12th National Conference
on Earthquake Engineering
Salt Lake City, Utah
27 June - 1 July 2022

Hosted by the Earthquake Engineering Research Institute

Integrated Strategies for Enhanced Rapid Earthquake Shaking, Ground Failure, and Impact Estimation Employing Remotely Sensed and Ground Truth Constraints

D. J. Wald[1] , S. Xu[2], H. Noh[3], J. T. Dimasaka[4], K.S. Jaiswal[5], K. E. Allstadt[6], and D. Engler[7]

ABSTRACT

Estimating earthquake impacts using physical or empirical models is challenging because the three components of loss estimation—shaking, exposure, and vulnerabilities—entail inherent uncertainties. Loss modeling in near-real-time adds additional uncertainties, yet expectations for actionable information with a reasonable level of confidence in the results are real. The modeling approaches described herein augment inherently uncertain prior hazard and loss models with an integrated strategy for updating these priors with ground-truth observations, thereby greatly reducing their uncertainties. Two strategies are employed. Early reports of casualties are used in a Bayesian updating fashion to constrain the possible range of fatalities and to lower the prior models' uncertainties. Additionally, remotely sensed satellite radar data, in the form of a Damage Proxy Map (or DPM), are used in a Bayesian causal graph framework combined with machine learning to optimize the mapping among the physical processes that cause shaking-based building damage, landslides, and liquefaction to prior expectation models. The casual graph framework also affords the potential for removing anthropogenetic noise contained in the imagery. Ultimately, our two-fold model updating strategy will accommodate key ground-truth observations such as fatality reports, locations of building damage, and ground failure reports to converge on actual losses more rapidly.

Introduction

At the USGS National Earthquake Information Center (NEIC), we continue to improve upon the suite of post-earthquake information systems and products that provide near-real-time estimates of the shaking distribution, casualties, and economic impacts. These products are aimed at improving situational awareness, targeted response, disaster financing, and earthquake-engineering forensics [1,2]. For each system, we have identified significant challenges as well as long-term upgrade paths [3,4]. Enhancements will include (1) more rapid and systematic acquisition of strong-motion data worldwide and adding duration-based shaking intensity metrics; (2) refined ground failure models employing local geotechnical layers and models; (3) the direct incorporation of ground failure effects

---

[1] Geophysicist, U.S. Geological Survey, National Earthq. Information Center, Golden, CO 80401 (email: wald@usgs.gov)
[2] Assistant Professor, Dept. of Civil Engineering, Stony Brook University, Stony Brook, NY 11794
[3] Associate Professor, Dept. of Civil and Environmental Engineering, Stanford University, Stanford, CA 94305
[4] Graduate Student Researcher, Dept. of Civil Engineering, Stanford University, Stanford, CA 80401
[5] Structural Engineer, U.S. Geological Survey, National Earthquake Information Center, Golden, CO 80401
[6] Geophysicist, U.S. Geological Survey, National Earthquake Information Center, Golden, CO 80401
[7] Mathematician, U.S. Geological Survey, National Earthquake Information Center, Golden, CO 80401

Wald, DJ at al. Integrated Strategies for Enhanced Rapid Shaking, Ground Failure, and Impact Estimation Employing Remotely Sensed and Ground Truth Constraints. *Proceedings of the 12th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Salt Lake City, UT. 2022.

on loss estimates (currently shaking-based only), and (4) improving the quality of worldwide building inventories and their fragilities.

A more vexing limitation operationally, however, is our inability to update ground failure and loss estimates despite ever-increasing, independent sources of available ground-truth observations. Thus, our prior models, though independent, are uninformed by potentially key observations of reported ground failure and damage, even as such information rapidly accumulates. Yet, recent technological advances—both in accessible imagery and ground truth reporting, and machine learning applications—allow us to now consider post-earthquake impact observations explicitly in our modeled losses. This paper outlines our current strategies to update model-based hazard and impact assessments with ground-truth information to improve such estimates and insure they converge to actual losses as quickly as possible.

