Xianhua Wu
Ji Guo

Economic Impacts and Emergency Management of Disasters in China

Springer

Economic Impacts and Emergency Management of Disasters in China

Xianhua Wu · Ji Guo

Economic Impacts and Emergency Management of Disasters in China

Springer

Xianhua Wu
School of Economics and Management
Shanghai Maritime University
Shanghai, China

Collaborative Innovation Center on Climate and Meteorological Disasters
Nanjing University of Information Science and Technology
Nanjing, China

Ji Guo
School of Economics and Management
Shanghai Maritime University
Shanghai, China

Collaborative Innovation Center on Climate and Meteorological Disasters
Nanjing University of Information Science and Technology
Nanjing, China

ISBN 978-981-16-1318-0 ISBN 978-981-16-1319-7 (eBook)
https://doi.org/10.1007/978-981-16-1319-7

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Contents

Part I
Disaster and Economic Development

Chapter 1
Disaster Probability, Optimal Government Expenditure for Disaster Prevention and Mitigation, and Expected Economic Growth

Abstract As global climate warms, the occurrence frequency and loss of natural disaster are both increasing, posing a great threat to the sustainable development of human society. One of the most important approaches of disaster management is to prevent disaster and reduce disaster loss through fiscal expenditure of government; however, the optimal proportion of expenditure for disaster prevention and mitigation has always been a difficult issue that people concern about. First, this paper, after considering the impact of disaster on human capital, established a resident-manufacturer-government decision making model which contains the probability of disaster, and then solved the optimal proportion of government expenditure for disaster prevention and reduction as well as the expected economic growth rates under different conditions. Second, through numerical simulation method, this paper studied the impacts of such factors as coefficient of risk aversion and elasticity coefficient of substitution on the optimal proportion of disaster prevention and reduction expenditure. Third, through constant elasticity of sub-situation (CES) production function and ridge regression method, this paper verified the applicability of the proposed model with the data of the expenditures for disaster prevention and mitigation of Hunan Province in 2014. Finally, this paper summarized the research results and put forward corresponding suggestions on policy. The theoretical model proposed in this paper enriches the related researches of disaster economics, and the conclusions of empirical analysis can provide government departments with useful reference for the practice of disaster prevention and mitigation.

Keywords Government expenditure for disaster prevention and mitigation · Residents-manufacturer-government decision model · Probability of disaster · Expected economic growth rate

Guo Wei, Tingting Feng also made great contributions to this manuscript. We express our heartfelt thanks to them.

X. Wu and J. Guo, *Economic Impacts and Emergency Management of Disasters in China*,
https://doi.org/10.1007/978-981-16-1319-7_1

1.1 Introduction

In recent years, influenced by climate change and human activities, natural disasters have become more frequent, causing increasingly great losses (IPCC 2014). For example, natural disasters like the 2004 tsunami in Indonesia, the 2008 Wen chuan Earthquake in China and the 2011 Fukushima Earthquake in Japan have inflicted heavy losses on people's lives and property and caused great damage to socio-economic development. One important task of government in regard to disaster prevention and mitigation is to reduce damage loss and guarantee people's livelihood through fiscal expenditure. For this reason, the appropriate proportion of government's fiscal expenditure on disaster prevention and mitigation has become a difficult issue of public concern (Sawada and Takasaki 2017). If the proportion is too low, it is not conductive to the implement of disaster-preventing and mitigating measures; if the proportion is too high, it will crowd out other investment expenditures, which does not contribute to the sustainable development of economy and the continuity of government's disaster reduction work (Benalia et al. 2016). Therefore, the government's expenditure on disaster prevention and mitigation should be appropriate. However, few scholars have quantitatively analyzed the proportion of financial expenditure on disaster prevention and mitigation, which can't meet the needs of disaster prevention and mitigation.

