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AN UPDATE ON USGS NEAR-REAL-TIME EARTHQUAKE SHAKING AND IMPACT PRODUCTS

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Abstract

We report on advancements in both hazard and consequence modeling that forms the core of the U.S. Geological Survey's (USGS) strategy to improve rapid earthquake shaking and loss estimates. Our primary goal is to improve our operational capabilities of the USGS National Earthquake Information Center. However, the science, software, and datasets behind these systems continues to advance studies of earthquake shaking and impact by the seismological, engineering, financial, and risk modeling communities. Several important updates to our integrated shaking and impact products are outlined, and we introduce new earthquake information products that have recently been brought online, including rapid ground failure estimates and more spatially refined loss estimates domestically (in the U.S). We continue to compile, develop, and refine key openly available models and datasets that contribute to calibrating these systems and report on the collection and storage of new inventories. We also describe some of the basic operational considerations in the current generation of these shaking and loss-estimation systems. A key aspect of the product integration and development is leveraging earthquake-hazard and loss-modeling science done internally (within the USGS) and by external researchers and collaborators. Lastly, we outline new opportunities for further research and development by emphasizing scientific, data, and application gaps and challenges that must be solved in order to improve our shaking and impact information tools.

Keywords: Earthquake Response; Earthquake Damage

1. Introduction

The U.S. Geological Survey's (USGS) Earthquake Program coordinates numerous earthquake-related systems, many which produce near real-time earthquake information products. The evolution of rapid earthquake information, beyond the standard "magnitude and location," proceeded with the development of a series of connected systems that initiate from basic earthquake information, then progressed to estimate shaking and impacts of each event (Fig. 1). Such estimates employ advanced algorithms and systems developed over the years from internal and external USGS support and benefit greatly from open research and partnerships guided by the USGS in the academic, nonprofit, and consulting communities.

Efforts take place primarily at USGS offices in Pasadena, San Francisco, Seattle, Reston, and Golden; the latter hosts the USGS National Earthquake Information Center (NEIC). As part of the Advanced National Seismic System (ANSS), NEIC and Regional Seismic Networks of the ANSS generate and distribute content for domestic events. Though generated in a distributed fashion, the use of a unique Product Distribution Layer (PDL) [1] that associates, aggregates, and exchanges all such products, allows for automatic content delivery via live feeds and web page generation that have been carefully developed in conjunction with scientists and software engineers, primarily at the NEIC (Fig. 2). Though USGS' initial primary Earthquake Notification Service (Fig. 1, ENS) [2] is still the alerting workhorse, internet, social media, and regular media outlets widely redistribute event origin information, and now further amplify our messages and increase access to the derived shaking and loss products discussed herein.

For each product, substantial efforts were required to achieve operational status. The most notable effort is acquiring and archiving observational databases needed for sufficient calibration of each system since each contains (or is fundamentally based on) empirical modeling methodologies. As described below, these essential data collection efforts warrant documentation and open access since they are each quite valuable to all for shaking or loss model calibration in their own right. Likewise, the algorithms used to generate shaking and loss models are provided in open-source software repositories in order to facilitate their use in other regions, countries, and across a wide range of sectors in the hazard and risk communities.

Recently, the 2018 Mw 7.1 Anchorage, Alaska earthquake event provided an opportunity to showcase many of the new products in an operational environment [3]. Here, we focus more on the product interdependencies, system integration, and future research and development strategies. Ongoing advancements will require continued USGS and community efforts. We also highlight recent advancements to these products newly available in the peer-reviewed literature.

Other prominent, newly released real-time earthquake information products have recently come online, most notably Earthquake Early Warning (EEW) [4] and Operational Aftershock Forecasting (OAF) [5]. These are mentioned for completeness, but our focus here is primarily on shaking and impact information systems. The Tweet Earthquake Dispatch (TED) is discussed by Earle et al. [6].

2. Earthquake Product Synopsis, Integration, Dependencies

The main earthquake information products discussed are depicted in Fig. 1, along with their dependencies. For example, PAGER requires ShakeMap input, and a finite fault is beneficial for ShakeMap, at least for large earthquakes, yet ShakeMaps must be generated initially for such events prior to determining the fault dimensions. Below, we discuss shaking and impact products. We describe their subsystems and datasets along with their other dependencies in an operational sense and also what's needed for calibrating and testing these systems.

2.1 Did You Feel It?

Did You Feel It?® (DYFI) has been in operation for nearly two decades (1999-2019) in the U.S. and for nearly 15 years globally. During that period, over 5 million individual DYFI intensity reports—spanning all magnitude and distance ranges—have been amassed and archived. The USGS recently released the updated DYFI source code online via GitHub; this code is used in several nations, including in Australia, Canada, the French territories, and Belgium. A wide range of scientific and social science research studies have utilized DYFI data, many of which were summarized earlier [7, 8]. One of the most vital roles of DYFI data—and macroseismic data more generally—is to add fundamental shaking constraints in ShakeMap (Figs. 3-4). ShakeMap accommodates both strong motion and macroseismic observations naturally, weighing their contributions based on the uncertainty of those data in constraining the particular intensity measure (IM) of interest as well as due to their distance with respect to any map grid location [9].

Dependencies: In addition to a host of crowd-sourced citizen scientists, DYFI depends on associating incoming reports based on earthquake information triggered by the ANSS and NEIC. However, incoming DYFI responses can now automatically be used to estimate the magnitude and epicenter often before or even when no existing event has been triggered. We report these automatic DYFI-based triggers to NEIC analysts so that they can locate any missing events that are felt.

