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RESEARCH ARTICLE

"How Do Shocks Affect International Reserves? A Quasi-Experiment of Earthquakes"

Quy Ta[1] · Yothin Jinjarak[1] · Ilan Noy[1]

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Abstract
We evaluate the change in international reserves in the aftermath of significant external shocks by using a quasi-experimental setup and focusing on earthquakes. Our objective is to understand the macroeconomic dynamics of quake-affected countries ex-post, and their ex-ante disaster risk mitigation strategies. The estimation is done on a panel of 103 countries over the period 1979–2016. We find that in the five years following a large earthquake: (i) Countries exposed to it accumulate reserves ex-post for precautionary reasons, supported by the inflows of foreign assistance and money expansion; (ii) Quake-prone countries tend to hold fewer reserves relative to the non-prone countries, suggested by the richer set of other disaster preventive measures in place for the former; (iii) The patterns of reserves holding post-earthquake vary with a country's income level and other macroeconomic fundamentals.

Keywords Disasters · Earthquakes · International Reserves · Foreign Exchange Holding

JEL Classification F31 · F41 · Q54

1 Introduction

Since 1995, more than 10,000 catastrophic disaster events have affected some 5.2 billion people. These catastrophes caused by natural hazards have caused hundreds of thousands of deaths and damages to assets valued at more than three trillion US

✉ Quy Ta
Quy.ta@vuw.ac.nz

Yothin Jinjarak
Yothin.jinjarak@vuw.ac.nz

Ilan Noy
Ilan.noy@vuw.ac.nz

1 School of Economics and Finance, Victoria University of Wellington, Wellington, New Zealand

dollars (EM-DAT 2020). The average damage caused by an earthquake was much larger than that of other types of disasters.[1] There were more than a thousand earthquakes and landslides that affected about 143 million people and caused damages to assets worth over 700 billion US dollars during this time. Among the types of damaging natural hazards, earthquakes are impossible to forecast their timing nor their intensity. Recent examples of major earthquakes include the 1999 Izmit earthquake in Turkey, the 2001 Gujarat earthquake in India, the 2005 Kashmir earthquake in Pakistan, the 2008 Wenchuan earthquake in China, the 2010 earthquake in Haiti, the 2011 Tohoku/Sendai earthquake in Japan, the 2015 earthquake in Nepal, and hundreds of other seismic events which have wrought economic pain. Better quantification of some of the macroeconomic impacts of disaster shocks (such as earthquakes) is the objective of this paper.

Recent studies have examined the effect of disasters on income growth, inflation, and trade. Evidence suggests that disasters worsen economic growth (Raddatz 2007, 2009; Toya and Skidmore 2007; Hochrainer 2009; Noy 2009; Strobl 2011; Cavallo et al. 2013; Felbermayr and Gröschl 2014); and distort inflation over the short-to-medium run (Fomby et al. 2013; Cavallo et al. 2014; Parker 2018; Heinen et al. 2019). A very limited number of empirical works, however, have addressed questions of monetary policy responses when such catastrophic events happen. Among very few studies, Klomp (2020) estimated a dynamic panel of 85 countries from 1960 and 2015, finding that, on average, the short-run policy interest rate falls in the first year after the earthquake to favour short-run economic recovery over price stability. Most relevant to our study is Strobl et al. (2020) on the evaluation of the short-term impact of hurricanes on international reserves (IR) in the Caribbean. Their evidence suggests that an increase in IR a month after the hurricane strike was followed by a decrease two months later. Given the relatively homogenous composition of their sample, they are only able to differentiate between high-income Caribbean Island countries (who mostly rely on income from services, especially financial services) and middle-income ones who rely more on tourism and agriculture). In contrast, our estimation of IR in the aftermath of disasters uses a sample that covers a larger and more diverse group of countries and a longer time horizon, thus allowing for a broader and more nuanced set of conclusions that seem to better reflect the motives of holding IR in the aftermath and over the medium term following a disaster.

In this paper, we examine the short- to medium-term impacts of disaster shocks on reserves holding in a panel of 103 countries; the sample is only constrained by the availablilty of data. Similar to Strobl et al. (2020), we use a quasi-experimental setup in which the timing and intensity of earthquakes are taken as measures of exogenous shocks impacting the economy. We use earthquakes as our indicator for disasters because earthquake occurrence has a spatial distribution that is wider than hurricanes or droughts. In addition, earthquakes predictions are still impossible with our current geo-seismic knowledge, so that one cannot expect anticipatory behaviour, unlike the case for hurricanes.

[1] We use data from EM-DAT (2020).

Specifically, our research questions are: (i) Did earthquake-affected countries accumulate IR at the onset and several years after a large earthquake, since they are vulnerable to these external shocks and because of the buffering role of IR?; (ii) Were there any resources available for affected countries to accumulate IR in such circumstances, e.g., the surge in foreign aid?; and (iii) Did quake-prone countries hold fewer IR than non-prone countries as the former were more likely to have other disaster preventive measures in place?

Our findings suggest that a large earthquake is associated, on average, with a five-year accumulation in the reserves-to-GDP ratio of 1%. We point out the rationale for holding IR in the aftermath of earthquakes, including the precautionary motive. We also examine possible channels through which affected countries raise foreign exchange reserves, including increasing broad money, receiving international assistance, and possibly receipt of international reinsurance claims. The patterns of holding reserves after quakes are also dependent on income levels and other characteristics of the affected countries. Reserves holding of middle-income countries tends to experience the largest change. Also, we find that quake-prone countries tend to end up holding fewer reserves by 1.1% of GDP, relative to their non-quake-prone counterparts, over a five-year horizon following an earthquake, suggested by the more significant role of other disaster preventive measures in place for the former group.

The rest of the paper is organized as follows. Section 2 discusses relevant studies and theoretical foundation. Section 3 presents the data and variable description while Sect. 4 describes the empirical specification. Section 5 discusses the estimation results, and Sect. 6 concludes.

2 Literature Review and Hypothesis

2.1 Existing Knowledge on Reserves Holding

Since the Asian financial crisis of 1997–1998, many developing and emerging market economies have accumulated large sums of IR in hard currency assets. Two motivations for accumulating large foreign exchange reserves are typically cited: First, from a mercantilist perspective, such accumulation helps nations promote exports by preventing or slowing domestic currency appreciation (Aizenman and Lee 2007). Second, reserves accumulation can arise from a "self-insurance" or "precautionary" motive. While formally disentangling the two motives of reserves holding is a challenge, the precautionary approach has gained more attention.

Allegret and Allegret (2018) point out that countries holding sufficient stock of foreign exchange reserves strengthen their ability to withstand disturbances resulting from boom-bust cycles in capital inflows. Using a sample of 134 countries over the period 1993–2004, Obstfeld et al. (2010) examine the financial motives behind reserves holding. They find that reserves holding is associated with the size of the banking system; i.e., countries with larger banking sectors tend to accumulate more reserves. They also find that holding reserves also helps shield domestic economies from the "double-drain" crisis scenarios in which banking and currency problems interact in ways likely to cause sharp and disruptive external currency depreciation.

Indeed, crises of this type are very costly over the 2–4 year period, as shown in Hutchison and Noy (2005). Third, reserves holding may be related to the trade-offs between monetary independence, financial openness, and exchange rate stability, i.e. the impossible trinity (Aizenman et al. 2013; Aizenman and Ito 2014). Aizenman and Hutchison (2012) find that the positive correlation between output volatility and the degree of capital account openness does not hold in countries with high levels of IR.

The empirical links between reserves holding and financial crises are most relevant to our analysis of the macroeconomic aftermath of disaster shocks across countries. The evidence along this line include Catão and Milesi-Ferretti (2014) that higher international reserves reduce the likelihood of external crises, Dominguez et al. (2012) that higher reserves accumulation prior to the global financial crisis was associated with higher post-crisis gross domestic product (GDP) growth, Noy (2009) that countries with more reserves appear more robust and better able to endure disasters, with less adverse spill-over into domestic production in the short term, and Aizenman and Jinjarak (2014) that counter-cyclical management of hoarding reserves in good times and selling them in bad times provides buffers stock financial services adding up to about 3% of the GDP in a sample of the eight largest emerging markets (BRICS, Indonesia, Mexico, Turkey) during 2000–2019.