After considering influencing factors like the impacts of disaster on capital stock and individual expected consumption, the distribution and constraints of fiscal policy, the complementary or substitutional relationship between private capital and government's productive expenditure, this paper establishes a resident-manufacturer-government decision making model which contains the probability of disaster. Aiming at the utility maximization of residents, this model is used to solve the optimal proportion of government expenditure on disaster prevention and reduction. Subsequently, this paper studies the impacts such factors as probability of disaster, residents' aversion to disaster risk, substitutional relationship between government's productive expenditure and private capital, input share of government's productive expenditure, and efficiency of disaster prevention and mitigation expenditure exert on the optimal proportion of government expenditure on disaster prevention and mitigation. Besides, the actual data of Hunan Province for disaster prevention and mitigation in 2014 are input into the proposed model to calculate the optimal proportion of government's expenditure on disaster prevention and reduction. The empirical results can provide government departments with useful reference for natural disaster prevention and mitigation and have good practical significance. The research findings of this paper not only enrich the related researches of disaster economics but also can provide government departments with theoretical support for the practice of disaster prevention and mitigation and the sustainable development of economic society.

The rest parts of the paper are arranged as follows: Sect. 1.2 is a literature review. Section 1.3 introduces the resident-manufacturer-government decision-making model and explains the specific steps. Section 1.4 is the numerical simulation and analysis of results. Section 1.5 is a case study, taking the flood disaster of Hunan Province in 2014 as an example. Section 1.6 is research conclusions and policy suggestions.

1.2 Literature Review

In recent years, many scholars have studied the role and scale of government expenditure on disaster prevention and mitigation from different perspectives. For example, Jena et al. (2020) thought that natural disasters caused severe damages to people's properties and lives. Therefore, they developed an urban seismic risk assessment model using the ANN-AHP integrated technique and the joint data of geomorphological, geological, and tectonic information and historical seismic data. The predictive models could effectively help government officials and policymakers to establish the strategic layout and planning of cities. From the EM-DAT database, Schumacher and Strobl (2011) found that natural disasters caused severe economic and human losses. The study showed different exposure levels of natural hazards and the stage of economic development with a non-linear relationship. The degree of risk of natural disasters was influenced by the relationship between disaster losses and the stage of socio-economic development. Yaron and Wilson (2020) proposed that floods were the most frequent and severe natural disaster; one of the maximum economic costs in emerging countries. The highest cost-benefit ratio could be generated by combining community and local government investment to build disaster prevention project infrastructure. Case study showed that the benefits of building flood prevention infrastructure far exceeded the costs. Wang et al. (2017) considered Typhoon disaster as a natural disaster with frequent occurrence and damage. Therefore, they proposed a combined static EC (econometric) and dynamic IO (input-output) model to estimate the direct and indirect economic losses caused by typhoons to related industries. The results of the research indicated that the total damage caused by typhoons to 17 industries in 2013 was 127,192.48 billion Yuan. The study revealed that the greater the cumulative economic damage caused by a hurricane, the longer the average time required resuming production in each industry. In short, natural disaster losses include both direct and indirect losses. Most direct losses could be expressed in physical form, and could be calculated directly or converted to monetary format to estimate approximate disaster losses. Disasters also caused more medium- to long-term hidden impacts that cannot be directly measured in monetary terms, especially non-structural indirect losses. Therefore, most scholars conducted their studies based on computable disaster losses. The value of measurable disaster losses reflects, to some extent, the scale of economic losses caused by disasters. Researches in this area emphasized the importance and irreplaceability of government involvement in disaster prevention and mitigation, and the necessity of government financial investment. Palm (1990) believed that government's investment in disaster prevention and mitigation was conductive to improving the human's ability to withstand natural disasters and was a major driving force for transforming people from passive defense to active mitigation when faced with disasters. Mileti (1999) put forward disaster control theory and believed that government's expenditure for pre-disaster prevention played a crucial role in controlling disasters, reducing disaster losses, and achieving sustainable development of economy. Alexander (1997) proposed that natural disaster not only destroyed capital stock and caused direct economic loss, but also affected individual's consumption expectation. Capital stock and expected consumption decision are important driving forces for economic development, thus it is of great significance to study government's expenditure on pre-disaster prevention. Haurie and Moresino (2006) argued that environmental disaster damage costs include productive physical capital, social costs, and investment capital. Hence, disaster prevention capital and government's investment could affect disaster preparedness. Capital stock and expected consumption decisions were crucial drivers of economic development, so it was significant to study government spending on disaster prevention. Meacher (2004), Hochrainer (2006), Hochrainer and Pflug (2009) et al., from the perspective of risk management, emphasized the necessity of increasing government's expenditure on disaster prevention and reduction. Anbarci et al. (2005) and Cohen and Werker (2008) believed that government's ability of disaster prevention played an important role in disaster mitigation even though the disaster risk was uncontrollable. Aldrich and Ono (2016) and Fraser et al. (2020) pointed out that the government carries out unified planning and coordination in disaster prevention and mitigation; develops assistance measures and emergency evacuation plans, implements disaster relief and reconstruction of infrastructure projects, and obtains the optimal disaster relief expenditures within limited resources. The government is the link and bridge of disaster management, as well as the leader, coordinator and organizer of disaster prevention, relief and reconstruction work. Through historical natural disaster cases in five dimensions, Ladds et al. (2017) analyzed the total disaster losses and impacts in Australia. The research showed that there were differences in the frequency and severity of damage caused by disasters. In addition to measuring the direct and indirect losses in monetary terms, it also included other intangible and non-measurable losses. The impact of natural disasters was widespread, and the value of the damage caused was severe. In conclusion, natural disasters had complex characteristics such as high frequency of occurrence, wide impact range, and severe economic losses. Hence, the government's investment in disaster management is necessary, and could reduce disaster losses, improve disaster defense capability, maintain regional stability, and restore regional economic development quickly. Based on this, the government must intervene in disaster risk management and invest in disaster prevention and mitigation.