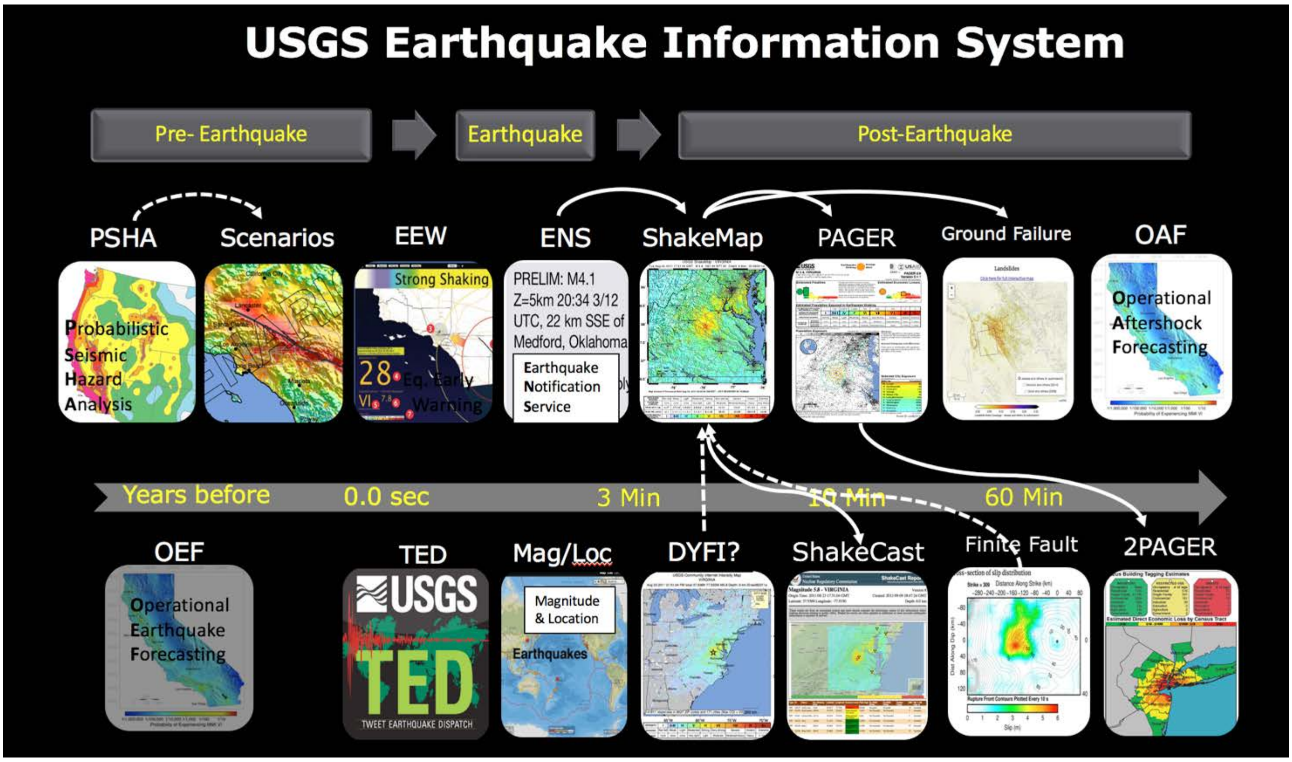


Fig. 1. Schematic summarizing the USGS Earthquake Program Earthquake Information System (EIS), an integrated set of products for earthquake planning, awareness, and response. Arrows depict dependences: solid lines indicate required inputs; dashed lines show optional inputs. Acronyms not described in the text are: Probabilistic Seismic Hazard Assessment (PSHA), Operational Earthquake Forecasting (OEF, greyed out; not yet operative).

Gaps and Opportunities: Currently, macroseismic data constraints for ShakeMap come directly from DYFI, which are volunteered by the public at large, rather than from expert-based observations. DYFI data have been shown to be rather robust [7, 8]; however, due to the wide range of ShakeMap users, including response and financial decision makers, substantial efforts are underway to assure quality control of such contributed data.

We are improving ways to incorporate data from not only DYFI but from other such systems worldwide in near-real time. For example, user-felt reports made from convenient, visually depicted cartoons allow for user-selected intensities [10]. Yet, using these data requires analysis of their uncertainties [8, 9] as we have done with DYFI data. Developing methods to compute these uncertainties systematically could make these outside data streams available to ShakeMap. Additionally, all crowd-sourced approaches for assigning intensity have a known limitation: they are inadequate for assigning intensity values greater than Modified Mercalli Intensity (MMI) VII, the level above which significant building damage occurs. Above VII, robust intensity assignment requires engineering knowledge of building type and damage levels. For destructive earthquakes, alternative macroseismic observations are typically used (e.g., engineering or press reports; field reconnaissance). With the need for seismologists and engineers to review the higher intensity assignments, the problem of how to automatically evaluate and assign higher shaking intensities has not yet been fully solved. Although DYFI successfully acquires the vast majority (>95%) of all intensities reported (higher intensities are relatively rare), we aim to revise the MMI scale in the U.S. to be compatible with EMS-98—a more modern scale better adapted to higher intensity assignments than MMI. This would allow us to improve U.S. strategies for rapid macroseismic assignments, particularly for higher intensities based on experts already in the field doing engineering evaluations.

