SEISMIC STRENGTHENING STRATEGY FOR WOOD FRAME DWELLINGS TARGETING TO MINIMIZE THE DEATH TOLL FROM A VIEW POINT OF TEMPORAL VARIATION

-Case study for Tokai region, Japan, in the forthcoming Tokai-Tonankai Earthquake-

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ABSTRACT :

We learned from the 1995 Hanshin Awaji earthquake that most of the death toll arisen from many vulnerable wooden houses collapsed by seismic ground motions and seismic strengthening wooden houses is the highest priority strategy for preventing death. This paper discusses effective strategy of seismic strengthening houses for reduction of death toll. In the first part, we construct the equations by which the death toll in districts can be estimated with considering the rate of seismic strengthening that is increased by rebuilding or seismic repairing, and the negative effect as aged deterioration of house. In the second part, we apply the equations to the area of four prefectures in Tokai district and estimate the time variation of death reduction in order to figure out the effect of some kinds of seismic strengthening strategies. As a result we simulated that when the seismic repairing of houses is planed in target districts the strategy giving priority to vulnerable houses is more effective to decrease the death toll than any other strategies having no priority on structural strength of house.

KEYWORDS: death toll, earthquake damage prediction, aged deterioration, seismic retrofit, rebuild, seismic strengthening strategy for wood frame

1. INTRODUCTION

We have learned from the 1995 Kobe Earthquake that most of the deaths resulted from many wooden and low-rise buildings without engineered structural systems crushed by hard ground motions and that rapid progress on seismic strengthening of such wooden building that is a basic structure in Japan is essential as the highest priority strategy for preventing human casualties. But the seismic strengthening policy authorized by Ministry of Land, Infrastructure and Transport Japan does not specify a process to prioritize the buildings to be reinforced, so that the effective and speedy action programs concerning the policy has not still been implemented in any municipal units in spite of the passage of decade from the Kobe Earthquake. Based on the background, the purpose of this study is to discuss effective strategy of seismic strengthening of houses in municipal units as an example of Tokai district, Middle Western Japan inclusive of Aichi, Gifu, Mie, and Shizuoka prefectures, with paying special attention to the time variation of reduction of death toll.

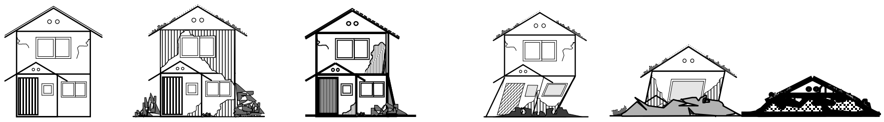
2. CONSTRUCTION OF EQUATIONS

2.1 Overview of Established Knowledge and Basic Data

Among a lot of papers and reports dealing with the Kobe Earthquake published, we have a special interest in papers by Okada and Takai (1999, 2004) which focus on the structural vulnerability characteristics of wooden-frame dwelling houses. The significant outcomes in their papers are as follows within the scope of our concern;

i) They defined “one dimensional damage scale ranging 0.0 to 1.0 (no damage to total collapse), with illustrated damage pattern chart”, which brings clear understanding of the damage states in terms of categorical and discrete scales (See Figure 1).

ii) Incorporated the plenty of structural scores data on wooden dwelling houses spreading all over Japan with field survey data on damage to building, they formulated the "nationwide and standard" relationship among three major variables of the structural scores (*s*)[1], which means earthquake-resistant capacity of building, the damage index (*x*), which means damage state of building and JMA seismic intensity (*I*) as degree of input motions to target buildings.



Category	None/Minor	Moderate	Heavy	Collapse	Total Collapse
Discrete (D)	$0.0 \leqq D \leqq 0.2$	$0.2 < D \leqq 0.4$	$0.4 < D \leqq 0.6$	$0.6 < D \leqq 0.8$	$0.8 < D \leqq 1.0$
Continuous (x)	x = 0.0 -1.0				
Function Form	Weibull (Density, Cumulative) Distribution Function				

Figure 1 Classification of damage states of wooden dwelling houses with damage pattern chart.

2.2 Equations Describing Damage to Wooden Dwelling Houses

As is summarized in Figure 1 the damage states of wooden dwelling houses are well expressed in categorical types of damage and damage level on the discrete scale. The damage state description in regular intervals of ΔD=0.2 is good for comparing with the damage pattern chart illustrated in Figure 1 and is also easy to relate, though rough, with inhabitants' living capability. It is tabulated as below.

$0.0 \leqq x \leqq 0.2$	none or minor effect
$0.2 < x \leqq 0.4$	preventable from the wet
$0.4 < x \leqq 0.6$	impossible to live on
$0.6 < x \leqq 0.8$	collapse beyond repair
$0.8 < x \leqq 1.0$	highly dangerous to deaths.