Increasing government's investment in disaster risk reduction has many benefits, yet it is usually constrained by government budget. Besides, overinvestment will do no good from dialectic perspective (Wu et al. 2019). Keefer et al. (2011) found that the death rate of earthquakes can be greatly reduced by implementing anti-seismic construction regulations. However, some governments chose not to take corresponding disaster prevention measures. The root cause is that the scale of government's investment in disaster prevention and reduction is affected and restricted by the state budget as well as government's political motivation. To be more specific, low-income countries have higher opportunity costs of disaster prevention than middle- and high-income countries, and thus the scale of government's investment in disaster risk reduction is relatively small. Moreover, in some dictatorships and countries with serious corruption problems, the political motivation of government to offer public security expenditure is not to ensure people's welfare; consequently, the scale of government investment in disaster prevention and mitigation is small as well. Some scholars believe that the excessive increase of government's investment in disaster prevention and reduction is not conducive to the sustainable development of the country's social economy. Shi (2012) pointed out that the government, as a leader in disaster management, could improve disaster response capacity, enhance the overall welfare of society, and maintain social stability by integrating resources, organizations, culture, and workforce. Even in low-income countries and regions, under a limited situation, the government could build sustainable disaster reduction and emergency response systems, and heighten overall disaster preparedness capabilities. However, some governments have chosen not to take corresponding disaster prevention measures. The scale of government investment in disaster prevention and mitigation was influenced and limited by national budgets and government political motivations. To be more specific, low-income countries have higher opportunity costs of disaster prevention than middle- and high-income countries, and the scale of the government's investment in disaster risk reduction was relatively small. Natural disasters had spatial spillover effects that would affect adjacent regions. Under such circumstances, disaster mitigation and prevention policies were relatively passive, and the final results of disaster management measures were related to multiple factors such as neighboring regions, industries, and economies. From a global perspective of disaster prevention and mitigation management, Kumar et al. (2020) confirmed that international cooperation mechanisms between countries were restricted by national development stages, implementation efficiency, and economic goals. Mahmud and Prowse (2012) studied the issue of corruption in disaster management. The research found varying degrees of corruption in pre-disaster interventions, relief processes, and post-disaster interventions, and there were great differences in the degree of influence on different income groups. Hence, it suggested that the government should input anti-corruption policy in disaster reduction and prevention management. Some scholars believed that the excessive increase of government's investment in disaster prevention and reduction was not conducive to the sustainable development of the country's social economy. For instance, Kunreuther and Pauly (2006) proposed that if the government put extra investment in disaster prevention and mitigation, it would bring crowding out effect to other investment expenditures and reduce direct economic benefits. The Insurance Institute for Property Loss Reduction of Boston (1995) found that if the government excessively increased the scale of investment in disaster prevention and reduction, residents would be excessively dependent on the government's disaster prevention work. Howard also found that individuals generally had the inertia to avoid advance expenditure; if the government excessively intervened in the autonomous disaster prevention measures of people, for example, increasing investment in disaster prevention and mitigation, people's initiative to transfer risks and avoid losses would be reduced. Slavíková (2016) intended to assess the crowding-out effect on a macroeconomic perspective about the flood expenditure of central governments. The government's development of effective flood risk management had highlighted the importance of government self-involvement. The crowding-out effect was explored from a macroeconomic perspective, based on the case of the devastating floods that hit the central government of the Czech Republic in 1997 and 2002. Bachner et al. (2019) mentioned that government budgets for disaster prevention and mitigation, and climate adaptation were constricted by the tax base and government spending patterns. A higher account would lead to a corresponding reduction in post-disaster relief and unemployment benefits, resulting in higher tax revenues. Therefore, increasing government budgets for disaster risk management was not the best option. Disaster risk management with balanced government revenues and expenditures could achieve better management efficiency and a higher return on investment. Therefore, the government should consider the financial budget, the crowding out effect of disaster prevention and reduction expenditure, and people's inertia in disaster prevention while deciding the scale of investment in disaster prevention and mitigation (Klomp and Valckx 2014; Klomp 2016).