The deadly August 2021 M7.2 Haiti earthquake highlighted one of the key problems we aim to solve. The Prompt Assessment of Global Earthquakes for Response (PAGER) system is a post-earthquake situational awareness tool used to estimate the range of fatalities and economic losses within about 20 minutes of significant earthquakes globally [5]. However, PAGER's fatality estimates are only considered to be accurate within one order-of magnitude [6]. For the Haiti event, the PAGER alert was correct, e.g., it was driven by a red alert for fatalities (>1,000 estimated fatalities), yet whereas the median initial fatality estimate was nearly 30K fatalities, reports later revealed about 2,200 actual deaths.

Immediately after the 2021 Haiti earthquake, evolving reports of fatalities pointed to losses at the lower end of the PAGER ranges but given the challenges of accurate reporting and interpreting imagery, it was difficult for the USGS and post-earthquake decision makers to reconcile early reports with the PAGER-estimated values quantitatively [7,8]. The strategy reported herein can incorporate any of the above-mentioned ground-truth content in an opportunistic, yet rigorous mathematical and operational framework to provide constantly improving PAGER loss estimates.

In addition to rapid loss estimates with the PAGER system, the USGS has now operational real-time landslide and liquefaction estimates [4]. These ground failure (GF) estimates, too, are uncertain and could benefit from ground-truth constraints, particularly if the prior landslide and liquefaction models could be adjusted on-the-fly based on actual occurrence combined with pre- and post-earthquake interferometric synthetic aperture radar (InSAR) radar changes, using Damage Proxy Maps, or DPMs [9].

Our GF models are global in scale, and each event is likely to have regional geotechnical characteristics that cannot be accounted for with our global models alone. The GF models are also strongly sensitive to shaking estimates, which are uncertain and not often well-constrained by data, especially in remote mountainous areas where landslides are most likely to occur. Thus, our vision here is a comprehensive, integrated loss-estimation system that incorporates ground-truth observations and imagery, and computes increasingly accurate losses that converge with reality over time. The next generation PAGER system will then assimilate disparate yet complementary efforts that will ultimately result in a more fully integrated, spatially accurate series of PAGER-related products, including more accurate ground failure estimates. This briefing provides an overview of the status of and science behind these efforts and describes both the challenges and the strategies we plan to employ to contend with them.

Methodology

ShakeMap shaking and PAGER loss estimates are made rapidly and automatically, independent of human review in most cases. Color-coded PAGER alerts [5] are automatically delivered, excepting initial orange or red alerts, for which "pending" alerts are provided until the PAGER team can verify that earthquake source parameters—primarily the magnitude and depth—have stabilized, and the ground motion and intensity data included are judged to be of sufficient quality.

Rapid updates to loss estimates are critical because of the inherent tradeoff between speed and accuracy. To date, updating loss estimates consists only of improved ShakeMaps as we add refined source information, the location of the causative fault, more intensity data, or additional seismic stations, primarily in the initial hours after the event. Any significant changes to the ShakeMap are immediately reflected in updates to GF assessments and PAGER loss estimates. However, to date we do not update the PAGER or GF model components for specific events; they are only calibrated prior to deployment based on previous earthquakes.

Going forward we plan to operationalize two key strategies for updating the loss models themselves (see Fig. 1). First, we are now able to manually update PAGER fatality estimates with early (uncertain) casualty reports [7,10]. Noh et al., 2020 [10] employ recursive Bayesian updating based upon our loss projection model, and uncertainties from both the loss modeling and reporting. After establishing a credible framework, we have tested this approach for several recent earthquakes to show that PAGER fatality estimates quickly and reliably centered on actual fatalities—with lower uncertainties—within the initial hours to days [7]. To fully operationalize this updating will require having National Earthquake Information Center (NEIC) 24x7 analysts aid in collecting and archiving early fatality reports in a PAGER-accessible database, which can then trigger PAGER updates. Analysts will need to be trained to recognize strengths and weakness of various fatality reports, whether from officials, reporting agencies (e.g., Reuters, Associated Press), or mainstream or social media. Updates can improve estimated fatalities both for PAGER under-and over-estimates, though a *lack* of reported fatalities entails more uncertainty than reported fatalities [7,10]. We must also modify PAGER product and web page content to reflect updating and properly explain such procedures.