On the other hand, there are opportunity costs associated with IR holding. In particular, the rate of return from holding IR should be lower than investing in other financial tools, including domestic investment, especially for developing countries. Economic theory generally suggests that IR should be negatively correlated with the opportunity cost of holding it; however, the empirical evidence is scant, due to the difficulty in assigning a single interest rate for IR holding while accounting for the associated risks (Flood and Marion 2002; Dabla-Norris et al. 2011). One study found the correlation between IR holding and its opportunity cost insignificant for advanced economies but relevant for emerging markets in the past; however, the rise in reserve holding in recent years has essentially eliminated this effect (IMF 2017).

Given the vulnerability of countries exposed to external shocks including disaster risks, the resources of the Global Financial Safety Net (GFSN) draw a lot of attentions, especially from poor countries. While alternative instruments for crisis prevention have gained popularity since the global financial crisis – e.g., bilateral swap lines—the International Monetary Fund (IMF) acting as a backstop (as a lender of last resort) still dominates the GFSN resources (IMF 2017; ECB 2018). As a result, the IMF regularly discusses annual proposals to reform its lending toolkit, with the aim of further strengthening the GFSN. Though, there is a concern about the cost of holding IR, it is still seen to be attractive as it provides full discretion to central banks against external liquidity shocks.

2.2 Hypothesis

Hypothesis 1 Countries exposed to disasters accumulate IR for a precautionary motive, given they are vulnerable to these external shocks, and therefore can utilize IR as a buffer.

One main incentive of reserves build-up in countries vulnerable to earthquakes is as self-insurance. Earthquakes are not randomly distributed around the world and tend to occur along the fault lines between tectonic plates; we control for this by including country fixed-effects. It may be that the occurrence of an earthquake makes this continuing (and constant) risk more salient, and therefore leads to additional holding of IR as self-insurance, similarly to the response to other external financial shocks. Put differently, disaster-afflicted countries are concerned about liquidity shortages and increase their holdings of IR as the liquidity risk becomes more salient.

Additionally, one could view the holding of reserves in the aftermath of a major quake as a means to insure against different types of financial crises that could be triggered by the seismic shock. For example, Klomp (2017) finds empirical evidence that large-scale disasters, notably major earthquakes and storms increase significantly the onset probability of a sovereign debt default by about 3 percentage points as these events worsen the government's balance sheet. Related recent research by Strobl et al. (2020) used a panel VAR with high-frequency (monthly) data on reserves to examine the short-term impact of hurricanes on reserve holdings. They found an immediate increase in foreign reserves (in the month after the hurricane strike), followed by a decline (observable over the next two months). Compared to Strobl et al. (2020), our study covers a much larger sample over a longer period, and importantly investigates the medium-term impacts of disaster shocks on IR holding, which better reflects the precautionary motive of holding IR.

Hypothesis 2 Affected countries accumulate IR over the medium term following a large earthquake to account for the money expansion in the banking system during the rebuild phase.

Affected countries' central banks would choose to stimulate economic growth by expanding money for the rebuild following the shock. The model given by Obstfeld et al. (2010) explains that the potential need for reserves is proportional to the size of broad money as authorities also typically prefer a degree of exchange rate stability.[2] Following destructive disasters, affected countries typically need financial resources for the rebuild. The event studies we describe in the Online Appendix also suggest India (Gujarat earthquake in 2001), Japan (Tohoku earthquake in 2011), and New Zealand (Canterbury earthquake in 2011) all expanded their broad money in the year of the quake and in the following years. Although the empirical findings from cross-country studies exploring the macroeconomic impacts of disasters are mixed, a major destructive disaster like an earthquake or a flood generally suggests that affected countries are likely to loosen monetary policy to assist the rebuild and economic growth (i.e., Skidmore and Toya 2002; Kahn 2005; Stromberg 2007; Toya and Skidmore

[2] Because the scope of the run out of domestic-currency deposits is proportional to the domestic banking system's liabilities. Deposits are perfectly liquid while bank assets are almost illiquid. Just in case of an adverse event, demand for foreign exchange goes up and the central bank needs to act as a lender of last resort.

2007; Belasen and Solomon 2008; Cuaresma et al. 2008; and Leiter et al. 2009; Klomp 2020, amongst other studies). As a result, reserves accumulation following a destructive disaster is aligned with this increase in broad money.[3]

Hypothesis 3 Following a major quake, affected countries can accumulate IR from the inflows of foreign assistance.

Evidence suggests that inflows of official development assistance (ODA) and remittances to vulnerable countries increase over the short-to-medium term after disaster shocks (Osberghaus 2019). Becerra et al. (2014) find that the median increase in ODA into low-income countries is 18% compared to the pre-disaster level of ODA flows, but that this increase inflow covers only 3% of the total estimated economic loss caused by these adverse events. Studies also show the positive association between disasters and remittances (Bluedorn 2005; Yang 2008; Amuedo-Dorantes et al. 2010; David 2011; Mohapatra et al. 2012; Bettin and Zazzaro 2018). Given quake-affected countries have motive of building up reserves following a quake, those countries could mobilize the financial liquidity available from international assistance to pursue this aim.

Hypothesis 4 Among quake-affected countries, quake-prone countries hold fewer IR than non-prone countries, as the former are more likely to have existing disaster preventive measures.

Countries vulnerable to disasters already have in place a suit of preventive measures, including emergency funds, contingent credit lines, insurance and reinsurance policies, catastrophe bonds (i.e., the Pacific Alliance Catastrophe Bond Program), and other financial instruments to absorb the shock.

For instance, access to the insurance schemes serves as an ex-ante preventive policy measure, transferring the country's disaster risks to the global capital markets. The Turkish Catastrophe Insurance Pool, a public–private partnership between the government of Turkey and the domestic insurance industry, provides earthquake insurance to homeowners. Several eearthquake-prone countries, jointly with multilateral organizations, have issued catastrophe bonds (CAT bonds). By June 30, 2018, CAT bonds had reached US$ 30 billion in international markets, including the issuance of US$ 1.36 billion Pacific Alliance CAT bonds in earthquake cover in February 2018 for Chile, Colombia, Mexico, and Peru (Aon 2018; World Bank 2019). Peru received a US$60 million payout from this CAT bond issuance for an 8.0 magnitude 2019 earthquake; while Mexico, in an earlier World Bank's MultiCat Program, received a US$150 million payout following an 8.2 magnitude earthquake in September 2017. These insurance-like financial instruments could help reduce the necessity of large IR holding for disaster-prone economies.

[3] A related question is whether countries exposed to disasters have adequate IR for this purpose. We provide some relevant discussion of this question in Sect. 6, without aiming to empirically and comprehensively answer it.

In another example, while Japan and New Zealand experienced severe earthquakes in early 2011, Japan's IR holding increased after the quake while New Zealand's IR did not, partly due to differences in their disaster-relief policies. In New Zealand, insurance coverage is over 95% for residential buildings, and international reinsurance covered half of the losses from disasters in New Zealand (Reserve Bank of New Zealand 2011). Japan, however, has a much lower insurance coverage with a relatively low rate of international reinsurance (Ito and McCauley 2019; Nguyen and Noy 2020).

Like all countries, earthquake-affected countries have to consider a tradeoff between IR holding and its opportunity costs. Given the role of the disaster preventive measures in buffering disaster shocks, one would hypothesize that quake-prone countries hold fewer IR than non-prone countries.