To sum up, the government's expenditure on disaster prevention and mitigation plays an important role in aspects like disaster loss reduction, but it is restricted by various factors, and excessive increase of investment in disaster prevention and reduction will not contribute to the sustainable development of society. To address this issue, some scholars have conducted researches on the optimal scale of government's disaster prevention and reduction expenditure. To solve this problem, some scholars studied the optimal scale of government expenditure on disaster prevention and reduction. The research focused on disaster prevention reserves, disaster mitigation investments, and post-disaster interventions. The whole process of disaster prevention and mitigation covered the household, enterprise and national levels. For example, Pindyck and Wang (2009) built a general equilibrium model which included production, capital accumulation, and family preference. This model assumes that in the coming decades, the United States is likely to experience a devastating earthquake that will significantly reduce the nation's capital stock, GDP, and wealth. In the case of known disaster risk distribution, this model takes taxes the major source of government's income for disaster prevention and mitigation to analyze how much tax residents are willing to pay to alleviate the impact of disasters. However, the obtained results mainly reflect residents' willingness rather than the optimal scale of government expenditure on disaster prevention and mitigation. Some other scholars studied the correlations among disaster prevention expenditure, disaster loss, and economic growth by establishing economic growth models so as to find the optimal scale of disaster prevention and reduction. For instance, Tian and Gao (2012) built a resident-government stochastic decision-making model to weigh-residents' welfare against financial gains and losses, and designed an optimal scale model of disaster relief which connected social environment with economic environment; yet this model failed to consider the crowing out effect the optimal scale of disaster prevention and reduction expenditure had on other investments. Liu et al. (2014) developed an observable and controllable urban seismic hazard risk model based on the system periphery theory. The system was applied to quantitatively analyze the relationship between urban seismic risk and system inputs, system state, and human seismic mitigation activities. The results showed that the model could achieve effective prevention, and control of urban seismic risk by analyzing the impact intensity of seismic hazard in peripheral systems and countries within the system. Several scholars studied the participation behavior and efficiency of government organizations in the disaster relief process. Based on the instant information obtained from social networks, they used disaster prediction tools to broadcast disaster damage in real-time. They found the optimal disaster relief solution through rational planning of funds, resources, labor and facilities.

