the older, International Terminal was still closed because of damage. Parts of the newer terminal were still closed, or had limited access, because airport the staff was still cleaning up damage, both architectural and to the concessions within the terminal building. Photographs of the new terminal and the observed damage are shown in the figures below. It was obvious that damage at the terminal was generally minor and repairable and presented no significant hazards to occupants. Our team, unfortunately, did not have time to investigate the effects of the earthquake to the primary equipment systems of the airport.

Exterior views of the newer steel framed Domestic Terminal building. The control tower is to the left. There was no obvious significant structural damage.

A notable success at the new terminal was the performance of the glazing. We found no damage to these large glass panels. Given the strength of the shaking at the airport, the design details for the glazing should be studied in further detail. Details such as these are difficult for engineers to analyze. Further, they are difficult to test on shake tables. Post-earthquake experience data, such as what we collected at the Kumamoto Airport, are valuable for future designs as well as for the development of adequate and not overly conservative building code requirements for architectural and equipment details.

The rigid suspended ceilings throughout the new terminal performed well. We did not notice any significant damage. There was minor damage at interfaces with columns and walls. In the past, damage to flexible suspended ceilings at airports has been a major cause of service interruptions.

The most life-threatening damage that we observed at the new terminal was the falling of inadequately anchored or braced light fixtures. Note the missing fixture in the right photo. Many of these fixtures had fallen. The ceilings around the failed fixtures are undamaged.

The old reinforced concrete International Terminal, built in the late 1960s, was closed at the time of our investigation due to reported structural damage. We could not observe the damage from the outside, but given the vintage of the structure and the outdated and inadequate code to which it was designed, plus the strength of the ground shaking, serious structural damage should have been expected unless the structure had been strengthened more recently. This type of structure is a classic example of a high-risk structure that often requires strengthening for life-safety and for the reduction of business interruptions.

The airport included several steel framed cargo warehouses, hangars, and other service buildings. None of these appeared to have significant structural damage. That included older steel structures that were designed and built to outdated codes. Over time, and in many earthquakes these types of structures, have proven to be much lower risk than comparable concrete frame, precast or tilt-up, and shear wall structures.

Damage to an older building at the airport training facility, where inadequate attachments for the heavy precast horizontal concrete cladding failed. I have observed this type of failure many times in earthquakes in Japan and elsewhere around the world. Typically, older buildings with these types of facades, as well as older precast concrete buildings, are much higher risks than comparable age steel framed and massive concrete shear wall buildings. Several other similar buildings at the airport had comparable, but less dramatic, damage.

At first glance, this aviation fuel storage facility at the airport appeared to have suffered damage to one of its two tanks. It turned out that the blue plastic tarps covering the effects of the earthquake were providing temporary cover replacing the damaged asphalt waterproofing around the tank base. The damage was inconsequential. Generally, equipment such as this had adequate anchorages and performed well.

In general, the Kumamoto Airport performed well, given the very strong ground motion recorded in its vicinity (on all sides). Part of the reason for this success is that the airport is founded on good and well-compacted volcanic soils. We observed minor settlement around buildings and at entrances, likely in construction backfill area, but no significant ground failures. There was evidence of the failure of at least two underground water lines in front of the International Terminal, caused by very localized ground settlement.

The Kumamoto Airport is, overall, a success story in this M7.0 earthquake, especially for the newer and larger terminal building. The latter performed much better than most terminal buildings in the US, Chile, and elsewhere in recent large earthquakes. Airport engineers would do well to study in detail the basic contemporary Japanese airport earthquake and structural engineering practices and requirements, as well as visit and interview in detail airports like the Kumamoto Airport in this earthquake, as well as the Santiago, Chile airport which suffered much more damage in the 2010 Maule, Chile earthquake. In the latter, many of the architectural features that performed well at Kumamoto failed because of inadequate design details, while the main terminals were essentially structurally undamaged. That caused much longer service interruption.

Shakeman: Strong Motion and Experience

Woody Epstein

Curtiss-Wright, Nuclear Division

Most of the calculations and visual depictions of ground motions and their damage indicating parameters (DIPs) in this report were made by the software which I wrote called Shakeman, named after the probabilistic risk assessment software, Riskman©, which I also wrote when at Pickard, Lowe, and Garrick. This section presents the software and the role which it plays in helping earthquake engineers to relate strong motion to successes and failures of systems, structures, and equipment (called SSC, where the "C" refers to components).

Background: the IAEA Mission to Onagawa NPS

The Great East Japan earthquake of 2011 (9.1Mw) was one of the largest ever recorded and by far the largest earthquake to affect any nuclear power station (NPS) anywhere in the world. The affected NPSs were: Onagawa, Fukushima Daiichi, Fukushima Daini, and Tokai Daini.

The Onagawa NPS, closest to the epicenter, subjected to 300 seconds of ground motion and a free field peak ground acceleration (pga) of 0.72, appeared to have emerged with little earthquake damage, especially to safety related components.

There was only way to ascertain if this appearance of little damage was true: to visit the Onagawa plant, collect success and failure data by conducting damage walk downs, and see for ourselves. Onagawa was a real-life shake table, yet no one had moved to systematically collect these data in detail, to relate successes and failures to ground motion records, and to bring the story to the public. Peter Yanev and I decided that we had to form a team and go to Onagawa.

We approached the International Seismic Safety Center at the IAEA whose director, Sujit Sammadar, whole heartedly agreed to join and support the project, and we brought together an international group of experts and received funding to make the IAEA Mission to Onagawa a reality.

The Mission was carried out successfully from July 30 to August 12 in 2012[9].

