Institute for Economic Studies, Keio University

Keio-IES Discussion Paper Series

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10 July, 2023
DP2023-013
https://ies.keio.ac.jp/en/publications/22893/

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Acknowledgement : We are grateful to Tadao Hoshino, Kentaro Nakajima, Ishino Takuya, Atsushi Yamagishi, and the participants at various conferences and seminars for their constructive comments. This research was supported by JSPS KAKENHI Grant Numbers JP20K01617, JP21K01447, and JP23K17559, as well as Keio Gijuku Academic Development Funds (Collaborative Research).

Earthquake risk reduction and land value along geographic boundaries of extremely high-risk urban districts in Tokyo[*]

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July 10, 2023

Abstract

We examine the impact of earthquake risk reduction on land values along the geographic boundaries of dense urban districts with an extremely high risk of earthquakes (high-risk DUDs) in Tokyo. Our analysis employs a spatial regression discontinuity design that takes advantage of the discontinuity in earthquake risk at the high-risk DUD boundary. Our conservative estimate indicates that removing high-risk DUDs increases land value by 5.2% near the boundary. Moreover, we find that the boundary effect increases as the road width at the boundary widens, suggesting that the sample limited to wide roads mitigates the spatial spillover of fire risk.

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1. Introduction

How does earthquake risk reduction affect land value? Earthquake-prone cities worldwide have attempted to reduce earthquake risks and enhance disaster resilience. Tokyo, one of the most earthquake-prone cities, has promoted urban redevelopment to reduce earthquake risk. In fact, recent estimates indicate a marked decrement in expected earthquake damage. According to the Tokyo Metropolitan Government's (TMG) damage estimates for the imminent Tokyo Inland Earthquake, revised for the first time in 10 years in 2022, the number of buildings that will completely collapse decreased from 120,000 to 80,000; those that will be destroyed by fire declined from 200,000 to 120,000; and the number of deaths from shaking and fire lessened from 9,200 to 5,700 (TMG, 2012b, 2022). Despite the ample literature on the economic impact of earthquake risk, (e.g., Brookshire et al., 1985; Beron et al., 1997; Naoi et al., 2009; Hidano et al., 2015; Aguirre et al., 2022), the economic benefits of urban redevelopment for earthquake risk reduction remain underexplored.

We provide new evidence on such benefits by examining the impact of earthquake risk on land values along the geographic boundaries of dense urban districts with an extremely high risk of earthquakes (high-risk DUDs) in Tokyo. Our analysis employs a spatial regression discontinuity (RD) design that takes advantage of the discontinuity in earthquake risk at the high-risk DUD boundary. Specifically, we ask two questions: (1) What is the impact of earthquake risk reduction on land value along the high-risk DUD boundary? (2) Does the impact increase as the road width at the high-risk DUD boundary widens? The second question is examined since the impact of earthquake risk may be underestimated owing to a possible spatial spillover of fire risk outward from the high-risk DUD boundary. Such spatial spillover violates the stable unit treatment value assumption (SUTVA) for the spatial RD design. We expect the earthquake risk impact to be greater when the sample is restricted to wider roads as they are more likely to prevent the spread of fire.

We find highly significant boundary effects, which demonstrate that being located outside high-risk DUDs increases land value. Our conservative estimate indicates that removing high-risk DUDs increases land value by 5.2% along the high-risk DUD boundary. Furthermore, the boundary effect increases as the road width at the high-risk DUD boundary widens, suggesting spatial spillover owing to fire spread from inside the high-risk DUDs to the outside. The boundary effect is as large as 20.1% when the road width is 13.0 m or wider. Given that wider roads are more likely to prevent fire spread than narrower roads, our results suggest that restricting the sample to wide roads at the boundary reduces spatial spillover and leads to a more reliable estimate.

The contributions of this study are threefold. First, this study provides empirical evidence on the economic impact of earthquake risk reduction, which has been seldom explored in the literature. (Related literature is reviewed in Section 2.) Second, by using high-risk DUDs as a measure of earthquake risk, we provide new evidence for the evaluation of urban redevelopment policies for earthquake risk mitigation. The high-risk DUDs are among the highest-risk urban districts that are priority areas for disaster prevention policies in Japan. The Ministry of Land, Infrastructure, Transport, and Tourism (MLIT) in Japan defines high-risk DUDs as dense urban districts with particularly high fire-spread risk and evacuation difficulties, potential for large fires, loss of evacuation routes out of the district owing to roads blocked by an earthquake, and extreme difficulty in securing the safety of life and property (MLIT, 2021). The national government and TMG have implemented various urban redevelopment projects to eliminate the high-risk DUDs, including the promotion of earthquake-resistant buildings and redevelopment of close-set old wooden residential areas. Owing to such urban redevelopment efforts, the high-risk DUD area in Tokyo has decreased markedly, from 1,683 ha in 2012 to 103 ha in 2021 (MLIT, 2022). However, little is known about the economic benefits of such urban redevelopment for earthquake risk reduction. Third, our results demonstrate that a sample restricted to wider roads at the high-risk DUD boundary has a greater boundary effect, suggesting that the use of wider roads mitigates the spatial spillover of fire risk or violation of SUTVA. This finding also has policy implications since the construction of wide roads that serve as fire spread barrier zones is one of the main measures in Tokyo's urban redevelopment to reduce earthquake risk.

The structure of this paper is as follows. Section 2 presents the related literature, and Section 3 provides the background information on earthquake risk and urban redevelopment for earthquake risk reduction in Japan and Tokyo. Section 4 explains our empirical specifications, and Section 5 describes the data. Section 6 reports the results, and Section 7 presents the robustness checks. Section 8 concludes the paper.