Oloruntoba (2010) conducted an analytical study of the emergency relief chain and cyclone relief management process in disaster management agencies based on disaster management literature. This paper argued that a well-designed emergency response strategy and rescue plan could help managers understand and implement it. It was also an essential factor in achieving effective and comprehensive rescue operations, improving the efficiency of disaster rescue and reducing losses. Du and Qian (2016) explored the cooperation between governmental nonprofit organizations based on an evolutionary game model. The game model used the benefits of cooperation, incentives, the penalties for inaction, response efficiency, and coordination costs as the critical factor. With limited resources, they went to look for ways to optimize government spending on disaster prevention and response that could simultaneously improve the efficiency of the response system and the effectiveness of assistance. Other scholars established economic loss evaluation indexes from the macro level, and constructed a comprehensive economic loss model. From a global perspective, they evaluated the economic losses and government investments in disaster prevention and mitigation, and obtained optimal spending options for the government's investments in disaster risk management. For instance, Barro (2009, 2015) introduced lucas-tree asset pricing model and Epstein-Zin-Weil utility function to establish an economic model and studied the investment range of disaster risk reduction; nevertheless, this model didn't take social welfare maximization as the government's goal of disaster risk reduction expenditure. Zhuo and Duan (2012) built a two-sage economic growth model that had taken consumption expectations into account, and based on the endogenous economic growth theory with risk constraint, established the relationship between government expenditure on disaster prevention and mitigation and economic growth, and then, by using the expected utility and risk decision principles under uncertain conditions, studied the impact of investment expenditure for disaster prevention and reduction on recent capital stock, recent capital accumulation, and consumption expectation. However, this economic model neglected the role of human input and failed to consider the impact of the relationship between private capital and government productive expenditure on the optimal scale of disaster prevention and reduction expenditure.

Motoyama (2017) established an economic model which taken the maximization of social welfare as the goal of government expenditure. Meanwhile, in order to consider the crowding out effect of disaster prevention and reduction expenditure on other investment expenditures, a constraint condition, namely, the distribution relationship between fiscal expenditure on disaster prevention and mitigation and productive expenditure was introduced into the model. Nevertheless, the established economic model also failed to consider the role of human input as well as the influence of the relationship between private capital and government's productive expenditure on the optimal scale of disaster prevention and reduction expenditure. Yu et al. (2015) argued that the government should treat the cost of recovery and damage reduction inputs to the affected areas equally. According to Yu et al. (2015), the government should treat recovery costs and mitigation inputs to disaster areas equally. Estimated of disaster losses were used to obtain reconstruction costs, and serve as a measure of a country's or region's ability to rebuild. From the calculated recovery costs, they found the most vulnerable parts of the reconstruction system. Prioritize them for the post-disaster reconstruction process, i.e., rank the vulnerability of the reconstruction efforts. Based on historical disaster losses and recovery costs, the government could assess the sustainability of disaster management expenditures, and effectively manage disaster prevention and control budgets. He and Zhuang (2016) proposed to correlate disaster losses with pre-disaster preparedness, and construct a disaster management system to develop post-disaster relief measures. Through the optimized model to obtain the decision efficiency in the pre-disaster planning and post-disaster relief phases. The values of optimal disaster prevention and response were obtained using the inverse induction method. The obtained values enable us to find the balanced optimal strategy for disaster prevention and relief. Ye et al. (2016) proposed that the government should conduct a cost-benefit analysis in disaster reduction investment decisions. The essay discussed government investment options for typhoon disaster prevention and control in Shenzhen, and proposed a framework for comprehensive government investment in disaster reduction. A coordinated assessment of labor capital, a comparative study of structural government investments, showed that premium subsidies have the highest returns. The research also confirmed the mutual spillover effects in the overall risk management framework.

According to Wang et al. (2020), complex disasters had a process of transformation from natural disasters to social crises. The government would involve multiple stakeholders such as enterprises, residents, and local governments in the process of disaster prevention and relief management, and there were conflicts and conflicting interests among them. From a holistic perspective, this research constructed a three-stage dynamic game model. Research indicated that governments need to provide more environmental compensation as a risk premium, to mitigate multiparty conflicts of interest in the evolution of natural disasters to social crises and to achieve the goal of globally optimal complex disaster management. To sum up, disaster prevention and mitigation was an ongoing task for government departments. Based on historical data and current fiscal revenues, the government determined the scale of budgetary expenditures for disaster prevention and mitigation, thereby formulating a disaster management budget for integrated planning of disaster prevention and mitigation efforts. At the same time, the government needed to consider the limitations of financial budget, economic sustainability, and resource facilities. The process of developing a disaster prevention and mitigation plan did not allow for the creation of a disaster management model with all elements. An increasing number of studies had exploring optimal global solutions under certain constraints, or unconstrained local optimal solutions.