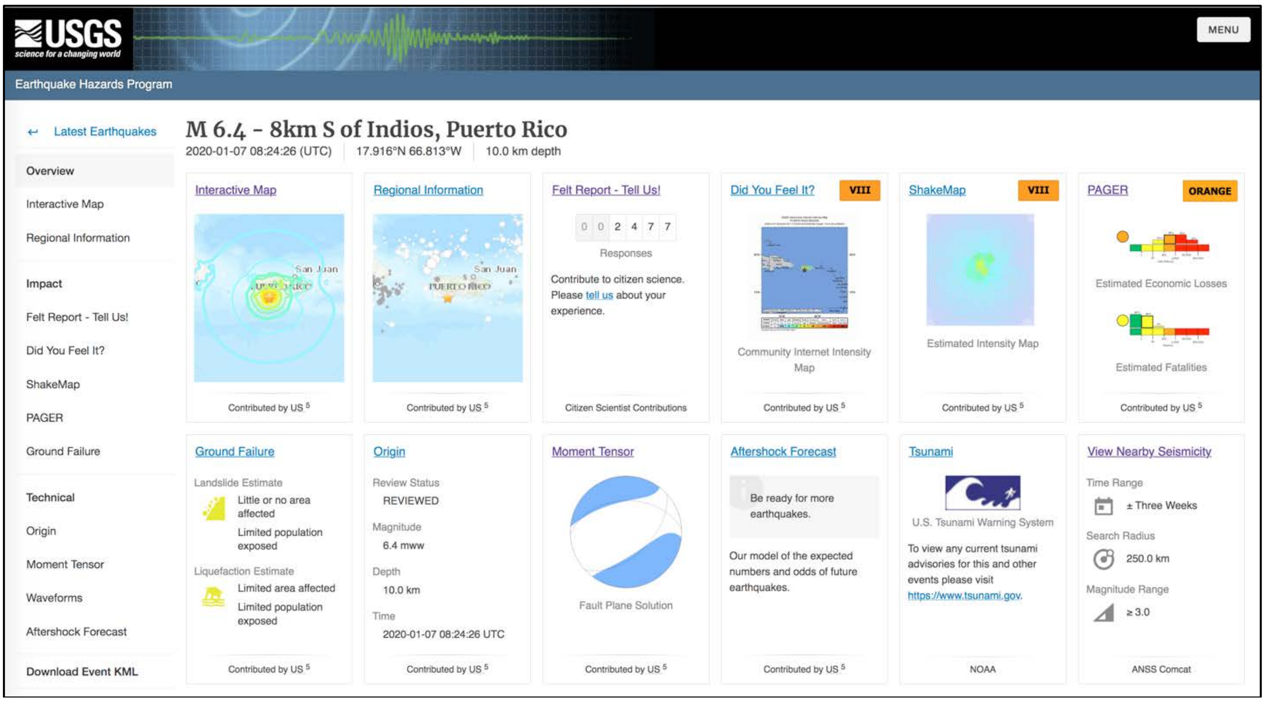


Fig. 2. Web rendering of several of the components of the EIS product package on the USGS Earthquake Program "Event Page". Individual products are linked via graphical or text-based "cards" which link directly to each's "landing page." Some of the elements are always available for any earthquake (e.g., interactive map), whereas some are dependent on the nature of the event (e.g., finite fault, PAGER).

Another opportunity presents itself with regard to the wide potential EEW audience. EEW ShakeAlert recipients could be sensors themselves: it would be beneficial if EEW alert recipients were to report observations needed for intensity assignments (e.g., via integrated access to DYFI) as well as to describe their reactions in response to the EEW alert. Ultimately, alerting apps tied to Internet-of-Things (IoT) appliances, including ShakeAlert apps (as prototyped in Berkeley's *myShake* cell-phone app, for instance), could be used for this purpose. Such hardware and apps would serve a dual goal. First, they help educate the populace about taking appropriate measures in response to shaking. Second, with the refinement of onboard sensors, they could provide instrumental shaking values co-located with intensity reports—a fundamental goal for relating shaking to intensity and a natural contribution to better-constrained ShakeMaps.

2.2 ShakeMap

ShakeMap® now forms the basis of a wide range of decision-making by depicting earthquake shaking, and through its use as input for damage assessments, both in planning and response. ShakeMap software enhancements now allow for more accurate interpolation both in space and as a function of frequency, as well as the use of multiple (weighted) ground motion model (GMM) sets specific to all regions of the globe. These and many other advancements are documented by Worden et al. [9] and in the ShakeMap Manual online [11]; the software is available in Github, where collaborative international efforts have led to further advances, additional GMPEs, and other features.

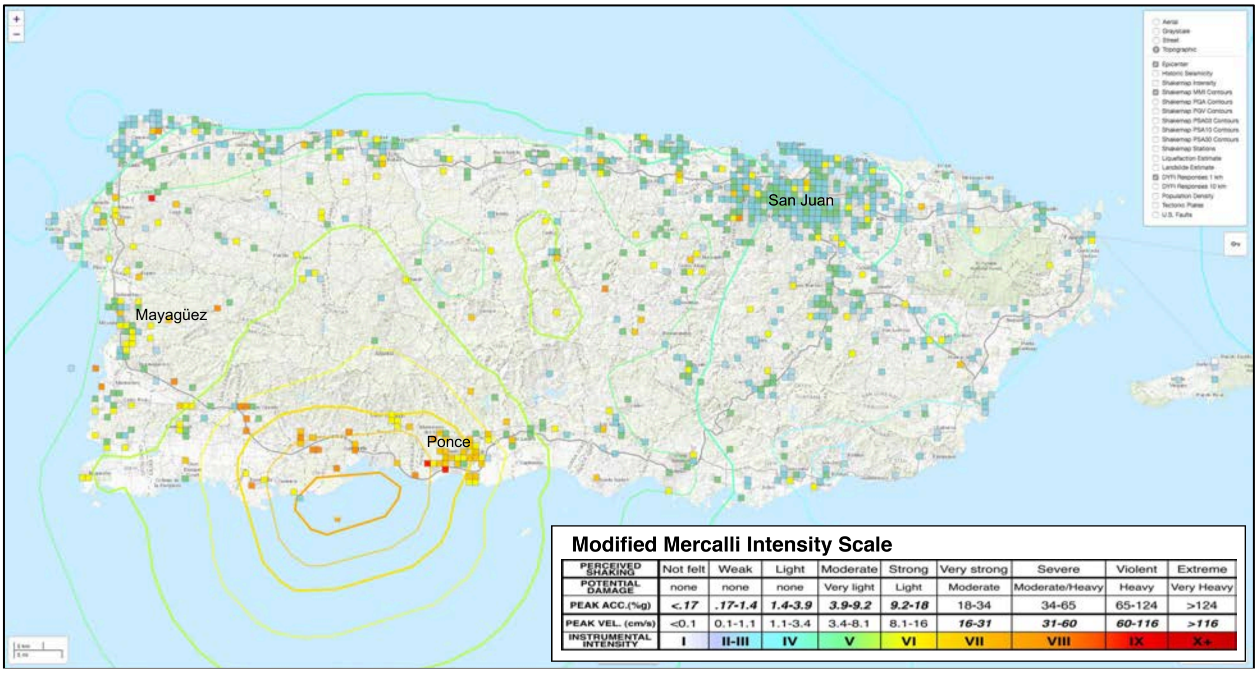


Fig. 3. Interactive map from the USGS event web pages for the 2020 magnitude 6.4 Indios, Puerto Rico earthquake. Over 2,500 DYFI data in the region are displayed in 1-km squares, color-coded to the inset legend used by ShakeMap to show the community decimal intensity [7]. ShakeMap intensity contours and seismic stations (triangles) are shown for comparison.

