Other External Events

Session Chair: Michael Golay

10:00 AM

Reducing the Risk of Turbine Missiles in a Nuclear Power Plant

Alexander Knoll
Consultant, Wyomissing, PA, USA

The presentation will identify the risk contributors to turbine missiles and other turbine blade failures. It will provide tangible recommendations to reduce the risk of turbine missiles and other turbine blade failures.
Turbine missiles are very expensive to repair and might have impact on safety risks, because: They are almost always accompanied by fire (Both Combustibles & Ignition sources are in the impact area), Vital electrical supplies are close in the turbine building area (offsite lines, 4KV vital buses), The Control Rooms might be close to the impacted area (plant specific location and orientation of the turbine-generator).
Turbine missiles have impact on financial risks: Hundreds of Millions in Repairs (and no on-the-shelf components), Hundreds of Millions in Generation Losses (up to two years of forced outage).
A generic Turbine Generator layout in a power plant will be presented, including the Control Room between twin units. The layout will show the High pressure turbine, three stages of Low Pressure turbines and the generator, which are all on the same shaft. The Failure Modes and Effects that could lead to turbine damage or missiles will be clarified, including: What turbine components may fail, Blade failures that required removal of damaged blades and rebalancing turbine for short term runs, What Human errors may induce failures, during operation (operator errors), or - during (engineering design), or - during oversight (QA and administration), What is the contribution of the Protective System (automatic or manual).
The turbine missile events at Salem-2 (November 1991) and DC Cook-1 -(Sept. 2008) will be described. Temporary modifications of degraded blades in aging turbines will be provided. Based on the Risk Assessment, recommendations will be provided how to reduce the risk of turbine missiles. (***Presentation only***)

10:25 AM

Treatment of the Loss of Heat Sink initiating events in the IRSN PSA

F. Corenwinder
Institute for Radiological Protection and Nuclear Safety, Fontenay-aux-Roses, France

Loss of ultimate heat sink is an initiating event which, even it is mainly of external origin, is considered in the frame of internal events Level 1 PSA by IRSN. Moreover, according to the French PSA fundamental safety rule this kind of initiators should be considered by the plant operator in the frame of the "Reference PSA". Nevertheless, the modelling of this initiating event is not always easy and the associated uncertainties are still quite important. The occurrence frequency, the restoration time, the impact on more than one plant, the impact on the emergency organisation, etc. are some of the aspects, for which, today there is not a full consensus between different PSA teams (IRSN, EDF). Recently, two events of loss of heat sink occurred in France (Cruas and Fessenheim). This recent operating experience should be fully used in order to ameliorate the modelling of the loss of heat sink initiating event in the PSA. The paper presents the methods used today by IRSN to model the loss of heat sink initiating event and the historical perspective. The two events will be shortly presents as well as the foreseen evolution of the PSA methods and models to best incorporate the operating experience.

10:50 AM

An Assessment of Large Dam Failure Frequencies Based on US Historical Data

F. Ferrante, S. Sancaktar, J. Mitman, and J. Wood
US Nuclear Regulatory Commission, Rockville, MD

Flooding events are part of the hazard categories commonly considered in assessing the design of industrial facilities. The failure of large upstream dams is one category of flooding event that can challenge the safety of these facilities. Additionally, the failure of dams downstream of facilities that depend on external water sources for their operations could also represent a concern from a safety standpoint. Generic dam failure estimates based on historical data are commonly relied on as screening values for use in design and risk assessment. This paper presents an in-depth analysis of currently available databases with information on US historical dam failure events and the dam population in order to estimate generic large dam failure rates while also addressing the challenges in deriving values supportable by historical data. Items such as completeness of data, applicability of generic values versus site-specific considerations, and screening criteria including dam types, construction vintage, and failure modes, are addressed via independent failure frequency point estimates. The work highlights the limitations of the derivation of a defensible screening value for dam failure frequency estimates.

11:15 AM

Application of FRANX Software to External Events

Jeff Riley
Electric Power Research Institute, Palo Alto, CA

The EPRI FRANX software has been used for several years as a tool to assist the PRA analyst in incorporating fire related impacts and modeling attributes into existing PRA models. This simplifies the process of performing a Fire PRA and the ultimate incorporation of the fire model into a configuration risk model.
Recent developments in FRANX have increased the capabilities to model numerous other spatially-dependent and scenario-dependent situations. More recent applications of the tool have included the modeling of flooding scenarios, thereby including these scenarios into the PRA in model in a structured and automated manner, avoiding laborious hand development of models.
Of particular note are improvements in the tool to support seismic analysis in a highly structured manner. These seismic add-ons allow for the simple development of seismic scenarios from the hazard curve, automatic implementation of the appropriate fragility information, and integration with the full Level 1 PRA model.
This paper discusses the expanded capabilities of the FRANX software tool, with particular emphasis on external event coverage such as flooding and seismic capabilities.

From: Criscione, Lawrence
Sent: Thursday, September 27, 2012 5:50 PM
To: 'dlochbaum@ucsusa.org'
Subject: FW: PSA 2011 Paper
Attachments: PSA 2011 An Assessment of Large Dam Failure Frequencies based on US Historical Data.pdf; PSAM11 Paper_Uncertainty Analysis for Large Dam Failure Frequencies.pdf

Dave,

Attached are some papers on assessing dam breaks. These are publicly releasable papers done by US government workers which were presented at scientific conferences (PSA 2011 and PSAM11).

I couldn't find them in NRC ADAMS. But as works presented by US federal employees at open international conferences, there should be no copyright restrictions on them. That is, PSA 2011 and PSAM11 should not be allowed to claim copyright, but it is possible they do.

Larry

From: Mitman, Jeffrey
Sent: Tuesday, September 25, 2012 11:28 AM
To: Criscione, Lawrence
Subject: RE: PSA 2011 Paper

Larry, attached is the PSA 2011 paper. I don't recall whether it's in ADAMS. Also attached is a second paper on dam failures which I'm also a co-author on. It was presented at PSAM earlier this year. There are many papers on dam failures, these are the only two that I've been involved with that were published outside of the NRC. I'm not sure what you're looking for so if you're interested let me know and I can send more.

Jeff Mitman

From: Criscione, Lawrence
Sent: Thursday, September 20, 2012 3:17 PM
To: Mitman, Jeffrey
Subject: PSA 2011 Paper

Jeff,

Is your PSA 2011 paper in ADAMS? If not, can you point me to it on the web or send me a copy?

Thanks,
Larry

B/38

ANS PSA 2011 International Topical Meeting on Probabilistic Safety Assesment and Analysis
Wilmington, NC, March 13-17, 2011, on CD-ROM, American Nuclear Society, LaGrange Park, IL (2008)

AN ASSESSMENT OF LARGE DAM FAILURE FREQUENCIES BASED ON US HISTORICAL DATA

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ABSTRACT

Flooding events are part of the hazard categories commonly considered in assessing the design of industrial facilities. The failure of large upstream dams is one category of flooding event that can challenge the safety of these facilities. Additionally, the failure of dams downstream of facilities that depend on external water sources for their operations could also represent a concern from a safety standpoint. Generic dam failure estimates based on historical data are commonly relied on as screening values for use in design and risk assessment. This paper presents an in-depth analysis of currently available databases with information on US historical dam failure events and the dam population in order to estimate generic large dam failure rates while also addressing the challenges in deriving values supportable by historical data. Items such as completeness of data, applicability of generic values versus site-specific considerations, and screening criteria including dam types, construction vintage, and failure modes, are addressed via independent failure frequency point estimates. The work highlights the limitations of the derivation of a defensible screening value for dam failure frequency estimates.

Key Words: External Flooding; Dam Failures; Initiating Event Frequency; Uncertainty

1 INTRODUCTION

External flooding considerations involve a series of hydrological and non-hydrological factors that may impact an industrial site. Hydrological factors include site-specific extreme phenomena characteristics (e.g., high tides, severe storms, wave action) with the potential to cause flooding, while non-hydrological events include a range of different phenomena (e.g., seismic activity). In both cases, there is a potential hazard due to the effect of hydrological and non-hydrological phenomena on manmade structures such as dams, levees, and dikes as contributors to flooding.

Available guidance on dam safety from entities such as the Federal Energy Regulatory Commission (FERC) [1], the US Bureau of Reclamation (USBR) [2], and the US Army Corps of Engineers (USACE) [3] describe mechanisms that may trigger the uncontrolled release of the reservoir impounded by a dam. These generally include (i) overtopping of a dam due to severe precipitation-induced flooding, (ii) seismically-induced failures, (iii) breaches caused by internal

* Corresponding Author

erosion/piping phenomena, (iv) operational errors or mechanical failures, and (iv) combinations of these various mechanisms. While severe phenomena have the potential to cause significant consequences, the lower likelihood of these events also needs to be considered from a risk perspective. On the other hand, failures other than severe storm and seismic events, which are grouped into a subset referred to as "sunny-day" failures in this work, can occur during normal operations (e.g., internal erosion and operational failures). Guidance from USBR indicates that these "sunny day" failures may, in fact, be higher contributors to risk when compared to low-frequency extreme events such as severe storms and earthquakes [2]. Additionally, when compared to severe weather events, "sunny day" failures may provide less time for warnings and mitigating actions to take place. Hence, the appropriate consideration of the risk spectrum when performing dam risk assessments is an important aspect when evaluating potential hazards for industrial facilities. The available literature from agencies such as FERC, USBR, USACE, and others suggests that the current state-of-the-art in providing better risk estimates of such contributors has evolved significantly in recent decades [4].

The USBR, in particular, has developed a framework for dam risk analysis that involves the creation of a risk portfolio for assessing public safety and cost-benefit improvements to dams [5]. Thresholds for taking specific actions are often the subject of much policy making debate, where the focus tends to remain on relative risk-ranking based on subjective metrics. As such, most current efforts are moving away from a purely statistical approach to dam failure rate estimation.

However, a question still remains with respect to generic failure rate estimates that can be used in screening criteria for various applications that consider the risk from external flooding contributors explicitly. For example, external flooding is a component of so-called "external hazards" (e.g., external flooding, seismic events, and other phenomena external to plant operations) [6] analyzed under Probabilistic Risk Assessment (PRA) studies for US nuclear power plants [7]. More specifically, external flooding events are part of the hazard categories considered in assessing the overall risk of nuclear power plants due to water sources external to the site. For plants with large dams upstream of the site, this category includes the potential for dam failures resulting in floods that can challenge the safety of the plants. Additionally, the failure of dams downstream of a nuclear power plant site can potentially affect the availability of cooling water.

A direct approach to estimating a dam failure rate is to perform a data analysis of past events and operational data yielding a generic failure rate. While such a generic failure rate is an approximation of a more detailed study of dam specific design, operations, failure mechanisms and the potential effects to a specific site, it can serve as a starting point for a more detailed screening analysis and evaluation of the potential effects. The approximate nature of this approach can involve both overestimation and underestimation of a dam failure rate for a specific site. For example, the inclusion of certain historical failure events, which are not necessarily candidates for challenging safety at a site, may result in overestimation of a failure rate. Also, consideration of site-specific characteristics such as meteorology and hydrology may either increase or decrease the likelihood of an event with respect to a generic estimate.

Two major databases are available that provide an opportunity to assess the derivation of such a generic failure rate estimate based on the US dam population [8] and the collection of events that have historically occurred with US dams [9]. It should be noted that these databases were not originally developed for quantification of dam failure rates, and the challenges in using these sources for this purpose are discussed in detail, along with the numerical results. As with

any data analysis, use of the information in these databases needs to carefully consider issues such as completeness, consistency, and applicability. Nonetheless, they provide valuable information with a clear understanding of the data. Based on these sources, a set of failures and operational data is used to derive generic dam failure rate. This paper also includes a discussion on the limitations of the general dam failure data, based on analysis of the generic estimates for a number of categories involving different dam parameters.

While a large number of papers addressing dam risk assessment are available in the literature, only a subset deal with estimating generic dam failure rates (including large and small dams) using historical data explicitly. An early example is Baecher *et al.* [10], which summarizes existing estimates developed up until that point and suggests "an average default value of about 10^{-4} failures per dam-year for major projects" in the U.S. Another interesting early study was published by Martz and Bryson [11]. This study considered how to include expert judgment as well as data in a Bayesian estimation framework (resulting in a median estimate of 8.7×10^{-5}/year) as a hypothetical example of the quantification of low-probability/high-consequence events for use in PRAs. The International Committee on Large Dams (ICOLD) published a report [12] that considered earlier dam incident collection efforts and produced statistics on international dam failures. Estimates in this study were based on the number of events divided by the total number of dams for a number of different categories (e.g., dam type, vintage, infant mortality). More recent analyses include the work of Tatalovich [13], Fell *et al.* [14], Foster *et al.* [15], Foster *et al.* [16], and Zhang *et al.* [17].

2 METHODOLOGY

The scope of this work is limited to US dams reported in the main databases used: (i) the National Inventory of Dams (NID) [8], maintained by USACE, and (ii) the National Performance of Dams Program (NPDP) [9], maintained by Stanford University. Additionally, only "large" dams are considered (with the definition of "large" used in this work discussed below). Tailings and debris control dams are treated as a separate category, given their distinct design characteristics and application when compared to the rest of the US dam population. With respect to events affecting dams, only failures leading to the uncontrolled release of all or a portion of the reservoir are included, with no distinction made in terms of the intensity or size of the breach.

It is recognized that breach size and the volume of reservoir released can result in different consequences to an upstream or downstream facility. However, taking these factors into consideration would require knowledge of dam-specific information including dam geometry and composition, as well as site-specific flood-routing information such as geomorphology and run-off conditions, which is beyond the scope of the generic dam failure frequency estimates in this work. The intent here is to provide a better understanding of the nature of the databases with the development of estimates that may be used for screening analysis purposes, as well as the strengths and limitations of the derived generic failure rates.

It should be noted that based on the available data, the scope of this study is limited to dam failures and operational information up to and including 2006. More recent large dam failures (post-2006) that have occurred are outside the scope of this study. The reason for this limitation is that, at the time this analysis was performed, more recent dam failures had not yet been incorporated into the NPDP historical database [9]. The NID database used here includes

information available up to 2008. Since this work was completed, USACE has released an update to the NID database in 2009, which was not included in this assessment but could be used for updating purposes in the future.

2.1 Definition of a Large Dam

The definition of what constitutes a "large" dam may be subjectively derived in a number of ways. With respect to deriving a dam failure frequency estimate, it is recognized that larger dams may be more robust than smaller dams in a variety of ways, including design practices, inspection and oversight, maintenance, and lower susceptibility to severe precipitation events.

The size of a dam may be characterized by two main parameters: dam height and reservoir impounding capacity. However, for most dams, height and reservoir impounding capacity are directly related (i.e. dams that are taller in height, generally have larger storage capacity). For the purposes of this study, only dam height was considered as the initial selection criterion, as this is a convenient way to eliminate many small dams, that most likely have no relevance to nuclear power plant safety, from further consideration. This study defines a "large" dam as any dam with a reported height equal to or above 12.2 meters [40 feet]. This criterion was chosen because the same value has been used as a basis for distinguishing small dams from larger dams by US state and federal organizations [18, 19]. It is acknowledged that there may be a small number of dams with heights less than 12.2 meters [40 feet] with large storage capacities, which could still pose significant flooding hazards. It is not expected, however, that other definitions will result in significantly different dam failure rate estimates, although this assumption is not explicitly assessed here.

2.2 Identification of Dam Failures

The NPDP database was used as the primary source of dam failure data. The NPDP database that was developed and is currently maintained by the Department of Civil and Environmental Engineering at Stanford University is a database of dam incidents and failures that have occurred in the US between 1848 and 2006. Dam incidents include a number of different criteria such as unsatisfactory dam inspection, dam modification to improve safety, dam breach, incorrect dam operation, and seismic events without complete failure of the dam. An assessment by the authors indicates that the data in the NPDP database does not provide a complete description of each failure event to (i) identify the magnitude of the event, and (ii) fully match the detailed description available in the NID database for the existing US dam population. The NPDP classifies each incident according to whether a dam "failure" occurred or not. The classification categories used are "failure," "non-failure," and "unknown." For the purposes of this study, only the dam incidents classified as "failure" are considered. The NPDP defines a dam failure as a "breach and uncontrolled release of the reservoir," although that definition may not strictly apply to all of the failures contained in the NPDP database. In fact, some event descriptions suggest that certain failure events are less severe than the definition above. Nevertheless, the authors chose to accept the NPDP classification of dam failure events as a basis for estimating a generic large dam failure rate. The potential for conservatism in applying this estimate is, however, acknowledged.

2.2.1 Applicable dam failures

As discussed above, the criterion used for large dams is a height equal to or greater than 12.2 meters [40 feet]. The data downloaded from NPDP does not contain height information for all of

the dam entries; however, each entry does contain a unique identifier for each dam. Using this identifier, the dams were matched to their corresponding heights using the NID database. Of the 1,019 total dams in the NPDP failure list, 623 dams were matched to a dam height from an entry in the NID database. In cases where the NID and NPDP showed differing heights, the NID value was used (typically, the height difference was within a few feet). The NID height value was used to maintain consistency in the analysis, which is not to imply that one database is deemed more accurate than the other. After identifying the dam heights, 142 dam failures were found to be in dams that have heights greater than or equal to 12.2 meters [40 feet], with 481 dams that have heights less than 12.2 meters [40 feet], and 396 dams had with no height information in either database. Due to the lack of data on a significant portion of these dams, the authors assume that the majority of dams with no height information are small dams (i.e., less than 12.2 meters [40 feet] in height) and thus not relevant to this study, with the understanding that this probably excludes some entries that would qualify as large dams.

Further inspection suggests that there is a relatively small number of additional events that should be considered for dam failures. For example, additional dam failures were found in supplementary sources. Several resources that include lists of major or notable dam incidents are available ([20], [21] and [22]). Using these sources, an additional 9 failures in large dams were identified, which had been included in the NPDP database with missing dam height information.

Finally, failures of tailings dams are included but were binned in a separate category. This category is commonly applied to embankment dams used to retain the waste material resulting from mining activities [22]. The construction and maintenance practices associated with tailings dams suggest that they may not be as reliable as dams established for other purposes, such as flood control and hydropower.

2.2.2 Dam failures excluded from consideration

Further inspection of the NPDP database revealed that a small number of dams had experienced multiple failures throughout their operational history (*i.e.* dams have been rebuilt or repaired after failures). In other cases, some descriptions and dam specifications suggested two separate entries describe a single individual event. To avoid duplication, only non-repeated single entries and valid multiple entries for an individual dam were included. All other repeated entries were removed from further consideration for failure frequency estimation.

Additionally, several of the failure event descriptions suggest that the occurrences may not have been severe enough to cause a complete dam failure. For example, some NPDP descriptions mention a "partial failure" of the dam or discuss a malfunction of a dam component (i.e., more closely matching the definition of an incident than a dam failure). However, in most cases the details provided are insufficient to make an informed assessment of the event severity.

In general, if the NPDP classifies an event as a failure, then it is also considered a failure for this study. However, a few exceptions are made to this criterion for certain dam failure events where compelling evidence supports its exclusion. For example, certain failure event descriptions indicate damage to appurtenant dam structures (e.g., spillways or outlets) with no breach, failure, or damage to the main dam and no subsequent large release of the reservoir. This also resulted in a small number of events being excluded. In addition, failures related to dams that were abandoned prior to completion or condemned without failing were excluded. While this category represents a subset of dams built in the US, it would not be appropriate to include such events in the derivation of a failure rate for dams that were brought to full operational

status. The derivation of a failure rate for failures that did take place during initial construction prior to operational status (i.e., infant mortality) is considered in a separate analysis.

2.3 Dam-Year Estimation

The main source of dam-year operational data is the NID database which provides an extensive amount of information on the current US dam population. The NID database is maintained by USACE, which periodically updates this listing of operational dams with a wide range of information, including dam height, dam type, and construction year, among many other categories.

In this work, NID was accessed to download information about the existing 80,000 plus dams in the US. The results presented here used the database version available prior to the 2009 update, which includes an additional approximate 1,300 dams. While not using the 2009 revision may result in slight numerical discrepancies with the results presented here, the overall conclusions resulting from the methodology used in this study are not expected to change substantially.

From the overall total US dam population in NID, 11,980 of these dams meet the "large" dam definition. The NID database also provides the construction completion year for a significant number of these dams. Since the NPDP database lists dam failure events through 2006, the difference between this date and the construction completion year in NID was used to estimate dam-year contributions. However, the NID database does not provide initial construction and failure dates for dams that were decommissioned after an accident and/or later rebuilt. Hence, a correction is introduced for failed and decommissioned dams that have known completion dates (i.e., this correction does not account for cases where this information is missing) which is small in magnitude when compared to total values.

Finally, for those dams for which the year of construction and/or start of operation is unknown, the dam is assigned the average life of other known dams. For example, for large debris control and tailings dams (considered as a separate category in this study), the average life is 27.5 years, while for all other large dams, it is 45.2 years.

3 ANALYSIS AND RESULTS

To estimate generic large dam failure rates, the applicable failure events were assessed against the criteria above, along with the corresponding total dam-years derived primarily from the NPDP and NID databases, respectively. For each failure in the list, several dam attributes are given. Certain key dam attributes were used to separate the data in ways that can significantly affect the dam failure frequency. These include dam type, dam vintage, infant mortality, and failure mode. For most of the attributes considered, the number of failures N is divided by the corresponding dam-year total T, for a point-estimate of the annualized dam failure rate. The overall generic dam failure rate encompassing all attributes was derived from a total of 518,358 dam-years and 148 failures, resulting in an estimate of 2.9×10^{-4}/dam-year.

3.1 Dam Failure Rate per Attribute

3.1.1 Dam Type

Typically, dams are classified by their structural design and construction material. The classification of dam types is not standardized, reflecting the wide variety of designs and construction techniques in the current dam population, but most classification systems available in literature use similar, overarching definitions for dam types.

For certain dams, the NID and NPDP dam type entries contain multiple attributes. For example, one dam is described as "concrete earth rockfill" in its dam type entry. Several large dams may be composed of multiple sections that include embankment and gravity dam characteristics, raising the issue of how their risk contribution is to be considered. The NPDP does not clearly define these combined dam types, so some assumptions were made to classify these dams into typical dam types. If no dam type information was given in NID or NPDP, or the dam type could not be categorized as earth, rockfill, concrete, or gravity, then it is categorized as "unknown."

Even for some dams with a single type listing there is significant difficulty in appropriately binning dams using strict definitions of dam type. For instance, a common definition of a rockfill dam is a dam in which a majority of the total volume is comprised of compacted or dumped pervious natural or crushed stone [22]. However, this is not an established definition, and it would not necessarily identify subsets of dam types that would be susceptible to different failure modes. Such definitions have not always been consistent in dam practice and often depend on visual inspection to estimate whether a dam is composed of predominantly rockfill or earthfill material based on definitions of gravel size. Additionally, various sources define dam types in different ways.

NID classifies dams into 12 categories: arch, buttress, concrete, earth, gravity, masonry, multi-arch, rockfill, stone, and timber crib. The authors binned these 12 categories into five grouped categories defined to encompass overarching dam types: earth, gravity, rockfill, concrete, and other/unknown materials. Table I shows dam-year totals per type, including applicable failure events, while Table II shows the resulting dam failure rate estimates of the grouped categories. Large dams used for the purpose of tailings and debris control (usually embankment dams) were also identified in NID and NPDP, with a total of 13,810 dam-years and six failures, i.e., 4.3×10^{-4}/dam-year. For large "embankment" dams (usually composed of earth, rockfill or a combination of both), the failure rate is derived using the earth and rockfill categories together as 2.3×10^{-4}/dam-year (93 failures in 402,185 dam-years).

3.1.2 Dam Vintage

The vintage of a dam (i.e., construction date) is one of the attributes expected to be a major factor influencing its failure frequency. Consideration of the major milestones in design can be used as a compelling reason for deriving different failure frequencies for different vintages. For example, the introduction of new construction techniques (e.g., soil compaction), administrative controls, or oversight could indicate "landmark" dates to be used in categorizing distinct construction periods. An assessment of the distribution of failure dates and construction completion year (see Fig. 1 and 2) was derived in this study to consider how dam vintage may be considered.

Table I. Dam types and dam-years

	Dam Type	Dam-years	Grouped Category
1	Arch	5354	V
2	Buttress	1175	V
3	Concrete	5262	IV
4	Earth	396033	I
5	Gravity	17277	II
6	Masonry	1475	V
7	Multi-Arch	1349	V
8	Other	2989	V
9	Rockfill	6152	III
10	Stone	228	V
11	Timber Crib	328	V
12	Other/Unknown	80736	V

Table II. Failure rates for grouped category dam types

	Grouped Category	Number of Failures	Dam-years	Failure Rate (/dam-year)
I	Earth	86	396033	2.2×10^{-4}
II	Gravity	7	17277	4.1×10^{-4}
III	Rockfill	7	6152	1.1×10^{-3}
IV	Concrete	6	5262	1.1×10^{-3}
V	Other/Unknown	42	93634	4.5×10^{-4}

Figure 1 shows the distribution of the 148 failure events obtained from NPDP per year of failure. There are two peaks in this histogram, one occurring around 1930 and the other around 1975. The authors could identify no basis in design evolution that explains these peaks and therefore, no reason to use the associated peak years as cutoff years for vintage binning. Figure 2 shows the distribution of construction completion years and indicates a peak between 1965 and 1970 (NOTE: The 1850 peak includes all dams in the database built up to and including 1850).

A study of the well-known Teton Dam failure that took place in Idaho, in 1976, asserts that "[f]or dams built in the United States before 1959, on the average one in fifty failed" [23]. The implication from this statement is that older dams failed more frequently than dams constructed in recent years. In this study the year 1960 was selected as a cutoff year for exploring the effects of dam vintage. Dams with a construction completion date prior to 1960 are identified as "pre-1960," and those with a date after to 1960 are identified as "post-1960."

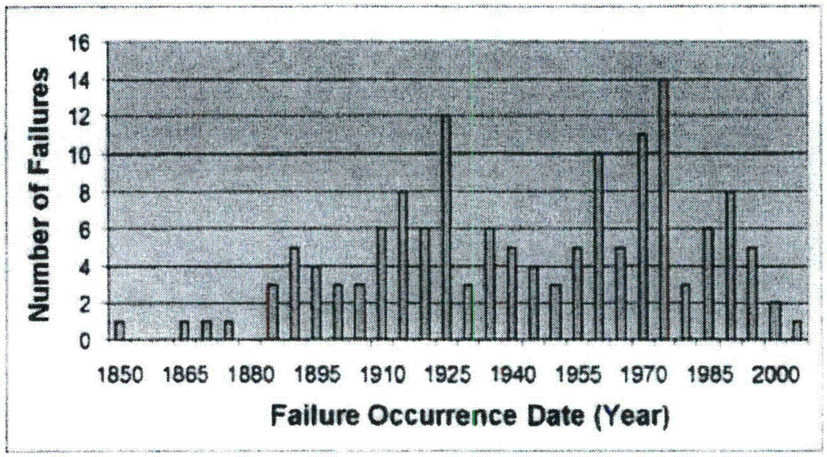

Figure 1. Distribution of dam failures per failure occurrence date

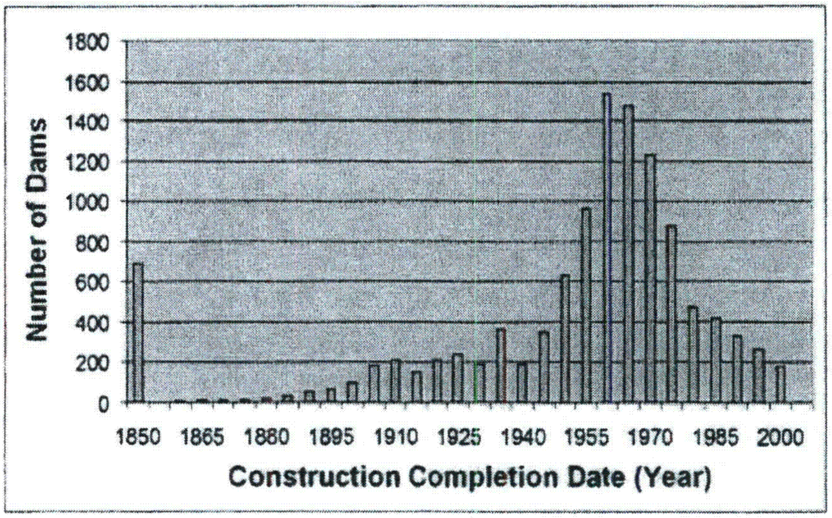

Figure 2. Distribution of dams per construction completion date

The dam construction completion year is taken from the NID or NPDP databases. If the year completed was not found in either database, then it is listed as unknown. Also, if the year the dam was completed occurs after the dam failure date, then the authors assume that the attributes from NID or NPDP apply to the current (possibly rebuilt) dam and not to the dam that failed. In these cases, the failed dam attributes are listed as unknown, unless other reference material was available. It should be noted that this definition of dam vintage is not intended to imply a measure of dam quality, and is another insight into the challenge of defining dam failure rates by completion date in a strict manner. For example, Hoover Dam was completed prior to 1960 and yet its likelihood of failure in practice is not necessarily anticipated to be equal to dams of lesser design characteristics built either before or after 1960.

Based on this criterion the databases provided 226,642 dam-years for "post-1960" dams with 24 failures, resulting in an estimated dam failure rate of 1.1×10^{-4}/dam-year, while "pre-1960" dams accounted for 261,004 dam-years and 114 failures, i.e., 4.4×10^{-4}/dam-year.

3.1.3 Infant mortality

In the dam safety literature, there is a common understanding that most dam failures occur within the few years of construction or early in the dam's operational lifetime [11]. This is the "infant mortality" phenomenon observed in many reliability analysis studies. In similar fashion, it can be concluded that for those dams that survived through the first few years of operation, some failure modes, such as construction and design defects, may be considerably reduced. It should be noted that although construction issues can qualify as infant mortality in the classical manufacturing definition, large dams may fail due to a number of complex issues during their lifetimes. For example, a dam that is challenged by a severe storm early during its operations may not be an infant mortality case. The authors did not attempt to investigate the root cause of failures occurring during the infant mortality period, focusing instead on available information.

A sensitivity analysis was performed to evaluate the effect of the choice of cutoff in the number of years after construction completion that defines an infant mortality period, under the assumption that events occurring close to or immediately after construction can be classified as such. In order to evaluate this sensitivity, the number of years after initial operation, K, is used to collect the dam-years and failure events to estimate the corresponding dam failure rate. Table III shows the results for $K = 2, 4, 6, 8$, and 10 years; in which the failure rate for an infant mortality period between 0 and K years is calculated alongside the corresponding failure rates for dams surviving beyond K years. It should be noted that dams with unknown construction dates are not included in the estimates, unless they failed during construction, in which case their failure is included with zero dam-years.

The total number of dam years estimated for infant mortality is slightly conservative since some dams failed in less than K years, but K years were assigned to them in calculating the total dam-years in this sensitivity calculation. This increases the denominator for the infant mortality period, but reduces the denominator for the period beyond infant mortality. The results indicate that the dam failure rates for a large dam that survives construction and the first K years of operation is not very sensitive to the cutoff years chosen for the definition of infant mortality (i.e., in the range of 1.5×10^{-4}/dam-year to 1.8×10^{-4}/dam-year). The failure rate for the infant mortality period, however, is sensitive to the choice of K, which appears to converge around 5×10^{-4}/dam-year. Hence, the authors chose $K = 8$ years as a cutoff for dam failure rate estimation purposes, where the failure rate in the infant mortality period is 5.3×10^{-4}/dam-year and dams surviving beyond this period have an estimated failure rate of 1.5×10^{-4}/dam-year.

Table III. Sensitivity to infant mortality cutoff year selection

***K* (year)**	**2**	**4**	**6**	**8**	**10**
Infant mortality failure rate (/dam-year)	1.1×10^{-3}	7.6×10^{-4}	6.3×10^{-4}	5.3×10^{-4}	4.5×10^{-4}
Failure rate for dams surviving infant mortality period (/dam-year)	1.8×10^{-4}	1.6×10^{-4}	1.5×10^{-4}	1.5×10^{-4}	1.5×10^{-4}

3.1.4 Failure Mode

In principle, one may consider partitioning dam failure data by incident type or failure mode. For a specific dam, a certain failure mode may have particular significance, while that same failure mode may not be applicable at a different dam site. For example, a dam failure caused by a flooding event can be highly dependent on the site-specific conditions. Based on the analysis conducted in this study, an attempt to partition dam failure data based on incident type or failure mode was not made, although it may be valid for other dam safety studies that have access to more detailed failure mode descriptions.

In practice, the authors found that there was insufficient basis for partitioning the data by failure mode, and concluded that attempting to partition could produce misleading results because of the limited information available on the details of the failure events. Additionally, in assessing the NPDP database and the ability to separate failure events by incident type or failure mode, the authors observe that multiple failure modes could have contributed in some failure events. For example, it was noted that a significant number of events in NPDP were categorized as "Inflow Flood - Hydrologic Event." Although several events have been classified in this incident type category it is unclear from the event descriptions if they all share the same underlying failure mode. It was also noted that none of the large dam failures in NPDP are classified as due to earthquakes. Despite the fact that a failure due to a purely seismic-induced event is not registered in the US historical data, there is a case where seismic activity has been involved in a near failure in the US. This well-known case involved the Lower Van Norman Dam in California during the 1971 San Fernando Earthquake, which came close to failure [22]. By most accounts, it is assumed that failure would have occurred due to seismic liquefaction if the reservoir water level was not lower than normal. This partial failure event does not appear in the NPDP database and highlights the shortcomings of pure data analysis when considering dam vulnerability due to earthquakes.

4 CONCLUSIONS

In this work, estimates of the dam failure rates in large dams (i.e., height above 12.2 meters [40 feet]) in the US were derived using available database information on historical failure events and calculated dam-year totals. These estimates encompass all documented dam failures, irrespective of their potential impacts on a downstream site. By including a large population of dams with a wide variety of features, the resulting failure frequency may or may not be appropriate for any one specific dam. The overall estimate for all large dams is 2.9×10^{-4}/dam-year. For specific categories considered as subsets of all large dams, the results indicate (i) 2.3×10^{-4}/dam-year for embankment dams, (ii) 4.3×10^{-4}/dam-year for tailings and debris control dams, (iii) 5.6×10^{-4}/dam-year for infant mortality failures (defined as occurring between initial operation and eight years afterward), and (iv) 1.1×10^{-4}/dam-year for dams built after 1960.

It is acknowledged that this direct approach to estimate a generic dam failure rate is an approximation of a more detailed study of dam specific design, operations, failure mechanisms and the potential effects to a specific site that may serve as a starting point for a more detailed screening analysis and evaluation of the potential effects. The approximate nature of this approach can involve both overestimation and underestimation of a dam failure rate for a specific site. As shown in the analysis of the results, use of the information in these databases needs to carefully consider issues such as completeness, consistency, and applicability.

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Uncertainty Analysis for Large Dam Failure Frequencies Based on Historical Data

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Abstract: External flooding hazard assessments typically include considerations for multiple water sources, including catastrophic dam failure accidents, if applicable. For large dams in the United States, a recent study identified a number of significant failures, of which a subset is classified as events involving catastrophic large dam failure. This analysis indicates that the dominant causes of failure are about the same as those for the entire population of dams: overtopping due to exceedance of the reservoir level (usually the result of severe weather phenomena), foundation effects and internal erosion, and miscellaneous other causes including poor design and maintenance, as well as seismic events. While there are well-documented cases of significant events involving such failures around the world, the specific likelihood of such an event is challenging to predict. In attempting to quantify the frequency of large dam failure events, it was recognized in the aforementioned study that reliance on anecdotal historical events must take into account the significant ambiguity and lack of information completeness involved in using such data. At the same time, the use of available databases provides a framework to evaluate in more detail the extent to which this uncertainty may impact the understanding of bounding dam failure rate estimates. In this work, sensitivity studies were performed in order to evaluate the changes due to a number of categorization bins for large dams including dam type, construction completion date, and dam incident information. Bayesian analysis tools were also used for the derivation of posterior uncertainty distributions that include subjective information such as data quality and expert judgment considerations. The extent of the variation in the commonly derived point estimate is documented and discussed for a number of the categories and assumptions usually relied upon in available literature when estimating failure rates for large dams.

Keywords: External Flooding, Dam Failures, Initiating Event Frequency, Uncertainty Analysis.

1. INTRODUCTION

Industrial sites are vulnerable to a wide range of natural hazards including earthquakes, high winds, tornados, hurricanes and floods. In particular, external flooding can be caused by initiators such as extreme meteorological events (e.g. severe storms, tides, and waves), seiche/tsunami, and dam failures. Understanding the risks posed to industrial facilities by these hazards is important for a variety of reasons, such as resource allocation (e.g. prioritization of funds for mitigation/remediation) and emergency planning. Despite the importance of understanding the risks posed by extreme natural events, the maturity of available methodologies and data for assessing the frequency of occurrence of these hazards varies significantly from hazard to hazard. In this paper, we focus specifically on understanding the frequency of dam failure events, which have the potential to affect facilities located both upstream and downstream of the dam. While failures of dams upstream of facilities pose a potential for flooding, failure of dams downstream of facilities can cause unavailability of water to the site.

Dam failures can be caused by a variety of mechanisms including overtopping, seismic events, internal erosion and piping, operational/mechanical failures, and combinations of these initiators. While severe earthquakes and extreme flood events can cause dam failures, these events have a relatively low likelihood of occurrence. Conversely, failures from internal erosion, piping, and operational/mechanical failures can occur without a specific initiator (e.g. earthquake, large rain event).

Dam-regulating entities in the United States (US), such as the US Army Corps of Engineers (USACE) (USACE, 2006), the US Bureau of Reclamation (USBR) (USBR, 2010), and the Federal Energy Regulatory Commission (FERC) (FERC, 2005) have developed frameworks for the purposes of understanding risks, assessing public safety, and allocating resources across portfolios of dams. Thresholds for taking action (e.g. to mitigate risks through retrofits) are often based on estimates of relative risk and subjective metrics. The risk frameworks typically are based on processes involving expert elicitation and, if appropriate or necessary, dam-specific engineering assessments. However, dam-specific assessments have not been performed for all dams, may not be cost-justified, or may not be readily available to all stakeholders. For this reason, it is

useful to have generic dam failure rate estimates than can be used as screening criteria or when more detailed assessments are not available.

The goal of this paper is to use classical and Bayesian statistical methods to develop generic estimates of dam failure frequency based on information contained in two major US databases. Because these databases were not originally developed to support the quantification of dam failure rates, there are several challenges associated with their use for the current application. The work by Ferrante et al (2011) provides a literature review of existing dam failure frequency studies and includes a detailed discussion of the challenges associated with using these databases for deriving dam failure frequencies. Due to the various limitations and caveats associated with use of the aforementioned databases, the sensitivity of statistically-based estimates to a variety of factors and assumptions is explored. These sensitivity studies are designed to help analysts understand the potential variability of the estimated generic values.

2. METHODOLOGY AND RESULTS

Two main sources of information are used in this work to perform sensitivity and uncertainty analysis on large dam failure frequency estimates for the US based on historical data: (1) the National Inventory of Dams (NID) database maintained by USACE (USACE, 2011), and (2) the National Performance of Dams Program (NPDP) database, maintained by Stanford University (Stanford, 2007). Currently, these sources facilitate the collection of (1) the total number of years of operation for US large dams of particular characteristics, such as dam type, and (2) the number of historical failures of US large dams. These databases contain the best available collection of US dams information and dam failure catalogues, and are more complete and accurate than previous efforts to compile such information,. However, they also contain significant sources of uncertainty and missing information, which needs to be carefully considered (as in any effort involving data analysis on such a scale). For example, it should be noted that the databases were not created for the specific purpose of performing dam failure frequency calculations and were not designed to be fully consistent with one other. Nevertheless, these databases are still the primary source of information on existing dams and events. This paper does not intend to express judgment on the quality of the efforts made to develop these databases; instead, it highlights the challenges in the input and categorization of data for such a wide population, which potential users also need to take into account when deriving estimates for low-probability events. The sources of uncertainty from the information gathered will be discussed in more detail in the subsections below.

Following the framework originally developed in Ferrante et al (2011), this work is restricted to the US dam population, to which a subjective (but necessary) "large" dam definition is imposed. There are a wide range of categorization criteria used by various US and international organizations to define classes of dam size, which are based primarily on height and volume of reservoir impounded. These criteria for categorizing a dam "large" or "small" can be highly subjective. However, for the current application, there is a clear need to establish criteria for distinguishing between large and small dams because an individual dam may be more or less susceptible to certain failure modes based on its size or reservoir volume (e.g. a dam with a large reservoir volume and substantial population downstream may have less vulnerabilities due to augmented inspection and maintenance programs). The International Commission on Large Dams (ICOLD) establishes that a dam can be defined as "large" if its height from the foundation exceeds 15 meters [49.2 feet]. For dams between 5 meters [16.4 feet] and 15 meters [49.2 feet] in height, ICOLD will apply the large dam definition if its reservoir volume exceeds 3 million cubic meters [3,923,852 cubic yards] (WCD, 2000). In USACE (1979), dams are defined according to height and reservoir requirements as well, where "small" dams are those between 7.6 meters [25 feet] and 12.2 meters [40 feet] in height, "intermediate" dams comprise those between 12.2 meters [40 feet] and 30.5 meters [100 feet] in height, and "large" dams exceed 30.5 meters [100 feet]. In the current work, we set the criteria for a "large" dam as those exceeding 12.2 meters [40 feet] in height (no reservoir volume definition is used). A sensitivity analysis for the impact of increased height thresholds is performed.

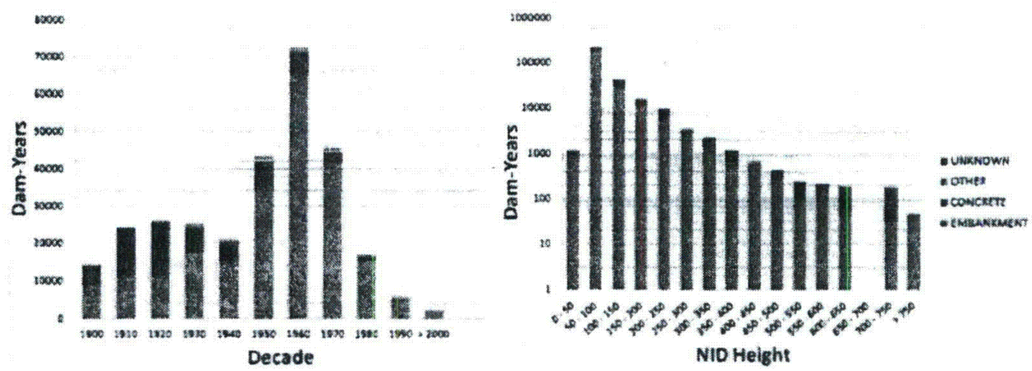
2.1. NID Database

The National Inventory of Dams (NID) database contains the most extensive listing of dams in the US. It is periodically updated and maintained by USACE with support from a number of state and federal agencies, which submit individual dam information through cooperative participation. A description of the inclusion

criteria and required submittal information are described in USACE (2008), which includes 60 fields such as dam height, dam type, storage, and location. The NID database also includes a number of fields restricted from public release, which were not used in this analysis. As in Ferrante et al (2011), the only source of dam-year operational data for this work continues to be the NID database, for which the 2010 update is used. The 2010 version of the NID database includes a listing of over 84,000 dams. Applying the large dam criteria used in this work yields 11,964 dams (approximately 14% of the dams in the database). For dam height, it should be noted that the database field "NID height" is used, which corresponds to the maximum value of dam height, structural height, and hydraulic height, as submitted by NID participants and established by USACE ("NID height" is accepted as the general height of the dam). Specific fields, aside from dam height, that were explicitly considered in this analysis include: dam type, purpose, and year completed. Only dams built since 1900 (i.e., 20[th] and 21[st] century dams) are considered in this study. A small percentage of dams (less than 10%) do not have entries for year of construction completion, which is defined by NID as the year in which the original main dam structure was completed. In these cases, the authors assumed an average completion year based on the available information is used, which corresponds to 1963 (i.e., 47 dam-years per dam with a cut-off date of 2010).

For dam type, NID specifies abbreviations to be used for commonly defined dam attributes: earthfill (RE), rockfill (ER), gravity (PG), buttress (CB), arch (VA), multi-arch (MV), concrete (CN), masonry (MS), stone (ST), timber crib (TC), and other (OT). Submittals often included a combination of attributes to define impoundments with distinctly designed sections. For example, a specific site may include a buttress or an arch gravity section supported by embankments, preventing a single classification in NID. According to the classification scheme, dam type combinations are expected to be provided in order of importance such that a dam type combination initiating with RE or ER (e.g., REPGCN) will indicate an impoundment consisting mostly of embankment sections.

The vast majority of entries are comprised of single attributes (90%), of which earthfill dams account for approximately 89%. It should be noted that a small percentage of dams (2%) have not been categorized with respect to dam type. In order to develop a feasible categorization scheme, four major overarching dam types are used to bin the various single and combination entries in NID: embankment dams (including earthfill, earthfill-rockfill, rockfill), concrete dams (arch, gravity, multi-arch, buttress, and concrete), other type dams (masonry, stone, timber crib, and other), and unknown type dams (empty entries). Entries with multiple dam attributes are categorized with respect to their order of importance, unless additional sources are available that suggest a different dam type category. Additionally, in this work, impoundment structures used to retain waste material resulting from activities such as mining (commonly known as "tailings dams" and usually categorized in NID as embankment dams) are also included in the "other" category because these types of dams are not usually designed and maintained to equivalent standards as other embankment dams. To segregate tailings dams from the overall embankment dam population, a NID category that lists the purpose of individual dams is used (i.e., tailings are identified with "T" in the field "purpose"). Furthermore, dams with names that contain key words such as "tailings", "slurry impoundment", and "mining refuse" are also segregated. Figure 1a shows the range of US large dams built per decade since 1900 with respect to the major dam types considered in this study; indicating a significant period of dam construction between 1950 and 1980. The distribution of dam height for large US dams (using the 12.2 meters [40 feet] criteria) is shown in logarithmic scale in Figure 1b.



(a) (b)

Figure 1. Dam-years (a) per decade and (b) per NID height for all large dam types in NID

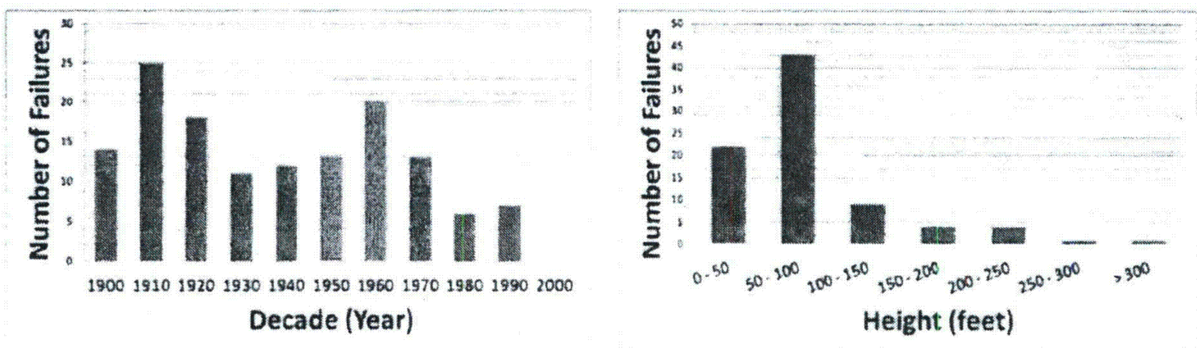
The main source of uncertainty from the NID database is the dam type characterization, as various entries could be misclassified with respect to their dominant attribute. It is unclear, for example, whether the distinction between earthfill versus rockfill composition in different entries is sufficiently robust to justify further parsing of embankment dams. The overarching major dam types used in this work are intended to address this issue to some extent, by avoiding a more granular categorization.

2.2. NPDP Database

The NPDP database was established in 1994 as an information resource for sharing dam incidents and failures within the engineering and dam safety professional community in the US, and is maintained by Stanford University (Stanford, 2007). It is the main source of data on dam failures used in this study. Similar to the NID database, it contains a large number of entries that include information on incident date, dam type, dam height, and other attributes for individual dam failures. There are 1109 dam failures identified, as well as 1776 dam incidents that are searchable by various attributes. NPDP defines a dam failure as a "breach and uncontrolled release of the reservoir." As noted in Ferrante et al. (2010), due to the difficulty in establishing accurate information for a large number of historical dam failure events, a complete description of each individual dam failure is not available for all entries. In particular, a significant number of failure events contained in the NPDP database do not have information regarding dam type, dam height H, and/or construction completion year T_{CY}.

A set of criteria similar to the one presented in the previous subsections was used to define applicable dam failure events: only dam failure events for dams with H equal to or above 12.2 meters [40 feet], built after 1900 were considered. Events with missing dam height information were excluded. However, in order to achieve as much information completeness as possible, additional sources of information were researched and reviewed to identify (1) dam failure events not included in NPDP, and (2) information missing from existing dam failure entries in the NPDP database. This was achieved by identifying individual documentation on specific dam failure events (Kocahan, Taylor, 2002) and cross-checking information with dam failure listings (e.g., VP Singh, 2010). It should be noted that several of the dams with failure events were also later rebuilt, and these dams are identified in NID. Limited cross-checking with the NID information is possible since there is a possibility that rebuilt dams do not exhibit the same attributes as the dams that failed.

Application of the height and vintage criteria utilized in this paper results in a set of 139 dam failure incidents. It is noted that a subset of these incidents are associated with NPDP database entries that are missing construction completion year information. In this report, analysts varied the construction completion year for dams that do not have this information available via NPDP (or other sources). For example, if such entries are assumed to have construction completion year equal to the year in which the failure incident occurred (i.e., infantile or early failure), the distribution of the number of failures with respect to decade and dam height, H, are shown in Figure 3. As demonstrated in this figure, failures of large dams in the US have historically clustered around dams built in the early and mid-20th century (i.e., 1910 – 1920 and around 1960) which are also associated with years of increased dam construction in the US (see Figure 3a). It is also observed that most failures impact dams with heights less than 30.5 meters [100 feet].



(a) (b)

Figure 3. Dam-years per (a) decade and (b) NID height (feet) for all large dam types in NID

The failure database constitutes a significant source of uncertainty in estimating dam failure rates, due to the incompleteness of information as well as the classification of failure modes and dam type attributes of individual events. It is unclear whether certain events identified as 'failures' would be best categorized as 'incidents' based on the event descriptions provided (e.g., certain events are categorized as 'partial failures'). Failure mechanisms are also identified with a number of key descriptors, such as "flood", "seepage", "piping", "spillway failure", "erosion", etc. Considering the description of specific events (including those with more detailed accounts), it is clear that developing a categorization of dam failure mechanisms poses a significant challenge because dams can fail due to a wide range of causes (including in combination with flooding events). While events such as overtopping of a dam due to extreme flooding can be identified, it was deemed in Ferrante et al (2010) that parsing selected failure modes without sufficient technical basis can produce artificially low dam failure frequencies; therefore, this is also not pursued here. Additionally, various sources indicate that certain failures were not included in NPDP or had information otherwise missing. While an attempt was made to compile a more complete list of failures for this work, an exhaustive and thorough investigation was not performed and it is possible that additional failures or more detailed information could be used to further refine dam failure events applicable to large dams. Finally, since there have been no major updates to NPDP since 2006, the estimation of dam failure frequencies will be limited to this date, as including dam-years accrued between 2006 and 2010 would not have an equivalent dam failure events contribution. In other words, although additional failures may have occurred since 2006, no effort has been made to collect such information in this work.

2.3. Point Estimate Calculation

Based on the assumptions discussed for the dam-year and dam failure events obtain primarily from NID and NPDP, a point-estimate of the annualized failure frequency, f, can be derived for various ranges of dam types, height H, and construction completion year T_{CY}.

For failure events with missing construction completion year, a value needs to be assumed for the time interval between known incident date and unknown completion year, ΔT_F. For example, assuming all failure events associated with unknown construction completion year correspond to "early mortality" such that $\Delta T_F = 0$ cases (i.e., the failures took place during or immediately after construction completion prior to operational status) and also assuming an average construction completion year of $T_{CY} = 1963$ for operating dams with missing construction completion year results in the point estimates shown in Table 1. An overall value of $f = 2.71\text{E-}4$/year is obtained, with a decreasing trend between early 20th century dams (1910 – 1920) and later periods. Table 1 also presents the results per dam height H, where the concentration of dam-years occurs at values of less than 61 meters [200 feet]. Due to the limited amount of available data, accurate estimates for dam heights above 61 meters [200 feet] are not possible given the lack of dam-years and dam failure events. However, it is noted that it is to be expected that larger dams have better maintenance and inspection programs and, therefore, lower failure frequencies.

Table 1. Dam failure frequencies for all dam types per construction year and height range

	CONSTRUCTION YEAR RANGE					DAM HEIGHT RANGE (feet)					
	1920	1940	1960	1980	2006	100	200	300	400	800	
TOTAL	1900	1920	1940	1960	1980	40	100	200	300	400	
512,745	61,194	73,366	105,060	240,332	32,793	431,276	59,851	13,721	4,708	3,189	DAM-YEARS
139	39	29	25	33	13	104	25	8	1	1	FAILURES
2.71E-4	6.37E-4	3.95E-4	2.38E-4	1.37E-4	3.96E-4	2.41E-4	4.18E-4	5.83E-4	2.12E-4	3.14E-4	*f (/year)*

Given that it may not be realistic to assume all failures with missing construction completion year have $\Delta T_F = 0$, a variation in ΔT_F was performed. Based on the existing information, the mean value for ΔT_F is 19.5 years. Using the failure frequency for all dam types, between 1900 and 2006 results in a failure frequency of $f = 2.40\text{E-}4$/year. While the sensitivity is small for the entire period considered, a reduction is achieved for later construction ranges since an increasing ΔT_F parameter eventually results in a reduction in the number of failures considered in later decades (e.g., for dams of all types built between 1980 and 2006, there is a reduction to $f = 1.22\text{E-}4$/year with $\Delta T_F = 19.5$ years). If all failure events for which ΔT_F is unknown are excluded, the failure frequency is $f = 1.64\text{E-}4$/year for the period 1900 – 2006.

The results discussed so far include a number of failures that may be considered representative of an early mortality period (in addition to those included by assuming $\Delta T_F = 0$). Some events are clearly indicative of failure during construction or initial filling of the reservoir, while others took place immediately after construction was completed. For a significant portion of the failures considered, it is not possible to ascertain when or how the failure took place to discern early mortality attributes. As discussed in Ferrante et al (2010), it would be expected that dams that survived through the first few years of operation would have reduced values for failure frequencies. However, the estimates are sensitive to the assumed range considered to represent an early mortality period and any assumptions need to be considered carefully. In order to assess this effect with the data developed in this work, an early mortality threshold ΔT_{EM} is used to represent the number of years for which an individual failure event should be excluded in order to assess a failure frequency for dams that survived the early mortality period. In other words, failure events with $\Delta T_F \leq \Delta T_{EM}$ are excluded from the point estimate calculation. Table 2 shows the sensitivity of f with respect to ΔT_{EM}, where ΔT_F is assigned values of either 0 years (i.e., all failures with missing information are excluded) or 19.5 years. Limited variation is observed due to changes in and with all values within the 1E-4/year range. While subjectivity may be involved in choosing a specific value for , it is clear that very high values for ΔT_{EM} will skew the estimates to potentially misleading results.

Table 2. Dam failure frequencies with varying ΔT_{EM} and $\Delta T_F = 0$, 19.5 years

ΔT_{EM}	0	2	4	6	8	10
ΔT_F = 19.5 years	2.40E-4	2.13E-4	1.91E-4	1.79E-4	1.72E-4	1.66E-4
ΔT_F = 0 years	1.64E-4	1.37E-4	1.15E-4	1.03E-4	9.56E-5	8.97E-5

With a value of ΔT_{EM} = 8 years and ΔT_F = 19.5 years (with T_{CY} = 1963), a comparison between the major dam types considered in this analysis can be made. For all dams, a value of f_{ALL} = 1.72E-4/year is obtained, with corresponding results for embankment and concrete dams yielding, f_E = 1.69E-4/year and f_C = 1.48E-4/year, respectively. Therefore, small differences between dam types are observed for the results during the 1900 – 2006 period. The convergence of the values of f_{ALL}, f_E, and f_C, are shown in Figure 4, where f is calculated using the cumulative number of dam-years and failures in time for each major dam type. The value of f increases until approximately 1920 – 1930 as the number of dam-years and failures accumulates, when f begins to decrease, converging to the results indicated above.

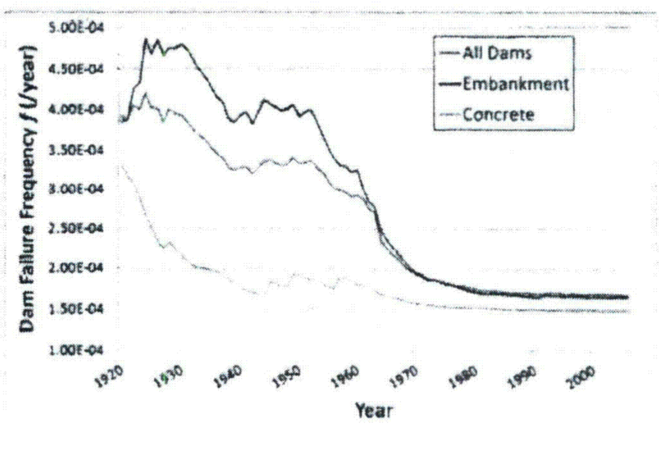


Figure 4. Convergence of dam failure frequency f (/year) for embankment, concrete, and all dams

Finally, the sensitivity to the selection of the large dam height criteria, H_{LARGE}, for all dam types is assessed by calculating f for a subset of increasing values as shown in Table 3. The value of f_{ALL} remains fairly constant as H_{LARGE} is increased from 12.2 meters [40 feet] to 61 meters [200 feet]. For values exceeding 76.2 meters [250 feet] (beyond which there are no reported failures), the value decreases to 8.31E-5/year. While there are no specific thresholds at which a distinction can be made in terms of susceptibility to failure modes for "large" versus "small" dams, care should be exercised in the choice of H_{LARGE} as selecting a high value will result in a significantly sparse subset of dam-years and failures as shown in Table 3. In fact, this would

also apply to any attempt to parse the estimation of f with respect to a large number of attributes simultaneously, as this can lead to artificially low estimates. Finally, it should be recognized that all estimates calculated in this work are generic in nature and are, therefore, an approximation of the results that may be obtained by performing a more detailed probabilistic analysis for a specific dam, given that dams are very unique with respect to design and site characteristics.

Table 3. Sensitivity of f for all dam types with respect to large dam height criteria

LARGE DAM HEIGHT CRITERIA, H_{LARGE} (feet)					
≥ 40	≥ 50	≥ 100	≥ 200	≥ 250	
512,745	293,835	81,469	21,618	12,036	**DAM-YEARS**
96	74	22	4	1	**FAILURES**
1.87E-4	2.52E-4	2.70E-4	1.85E-4	8.31E-5	**f (/year)**

2.4. Uncertainty Analysis

To address the limitations associated with the datasets and the uncertainty associated with classically derived statistical failure rates, an approach using a Bayesian framework is implemented (Kelly, Smith, 2011). A model based on the assumption that the occurrences of dam failure events follow a homogenous Poisson process with rate parameter , which is equal to the mean rate of events, is considered first. In this model, we address missing data using the same data assumptions used to derive the point estimates above. Next, we consider an exponential model that assumes the failure rate for a dam is constant over the life of the dam. In conjunction with the exponential model, we do not make any assumptions about the values of missing data. Instead, we treat observations with missing data as censored observations. We further describe these models below.

Utilizing the Poisson model, the number of dam failures events for a specified period of cumulative operating experience follows a Poisson distribution. In this paper, the conjugate Gamma prior distribution as well as a non-informative prior were considered for the parameter of the Poisson distribution. It is noted that the parameters of the prior distribution will be denoted with a subscript "1" and posterior parameters will use a subscript "2." Data derived from the NPDP and NID databases were used to obtain a posterior distribution based on the number of dam failure events observed and the cumulative number of observed dam-years using well-established analytical relationships for the conjugate pair. In this work, the cumulative years of operating experience is calculated only using dam-years for the dams that have not failed due to problems with repeated observations in both datasets (e.g., some failed dams appear in the NID database).

Table 4 provides a comparison of posterior mean failure frequencies (as well as 5th and 95th percentiles) obtained using the Gamma prior distribution with parameters and for embankment and concrete dams, when varying the values of and . The prior distribution parameters for the Gamma distribution were subjectively chosen because they yield a prior distribution with 5th percentile corresponding to 1E-3/dam-year, a 95th percentile corresponding to 1E-5/dam-year, and a mean consistent with the values obtained from the point estimate calculations. This is consistent with the statements in the addenda to the ASME/ANS RA-S-2008 Standard (2009) on the mean failure rate for all US dams with respect to external flooding hazard evaluations for nuclear power plant applications (ASME/ANS, 2007). As can be seen, the posterior mean values are consistent with the point estimates presented in Table 2. Furthermore, the 5th and 95th percentiles correspond to a relatively narrow spread around the mean, particularly for the cases in which data pertaining to embankment dams are used (which provides a larger dataset than the case utilizing data information on concrete dams).

For embankment dams, Figure 5 compares the prior and posterior distributions for a range of prior parameter values and when was selected as the early mortality cut-off point, was assigned to dams that have failed but for which the construction completion year is unknown, and the construction completion year 1963 was assigned to non-failed dams missing this information. In general, it was found that when considering the larger datasets (i.e. for the datasets containing data on all dams or embankment dams); the posterior distributions are relatively insensitive to the parameters of the prior distributions. For more

finely parsed data (e.g. when considering data for concrete dams), it was found that the values of the prior distribution are relatively more influential.

Table 4. Posterior mean dam failure frequencies with varying ΔT_{EM} and $\Delta T_F = 0$, 19.5 years for the Poisson-Gamma model with and for embankment and concrete dams

		Embankment Dams						Concrete Dams					
ΔT_{EM}		0	2	4	6	8	10	0	2	4	6	8	10
$\Delta T_F =$ 19.5 years	μ_2	2.4E-4	2.1E-4	2.0E-4	1.8E-4	1.7E-4	1.7E-4	2.1E-4	1.9E-4	1.5E-4	1.5E-4	1.5E-4	1.4E-4
	5th	2.0E-4	1.8E-4	1.6E-4	1.5E-4	1.4E-4	1.3E-4	1.4E-4	1.2E-4	9.0E-5	9.0E-5	9.0E-5	8.1E-5
	95th	2.9E-4	2.5E-4	2.3E-4	2.2E-4	2.1E-4	2.0E-4	3.0E-4	2.7E-4	2.3E-4	2.3E-4	2.3E-4	2.1E-4
$\Delta T_F =$ 0 years	μ_2	1.7E-4	1.4E-4	1.3E-4	1.1E-4	1.0E-4	9.5E-5	1.7E-4	1.4E-4	1.1E-4	1.1E-4	1.1E-4	9.3E-5
	5th	1.4E-4	1.1E-4	9.7E-5	8.4E-5	7.5E-5	7.1E-5	9.9E-5	8.1E-5	5.5E-5	5.5E-5	5.5E-5	4.6E-5
	95th	2.1E-4	1.8E-4	1.6E-4	1.4E-4	1.3E-4	1.2E-4	2.4E-4	2.1E-4	1.7E-4	1.7E-4	1.7E-4	1.5E-4

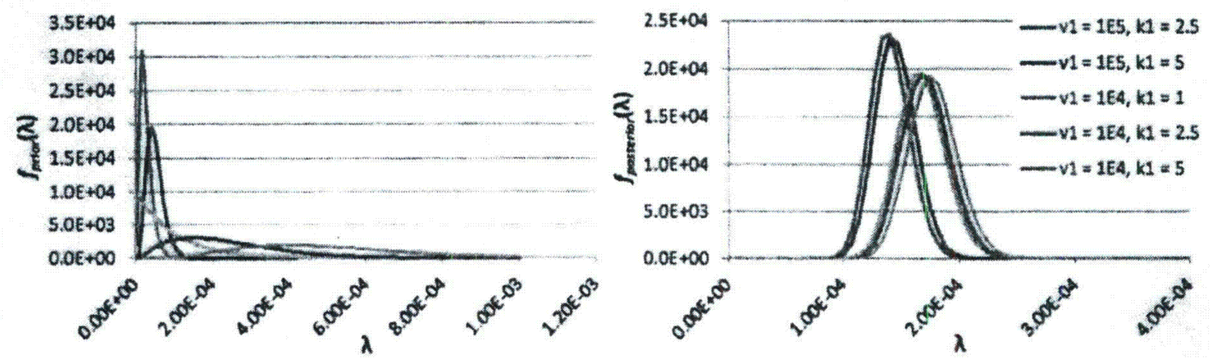


Figure 5. Prior distribution with parameters and (left) and posterior distributions (right) when and using data for embankment dams

Previously it was observed that parsing data by dam height could lead to erroneous results for point estimates when considering dams in excess of 61 meters [200 feet] due to the limited number of observations available. To address the potential uncertainty in this estimate, the Gamma prior distribution (with and) and non-informative prior were utilized to compute the posterior distribution of when considering all failure events (i.e. excluding no observations on the basis of early mortality) and assigning for all failed dams missing the construction completion year (comparable to the point estimates presented in Table 2). The results are shown in Table 5. Results obtained using the informative prior are fairly consistent with the point estimate provided in Table 2. When using the non-informative prior, results are less consistent with the point estimates for the larger dam heights.

Table 5. Posterior mean dam failure frequencies for all dam types with varying dam heights

	Gamma Prior (					Non-Informative Prior				
Height Range (ft)	40-100	100-200	200-300	300-400	400-800	40-100	100-200	200-300	300-400	400-800
μ_2	2.4E-4	4.1E-4	5.4E-4	2.5E-4	3.2E-4	2.4E-4	4.3E-4	6.2E-4	3.2E-4	4.7E-4
5th %	2.0E-4	2.9E-4	2.8E-4	4.0E-5	5.0E-5	2.0E-4	3.0E-4	3.2E-4	3.7E-5	5.5E-5
95th %	2.8E-4	5.6E-4	8.7E-4	6.1E-4	7.7E-4	2.8E-4	5.7E-4	1.0E-3	8.3E-4	1.2E-3

To understand the effect of assumptions made about missing observations in the context of a Bayesian assessment, we utilize an exponential model and consider missing observations as censored. Of course, the exponential model is directly related to the Poisson model used above. The exponential model is updated based on observations of individual component life-spans. The Gamma distribution is employed in this paper as the prior distribution on the parameter (equal to the mean rate of events) of the exponential model. There are multiple types of "life-span observations" available based on the NPDP and NID datasets. Dams

that have failed and have known construction completion and failure dates provide direct information about their known lifespan. Dams that have not failed and have known construction completion dates provide information that the lifespan of the dam is at least equal to the difference between the year for which the most recent information is available (i.e. 2006 in this paper) and the construction completion year (i.e. they provide lowerbound observations). However, as described above, the NPDP and NID databases are missing construction completion dates for some dams. For failed dams missing this information, it is known that the lifespan of the dam is no more than years, where is equal to the year in which the dam failure event occurred minus a reference year that bounds the potential year of construction (assumed to be 1900 in this paper). We refer to these as upperbound observations to indicate that the lifespan of the dam is less than or equal to years. For dams that have not failed and for which we do not have the construction year, the observations are assumed to be bounded at the lower-end by zero years.

To compute posterior distributions using this model in conjunction with the censored observations, we utilize the WinBUGS software (Lunn et al, 2000), which uses Markov chain Monte Carlo (MCMC) methods to compute posterior distributions. Table 6 provides the posterior means (and 5th and 95th percentiles) for embankment and concrete dams when considering all dam failure events. The parameters of the Gamma prior distribution are once again and . For comparison, Table 6 also provides the values obtained using the Poisson-Gamma model as well as the point estimate (with assumed values for missing data). In general, it is seen that the results obtained when considering observations as censored are fairly consistent with the results obtained by assuming values for missing data.

Table 6. Posterior mean dam failure frequencies using exponential-Gamma model with censoring and Poisson-Gamma model as well as point estimate

	Embankment Dams			Concrete Dams		
	Exponential	**Poisson**	**Point Estimate**	**Exponential**	**Poisson**	**Point Estimate**
μ_2 (or pt est.)	2.87E-4	2.76E-4	2.76E-4	2.40E-4	2.49E-4	2.46E-4
5th	2.46E-4	2.34E-4	–	1.54E-4	1.66E-4	–
95th	3.33E-4	3.20E-4	–	3.37E-4	3.44E-4	–
MC error	4.60E-7	–	–	9.01E-7	–	–

In general, the results of the Bayesian assessments are consistent with the point estimates. When working with the larger datasets, the effects of the prior distribution parameter assumptions are minimal. However, when the data is parsed into smaller subsets, the influence of the prior becomes more significant. Overall, all estimates are in the range of 1E-4/dam-year regardless of the method used to derive the estimate of dam failure frequency.

4. CONCLUSION

Sensitivity studies on the dam failure frequency for US large dams were performed in this study to evaluate the impact of various attributes and sources of uncertainty when using historical dam information. Bayesian analysis tools were also used for the derivation of posterior uncertainty distributions that include subjective information such as data quality and expert judgment considerations. The extent of the variation in the commonly derived point estimate was documented and discussed for a number of categories and assumptions. It is stressed that the goal of this work is solely to develop generic dam failure frequencies based on information contained in databases and readily available historical records. As such, it is not a replacement for more detailed probabilistic assessments and/or dam-specific studies (which could yield higher or lower failure frequency estimates). Although historical dam failure information can provide useful qualitative insights on the general performance and failure modes for certain categories, its applicability to specific dams has to be assessed to establish sufficient technical bases for decision-making. This is due to the variability in site-specific characteristics (e.g., hydrologic, geologic, and operational) and the potential contributions of site-specific failure modes. Despite the limitations of working with data-driven estimates of dam failure frequencies, this work provides insights into the variability and subjectivity of the estimates and their sensitivity to input information (particularly historical dam failure accounts). The series of assessments performed in this paper generally support dam failure frequencies in the range of 1E-4/dam-year, though it is shown that variability exists based on the assumptions utilized relative to parsing data and addressing missing observations.

Acknowledgements

The authors would like to thank Sunil Weerakkody, Branch Chief, PRA Operational Support Branch, Division of Risk Assessment, Office of Nuclear Reactor Regulation; and Benjamin Beasley, Branch Chief, Operational Experience and Generic Issues Branch, Division of Risk Assessment, Office of Nuclear Regulatory Research, for their support and feedback during the development of this paper.

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[1] This paper was prepared, in part, by employees of the U.S. Nuclear Regulatory Commission on his or her own time apart from his or her regular duties. NRC has neither approved nor disapproved its technical content.

From: Criscione, Lawrence
Sent: Tuesday, October 02, 2012 3:31 PM
To: Ake, Jon
Subject: FW: GI 199 and Mineral, VA earthquake

Jon,

Can I get the slides and poster from the Mineral, VA earthquake RES Seminar (#102)?

Thanks,
Larry

From: McGee, Jim (HSGAC) [mailto:Jim_McGee@hsgac.senate.gov]
Sent: Tuesday, October 02, 2012 9:50 AM
To: Criscione, Lawrence
Subject: RE: GI 199 and Mineral, VA earthquake

Thanks. I couldn't get any of these links to work. I highlighted the topics that appear germane. Will try to track down those slides or DVD's, unless you have them.

Jim McGee
Professional Staff/Investigations
Senate Committee on Homeland Security and Governmental Affairs
202-224-2627

From: Criscione, Lawrence [mailto:Lawrence.Criscione@nrc.gov]
Sent: Monday, October 01, 2012 8:00 PM
To: McGee, Jim (HSGAC)
Subject: FW: GI 199 and Mineral, VA earthquake

Jim,

I meant to send this to you a couple of weeks ago, but accidently sent it to Jon Ake, Marty Stutzke and Ben Beasley (I had "temporarily" put their names in the "To" line to copy down their email addresses).

Anyways, at the very bottom of this email is a list of RES seminars. You might find #99, #102 and #112 interesting pertaining to dam failures, earthquakes and paleofloods.

Larry Criscione

From: Criscione, Lawrence
Sent: Friday, September 21, 2012 2:38 PM
To: Ake, Jon; Beasley, Benjamin; Stutzke, Martin
Subject: GI 199 and Mineral, VA earthquake

Jim,

Below is a list of Seminars given to the Office of Research.

B/29

One of them was on the Mineral, VA Earthquake of August 23, 2011. It was given by Dr. Leith of the USGS. The NRC contact was Jon.Ake@nrc.gov, 301-251-7626. He could probably send you the seminar material.

Marty Stutzke (martin.stutzke@nrc.gov, 301-251-7614) was one of the chief scientists on GI 199 (the earthquake Generic Issue) if you have any questions about what was looked at and what the conclusions were. Ben Beasley (Benjamin.Beasley@nrc.gov, 301-251-7676) should be able to either tell you what the status of it is or direct you to a contact in the office assigned to implement it.

Larry

From: Perkins, Richard
Sent: Friday, September 21, 2012 2:19 PM
To: Criscione, Lawrence
Subject: RE: Info

I found this, but there are no slides available. It was recorded.

12/14/10
Success and Failure: A Paradoxical Relationship
Prof. Henry Petroski
Duke University
Nathan Siu
DRA

Here's a copy of the RES Seminar Table through 2009 (if you can read this)

Seminar #114	09/19/12	Long-Term Research Program Overview	Robert Tregoning, Ph.D Michael B. Rubin, LTRP PM David W. Stroup, P.E. Jacob Philip, P.E	
Seminar #113	08/08/12	The NRC and Social Media – What We're Doing, Why We're Doing It, and How You Can Get Involved [View Poster]	Holly Harrington – Office of Public Affairs	**No DVD available for this seminar**
Seminar #112	07/10/12	Dam Failure, Nuclear Power Plant Flooding, and the Outlook for Generic Issue 204 [View Slide 1] [View Slide 2] [View Slide 3]	Richard Perkins & Jacob Philip RES/DRA	DVD
Seminar # 111	06/19/12	Training Range Environmental Evaluation and Characterization System (TREECS) Applications - [View Slide]	Billy E. Johnson, U.S. Army Corps of Engineers; Mark S. Dortch, MSD Inc., and Boris Faybishenko, Lawrence Berkeley National Laboratory Sponsored by Tom Nicholson, DRA/RES	**No DVD available for this seminar**
Seminar # 110	06/07/12	ASR Degradation of Concrete affecting Nuclear Power Plant Structures - [View Slide] [Presentation 1][Presentation 2]	Jason Weiss, Purdue University; Kenneth Snyder, NIST; and Fahim Sadek, NIST. Sponsored by Jacob Philip, ETB/DRA/RES	**No DVD available for this seminar**

Seminar # 109	06/06/12	Live webcast of Zirconium Fire Experiment on PWR Spent Fuel Pool Complete Loss of Coolant Accident	Ghani Zigh, RES/DSA	**No DVD available for this seminar**
Seminar #108	6/4/2012	State-of-the-Art Reactor Consequence Analyses (SOCRCA) RES Seminar - [View Slides]	Richard Chang, Jonathan Barr & Jason Schaperow (SOARCA Team)	DVD
Seminar #107	5/21/2012	Health Physics Brown Bag 2012 Series: US Federal Agency Response to Fukushima Incident	Dr. Luis Benevides from NAVY, sponsored by Gladys Figueroa, RES/DSA/RPB	DVD
Seminar #106	4/17/2012	Multi-Scale Assessment of Prediction Uncertainty in Coupled Reactive Transport Models Curtis Flyer Announcement	Gary P. Curtis(USGS) Ming Ye(FSU) Philip D. Meyer(PNNL) Steve Yabusaki(PNNL)	**No DVD available for this seminar**
Seminar #105	3/27/2012	Development of the Extremely Low Probability of Rupture (xLPR) Assessment Tool View Slides	Dave Rudland, RES/DE	DVD
Seminar #104	2/13/12	The NRC's Simulator-based Human Performance Testing Program –| Advancing Model Validity with Data	Amy D'Agostino & James Chang, RES/DRA	DVD
Seminar #103	1/25/12	Computational Fluid Dynamics for Nuclear Safety Analysis	Christopher Boyd RES/DSA	DVD
Seminar #102	12/13/11	The Mineral, VA Earthquake of August 23, 2011 [view poster] [view presentation]	Dr. William Leith, U.S. Geological Survey / Jon Ake, RES/DE/SGSEB	**No DVD available for this seminar**
Seminar #101	11/01/11	Lessons Learned from Investigations of Oil and Chemical Industry Events [View Presentation]	**Mark Griffon** Board Member U.S. Chemical Safety and Hazard Investigation Board	DVD
Seminar #100	10/05/11	Investigations of Zirconium Fires during Spent Fuel Pool Loss of Coolant Accidents	Ghani Zigh RES/DSA	DVD
Seminar #99	08/23/11	The Value of Paleoflood Information when Estimating Flood Risk [Slides] [Background Info 1] [Background Info 2]	Dr. Timothy Cohn, U.S. Geological Survey Thomas Nicholson DRA	DVD
Seminar #98	07/11/11	Research Topics and Experiences on Safety Assessment Methods of Radioactive Materials (RAM) Containers German Federal Institute for Materials Research and Testing (BAM), Berlin, Germany	Dr. Frank Wille, "Requirements for Transport Packages after Interim Storage" Dr. Karsten Muller, "Recent Activities on Experimental Package and Component Testing at BAM" Mr. Germar Eisenacher "Impact Limiter Modeling - An Approach for a Finite Element Material Mode l for Wood" Dr. Jose Pires,	DVD

			RES/DE/SGSEB	
Seminar #97	06/21/11	Assuring Durable Concrete: Chemical Degradation Processes and Modeling Service Life - [View Slides]	Dr. Kenneth A. Snyder National Institute of Standards and Technology Jacob Philip, DRA/ETB	DVD
Seminar #96	04/26/11	Chernobyl 25th Anniversary 1. Mike Weber's Introduction 2. Dr. Brian Sheron's Presentation 3. Dr. Frank Congel's Presentation 4. Dr. John Boice's Presentation	Dr. Brian Sheron, RES Frank Congel, Former NRC Employee Dr. John Boice, IEI	DVD
Seminar #95	04/19/11	A Probabilistic Risk Assessment View of Consequential Steam Generator Tube Rupture [View Slides]	Selim Sancaktar, RES/DRA/PRAB	No DVD available for this seminar
Seminar #94	02/22/11	Radiation Epidemiology Past Studies and Future Opportunities [View Poster]	Dr. John Boice, Medicine at Vanderbilt University School of Medicine and Scientific Director of the International Epidemiology Institute (IEI) / Stephanie Bush-Goddard, RES/DSA/HEB	DVD
Seminar #93	02/15/11	American Society of Mechanical Engineers [View Slides]	Rick Swayne, ASME Carol Moyer, RES/DE/CMB	DVD
Seminar #92	01/20/11	Weather and Hydrologic Extremes in a Non-stationary Climate with Implications for Managing Critical Infrastructures and Key Resources Presentation Slides	Dr. Auroop Ganguly(ORNL) Joe Kanney (RES/DRA/ETB) Tom Nicholson (RES/DRA)	DVD
Seminar #91	01/12/11	Field and Modeling Studies to Assess Radionuclide Transport in the Subsurface	Dr. Andy Ward, Senior Research Scientist, Pacific Northwest National Laboratory Tom Nicholson (RES/DRA)	DVD
Seminar #90	12/14/10	Success and Failure: A Paradoxical Relationship	Prof. Henry Petroski Duke University Nathan Siu DRA	DVD
Seminar #89	11/10/2010	Zirconium in the Nuclear Industry - [View Slides]	Patrick Raynaud DSA / FSTB	DVD
Seminar #88	10/20/2010	ASME Codes and Standards: History, Content, Development, and Endorsement	Carol Moyer & Gary Stevens, RES/DE	No DVD available for this seminar
Seminar #87	09/23/2010	Seismic-related Generic Issue (GI-199) Safety /Risk Assessment Methods and Results - [Detail] [view Slides]	Marty Stutzke (RES/DRA) Jon Ake (RES/DE/SGSEB) Lauren Killian (RES/DRA/OEGIB)	DVD

Seminar #86	07/23/2010	Risk and Uncertainty in Dam Safety [View Detail 1] [View Detail 2] [View Detail 3]	Professor Gregory B. Baecher University of Maryland, College Park/ Thomas Nicholson, RES/DRA	No DVD available for this seminar
Seminar #85	07/19/2010	The Evolution of Radiation Protection: From Erythema to Genetic Risks to Risks of Cancer [View Slides]	Charles Meinhold / Terry Brock, RES/DSA/HEB	DVD
Seminar #84	07/12/2010	Advanced Control Room Human Factors [View Slides]	Jing Xing & Stephen Fiegen RES/ DRA/HFRB	No DVD available for this seminar
Seminar #83	06/17/2010	Severe Accident Response for Steam Generator Tubing [View Slides]	Saurin Majumdar, ANL	No DVD available for this seminar
Seminar #82	06/17/2010	Lean Six Sigma on Internal Contracting	Mary Muessle, PMDA	No DVD available for this seminar
Seminar #81	05/13/2010	Overview of the Electric, Power Research Institute Organizational and Program Structure and its Relationship to the Industry's Materials Initiative	David Modeen / hosted by DE, David Rudland	DVD
Seminar #80	04/29/2010	Lessons Learned in Detecting, Monitoring, Modeling, and Remediating Radioactive Groundwater Contamination at Brookhaven National Laboratory; - [Handout]	Dr. William Gunther, Dr. Mike Hauptmann, and Dr. Terry Sullivan / hosted by DRA Thomas Nicholson	DVD
Seminar #79	04/15/2010	Human-Rating of Space Systems - [View Slides]	Mr. Bryan O'Connor, Chief, Office of Safety and Mission Assurance, NASA	No DVD available for this seminar
Seminar #78	03/26/2010	Browns Ferry Seminar	Jack Lewis & Felix Gonzalez, DRA Dr.	DVD
Seminar #77	03/25/2010	Fundamentals of Structural Dynamics - [View Slides]	Dr. Abhinav Gupta	No DVD available for this seminar
Seminar #76	02/23/2010	Recent United States Geological Survey (USGS) Research on Seismic Hazards and Ground Motions in the Eastern U.S.	Dr. Paul Spudich, USGS colleagues & Jon Ake, DE	DVD
Seminar #75	01/21/2010	Improving the State-of-the-Art in Severe Accident Analysis [View Slides]	Richard Lee	No DVD available for this seminar
Seminar #74	01/05/2010	State of the Practice of Seismic Hazard Analysis: From the Good to the Bad	Dr. Norman Abrahamson	DVD
Seminar #73	12/10/2009	Experimental Basis for Modification of Cladding Embrittlement Criteria	Michelle Flanagan	DVD
Seminar #72	11/30/2009	Pressurized Thermal Shock	Mark Kirk	DVD
Seminar #71	10/26/2009	Health Effects as a Function of Dose Rate Delivered [View Slides]	Dr. Jacquelyn Yanch, MIT	No DVD available for this seminar
Seminar #70	09/11/2009	THE COLLAPSE OF WORLD TRADE CENTER 7- THE FORGOTTEN BUILDING OF 9/11	Dr. Therese McAllister National Institute of Standards and Technology (NIST)	DVD
Seminar #69	09/08/2009	Geophysical Surveys Supporting Analysis of Contaminant Transport through Fractures	Dr. John Williams, USGS [View Bio]	DVD

		[View Slides]		
Seminar #68	08/24/2009	Safety and Regulatory Perspectives on Protective Coatings for Nuclear Facilities [View Slides]	Bruce Lin, RES/DE/MEEB	DVD
Seminar #67	07/21/2009	Performance of Engineered Covers for Waste Disposal with Implications for PA [View Slides]	Professor Craig Benson , University of Wisconsin [View Bio]	DVD
Seminar #66	05/11/2009	The Spent Nuclear Fuel Burnup Credit Research	John Wagner, ORNL	DVD
Seminar #65	05/07/2009	2009 William B. Joyner Memorial Lecture, entitled "Earthquakes, Seismic Hazard, and Performance-Based Design"	Dr. Robin McGuire	DVD
Seminar #64	04/24/2009	Modeling Uranium Behavior during In-Situ Bioremediation	Steven Yabusaki, Pacific Northwest National Laboratory	No DVD available for this seminar
Seminar #63	04/22/2009	Screening Methods for Estimating Storm-Surge Levels and Severity	Dr. Donald Resio US Army Corps of Engineers	DVD
Seminar #62	03/25/2009	The Accident at Three Mile Island – 30th Anniversary A Look Back: Preserving the Institutional Memory March 25, 2009 [Details] - [Poster] - [View Presentations]	Brian Sheron Edward Frederick Harold Denton Gary Holahan	Please Contact Amy Bonaccorso
Seminar #61	02/10/2009	Perspectives on HTGR Safety and Design Considerations [View Slides]	Dr. Kenneth Stroh (VP, Sentech Inc. and Retired Guest Scientist, LANL)	DVD
Seminar #60	01/21/2009	Modeling of the Dynamics of the Nucleation and Growth of Cracks Initiated due to Stress in Materials	Dr. Appajosula Rao, Material Engineer, DE/CMB	DVD

From: Criscione, Lawrence
Sent: Friday, September 21, 2012 3:09 PM
To: Perkins, Richard
Subject: RE: Info

It was really about how engineering lessons learned are forgotten over time, but the guy giving it used bridge design as his basis. It was in 2010 or 2011. I'm not certain it was a RES seminar. It was in the same auditorium as our seminars and I know I went to it with Kauffman so I assume it was a seminar. Do other offices do seminars?

From: Perkins, Richard
Sent: Friday, September 21, 2012 1:53 PM
To: Criscione, Lawrence
Subject: Info

Energy Daily did a front page story today on FERC standing up a new office. You should take a look at that if you haven't.

I just sent the info on paleofloods (previous e-mail). Let me know if you don't get it.

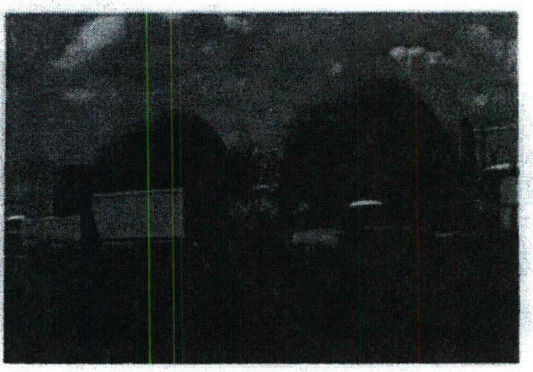
I don't recall the brief about bridge failure. Anything to help me find it? Didn't see it in the RES seminar list (or I didn't recognize it as bridge failure related).

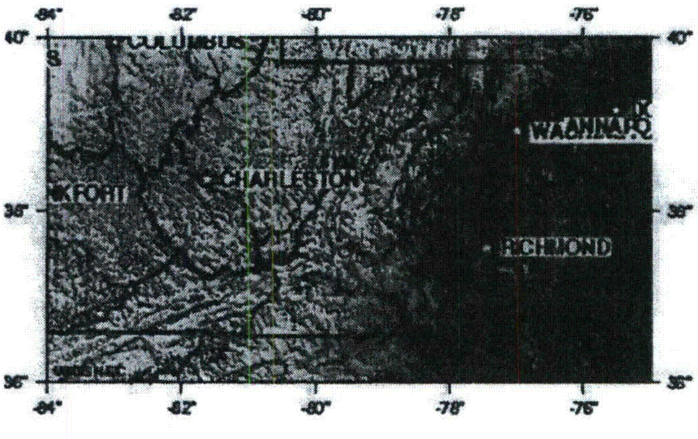
Richard H. Perkins, P.E.
Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Division of Risk Analysis
Operating Experience and Generic Issues Branch
Phone - 301/251-7479

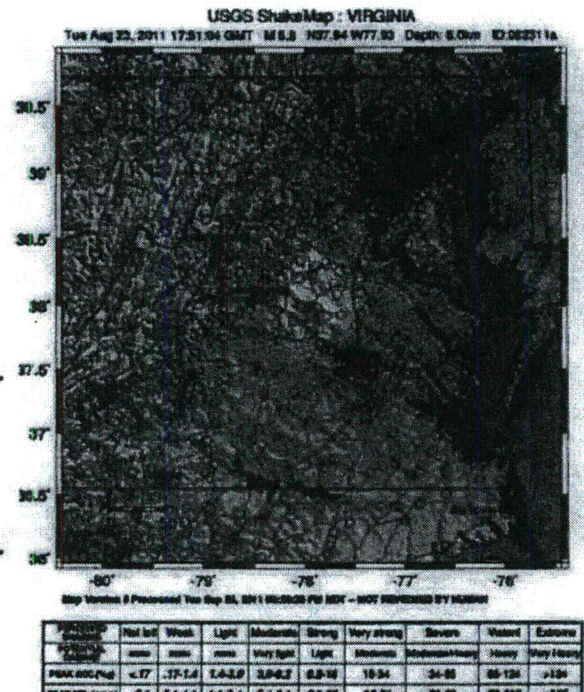
U.S.NRC

The Mineral, VA Earthquake of August 23, 2011

Presenter: Dr. William Leith, U.S. Geological Survey
Tuesday, December 13, 2011
10:00 A.M. to 12:00 P.M.
TWFN Auditorium







USGS
science for a changing world

n hrp

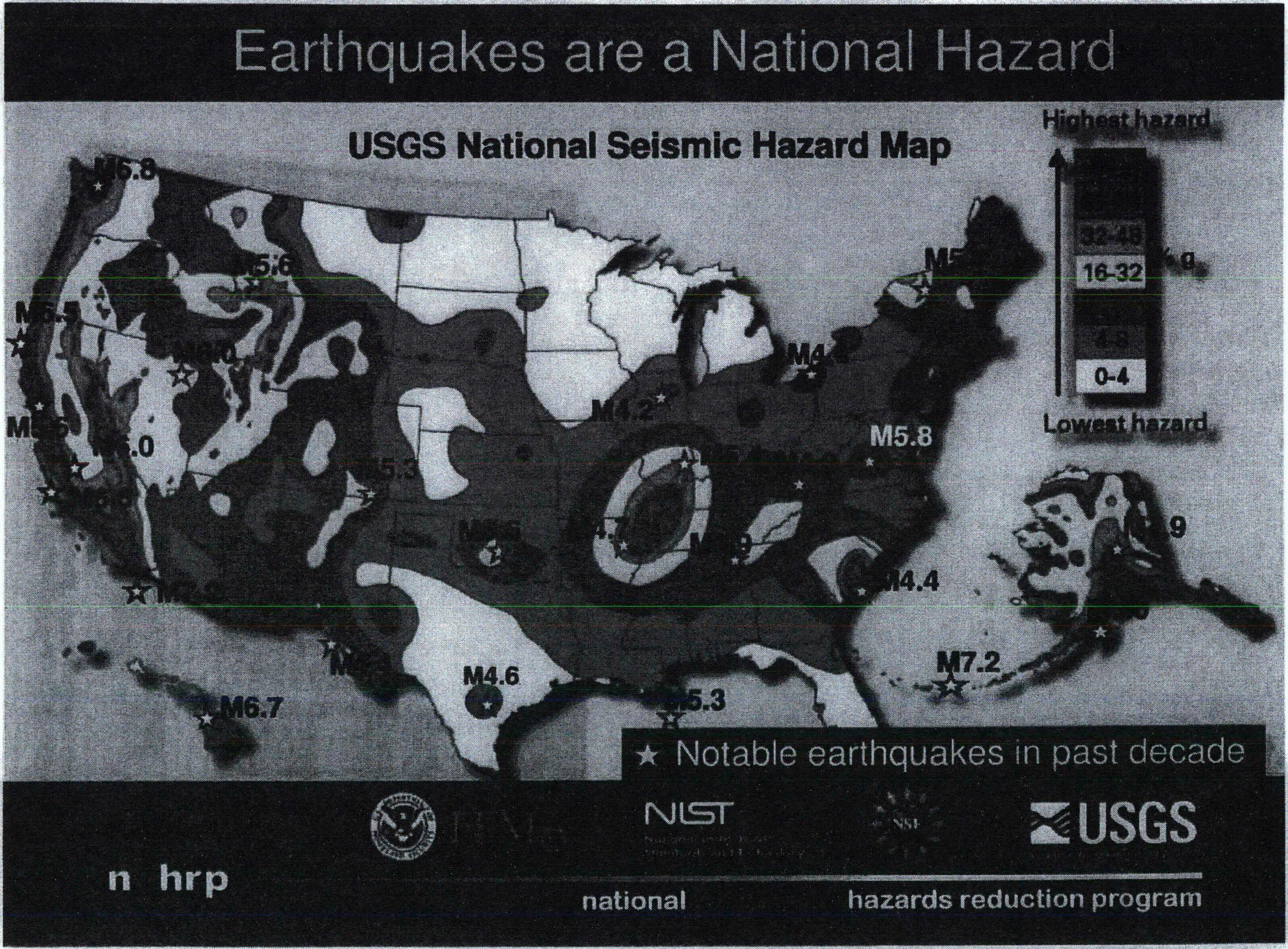
The August 2011 Virginia Earthquake

Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Rockville, MD

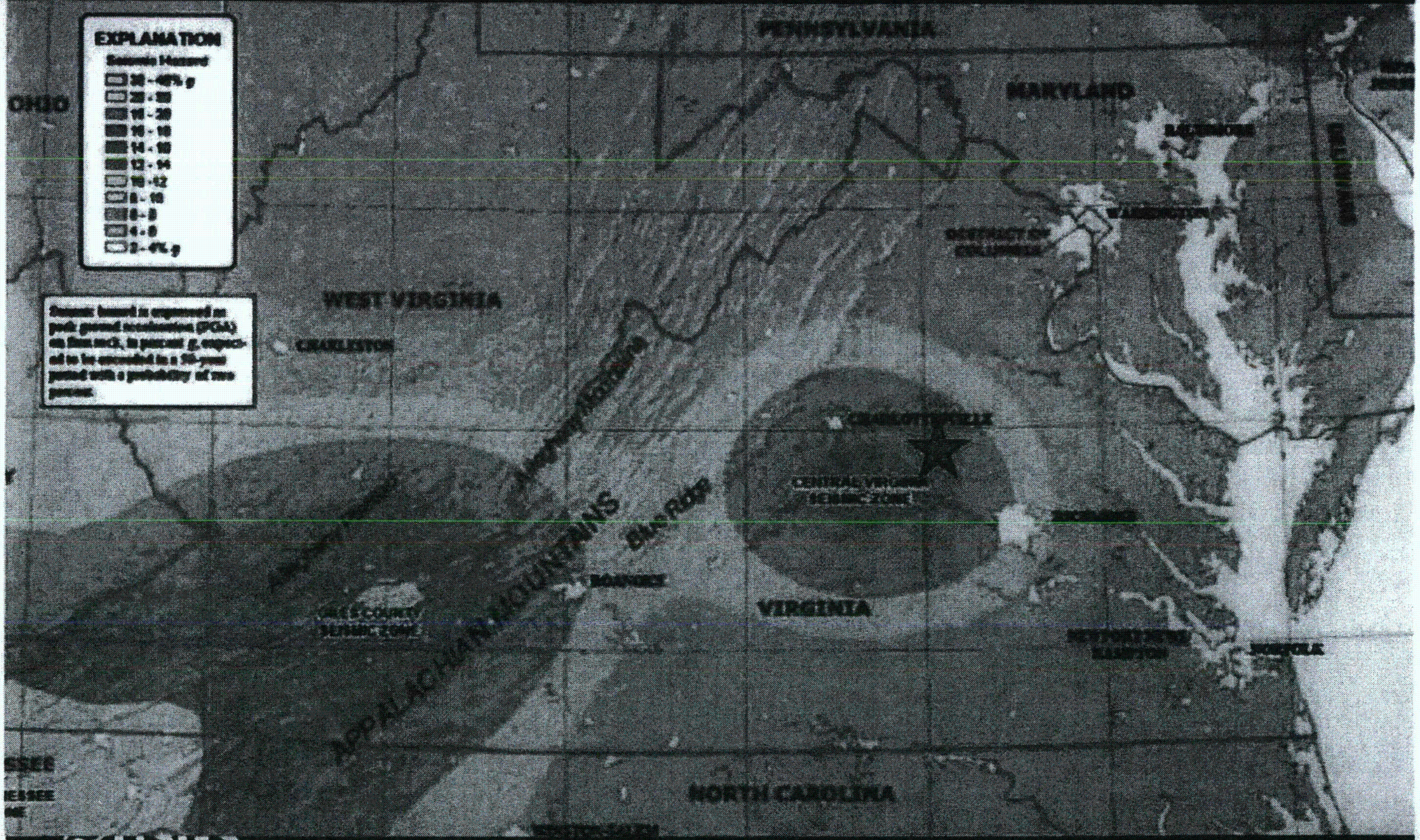
Bill Leith
Coordinator, Advanced National Seismic System
U.S. Geological Survey

December 13, 2011

USGS


Earthquakes are a National Hazard
USGS National Seismic Hazard Map
Highest hazard
32-48
16-32
% g
4-8
0-4
Lowest hazard
M6.8
M5.5
M4.2
M4.4
M5.8
M5.3
M4.4
M4.6
M7.2
M6.7
★ Notable earthquakes in past decade
NIST
USGS
n hrp
national
hazards reduction program

Earthquake hazard in the Mid-Atlantic Region



USGS

Virginia Earthquake of August 23, 2011

Largest earthquake in Virginia In 114 years

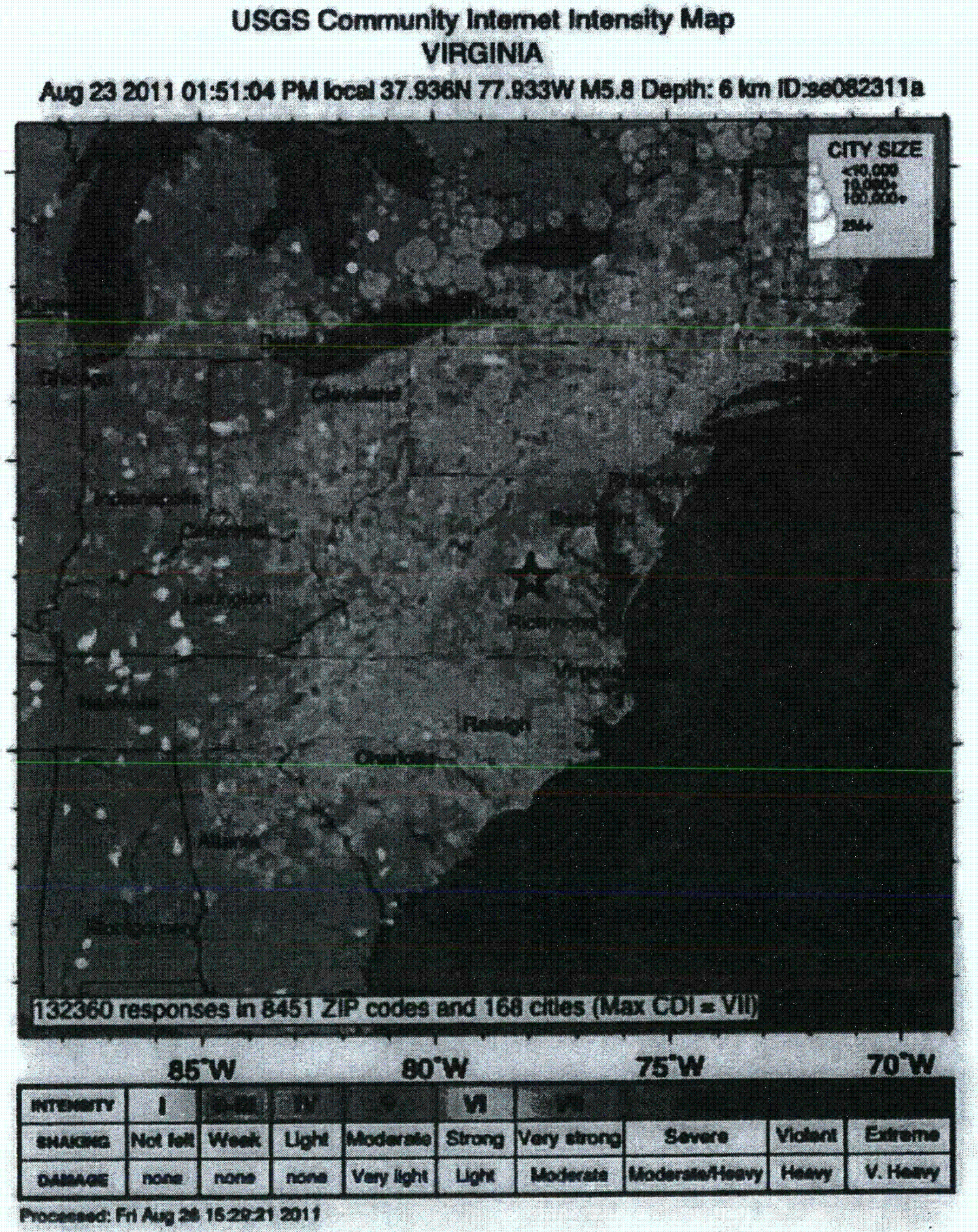
Centered in low-population area between Richmond and Charlottesville

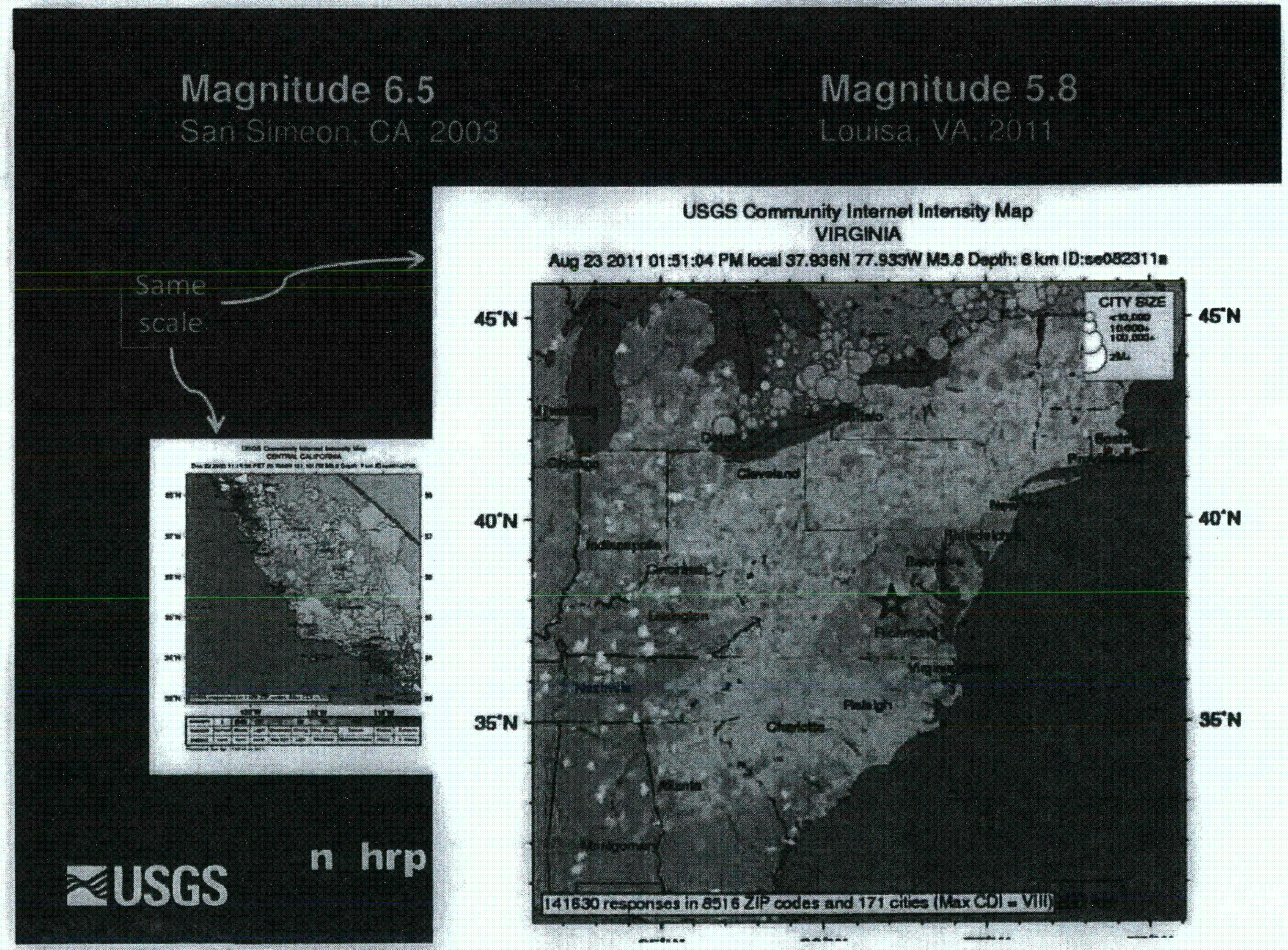
No fatalities
Estimated Damage >$100M

Felt from Florida to Maine to Missouri (>140,000 reports)

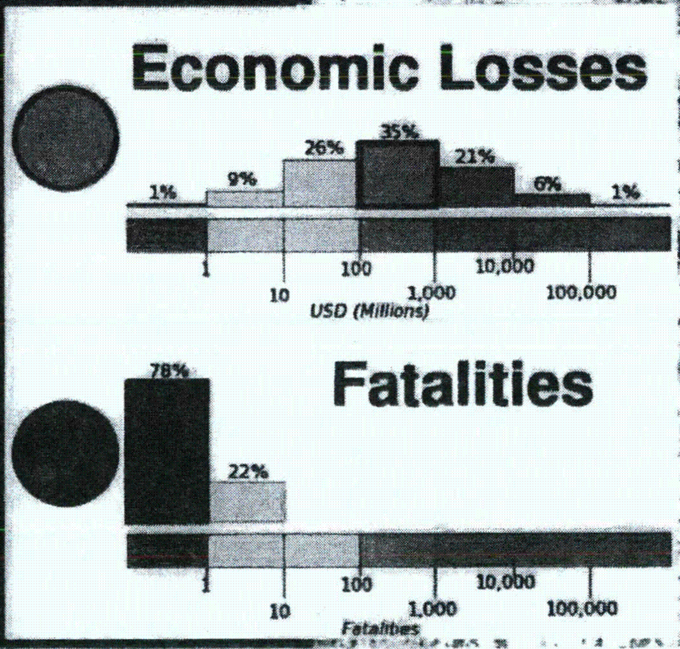
Caused evacuations across Washington DC metropolitan area, and damage to historic structures.

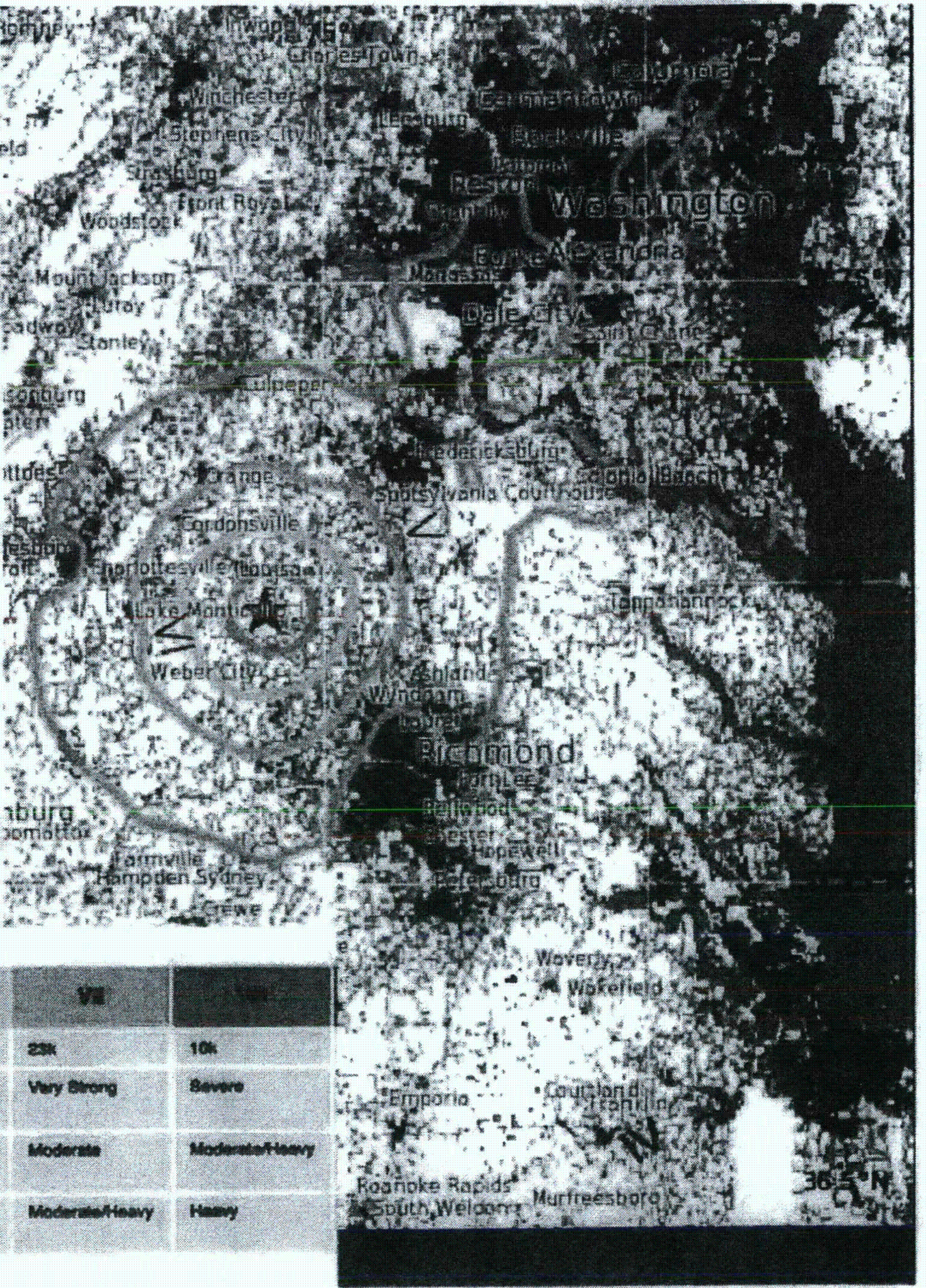
USGS n hrp




Magnitude 6.5
San Simeon, CA, 2003
Magnitude 5.8
Louisa, VA, 2011
Same scale
USGS Community Internet Intensity Map
CENTRAL CALIFORNIA
USGS Community Internet Intensity Map
VIRGINIA
Aug 23 2011 01:51:04 PM local 37.936N 77.933W M5.8 Depth: 6 km ID:se082311a
45°N
40°N
35°N
CITY SIZE
Chicago
Cleveland
Indianapolis
Lexington
Richmond
Nashville
Raleigh
Charlotte
Atlanta
Montgomery
141630 responses in 8516 ZIP codes and 171 cities (Max CDI = VIII)
USGS
n hrp

PAGER rapid loss estimates



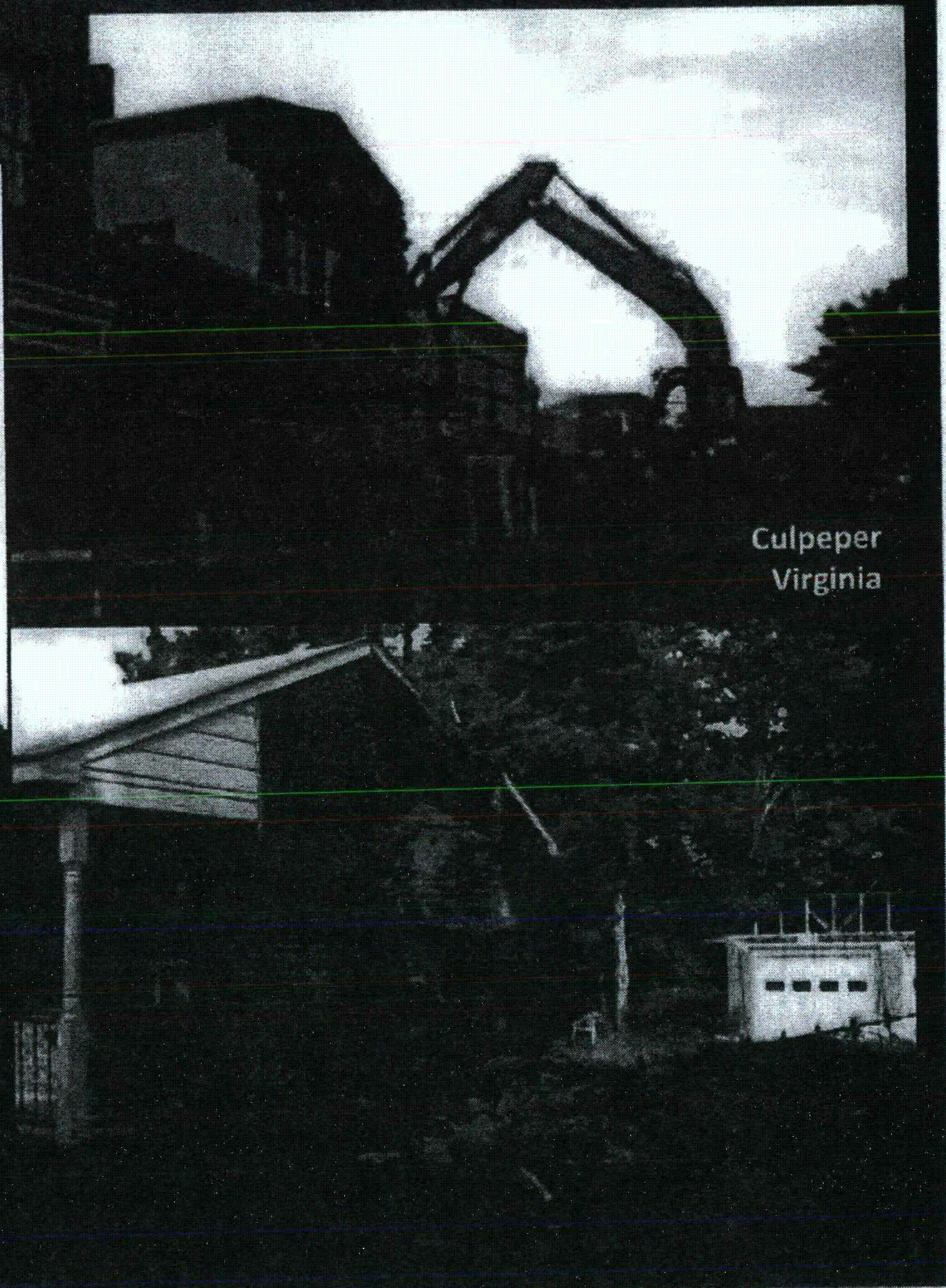


Estimated Population Exposed to Earthquake Shaking

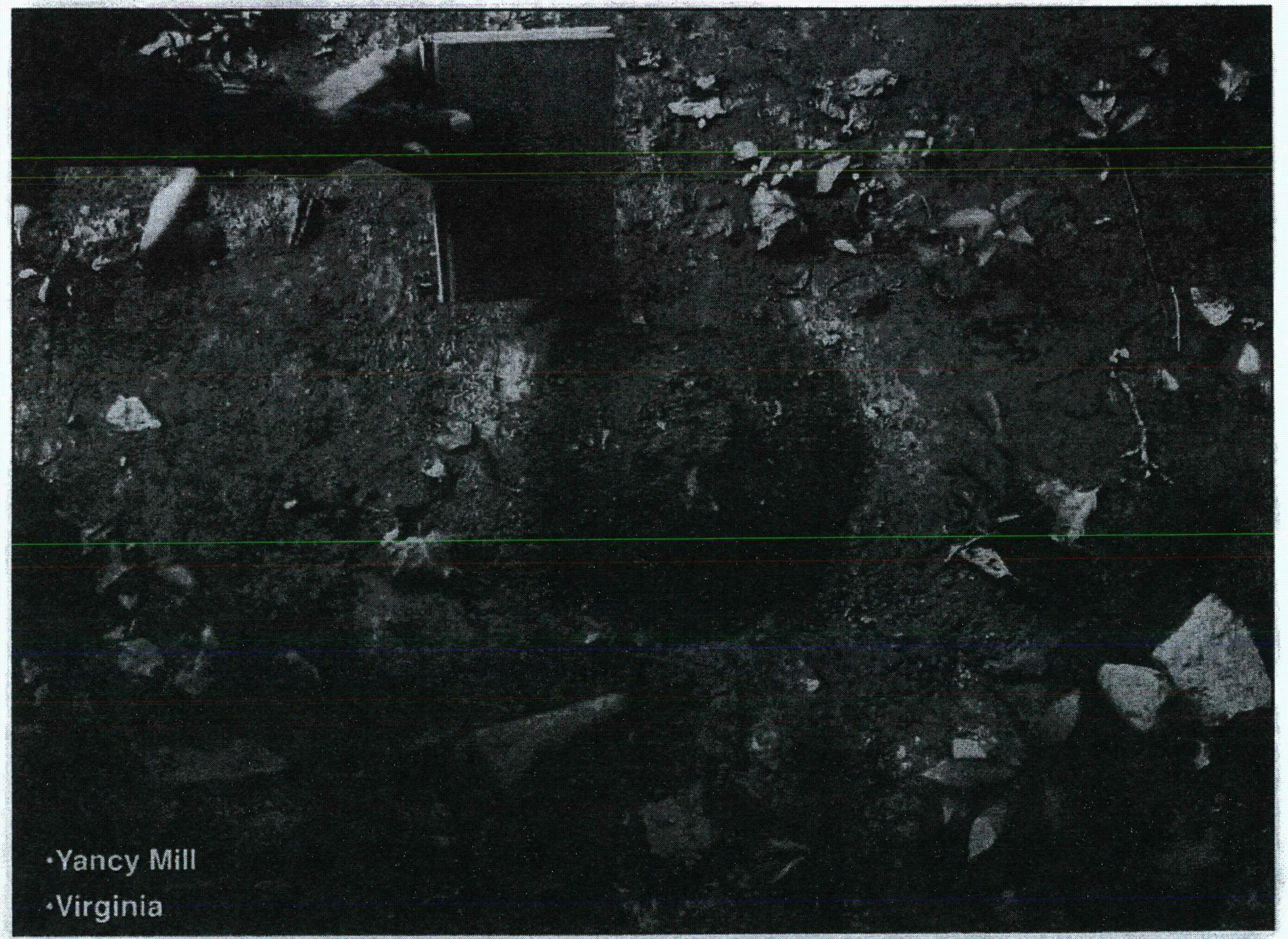
Estimated Modified Mercalli Intensity		I	II-III	IV	V	VI	VII	VIII
Est. Population Exposure		--*	19k*	9,627k*	2,295k	79k	23k	10k
Perceived Shaking		Not Felt	Weak	Light	Moderate	Strong	Very Strong	Severe
Potential Structure Damage	Resistant	none	none	none	V. Light	Light	Moderate	Moderate/Heavy
	Vulnerable	none	none	none	Light	Moderate	Moderate/Heavy	Heavy

*Estimated exposure only includes population within calculated shake map area

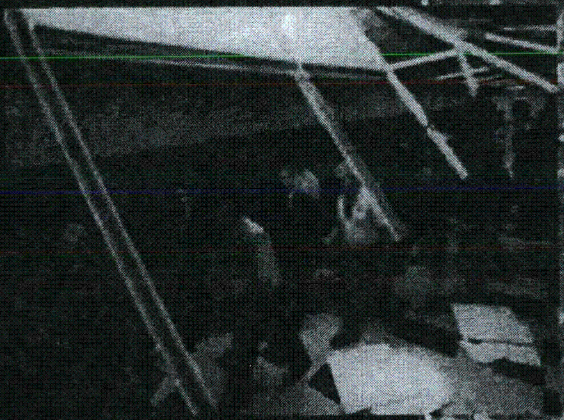
Damage in Epicentral Area

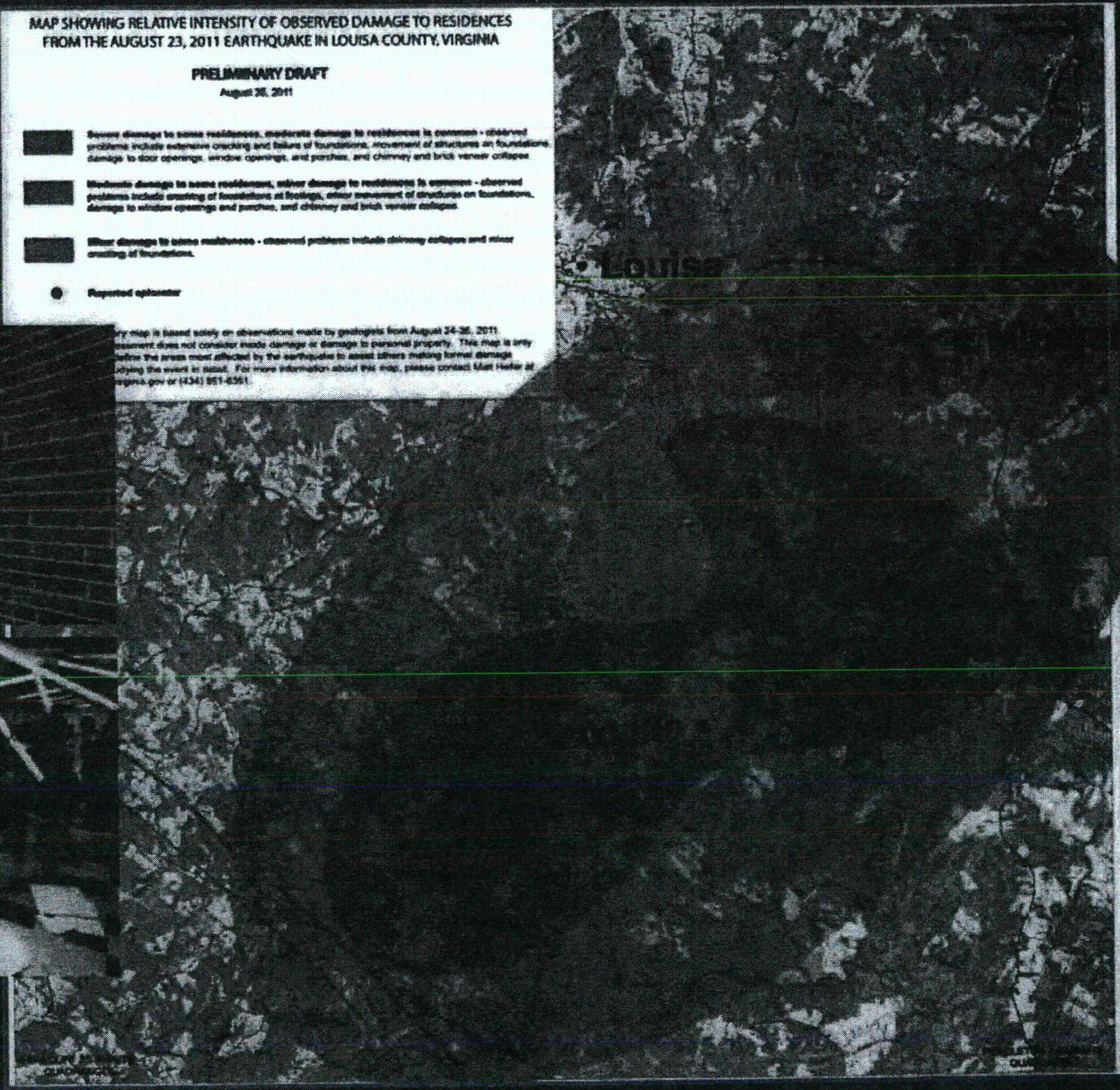


Scant Evidence of Liquefaction

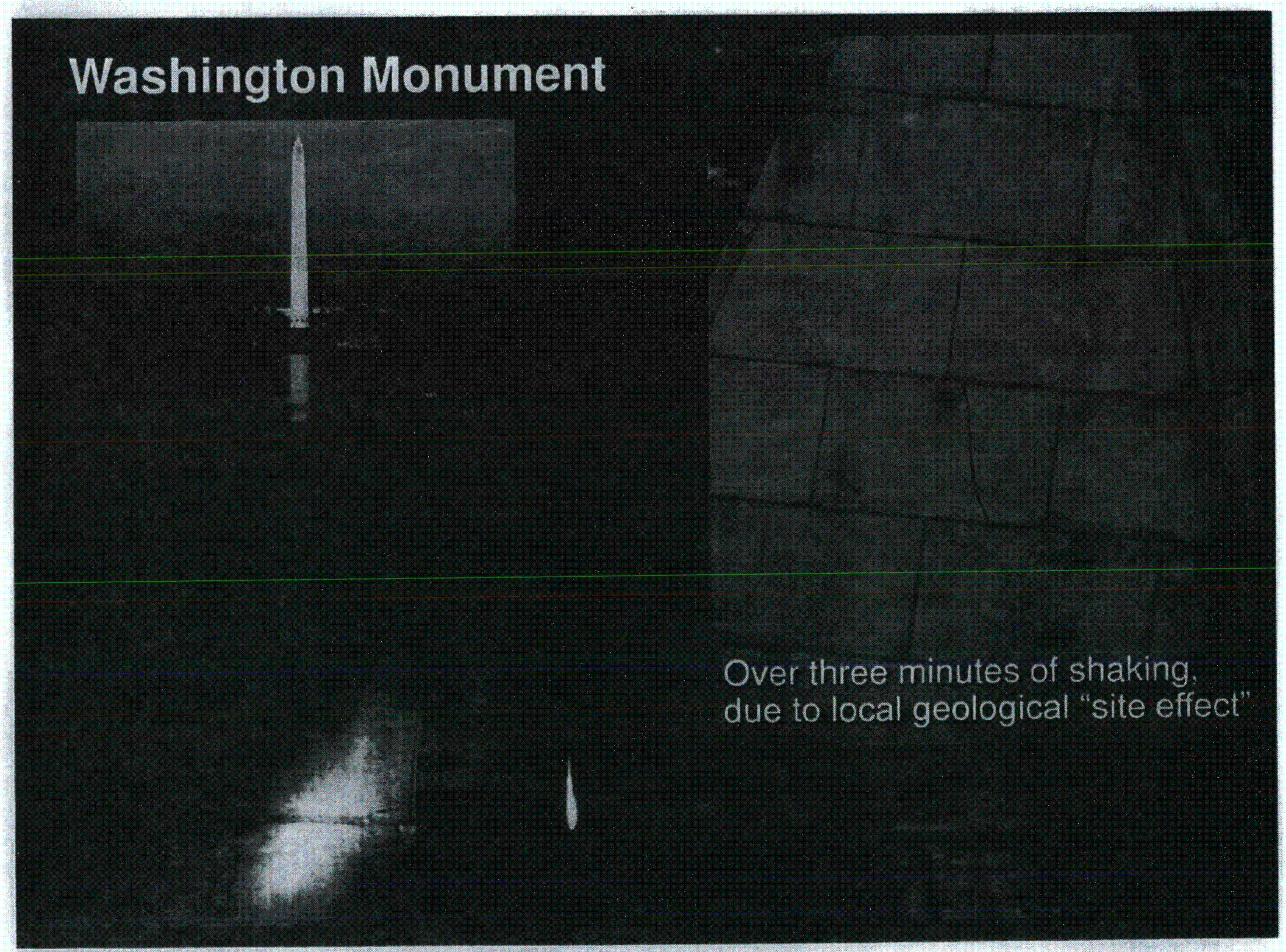


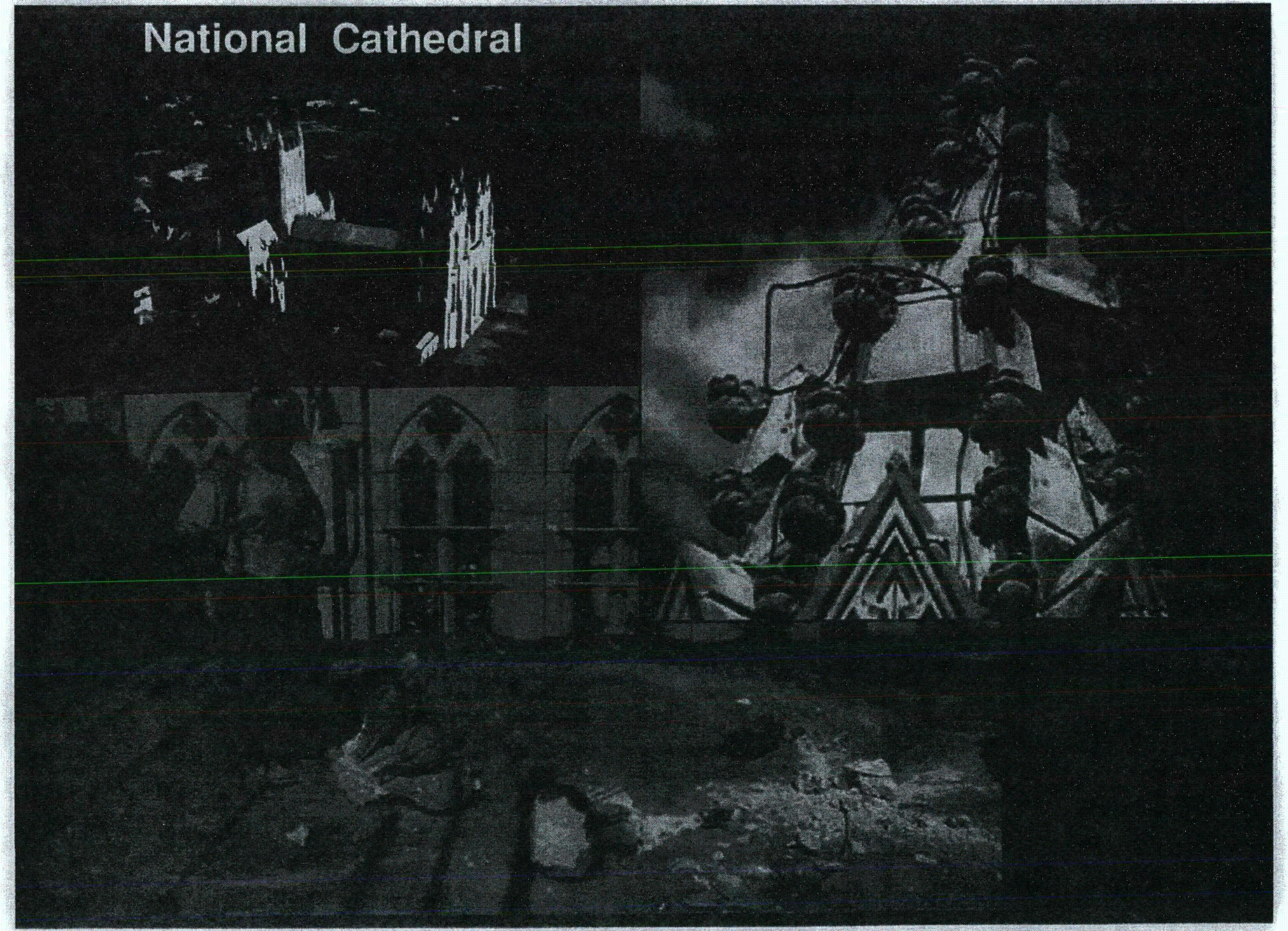
Areas of greatest damage to buildings

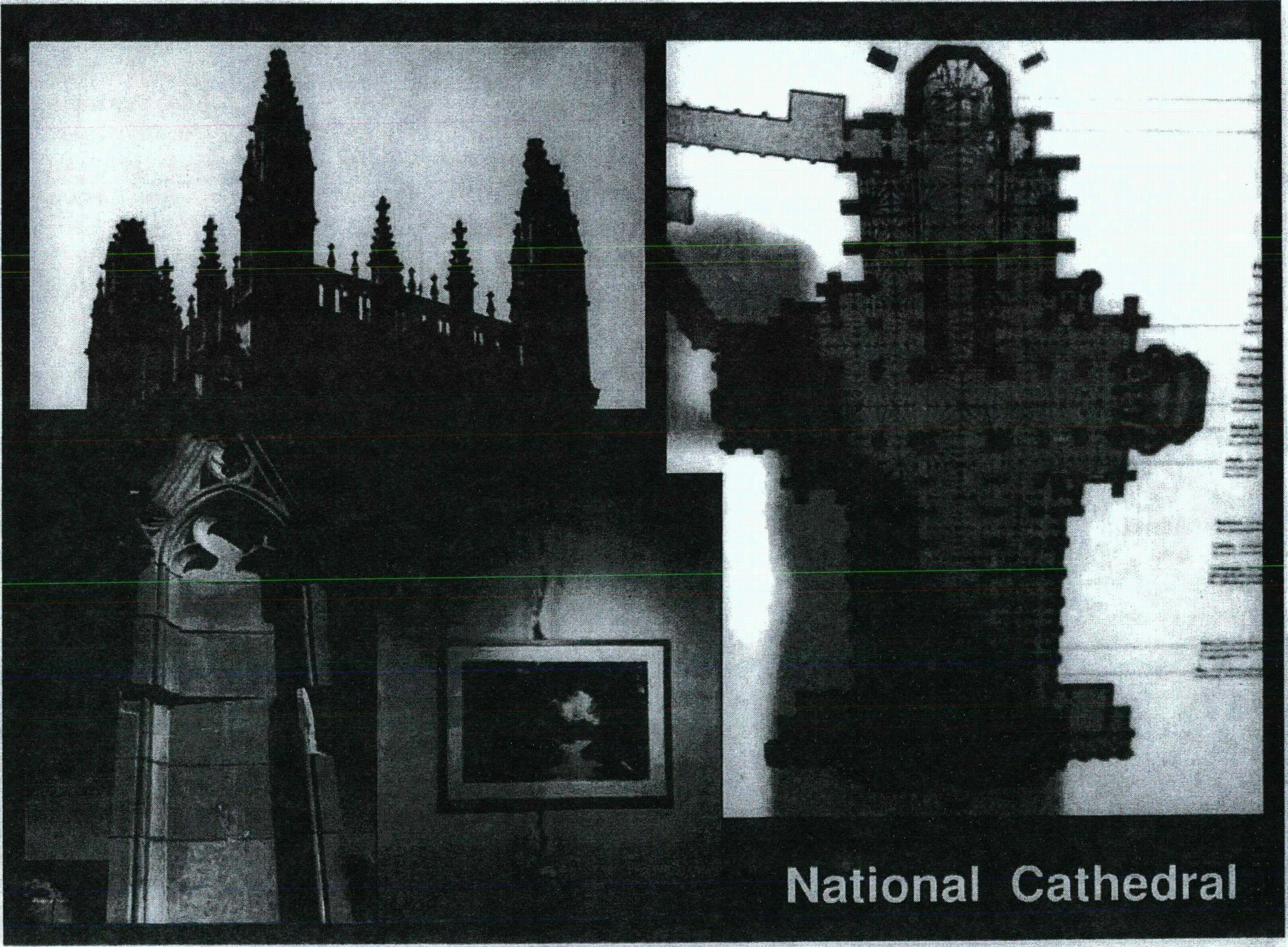




USGS


Washington Monument
Over three minutes of shaking,
due to local geological "site effect"

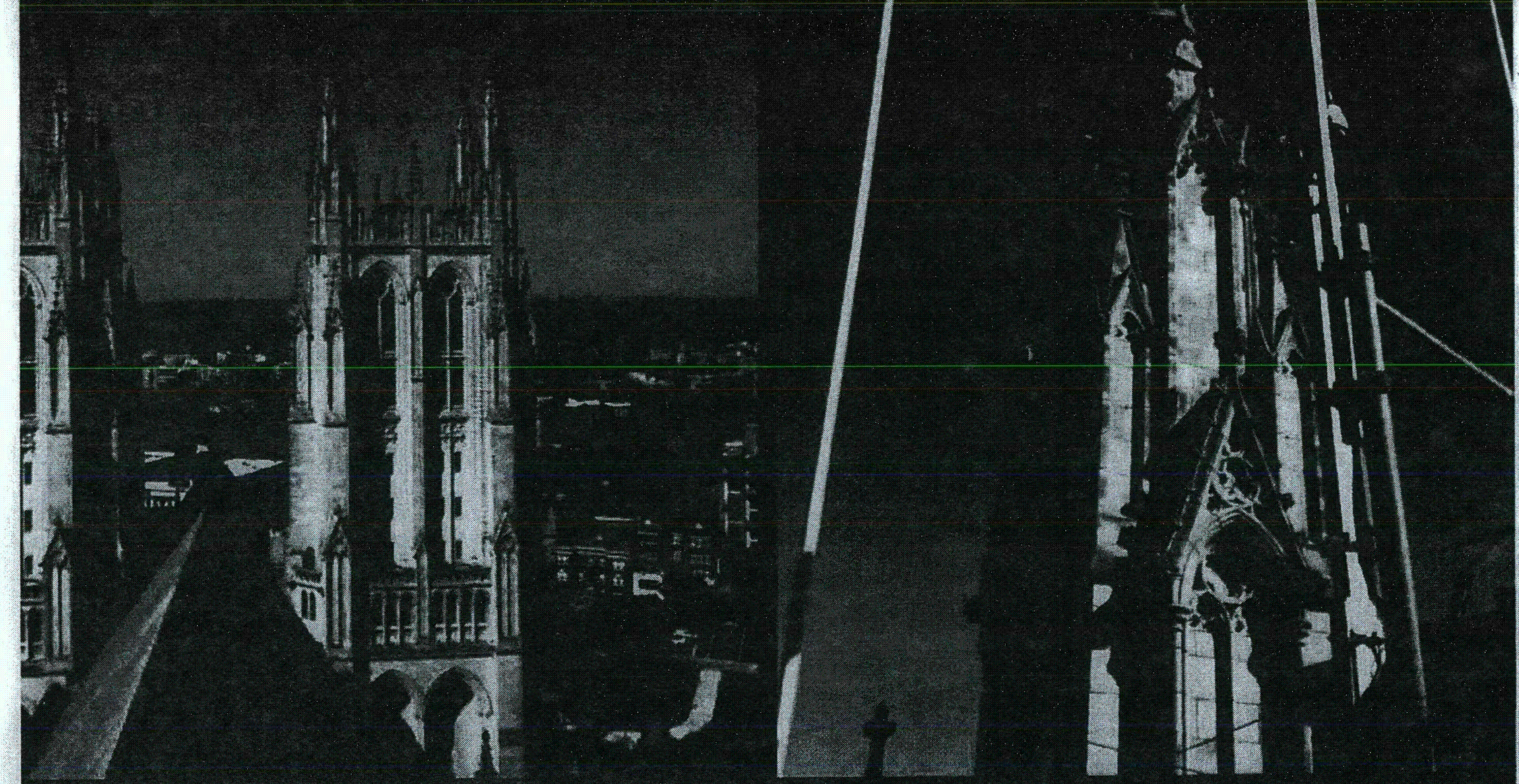

National Cathedral


National Cathedral

National Cathedral

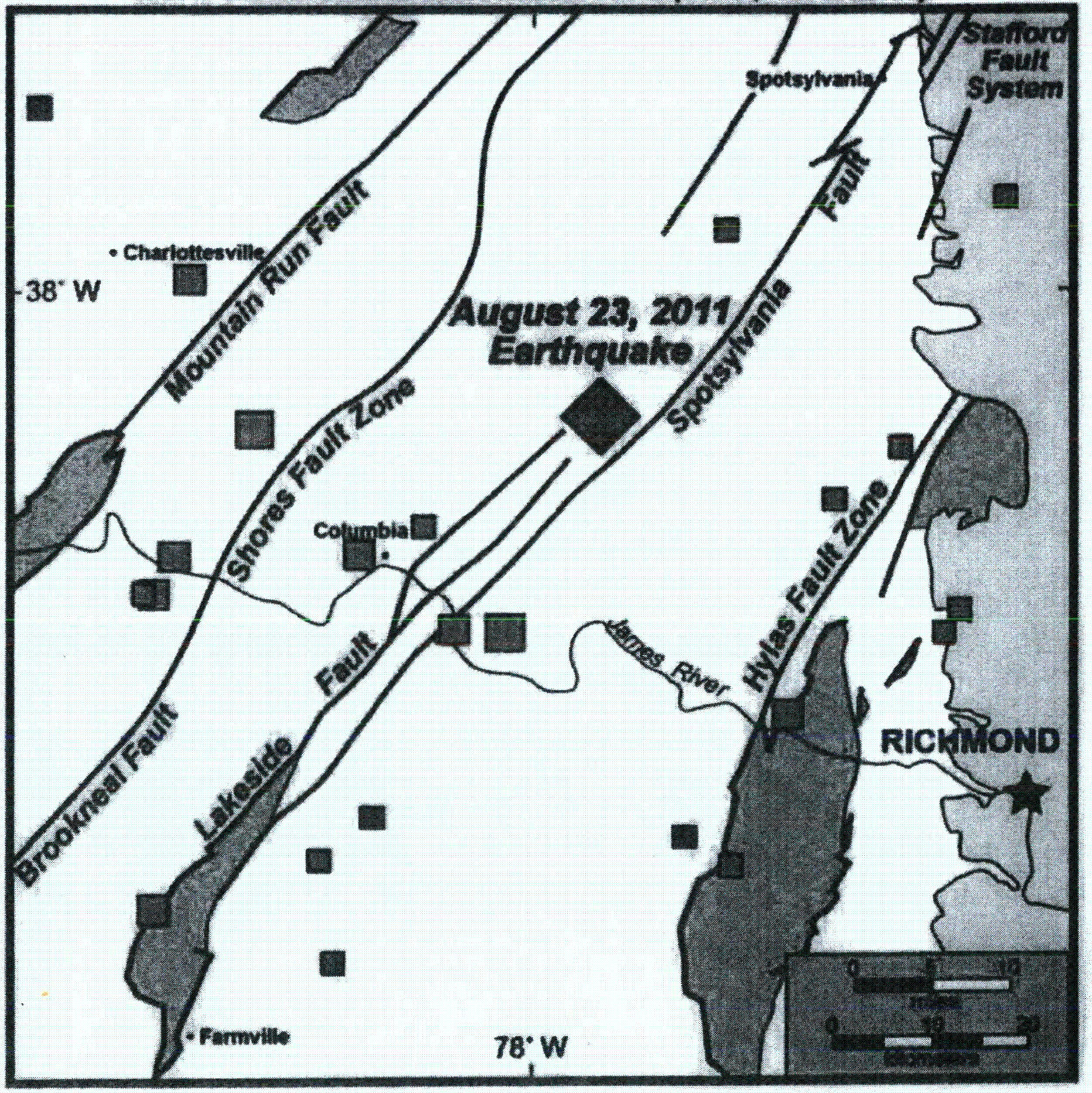
Later-constructed towers were undamaged

Cables used to secure precarious pieces in advance of Hurricane Irene



Locations of past earthquakes in central Virginia

GENERALIZED GEOLOGIC MAP OF THE CENTRAL VIRGINIA PIEDMONT WITH FAULTS AND EARTHQUAKES (M >2, 1973-2011)



Earthquake Epicenters

- M > 5
- M = 4
- M = 3.0 - 3.9
- M = 2.0 - 2.9

data from: Virginia Tech Seismological Observatory and USGS National Earthquake Information Center

•Map by C.M. Bailey, College of Wm & Mary