Based on the above researches, in this paper, we construct multi-factor optimal disaster prevention and mitigation model with human investment, producer contribution, capital and effective government expenditure as influencing factors. The model simulates the optimal strategy of government disaster relief under different conditions and analyzes, and discusses the optimal scale of disaster prevention and mitigation expenditures under various factors. Finally, a practical case is adopted for empirical study, which can be regarded as a beneficial supplement to the above researches.

1.3 Method and Model

1.3.1 Principle of Model

The impact of disaster on economy is the key to establishing the model. The economic impact of disasters is mainly reflected in the following three aspects. First, disasters directly impact and reduce the social capital stock; second, disasters indirectly impact social capital stock by affecting residents' expected consumption. That's because the known disaster risk will increase the uncertainty of residents' future income and property. Thus, influenced by risk aversion, residents will be more cautious about making decisions. Specifically, without any external assistance or channel for diversification of risk, residents will take the initiative to spread the disaster risk. For instance, residents can realize inter-temporal risk sharing by choosing inter-temporal consumption and reducing the current consumption, thereby leading to the increase of capital stock. Third, the changes in disaster prevention and reduction expenditure affect socio-economic development. Increasing expenditure on disaster prevention and mitigation can not only enhance the ability of cities to resist disasters, but also reduce the direct economic loss caused by disasters. Moreover, it can save fiscal expenditures and ease the financial burden of the state in the case of emergency relief. It also can increase government procurement and improve infrastructures like water conservancy facilities. In addition, it contributes to changing the prudent consumption decisions of residents and increasing the current consumption. The disadvantages of increasing disaster prevention expenditures lie in that, under the constraints of fiscal budget, the government needs to reasonably allocate expenditures on disaster prevention and reduction and production; and excessive expenditure for the former will lead to the decrease of productive expenditure, which will possibly lead to more taxes, thereby affecting residents' saving level and retarding economic development.

Next, based on the impact of disaster on economy, the basic assumptions of the model are illustrated. To reflect the inter-temporal sharing of disaster risk, this paper constructed a two-phase economic model based on the closed economy of residents, manufacturers, and government. The model assumes that disasters occur after the production of manufacturers, consumption and saving of families, and tax collection of government. When a disaster occurs, a certain proportion of existing capital stock is destroyed. And the proportion of fiscal expenditure on disaster prevention and reduction (h) will influence the disaster loss ratio which is set as $D(h)$[1] ($D(h) \in [0, 1]$). When the government increases the proportion of fiscal expenditure on disaster prevention and reduction (h), the disaster loss ratio ($D(h)$) will decrease to some extent, then $D'(h) < 0$. Let the probability of disaster be p. As natural disasters are mostly inevitable but predictable (Nagasaka 2008), this paper assumes the probability of disaster (p) is an exogenous variable and meanwhile a known constant. Therefore, the social capital stock s_{t+1} influenced by disaster risk can be formulated as:

$$s_{t+1} = p(1 - D_t)a_{t+1} + (1 - p)a_{t+1} \tag{1.1}$$

Where s_{t+1} represents the social capital stock of the $(t + 1)$-th period under the influence of the t-th period disaster risk, a_{t+1} represents the capital stock of the $(t + 1)$-th period that is not influenced by disaster risk, D_t is the loss ratio of the t-th period caused by disaster, and p is the probability of disaster.

1.3.2 Model Building

1.3.2.1 Residents

Assuming that residents have an infinite life span and their utility function under budget constraints is maximized, so the discounted utility is:

$$U(C_t) = E_0 \sum_{t=0}^{\infty} \beta^t \frac{C_t^{1-\gamma}}{1-\gamma} \tag{1.2}$$

where C_t is residents' consumption at moment t, and $u(C_t)$ is instantaneous utility function which represents the utility of residents' consumption at a set moment. The instantaneous utility function is in the form of $u(C_t) = \frac{C_t^{1-\gamma}}{1-\gamma}$, namely, CRRA (Coefficient of Relative Risk Aversion) model. It is a utility function determined by differential equation $\gamma = -Cu''(c)/u'(C)$. Here, γ refers to the coefficient of relative risk aversion and is a constant.