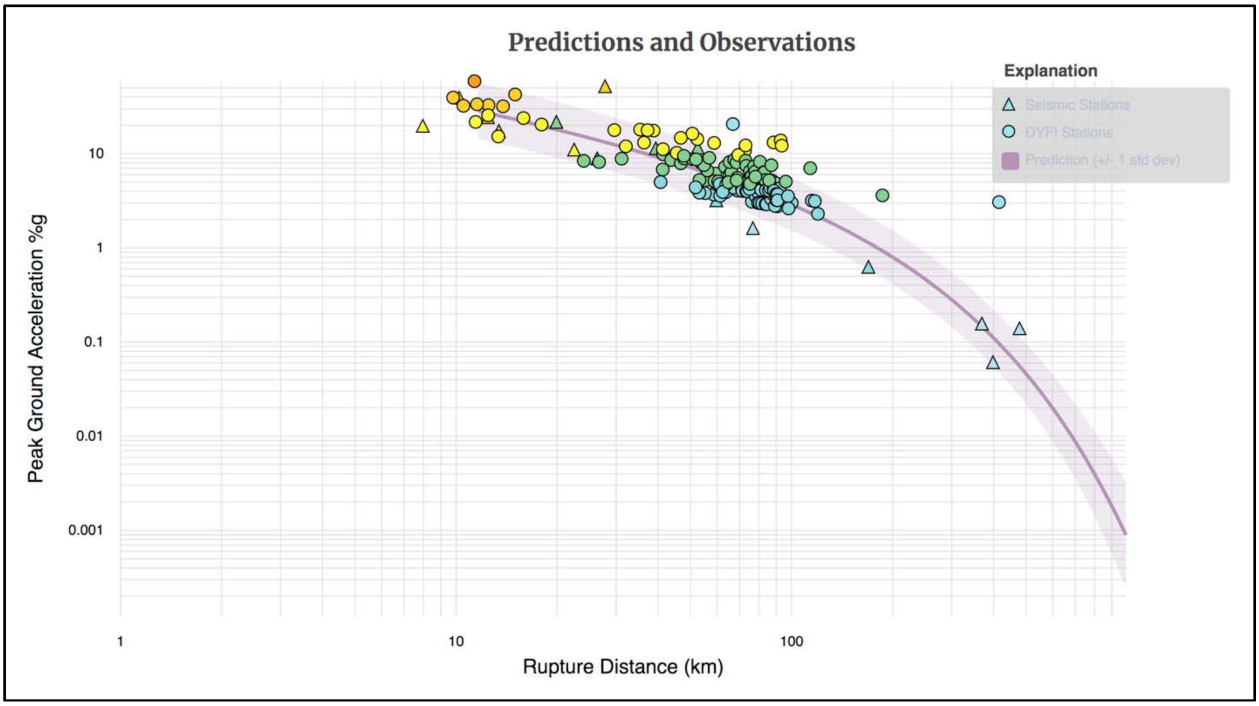


Fig. 4. Interactive plot of intensity versus fault rupture distance for the M6.4 Indios, Puerto Rico earthquake. Scrolling over symbols shows the data for individual geocoded blocks. The colored trend line is the predicted acceleration based on the GMMs used in ShakeMap. The shaded area is one standard deviation above and below the predicted accelerations. Circles are individual accelerations values converted from the 1-km geocoded block data [11]. Triangles are seismic stations reporting to ShakeMap.

Dependencies: ShakeMap is triggered by suitable magnitude and hypocenters via PDL, and utilizes associated ground motion amplitudes, real-time DYFI intensities, GMMs, and mapped Vs_{30} estimates. The suites of GMMs employed in ShakeMap depend on Global Earthquake Model's (GEM) OpenQuake libraries [12]. Likewise, ShakeMap employs ground-motion conversion equations to convert among native IMs (e.g., seismic data) and inferred IMs (e.g., DYFI intensity observations). ShakeMap also ingests USGS' rapid ***Finite Fault*** (FF) models [13] or other available models, when available, for improved distance calculations for its shaking estimates. FF models, in turn, often rely on geometric constraints provided for subduction zone interfaces derived from ***Slab2.0*** [14] or other mapped fault geometries.

Status and Successes: ShakeMap can incorporate historical macroseismic intensity data naturally [9]. For earthquakes that occurred decades ago, typically few ground motion recordings are available, yet rich macroseismic datasets can oftentimes allow for the recovery of a well-constrained ground shaking pattern (e.g., Fig. 5). The explicit incorporation of macroseismic data for past and modern events allows continuity and comparison of ground motion fields over time, greatly facilitating the continued buildup of the ***ShakeMap Atlas***. The *Atlas*, a compendium of over 10,000 earthquake ShakeMaps from 1970 on, is continuously updated and a revision (version 4) for events up through 2019 will be released in 2020. Likewise, our ShakeMap scenario catalog continues to expand. Both historical and recent events benefit from the use of our new ***Global Vs_{30} Map***. The map is a mosaicked Vs30 grid sourced from both published regional Vs30 maps and—in regions without local maps—Vs30 from the topographic slope-based proxy [15]. In addition, we recently released the ***Ground Motion Processing Software Package,*** an open-source, ground motion time history acquisition and processing package, coded in Python. The package leverages ObsPy libraries, facilitates real-time ShakeMap data acquisition globally and standardizes processing for engineering and seismological research [16].

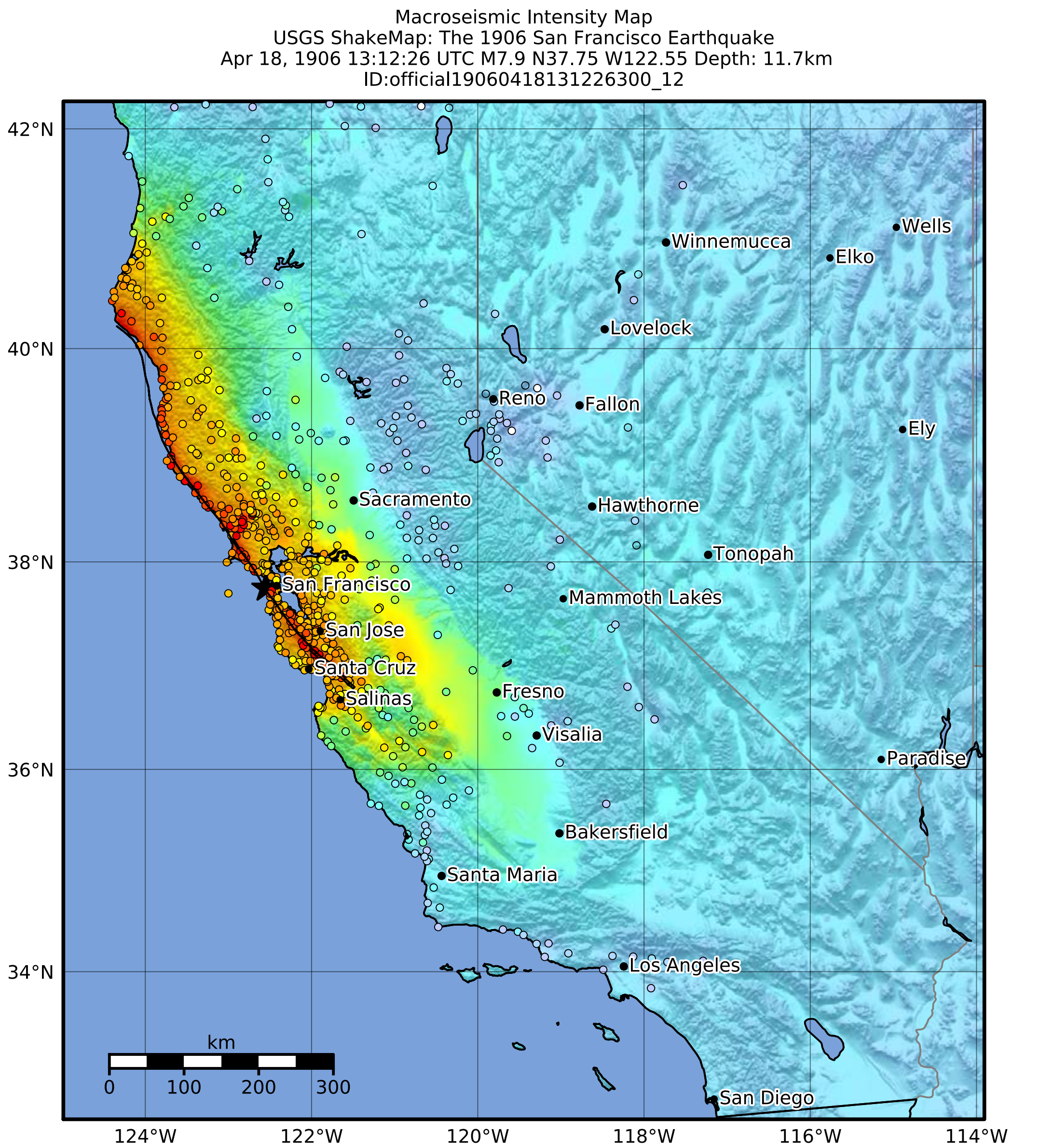
Gaps and Opportunities: Enhancements envisioned for ShakeMap include (1) strategies for selecting consequence-driven scenarios for areas without known faults [17], and (2) suites of 3-D simulated ground motion IMs for scenario use. The use of duration-based IMs in ShakeMap that are computable with low uncertainty (efficient) and useful for loss estimation (sufficient) would improve ground failure calculations and estimates of structural fragility.

A new frontier for the evolution of rapid earthquake information entails the delivery of a continuum of real-time earthquake information products, initiated by EEW algorithms. An attractive option for depicting shaking involves real-time mapping of the continuously changing shaking at each seismic station. Later, the maps would evolve into an event-specific intensity map based initially on peak shaking associated with the EEW triggers along with shaking estimates elsewhere [18]. The evolving maps could then be seamlessly replaced with the comprehensive suite of ShakeMap products and formats needed for inspection evaluation and damage estimation as soon as event-specific summary peak values are delivered [19].

2.3 PAGER

Since 2010, PAGER has been USGS' leading tool for providing actionable loss estimates for response, aid, and financial institutions for earthquakes around the globe. From September 2010 through April 2019, PAGER issued 4,903 green-, 175 yellow-, 40 orange-, and 18 red-level alerts [13].

Dependencies: PAGER requires ShakeMap as the gridded shaking input and a global gridded population dataset. In addition, the PAGER loss models also fundamentally rely on the ShakeMap Atlas for country-specific vulnerability model calibration. Thus, the ongoing improvement of PAGER vulnerability functions requires upkeep of the ShakeMap Atlas with recent earthquakes and databasing of high-quality reported losses. The combination of *ShakeMap Atlas* events, the estimated population exposures for each intensity level, and reported losses constitute *PAGER-Cat* and *Expo-Cat*, respectively, scheduled for release in an updated form in 2020. Whereas both PAGER-Cat and Expo-Cat were published separately, the next round of catalogues will be provided via NEIC's ComCat. Although PAGER runs fully automatically, initiated by a ShakeMap arrival via PDL, for Orange or Red alerts a Subject Matter Expert (SME) from the ShakeMap/PAGER team must first review the results before releasing them to public servers and critical users.



SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	None	None	None	Very light	Light	Moderate	Moderate/heavy	Heavy	Very heavy
PGA(%g)	<0.05	0.3	2.76	6.2	11.5	21.5	40.1	74.7	>139
PGV(cm/s)	<0.02	0.13	1.41	4.65	9.64	20	41.4	85.8	>178
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based on Worden et al. (2012) Version 7: Processed 2020-01-22T18:04:36Z
△ Seismic Instrument ○ Reported Intensity ★ Epicenter ▭ Rupture

Fig. 5. ShakeMap representing the shaking intensity pattern of the great 1906 M7.9 San Francisco earthquake. The shaking distribution is remarkably well recovered due to both a well-constrained fault geometry and nearly 1,000 intensity observations for constraints.

Gaps and Opportunities: Introducing new methods will enable us to continually update loss models based on ground-truth observations. The two strategies being pursued are (1) updating total fatalities based on reported fatalities in the immediate aftermath of an event based on a Bayesian updating framework [19, 20], and (2) updating loss estimates spatially based on NASA's Damage Proxy Maps (DPM) [21] used as constraints on actual affected sites. As an ongoing effort to improve PAGER loss estimates, we plan to update several national vulnerability models with the revised ShakeMap Atlas in 2020.

2.4 2PAGER

Whereas the PAGER automated alert system provides rapid (10-20 min) loss estimates in the form of ranges of fatalities and economic impact for significant earthquakes around the globe, FEMA's Hazus software [22], operated manually by FEMA personnel, provides more detailed loss information. Hazus quantifies physical damage to the building stock, as well as a broad range of social and economic consequences estimated at a much higher spatial resolution domestically (the population census-tract level). A new *2PAGER* report, serves as a supplement to the widely deployed standard *onePAGE*R product for all significant domestic earthquakes [23]. Page one is the standard, automated PAGER alert content, with summary alert levels for overall fatality and economic loss estimates, as well as summary content on recent earthquakes, structure vulnerability, and historical secondary hazards.

However, as soon as FEMA runs Hazus using USGS ShakeMap and it is reviewed by both agencies, the second alert page is generated and delivered via PAGER notifications and the USGS website. This second page (Fig. 6) synopsizes the comprehensive Hazus model results, including spatially distributed estimates of affected population, economic impact, non-fatal injuries, displaced households, and the number of damaged buildings—including estimates of required building tags (safety evaluation requirements). The 2PAGER report provides more detailed damage and loss/impact content for U.S. earthquakes than can PAGER's global model in the critical hours following a damaging earthquake. 2PAGER reports can also be readily used for better communicating earthquake scenario losses [23].

Dependencies: The 2PAGER requires a ShakeMap, the PAGER output in the form of the pager.xml summary file, and FEMA's Hazus loss-model output, parsed through specific scripts to produce unique 2PAGER content, including losses by U.S. county and green, yellow, and red building tagging estimates [23].Whereas the PAGER content is automatically delivered, FEMA runs Hazus interactively after receiving ShakeMap shaking grids, and then—after review—delivers Hazus-2PAGER inputs to the NEIC. PAGER SMEs then run scripts to produce and deliver the 2PAGER products, after careful review.

2.5 ShakeCast

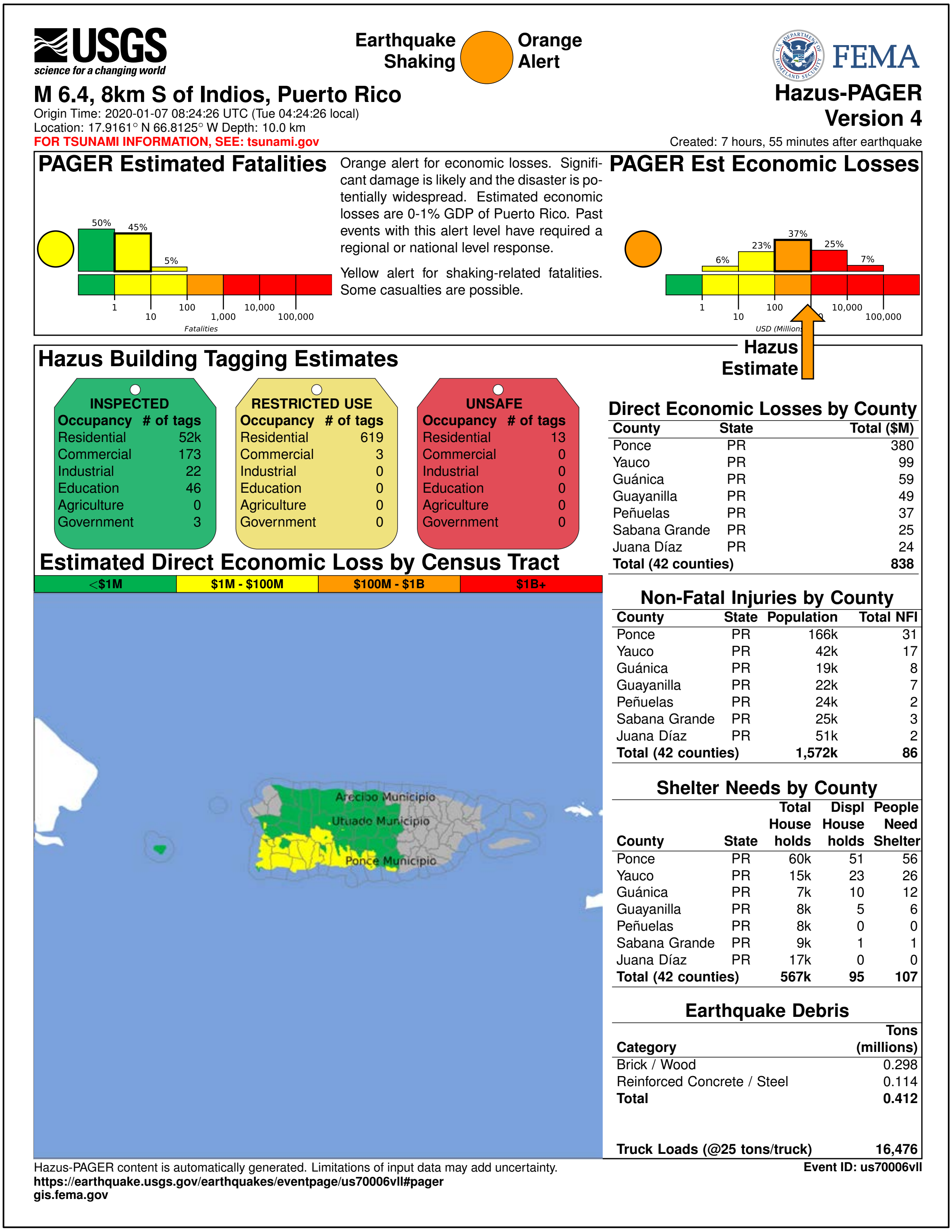
ShakeCast® is a software application that automatically retrieves ShakeMap shaking estimates and performs analyses using fragility functions for bridges, buildings, and other structures (Fig. 7). The ShakeCast system aims to identify which facilities are most likely to be impacted by shaking—and thus which ones should be prioritized for inspection and response. ShakeCast then sends notifications to responders in the minutes after an event. The use of ShakeCast within a wide range of critical lifeline communities and use sectors, and their post-earthquake response protocols are discussed in companion papers [24, 25].

Dependencies: ShakeCast requires ShakeMap products delivered via PDL [1] since it uses a number of ShakeMap layers, primarily the ShakeMap grid of peak intensity measures. Users' inventories require a knowledge of each facility's fragility as a function of one of ShakeMap's IMs.

Gaps and Opportunities: ShakeCast could benefit greatly from the explicit use of ground failure estimates, more default classes of fragilities for facilities such as dams, pipelines, and other critical infrastructure that are based specifically on ShakeMap IMs. Likewise, more advanced fragilities, including vector-based models that are based on duration-based IMs (to be generated by ShakeMap in the future) could provide more accurate damage, inspection, and loss estimates specifically for such real-time, post-earthquake applications.

2.6 Ground Failure

The "Ground Failure" (GF) algorithms produce a new USGS earthquake information product that estimates landslide and liquefaction distributions in near-real-time [26]. GF went live on the USGS web pages in September 2018. The likelihood and distribution of landsliding and liquefaction are based on ShakeMap IMs and models developed with USGS external grants [26]. The GF product consists of maps and layers of the likelihood of sliding and liquefaction over the ShakeMap domain as well as quantitative estimates of the population exposed to these hazards. GF now assumes a proper position among the event-specific product "cards" on the Earthquake Program event pages (Fig. 2), and as layers on the interactive map therein (Fig. 8).



USGS science for a changing world

Earthquake Shaking Orange Alert

FEMA

M 6.4, 8km S of Indios, Puerto Rico

Origin Time: 2020-01-07 08:24:26 UTC (Tue 04:24:26 local)
Location: 17.9161° N 66.8125° W Depth: 10.0 km
FOR TSUNAMI INFORMATION, SEE: tsunami.gov

Hazus-PAGER Version 4

Created: 7 hours, 55 minutes after earthquake

PAGER Estimated Fatalities

Orange alert for economic losses. Significant damage is likely and the disaster is potentially widespread. Estimated economic losses are 0-1% GDP of Puerto Rico. Past events with this alert level have required a regional or national level response.

Yellow alert for shaking-related fatalities. Some casualties are possible.

PAGER Est Economic Losses

Hazus Building Tagging Estimates

INSPECTED

Occupancy	# of tags
Residential	52k
Commercial	173
Industrial	22
Education	46
Agriculture	0
Government	3

RESTRICTED USE

Occupancy	# of tags
Residential	619
Commercial	3
Industrial	0
Education	0
Agriculture	0
Government	0

UNSAFE

Occupancy	# of tags
Residential	13
Commercial	0
Industrial	0
Education	0
Agriculture	0
Government	0

Estimated Direct Economic Loss by Census Tract

Direct Economic Losses by County

County	State	Total ($M)
Ponce	PR	380
Yauco	PR	99
Guánica	PR	59
Guayanilla	PR	49
Peñuelas	PR	37
Sabana Grande	PR	25
Juana Díaz	PR	24
Total (42 counties)		**838**

Non-Fatal Injuries by County

County	State	Population	Total NFI
Ponce	PR	166k	31
Yauco	PR	42k	17
Guánica	PR	19k	8
Guayanilla	PR	22k	7
Peñuelas	PR	24k	2
Sabana Grande	PR	25k	3
Juana Díaz	PR	51k	2
Total (42 counties)		**1,572k**	**86**

Shelter Needs by County

County	State	Total House holds	Displ House holds	People Need Shelter
Ponce	PR	60k	51	56
Yauco	PR	15k	23	26
Guánica	PR	7k	10	12
Guayanilla	PR	8k	5	6
Peñuelas	PR	8k	0	0
Sabana Grande	PR	9k	1	1
Juana Díaz	PR	17k	0	0
Total (42 counties)		**567k**	**95**	**107**

Earthquake Debris

Category	Tons (millions)
Brick / Wood	0.298
Reinforced Concrete / Steel	0.114
Total	**0.412**
Truck Loads (@25 tons/truck)	**16,476**

Hazus-PAGER content is automatically generated. Limitations of input data may add uncertainty.
https://earthquake.usgs.gov/earthquakes/eventpage/us70006vll#pager
gis.fema.gov

Event ID: us70006vll

Fig. 6. Example of second page of 2PAGER for the M6.4 Indios, Puerto Rico earthquake. Top portion depicts PAGER loss model estimates; the lower portion presents Hazards U.S. (HAZUS) loss model estimates. The alert level, color-coded arrow connects the loss models, allowing PAGER and HAZUS economic loss model comparison. Field reconnaissance for both the Anchorage [3] and the Puerto Rico events showed reasonable performance in terms of the overall degree and distribution of these effects.

U.S. Department of Transportation
Federal Highway Administration

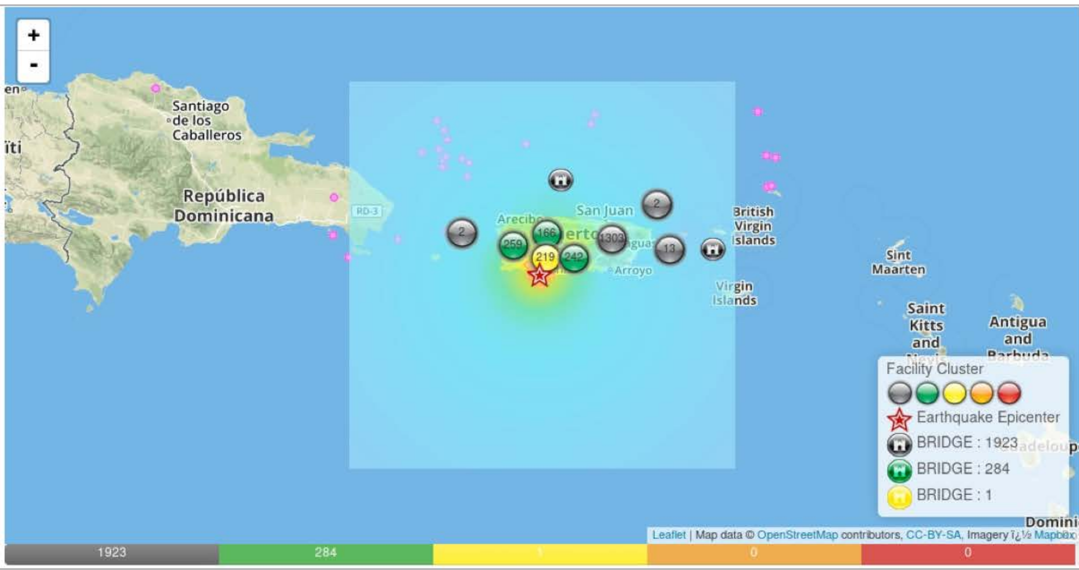
ShakeCast Report
National Earthquake Information Center (NEIC)

Magnitude 6.4 - 8 km S of Indios, Guayanilla, PR Version 5

Origin Time: 2020-01-07 03:24:26EST Process Time: 2020-01-07 17:58:00EST

Latitude: 17.9161 Longitude: -66.8125 Depth: 10.0 km

These results are from an automated system and users should consider the preliminary nature of this information when making decisions relating to public safety. ShakeCast results are often updated as additional or more accurate earthquake information is reported or derived.



Type	ID	Name	Ep. Distance (km)	Inspection Priority	PGA (%g)	PGV (cm/s)	PSA 1s (%g)	MMI	Vs30 (m/s)
BRIDGE	72_009121	009121 - LOCO RIVER	15.04	Moderate	29.35	27.65	32.56	VII	189.1
BRIDGE	72_005481	005481 - YAUCO RIVER	8.08	Low	34.85	22.01	20.64	VII	510.8
BRIDGE	72_029591	029591 - YAUCO RIVER	8.39	Low	33.76	20.83	19.22	VII	547.5
BRIDGE	72_010651	010651 - YAUCO RIVER	9.22	Low	34.16	22.31	21.41	VII	468
BRIDGE	72_024821	024821 - YAUCO RIVER	9.79	Low	34.32	23.71	23.57	VII	401.1
BRIDGE	72_018531	018531 - WATERWAY	10.49	Low	34.58	28.02	29.78	VII	288.4
BRIDGE	72_007341	007341 - LA MANUELA CREEK	10.72	Low	35.03	25.64	26.52	VII	328.4
BRIDGE	72_028001	028001 - PR 2	10.96	Low	34.05	24.34	24.75	VII	357.2
BRIDGE	72_009431	009431 - PR 2	11.64	Low	32.72	21.7	21.22	VII	426.5
BRIDGE	72_007961	007961 - PR 2	11.64	Low	31.9	20.51	19.7	VII	460.9
BRIDGE	72_024011	024011 - GUAYANILLA RIVER	11.78	Low	32.72	21.7	21.22	VII	426.5
BRIDGE	72_009452	009452 - WATERWAY	11.87	Low	32.5	21.04	20.34	VII	444.3
BRIDGE	72_009442	009442 - WATERWAY	11.87	Low	32.5	21.04	20.34	VII	444.3
BRIDGE	72_026251	026251 - LOCO RIVER	11.93	Low	30.55	20.23	19.72	VII	455.4

* MMI level may extend beyond map boundary; some facilities may not appear on the map due to space restriction

Fig. 7. Example of ShakeCast report for the M6.4 Indios, Puerto Rico earthquake. The Federal Highway Administration (FHWA) system provides inspection priorities based on likely bridge impact for all 50 states and Puerto Rico.

Dependencies and Datasets: GF calculations require ShakeMap shaking grids, and a number of globally available datasets and proxy datasets including topographic slope, Vs_{30}, geology, and wetness [24]. In developing GF algorithms, the USGS and many colleagues created an ***Open Repository of Earthquake-Triggered Ground-Failure Inventories*** [26], providing geospatial datasets for landslide and liquefaction model development.

Gaps and Opportunities: A remaining challenge with GF is accommodating regional and local geotechnical information where they are available to refine GF occurrence estimates, yet within the framework of coarser resolution global layers that were used to derive empirical, calibrated models of GF. Whereas local datasets *should* render higher-quality susceptibility layers for improved GF estimates, they are no longer part of the explicit model calibration and thus warrant additional validation. Further, the challenge remains of computing losses from GF probabilities where displacements must be inferred. Pursuing geospatially intersecting GF areas with critical infrastructure and population as a proxy for impact still does not allow for quantitative losses that could augment systems such as ShakeCast and PAGER's shaking-based loss estimates.

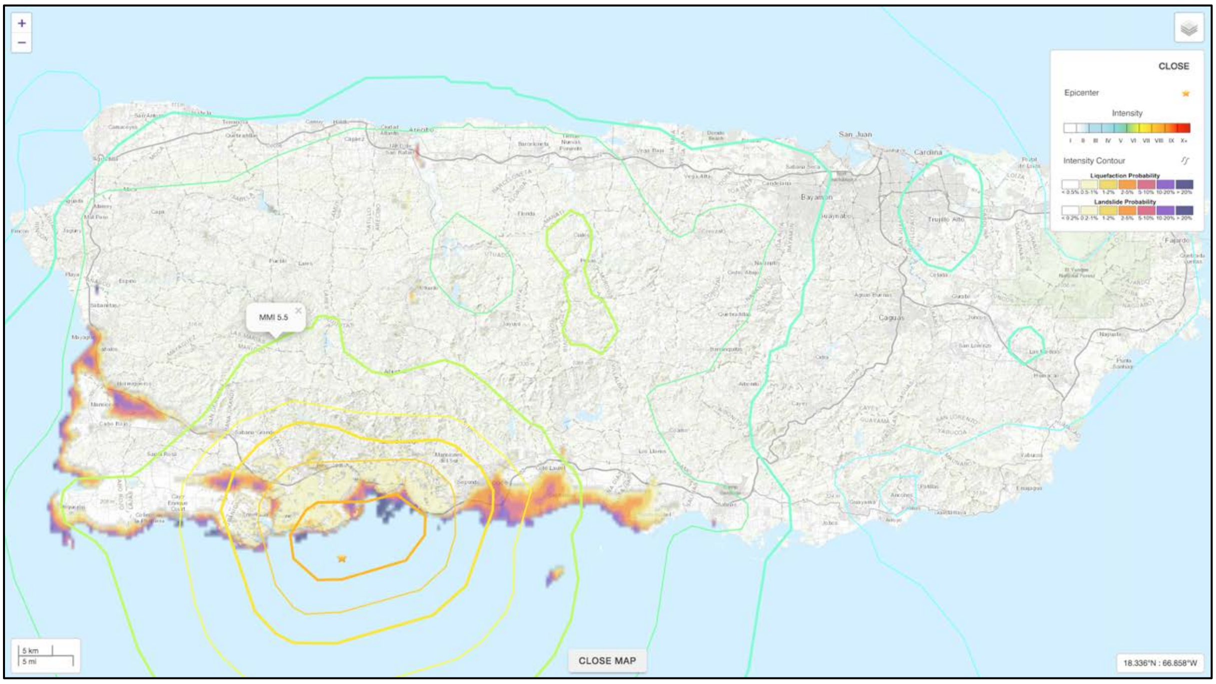


Fig. 8. Example of the USGS Ground Failure (GF) product as viewed via the interactive map for the M6.4 Indios, Puerto Rico earthquake.

4. Conclusion

The continual improvements and introduction of new USGS near-real-time shaking and impact products warrant occasional updates through international conferences and their proceedings. Herein, we've described advances in several of the existing shaking and loss estimation systems, focusing on new introductions and relating these systems to the interdependency on earlier products. We highlight advances on all operational earthquake shaking and impact estimation systems and describe two new tools in our portfolio: Ground Failure estimates wherein the likelihood and distribution of liquefaction and landsliding is depicted, and a derivative of the PAGER system for domestic use that combines the best aspects of USGS PAGER and FEMA's Hazus impact assessments. We also describe the underlying datasets we developed specifically to calibrate those systems. This summary also provides an up-to-date collection of relevant references of these systems, online datasets, and software repositories.

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