The Birth of Shakeman

Now I am not a structural engineer, nor a seismologist, nor a geologist. I am a mathematician, computer scientist, and software engineer. However, I have worked almost

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[9] The mission report can be downloaded from here: https://www.iaea.org/sites/default/files/iaeamissiononagawa.pdf

exclusively with nuclear and earthquake engineers since 1983; I know how to listen to the problems which they need to solve, create mathematical solutions, and realize the solutions in software; on the project teams on which I have worked, this role is called the "tool maker". The Onagawa Mission proved to be no different.

My job on the Mission was to analyze strong ground motion records, to calculate the DIPs, and to make the DIPs available to the structural and earthquake engineers in both tabular and visual forms. There were over 70 strong ground motion records from strong motion recording stations located on all floors of the three reactor buildings (which measure the motion inside of the buildings) and the free field (which measures the ground motion in the soil itself).

Each earthquake engineer likes to relate different DIPs to the successes and failures. There was no existing software which could easily calculate and present all the DIPs of interest and relate them to damage and successes. Therefore, as the tool maker, I created Shakeman.

How Shakeman Was Used in the Kumamoto Investigation

Before the team left their homes, I downloaded the strong motion records of both the foreshock and main shock of the Kumamoto earthquake. I impoted them into Shakeman; calculated the DIPs and visual representations; and sent them to the team members to help them plan, in the short time available to us in the Kumamoto area, where we would go and what we would look for.

The strong motion records came from the Japan National Research Institute for Earth Science and Disaster Prevention's (NIED) strong motion network databases (http://www.kyoshin.bosai.go.jp/). There are two networks' data available: K-NET is a network of strong-motion recorders installed at approximately 1,000 locations nationwide. KiK-net consists of pairs of strong-motion recorders installed in a borehole and on the ground surface.

We are now entering the success and failure information into Shakeman's SSC database. Screen shots of the software follow.

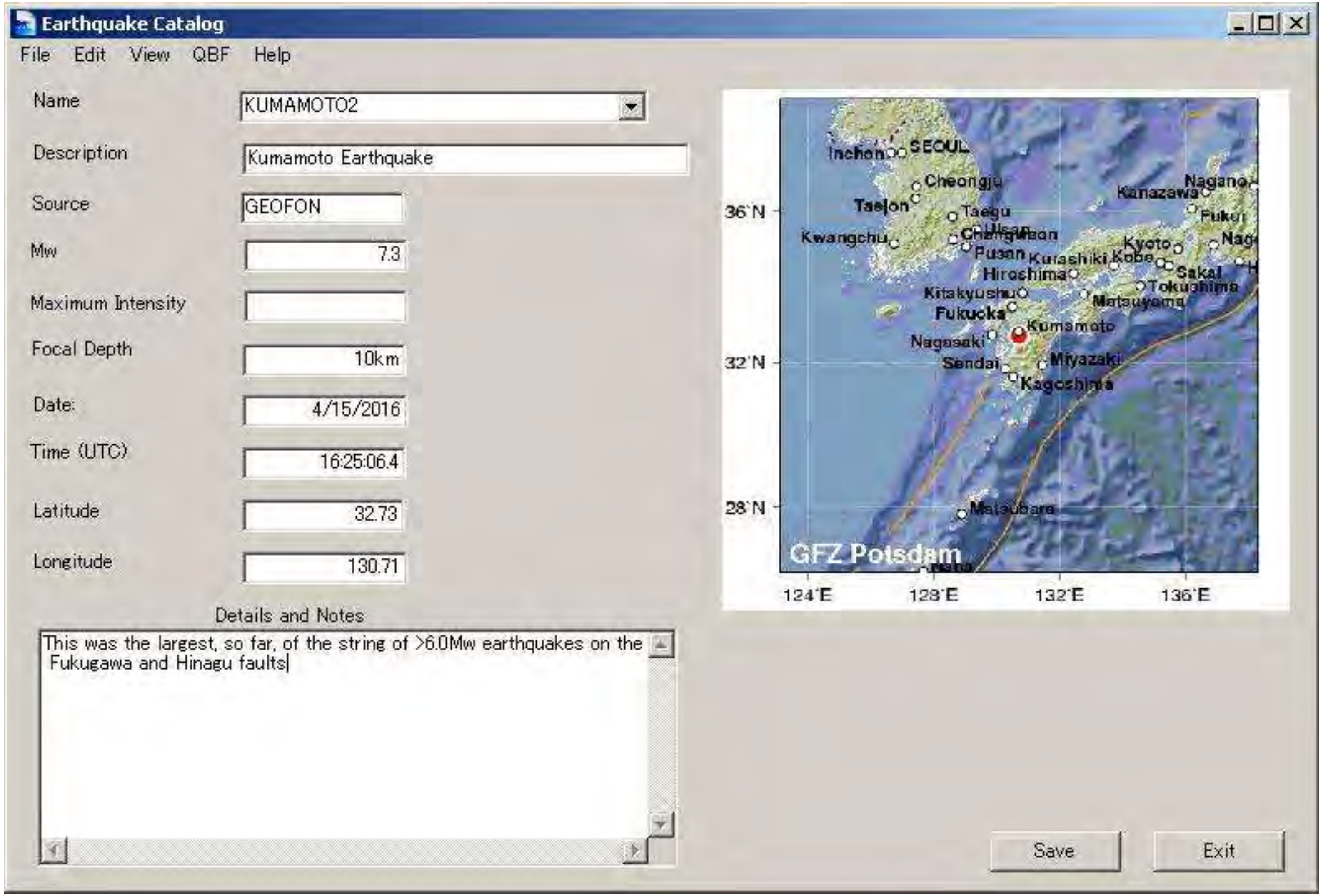
Examples from Shakeman

Model Name: KUMAMTO

Model Path: C:\HAZMODS\KUMAMTO

Kumamoto Earthquake
04/14/16 and 04/16/16

This is the main screen of Shakeman. Notice that besides giving access to the earthquake catalog, strong motion records, the SSC database fragility calculation, data analysis; it connects with the SeismoSoft software, the K-Net online databse, and the PEER database.