2. Related literature

This study ties in with a large body of literature on the economic impact of earthquake risk. Particularly, the relevant literature examines the effects of earthquake risk information on housing and land prices. Brookshire et al. (1985) demonstrate that after the publication of California's high seismic risk zone map in 1974, housing prices in high-risk zones in Los Angeles and the San Francisco Bay Area became significantly discounted. Several studies use TMG's community earthquake risk measures at the district level for Tokyo. Using building collapse risk as part of the community earthquake risk measures, Nakagawa et al. (2007, 2009) show that housing rents and land prices are significantly lower in high-risk areas. Hidano et al. (2015) employ building collapse risk and combined risk, which are included in the TMG's community earthquake risk measures. Their results indicate that the unit prices of residential properties in low-risk districts are approximately 13,970–17,380 JPY higher than those in high-risk districts, depending on the type of risk. Note that the TMG's community earthquake risk measures differ from the high-risk DUDs employed in our analysis in that the community earthquake risk is a relative measure ranging from 1 (lowest risk) to 5 (highest risk). Therefore, even if the absolute risk decreases, community earthquake risk levels may remain unchanged or even increase. On the other hand, high-risk DUDs are defined based on the absolute risk levels; if the actual risk declines, the high-risk DUD area also decreases. Moreover, whereas TMG's community earthquake risk is an assessment of the relative level of risk status, high-risk DUDs are a policy target that should be eliminated. A recent study by Singh (2019) utilizes revisions to California earthquake fault zone maps over time. The results indicate that, on average, the delineation of the fault zone reduces property values by 6.6% and lowers rents by approximately 3.3%.

Another stream of literature examines housing and land prices before and after specific earthquakes, often demonstrating changes in the subjective perception of earthquake risk. Beron et al. (1997) show that the hedonic price in the San Francisco Bay area declined after the 1989 Loma Prieta Earthquake, suggesting that consumers had overestimated the market value of the earthquake risk. Önder et al. (2004) find that the distance from fault lines had a significant positive impact on housing values in Istanbul in 1995 and 2000, but the impact was greater in 2000, after the 1999 Kocaeli earthquake. Naoi et al. (2009) demonstrate that immediately after a strong earthquake, owner-occupied house prices and housing rents in earthquake-prone areas were significantly discounted compared to those before the earthquake in Japan. Their results suggest that earthquake risk tends to be underestimated in areas where earthquakes have not occurred in recent years. Gu et al. (2018) show that non-residential land prices closer to the Uemachi fault in Osaka were significantly discounted after the Great Hanshin earthquake. Fekrazad (2019) finds that a high-casualty earthquake outside of California reduced the home value index by approximately 6% and the median listing price by approximately 3% in high-risk areas compared to low-risk areas.

A strand of literature also examines the macroeconomic and local economic impacts of earthquakes. The empirical evidence of these studies is mixed, perhaps owing to differences in study areas, time periods, earthquakes, and methods. The cross-country analysis of Skidmore and Toya (2002) indicates that geologic disasters, including earthquakes, are negatively correlated with long-term economic growth. Using a difference-in-difference approach, Aguirre et al. (2022) find that 8–9 years after the 2010 Chile earthquake with a magnitude of 8.8, economic activity in affected municipalities is approximately 10% lower than in unaffected municipalities. Conversely, Fujiki and Hsiao (2015) find no persistent effects after the 1995 Great Hanshin-Awaji earthquake in Japan.

Several studies exhibit heterogenous impacts. Using a cross-country panel, Fomby et al. (2013) find negative and insignificant effects of earthquakes on economic growth but a positive effect on non-agricultural growth one year later, associated with reconstruction activities in housing, infrastructure, and production plants. Barone and Mocetti (2014) demonstrate that large earthquakes in two different regions of Italy, Friuli in 1976 and Irpinia in 1980, have opposite long-run effects on GDP per capita, with higher pre-earthquake institutional quality having a positive impact. Cole et al. (2019) show that building-level damage negatively affects the survival of manufacturing plants after the Kobe earthquake in Japan. Their analysis further reveals cleansing and 'build back better' effects, as the plants that are most likely to exit are the least productive, while those that survive are temporarily more productive. Nguyen and Noy (2020) report that after the Canterbury Earthquake Sequence (2010–2011) in New Zealand, insurance payments significantly affected the recovery process of the local economy, as measured by night-time luminosity.

Thus far, few studies have focused on the economic impact of earthquake risk reduction. Using spatial panel data models, Kawabata et al. (2022) demonstrate that a reduction in high-risk DUDs, as well as in fire risk and the combined risk of the TMG's community earthquake risk measures, increases land prices not only in the lot's own district but also in neighboring districts in Tokyo. However, the causal relationship is not specified in their analysis. By using a spatial RD design, this study provides policy-relevant and novel empirical evidence to the literature.

3. Background

3.1 Earthquake risk in Japan and Tokyo

Located at the collision of the four tectonic plates, Japan faces a particularly high earthquake risk. Although the country covers only 0.25% of the world's land area, it accounts for 18.5% (326) of the 1856 earthquakes of magnitude 6.0 or greater that occurred between 2004 and 2013 (Cabinet Office, 2016). Over the past decades, Japan has suffered tremendous damage from massive earthquakes. The 1995 Great Hanshin-Awaji Earthquake, the largest inland earthquake recorded up to that time in Japan, resulted in more than 6,400 deaths and 40,000 injuries (Fire and Disaster Management Agency, 2006). This inland earthquake also caused severe damage to a wide range of structures, including houses and businesses, highways, railroads, ports, and lifelines, with the total damage amounting to approximately 10 trillion yen (Cabinet Office, 2017). The devastation from collapsed buildings and fires was particularly serious in urban areas where old wooden houses were densely located. Subsequently, the strengthening of earthquake resistance standards and the elimination of urban areas with close-set old wooden houses have emerged as new disaster prevention policies. In 2011, the even more devastating Great East Japan Earthquake struck the Tohoku region. With a magnitude of 9.0, it caused fatal tremors, tsunamis, and fires, leaving more than 22,200 people dead or missing (Fire and Disaster Management Agency, 2022). More than 120,000 dwellings were completely destroyed, 280,000 were partially destroyed, and approximately 750,000 were partially damaged (Fire and Disaster Management Agency, 2022). The total damage from this earthquake was estimated at approximately 16.9 trillion yen (Cabinet Office, 2011).