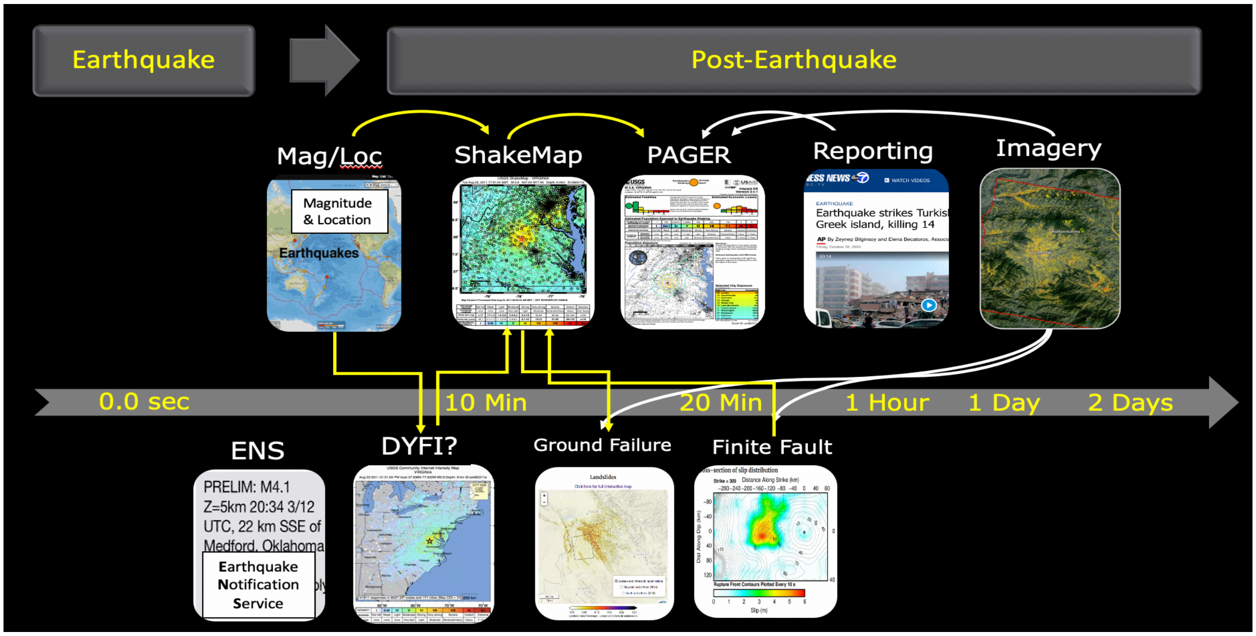

Figure 1. Schematic of USGS real-time earthquake response system dependences (yellow arrows) with post-event observations. Fatality reports (white arrows) can lead to rapidly updated PAGER fatality estimates; satellite imagery (white arrows) can contribute to greatly improved landslide and liquefaction estimates, fault dimensions (needed to improve ShakeMap), and more accurate building damage and economic loss estimates.

Second, we have shown that rapid (8 hours to 1-2 days) satellite imagery has the potential to greatly improve both ground failure and building damage estimates. We will employ satellite radar as opposed to optical imagery since it sees through clouds and in darkness and is thus more readily available. InSAR imagery is now obtainable usually within a day or two of any significant events. The mathematical framework employed for incorporating such imagery is a Bayesian network in the form of a causal graph model recently described by [11,12]. A Bayesian network is a probabilistic graphical model that represents the paths of dependency for a set of variables as well as their joint distribution, one that can often be solved efficiently with machine learning strategies. The conditional probability distribution of each variable given its parents can be gleaned from data (in our case the DPM), and the Bayesian network itself offers a graphical representation that can be readily interpreted and explained intuitively (see Fig 2).