Name: KUMAMOTO2

Description: Kumamoto Earthquake

Source: GEOFON

Mw: 7.3

Maximum Intensity:

Focal Depth: 10km

Date: 4/15/2016

Time (UTC): 16:25:06.4

Latitude: 32.73

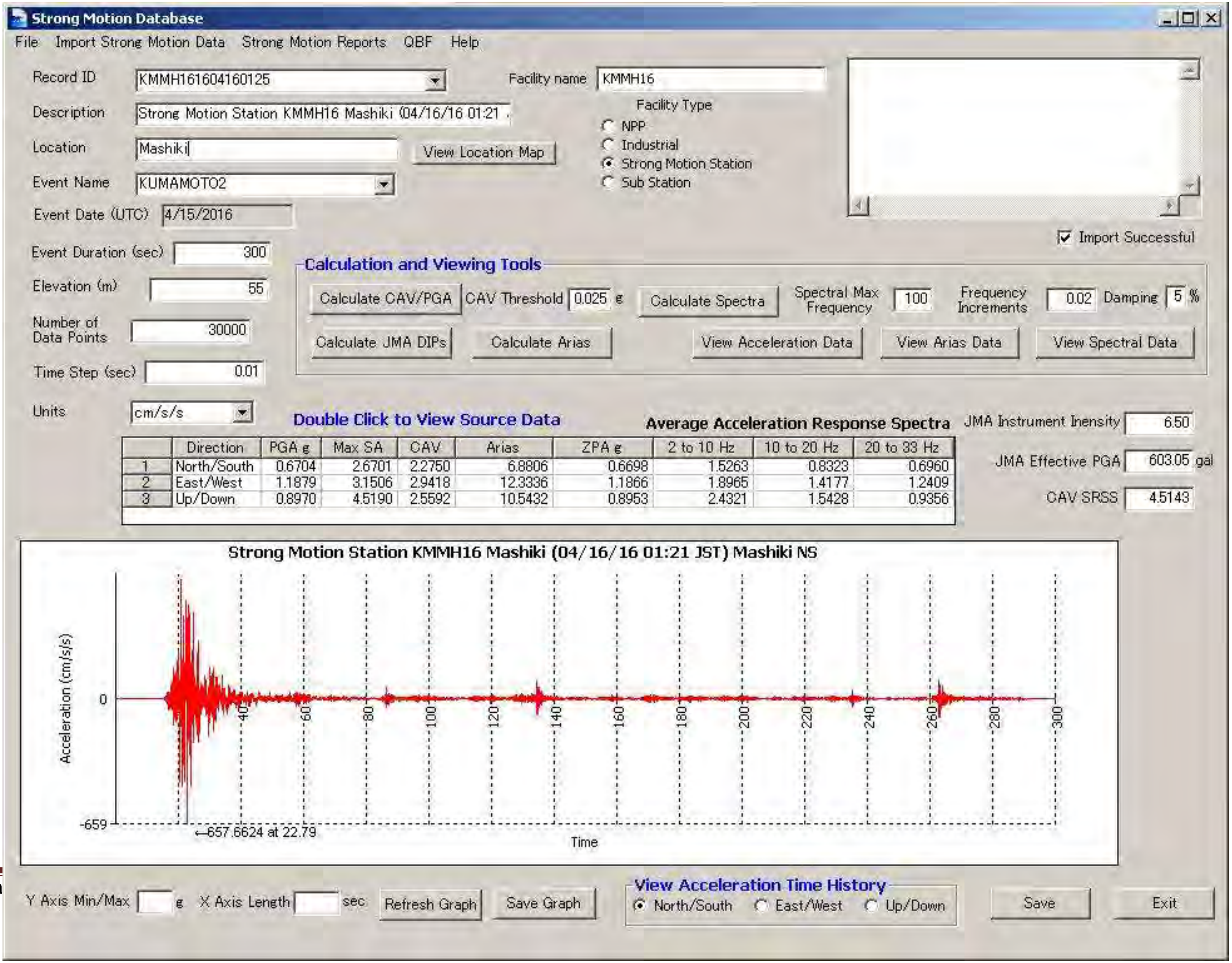
Longitude: 130.71

Details and Notes

This was the largest, so far, of the string of >6.0Mw earthquakes on the Fukugawa and Hinagu faults

The earthquake catalog allows the analyst to relate strong motion records to the earthquake involved.

Strong motion records are imported into the strong motion database. PGA, CAV, Arias, Shindo, spectral response, and other DIPs are all calculated and portrayed graphically. Notice that you can choose N/S, E/W, or Up/Down time histories as well as being able to scale the X and Y axes.