Risk aversion coefficient determines the willingness of residents to transfer their consumption indifferent periods: when the coefficient of risk aversion (γ) is larger

[1] The disaster loss ratio is from the assumption of Motoyama (2017):$(h) = \frac{\hat{d}}{1-\hat{d}} - \frac{\hat{d}}{h-\hat{d}}$, where $\hat{d} = -\frac{1-\bar{d}}{\bar{d}}$, $\bar{d} \in (0, 1)$, $\bar{d}$ is the upper limit of disaster loss ratio, $D(0) = \bar{d}$, the lower limit of the loss ratio is zero $D(1) = 0$, and h is the proportion of fiscal expenditure on disaster prevention and reduction.

than 0, it means risk aversion; and the larger the coefficient, the higher the degree of risk aversion, which means that residents are more concerned about the loss caused by disaster and tend to avoid risks through inter-temporal consumption. When the coefficient of risk aversion (γ) is equal to 0, it means risk neutral; it indicates that residents are neutral to disaster risk, that is, disaster has little impact on residents. In this case, the instantaneous utility function has two characteristics: First, if the coefficient of risk aversion (γ) is below 1, $C^{1-\gamma}$ increases along with C; if the coefficient of risk aversion (γ) is larger than 1, then $C^{1-\gamma}$ decreases as C increases. Thus, $C^{1-\gamma}$ is divided by $1-\gamma$ to ensure that the marginal utility of consumption is positive whatever the coefficient of risk aversion (γ) is. Second, in special case where the coefficient of risk aversion γ is close to 1, the instantaneous utility function can be simplified into lnC. In Eq. (1.2), E denotes expectation, and it is used due to the uncertainty of probability of disaster (p). β is time preference rate whose value ranges between 0 and 1, it indicates residents will discount further consumption. According to Mehra and Prescott (1985), most residents are averse to disaster risk, so the coefficient of risk aversion γ is assumed to range within 1–10 (Liu 2013) (risk aversion coefficient $\gamma > 10$ indicates residents' strong aversion to risk). The budget constraint faced by residents can be expressed as:

$$\tilde{a} = [1 + (1 - \tau_t)r_t - \delta_t] * s_t - c_t \tag{1.3}$$

where, capital stock $\tilde{a}$ is the capital stock of the $(t+1)$-th period that converted from the t-th period, $\delta_t \in (0, 1)$ is generalized capital depreciation rate, s_t is the capital stock affected by disaster risk, r_t is generalized return on capital, and τ_t is composite tax rate.

The utility value of residents' utility function after discount is denoted as $V(s)$. It is the discounted value of utility obtained after solving the utility maximization problem for residents on condition that the initial capital stock s_0 and government disaster prevention strategy (τ, g, h) are given. Residents' maximum utility value of t-th period can be formulated as:

$$V(s) = max_{\{C,\tilde{a}\}}\left\{\frac{1}{1-\gamma}C^{1-\gamma} + \beta E_t V(\tilde{s})\right\}$$
$$s.t.\begin{cases} \tilde{a} = [1 + (1 - \tau)r - \delta]s - C = Rs - C \\ s_0, \pi(\tau, g, h) \end{cases} \tag{1.4}$$

where

$$\tilde{s} = \tilde{a}((1 - D(h))p + 1 - p) \tag{1.5}$$

$$R = [1 + (1 - \tau)r - \delta] \tag{1.6}$$

For the convenience of expression, the symbol for the t-th period is omitted. Superscript ~represents the value of variable for the next period, and $\tilde{s}$ is the capital stock after disaster. In Eq. (1.6), $R = [1 + (1 - \tau)r - \delta]$ represents the rate of return on savings, p is the probability of disaster, and $D(h)$ is disaster loss ratio. By solving Eq. (1.4), the savings function and consumption function of residents can be obtained, and they are respectively formulated as:

$$\tilde{a} = R^{1/\gamma}\left[\beta(p\big(1 - D(h)\big)^{1-\gamma} + 1 - p)\right]^{1/\gamma} s = (R(\rho(h))^{1/\gamma} s = \sigma(\tau, h)s \quad (1.7)$$

$$C = (R - \sigma(\tau, h))s \quad (1.8)$$

In the above equations, $\rho(h) = \beta(p\big(1 - D(h)\big)^{1-\gamma} + 1 - p\big)$ is the discount rate after taking disaster risk into account, and $\sigma(\tau, h) = (R(\rho(h))^{1/\gamma}$ is the saving rate of the current capital of residents. Assuming that residents' consumption is larger than 0, then $R - \sigma(\tau, h) > 0$ (see Section "The Value Function of the Residents' Utility" for the details on the derivation process of Eq. (1.7)).