Furthermore, Japan is at imminent risk of several massive earthquakes, including the magnitude 8–9 class Nankai Trough Earthquake and magnitude 7 class Tokyo Inland Earthquake. Within the next 30 years, the probability of the Nankai Trough Earthquake is predicted to be approximately 70–80%, and that of the Tokyo Inland Earthquake is approximately 70% (Cabinet

Office, 2021; The Headquarters for Earthquake Research Promotion, 2022). The Nankai Trough Earthquake is expected to cause a major disaster throughout western Japan. According to the damage assumptions for the landward case of this earthquake, the maximum number of houses totally destroyed or burned down is estimated at approximately 2,386,000, the maximum number of fatalities at 323,000, and the economic damage at approximately 214 trillion yen (Cabinet Secretariat, 2021; Central Disaster Management Council's Nankai Trough Earthquake Countermeasures Study Working Group, 2013).

Regarding the Tokyo Inland Earthquake, the most damage is expected from collapsed buildings and large fires in urban areas where old wooden houses are densely built, as in the case of the 1995 Great Hanshin-Awaji Earthquake. According to the government's report in 2013, in the event of an earthquake with an epicenter directly under the southern part of Tokyo (assuming a magnitude of 7.3), the maximum number of fatalities is estimated at approximately 23,000, with approximately 72,000 people requiring rescue assistance, and approximately 610,000 houses completely destroyed or burned to the ground. The total economic damage, including direct damage to assets and indirect damage from reduced production and services, is estimated at approximately 95 trillion yen (Central Disaster Management Council's Tokyo Inland Earthquake Countermeasures Study Working Group, 2013; Cabinet Office, 2021).

3.2 Urban redevelopment for earthquake risk reduction in Tokyo

In preparation for the impending Tokyo Inland Earthquake, the national government and TMG have been promoting urban redevelopment to mitigate disaster risk. In 2011, the Cabinet approved the Basic Plan for Housing and Living Standards (National Plan), whose goal is to eliminate most of the high-risk DUDs that existed in Japan at that time, approximately 6,000 ha, by 2020 (MLIT, 2011). In 2012, the government announced that the number of high-risk DUDs in Tokyo was 113, covering an area of

1,683 ha (MLIT, 2012). The high-risk DUDs are identified as areas with particularly high fire spread risk and evacuation difficulty. The fire spread risk is determined based on indicators such as residential unit density, proportion of fire-resistant buildings, and open space area. The evacuation difficulty represents the difficulty of evacuating from inside the district to outside, which is evaluated based on indicators such as district area, road width and shape, and earthquake and fire resistance of buildings (MLIT, 2012).

In 2013, the national government announced 15 priority programs to promote national land resilience and listed the avoidance of fire-related casualties in dense urban districts in the first of the 15 programs (MLIT, 2013). Examples of specific urban redevelopment measures to avoid fire-related casualties are: promotion of earthquake resistance of houses and buildings; development of parks, green spaces, and open spaces as evacuation sites; development of roads and greenways as evacuation routes and widening of narrow roads; adoption of nonflammable measures around evacuation sites, evacuation routes, and firebreak zones; renovation and reconstruction of buildings along evacuation routes; and joint reconstruction of old buildings into fire-resistant buildings in conjunction with the removal of old buildings (MLIT, 2013).

The TMG has also promoted urban redevelopment for earthquake reduction. A major policy is the promotion of earthquake-resistant buildings. In 2011, the TMG enacted the Ordinance to Promote Earthquake Resistance of Building along emergency transportation roads in Tokyo (TMG, 2011). Since 2012, seismic diagnosis has been mandatory for buildings along specified emergency transportation roads, and subsidies have been provided to cover the costs of seismic diagnosis and renovation. Furthermore, the TMG has developed the Tokyo Earthquake Renovation Promotion Plan (for FY2016–2025) to promote earthquake resistance in buildings systematically and comprehensively (TMG, 2016). Another major policy is the promotion of fire resistance, with an emphasis on the redevelopment of dense wood-frame residential districts with a high fire risk. The TMG initiated a 10-

year redevelopment project to enhance the fire resistance of close-set wooden housing districts in 2012 (TMG, 2012a). The project has supported the joint reconstruction of old buildings and the improvement of roads, parks, and other public facilities to secure evacuation routes and open spaces. The project has also promoted the use of special zones to enhance fire resistance and the construction of specific maintenance roads to block fire spread.

Consequently, the area of close-set wooden housing districts defined by the TMG decreased from 16,000 ha in 2012 to 8,600 ha in 2020 (TMG, 2022b), and the area of high-risk DUDs in Tokyo declined from 1,683 ha in 2012 to 103 ha in 2021 (MLIT, 2022). The high-risk DUDs in Tokyo largely overlap with the TMG's close-set wooden housing districts, but the area of the former is smaller, thus reflecting its extremely high risk level. In 2021, the Cabinet approved the new Basic Plan for Housing (National Planning), which includes the goal of eliminating most of the remaining high-risk DUDs by 2030 (MLIT, 2021).

Despite such substantial reductions in earthquake risk, the economic benefits of urban redevelopment for mitigating earthquake risks, such as high-risk DUD removal, have been rarely explored in the empirical literature.

4. Empirical specification

We employ a spatial RD design that exploits the discontinuity in earthquake risk at the high-risk DUD boundary. As the high-risk DUD boundary is two-dimensional, our spatial RD specification uses the distance to the nearest high-risk DUD boundary as a one-dimensional forcing variable, following the approach often employed in the literature (Holmes, 1998; Black, 1999; Kane et al., 2006; Lalive, 2008; Dell, 2010; Ambrus et al., 2020). To examine the impact of earthquake risk reduction on land value, we estimate the following local linear regression equation with a sample restricted to locations within bandwidth h of the high-risk DUD boundary:

$$\ln p_i = \alpha_{b(i)} + \tau Outside\_DUD_i + \beta Dist_i + \gamma Dist_i \times Outside\_DUD_i + \boldsymbol{X}_i'\delta + \varepsilon_i \text{ for } |Dist_i| < h, (1)$$

where p_i is the roadside land value of location i, the midpoint of each road (line) segment; $Outside\_DUD_i$ is an indicator equal to 1 if location i falls outside the high-risk DUDs and 0 otherwise; $Dist_i$ is the distance between location i and the closest high-risk DUD boundary, which takes a negative value for locations inside the high-risk DUDs; and $\boldsymbol{X}_i$ is a vector of additional control variables. Equation (1) includes location fixed effects $\alpha_{b(i)}$, where $b(i)$ is an index for location i's closest line segment of the high-risk DUD boundary. In our dataset, the high-risk DUD boundary consists of 1,607 line segments, with an average line segment length of approximately 24.5 m.

Our parameter of interest is τ, which represents the boundary effect of being located outside high-risk DUDs, that is, discontinuous changes in land values at the high-risk DUD boundary. This boundary effect is interpreted as the average treatment effect of a reduction in earthquake risk just outside the high-risk DUD boundary. We estimate Equation (1) with the optimal bandwidth determined as in Calonico et al. (2014a).[1] As the optimal bandwidth varies with the regression specification, we also present the results using a fixed bandwidth of 100 m to examine whether our results are robust to bandwidth selection. While additional control variables $\boldsymbol{X}_i$ are, in principle, not required for identification in the RD design, they can improve the precision of the estimates (Imbens and Lemieux, 2008; Lee, 2008). Therefore, we start with a model with no control variables other than boundary fixed effects, and then add a set of controls: distance to the nearest rail station, land use categories, elevation, slope angle, and flood hazard (the depth of potential flooding) at location i. Furthermore, we estimate Equation (1) for each subsample by road width at the high-risk DUD boundary to examine whether the boundary effect is greater for the subsample with wider roads that could prevent fire spread. Finally, we perform standard robustness and sensitivity checks on our baseline results, including sensitivity to

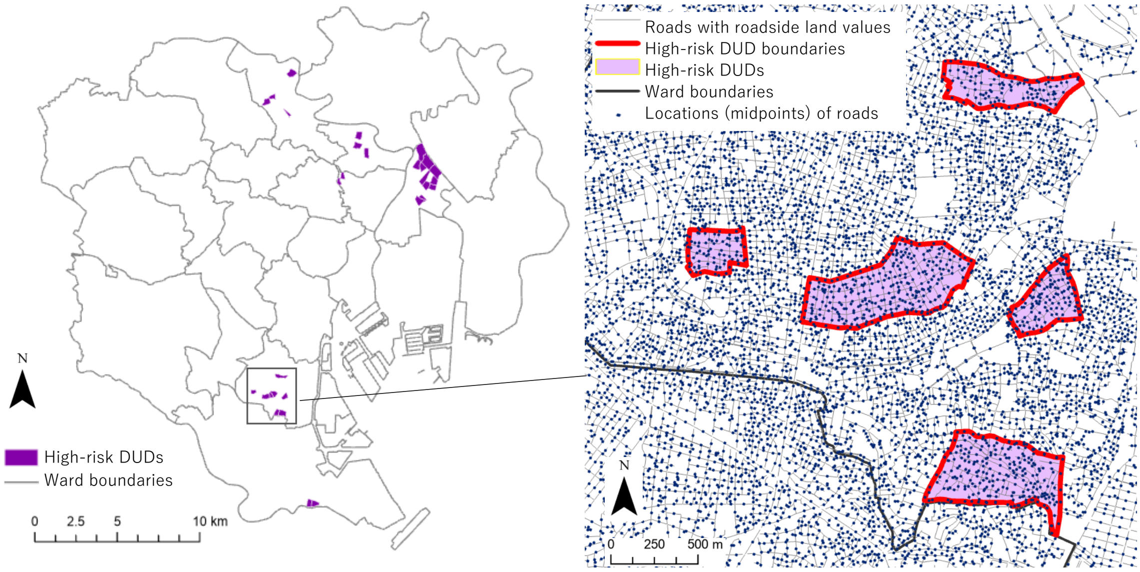
[1] The optimal bandwidth is calculated using Stata's rdrobust package provided by Calonico et al. (2014b).

the bandwidth selection and the choice of polynomial orders, and a falsification test using fake boundaries.

5. Data

We employ high-risk DUD data in 2017 obtained from the MLIT. At that time, there were 30 high-risk DUDs remaining in Tokyo (Figure 1a). For land value, we use property tax roadside land value data published in 2018; the property tax roadside land values are assessed at land prices as of January 1, 2017, the previous year. We obtain shapefiles of the property tax roadside land value data from the Research Center for Property Assessment System (RECPAS).[2] Each roadside land value is the price (in JPY) per square meter of standard land along a road. In our analysis, the midpoint of each road (line) segment is used as the location of the roadside land value (Figure 1b). The spatially detailed roadside land value data allow us to examine the difference in land value just outside and just inside the high-risk DUDs using a spatial RD design that addresses the discontinuous change in earthquake risk at the boundary.

[2] The shapefile is a data format for data processing in geographic information systems. Publicly available roadside land value data are not in such a data format. Another type of roadside land value data exists: annual inheritance tax on roadside land values; however, shapefiles of these data are not available from the RECPAS.



(a) High-risk DUDs in Tokyo (b) High-risk DUDs and roads with land values

Figure 1. High-risk DUDs and locations of roadside land values

Railway station, land use, slope angle, and flood hazard data are obtained from the National Land Numerical Information download service. The data are selected for the years closest to 2017, the year of the high-risk DUD data. The railway station data are from 2017, and land use data are from 2019. We categorize the original 12 land use types into three categories: residential, commercial, and industrial. The slope angle data are from the average slope angle for 250-meter grid included in the elevation and slope data in 2011. The flood hazard data are from potential flood zone data in 2012, which include the depth of potential flooding. Our flood hazard data categorizes each location into one of the following four groups based on potential flood depth: (1) no potential flood risk; (2) potential flood depth of less than 1.0 m; (3) potential flood depth of 1.0 to 2.0 m; and (4) potential flood depth of 2.0 m or greater. We use dummy variables for each of these categories in our regression. The elevation data are from the 5-meter digital elevation model (DEM) for 2014 and 2017, depending on the location of the study area. We obtain the 5-meter DEM data from the basic map information maintained by the Geospatial Information Authority of Japan. Road width data are extracted from the 2017 Digital Road Map, which was provided by the Japan Digital Road Map Association. As the road width is categorical data, we use three dummy variables indicating road width of 13.0 m or wider, between 5.5 and 13.0 m, and less than 5.5 m.

Table 1 presents summary statistics for our samples. The full sample is restricted to locations that have a distance to the high-risk DUD boundary of less than 402.5 m on either side of the high-risk DUD boundary. The distance of 402.5 m is selected because it is the maximum distance inside the high-risk DUDs in our dataset. We exclude locations where the nearest high-risk DUD boundary coincides with a ward boundary, river, railroad (excluding subways), or large park because district characteristics are likely to differ inside and outside such boundaries. We also exclude locations that could not be identified as inside or outside the high-risk DUDs.[3] The sample restricted to locations within a 100-meter bandwidth (i.e., locations closer to the high-risk DUD boundary) is used for comparison. (As shown later in the study, the optimal bandwidths in our regression are less than 100 m.)

Columns 1 and 2 of Table 1 denote the means and standard deviations for the full sample outside and inside the high-risk DUD boundary, respectively. To assess the continuity assumption, column 3 presents the RD estimates using a local linear specification with each variable in Table 1 as the dependent variable. Columns 4, 5, and 6 provide the same information for locations within 100 m of the boundary. As expected, the average land values are lower inside high-risk DUDs than outside, but the difference is somewhat smaller within the 100-meter bandwidth than in the full sample. For the full sample, land use inside the high-risk DUDs is more likely to be industrial and less likely to be residential or commercial. There are some topographic differences between the outside and inside of the high-risk DUDs. Locations inside the high-risk DUDs have, on average, lower elevations, smaller slope angles, and higher flood hazards with potential flood depths of 2.0 m or greater. Columns 3 and 6 indicate the local linear RD estimates. While the RD estimates are significant for some control

[3] There are locations very close to the high-risk DUD boundary that might be recognized as inside when they should be outside the high-risk DUDs, or outside when they should be inside the high-risk DUDs.

variables in the full sample, they are statistically insignificant in the 100-meter bandwidth sample. The RD estimate for potential flood depths of 2.0 m or greater in the 100-meter bandwidth sample is significant, but we do not find any firm evidence that the other control variables are changed discontinuously at the high-risk DUD boundary.

Table 1. Summary statistics

	Full sample						100m bandwidth sample					
	Outside		Inside		RD est.		Outside		Inside		RD est.	
	(1)		(2)		(3)		(4)		(5)		(6)	
Land price (in logs)	12.52	(0.35)	12.28	(0.26)	0.057	***	12.44	(0.32)	12.32	(0.27)	0.061	***
Distance to nearest railway station (m)	387.0	(210.1)	434.2	(193.5)	-16.561	***	405.3	(205.5)	448.1	(197.8)	0.928	
Land use												
Residential	0.412	(0.492)	0.388	(0.487)	-0.139	***	0.397	(0.489)	0.464	(0.499)	-0.036	
Commercial	0.304	(0.460)	0.173	(0.378)	0.025		0.331	(0.471)	0.196	(0.397)	-0.003	
Industrial	0.284	(0.451)	0.439	(0.496)	0.114	***	0.272	(0.445)	0.339	(0.474)	0.039	
Elevation	9.974	(9.069)	6.342	(8.817)	-0.431	***	9.135	(9.136)	7.995	(9.133)	0.092	
Slope angle	0.599	(0.704)	0.418	(0.642)	-0.004		0.589	(0.748)	0.556	(0.742)	0.002	
Flood risk (depth of potential flooding)												
N/A	0.567	(0.496)	0.344	(0.475)	0.004		0.507	(0.500)	0.440	(0.497)	0.002	
0.0-1.0m	0.025	(0.157)	0.019	(0.136)	0.004		0.016	(0.127)	0.015	(0.123)	-0.007	
1.0-2.0m	0.058	(0.233)	0.039	(0.194)	-0.003		0.038	(0.191)	0.033	(0.179)	-0.011	
2.0m+	0.350	(0.477)	0.598	(0.490)	-0.005		0.438	(0.496)	0.512	(0.500)	0.016	**
N	7,876		2,350				1,825		1,507			

Notes: *** and ** indicate that estimated coefficients are statistically significant at the 1% and 5% levels, respectively. Columns 1, 2, 4 and 5 show the sample means and standard deviations in the parentheses. Columns 3 and 6 show the local linear RD estimates using each variable as the dependent variable. The distance to the DUD boundary for locations inside the high-risk DUD takes negative values. Full sample includes all locations with distance to the high-risk DUD boundary less than 402.5m (maximum distance inside those DUDs).

6. Empirical results

We present RD plots that graphically illustrate the discontinuity in land values at the high-risk DUD boundary. Figure 2 plots average land values (bin averages, vertical axis) against the distance to the closest high-risk DUD boundary (forcing variable, horizontal axis). The hollow and solid dots represent the average land values within the 20- and 50-meter distance bins, respectively.[4] The solid vertical line (distance = 0) represents the high-risk DUD boundary, where locations inside (outside) the high-risk DUDs have negative (positive) distance values. We also present fourth-order polynomial

[4] For the RD plots in Figure 2, we do not use the control variables. We have similar results with a covariate adjustment using these variables.

fits separately for inside and outside of the high-risk DUDs. Figure 2 reveals a spatial discontinuity in the average land values at the high-risk DUD boundary; locations just outside the boundary have higher land values than those just inside.

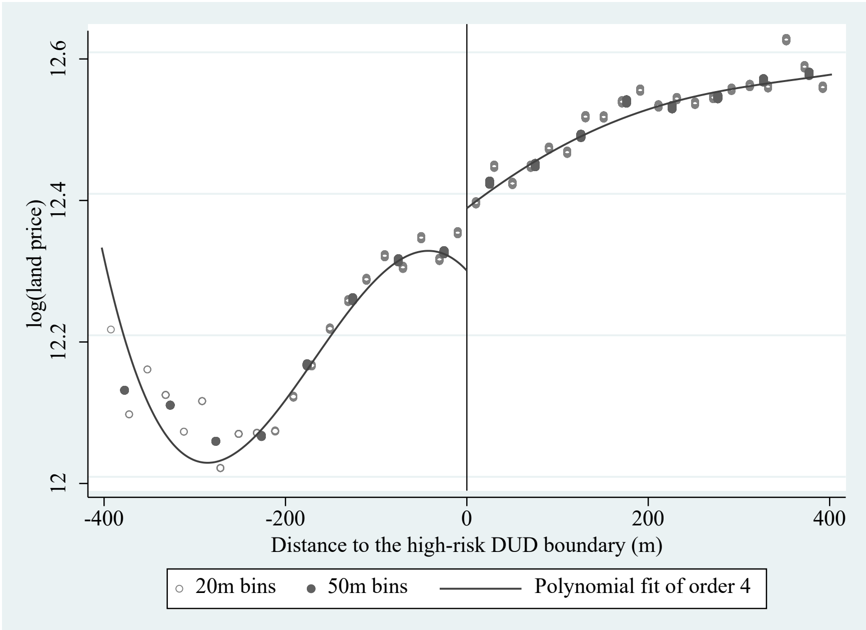


Figure 2. RD plot for land values

To obtain more rigorous insights, we estimate local linear spatial RD models using Equation (1). Table 2 reports our baseline results and summarizes the boundary effects (τ). Columns 1 and 2 indicate the results using optimal bandwidths of 69.6 and 66.9 m, respectively. Considering that the optimal bandwidth varies by specification, we also present results using the fixed bandwidth of 100 m in columns 3 and 4 for comparison. Columns 1 and 3 report raw estimates with no controls other than boundary fixed effects, whereas columns 2 and 4 include additional controls for the distance to the nearest station, land use categories, elevation, slope angle, and potential flood depth.

In all specifications, we find positive and highly significant boundary effects. Column 1 indicates that locations just outside the high-risk DUDs have 5.6% higher land values than those just inside. As shown in column 2, adding a set of control variables changes the magnitude of the boundary effect only slightly, to 5.2%.[5] We obtain similar results for the fixed bandwidth of 100 m (columns 3 and 4). Overall, the baseline results show that locations just outside the high-risk DUD have significantly higher land values than those just inside, regardless of the bandwidths and additional controls.[6]

Table 2. Boundary effects on land values

	Optimal bandwidth		Fixed bandwidth (100m)	
	(1)	(2)	(3)	(4)
Outside high-risk DUDs	0.056 ***	0.052 ***	0.061 ***	0.061 ***
	(0.012)	(0.012)	(0.011)	(0.010)
Bandwidth (m)	69.6	66.9	100.0	100.0
Boundary FE	X	X	X	X
Controls		X		X
N (outside)	1,192	1,126	1,825	1,825
N (inside)	1,066	1,024	1,507	1,507
N (total)	2,258	2,150	3,332	3,332

Notes: *** indicates that estimated coefficients are statistically significant at the 1% level. Standard errors are in the parentheses. All models use the polynomial order of 1 (i.e., local linear specification) and include boundary fixed effects. Columns 2 and 4 include distance to the nearest station, land use categories, elevation, slope angle, and potential flood depth as additional controls.

A concern with our baseline results is that locations inside and outside of the high-risk DUDs have inherently different characteristics owing to, for example, different topography and historical development processes, which may distort our RD estimates. To address this issue, we also estimate models focusing on the boundaries of the current high-risk DUDs that were inside the former high-

[5] If we further include road width at each location as an additional control, the boundary effects become somewhat smaller but remain significantly positive (0.042 and 0.050 for optimal and fixed bandwidths, respectively). This result is not surprising because the high-risk DUDs, by definition, have numerous narrow streets with poor accessibility and potentially strict building restrictions. Because narrow streets also increase fire risk and evacuation difficulties, which are considered in the definition of the high-risk DUDs, our models do not include road width at each location as a control.

[6] Considering that unobserved variables might be spatially correlated, we also estimate models that allow for spatial autocorrelation in the error terms (Conley, 1999), using Stata's acreg package. The results in Table A1 indicate that the boundary effects are positive and marginally significant even when we allow for the spatially autocorrelated error terms.

risk DUDs. Specifically, we compare locations inside and outside of the high-risk DUDs in 2017, where all these locations are inside the former high-risk DUDs in 2012.[7] The idea is that these locations have similar topographic or historical characteristics, but the former high-risk DUDs became non−high-risk DUDs owing to urban redevelopment and associated risk reductions that took place between 2012 and 2017. Table 3 summarizes the results, which show a somewhat smaller magnitude but still significantly positive boundary effects.[8]

Table 3. Boundary effects on land values using locations inside the former high-risk DUDs

	Optimal bandwidth		Fixed bandwidth (100m)	
	(1)	(2)	(3)	(4)
Outside high-risk DUDs	0.033 **	0.043 ***	0.040 ***	0.051 ***
	(0.015)	(0.014)	(0.013)	(0.013)
Bandwidth (m)	78.3	80.9	100.0	100.0
Boundary FE	X	X	X	X
Controls		X		X
N (outside)	651	676	861	861
N (inside)	605	626	743	743
N (total)	1,256	1,302	1,604	1,604

Notes :*** indicates that estimated coefficients are statistically significant at the 1% level. Standard errors are in the parentheses. All models use the polynomial order of 1 (i.e., local linear specification) and include boundary fixed effects. Columns 2 and 4 include distance to the nearest station, land use categories, elevation, slope angle, and potential flood depth as additional controls.

Another concern is spatial spillover owing to fire spreading from inside to outside high-risk DUDs. Locations immediately outside the high-risk DUDs would have a lower risk if they were not adjacent to the high-risk DUDs. Such spatial spillover of fire risk leads to the violation of the SUTVA, which may result in underestimating the boundary effects. To address this issue, we divide the sample based on the road width at the high-risk DUD boundary and estimate Equation (1) separately for each subsample. We expect that fire spread from the inside to the outside of the high-risk DUDs is less

[7] From 2012 to 2017, the number of high-risk DUDs in Tokyo decreased from 113 to 30.
[8] We do not proceed with further analysis using this sample, since the results are unstable perhaps owing to smaller sample size.

likely to occur if the road at the boundary is wider, making SUTVA more plausible.

Table 4 summarizes the estimation results using the subsamples by road width at the high-risk DUD boundary, controlling for the full set of control variables. The road width at the high-risk DUD boundary is categorized into three groups: 13.0 m or wider, between 5.5 and 13.0 m, and less than 5.5 m. Columns 1–3 of Table 4 show the results using the optimal bandwidths, ranging from 65.1 to 86.1 m. The boundary effects are all positive, but their magnitudes differ substantially depending on the road width at the boundary. In accordance with our expectation, the boundary effects are larger for subsamples with wider roads at the high-risk DUD boundary. When the road width at the boundary is 13.0 m or wider (column 1), the boundary effect is 0.201, which is almost four times as large as that in our baseline estimate of 0.052 (column 2 of Table 2). When the road width at the boundary is between 5.5 and 13.0 m (column 2), the boundary effect is 0.066, which is smaller than that of the wider road width but remains greater than that of the baseline estimate. When the road width at the boundary is less than 5.5 m (column 3), the boundary effect is 0.031, which is smaller than those of the wider roads and the baseline result and is only marginally significant at the 10% level. We find a similar pattern for specifications with a fixed bandwidth of 100 m (columns 4–6). These results suggest a spatial spillover owing to fire spreading from inside to outside the high-risk DUDs.

Table 4. Boundary effects on land values by road width at the high-risk DUD boundary

	Optimal bandwidth			Fixed bandwidth (100m)		
	(1)	(2)	(3)	(4)	(5)	(6)
Outside high-risk DUDs	0.201 ***	0.066 ***	0.031 *	0.101 ***	0.073 ***	0.044 ***
	(0.038)	(0.021)	(0.018)	(0.030)	(0.019)	(0.015)
Bandwidth (m)	65.1	86.1	67.9	100.0	100.0	100.0
Road width at the DUD boundary	13.0m+	5.5-13.0m	5.5m-	13.0m+	5.5-13.0m	5.5m-
N (outside)	147	569	523	258	679	821
N (inside)	198	513	413	311	582	592
N (total)	345	1,082	936	569	1,261	1,413

Notes : *** and * indicate that estimated coefficients are statistically significant at the 1% and 10% levels, respectively. Standard errors are in the parentheses. All models use the polynomial order of 1 (i.e., local linear specification) and include boundary fixed effects, distance to the nearest station, land use categories, elevation, slope angle, and potential flood depth as controls.

7. Robustness checks

We conduct a standard set of robustness and sensitivity checks on our baseline results, including sensitivity to bandwidth selection and choice of polynomial orders, and a falsification test using fake boundaries.

To examine sensitivity to bandwidth selection, Figure 3 illustrates the boundary effect estimates (with a set of control variables) and associated 95% confidence intervals as a function of the bandwidth between 25 and 300 m. The dashed vertical line indicates the optimal bandwidth of 66.9 m in our benchmark result (column 2 of Table 2). We find that the magnitude and significance of the boundary effects are largely stable within a range of bandwidths, including our baseline cases of optimal and fixed (100-meter) bandwidths.

To investigate sensitivity to polynomial order, Table 5 summarizes the boundary effect estimates for models with polynomial orders of up to four. Overall, our baseline boundary effect estimates are not very sensitive to the choice of the polynomial order.

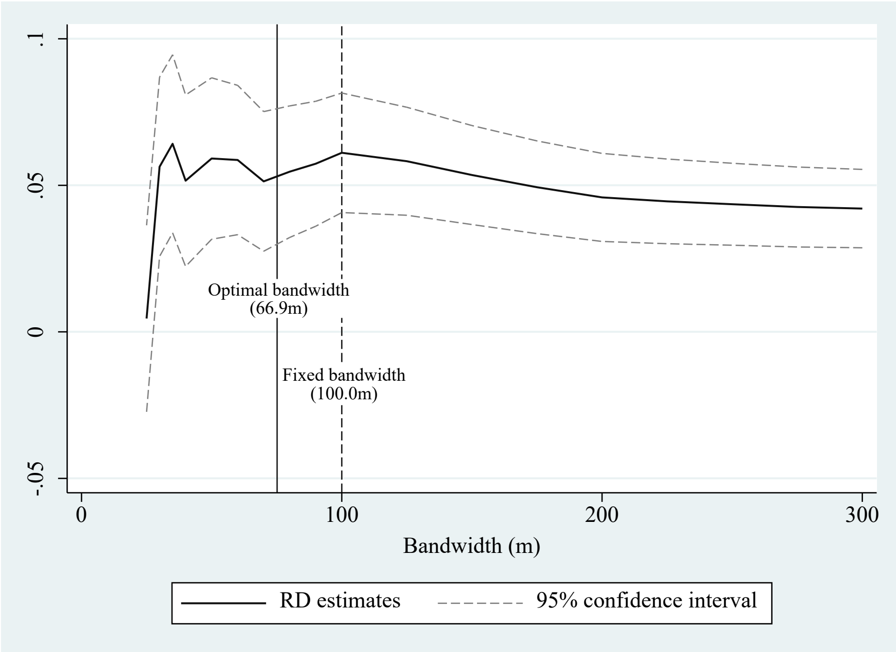


Figure 3. Sensitivity to bandwidth selection

Table 5. Boundary effects with different polynomial orders

	(1)	(2)	(3)	(4)	(5)
Outside high-risk DUDs	0.041 ***	0.052 ***	0.059 **	0.051 **	0.057 **
	(0.005)	(0.012)	(0.024)	(0.025)	(0.027)
Bandwidth (m)	26.0	66.9	75.6	164.6	268.5
Polynomial order	0	1	2	3	4
N (outside)	252	1,126	1,321	3,089	5,234
N (inside)	245	1,024	1,168	2,075	2,310
N (total)	497	2,150	2,489	5,164	7,544

Notes: *** and ** indicate that estimated coefficients are statistically significant at the 1% and 5% levels, respectively. Standard errors are in the parentheses. All models include boundary fixed effects and the following controls: distance to the nearest station, land use categories, elevation, slope angle, and flood risk.

Finally, we conduct a falsification test based on fake boundaries. We create a fake boundary δ meters away from the actual boundary, and obtain a placebo estimate under the fake boundary. Figure 4 illustrates the placebo estimates with δ varying between -50 and 50, where a positive (negative) δ indicates that the fake boundary lies outside (inside) the true boundary. The placebo estimates are found to be substantially larger than our baseline result (column 2 of Table 2) when the fake boundary is approximately 8 m inside the actual boundary (i.e., $\delta = -8$). This result is perhaps because of the specific characteristics of locations inside, but very close to the high-risk DUD boundary. The high-risk DUDs are often divided by relatively wide roads. Locations facing such wide roads tend to have newer and fire-resistant buildings, even inside the high-risk DUDs. Conversely, locations that are few meters inward from the high-risk DUD boundary tend to have dense, older wooden houses. Thus, our baseline result under the actual high-risk DUD boundary (column 2 of Table 2) is considered a conservative estimate of the impact of earthquake risk reduction on land values.

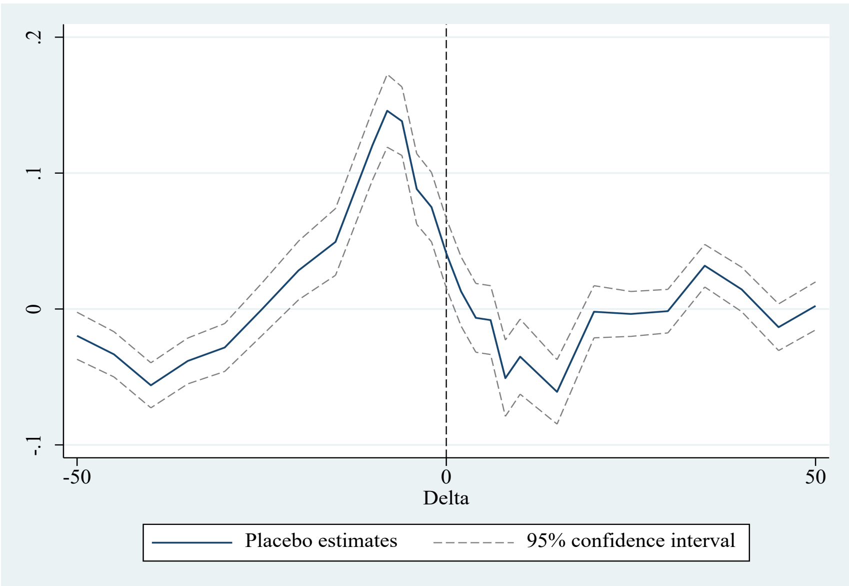


Figure 4. Placebo estimates under the fake boundaries

8. Conclusions

In anticipation of the occurrence of a massive inland earthquake, Tokyo has been promoting urban redevelopment to reduce earthquake risk. Our findings provide novel evidence on the benefits of earthquake risk reduction in the two points that follow. First, the estimated boundary effects suggest that urban redevelopment for the elimination of high-risk DUDs promote sizable benefits. Our conservative estimate (column 2 of Table 2) indicates that removing high-risk DUDs increases land values by 5.2% near the high-risk DUD boundary. Second, we find that the boundary effect increases as the road width at the high-risk DUD boundary widens. When we focus on the sample with road widths of 13.0 m or wider at the high-risk DUD boundary, our estimate (column 1 of Table 4) is larger at 20.1%. Spatial spillover of fire risk was a concern in our RD analysis because fire-risk mitigation has a spatial spillover effect, as indicated by Kawabata et al. (2022). Given that wider roads are more likely to prevent fire spread than narrower roads, our results suggest that using a sample with wider roads at the high-risk DUD boundary reduces the spatial spillover or the SUTVA violation, leading to a more reliable estimate. In Tokyo, the construction of wide roads that serve as fire spread blocking zones is an important urban redevelopment policy for creating a disaster-resistant city (TMG, 2021). Our results imply that such urban redevelopment can have substantial economic benefits.

Our estimates focus only on the effects along the boundaries of high-risk DUDs. The economic impact of eliminating the high-risk DUDs, however, is likely to be greater when it is further inside those DUDs. An analysis to examine such an impact is a direction for future research. Another direction is to develop panel data on high-risk DUDs and conduct a similar analysis. Such analyses deepen our understanding of the economic benefits of urban redevelopment for earthquake risk reduction.

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Appendix

Table A1. Boundary effects on land values in models with spatially autocorrelated error terms

	Optimal bandwidth		Fixed bandwidth (100m)	
	(1)	(2)	(3)	(4)
Outside DUDs	0.049 **	0.040 *	0.061 ***	0.062 ***
	(0.022)	(0.023)	(0.019)	(0.019)
Bandwidth (m)	69.6	66.9	100.0	100.0
Boundary FE	X	X	X	X
Controls		X		X
N (outside)	1,192	1,126	1,825	1,825
N (inside)	1,066	1,024	1,507	1,507
N (total)	2,258	2,150	3,332	3,332

Notes : ***, ** and * indicate that estimated coefficients are statistically significant at the 1%, 5% and 10% levels, respectively. Standard errors are in the parentheses. We choose the polynomial order of 1 (i.e., local linear specification) in all models. All models include boundary fixed effects. Columns 2 and 4 include distance to the nearest station, land use categories, elevation, slope angle, and potential flood depth as additional controls.