3 Data

3.1 International Reserves and Control Variables

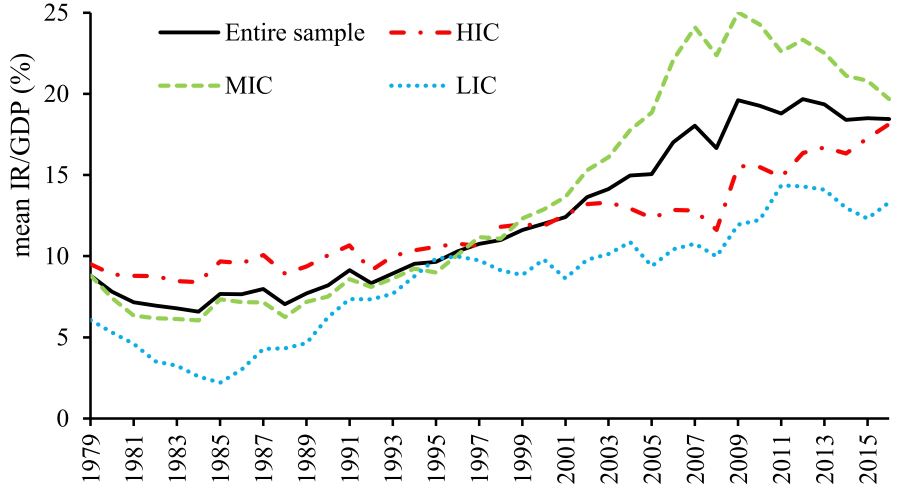
We use the reserves-to-GDP ratio as the main dependent variable.[4] Since earthquakes have an impact on the GDP of the affected countries, we use lagged pre-quake GDP in the denominator. We also adopt two panel unit root tests that accommodate unbalanced panel data, including the Fisher-ADF-type test and the Im et al. (2003) test. The former test portrays the reserves/GDP ratio as stationary while the latter shows this variable is integrated of order 1 (see Online Appendix Table 1). Therefore, we further render that variable stationarity by taking the first difference over pre-quake GDP. Lastly, we use real reserves in dollars (logged) as an alternative measure of our dependent variable.[5]

From Fig. 1, we note that there is an increasing trend in reserves/GDP ratio over time, with a significant increase following the Asian financial crisis. Regarding the reserves accumulation across countries, middle-income countries appear to hold more reserves (a sample mean of 14.3%) relative to high-income and low-income groups (sample means of 12% and 9%, respectively).

Besides, as far as the precautionary-insurance motive is concerned, the demand for reserves holding may also relate to capital outflows to GDP. Obstfeld et al. (2010) also point to the role of financial depth (measured by the broad money to GDP ratio) in driving the demand for foreign exchange reserves. Our estimation investigates these variables of interest.

[4] Related studies in international macroeconomics normalized IR with the economy's size, measured by GDP. See Aizenman and Lee (2007; 2008), Obstfeld et al. (2010), Aizenman and Hutchison (2012), Aizenman et al. (2013); Aizenman and Ito (2014), Catão and Milesi-Ferretti (2014), Allegret and Allegret (2018), etc.

[5] The choice of using the ratio of IR to initial GDP is not popular in the literature; however, this normalizes IR with the initial economy's size. We found robust findings for this alternative measure, provided in Online Appendix Table 2.



Source: World Development Indicators.

Fig. 1 IR/GDP by income level over the period 1979 – 2016

Following the relevant literature, a traditional set of control variables includes income per capita growth, exchange rate regime, trade openness, capital account openness, an index of political rights, and a financial crises indicator (see Aizenman and Lee 2007; 2008; Obstfeld et al. 2010; Dabla-Norris et al. 2011; Aizenman and Hutchison 2012; Aizenman et al. 2013; Aizenman and Ito 2014; and Allegret and Allegret 2018; etc.)[6][7]. We obtain data on most of the macroeconomic variables from the World Development Indicators of the World Bank. The data include income per capita growth rate, trade-to-GDP ratio, broad money to GDP, and population growth rate. Capital account openness data are from Chinn and Ito (2006).[8] Exchange rate regime data are from Shambaugh (2004) and Klein and Shambaugh (2008). A country–year observation is classified as being in a "peg" regime (as opposed to a

[6] To mitigate endogeneity concerns, we construct binary variables for trade and capital account openness using the means and medians as the cut-offs; the sample statistics suggest that the binary variables using either cut-off are interchangeable. The estimated results shown in this paper use the mean as the cut-off. The results using the median as the cut-off are robust and can be provided upon request.

Empirical studies show the quality of institutions could affect IR holding, for instance, countries with weaker institutions may need to hold more IR in order to shore up confidence or demonstrate fundamental soundness (Aizenmann and Marion 2004; Mwase 2012). Thus, we include 'an index of political rights' to account for institutional quality.

[7] Regarding the control for the opportunity cost of holding IR, as suggested in the relevant literature, this proxy can be measured by the interest rate differential between the U.S. treasury and a country's comparable rate (Dabla-Norris et al. 2011). However, once we include this variable, the sample size is reduced by two-thirds. We therefore only include this variable in a smaller sample as another robustness check.

[8] Updated data is made available by Chinn and Ito at: http://web.pdx.edu/~ito/Chinn-Ito_website.htm [Accessed 28th of April, 2021].

non-peg) if its currency is within a band against the base currency, or zero volatility in all months except for a one-off devaluation.[9] We follow the identification of inflation targeting regime countries of the IMF (see Jahan 2016 and more details on the exchange rate and IT regimes from Table 3 in the Appendix). Finally, we use financial crisis episodes from Laeven and Valencia (2018).

Our final sample covers 1979 to 2016 for all countries for which data are available: for the benchmark specifications, we have data for 103 countries. The variable description and sources are in the Appendix (Table 1-4).

3.2 Earthquakes

To quantify earthquakes, we use the Significant Earthquake Database collected by the National Oceanic and Atmospheric Administration (NOAA).[10] The NOAA database has worldwide coverage and information for each event on the physical magnitude, date and time of occurrence, latitude and longitude, focal depth, magnitude, maximum Modified Mercalli intensity, and socio-economic data such as the total number of casualties, injuries, houses destroyed, houses damaged, and dollar-damage estimates. A significant earthquake, in the NOAA database, meets at least one of the following criteria: caused any deaths, caused moderate damage (approximately one million US dollars or more), magnitude 7.5 or greater, Modified Mercalli Intensity X or greater, or the earthquake generated a tsunami.

In comparison to other data sources (i.e., the EM-DAT database from the Centre for Research on the Epidemiology of Disasters), the NOAA data record a larger number of earthquake events for almost all countries worldwide and more specific information about each one, especially their physical features. NOAA records every single significant earthquake and classifies it into a five-level scale based on both actual figures and estimates.[11] For instance, a five-level scale was used to classify monetary damage, which includes: 0 (no damage), 1 (limited), 2 (moderate), 3 (severe) and 4 (extreme). Although the NOAA database includes only 'significant' earthquakes, many of them may cause only minor physical damage and are likely to have only a negligible impact on the economy. For this reason, we filter the observations to only include events with scales 3 and 4 according to any one of the following criteria: number of deaths, number of injuries, monetary damage, and number of destroyed or damaged houses.

After combining with macroeconomic series, we have 356 large events (from 1,180 recorded events) in the final sample of 103 countries spanning 38 years. The

[9] There are 1,389 pegs in this sample.

[10] Another option would have been measuring these disasters in terms of the number of people affected or physical damage. But these depend on socio-economic factors and government policy choices made before and maybe even after the event (Felbermayr and Gröschl 2014; Klomp 2020). For instance, the total damage caused by a disaster is often positively correlated with the income level, while the number of people affected is negatively associated with income. As such, these measures will not be fully exogenous.

[11] The estimated data are only for some earthquakes with missing monetary damages. The figures for physical features are actual data.

average magnitude of these earthquakes is 6.2 on the Richter scale. The average Richter scale does not vary across different income groups, further supporting our selection criteria. There are 85 events in the high-income group of 34 countries, 258 events in the middle-income group of 51 countries, and 13 events in 18 low-income economies. Our baseline quake measure is the frequency of quake events in a specific country-year, an earthquake count variable that takes the timing of the event in a year into account (using the month when the particular event happened). More specifically, this measure is the number of large events that happened in a specific country in a designated year (accounting for each event's calendar month). This configuration allows an event happening earlier in the year to have a different impact than the one happening later, computed as follows:

$$\text{quake}_{i,t} = \text{frequency}_{i,t} * \frac{12 - \text{M}_{i,t}}{12} \tag{1}$$

where frequency_{it} is the number of quake events that happened in country i and year t, and M_{it} is the event's calendar month when a quake happened in country i and year t.

The baseline quake measure has a mean of 0.09 and a standard deviation of 0.39. From the distribution of quake events across countries in Table 1, on average, middle-income countries are the most exposed to earthquake risks with an average of 5 quakes per country (i.e., over the past four decades), followed by the high-income group (an average of 2.5 quakes per country) and low-income group (an average of 0.72 quakes per country). Besides, lower-income groups experience more severe events and more economic damage. The average damage/GDP ratio of an event is just over 1% for low-to-middle income countries, while for high-income countries the cost is, on average, 0.4% of GDP.

For robustness, we weigh the frequency of earthquakes by the land area of the affected countries to account for the country size.[12] We also use a physical measure of the intensity of the earthquakes (Richter scale) to validate the estimation results. For further comparison among the earthquake measures, we rescale the two alternative measures so that they have the same mean statistics as the benchmark earthquake measure[13], following similar approaches in related studies (e.g., Raddatz 2007; Ramcharan 2007; Noy 2009; Gassebner et al. 2010; Cuaresma et al. 2008; Oh and Reuveny 2010; Felbermayr and Gröschl 2014; Oh 2017; Klomp 2017; and Klomp 2020).

4 Empirical Specification

We incorporate the specifications of Ramcharan (2007) and Bettin and Zazzaro (2018) which analyse the medium-term impacts of disaster shocks by adding a number of lags of the disaster measure, given that large disasters are expected to have

[12] Dividing the baseline measure by land area in 1,000 km^2.

[13] Among the three measures, the one scaled by land area has the smallest standard deviation of 0.37 while the other two have a similarly close standard deviation of 0.39. The three measures are strongly correlated (correlation coefficient > 0.96).

Table 1 Earthquake distribution across countries

	All countries	HIC	MIC	LIC
Country number	103	34	51	18
Event number	356	85	258	13
Average number of quakes per country over the period 1979–2016	3.46	2.5	5.06	0.72
Quake measure in mean frequency (standard deviation)	0.091 (0.391)	0.065 (0.275)	0.133 (0.498)	0.019 (0.125)
Richter (average event)	6.2	6.23	6.2	6.1
Damage/GDP (average event)	1.05%	0.4%	1.2%	1%

Source: NOAA and authors' calculation

lasting impacts on the outcomes and considered as exogenous shocks. Following the approach in Obstfeld et al. (2010) which examine the motives of reserves holding, we include a set of control variables with one lag Zit-1, known as the conventional determinants of IR holding. All three referenced papers use a panel fixed-effects model.

The occurrence and physical feature (Richter scale) of earthquakes, in general, are assumed to be exogenous; i.e., unaffected by the level of reserves. Also, the large quakes are likely to have lasting impacts on macroeconomy of the affected countries. Thus, the estimating equation is used to examine the time path of reserves holding after the onset of real shocks as follows:

$$\text{Reserves/GDP}_{i,t} = \sum_{j=0}^{4}\left(\alpha_j \text{quake}_{i,t-j}\right) + \mu Z_{i,t-1} + v_t + \varepsilon_i + u_{it} \tag{2}$$

where $\text{quake}_{i,t-j}$ denote the earthquake measure and its four lags; Z_{it-1} denote the set of control variables with one lag, including income per capita growth, exchange rate regime, trade openness, capital account openness, political right index, and financial crises. We also include v_t (year fixed effects) to capture the global trend of increasing reserves in recent decades, and ε_i (country fixed effects) to account for the time-invariant factors determining reserves holding within countries.[14] We employ the Hausman (1978) specification test under the null hypothesis of an unbiased random effect estimator. We reject the null which suggests that the fixed-effects model is preferable. Finally, u_{it} are the residual error terms clustered at the country level.[15] Bertrand et al. (2004) and Obstfeld et al. (2010) argue that clustering standard errors by country allows for heteroskedasticity across countries, and more

[14] Some countries are more exposed to seismic risks than others, though that might not manifest itself in the actual experience of earthquakes in the seismically short time period we base our estimates on. The country fixed effects account for any differences in reserves holding policy that arises out of these differences in exposure.

[15] Our fixed-effects model allows for arbitrary dependence between the unobserved effect ε_i and the quake measure or other explanatory variables. It is unlikely that the unobserved factors in our sample are uncorrelated with the quake measure and other control variables.

importantly, allows for an unstructured serial correlation in the error terms within countries. In addition to the ordinary least square fixed-effects model, we apply the Arellano and Bond generalized method of moments (GMM) approach under a linear dynamic panel-data estimation and the Seemingly Unrelated Regressions (SUR) methodology. The GMM estimation is suitable for exploring the dynamic impacts of the shock while the SUR approach accounts for the fact that the disasters are exogeneous shocks that affect a set of variables at the same time, e.g., due to domestic absorption and terms of trade. Besides these econometric specifications, we introduce several case studies to further support our estimation results.

The shock is assumed to be exogenous and does not systematically alter the exchange rate regime or inflation targeting regime.[16] Equation (3) further examines the role of country macroeconomic fundamentals in explaining the patterns of reserves holding after the shocks.

$$\begin{aligned} \text{Reserves/GDP}_{i,t} = \sum_{j=0}^{4} \left(\alpha_j \text{ quake}_{i,t-j} + \beta_j \text{ quake}_{i,t-j} * \text{X}_{i,t-1} \right) \\ + \pi \text{X}_{i,t-1} + \mu \text{Y}_{i,t-1} + v_t + \varepsilon_i + u_{it} \end{aligned} \quad (3)$$

where $\text{quake}_{i,t-j}$ denote the earthquake measure and its four lags; X_{it-1} denote explanatory variables with one lag, including trade openness, or exchange rate regime or IT regime; Y_{it-1} denote another set of control variables with one lag, including income per capita growth, exchange rate regime, trade openness, capital account openness, political right index, and financial crises without repetitions in any explanatory variables X_{it-1}. Thus, including X_{it-1} and Y_{it-1} reflects the full set of control variables in the baseline Eq. (2). Regarding the lag selection of the quake measure, we verify the persistence of the shock on the outcome variables (including different measures of IR) over a five-year horizon (average business-cycle frequency) using four lags in the baseline specifications. However, adjusting with a larger or smaller lag number compared to the baseline does not overturn our main findings. We show these results in the robustness checks (Table 7 and Appendix Table 4).

5 Results

5.1 Reserves Holding in the Aftermath of Earthquakes

Table 2 reports the average increase in IR over a five-year horizon following earthquakes.[17] Earthquakes generally have both contemporary and medium-term impacts

[16] To interpret the estimated coefficients β_j as the causal effect, as discussed in Ramcharan (2007), requires controls for other potential country features that could affect both explanatory variable X_{it} (exchange rate or monetary regimes) and the response to the shock.

[17] We also estimate leads of quake measure in the regressions to examine if vulnerable countries accumulate more reserves before the events. This alternative specification may serve as a falsification test for whether the quake-affected countries and others were on a different trajectory of reserves accumulation. There are no significant coefficients on these leads of the quake measure.

on IR across countries. All other things being equal, in column 1 of Table 2, the occurrence of an earthquake is associated with an increase in a five-year accumulation in the reserves-to-GDP ratio by 1.03%.[18],[19] Our estimates are robust for when the other measures of reserves are used (first difference of reserves over pre-quake GDP; and real reserves in logged terms). In column 2, the accumulative impact of the same shock on the change in reserves is 0.66% of the GDP while columns 3 shows the increase in real reserves by 8.7 percentage points after an earthquake which is equivalent to just over 1% of GDP in our sample[20]. The impact of earthquakes on international reserves appears both statistically and economically significant. Likewise, when the alternative measures for earthquakes are used, the impacts remain robust as in the baseline estimation (columns 5 to 12 of Table 2). Specifically, an earthquake shock is associated with an increase in reserves/GDP by 1.01% for the model with the weighted quake measure (column 5) and 1.45% for the one with the Richter measure (column 9).

5.2 Macroeconomics of IR Response to Earthquakes

One main incentive of reserves build-up in countries vulnerable to quakes is a precautionary and self-insurance motive. Our findings in Table 2 are largely supportive of this hypothesis.

Also, column 4 of Table 2 suggests that an earthquake is associated with an accumulated increase in broad money by 6.55% of GDP over the five-year horizon. The model given by Obstfeld et al. (2010) explains that the potential need for reserves is proportional to the size of broad money. We find that reserves accumulation after the quakes is consistent with the increase in broad money level relative to its economic size. The event studies we describe in (Online) Appendix Case studies also suggest Haiti (earthquake in 2010), India (Gujarat earthquake in 2001), Japan (Tohoku earthquake in 2011), and New Zealand (Canterbury earthquake in 2011) all expanded their broad money in the year of the quake and in the following years.

Given the motives of holding IR in the presence of a quake, those affected countries could mobilize their reserves holding aided by the financial liquidity available from international assistance in response to the quake shocks. Our estimates in Table 3 are in line with the findings in the relevant literature. Because those financial flows (ODA and remittances) are largely only relevant for middle-income and

18 The five-year accumulated impact of an earthquake on reserves is the summation of the statistically significant coefficients on the quake measure and its lags, in particular, it is (0.601 + 0.43 = 1.031%).

19 Instead of using trade/GDP as a control variable, we include exports/GDP, or imports/GDP separately, then combine both of them, we end up having robust results: the marginal and aggregate impacts of quake shocks on IR holding remain almost similar (e.g., a five-year impacts of IR accumulation by 0.93% to 1% of GDP).

20 Mean IR/GDP in our sample is around 13%, so an 8.7 percentage point increase in real reserves is equivalent to 13%*8.7% or just over 1% of GDP.

Table 2 Five-year impact of earthquakes on international reserves

Dependent variable	IR/GDP	ΔIR/GDP	ln_IR	M2/GDP	IR/GDP	ΔIR/GDP	ln_IR	M2/GDP	IR/GDP	ΔIR/GDP	ln_IR	M2/GDP
Quake measure	**Baseline**				**weighted**				**Richter**			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
quake	.601***	.320**	.043*	3.748***	.581**	.325*	.041*	3.531**	.951***	.556**	.053**	4.12**
	(.216)	(.152)	(.022)	(1.377)	(.241)	(.164)	(.023)	(1.471)	(.332)	(.246)	(.022)	(1.616)
quakeL1	.838	.302	.044*	3.71	.723	.269	.043*	3.309	.589	.052	.028*	3.26
	(.666)	(.238)	(.022)	(2.558)	(.612)	(.235)	(.023)	(2.464)	(.556)	(.226)	(.017)	(2.313)
quakeL2	.43***	.339**	.017	2.806***	.424***	.316**	.016	2.624**	.496***	.346***	.017	2.694**
	(.132)	(.132)	(.013)	(1.01)	(.138)	(.142)	(.014)	(1.011)	(.151)	(.129)	(.013)	(1.198)
quakeL3	-.513	-.035	-.011	-.874	-.388	.005	-.008	-.547	-.412	.013	-.013	-.724
	(.539)	(.193)	(.027)	(1.847)	(.479)	(.188)	(.026)	(1.615)	(.495)	(.184)	(.023)	(1.582)
quakeL4	.465	.426	-.029	2.589	.409	.361	-.031	2.465	.202	.206	-.027	1.962
	(.343)	(.298)	(.028)	(1.576)	(.328)	(.296)	(.027)	(1.623)	(.316)	(.313)	(.026)	(1.485)
Observations	2923	2912	2922	2772	2923	2912	2922	2772	2923	2912	2922	2772
R-squared	.858	.172	.893	.785	.857	.171	.893	.784	.858	.171	.893	.785

All columns add time and country fixed effects. Standard errors in parenthesis are clustered by country. quakeL1, quakeL2, quakeL3, quakeL4 are lagged 1–4 year earthquake measures. Columns (1)—(3), (5) – (7), (9) – (11) control one lag of the dependent variable, per capita GDP growth rate, trade, capital account openness, exchange rate regime, political right, and financial crises. Columns (4), (8), (12) controls one lag of M2/GDP, per capita GDP growth rate, trade and capital account openness, political right, and financial crises (one lag for all controls)

*** $p<.01$; ** $p<.05$; * $p<.1$

low-income countries, we provide a more relevant discussion in the next section evaluating the impacts of quakes across countries with different levels of income per capita. Note that some countries rely more on remittances; for instance, India (2001), Nepal (2015), and Pakistan (Kashmir 2005). Some other countries receive significant inflows of ODA; for instance, ODA to Haiti doubled after the 2010 earthquake (increase by 17% of GDP) and cumulatively increased by more than 50% of GDP over the five-year horizon since 2010 relative to the pre-quake average level; ODA to Nepal increased by 1.3% of GDP in 2015 when the quake hit and cumulatively increased by 4% of GDP over the period 2015–2019 (ODA was 5.6% of GDP in 2015 compared to 4.3% in 2014).

Countries might also accumulate foreign exchange from international (re)insurance payments. Ito and McCauley (2019) show empirical evidence that the international reinsurance share is positively associated with IR. They also found that losses from disasters are only shared internationally to a very limited extent across countries; the average portion of economic damage offset by reinsurance is less than 5%. According to World Bank (2019), the investment in CAT bonds has resulted in approximately US$ 2.5 billion in investor orders and lower premium rates due to high demand for these instruments. Reserve Bank of New Zealand (2011) provides a useful case study. Following the Canterbury earthquakes in 2010–11, reinsurers contributed 66% of the total insurance claims, and thus significant funding for settling earthquake compensation claims was from large global insurers.

5.3 Impact of Earthquakes on IR Accumulation by Income Level

Table 3 presents the five-year impact of earthquakes by income group (using the World Bank's classification). The baseline estimation results in Table 3 show different patterns across the income groups (results using the other two quake measures are available upon request).

In Table 3, we can see the five-year accumulated impact of an earthquake on reserves/GDP is significant across high- and middle-income countries (columns 1 and 2) while there is no observable robust impact for the low-income group. The reserves holding of high-income countries is possibly linked to trade channel we discuss later while reserves accumulation of the middle-income countries is the most responsive. Given that middle-income countries experienced the most frequent and severe earthquakes on average (Table 1), our estimates of the significant increase in IR after the earthquake shocks for those countries are supportive of the motives of IR accumulation explained earlier.

Regarding the channels for reserves accumulation following a quake, we also find a significant increase in broad money in middle- and low-income countries (columns 3 and 6 of Table 3). Both middle- and low-income groups registered a significant increase in remittances and ODA following the quakes (the data on remittances and ODA are only applicable and available for middle- and low-income countries). While the middle-income group is more dependent on

Table 3 Five-year impact of earthquakes by income level (baseline)

Dependent variable	**IR/GDP**	**IR/GDP**	**M2/GDP**	**ln_remittance**	**ln_ODA**	**M2/GDP**	**ln_remittance**	**ODA/GDP**
Income level	**HIC**	**MIC**				**LIC**		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
quake	.409	.503*	2.961***	.18**	.129**	3.087*	-.214	1.676
	(.282)	(.259)	(.973)	(.073)	(.055)	(1.696)	(.471)	(1.245)
quakeL1	-.134	1.227	4.334	.111	.055	-1.029	.576**	1.572*
	(.221)	(.845)	(3.447)	(.066)	(.057)	(1.517)	(.214)	(.766)
quakeL2	.215	.396**	2.534***	.094**	.036	2.335*	.312	1.97
	(.25)	(.175)	(.825)	(.046)	(.104)	(1.24)	(.228)	(1.199)
quakeL3	.596*	-.992	-1.877	.019	.037	-2.358	.913***	4.321**
	(.312)	(.67)	(2.229)	(.063)	(.158)	(5.09)	(.224)	(1.877)
quakeL4	-.069	.719	1.758	.13*	.065	2.805	.251	-1.093
	(.344)	(.449)	(1.227)	(.067)	(.109)	(2.249)	(.536)	(1.659)
Observations	1037	1443	1484	1478	1399	515	448	542
R-squared	.833	.872	.84	.077	.334	.902	.355	.209

Notes: All columns add time and country fixed effects. Standard errors in parenthesis are clustered by country. quakeL1, quakeL2, quakeL3, quakeL4 are lagged 1–4 year earthquake measure. Columns (1) and (2) control one lag of IR/GDP, per capita GDP growth rate, trade, capital account openness, exchange rate regime, political right, and financial crises. Columns (3) and control one lag of M2/GDP, per capita GDP growth rate, trade and capital account openness, political right, and financial crises. Columns (4), (5), (7) and (8) control per capita GDP growth rate, trade, political right, and financial crises (one lag for all controls)

*** $p<0.01$; ** $p<0.05$; * $p<0.1$

remittance inflows, the low-income group is dependent on both remittances and foreign aid. For the former group, columns 4 and 5 of Table 3 present the cumulative increases in remittances and ODA after an earthquake are 40 percentage points and 13 percentage points respectively. Though columns 6 to 8 of Table 3 report the increases in broad money, remittances, and ODA in low-income countries following a quake, we do not find robust impacts of the quake shock on reserves for those countries.

5.4 Impact of Earthquakes on IR Accumulation in Quake-Prone Countries

We further investigate the dynamics of reserves holding based on the location of the affected countries. We define earthquake-prone countries as those on the Pacific Rim, in South Asia (India, Nepal, Pakistan, Afghanistan), South-East Europe (Italy, Greece, Turkey), the Caribbean, and South Pacific island countries (these are all regions that are located on or near tectonic plate boundaries). In the estimation, we added a dummy variable representing these earthquake-prone countries. We subsequently estimated the sample allowing for different coefficients for these countries by interacting the earthquake-prone dummy with the earthquake measures (Table 4). Our results show that these earthquake-prone countries tend to accumulate fewer reserves relative to other countries. In particular, quake-prone countries tend to hold fewer reserves ex-post (by 1.1% of GDP) relative to the non-prone countries (column 1). This finding is consistent using alternative earthquakes and IR measures. Our results presented in Table 4 support the hypothesis that quake-prone countries hold fewer IR than non-prone countries, given the availability of preventive and buffering measures against disasters[21].

5.5 Impact of Earthquakes on IR Accumulation by Trade Openness

Trade openness may influence reserves holding patterns across countries in the aftermath of quakes. Our findings indicate the degree of trade openness is positively associated with reserves accumulation in high-income countries and negatively associated with reserves in middle-income countries (Table 5).[22] The estimates are robust for the whole sample and the sub-samples of high- and middle-income countries, using any of the available earthquake measures.[23]

[21] For estimations controlling for the opportunity cost of holding IR (the sample size is reduced by two-thirds), we found negative yet statistically insiginificant coefficients for this control variable.

[22] Trade openness is defined as a binary variable using the mean of trade/GDP as the cut-off. Trade/GDP ratio which is higher than the cut-off represents high trade openness; otherwise, it is low trade openness.

[23] Due to the data availability of some of the macroeconomic variables, especially the reserves/GDP, our sample includes only 18 low-income countries. In those countries, the number of events is insufficient to continue with this investigation separately. Moreover, we do not find the robust impact of the quake shock on reserves in those countries earlier.

Table 4 Impact of earthquakes on international reserves in quake-prone countries

Dependent variable	IR/GDP				ΔIR/GDP	
Income level	All	MIC	All	MIC	All	MIC
Quake measure	Baseline		weighted		Baseline	
	(1)	(2)	(3)	(4)	(5)	(6)
quake	.652***	.647***	.683***	.686**	.189	.177
	(.195)	(.233)	(.255)	(.283)	(.166)	(.165)
quakeL1	1.588	1.724	1.517	1.695	.707*	.677*
	(1.07)	(1.128)	(1.077)	(1.169)	(.365)	(.393)
quakeL2	.442**	.332	.473**	.358*	.398	.249
	(.209)	(.206)	(.207)	(.21)	(.24)	(.25)
quakeL3	-.848	-.977	-.709	-.878	.015	-.162
	(.972)	(1.02)	(.939)	(1.008)	(.361)	(.379)
quakeL4	.898*	1.085**	.86*	1.089**	.884***	1.051***
	(.468)	(.472)	(.476)	(.487)	(.316)	(.297)
quake*prone	-.278	-.795**	-.325	-.858**	.146	.052
	(.286)	(.344)	(.327)	(.371)	(.247)	(.327)
quakeL1*prone	-1.671	-1.776	-1.625	-1.823	-.954**	-.949*
	(1.091)	(1.189)	(1.098)	(1.215)	(.415)	(.548)
quakeL2*prone	-.21	-.217	-.254	-.308	-.291	-.191
	(.302)	(.446)	(.288)	(.406)	(.287)	(.413)
quakeL3*prone	.572	-.315	.52	-.282	-.252	-.653
	(1.063)	(1.161)	(1.019)	(1.124)	(.423)	(.509)
quakeL4*prone	-1.073*	-1.6**	-1.013*	-1.549**	-1.188***	-1.579***
	(.562)	(.695)	(.544)	(.637)	(.405)	(.556)
Observations	2923	1443	2923	1443	2912	1438
R-squared	.859	.873	.858	.873	.176	.252

All columns add time and country fixed effects. Standard errors in parenthesis are clustered by country. quakeL1, quakeL2, quakeL3, quakeL4 are lagged 1–4 year earthquake measure. All columns control one lag of the dependent variable, per capita GDP growth rate, trade, capital account openness, exchange rate regime, political right, and financial crises (one lag for all controls)

*** $p<0.01$; ** $p<0.05$; * $p<0.1$

In the baseline estimation, very open economies accumulated fewer reserves by 0.77% of GDP over a five-year horizon after an earthquake, compared to their low trade openness counterparts (Column 1). This finding is obviously driven by the sub-sample of middle-income countries (Column 3).

In contrast, for the high-income group, the more open they are to trade, the higher their capacity to accumulate reserves over the medium run following a quake. Interestingly, we find that high-income countries appear to depreciate real effective exchange rate in the second and third years following the shock that might support their trade balance (Column 7).

Table 5 Impact of earthquakes on international reserves leveraged by trade openness

Dependent variable	IR/GDP						REER
Income level	All	HIC	MIC	All	HIC	MIC	HIC
Quake measure	Baseline			weighted			Baseline
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
quake	.718***	.338	.59***	.743***	.332	.64***	-.229
	(.177)	(.304)	(.198)	(.214)	(.307)	(.232)	(2.324)
quakeL1	.988	-.157	1.589	.868	-.182	1.504	-.99
	(.788)	(.228)	(1.015)	(.765)	(.235)	(1.065)	(1.01)
quakeL2	.318**	.168	.275	.321**	.162	.267	-2.705**
	(.157)	(.265)	(.263)	(.159)	(.261)	(.266)	(1.002)
quakeL3	-.536	.473	-1.145	-.422	.475*	-1.058	-2.607*
	(.648)	(.29)	(.832)	(.605)	(.268)	(.824)	(1.358)
quakeL4	.516	-.133	.893	.457	-.187	.857	-2.48**
	(.415)	(.361)	(.567)	(.412)	(.354)	(.581)	(1.076)
quake*trade	-.769***	2.368	-.724**	-.752***	1.624	-.745***	
	(.23)	(1.572)	(.292)	(.21)	(1.062)	(.25)	
quakeL1*trade	-.665	.319	-1.254	-.561	.234	-1.17	
	(.874)	(.902)	(1.128)	(.817)	(.665)	(1.137)	
quakeL2*trade	.608	1.484**	.501	.467	1.022**	.402	
	(.623)	(.698)	(.754)	(.567)	(.5)	(.701)	
quakeL3*trade	.345	3.86*	.816	.29	2.736**	.722	
	(.741)	(2.067)	(.891)	(.692)	(1.329)	(.882)	
quakeL4*trade	-.352	1.638	-.676	-.273	1.237	-.637	
	(.425)	(2.025)	(.555)	(.403)	(1.385)	(.551)	
Observations	2918	1035	1442	2918	1035	1442	1037
R-squared	.858	.832	.873	.857	.833	.872	0.169

All columns add time and country fixed effects. Standard errors in parenthesis are clustered by country. quakeL1, quakeL2, quakeL3, quakeL4 are lagged 1–4 year earthquake measure. All columns control per capita GDP growth rate, trade, capital account openness, exchange rate regime, political right, and financial crises (one lag for all controls). Columns (1) – (6) add one lag of IR/GDP

*** $p<0.01$; ** $p<0.05$; * $p<0.1$

5.6 Impact of Earthquakes on IR Accumulation by the Exchange Rate and Monetary Regimes

We control for the exchange rate regime and find its coefficient positive and statistically significant in the main regressions, supporting the role of exchange-rate stability in reserves hoarding (Obstfeld et al. 2010). We also find the exchange rate regime plays a role in explaining reserves patterns in the onset of quake shocks. In particular, countries with fixed-rate regimes appear to hold more reserves until the second year after the quake compared to flexible rate regime countries, in both high-income and middle-income countries (Columns 1 to 3 of Table 6). Similar results are found

Table 6 Impact of earthquakes on IR leveraged by exchange rate and IT regimes (baseline)

Dependent variable	IR/GDP								
Income level	All	HIC	MIC	All	HIC	MIC	All	HIC	MIC
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
quake	.082	.491**	-.094	.557**	.319	.406	-.021	.483*	-.281
	(.152)	(.234)	(.247)	(.228)	(.295)	(.272)	(.204)	(.268)	(.294)
quakeL1	-.011	-.066	.045	.938	-.168	1.423	-.017	-.041	.043
	(.192)	(.169)	(.294)	(.775)	(.217)	(.998)	(.261)	(.144)	(.422)
quakeL2	.043	.076	-.048	.497***	.221	.527*	-.046	.123	-.13
	(.319)	(.302)	(.369)	(.187)	(.206)	(.274)	(.359)	(.276)	(.473)
quakeL3	-.638	.52	-1.047	-.542	.675*	-1.108	-.681	.557	-1.136
	(.538)	(.335)	(.705)	(.665)	(.345)	(.83)	(.628)	(.37)	(.816)
quakeL4	.252	.367*	.28	.611	.132	.97*	.389	.362*	.529
	(.322)	(.21)	(.462)	(.378)	(.241)	(.5)	(.378)	(.212)	(.581)
quake*peg	1.395***	-.594	1.573***				1.464***	-.578	1.705***
	(.29)	(.5)	(.476)				(.309)	(.511)	(.526)
quakeL1*peg	.797**	-.42	.651*				.816**	-.44	.689*
	(.362)	(.809)	(.347)				(.381)	(.814)	(.401)
quakeL2*peg	1.413**	.914**	1.649**				1.49**	.873**	1.706**
	(.627)	(.423)	(.736)				(.654)	(.423)	(.812)
quakeL3*peg	.741	.983	.179				.784	.959	.266
	(.519)	(.714)	(.539)				(.521)	(.713)	(.586)
quakeL4*peg	.597	-1.155***	1.145				.47	-1.14***	.915
	(.719)	(.312)	(.741)				(.723)	(.32)	(.793)
quake*IT				.191	.035	.356	.39	-.108	.58
				(.631)	(.382)	(.709)	(.762)	(.368)	(.929)
quakeL1*IT				-.425	.195	-.799	.049	-.169	.037
				(.845)	(.641)	(1.093)	(.34)	(.506)	(.463)
quakeL2*IT				-.237	.014	-.477	.361	-.302	.248
				(.329)	(.636)	(.512)	(.383)	(.385)	(.589)
quakeL3*IT				.119	-.425	.428	.173	-.28	.281
				(.869)	(.612)	(1.045)	(.693)	(.431)	(.886)
quakeL4*IT				-.703	-1.469	-.992	-.603	.185	-.792
				(.535)	(.872)	(.745)	(.433)	(.879)	(.637)
Observations	2829	1004	1394	2923	1037	1443	2829	1004	1394
R-squared	.861	.822	.878	.858	.833	.873	.861	.822	.878

All columns add time and country fixed effects. Standard errors in parenthesis are clustered by country. quakeL1, quakeL2, quakeL3, quakeL4 are lagged 1–4 year earthquake measure. All columns control one lag of IR/GDP, per capita GDP growth rate, trade, capital account openness, exchange rate regime, political right, and financial crises. Columns (4) – (9) add IT regime (one lag for all controls)

*** $p<0.01$; ** $p<0.05$; * $p<0.1$

when using the two alternative quake measures (see Appendix Table 5 for further comparison). This finding might be relevant to the estimates given by Klomp (2020) in which central banks with a fixed exchange rate choose to raise the interest rate to fight against inflation pressure over the short-run (up to two years)[24]. In addition to this, in the medium-term following the shock, the high-income countries with peg regimes tend to deplete their reserves by 0.79% GDP in the fourth year after the shock.[25] It might be relevant to the continuous depreciation in the real exchange rate from the second year following a quake only observed in the high-income economies (column 7 of Table 5)[26].

Regarding the role of the monetary regime, our findings show similar patterns across high-income and middle-income countries. Specifically, countries with or without inflation targeting (IT) regimes tend to be homogenous in reserves holding patterns after the earthquakes, though the potential channels might not be the same (Columns 4 to 6 of Table 6). Klomp (2020) found IT countries are more likely to raise interest rates to keep their inflation within the target, while non-IT countries appear to be more willing to cut the policy rate. A hypothesis to be tested could be: the former group could experience capital inflows triggered by higher domestic interest rates while the latter group could improve trade balance due to the exchange rate depreciation. Our findings are again consistent across the alternative quake measures (see Appendix Table 5).

We further combine these above-mentioned variables and their interactions with the quake measure to reaffirm the findings. The results remain robust for the estimates of interactions of exchange rate regime and IT regime with the quake measure (columns 7 to 9 of Table 6, and Appendix Table 5).

5.7 Additional Robustness Checks

All the alternative specifications that we estimated yielded largely consistent impacts of quakes on IR. These were: (i) Using four different measures of reserves, including IR/pre-quake GDP as the baseline measure, change in IR/pre-quake GDP, IR/initial GDP, and real reserves in dollar value in logged terms (see Tables 2–7); (ii) Using three quake measures, including frequency of earthquakes, frequency weighted by land area, and Richter scale (see Tables 2 and 4); and (iii) Using different estimation techniques, including panel fixed effects (Tables 2-6); GMM; and SUR (Table 7).

Our estimates remain largely consistent across different specifications, dependent variables, and quake measures, and when compared to the baseline shown in Tables 2 and 5; and Appendix Tables 4-5. The GMM and SUR estimates are consistent, though show somewhat larger coefficients than the baseline findings. For

24 This possible policy action might trigger capital inflows.

25 To be precise, in column 2 of Table 4, the estimated coefficient of the interaction term quakeL4*peg is -1.155 (negative and statistically significant) while the coefficient of the quakeL4 is 0.367 (positive and significant). Thus, pegged countries in the high-income group appear to deplete reserves by 0.788% of GDP (= 1.155 – 0.367).

26 If the depreciation in the real exchange rate is traded by the expansionary monetary policy that might trigger capital outflows there, some reserves loss could be expected.

Table 7 Impact of earthquakes on international reserves – GMM and SUR estimations

Estimation	GMM								SUR	
Dependent variable	**IR/GDP**	**IR/GDP**	**IR/GDP**	**M2/GDP**	**IR/GDP**	**IR/GDP**	**ln_IR**	**ΔIR/GDP**	**IR/GDP**	**ΔIR/GDP**
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
quake	1.125***	.75***	.16	3.643***	.812***	.75***	.048*	.291*	.605**	.408
	(.336)	(.225)	(.269)	(.956)	(.25)	(.22)	(.026)	(.176)	(.269)	(.251)
quakeL1	.8	1.1	.691**	4.422	1.121	1.05*	.085**	.509**	.974***	.507*
	(.562)	(.686)	(.341)	(3.211)	(.701)	(.583)	(.034)	(.233)	(.284)	(.265)
quakeL2	.693***	.585***	.075	2.222***	.511***	.532***	.016	.306**	.453	.462*
	(.226)	(.163)	(.265)	(.631)	(.157)	(.199)	(.017)	(.14)	(.282)	(.263)
quakeL3	-.539	-.482	-.442	-1.997	-.302	-.486	.021	-.027	-.576**	.011
	(.856)	(.73)	(.401)	(2.862)	(.652)	(.778)	(.028)	(.187)	(.271)	(.252)
quakeL4	.281	.395	.184	2.339*		.121	-.016	.472*	.523**	.552**
	(.242)	(.259)	(.279)	(1.351)		(.3)	(.024)	(.261)	(.260)	(.242)
quakeL5						.898				
						(.981)				
M2/GDP			.132***							
			(.044)							
Observations	3163	2922	2648	2814	2988	2856	2922	2911	2,648	2,648

All columns add time fixed effects. Robust standard errors in parenthesis. quakeL1, quakeL2, quakeL3, quakeL4, quakeL5 are lagged 1–5 year earthquake measure

For the Generalized Method of Moments Estimation (GMM): Column (1) only includes one lag of IR/GDP. All other columns control one lag of the dependent variable, per capita GDP growth rate (as an endogenous variable), and other predetermined variables including trade, capital account openness, exchange rate regime, political right, and financial crises (one lag). Column (3) further adds M2/GDP (as another endogenous variable)

For the Seemingly Unrelated Regression Estimation (SUR): Columns (9) and (10) control one lag of the dependent variable, per capita GDP growth rate, trade, capital account openness, exchange rate regime, political right, and financial crises (one lag for all controls) and country-dummies

*** $p<0.01$; ** $p<0.05$; * $p<0.1$

instance, the five-year accumulative impact of an earthquake on the IR/GDP ratio is 1.3% in GMM and 1.5% in SUR, compared to 1.0% in the baseline estimation (Table 7).

Additionally, we examine several case studies to bring our analysis on earthquakes and IR holding to the fore. These include the Haiti earthquake in 2010 (Appendix), the Gujarat earthquake in 2001 in India; the Tohoku in 2011 in Japan; and the Canterbury earthquake in 2011 in New Zealand (Online Appendix), suggesting that these quake-affected countries increased IR holding in the short-to-medium run (five years) following the disaster.

6 Discussion and Conclusion

To better understand the dynamics of international reserves after shocks, we focus on the case of earthquakes in a cross-country sample. As the disasters are empirically exogenous, our quasi-experiment allows us to examine IR's responses to external shocks directly. Arguably, this setup is better suited to track reserves than alternative setups using financial shocks (e.g., currency and banking crises). We find evidence suggestive of precautionary motives for accumulating reserves in countries affected by disasters over the past four decades.

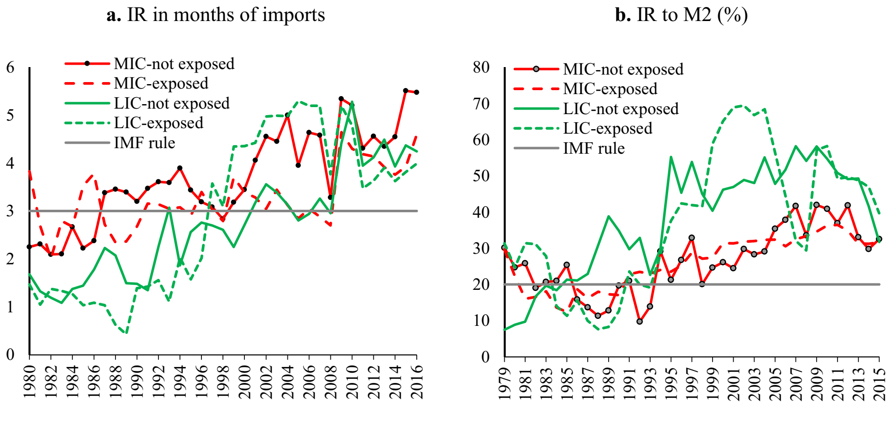
Is a disaster followed by currency appreciation or depreciation? Funding currencies like the Japanese yen or Swiss franc tend to appreciate when the economy is hit by a negative shock – the yen appreciated significantly in the immediate aftermath of the 2011 Tohoku Earthquake and Tsunami. Presumably, developing countries may opt to experience currency depreciation when they are hit by a disaster, given the negative shock suffered and the expansionary aspect of a depreciation. In addition, however, the consequences from disasters-induced exchange rate change can also be mediated by currency exposure in the balance of payments. Does this variant of 'original sin' matter for the movement of exchange rates post-disaster? We leave these questions for future research, but, in any case, disaster-afflicted countries have a precautionary motive of holding IR because of 'the fear of currency volatility'.

While our study provides new evidence on the patterns of reserves accumulation in the aftermath of disaster shocks, future research could delve further into the interactions between the external positions (IR and external net debt more broadly), financial risk transfer mechanisms (such as insurance), and domestic resource mobilization (fiscal and monetary) following shock events. These interactions have potentially important implications for the most optimal disaster risk management policies governments should follow. IR holding is a financial buffer that can help mitigate the impact of disasters, but it is only one of several tools that could be used for this purpose. One more potential issue would be investigating the possibility that disasters might trigger currency or banking crises and the role of reserves scales and response in such circumstances.

Multilateral organizations such as the IMF offer some guidelines for vulnerable and exposed countries, but these can be further fine-tuned to reflect a balanced assessment of all the different financial tools that be leveraged for this purpose. The

World Bank (2019), for example, recommends that disaster-affected countries consider issuing CAT bonds as important complements to fiscal budgetary reserves, while the Asian Development Bank implements fast-tracked support through contingent emergency assistance loan programs in the aftermath of disasters. The optimal balance between these various tools may still be insufficiently explored.

A series of studies from the IMF and others tries to examine the IR adequacy in emerging markets and developing countries, given the tradeoff between IR role as a buffer against crises and its opportunity cost (see Dabla-Norris et al. 2011; Mwase 2012; IMF 2017). *Ceteris paribus*, countries that are more exposed to external shocks should hold more IR. However, these IR adequacy models generally do not incorporate natural-hazard disaster shocks. Thus, whether countries exposed to such disasters have adequate IR remains an open question, especially for middle- and low-income countries. Though this study does not aim to empirically answer this question, one could hypothesize that disaster-afflicted countries should accumulate more IR than non-afflicted countries. Figure 2 provides a cursory observation regarding IR adequacy among middle- and low-income countries based on traditional metrics. A traditional 'rules-of-thumb' suggests that countries should hold IR equivalent to three-month worth of imports or 20% of broad money (e.g., Mwase 2012). The judgement here, of course, is incomplete given the lack of an econometric model that accounts for all possible factors driving demand for IR holding. Generally, middle- and low-income countries did not satisfy this rule before the 1997–98 Asian financial crisis and generally have held more IR since then. For the period after the Asian crisis and before the global financial crisis of 2008, low-income countries that were disaster-affected appeared to hold more IR in both imports and broad money scales than non-affected countries. However, among middle-income countries, disaster-affected ones held less IR, over the same period. To better examine IR adequacy among



Source: World Development Indicators.

Fig. 2 Reserves (median) Adequacy: Traditional Metrics disaster-affected countries, an econometric model accounting for their exposure and vulnerability to different types of disasters is required.

Ultimately, understanding the monetary costs of disasters and the availability of financial resources will help disaster-prone countries prepare better for disasters by producing better costings of the various risk mitigation and insurance policies that might be plausibly implemented. It is, of course, still clear that the best practices for risk reduction include public investment in disaster prevention and preparedness and the provision of accurate and adequate information about risks. These policies could supplement or even supplant the need for holding costly international reserves in disaster-prone countries.

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Declarations

Conflict of Interest None.

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