A key aspect of the causal graph approach is that we can now take advantage of new global building footprint datasets that, when combined with prior model, could greatly refine the location of building damage, potentially down to individual buildings in some cases. This level of detail in the loss updating is quite feasible since building footprints are highly accurate so that when there is a change in post-event high-resolution (30m) imagery that overlaps with a building the logical source is building damage. Not only does the causal graph framework employ imagery for updating models, it also has the potential to ingest individual ground-truth observations of landslide, liquefaction, and building damage occurrences. This latter attribute means that the models could be rapidly and substantively updated, such that the model will converge with reality more quickly, and we are currently exploring strategies to directly incorporate ground-truth datasets. The estimates might then be used to inform both response and longer-term recovery efforts since they can then better provide a clearer, spatially accurate assessment of losses to decision-makers well before comprehensive ground truth data are gathered.

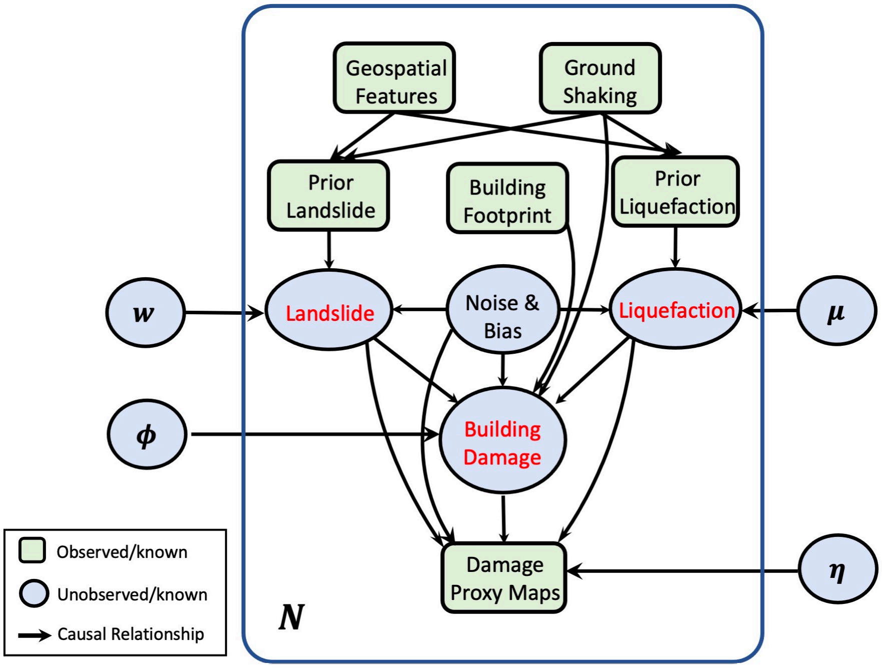

Figure 2. Causal Graph network example (from [12]) depicting causal dependencies among ground failure, building damage, DPMs, and noise sources. The posterior probability of landslide, liquefaction, and building damage at each location are the objectives for which we solve. Green boxes refer to the variables that have data constraints. Blue circles refer to nodes that are not observed or known. ω, μ, ϕ, and η are the unknown causal coefficients that quantify the causal effects of parent nodes to landslide, liquefaction, building damage, and DPMs. See [11,12] for more details.

Conclusions

Advancements in remote sensing, rapid in-situ impact reporting, and machine learning—combined with new datasets such as global building footprints—will allow for innovative data-fusion strategies that integrate with existing models and should greatly improve the *accuracy and spatial resolution* of our shaking and loss estimates**.** We have proposed two strategies for updating our ground failure and loss models to converge to the ground truth. The first employs reported fatalities to update PAGER fatality estimates; the second utilizes satellite imagery (DPMs) to determine where and what specific earthquake processes contributed to post-earthquake image changes. We have described our integrated strategy underway aimed at updating uncertain ground failure and loss models. The main findings when employing both approaches is that (1) updating the PAGER fatality model can prevent cases where PAGER losses are initially significantly off (e.g., the incorrect alert level) by quickly allowing updates, and that (2) the imagery—while slower than ground-truth observations—provide more spatially accurate impact assessments, well beyond the capabilities of the generalized loss and ground failure models.

Both strategies require continued research and development, additional case histories, and working out communication and operational considerations. In fact, a significant gap in the use of imagery for building loss assessment remains in that our PAGER loss models are computed and provided only in aggregate form (total losses). The most opportune use of the causal graph strategy with satellite imagery requires an *a priori* model of the location of buildings impacted, even if imperfect. We expect this will be done with a revised implementation of the PAGER semi-empirical model which includes estimates of losses for different building types. The degree to which this can be done readily depends on the country of interest (some national building-loss models are of better quality than others). Ultimately, it would be highly beneficial and worthwhile to perfect and incorporate these capabilities into the operational earthquake response toolkit at the National Earthquake Information Center.

References

1. Thompson EM, McBride SK, Hayes GP, Allstadt, KE, Wald LA, Wald DJ, Knudsen KL, Worden CB, Marano KD, Jibson RW, Grant AR. USGS near-real-time products—and their use—for the 2018 Anchorage earthquake, *Seismol. Res. Lett.* 2020, 91(1): 94–113.
2. Wald DJ, Jaiswal KS, Marano K, Hearne M, Lin K, Slosky D, Allstadt KE, Thompson EM, Worden CB, Hayes GP, Quitoriano V. An update on USGS near-real-time earthquake shaking and impact products, *Proceedings of the 17th World Conf. Earthq. Eng.* 2021, Sendai.
3. Hayes GP, Earle PS, Benz HM, Wald DJ, Yeck WL. National Earthquake Information Center strategic plan, 2019–23. *U.S. Geological Survey Circular 1457* 2019, 17 pp.
4. Allstadt KE, Thompson EM, Jibson RW, Wald DJ, Hearne M, Hunter EJ, Fee J, Schovanec H, Slosky, D, Haynie, KL. The US Geological Survey ground failure product: Near-real-time estimates of earthquake-triggered landslides and liquefaction. *Earthquake Spectra* 2021, doi:10.1177/87552930211032685.
5. Wald DJ, Earle PS, Porter K, Jaiswal KS, Allen, TI. Development of the U.S. Geological Survey's Prompt Assessment of Global Earthquakes for Response (PAGER) System, *14th World Conf. Earthq. Eng.* 2008, Beijing.
6. Jaiswal KS, Wald DJ. An empirical model for global earthquake fatality estimation. *Earthquake Spectra* 2010, 26(4): 1017–1037.
7. Engler D, Jaiswal KS, Noh HY, Wald DJ. An accounting of USGS PAGER post-event loss estimates and updates for the 2021 Haiti (M7.2) earthquake. *Proceedings of the 12th National Conf. in Earthquake Eng.* 2022, Salt Lake City, UT.
8. Wald DJ, Marano K, Jaiswal KS, James-Ravenell M. Evaluating of a decade of PAGER loss estimates, *Proceedings of the 12th National Conf. on Earthquake Eng.* 2022, Salt Lake City, UT.
9. Yun S-H, Fielding EJ, Webb FH, Simons M. Advanced Rapid Imaging and Analysis (ARIA) – Center for Natural Hazards ARIA Data Share. Available at https://aria-share.jpl.nasa.gov/20200106-PuertoRicoEQ/DPM/388 (2020/10/26)
10. Noh H, Jaiswal KS, Engler D, Wald DJ. An efficient Bayesian framework for updating PAGER loss estimates. *Earthquake Spectra* 2020, 36(4): 1719-1742.
11. Xu S, Dimasaka JS, Wald DJ, Noh H. Bayesian updating of seismic ground failure estimates via causal graphical models and satellite imagery. *Proceedings of the 17th World Conf. Earthq. Eng.* 2021, Sendai.
12. Xu S, Dimasaka JS, Wald DJ, Noh H. Seismic multihazard estimation via causal inference from satellite imagery, *Nature Computer Science* 2021, in review.