1.3.2.2 Manufacturers

Manufacturers produce final product with the capital provided by residents. Considering the positive effect of government's productive expenditure on the production of manufacturers, this paper introduces government's productive expenditure into production function model. In terms of production function, this paper chooses CES (constant elasticity of substitution) production function rather than the C-D function model used by Motoyama (2017). Because the CES production function is conducive to studying the influence of the complementary or substitutional relationship between private capital and government's productive expenditure on the optimal scale of disaster prevention and reduction expenditure (Bucci and Bo 2012; Bom 2017). Here, the elasticity coefficient of substitution of private capital factor and government productive expenditure is the core parameter of the complementary or substitutional relationship, and the CES production function is formulated as:

$$Y = A(b_1\big(\theta_1 k^m + \theta_2 l^m\big)^{\frac{m_1}{m}} + b_2 G^{m_1})^{\frac{\alpha}{m_1}} \quad (1.9)$$

In this model, Y represents total output, α represents the economies of scale of production function, A is efficiency parameter which refers to the output efficiency of economic system, and $\theta, b \in (0, 1)$ is the efficiency of production factors that are put into the production process. The elasticity coefficient of substitution of material input and human input is $e = \frac{1}{1-m}$; and the elasticity coefficient of substitution of private capital and government productive expenditure is $x = \frac{1}{1-m_1}$ (see Section "Substitute Elasticity Derivation of CES Production Function" for the details on the derivation process of elasticity coefficient of substitution). In Eq. (1.8), G is the productive input allocated by the government, and g is the ratio of productive expenditure ($G = gY$, $g \in (0, 1)$).

Let $K = (\theta_1 k^m + \theta_2 l^m)^{\frac{1}{m}}$, where the private capital K includes both material capital (k) and labor capital (l). The goal of manufacturers is to maximize the profit. Assuming that $\alpha = 1$, then Eq. (1.9) can be further transformed into (see Section "Conversion of CES Function Form" for the details on the transformation process of function):

$$Y = Ab_1^{\frac{1}{m_1}} K\left(1 - b_2 A^{m_1} g^{m_1}\right)^{-\frac{1}{m_1}} \tag{1.10}$$

1.3.2.3 Government

After a disaster occurs, the government's responsibility is to reduce the welfare loss caused by risk aversion as well as the impact of disaster risk on residents' expected consumption behavior. Specifically, the government should, on the premise of known probability of disaster (p), reasonably allocate disaster prevention and reduction expenditure (H) and productive expenditure (G), and maximize the overall welfare of residents. In the present paper, $G = gY$, $g \in (0, 1)$; $H = hY$, and $h \in (0, 1)$. Disaster prevention and reduction expenditure (H) can reduce the loss of capital stock caused by disasters. Assuming that the government has a balanced budget in each period, then the budget constraint is:

$$\mathrm{\tau * r * s = (g + h)Y} \tag{1.11}$$

where τ denotes composite tax rate, r denotes generalized return on capital, s denotes social capital stock, h is the ratio of fiscal expenditure on disaster prevention and reduction and g is the ratio of productive expenditure.

1.3.3 Model Solution

1.3.3.1 Optimal Strategy for Disaster Prevention and Reduction

Based on the given government disaster prevention strategy $\pi = \{\tau, h, g\}$ and initial savings s_0, residents' consumption function (Eq. 1.7) and savings function (Eq. 1.8) after maximizing the inter-temporal utility of residents can be obtained. Assuming that the manufacturers' goal is to maximize profit, in the case of unchanged returns to scale ($\alpha = 1$), the marginal output of capital is equal to the capital return r, namely:

$$\mathrm{r = Ab_1^{\frac{1}{m_1}} (1 - b_2 A^{m_1} g^{m_1})^{-\frac{1}{m_1}} = Ab_1^{\frac{1}{m_1}} B(g)} \tag{1.12}$$

To simplify the expression, there is: