RIETI Discussion Paper Series 13-E-072

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An example of coastal levee improvement in the city of Rikuzentakata

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http://www.rieti.go.jp/en/

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September 2013

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Abstract

Cost-benefit analysis (CBA) is considered as an effective means to avoid the government's failures of public projects. However, once CBA becomes mandatory and residents expect a public project to be established based upon it, there is the potential for a dynamic inconsistency problem to arise. Taking as an example the coastal levee improvement policy in the city of Rikuzentakata in Japan, the present study clarifies the mechanism behind the dynamic inconsistency problem that is attributable to mandatory CBA and also discusses quantitatively the influence of the dynamic inconsistency problem on social welfare. In addition, through examining the quantitative result, we indicate that, in the projects where the improvement cost increases gradually with the scale, the inefficiency of the dynamic inconsistency problem is incurred on a larger scale.

***Keywords*:** Dynamic (or time) inconsistency problem, Cost-benefit analysis, Public investment.

***JEL classification*:** R14, R53, R54

Acknowledgments. This research is sponsored by the Research Institute of Economy, Trade and Industry (RIETI). We are very grateful for the useful comments and suggestions from the participants at the RIETI meeting, in particular, Keiichiro Oda, Minoru Kaneko, Atsushi Nakajima, Nobuaki Hamaguchi, Masahisa Fujita, Masahiro Morikawa, and Munehisa Yamashiro.

1. Introduction

Cost-benefit analysis (CBA) for public investments has become mandatory in Japan since 2001, and CBA manuals are increasingly put in place for each type of project. Based on CBA, only those projects for which the benefit exceeds the cost are adopted, and CBA is considered as an effective means to avoid the government's failures, which include implementing futile public projects. However, once CBA becomes mandatory, residents behave strategically with the expectation that a public project is established based upon it, which has the potential to result in failing to achieve the optimal social welfare, and this is known as the so-called dynamic inconsistency problem.[1]

One example of this problem, which is indicated by Kydland and Prescott (1977), is "the problem of constructing levees because many people have migrated to the area prone to flooding, where land prices are low." In this example, if many people migrate to such areas with the expectation that levees will be constructed, optimal social welfare cannot be achieved because costly levees are eventually constructed. This migration can take place in two ways: one where residents migrate at their own discretion, and the other where many residents migrate together through the coordination of developers. Mandatory CBA underpins the residents' expectation that levees will be constructed and thus accelerates the occurrence of the dynamic inconsistency problem.

This type of problem arises because CBA, which should originally evaluate public investment from outside of the social system, is built into the social system once it has become mandatory and residents utilize CBA strategically. In other words, an inconsistency arises in which the CBA-based optimal policy changes if the residential distribution changes due to the strategic migration of residents. Indeed, since public investment is

[1] The mechanism of the dynamic inconsistency problem can be roughly categorized into two cases: one where the optimal dynamic policy at a certain time ceases to become optimal only with the lapse of time; and the other where, in a Stackelberg game for two or more players, the sub-game perfect solution differs from the optimal social solution. The present study targets the latter. The dynamic inconsistency problem is also called the time inconsistency problem.

evaluated based on residents' behavior (i.e., revealed preference data) in CBA, what is determined as the optimal policy differs before and after the residents' actions. The CBA is based on residents' behavior[2] because the government cannot directly observe the change in the utility level. In other words, information on residents' preference is asymmetric between residents and the government.

The fact that the optimal policy differs before and after the dynamic timing (in this case, the timing of residents' actions) is known as the dynamic inconsistency problem (or time inconsistency problem). The general structure that is the cause of this problem was indicated by Kydland and Prescott (1977). "Constructing levees because residents have migrated to the area prone to flooding" mentioned above is one of several examples of the dynamic inconsistency problem indicated in their paper. However, no specific modeling or analysis, including a CBA of levees, of this example has yet been made.

The dynamic inconsistency problem is formulated as a Stackelberg game between the policymaker and the private sector and has been studied by many papers concerning monetary policies (e.g., Barro and Gordon (1983), Calvo (1978a), Calvo (1978b)). Studies have been also conducted concerning various public policies.[3] However, an analysis of the dynamic inconsistency problem related to CBA is limited to the example case made for transportation policy by Kono and Notoya (2012). They showed the mechanism of how the dynamic inconsistency problem arises and the sufficient conditions under which the

[2] If the utility level could be measured directly, the policymaking authorities would be able to determine the best investment level and commit to the optimal policy. If they could commit to the optimal policy, residents' strategic migration could be prevented, and no dynamic inconsistency problem would arise. Even in such a case, however, if the migration cost is high, the policymaking authorities must change their original optimal policy from the perspective of efficiency in the event of residents' strategic migration. Next, the best policy can also be achieved by controlling the residential population. However, the policy of controlling the residential population itself does not generally exist and only land use regulation is in place. Hence, even if an optimal residential population can be calculated, it is generally difficult for the policymaking authorities to limit the population.

[3] Included in analyses other than for monetary policy are those by Boadway et al. (1996) for educational investment, Glazer (2000) for traffic toll, Richer (1995) for urban development, Kornai (1979), Qian and Roland (1998), Sato (2002), and Akai and Sato (2008) for soft budget problems in local government finance, Bassetto (2008) and Mitsui and Sato (2001) for the issue of public-goods cost burden sharing among generations, and Fisher (1980) and Mino (2001) for the taxation issue.

problem arises for cases where transportation service is a fixed capital service (e.g., highway investment) and a variable flow service (e.g., bus services), respectively. However, their analysis is limited to a qualitative one, and the degree of inefficiency is not analyzed. Even in cases that do not involve CBA, the number of quantitative analyses of the dynamic inconsistency problem is extremely limited (Kiuchi, 2005).[4]

Under such circumstances, the present study makes an analysis using the example of coastal levee improvement, with an eye to showing the degree of inefficiency of the dynamic inconsistency problem brought about by the use of CBA. Coastal levee improvement is taken as an example here because the mechanism is roughly the same as the example of levees used by Kydland and Prescott (1977), and, in addition, a similar dynamic inconsistency problem can arise in practice because of the necessity to construct coastal levees in the area devastated by the Great East Japan Earthquake. Through examining a quantitative relationship between the degree of inefficiency of the dynamic inconsistency problem related to CBA and the nature of the infrastructure to be improved, we examine what kinds of infrastructure improvements are necessary to take the inefficiency of the dynamic inconsistency problem related to CBA into consideration.

The location equilibrium model used is a model with the effect of coastal levee improvement incorporated into the computable urban economic (CUE) model from Ueda et al. (2009) and Ueda et al. (2013). Rikuzentakata (see Fig. 1 for the location), which suffered from the devastating tsunami in the wake of the Great East Japan Earthquake, is selected as the study area and divided into 111 zones. The parameters of the location equilibrium model of the study area are calibrated using actual data. Simulation is conducted for the following two cases to obtain the location equilibrium and coastal levee height for each to compare the social welfare.

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[4] Referring to the reason why only a few positive analyses are available, Kiuchi (2005) states that it is considered impossible to observe variables, such as discipline and incentive, in many cases. Included in the examples of quantitative analyses are those by Persson and Tabellini (2004), Klein et al. (2008), and Pettersson-Lidbom (2010).

Case 1: Optimal social case where the social welfare is maximized, and

Case 2: Dynamic inconsistency case where the government determines the coastal levee height through CBA after residents have strategically migrated.

In Case 1, the coastal levee height is determined to maximize the social surplus in the location equilibrium model with the coastal levee height as a given condition. In Case 2, the coastal levee height is determined from the Stackelberg game, where residents are the leader and the government that determines the levee height is the follower[5].

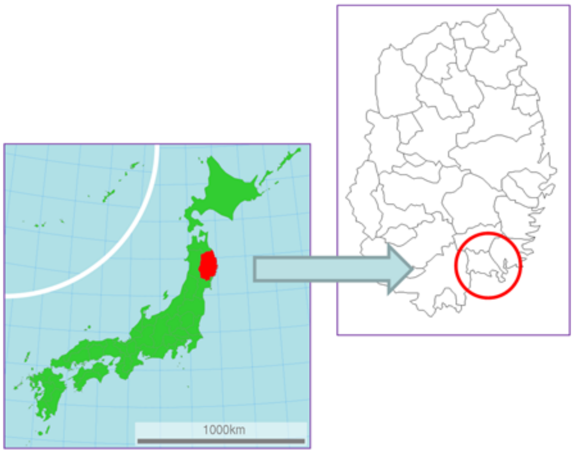

Figure 1 Location of Rikuzentakata

The present study aims to analyze quantitatively the mechanism behind the dynamic inconsistency problem in infrastructure improvement but does not intend to evaluate the actual restoration plan. As a matter of fact, the restoration plan being developed in Rikuzentakata is significantly different from the land use plan before the earthquake. The current plan is to locate parks and industrial zones in the previous urban zone, to where the residential area used to extend before the earthquake[6]. However, the dynamic inconsistency problem covered in the present study can occur in almost the same mechanism, meaning that the planned scale and daytime population can be set larger even in the parks and

[5] This type of dynamic efficiency is, however, not likely to arise in most of the Tohoku coastal area after the Great East Japan Earthquake at least for the moment because the policymaking authorities have announced to build a (probably too) high height of coastal levees before people decide their residential places.

[6] Actually, it is difficult for the present study, whereby calibration is made based on conventional land use, to express this totally different type of restoration plan.

industrial zones to obtain more advantageous CBA results.

Consequently, in terms of the scope of application of the present study results to the actual restoration plan, the qualitative mechanism in the present study can be considered to occur potentially as a problem in the actual restoration plan. On the other hand, the quantitative results show the degree of the dynamic inconsistency problem with the assumption that the plan implemented is similar to the actual land use before the earthquake. In addition, using the results, the coastal levee height before the earthquake can be evaluated ex post facto, and the validity of the coastal levees with a height of 12.5m currently planned can be examined. While these are not included in the main subjects of the present paper, the results for these subjects will be shown where necessary.

2. Location Equilibrium Model: Rikuzentakata Model

The model covers Rikuzentakata and comprises 111 zones by town-*chome*[7], with the computable urban economic (CUE) model by Ueda et.al. (2009) and Ueda et al. (2013) used as a basis. This is a model where the demand and supply, not only in the goods market but also for land, are at equilibrium. Aside from the government, there are two agents: residents and absentee land owners. The respective incomes and heterogeneities in preference for the residents are modeled for two age groups: the elderly and the rest. Residents select their residential locations. The migration cost is assumed to be zero to obtain long-term equilibrium. Land is owned by absentee landlords.

2.1 Residents

Residents consume on personal trips x_i^m (number of trips), land area l_i^m (consumption on residential land), and composite goods Z_i^m. The utility function is specified to be quasi-linear for simplicity and can be expressed using Eq. (1). Equation (2) shows the constraint to income.

$$V(q_i, r_i, I_i^m) = \max[\alpha_x^m \ln x_i^m + \alpha_l^m \ln l_i^m + Z_i^m] + \tau_i^m \tag{1}$$

[7] See Appended Figure 1 for the zone segments.

$$s.t. \qquad Z_i^m + q_i x_i^m + r_i\, l_i^m = I_i^m - D_i^m \quad (\text{where, } I_i^m \equiv w(t^m - s_i^m)) \tag{2}$$

where *i*: Subscript showing the zone (111zones), *m*: Superscript showing the age group (the non-elderly and the elderly), q_i : Personal trip cost, r_i : Residential land rent, I_i^m : Income per capita, α_x^m, α_l^m : Parameters, w : Time value, t^m : Binding hour, s_i^m : Commuting time, D_i : Expected value of tsunami damage per year by zone, and τ_i^m : Degree of attraction specific to the zone (simple sum of the fixed value $\bar{\tau}_i$ and the random variable ε_i different between individuals).

In principle, the risk premium should be also taken into consideration using an expected utility function and a strictly concave utility function. Due to the constraint on the data, however, it is impossible to calibrate a complex model. Hence, the present study uses a quasi-linear utility function with no risk premium as a primary approximation. Consequently, the influence of tsunami damage can be expressed by the expected value D_i . This can be interpreted to mean that residents are preparing for the damage by accumulating the expected value of damage suffered annually. This can also be interpreted as the case where full insurance is available and residents have taken out insurance.

Solving Eqs. (1) and (2) for utility maximization yields Eqs. (3) and (4).

$$x_i^m = \frac{\alpha_x^m}{q_i} \quad \text{and} \quad l_i^m = \frac{\alpha_l^m}{r_i} \tag{3}$$

$$V_i^m = I_i^m - D_i^m - \alpha_x^m \ln q_i - \alpha_l^m \ln r_i - \alpha_x^m - \alpha_l^m + \tau_i^m \tag{4}$$

According to Eqs. (3), parameters α_x^m and α_l^m can be expressed using the annual amount of consumption on traffic and land, respectively, as shown by Eq. (5).

$$\alpha_x^m = q_i x_i^m \quad \text{and} \quad \alpha_l^m = l_i^m r_i \tag{5}$$

The residents in age group *m* change their location to the zone where the utility level V_i^m is higher. Assuming that the random variable ε_i follows the Gumbel distribution (average: zero, variance: $\pi^2 / 6(\theta^m)^2$), the location selection behavior can be expressed by a logit model. The zone population N_i^m is calculated by multiplying the total population of the zone by age group N_T^m and the location selection probability P_i^m together.

$$P_i^m = \frac{\exp\theta^m (V_i^m + \overline{\tau}_i^m)}{\sum_i \exp\theta^m (V_i^m + \overline{\tau}_i^m)} \qquad i \in \{1,\cdots,111\} \tag{6}$$

$$N_i^m = P_i^m \cdot N_T^m \qquad i \in \{1,\cdots,111\} \tag{7}$$

where θ^m is the logit parameter (normalized to 1) of the location selection model.

The total land demand L_i^m can be expressed by multiplying the consumption on land area per person and the number of residents in each location together as shown by eq. (8).

$$L_i^m = l_i^m \cdot N_i^m \qquad i \in \{1,\cdots,111\} \tag{8}$$

Shown below in the following sequence are the estimated time value, income, land and traffic parameters, and commuting time to be used in the residents' model, together with the respective sources of data used for calibration and the method thereof.

○ Time value w (= average wage rate): Weight-average the binding hour per person[9] (hours/man-day) in the 2000 NHK Japanese Time Use Survey (National Version) using the population (people) by age group obtained in the 2005 national census and multiply 365 (days) and the total population (people) together to obtain the total annual working hours (hours). Subsequently, divide the employees' income (yen) in Prefectural Economic Accounts by the total annual working hours to determine the time value. Data sources and other details such as the units are shown in Table 1 (see No. 1 to 5 in Table 1).

○ Income by age group I_i^m: Create the data by multiplying the estimated time value (yen/hour) and the value obtained by subtracting the commuting time by zone subsequently created from the binding hour per person (i.e., $I_i^m \equiv w(t^m - s_i^m)$). (See Nos. 5 and 6 in Table 1 as well as Table 2.)

○ Traffic parameter α_x^m: As shown in Eq. (5), the traffic parameter shows the annual consumption on traffic (yen/year), which is created by multiplying the time value and the number of personal trips per person (trips/person) × personal trip time per person (hours/trip) × 365 (days) together. (See Nos. 5, 7, 8, and 9 in Table 1.)

9 Defined as the behavior with high obligation and restriction to maintain and improve households and society, comprising jobs and related matters, academic work, household work, and social participation.

○ Land parameter α_l^m : As shown in Eq. (5), the land parameter shows the annual consumption on land (yen/year), which is created by multiplying the income by age group by the housing loan to income ratio. (See Nos. 10 and 11 in Table 1.)

Table 1 Time value, income, traffic and land parameters

No.	Item	Unit	Data source or calculating method
1	Binding hour per person by age group	hours/ person-day	2000 Japanese Time Use Survey (National Version), Weekdays, Total average time use, The non-elderly, The elderly (Average of those in their 60s and 70s and older)
2	Population by age group	people	2005 national census
3	Total annual working hours by age group	hours/year	1. Annual working hours per person × 2. Population by age group × 365 days
4	Employees' income	yen/year	Prefectural Economic Accounts, Compensation of Employees
5	Time value w	yen/hour	4. Employees' income/3. Annual working hours
6	Income $I=w(t-s)$	yen/year	5. Time value w × (1. Binding hour t – Commuting time s)
7	Number of personal trips per person	trip/person	Estimated number of personal trips (seeAppendix 2)/population
8	Personal trip time per person	hours/person	Minimum expected cost by origin zone
9	$\alpha^m{}_x$ (= Consumption on traffic)	yen/year	365 days × 5. Time value × 7. Number of personal trips per person × 8. Personal trip time
10	Housing loan to income ratio	%	Annual report on family income and expenditure survey, Ratio of the amount of repayment of loans for house & land purchases to real income for households with housing loans (repaying loans for house & land purchases) (Average for all age groups: 15.5%*)
11	$\alpha^m{}_l$ (= Consumption on land)	yen/year	6. Income × 10. Housing loan to income ratio

○ Commuting time s_i^m : The non-elderly and elderly commute to work or school. The commuting time is the average time by origin zone, which is created by multiplying the value obtained by weight-averaging the time required to travel between the respective zones with respect to the number of commuting trips at the destination by the number of commuting trips per person (trips/person) (see Table 2 for the detailed).

Table 2 Commuting time

No.	Item	Units	Remarks
1	Commuting time to work per trip	hours/trip	Weight-average the required time between zones using the trips to work at the destination.
2	Commuting time to school per trip	hours/trip	Weight-average the required time between zones using the trips to school at the destination.
3	Number of trips to work per person	trips/person	Number of trips to work/population
4	Number of trips to school per person	trips/person	Number of trips to school/population
5	Commuting time s	hours/person	1. Commuting time to work × 3. Number of trips to work per person + 2. Commuting time to school × 4. Number of trips to school per person

Finally, the time value, income, and land/traffic parameters shown in Table 3 were obtained.

Table 3 Domestic account parameters

	Symbol of the model	Less than 65 years old	65 years old or more
Time value	w	538.0	538.0
Traffic parameter	$\alpha^m{}_x$	40.8	41.6
Land parameter	$\alpha^m{}_l$	18.0	20.2

2.2 Companies

The employment locations, or commuting destinations, are fixed, and the actual data before the Great East Japan Earthquake are used for the number of employees by zone[10].

2.3 Land owners

A land supply function for residential use is set as shown by Eq. (9) to create the land supply function using actual data. Land owners supply the residential land to residents and earn income from land rent.

$$y_i = A(r_i)^{\sigma} Y_i \tag{9}$$

where y_i : Residential land supply area, Y_i: Maximum residential land area that can be supplied, A and σ: Parameter.

A regression analysis[11] was made using the data, y_i, Y_i, and r_i for Eq. (9) to obtain parameters σ and A. Here, in order to match completely the land supply area by zone y_i obtained and the actual land supply area by zone, the constant term by zone Δ_i is multiplied to obtain the residential use land supply function as shown by Eq. (10).

$$y_i = exp(1.508)(r_i)^{0.533} Y_i \cdot \Delta_i \tag{10}$$

2.4 Equilibrium condition

The equilibrium condition for the land market can be expressed by Eq. (11), and the constraint on the population is expressed by Eq. (12).

$$y_i = \sum_m L_i^m \qquad i \in \{1, \cdots, 111\} \tag{11}$$

$$\sum_i N_i^m = N_T^m \qquad m \in \{1, 2\} \tag{12}$$

[10] According to the actual current restoration plan, this setting is unrealistic. However, as already denoted in Introduction, the present study does not intend to evaluate the actual restoration plan.

[11] The land use data creation and the regression results are described in Appendix 1 and 3, respectively.

2.5 Coastal levee improvement model

Subtract the annual tsunami damage by zone from the income by zone to incorporate the tsunami risk into the location model. As the improved coastal levee height increases, the tsunami damage risk decreases, and the annual amount of damage eventually decreases.

To calculate the annual amount of damage, initially set the flood water depth by tsunami height by levee height for each zone and subsequently take into consideration the probability of occurrence of a tsunami by the tsunami run-up height to calculate the tsunami damage, namely, the risk of damage to houses and the risk of death. Here, the flood water depth means the height (depth) from the ground surface to the water surface in the flooded area as shown in Fig. 2, and the run-up height means the altitude reached by the tsunami that has landed as shown in Fig. 2.

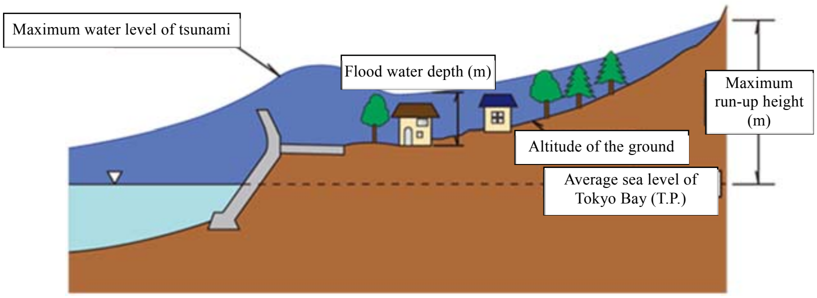

Figure 2 Flood water depth and run-up height (Source: Otaru City Homepage[13])

The method used to set the flood water depth is as follows: Set the flood water depth by zone by using the data for the Earthquake and Tsunami Simulation and Damage Estimation Survey for Rikuzentakata (Iwate Prefecture, 2003) over the zones by town-*chome* for the Takata area[15] (see Fig. 6) in the central part of Rikuzentakata. The tsunami simulation (Iwate Prefecture, 2003) is shown in Fig. 3. The run-up height in the Takata area in the tsunami simulation is calculated supposing the same scale earthquake as the three past big earthquakes, which were different in run-up height, namely, the

[13] See http://www.city.otaru.lg.jp/simin/anzen/bosai/hageniki_sinsuiyosokuzu.html.

[15] Term used for the purpose of the present study and the collective designation of the zones affected by the coastal levee improvement. A map is shown in Fig. 7.

Meiji-Sanriku Earthquake at 10.4m, the Showa-Sanriku Earthquake at 6.0m, and the Miyagi-oki Earthquake at 10.2m. Because we need to set an exact run-up height for our simulation to calculate the flood water depth at each zone, we assume that the run-up height based in their simulation is 10m.

Set the flood water depth $\Lambda_i(K,\Phi)$ by zone for each coastal levee height. Initially, as Case i), for a tsunami with a run-up height Φ of 10m or less, if the run-up height exceeds the improved coastal levee height K, the flood water depth $\Lambda_i(K,\Phi)$ will be the same as the estimated flood water depth Ω_i in the tsunami simulation (2003) (Fig. 3) as shown in Eq. (13). Subsequently, as Case ii), for a tsunami run-up height Φ exceeding a run-up height of 10m set in the tsunami simulation (2003), if the run-up height exceeds the improved coastal levee height K, the value obtained by adding the portion in excess of 10m to the estimated flood water depth Ω_i in the tsunami simulation is set as the flood water depth[17] as shown in Eq. (14). If the improved coastal levee height K is higher than the run-up height Φ, the flood water depth in all zones will be zero as shown in Eq. (15).

i) Run-up height $\Phi \leqq 10m$ and Run-up height Φ > Coastal levee height K

$$\Lambda_i(K,\Phi) = \Omega_i \tag{13}$$

ii) Run-up height $\Phi > 10m$ and Run-up height Φ > Coastal levee height K

$$\Lambda_i(K,\Phi) = \Omega_i + (\Phi\text{-}10) \tag{14}$$

iii) Coastal levee height $K \geqq$ Run-up height Φ

$$\Lambda_i(K,\Phi) = 0 \tag{15}$$

where Φ : Run-up height, $\boldsymbol{\Lambda_i}$: Flood water depth, Ω_i : Flood water depth in the tsunami simulation (2003), and K : Improved coastal levee height above *T.P. (m)*.

Subsequently, formulate the probability of occurrence of a tsunami $T(\Phi)$ by run-up height Φ per year. First, the data of the run-up heights of the past tsunamis to the Sanriku

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[17] There are new flooded zones in the event of a larger-scale tsunami with a run-up height exceeding 10m, which is the estimated run-up height in the simulation. However, since the Takata area is a flat urban area surrounded by mountains, there are only two relevant zones. For these zones, the flood water depth is set to 0m where the run-up height of the arriving tsunami is 10m and set to the portion in excess of 10m where the tsunami run-up height exceeds 10m.

district were mainly[18] extracted from the tsunami observation data (for a period of 400 years from 1611 to 2011) summarized on the website of the National Geographical Data Center of the National Oceanic and Atmospheric Administration (NOAA).

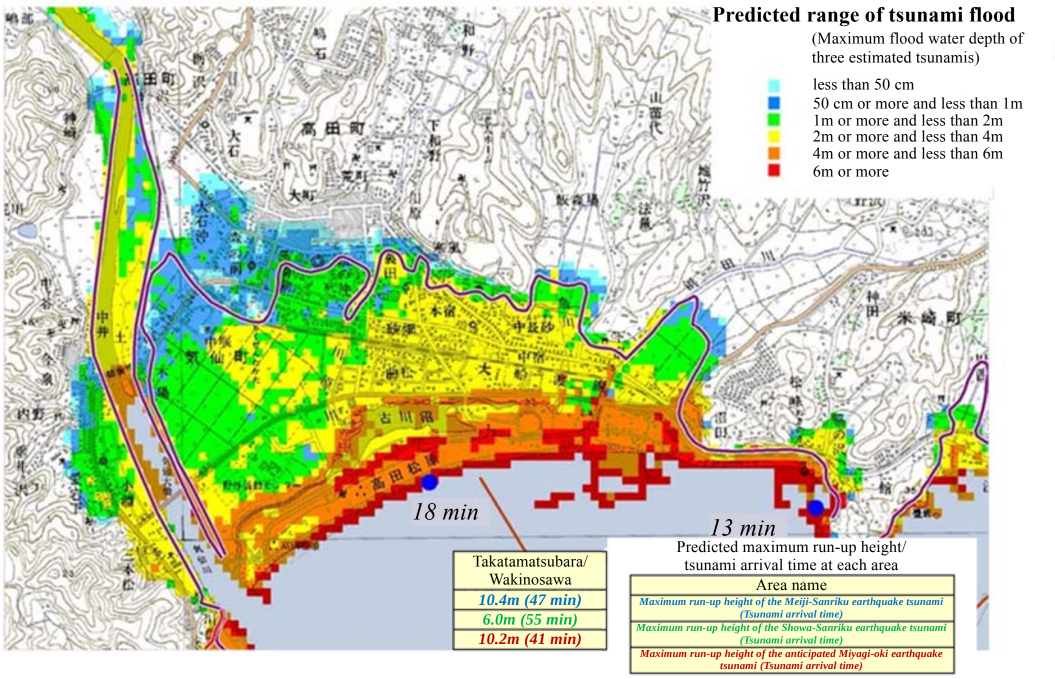

Figure 3 Tsunami Damage Estimation Survey for Rikuzentakata (Iwate Prefecture, 2003)

To estimate the predicted distribution in the future based on these actual data, with an assumption that tsunami with a height within 2m of that of the actual tsunami would occur with the same probability, the frequency of tsunami arrival by actual run-up height Φ was evenly allocated within the range of ±2m from the run-up height actually observed.[19] When the data is divided by 400 (years), the probability of occurrence of tsunami $T(\Phi)$ by run-up height Φ per year can be obtained as shown in Figure 4.

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[18] For large-scale earthquakes, namely, the Great East Japan Earthquake (15m), the Chilean Earthquake (6m), the Showa-Sanriku Earthquake (6m), the Meiji-Sanriku Earthquake (10m), and the Keicho Sanriku Earthquake (20m), the data in the study area were individually investigated, and the values obtained were used. The NOAA data are for the whole Sanriku district but not for the study area, or Rikuzentakata. Hence, only for those large-scale tsunamis, the data of Rikuzentakata or Tarocho near Rikuzentakata were used.

[19] For tsunami less than 3m in height, actual data were used. As shown in the subsequent analysis, the optimal coastal levee height is 10m. Since the optimal height is determined based on a comparison of the marginal benefit and the marginal cost, the way of allocating low tsunami has no influence at all on the determination of the optimal height as long as the expected value for damage does not change.

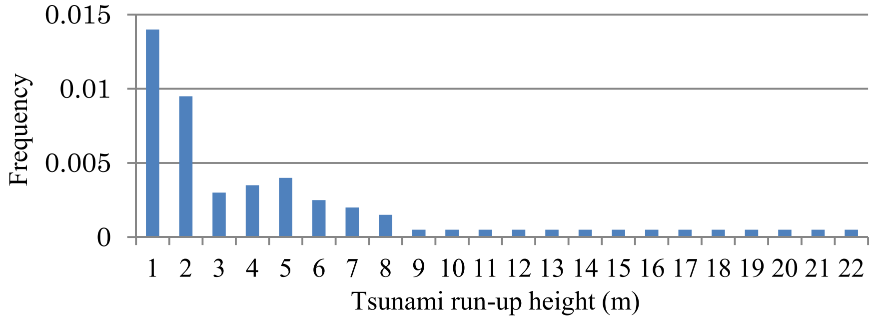

Figure 4 Frequency of tsunami arrival by run-up height per year (estimated)

Using the above settings, calculate the annual amount of damage $D_i(K)$.[23] Limit the possible tsunami damage to the residents in each zone to only two items, 1) damage to their house and 2) their death.

Initially, calculate 1) the deduction caused by the damage to their house. Set the price of houses to ¥20 million per house, the average number of people per household in Rikuzentakata to 3.2 (2005 national census), and the social discount rate to 4%. Divide the value of their house at 20 million yen by the average number of people per household of 3.2 to determine the amount of damage to their house in the event of a flood. Multiply this amount by the probability of occurrence of a tsunami $T(\Phi)$ and add each amount obtained to determine the annual deduction per person $D_i^{Comp}(K)$ in the zone defined as completely destroyed ($\Lambda_i(K,\Phi) \geq 2$). The annual deduction per person $D_i^{Half}(K)$ in the zone defined as half destroyed ($0 < \Lambda_i(K,\Phi) < 2$) will be half of the above. (Only in the case where the run-up height Φ exceeds the set coastal levee height K)

$$D_i^{Comp}(K) = \{\sum_{\Phi=1}^{22}(2000/3.2)T_i(\Phi) : \Lambda_i(K,\Phi) \geq 2\} \tag{16}$$

$$D_i^{Half}(K) = \{\sum_{\Phi=1}^{22}(1000/3.2)T_i(\Phi) : 0 < \Lambda_i(K,\Phi) < 2\} \tag{17}$$

where $T(\Phi)$: Tsunami arrival probability by run-up height Φ by meter.

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[23] The annual amount of damage per person *D* deducted from the income in the present study is the annual cost, which is a flow value. To obtain *D*, however, it is not necessary to change the amount of damage to the stock due to property damage or death into a flow value. Since a tsunami causing damage may potentially occur every year, the value obtained by multiplying the amount of damage to stock and the probability of damage per year together eventually is the expected flow value.

Subsequently, calculate 2) the annual amount of damage caused by the risk of death. For the risk of death, divide the number of fatalities in Rikuzentakata from the Great East Japan Earthquake by the population of Rikuzentakata at the 2005 national census to determine the fatality rate when a tsunami overflows the levees (i.e, the tsunami fatality ratio R is 1,554 people /24,709 people =6.29%). Use 260 million (yen/person)[24] estimated by the Cabinet Office (2007) for the value of statistical life. Multiply the set tsunami fatality rate (R) by the value of statistical life (L) to determine the amount of damage to stock for the risk of death in the event of a flood. Multiply this amount by the probability of occurrence of a tsunami by the run-up height $T(\Phi)$ to determine the annual deduction per person D_i^{Death} in the zone (only in the case where the run-up height Φ exceeds the set coastal levee height K).

$$D_i^{Death}(K) = \{(R \times L)\, T_i(\Phi) : \Lambda_i(K,\Phi) > 0\} \tag{18}$$

Based on the above, the annual total amount of damage by zone $D_i(K)$ is obtained by adding the annual amount of damage caused by damage to houses and the annual amount of damage due to the calculated risk of death.

$$D_i(K) = D_i^{Comp}(K) + D_i^{Half}(K) + D_i^{Death}(K) \tag{19}$$

2.6 Calculation of the gross social welfare

The gross social welfare is obtained from the sum of the welfare of the residents and the welfare of the absent landowners. Gross welfare means the welfare before the coastal levee cost is deducted from the social welfare. Initially, obtain the welfare of the residents W^H through calculating the log-sum of the residents' indirect utility in all 111 zones.

$$W^H = \sum_m N_T^m Exp\{\max_i (V_i^m + \tau_i)\} = \sum_m N_T^m \ln \sum_{i=1}^{111} \exp(V_i) \tag{20}$$

where N_T: Total population of Rikuzentakata, V_i: Utility by zone

Obtain the welfare of the absent landowners W^L by adding the incomes obtained by

[24] The pecuniary loss (¥33 million) was added to the death loss (¥226 million).

the absent landowners supplying land to residents in all 111 zones.[25, 26]

$$W^L = \sum_{i=1}^{111} r_i y_i \tag{21}$$

where r_i: Land rent, y_i: Residential land supply area

Finally, add the welfare of the residents and the welfare of the absent landowners to obtain the gross social welfare.

$$W = W^H + W^L \tag{22}$$

The gross social welfare changed when coastal levees are improved. To compare with the coastal levee improvement cost, which is a stock variable, obtain the benefit through converting into a present value using a social discount rate of 4%.

2.7 Calculation of the coastal levee improvement cost

Calculate the coastal levee improvement cost by height using the regression analysis[27] based on past coastal levee improvement costs for Iwate Prefecture (1969) and the data of the coastal levee improvement cost (Takata coast) currently estimated by Iwate Prefecture (see Fig. 5). In this case, the construction cost deflator is used to convert the nominal cost into the real cost (convert it into the present value). The function form is set as follows:

$$C(K) = \gamma \exp(\phi \cdot K) \tag{23}$$

where $C(K)$: Improvement cost by improved coastal levee height K, γ, θ: Parameters

[25] Since a flexible residential land supply function is taken into consideration, an opportunity cost concerning the residential land supply is incurred. This opportunity cost is composed of, for example, the cost of cutting down trees to prepare the land for residential use and the income from alternative use such as agriculture. In the latter case, the rental income from agricultural land merely changes to rental income from residential land, and thus it is not necessary to reduce any income for the absent landowner. However, this ratio is unknown. Hence, in the social welfare function in the present study, most of the opportunity cost was considered to be income from alternative use (e.g., income from agricultural land rent), and this opportunity cost was not deducted. Since the income from land rent is considerably less significant than utility (see Table 6 or Figure 9), neither consideration nor ignorance of the amount of this opportunity cost has any significant influence on the results.

[26] The current simulation assumes that the location of firms is fixed, so firms' land demand is not changed. However, since the land rent for business use can be indirectly affected by the change in residential land use, it must be taken into consideration to be exact. However, as shown by the simulation results in Table 6 and Figure 9, the ratio of the change in land rent income to the change in social welfare is significantly low. In addition, since no modeling of companies is performed, the influence of the increase in the land rent for business use on social welfare is ignored.

[27] The data used for the regression analysis and the statistical results are shown in Appendices.

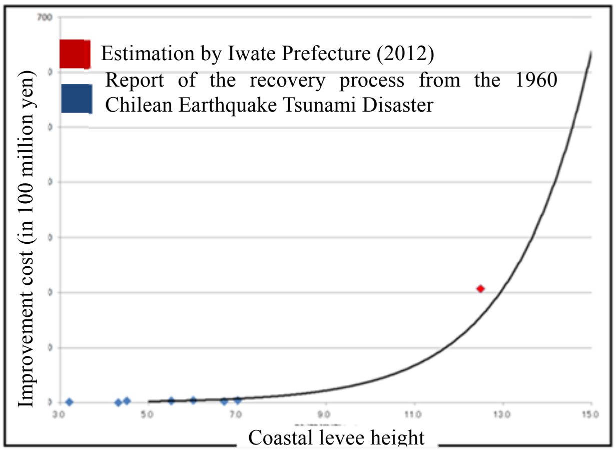

Figure 5 Coastal levee improvement cost

The cost function and the coastal levee improvement cost by set coastal levee height calculated using the regression analysis[28] are shown by the regression line in Fig. 5 and the numerical values in Table 6, respectively. The regressed cost function is shown by Eq. (24). The coastal levees to be discussed in the present study for improvement are those with a total length of 1,977m planned to be developed (by Iwate Prefecture) along the Takata area coast. The location of the improved coastal levees is shown by the blue line in Figure 7.

$$C(K) = 1977[0.71\exp(0.56 \cdot K)] \tag{24}$$

Table 5 Estimated coastal levee improvement cost

Coastal levee height (above T.P.)	5m	6m	7m	8m	9m	10m	11m	12m	13m	14m	15m
Improvement cost (in 100 million of yen)	2.3	4.1	7.1	12.5	22.0	38.5	67.5	118.3	207.5	363.7	637.5

2.8 Formation of the standard

Calculate the risk $D_i\ (K=6)$ for a coastal levee height of 6m above T.P.,[30] the same as that before the Great East Japan Earthquake, and calculate the equilibrium of the model to obtain the degree of each zone's own attraction $\overline{\tau}_i$ with the population density of each zone maintained identical to that before the earthquake. The equilibrium of this model is determined to be the standard equilibrium.

28 The results and data are shown in Appendix 3.

30 The actual levee height before the Great East Japan Earthquake is 5.5m. In the present study, however, calculation is made in 1m increments of the coastal levee height, and the levee height before the earthquake is assumed to be 6m. This approximation does not affect the simulation results.

3. Simulation

The simulation process and results are shown in section 3.1 and 3.2, respectively. Discussion on these results is in Section 3.3.

3.1 Simulation for each of the two cases

Optimal social case. In the optimal social case, use the model with parameters calibrated in Section 2 and change the coastal levee height from 5m to 15m above T.P. to obtain the coastal levee height that maximizes the social welfare.[31] The simulation is made in 1m increments.

Dynamic inconsistency case. In the dynamic inconsistency case, the coastal levees are improved to ones of optimal height based on the residential population (or the planned population announced by the developers). Divide the area into two types of zones: the Takata area (see Fig. 6), where the flood damage level varies depending on the coastal levees; and other zones. Subsequently, set the population of the Takata area to 1.0 to 2.0 times that before the earthquake (with the population of other zones set to the one obtained by subtracting the population of the Takata area from the total population of Rikuzentakata) and determine the coastal levee height corresponding to each population using CBA.

Here, obtain the benefit of the coastal levees as the “amount of tsunami damage reduced by the coastal levees”. Calculate for 1m increments of the coastal levee height. The increment of the benefit $\Delta Benefit(K)$ by further increasing the height of the coastal levee K m high by 1m can be calculated as shown in Eq. (25). For an optimal coastal levee height of K^*, the increment in the cost exceeds the increment in the benefit when the coastal levee height is further increased by 1m. Eq. (26) is the optimum conditional equation.

$$\Delta Benefit(K) = \sum_{i=1}^{111} [D_i(K) - D_i(K+1)] \tag{25}$$

[31] This can be obtained through a simple calculation as follows:

$$dW^H = N_T^m \sum_m \sum_{i=1}^{111} P_i^m dV_i^m = \sum_m \sum_{i=1}^{111} N_i^m dV_i^m$$

$$\Delta Benefit(K^*) \geq \Delta Cost(K^*)\ (\equiv C(K^*) - C(K^* - 1)) \text{ and} \\ \Delta Benefit(K^* + 1) < \Delta Cost(K^* + 1)\ (\equiv C(K^* + 1) - C(K^*)) \tag{26}$$

where D_i: Annual amount of damage by zone, K: Improved coastal levee height (*above T.P.*), and K^*: Optimal coastal levee height (above *T.P.*)

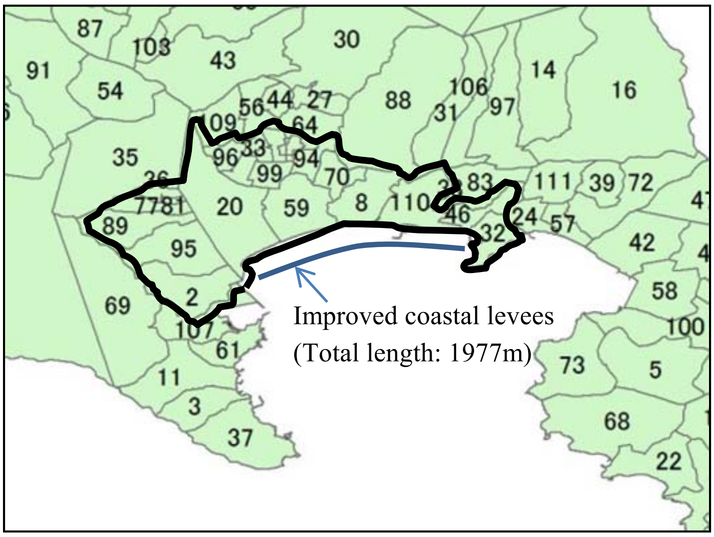

Figure 6 Takata area (Area enclosed by the bold line; Number: Zone number)

3.2 Simulation results

Optimal social case. Table 6 shows the benefit, or the sum of the change in residents' welfare and the change in land owners' income, when coastal levees with a height of 5m to 15m above T.P. are developed in the Takata area. The benefit and cost are shown as an increase or decrease from the standard (with a coastal levee height of 6m).

Figure 7 shows the same as a graph. The benefit is shown by the light blue line whereas the coastal levee improvement cost is shown by the dark blue line. The net benefit obtained by subtracting the improvement cost from the benefit (= change in the social welfare) is shown by the red line. If the improved coastal levees exceed the tsunami height of 8m, the growth of the benefit slows down. This is attributable to the decrease in the frequency of arrival of tsunamis that exceed 8m high as shown in Fig. 4. The optimal social coastal levee height in Takata area is 10m above T.P., where the net benefit is about ¥11.4 billion.

Table 6 Results in the optimal social case (Units: Present value)

Coastal levee height (above T.P.)		5m	6m (Standard)	7m	8m	9m	10m	11m	12m	13m	14m	15m
Benefit	Domestic accounts (in ¥100 million)	-66.1	**0.0**	59.3	107.8	124.8	142.2	163.1	185.0	207.3	230.2	253.7
	Land owners (in ¥100 million)	-3.1	**0.0**	2.7	4.7	5.4	6.1	7.2	8.3	9.4	10.5	11.7
	Increase/decrease (in ¥100 million)	-69.2	**0.0**	62.0	112.5	130.2	148.3	170.3	193.2	216.7	240.7	265.3
Cost	Increase/decrease (in ¥100 million)	-1.8	**0.0**	3.1	8.5	17.9	34.4	63.4	114.3	203.4	359.6	633.5
Net benefit (in ¥100 million)		-67	**0**	59	104	112	114	107	79	13	-119	-368

Note: Increase/decrease means the difference from the standard, where the coastal levee height is 6m, due to the increase/decrease in the coastal levee height.

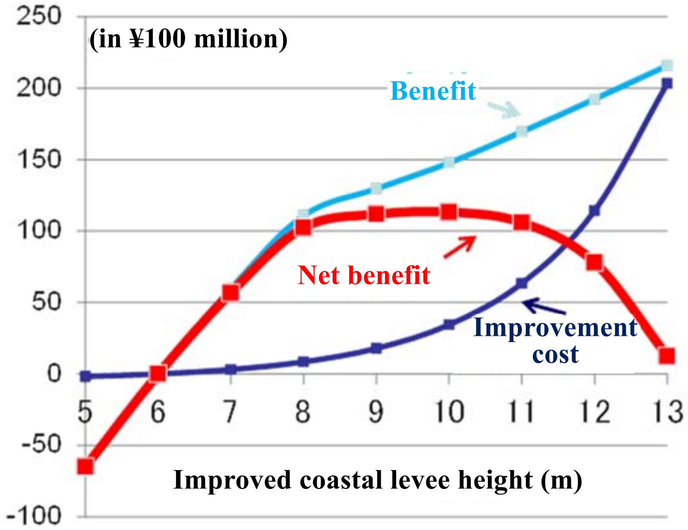

Figure 7 Results in the optimal social case

Dynamic inconsistency case. In Dynamic inconsistency case, the government determines the coastal levee height through CBA after residents have strategically migrated. The optimal coastal levee height for each population obtained through CBA is shown in Table 7. When the population of the Takata area is increased to about 1.5 times (13,080 people) from the optimal social condition (8,440 people), the improved coastal levee height was 11m above T.P., 1m higher than in the optimal social case.

Table 7 Coastal levee height obtained through CBA with the population as a given condition

Given condition: Population of the Takata area (people)	Optimum coastal levee height through CBA: T.P. (m)	Results: Amount of damage reduced (in ¥100 million)
(Before the Earthquake) 6885	9.5	128.0
7575	9.5	145.0
(Optimal) 8440	10.0	167.9
8950	10.0	181.8
9640	10.0	189.8
10330	10.0	209.8
11015	10.0	223.8
11705	10.5	251.0
12395	10.5	265.8
13080	11.0	289.0
13770	11.0	313.3

3.3 Discussion

Optimal social case. The optimal social coastal levee height in the Takata area is 10m above T.P., which is is considerably greater than the coastal levee height of 6m above T.P. before the earthquake.[32] The coastal levees with a height of 6m above T.P. before the earthquake are considered to have been inadequate. Also from the perspective of the population of the Takata area, since the population for an optimal social coastal levee height of 10m above T.P. is 8,440 whereas the population before the earthquake (coastal levees height of 6m above T.P.) was 6,885, the actual residential population may have been eventually less than the optimal population due to the insufficient coastal levee height.

Table 8 Population in equilibrium with the coastal levee height as a given condition

Given condition: Coastal levee height above T.P. (m)	Results: Population in the Takata area (people)
6.0	(Before the earthquake) 6885
7.0	7600
8.0	8095
9.0	8265
10.0	(Optimal) 8440
11.0	8645
12.0	8860

Dynamic inconsistency case. In the optimal social case, the optimal social coastal levee height in the Takata area was 10m above T.P. (see Table 6 and Fig. 7). In the dynamic

[32] As of April 2013, the improved coastal levee height being planned is 12.5m. No CBA for this coastal levee height has been made by Iwate Prefecture, which improves coastal levees.

inconsistency case, it emerged that the improved coastal levee height was 11m above T.P. if developers strategically made residents migrate and the population of the Takata area increased to 13,080, or about 1.5 times the optimal social condition (about twice the population before the earthquake).

Here, the above two cases are compared using Fig. 8.[33] In Fig. 8, the vertical axis (A) represents the improved coastal levee height, the vertical axis (B) represents the net benefit to the Takata area, and the horizontal axes for both (A) and (B) represent the population of the Takata area. On the horizontal axis, the minimum value is the population of the Takata area before the earthquake and the maximum value is about twice that.

Curve (a) is the result in the optimal social case and shows the population of the Takata area when the population in equilibrium after the coastal levee height has been determined settles. Curve (b) is the result in the dynamic inconsistency case and shows the improved coastal levees determined through CBA after the population of the Takata area has been determined. Curve (c) shows the benefit to the Takata area for each improved coastal levee height following the comparison of the amount of damage reduced for each improved coastal levee height with the case of the coastal levee height of 6m above T.P. before the earthquake. These benefits can be distributed to the residents and/or the absent landowners, and developers can distribute them. Consequently, the difference between (a) and (b) shows the existence of a dynamic inconsistency problem as well as its degree, and curve (c) shows the benefit that causes the dynamic inconsistency.

Actually, the benefit continues to increase even if the population exceeds 13,080 shown at the right end of the graph.[34] Hence, if the government improves the coastal levees based on the benefit and cost according to the population scale, further higher coastal levees can be constructed. However, since developers and/or residents cannot continue to mislead the

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[33] This figure corresponds roughly to Figure 2 by Kono and Notoya (2012).

[34] The population of Rikuzentakata before the Great East Japan Earthquake was about 24,000. In the case where this entire population lives in the Takata area, the optimal coastal levee height from CBA was 12m.

government infinitely, the following discussion limits the population to a population twice (i.e., 13,080) that of the Takata area before the earthquake.

Assuming that the improved coastal levee is 11m above T.P. in the case where the population of the Takata area is 1.5 times (i.e., 13,080) the optimal social condition, the difference in cost is about ¥2,900 million compared with the case where improved coastal levees with an optimal social height of 10m above T.P. are developed. This means that taxes are injected into a useless public investment. If the difference in cost is converted into a flow value using a social discount rate of 4%, this is equivalent to about ¥120 million. Since the budget of Rikuzentakata for fiscal 2009 was about ¥10,300 million, this amount was equivalent to over 1% of the city's annual budget.

Tables 7 and 8 (and Fig. 8) clarify that the improved coastal levee height determined through CBA is 11m when the population of the Takata area is 13,080, whereas the population in equilibrium is 8,645 when the improved coastal levee height is 11m. This means that, the population 13,080 is not an equilibrium population at 11m height. Even though the residents who have migrated to the Takata area in order to make use of the coastal levee improvement, many people leave the Takata area again to eventually achieve the equilibrium. In order for the government to project this equilibrium in adovance, however, it is necessary to know the residents' preference. In the present study, since the utility function of the residents has been assumed, this equilibrium can be projected. Generally speaking, however, the government cannot know the residents' preference and therefore have to measure the benefit only through CBA.

Finally, the infrastructure improvement cost and the degree of the dynamic inconsistency problem are analyzed to discuss the dynamic inconsistency problem in infrastructure other than coastal levees. The coastal levee improvement cost is characterized by a cost increase that accelerates with the increase in the scale of improvement as shown by the dark blue line in Fig. 7. Consequently, the coastal levee improvement is considered as an infrastructure improvement with a cost that increases intensively with an increase in scale. Hence, even though many residents have migrated to the Takata area to increase the population to a level of about 1.5 times the optimal population as a result of the strategic behavior of the developers, the coastal levee height has changed from an optimal social height of 10m above T.P. only to a height of 11m above T.P. However, in the case of an infrastructure improvement where the improvement cost gradually increases with the increase in scale, such as road improvement, the increase in the scale of improvement is more sensitive to the strategic behavior using CBA, and the inefficiency of the dynamic inconsistency problem is incurred on a larger scale.

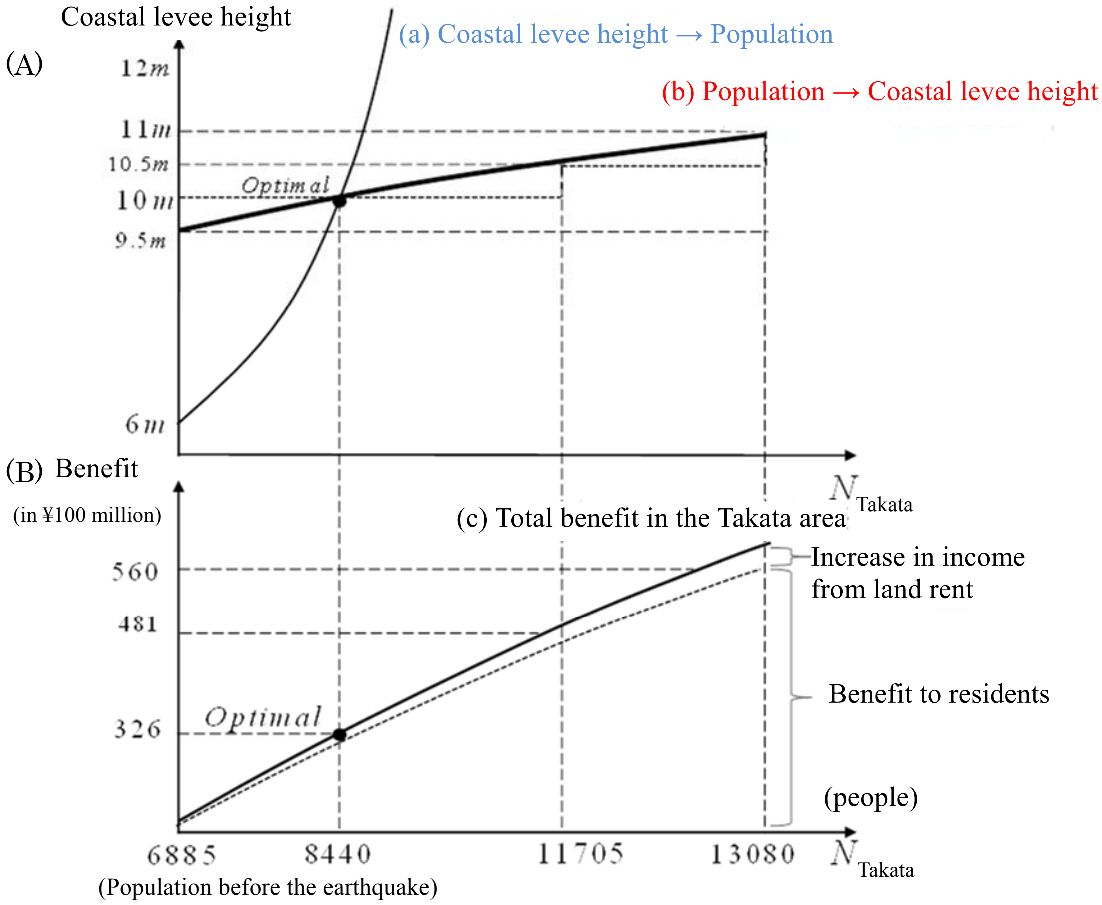


Figure 8 Results of dynamic inconsistency

4. Conclusions

The degree of inefficiency of the dynamic inconsistency problem in the coastal levee improvement in Rikuzentakata was shown using a calibrated location equilibrium model. If the population of the Takata area were twice what it was before the Great East Japan Earthquake, the coastal levees would be increased to 1m higher than the optimal height of 10m. This additional cost is equivalent to over 1% of the annual budget of Rikuzentakata.

The cost of the coastal levees increases significantly as the improved height increases. The cost increase is particularly significant when the height exceeds 10m. Hence, even if many people migrate strategically, the increase in the optimal height is limited to 1m. However, in the case of infrastructure improvement, such as road improvements, where the cost increases only gradually with an increase in the scale of improvement, the inefficiency that accompanies the dynamic inconsistency problem is eventually incurred on a larger scale. Consequently, careful attention must be paid to the dynamic inconsistency problem particularly concerning projects where the improvement cost increases only gradually.

To avoid the dynamic inconsistency problem in public projects, it is reasonable for the residents, who are the beneficiaries, to bear all of the costs. However, it is generally difficult to establish a system whereby residents bear all of the costs. For example, in the case of the present study, the cost can be recovered by means of fixed asset taxation in the area where the benefit is received. However, it is generally impossible to increase the fixed asset tax rate only in some particular areas. Even in the case where the city of Rikuzentakata bears all of the costs by a method other than imposing a tax on assets, it is inadequate because it puts an additional burden on the residents who do not receive the benefit (i.e. the residents outside the Takata area). Since it is also difficult to use various other taxes that can conceivably establish a framework whereby only beneficiaries bear the costs, it will be impossible to completely avoid the beneficiaries getting a free ride. Hence, it is necessary to handle the improvement work taking into account the unavoidable dynamic inconsistency problem.

Appendices

Appendix 1. Land use data creation

For the model divided into zones by town-*chome*, create the land use data for the population, number of employees, land rent, land area, and usable land area by zone for each town-*chome*. Rikuzentakata is divided into 111 zones as shown in Appended Figure 1.

The land use data shall consist of the population (for two age groups), number of employees (for three industrial categories), land price (for residential and industrial areas), land area (for residential and industrial land), and usable land area (for residential and industrial land) by zone for each town-*chome* in Rikuzentakata.

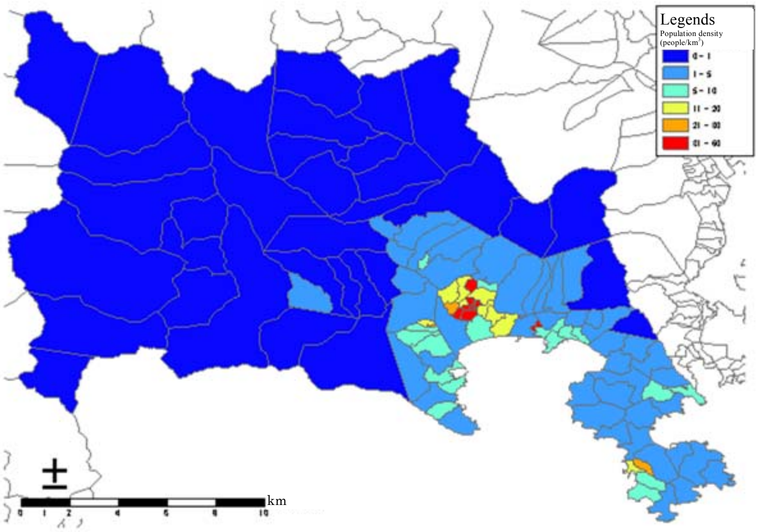
(1) Population: Create the population data for two age groups (the elderly and others) by zone based on the 2005 national census (summation of each town-*chome*/*aza* etc.).

(2) Number of employees: Create the data for the number of employees by zone by industry using the number of employees by industry in the 2006 Establishment and Enterprise Census (summation for the survey areas, etc.) and zone polygons.

(3) Land price: Create the data for the residential land price and the commercial land price by model zone using the official announcement of land prices in 2005, the prefectural land price research in 2004, and the prefectural land price research in 2005.

(4) Residential land area/usable land area: Define "residential land area" and "usable land area" using the detailed land use mesh data for the digital national land information in 2006, etc. to create the data for the residential and commercial land area and usable land area by zone.

The figure below illustrates 111 zones of Rikuzentakata and the population density created.



Appended Figure 1 Zones segments and population density of Rikuzentakata

Appendix 2. Traffic volume data creation

The traffic volume data consist of OD trips between zones *i* and *j* by means *k* by purpose *n* by age group *m*. Multiply the number of trips generated per person by means *k* by purpose *n* by age group *m* in the Nationwide Person Trip Survey(1999) and the population by age group *m* in the National census (2005) together to create the data for the number of trips generated by means *k* by purpose *n* by age group *m*. Subsequently distribute the number of trips generated to OD trips using both the distance decay parameter by means *k* by purpose *n* by age group *m* and the travel time between zones by means *k*.

To create the OD trip data, we have three steps: in step 1, create the data for trips generated per person; in step 2, create the data for trips generated by zone; in step 3, create the data for OD trips. The details of these three steps are described in Supplement.

Appendix 3. Regression analysis

(1) Residential land supply function estimation

The regression analysis results for Eq. (9) to obtain the residential land supply parameters are shown below. The data used were extracted from the data in the Takata area.

	coefficient	t-value
$\ln A$	1.5077	1.95
σ	0.53335	2.04
Corrected R^2-value	0.195	

(2) Coastal levee improvement cost estimation

The regression analysis results and data when the coastal levee improvement cost function was obtained are shown below. The data are from p. 205 of the "Report on the Recovery Process from the 1960 Chilean Earthquake Tsunami Disaster" by Iwate Prefecture and the coastal levee improvement cost approximation (12.5m above T.P.) as of 2012. The construction deflator is used to convert the project cost in 1969 into a present value.

Appendix Table 1 Actual coastal levee improvement cost data (for each 1m extension)

Levee height (above T.P.)		3.2m	4.3m	4.5m	5.5m	5.5m	6m	6.7m	7m	12.5m
Cost	1969 (in ¥10,000)	1.7	1.5	5.2	5.1	5.2	7.3	4.6	7.7	-
	Present value (in ¥10,000)	5.5	5.1	17.2	16.7	17.2	24.1	15.2	25.3	1050

The regression analysis results for Eq. (23) are shown in the table below.

	coefficient	t-value
$\ln \gamma$	-0.34170	-0.86
ϕ	0.56136	9.38
Corrected R^2-value	0.916	

The coastal levee improvement cost function shown in Eq. (24) can be obtained based on the regression analysis results and the 1,977m extension of the improved coastal levees in the Takata area determined by Iwate Prefecture.

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Supplement

Data for each zone

Initial data of Population, Land area and Land rent by zone

ZONE	Population (people)		Land area (m²)			Land rent (in ¥10,000/m²)
	Elderly	Others	Usable area	Residential land area	Area of flood	
1	53	109	417391	101468	0	0.040
2	88	194	377623	16110	41450	0.033
3	85	177	195988	29127	23489	0.025
4	85	204	284840	38611	150737	0.022
5	43	81	189070	40677	0	0.021
6	31	94	193473	89479	145260	0.047
7	39	70	249724	26336	0	0.032
8	128	597	432677	91389	481694	0.039
9	154	303	194015	120438	34657	0.016
10	84	139	191108	48544	193259	0.017
11	86	220	436354	16812	74903	0.027
12	64	135	200648	50228	0	0.041
13	61	114	454883	38520	187414	0.046
14	44	106	369884	4498	0	0.034
15	1	1	42736	100	0	0.021
16	76	124	326850	26980	0	0.033
17	88	166	133829	63408	92342	0.016
18	39	76	393088	63970	0	0.043
19	1	1	200	100	0	0.031
20	80	247	817834	89227	1304801	0.050
21	55	114	534094	84943	373347	0.025
22	37	107	188544	3396	25741	0.018
23	12	11	110111	8352	0	0.029
24	42	93	169992	50804	180716	0.026
25	41	119	210031	7885	15720	0.015
26	1	1	200	100	0	0.037
27	68	136	173142	88379	0	0.035
28	74	145	182662	48078	110719	0.016
29	28	28	87288	100	0	0.019
30	104	336	386924	120665	0	0.038
31	53	154	328306	37598	73990	0.033
32	80	145	150521	62381	132081	0.026
33	112	301	117709	85453	117709	0.059
34	24	64	236925	6471	177556	0.042
35	66	175	224111	38378	450441	0.053
36	77	136	37329	37321	48016	0.051
37	64	139	261628	7232	19501	0.022
38	80	345	65804	58770	1377	0.027
39	31	66	181131	2806	91033	0.028
40	74	129	480097	49048	386485	0.026
41	57	122	561598	60683	155172	0.024
42	74	140	366263	8333	404862	0.026
43	66	179	682004	52560	0	0.047
44	64	499	161677	85610	0	0.042
45	60	98	418314	7026	0	0.033
46	56	133	208381	36970	70941	0.026
47	1	1	30046	100	0	0.028
48	111	244	333895	105718	160986	0.022
49	110	218	378488	25329	3273	0.016
50	78	157	283375	86769	0	0.042
51	51	66	266597	16445	0	0.020
52	71	124	305283	92347	0	0.037
53	66	161	222966	47824	80660	0.014
54	28	77	189376	49646	264246	0.052
55	61	161	508035	51081	5613	0.044
56	132	455	242284	185321	16775	0.048
57	43	104	177206	23609	133897	0.026
58	72	142	576672	7785	539004	0.024
59	155	499	448308	204289	688401	0.044
60	91	172	675041	92683	0	0.037

ZONE	Population (people)		Land area (m^2)			Land rent (in ¥10,000/m^2)
	Elderly	Others	Usable area	Residential land area	Area of flood	
61	51	126	264771	1518	36418	0.028
62	42	72	180204	114166	49882	0.045
63	49	77	376440	30444	0	0.024
64	216	279	247495	177085	41566	0.033
65	63	138	49075	29034	49075	0.057
66	40	51	295808	78544	0	0.026
67	37	124	29766	23154	29766	0.053
68	56	94	209654	20078	19439	0.019
69	65	164	467404	55330	168512	0.033
70	95	284	205694	130578	161914	0.047
71	1	1	2716	100	0	0.043
72	39	88	253725	34461	5335	0.028
73	63	112	232412	56242	47407	0.021
74	53	103	736384	8915	0	0.028
75	30	56	462778	26056	0	0.041
76	55	125	239200	76721	99099	0.045
77	72	137	74120	66560	86623	0.047
78	1	1	200	100	0	0.040
79	69	192	202212	2858	134557	0.021
80	61	98	583149	12317	0	0.045
81	22	55	23976	23974	28614	0.050
82	105	216	77775	58533	48870	0.052
83	38	107	341134	90714	136530	0.028
84	63	148	245265	48276	59233	0.014
85	66	122	498251	37633	83622	0.043
86	44	111	650499	25055	12023	0.039
87	46	89	127462	18671	253629	0.048
88	233	239	622988	31903	243678	0.034
89	95	183	98820	56152	89949	0.043
90	109	213	288305	131083	69112	0.015
91	38	40	383926	61476	484109	0.049
92	56	75	228523	100327	0	0.028
93	65	82	522994	95292	0	0.024
94	118	244	98086	76994	93571	0.056
95	109	270	223552	73551	275847	0.036
96	115	309	157253	123817	164551	0.065
97	40	122	375162	82443	31572	0.032
98	74	213	161745	37099	44507	0.015
99	149	418	179714	82358	179716	0.056
100	45	122	416607	40350	332669	0.023
101	110	288	542418	82259	367567	0.016
102	94	171	251421	48265	14382	0.020
103	23	51	109848	38627	112467	0.049
104	41	74	39370	34193	26727	0.056
105	65	119	47127	39048	45382	0.049
106	47	102	245253	5383	86095	0.033
107	125	264	429102	73519	340099	0.031
108	79	147	673924	86406	24069	0.042
109	128	316	263157	172610	189561	0.056
110	86	197	375481	110600	532625	0.031
111	50	102	343170	75249	96562	0.028

Income excluding transportation cost, indirect utility value, and flood water depth of each zone when the coastal levee height is 6m (standard)

ZONE	Income (in ¥10,000)		Indirect utility		Initial flood water depth (m)
	Elderly	Others	Elderly	Others	
1	106.0	127.6	411	418	—
2	85.3	110.6	399	410	4
3	107.8	131.4	432	441	—
4	107.7	130.7	438	446	—
5	106.8	130.8	438	448	—
6	109.9	129.0	408	413	—
7	108.1	126.5	423	427	—
8	85.2	110.6	392	403	5
9	107.0	128.0	451	457	—
10	107.5	129.4	448	454	—

ZONE	Income (in ¥10,000)		Indirect utility		Initial flood w ater depth (m)
	Elderly	Others	Elderly	Others	
11	107.8	130.2	429	437	—
12	107.0	125.8	411	416	—
13	107.0	128.3	406	413	—
14	106.7	129.9	419	427	—
15	112.5	173.8	442	489	—
16	107.2	131.8	421	431	—
17	106.7	127.9	451	457	—
18	107.5	120.4	408	407	—
19	112.5	173.8	425	472	—
20	85.8	110.8	382	393	2
21	106.5	129.1	431	439	—
22	110.3	131.4	449	455	—
23	112.5	130.0	429	432	—
24	108.8	132.0	432	441	—
25	108.2	125.7	454	456	—
26	112.5	173.8	420	467	—
27	107.8	131.5	418	428	—
28	106.7	127.6	449	455	—
29	109.2	123.2	445	444	—
30	106.9	129.2	414	422	—
31	106.3	130.0	420	429	—
32	85.9	111.5	410	421	2
33	90.5	116.3	380	392	1
34	108.6	122.7	410	410	—
35	107.5	130.4	401	410	—
36	85.6	110.3	381	392	2
37	107.2	128.8	437	444	—
38	107.6	132.9	430	440	—
39	109.9	129.7	430	436	—
40	106.7	128.0	429	436	—
41	106.7	129.9	434	442	—
42	106.9	130.4	431	439	—
43	107.6	131.6	406	416	—
44	107.5	130.5	411	420	—
45	106.5	125.4	419	423	—
46	85.1	111.5	408	420	3
47	112.5	173.8	432	479	—
48	107.1	128.0	437	443	—
49	107.0	127.6	451	456	—
50	106.9	127.1	410	416	—
51	105.1	121.6	438	440	—
52	106.3	127.0	414	421	—
53	107.3	127.0	455	459	—
54	109.6	129.9	404	410	—
55	107.0	129.2	408	416	—
56	107.1	131.3	405	415	—
57	107.1	133.4	431	443	—
58	107.0	131.8	434	444	—
59	85.1	110.3	387	398	4
60	106.9	127.7	416	422	—
61	106.0	129.4	426	435	—
62	108.5	128.9	408	415	—
63	104.9	122.5	431	434	—
64	107.4	132.6	420	431	—
65	90.4	116.0	382	393	1
66	107.9	123.3	430	431	—
67	98.5	121.9	393	402	0
68	106.4	127.2	442	448	—
69	107.3	128.0	420	426	—
70	85.8	111.3	385	396	3
71	112.5	173.8	414	461	—
72	108.3	129.5	429	435	—
73	107.1	127.1	438	444	—
74	105.9	127.9	426	433	—
75	109.5	127.5	413	417	—
76	106.6	130.8	407	417	—
77	89.9	114.9	389	399	1
78	112.5	173.8	417	464	—
79	107.8	130.1	441	448	—
80	106.9	127.7	406	413	—
81	87.2	112.1	384	395	2

ZONE	Income (in ¥10,000)		Indirect utility		Initial flood water depth (m)
	Elderly	Others	Elderly	Others	
82	90.2	115.7	385	397	1
83	110.4	133.9	431	440	—
84	107.0	127.6	455	461	—
85	107.4	128.7	409	416	—
86	106.6	126.3	412	418	—
87	107.3	131.7	405	415	—
88	107.5	129.8	419	427	—
89	90.3	114.3	393	403	1
90	107.0	127.9	453	459	—
91	110.4	130.2	408	413	—
92	106.2	126.6	425	431	—
93	106.9	125.1	432	436	—
94	85.4	111.3	377	389	2
95	85.7	111.1	396	407	2
96	90.6	115.8	376	387	1
97	108.5	130.7	423	431	—
98	106.7	127.8	454	460	—
99	85.4	110.4	377	388	2
100	107.1	130.7	436	445	—
101	107.1	127.5	450	456	—
102	107.2	129.9	442	450	—
103	109.1	131.7	406	415	—
104	91.6	116.9	383	394	1
105	95.8	120.8	393	404	0
106	107.3	131.0	421	430	—
107	107.4	131.7	424	434	—
108	107.0	127.8	410	416	—
109	107.0	132.8	399	411	—
110	86.2	111.3	403	413	5
111	106.2	132.6	427	439	—

Note: The initial flood water depth is the flood water depth in the Tsunami Damage Estimation for Rikuzentakata shown in Figure 3.

Number of trips for each zone

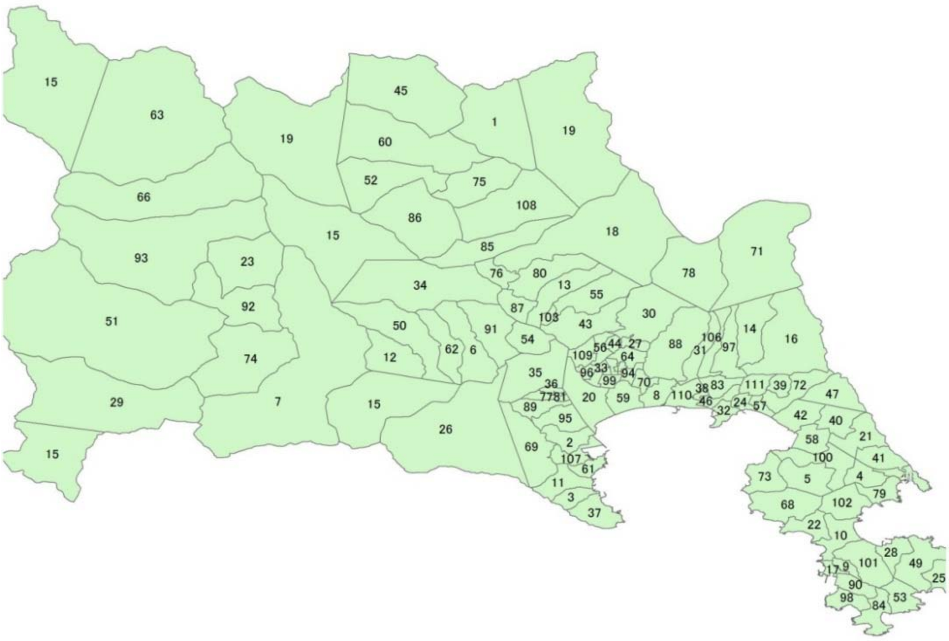
ZONE	Number of trip per person (frequency/day)					
	Commuting to work	Commuting to school	Private	Commuting to work	Commuting to school	Private
	Elderly			Others		
1	0.075	0.000	0.698	0.422	0.211	0.550
2	0.068	0.000	0.716	0.428	0.206	0.541
3	0.059	0.000	0.718	0.424	0.209	0.542
4	0.059	0.000	0.718	0.422	0.211	0.544
5	0.070	0.000	0.698	0.420	0.210	0.556
6	0.032	0.000	0.710	0.436	0.213	0.543
7	0.051	0.000	0.718	0.429	0.229	0.557
8	0.070	0.000	0.703	0.425	0.211	0.543
9	0.065	0.000	0.701	0.422	0.211	0.548
10	0.060	0.000	0.702	0.424	0.209	0.547
11	0.058	0.000	0.709	0.427	0.209	0.541
12	0.063	0.000	0.703	0.430	0.207	0.541
13	0.066	0.000	0.705	0.430	0.219	0.544
14	0.068	0.000	0.705	0.415	0.198	0.538
15	0.000	0.000	0.000	0.000	0.000	0.000
16	0.066	0.000	0.697	0.419	0.210	0.548
17	0.068	0.000	0.716	0.428	0.211	0.548
18	0.051	0.000	0.718	0.421	0.224	0.539
19	0.000	0.000	0.000	0.000	0.000	0.000
20	0.063	0.000	0.700	0.425	0.211	0.543
21	0.073	0.000	0.727	0.430	0.219	0.544
22	0.027	0.000	0.703	0.411	0.196	0.533
23	0.000	0.000	0.667	0.364	0.182	0.545
24	0.048	0.000	0.690	0.430	0.215	0.548
25	0.049	0.000	0.707	0.429	0.218	0.546
26	0.000	0.000	0.000	0.000	0.000	0.000
27	0.059	0.000	0.691	0.426	0.206	0.544
28	0.068	0.000	0.703	0.428	0.207	0.545
29	0.036	0.000	0.679	0.429	0.214	0.571
30	0.067	0.000	0.712	0.426	0.211	0.545

ZONE	Number of trip per person (frequency/day)					
	Commuting to work	Commuting to school	Private	Commuting to work	Commuting to school	Private
	Elderly			Others		
31	0.075	0.000	0.698	0.422	0.221	0.552
32	0.063	0.000	0.700	0.428	0.207	0.545
33	0.063	0.000	0.705	0.422	0.209	0.542
34	0.042	0.000	0.708	0.438	0.188	0.531
35	0.061	0.000	0.697	0.417	0.211	0.543
36	0.065	0.000	0.714	0.426	0.206	0.544
37	0.063	0.000	0.703	0.424	0.209	0.547
38	0.063	0.000	0.700	0.423	0.209	0.545
39	0.032	0.000	0.710	0.424	0.227	0.545
40	0.068	0.000	0.703	0.426	0.209	0.543
41	0.070	0.000	0.702	0.426	0.213	0.549
42	0.068	0.000	0.703	0.421	0.207	0.543
43	0.061	0.000	0.697	0.425	0.207	0.542
44	0.062	0.000	0.702	0.425	0.212	0.545
45	0.067	0.000	0.700	0.429	0.204	0.541
46	0.071	0.000	0.714	0.421	0.211	0.549
47	0.000	0.000	0.000	0.000	0.000	0.000
48	0.063	0.000	0.712	0.426	0.213	0.545
49	0.064	0.000	0.700	0.427	0.211	0.546
50	0.064	0.000	0.705	0.420	0.217	0.548
51	0.078	0.000	0.706	0.424	0.227	0.545
52	0.070	0.000	0.718	0.419	0.210	0.548
53	0.061	0.000	0.697	0.429	0.211	0.547
54	0.036	0.000	0.679	0.429	0.221	0.545
55	0.066	0.000	0.705	0.429	0.211	0.547
56	0.068	0.000	0.705	0.426	0.213	0.543
57	0.070	0.000	0.698	0.423	0.202	0.538
58	0.069	0.000	0.708	0.430	0.204	0.542
59	0.071	0.000	0.703	0.425	0.212	0.545
60	0.066	0.000	0.703	0.424	0.215	0.541
61	0.078	0.000	0.706	0.429	0.206	0.540
62	0.048	0.000	0.690	0.417	0.222	0.556
63	0.082	0.000	0.694	0.429	0.221	0.545
64	0.065	0.000	0.708	0.423	0.208	0.542
65	0.063	0.000	0.714	0.428	0.210	0.536
66	0.050	0.000	0.725	0.431	0.216	0.549
67	0.027	0.000	0.703	0.419	0.210	0.548
68	0.071	0.000	0.714	0.436	0.213	0.543
69	0.062	0.000	0.692	0.427	0.213	0.543
70	0.063	0.000	0.705	0.426	0.211	0.546
71	0.000	0.000	0.000	0.000	0.000	0.000
72	0.051	0.000	0.718	0.432	0.205	0.545
73	0.063	0.000	0.714	0.429	0.223	0.554
74	0.075	0.000	0.698	0.417	0.204	0.544
75	0.033	0.000	0.700	0.411	0.196	0.518
76	0.073	0.000	0.727	0.424	0.208	0.544
77	0.069	0.000	0.708	0.423	0.212	0.540
78	0.000	0.000	0.000	0.000	0.000	0.000
79	0.058	0.000	0.710	0.427	0.208	0.542
80	0.066	0.000	0.705	0.429	0.204	0.541
81	0.045	0.000	0.682	0.418	0.200	0.527
82	0.067	0.000	0.705	0.426	0.213	0.542
83	0.026	0.000	0.684	0.411	0.196	0.533
84	0.063	0.000	0.714	0.426	0.203	0.541
85	0.061	0.000	0.697	0.426	0.213	0.549
86	0.068	0.000	0.705	0.432	0.225	0.541
87	0.065	0.000	0.696	0.427	0.202	0.539
88	0.060	0.000	0.704	0.423	0.213	0.544
89	0.063	0.000	0.705	0.426	0.208	0.541
90	0.064	0.000	0.706	0.427	0.211	0.545
91	0.026	0.000	0.684	0.425	0.225	0.550
92	0.071	0.000	0.714	0.413	0.227	0.547
93	0.062	0.000	0.692	0.415	0.207	0.549
94	0.068	0.000	0.712	0.426	0.213	0.545
95	0.064	0.000	0.706	0.422	0.211	0.544

ZONE	Number of trip per person (frequency/day)					
	Commuting to w ork	Commuting to school	Private	Commuting to w ork	Commuting to school	Private
	Elderly			Others		
96	0.061	0.000	0.713	0.427	0.207	0.540
97	0.050	0.000	0.725	0.426	0.213	0.549
98	0.068	0.000	0.703	0.427	0.211	0.545
99	0.067	0.000	0.711	0.426	0.213	0.543
100	0.067	0.000	0.711	0.426	0.213	0.549
101	0.064	0.000	0.700	0.427	0.212	0.545
102	0.064	0.000	0.702	0.421	0.211	0.544
103	0.043	0.000	0.739	0.431	0.216	0.549
104	0.049	0.000	0.707	0.419	0.216	0.541
105	0.062	0.000	0.692	0.429	0.218	0.546
106	0.064	0.000	0.723	0.422	0.206	0.539
107	0.064	0.000	0.704	0.428	0.208	0.545
108	0.063	0.000	0.709	0.422	0.204	0.537
109	0.070	0.000	0.703	0.427	0.209	0.544
110	0.058	0.000	0.709	0.426	0.213	0.548
111	0.080	0.000	0.680	0.422	0.206	0.539

Zone number map

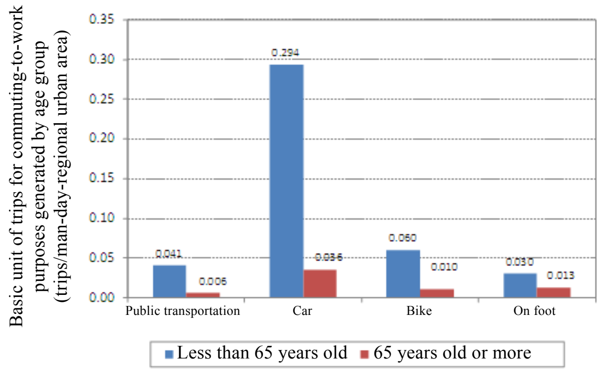
The map below shows the zone numbers and their respective locations when Rikuzentakata was divided into 111 zones by town-*chome*.

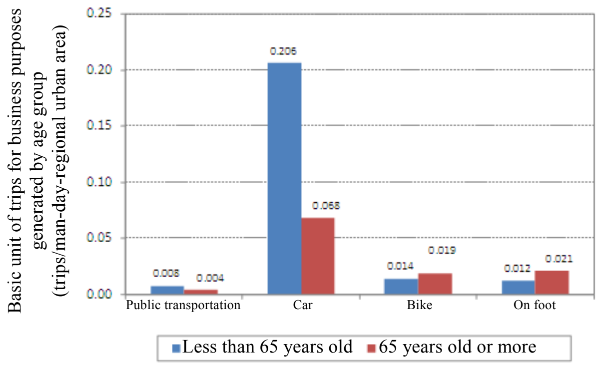


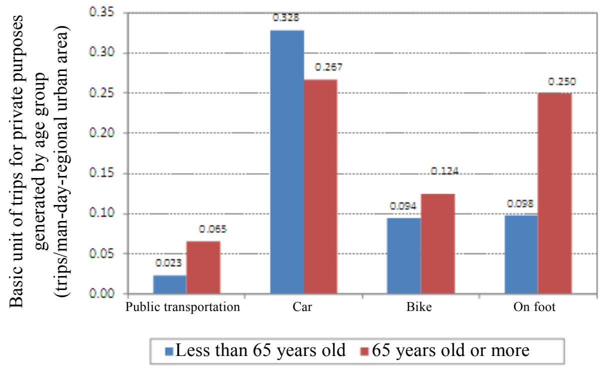
Creation of OD trip data

STEP 1: Create the data for trips generated per person

Use the number of trips per person by means k by purpose n by age group m α^{knm} created using the Nationwide Person Trip Survey (1999).







STEP 2: Create the data for trips generated by zone

Multiply the population by zone and the number of trips generated per person by purpose together to create the data for the number of trips generated by zone (weekdays). Multiply the number of trips generated by zone (weekdays) and the ratio of holidays to weekdays (ratio of the number of trips generated per person by purpose on holidays to that on weekdays) together to create the data for the number of trips generated by zone (holidays).

Number of trips generated by zone T_i^{wkmn} (weekdays)

To calculate the number of trips generated by zone by means k by purpose n by age group m on weekdays, multiply the number of trips per person α^{knm} and the population by zone by age group POP_i^m together.

$$T_i^{wknm} = \alpha^{knm} \cdot POP_i^m$$

Number of trips generated by zone T_i^{hknm} (holidays)

To calculate the number of trips generated by zone by means *k* by purpose *n* by age group *m* on holidays, multiply the number of trips generated by zone on weekdays T_i^{wkmn} and the ratio of holidays to weekdays β^n together.

$$T_i^{hknm} = T_i^{wknm} \cdot \beta^n$$

Appendix Table 2: Ratio of the number of trips on holidays to that on weekdays

	Commuting to Work/School	Commuting to School	Private	Business	Going Home
Ratio of holidays to weekdays β^n	0.2	0.1	1.51	0.28	0.79
Holidays/weekdays*			0.94/0.62	0.05/0.19	0.75/0.95

STEP 3: Create the data for OD trips

To create the data for OD trips, initially create the data for the time required to travel between zones by transportation means C_{ij}^k. Subsequently, in addition to creating the data for the time required to travel between zones by transportation means and the number of trips generated, which have been created, create the data on the number of employees at destination j EOP_j (only in the case of commuting-to-school purposes, the population by age group m at the destination j POP_j^m) and the distance decay parameter by means *k* by age group *n* by purpose *m* λ^{wknm}. Using these data, estimate the number of OD trips between zones in the narrow area model.

If both the generated volume and the concentrated volume have been obtained, a double constraint model can be established to estimate the number of OD trips. In the present study, however, only the generated volume is obtained. Consequently, using the number of employees (only in the case of commuting-to-school purposes, the population at the destination) as an alternative index to the concentrated volume, create the function for the number of employees (only in the case of commuting-to-school purposes, the population at the destination) and the distance resistance (required time) as shown in the equation below to distribute proportionally the generated volume.

○ Commuting-to-work/private/business purposes

For OD trips for commuting-to-work/private/business purposes, proportionally distribute the number of trips generated with respect to the number of employees at the destination and the traffic resistance.

$$OD_{ij}^{wknm} = \frac{\dfrac{EOP_j}{\exp\left(\lambda^{wknm} \cdot C_{ij}^{k}\right)}}{\sum_j \dfrac{EOP_j}{\exp\left(\lambda^{wknm} \cdot C_{ij}^{k}\right)}} \cdot T_i^{wknm} \quad \text{and} \quad OD_{ij}^{hknm} = \frac{\dfrac{EOP_j^m}{\exp\left(\lambda^{hknm} \cdot C_{ij}^{k}\right)}}{\sum_j \dfrac{EOP_j^m}{\exp\left(\lambda^{hknm} \cdot C_{ij}^{k}\right)}} \cdot T_i^{hknm}$$

○ Commuting-to-school purposes

For OD trips for commuting-to-school purposes, proportionally distribute the number of trips generated with respect to the population at destination POP_j^m and the traffic resistance.

$$OD_{ij}^{wknm} = \frac{\dfrac{POP_j}{\exp\left(\lambda^{wknm} \cdot C_{ij}^{k}\right)}}{\sum_j \dfrac{POP_j}{\exp\left(\lambda^{wknm} \cdot C_{ij}^{k}\right)}} \cdot T_i^{wknm} \quad \text{and} \quad OD_{ij}^{hknm} = \frac{\dfrac{POP_j^m}{\exp\left(\lambda^{hknm} \cdot C_{ij}^{k}\right)}}{\sum_j \dfrac{POP_j^m}{\exp\left(\lambda^{hknm} \cdot C_{ij}^{k}\right)}} \cdot T_i^{hknm}$$

○ Time required to travel between zones

Time required for inter-zone trips

$C_{ij(i \neq j)}^{byc} = v^{byc} \cdot k_{ij}^{car}$ and $C_{ij(i \neq j)}^{wak} = v^{wak} \cdot k_{ij}^{car}$

$C_{ij(i \neq j)}^{pub}$: Distribute all or nothing subject to the public transportation network (no congestion)

Time required for intra-zone trips

$$k_{ij(i=j)} = \left(\frac{A_i}{\pi}\right)^{\frac{1}{2}}$$

$C_{ij(i=j)}^{byc} = v^{byc} \cdot k_{ij(i=j)}$, $C_{ij(i=j)}^{wak} = v^{wak} \cdot k_{ij(i=j)}$, $C_{ij(i=j)}^{pub} = v^{pub} \cdot k_{ij(i=j)}$, and $C_{ij(i=j)}^{car} = v^{car} \cdot k_{ij(i=j)}$

○ Distance decay parameter

The distance decay parameter λ^{wknm} was obtained where the correlation factor r of the double constraint entropy model shown in the equation below was maximized using the time required to travel between zones and person trips in the Tokyo Metro Area Person Trip Survey.

$$Q_{ij}^{wknm} = \frac{\alpha_i^{wknm} GA_i^{wknm} \beta_j^{wknm} AT_j^{wknm}}{\exp\left(\lambda^{wknm} C_{ij}^k\right)}$$

The parameters for holidays were created through reduction by multiplying the inverse of the ratio of the average trip length on holidays to that on weekdays (ratio of holidays/weekdays) and the parameters for weekdays together.

$$\lambda^{hknm} = \lambda^{wknm} \cdot \gamma$$

Appendix Table 3: Distance decay parameter (weekdays)

Age Group	Juvenile/Productive Age (less than 65 years old)				Elderly (65 years old or more)			
Purpose	Commuting to work	Commuting to school	Private	Business	Commuting to work	Commuting to school	Private	Business
Passenger car	9.82	5.21	10.23	5.46	8.58	4.55	8.55	4.97
Public transportation	0.79	0.50	1.43	0.82	0.81	0.51	2.87	0.84
Bike	11.10	5.89	11.56	2.58	16.85	8.94	23.24	2.65
On foot	12.40	9.01	12.80	8.44	18.83	13.68	25.73	8.66

Appendix Table 4: Distance decay parameter (holidays)

Age Group	Juvenile/Productive Age (less than 65 years old)				Elderly (65 years old or more)			
Purpose	Commuting to work	Commuting to school	Private	Business	Commuting to work	Commuting to school	Private	Business
Passenger car	8.75	4.64	9.11	4.86	7.63	4.05	7.61	4.42
Public transportation	0.70	0.44	1.27	0.73	0.72	0.45	2.56	0.75
Bike	9.88	5.24	10.29	2.30	15.00	7.96	20.69	2.36
On foot	11.04	8.02	11.40	7.51	16.76	12.18	22.91	7.71