Record ID: KMMH161604160125

Facility name: KMMH16

Description: Strong Motion Station KMMH16 Mashiki (04/16/16 01:21

Location: Mashiki

Event Name: KUMAMOTO2

Event Date (UTC): 4/15/2016

Event Duration (sec): 300

Elevation (m): 55

Number of Data Points: 30000

Time Step (sec): 0.01

Units: cm/s/s

Facility Type:
○ NPP
○ Industrial
● Strong Motion Station
○ Sub Station

☑ Import Successful

Calculation and Viewing Tools

CAV Threshold: 0.025 g

Spectral Max Frequency: 100

Frequency Increments: 0.02

Damping: 5 %

Double Click to View Source Data

Average Acceleration Response Spectra

	Direction	PGA g	Max SA	CAV	Arias	ZPA g	2 to 10 Hz	10 to 20 Hz	20 to 33 Hz
1	North/South	0.6704	2.6701	2.2750	6.8806	0.6698	1.5263	0.8323	0.6960
2	East/West	1.1879	3.1506	2.9418	12.3336	1.1866	1.8965	1.4177	1.2409
3	Up/Down	0.8970	4.5190	2.5592	10.5432	0.8953	2.4321	1.5428	0.9356

JMA Instrument Inensity: 6.50

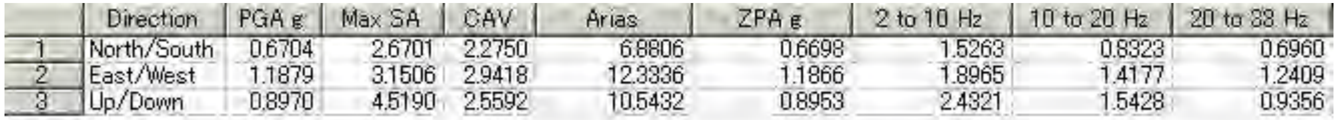
JMA Effective PGA: 603.05 gal

CAV SRSS: 4.5143

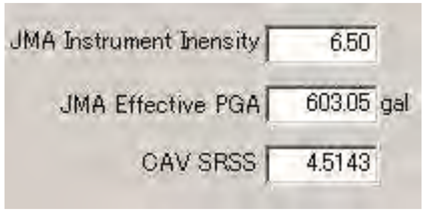
Y Axis Min/Max: g

X Axis Length: sec

View Acceleration Time History
● North/South ○ East/West ○ Up/Down



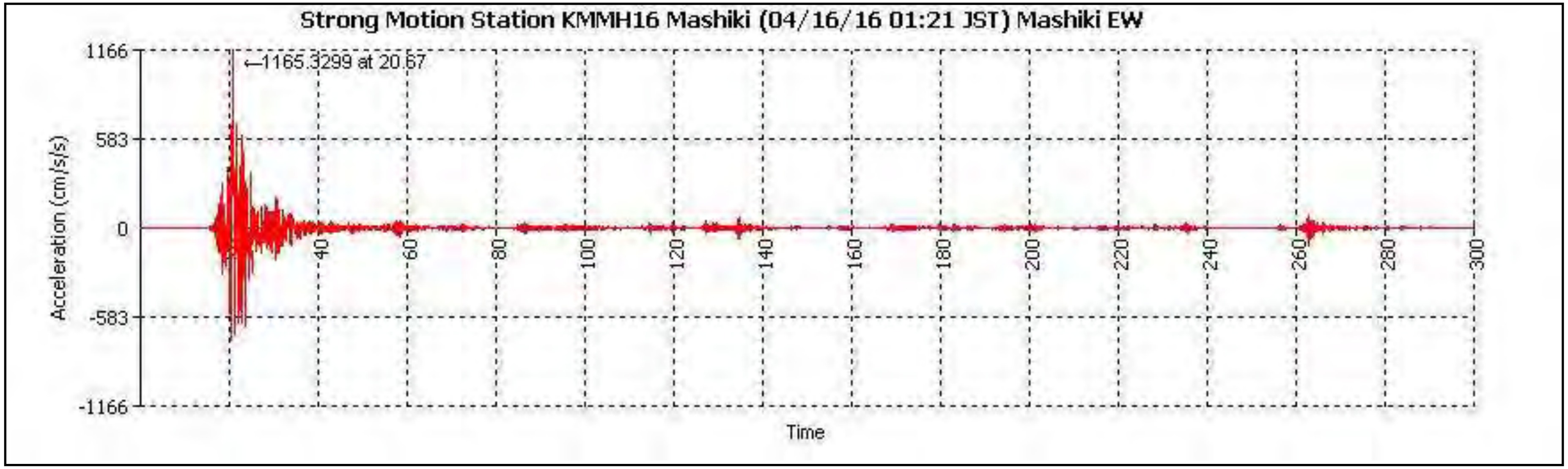
	Direction	PGA g	Max SA	CAV	Arias	ZPA g	2 to 10 Hz	10 to 20 Hz	20 to 38 Hz
1	North/South	0.6704	2.6701	2.2750	6.8806	0.6698	1.5263	0.8323	0.6960
2	East/West	1.1879	3.1506	2.9418	12.3336	1.1866	1.8965	1.4177	1.2409
3	Up/Down	0.8970	4.5190	2.5592	10.5432	0.8953	2.4321	1.5428	0.9356



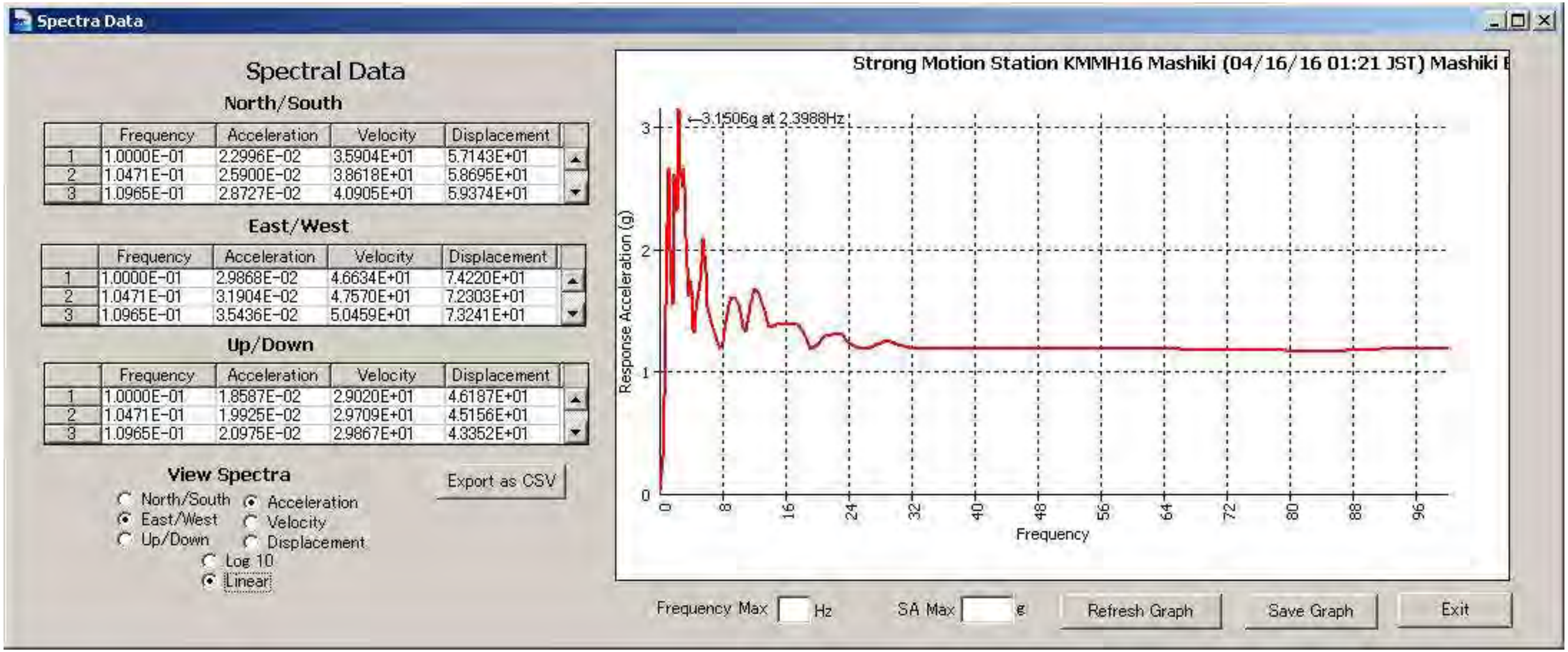
JMA Instrument Inensity 6.50

JMA Effective PGA 603.05 gal

CAV SRSS 4.5143



Close-ups' of the DIPs and the acceleration time history



Spectra Data

Spectral Data

North/South

	Frequency	Acceleration	Velocity	Displacement
1	1.0000E-01	2.2996E-02	3.5904E+01	5.7143E+01
2	1.0471E-01	2.5900E-02	3.8618E+01	5.8695E+01
3	1.0965E-01	2.8727E-02	4.0905E+01	5.9374E+01

East/West

	Frequency	Acceleration	Velocity	Displacement
1	1.0000E-01	2.9868E-02	4.6634E+01	7.4220E+01
2	1.0471E-01	3.1904E-02	4.7570E+01	7.2303E+01
3	1.0965E-01	3.5436E-02	5.0459E+01	7.3241E+01

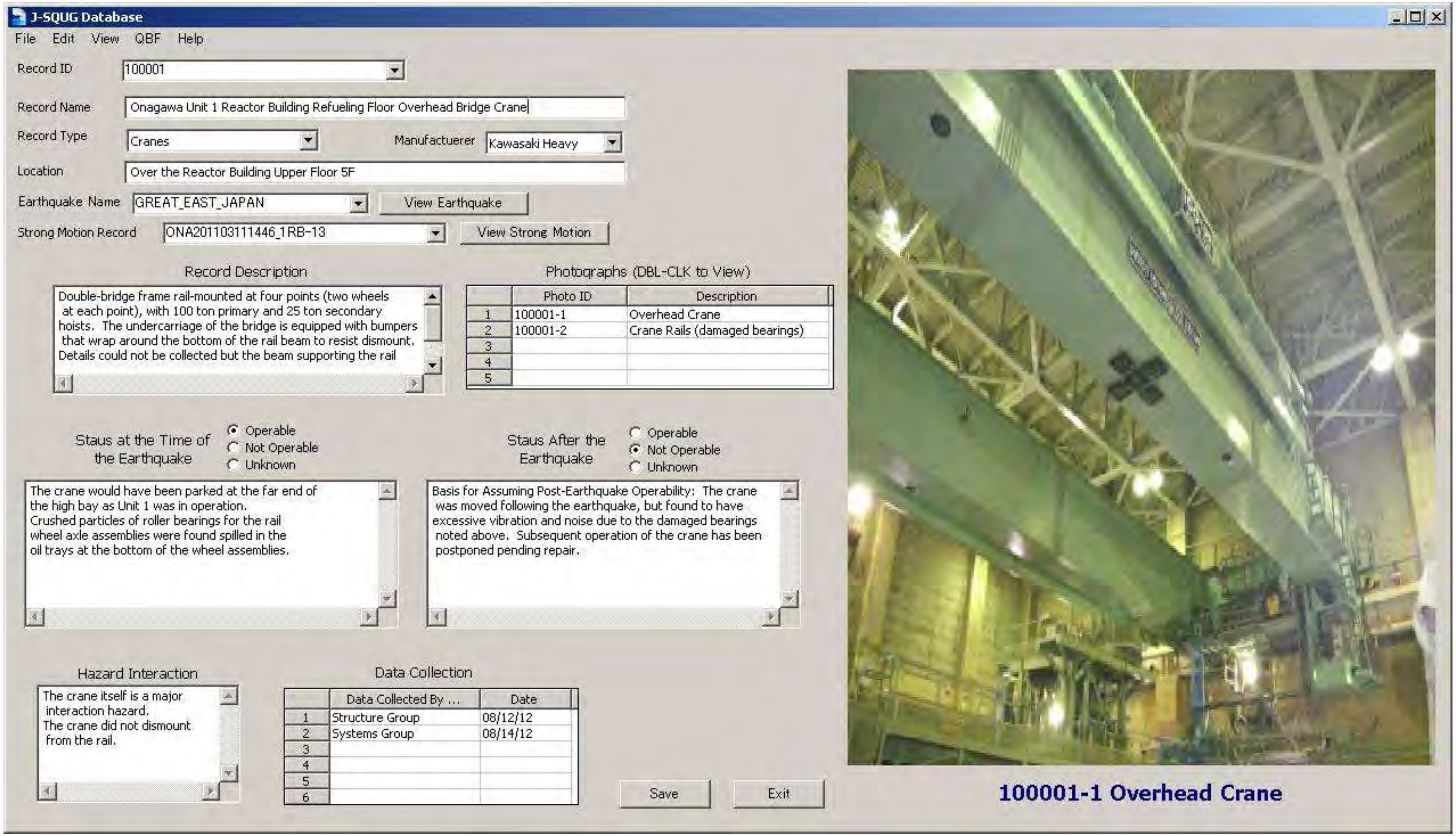
Up/Down

	Frequency	Acceleration	Velocity	Displacement
1	1.0000E-01	1.8587E-02	2.9020E+01	4.6187E+01
2	1.0471E-01	1.9925E-02	2.9709E+01	4.5156E+01
3	1.0965E-01	2.0975E-02	2.9867E+01	4.3352E+01

View Spectra

○ North/South ● Acceleration
● East/West ○ Velocity
○ Up/Down ○ Displacement
○ Log 10
● Linear

The spectral data screen. You can view response acceleration, velocity, or displacement; N/S, E/W, and U/D directions; log or linear scales; and scale the graph. The graph can be saved as JPEG file and the data as a CSV file.



Record ID: 100001

Record Name: Onagawa Unit 1 Reactor Building Refueling Floor Overhead Bridge Crane

Record Type: Cranes

Manufactuerer: Kawasaki Heavy

Location: Over the Reactor Building Upper Floor 5F

Earthquake Name: GREAT_EAST_JAPAN

Strong Motion Record: ONA201103111446_1RB-13

Record Description

Double-bridge frame rail-mounted at four points (two wheels at each point), with 100 ton primary and 25 ton secondary hoists. The undercarriage of the bridge is equipped with bumpers that wrap around the bottom of the rail beam to resist dismount. Details could not be collected but the beam supporting the rail

Photographs (DBL-CLK to View)

	Photo ID	Description
1	100001-1	Overhead Crane
2	100001-2	Crane Rails (damaged bearings)
3		
4		
5		

Staus at the Time of the Earthquake: ● Operable ○ Not Operable ○ Unknown

The crane would have been parked at the far end of the high bay as Unit 1 was in operation.
Crushed particles of roller bearings for the rail wheel axle assemblies were found spilled in the oil trays at the bottom of the wheel assemblies.

Staus After the Earthquake: ○ Operable ● Not Operable ○ Unknown

Basis for Assuming Post-Earthquake Operability: The crane was moved following the earthquake, but found to have excessive vibration and noise due to the damaged bearings noted above. Subsequent operation of the crane has been postponed pending repair.

Hazard Interaction

The crane itself is a major interaction hazard.
The crane did not dismount from the rail.

Data Collection

	Data Collected By ...	Date
1	Structure Group	08/12/12
2	Systems Group	08/14/12
3		
4		
5		
6		

100001-1 Overhead Crane

Here is the SSC success and failure database. It incorporates all of the data fields available in the SQUG database, plus all databases are relational and interconnected; earthquakes and strong motion records are connected; and the SSCs are completely searchable by query.

How We Envision the Future Use of Shakeman for Earthquake Engineers

We, who write this report, are proponents of the use of experience data to make earthquake engineering decisions. While the use of shake tables, finite element modeling, and current theories of what is good, and what is not, is indispensible for making sound engineering decisions, field experience and capturing it in a structured way has no peer; in this sense, Onagawa was the ultimate shake table.

The Seismic Qualification Utility Group (SQUG) database is a good start. SQUG is now run by EPRI and was conceived and implemented by team members Peter Yanev and Sam Swan. But it must be connected to the earthquakes from which the data comes.

We have several measures and of earthquake intensity and DIPs which we try to use as the silver bullet of damage predictions: pga, max SA, response spectra, cumulative absolute velocity (CAV), Shindo (I_{JMA}), Arias, and others.

To understand which measurements, and under what conditions including distance from fault, soil structure, elevation, etc., are the best danmage indicators, we must …

1. Create a database which includes both SSC successes and failures;
2. It must be a interconnected database which links:
    a. an earthquake catalog;
    b. strong motion records;
    c. site information, like soil structure, distance from a fault …;
    d. and is completely searchable in a relational way.

Only in this way can we make proper judgments about which measures to use in a specific location.

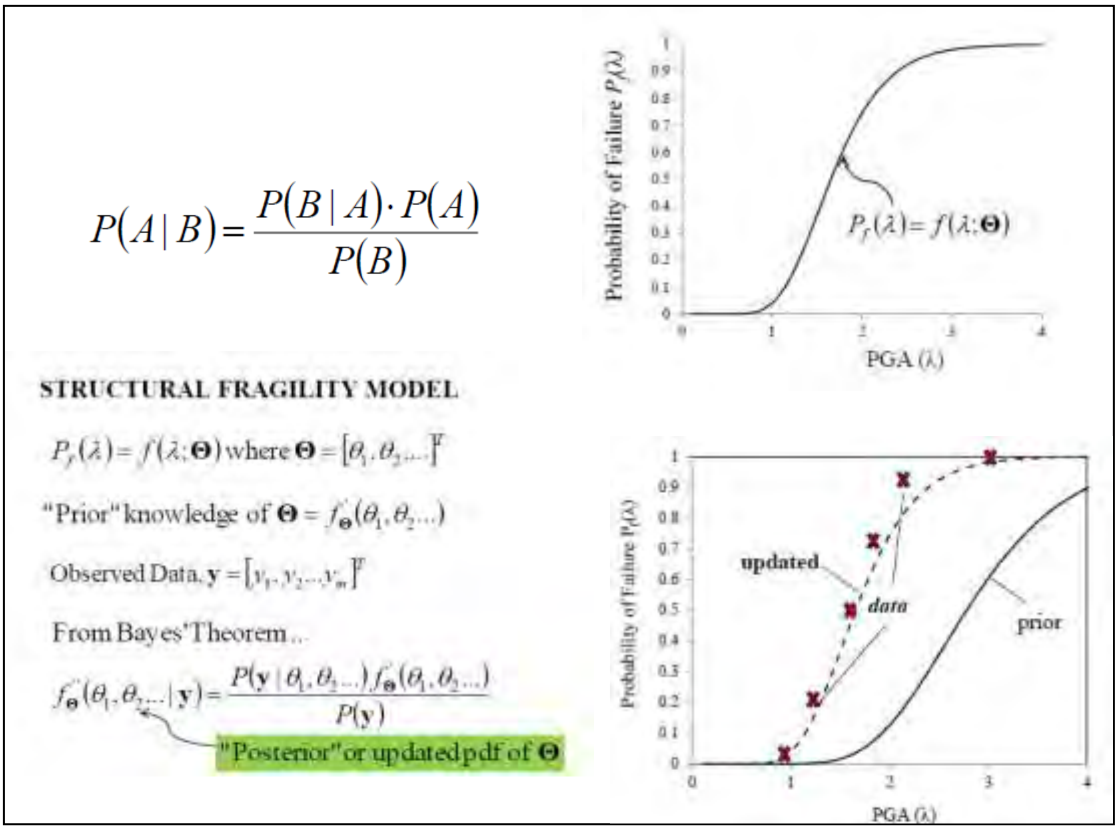
And lastly, we must use Bayes' Theorem, simulations, and spectral response experience data to update fragilities with actual experience data.

Here are examples of fragility updating by using experience data from the Chuetsu earthquake at Kashiwazaki-Kariwa and the Great Eastern Japan earthquake at Onagawa, Fukushima Daini, and Tokai Daini. Three different methods are be proposed.

The three methods are:

1. Bayesian updating using the method suggested by Yamaguchi, et. al. (Epistemic Uncertainty Reduction in the PSA of Nuclear Power Plant using Bayesian Approach and Information Entropy, PSAM 2010).
2. Fragility calculations using time histories suggested by Abhinav Gupta (Center for Nuclear Power Plant Structures, Equipment, and Piping North Carolina State University Raleigh, North Carolina 27695-7908, USA, December 2012).
3. The experience driven seismic margin method developed by Sam Swan and Woody Epstein an NPS (January, February 2013).

Visual depictions follow.



$$P(A|B)=\frac{P(B|A)\cdot P(A)}{P(B)}$$

STRUCTURAL FRAGILITY MODEL

$P_f(\lambda)=f(\lambda;\mathbf{\Theta})$ where $\mathbf{\Theta}=[\theta_1,\theta_2,...]^T$

"Prior" knowledge of $\mathbf{\Theta}=f'_{\mathbf{\Theta}}(\theta_1,\theta_2,...)$

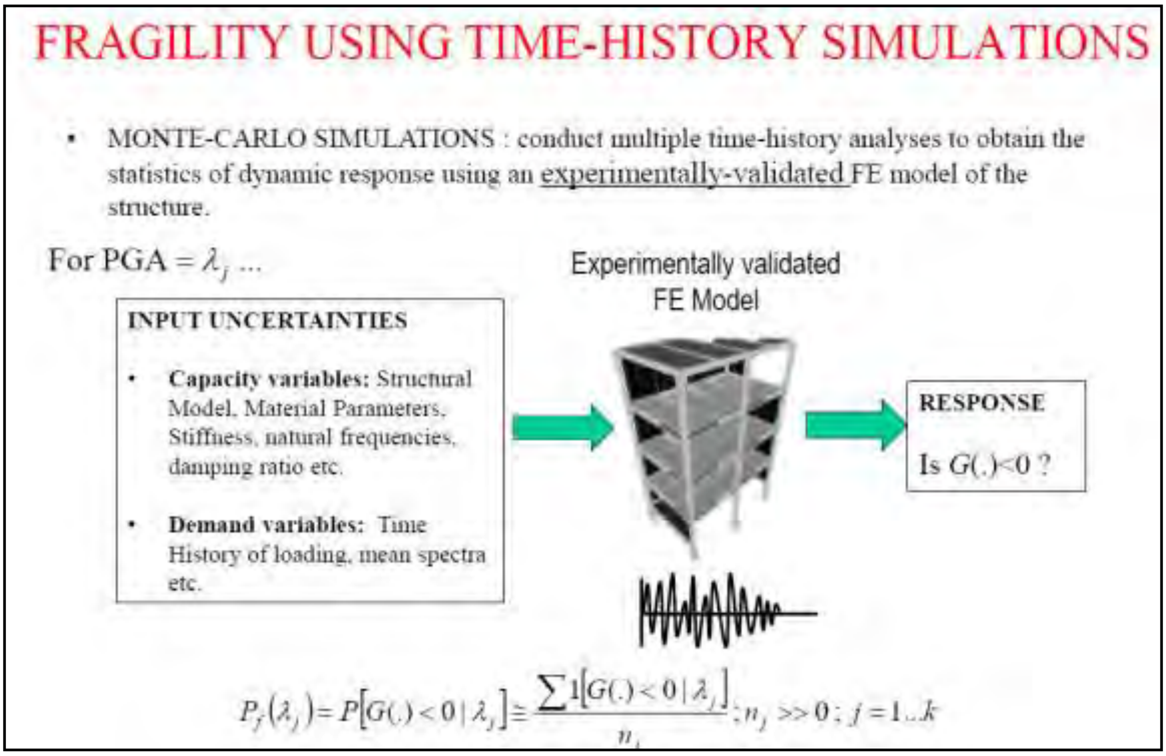
Observed Data, $\mathbf{y}=[y_1,y_2...y_m]^T$

From Bayes' Theorem...

$$f''_{\mathbf{\Theta}}(\theta_1,\theta_2...|\mathbf{y})=\frac{P(\mathbf{y}|\theta_1,\theta_2...)f'_{\mathbf{\Theta}}(\theta_1,\theta_2...)}{P(\mathbf{y})}$$

"Posterior" or updated pdf of $\mathbf{\Theta}$

Above: Yamaguchi's proposed method and a conceptual example using Bayes' Theorem to update an analytic fragility curve with damage from earthquake data.



FRAGILITY USING TIME-HISTORY SIMULATIONS

- MONTE-CARLO SIMULATIONS : conduct multiple time-history analyses to obtain the statistics of dynamic response using an experimentally-validated FE model of the structure.

For PGA = λ_j ...

INPUT UNCERTAINTIES

- **Capacity variables:** Structural Model, Material Parameters, Stiffness, natural frequencies, damping ratio etc.
- **Demand variables:** Time History of loading, mean spectra etc.

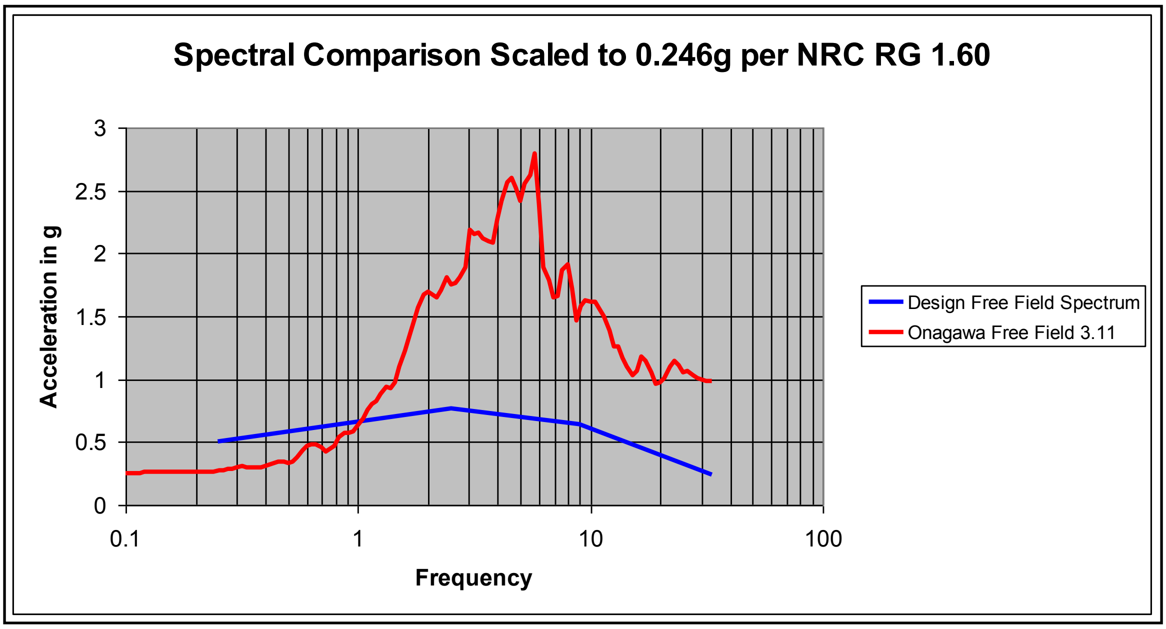
Experimentally validated FE Model

RESPONSE

Is $G(.)<0$?

$$P_f(\lambda_j)=P[G(.)<0\,|\,\lambda_j]\cong\frac{\sum 1[G(.)<0\,|\,\lambda_j]}{n_j};n_j>>0;\ j=1..k$$

Above: the method proposed by Abhinav Gupta.



Above: Sam Swan and Woody Epstein's proposed method. We know that no critical SSCs were damaged at Onagawa. Therefore, if the SSCs at the unnamed NPS are like Onagawa, then we have good evidence that we have a safe seismic margin.