The originated relationship of three major variables is given as the following Weibull distribution function by Okada and Takai (2004).

$$x = 1 - e^{-(\log I/\eta)^m} \qquad (1)$$

where *x* is damage index meaning the state of damage degree of building, *I* is the JMA seismic intensity in assumable input motions, and *m* and η are the shape parameter and the scale parameter depending on the structural scores of buildings, respectively. In the first step of this study, we tried to modify Equation (1) to (2) for situating the structural score as a response variable (See Figure 2)

$$s = \{(I - a(x))/b(x)\}^{1/c(x)} \qquad (2)$$

Table1 Coefficients in each damage index classified in Equation (2)

x	x=0.1	x=0.2	x=0.3	x=0.4	x=0.5	x=0.6	x=0.7	x=0.8	x=0.9
a	1.5909	1.2795	0.9283	0.4900	-0.0530	-0.8875	-2.1635	-4.7189	-14.483
b	4.4780	5.0712	5.6077	6.1884	6.8585	7.8079	9.1833	11.879	21.795
c	0.2136	0.1714	0.1446	0.1229	0.1050	0.0865	0.0687	0.0495	0.0243

[1] An easy method, called Seismic Inspection (SI), to examine the seismic performance of wooden dwelling houses has been given currency to Japan. We call the structural score and express as "s". The integrated score (s) ranges roughly from 0.0 to 2.5 (weakest to strong enough) and the known criterion is safe for $s \geqq 1.5$, roughly safe for $1.5 > s \geqq 1.0$, somewhat dangerous for $0.7 \leqq s < 1.0$, and in danger of collapse for $s < 0.7$. Thus, the Japanese government has highly been recommending to keep the score as $s \geqq 1.0$, or to retrofit when the score is lower .

In case for the average wooden dwelling houses in Japan[2], the optimal log - normal density function of structural scores *s* by building age *q* of building, which means the passed year since a building was constructed, comes to the followings (See Figure 3):

$$\mathbf{g}(q,s)=\frac{1}{\sqrt{2\pi}\,\sigma}\mathbf{exp}\left(\frac{(\ln(s)-\mu)^2}{2\sigma^2}\right) \qquad (3)$$

Table2 Coefficients of classified by built-years

Years	-1950	1951-1960	1961-1970	1971-1980	1981-1990	1991-	All
μ	-1.0968	-0.7598	-0.5854	-0.4018	-0.1862	-0.0303	-0.3678
σ	0.8229	0.7046	0.5579	0.5335	0.5125	0.4809	0.5970

Therefore, the distribution of structural scores in district unit can be obtained by multiplying *g(q,s)* with the distribution ratio of houses classified by built-year in a district *T(q)* and by summing-up in terms of age *q*:

$$g(s)=\sum_q\left(g(q,s)\times T(q)\right) \qquad (4)$$

The excess probability of damage to building under the situation that the damage state is *x* in assumable input motions *I* am given by substituting Equation (2) into the above equation as follows:

$$P(I,x)=\int_0^s\sum_q\left(\mathbf{g}(q,(I-a(x))/b(x)^{1/c(x)})\times T(q)\right)\cdot ds \qquad (5)$$

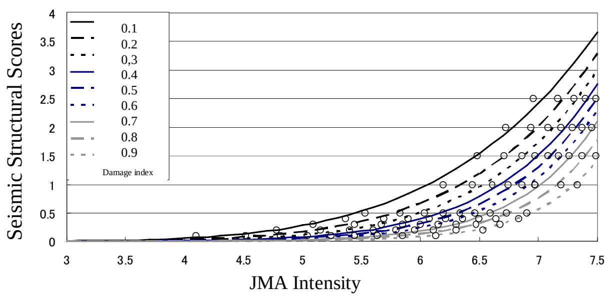


Figure 2 Relation among three major variables

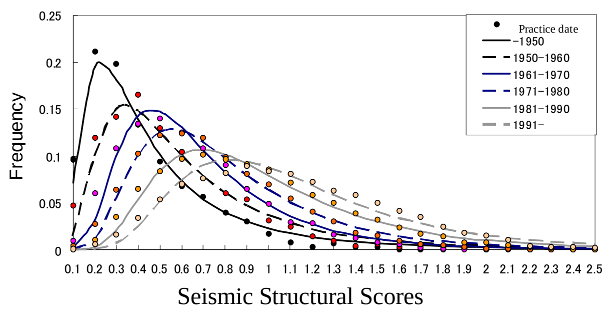


Figure 3 Density function of built-year

2.3 Equations Describing Human Casualties

In order to transform the probability function of damage to building given in Equation (3) to the estimation equation for death toll in district, we apply the death risk function for casualties per house obtained by Tabata et al. (2004) to this study. They proposed the following two kinds of equations for death risk in each building type, that is, detached house and cooperative house composed of plural households:

Detached house:

$$Dnk(x,y)=(0.0104e^{6.68x}+11.0xy^2)/100 \qquad (6)$$

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[2]The seismic inspection has been conducted for the existing wooden-frame dwelling houses of which built-years range from pre-1950s to the present days, amounting totally to several tens of thousands, and based on those data the general and average seismic performance characteristics in terms of the structural score has well been examined.

Cooperative house:

$$Dnt(x, y) = (0.00058e^{9.32x} + 6.69xy^2)/100 \qquad (7)$$

where $D_{nk}(x,y)$ is death ratio per detached house, $D_{nt}(x,y)$ is death ratio per cooperative house, x is damage index, and y is the ratio of destroyed houses in the vicinity.

Besides, the idea of population exposure to seismic intensity is proposed by Nojima et al., the idea which means the amount of spatially distributed population exposed to a certain level of seismic intensity, is available to estimate the death toll in districts. By multiplying the population exposure living in wooden houses *Mf(I)* with Equation (4) we can obtain the total population living in wooden houses which are exposed to seismic intensity *I* and damaged in some ranges of damage index Δx; as follows:

$$Mf(I,\Delta x) = Mf(I) \times P(I,\Delta x) \qquad (8)$$

where *Mf(I)* can be obtained by considering the total population exposure in all types of buildings defined by Nojima et al. *f(I)* with the ratio of population in wooden houses. In addition, considering Equation (6) and (7), we obtain the estimation equation for death toll caused by wooden houses destroyed in district unit as follows:

$$Dn = \sum_{x=0.6}^{1}\sum_{I=0}^{1} Dnk(x, y) \times Mf(I,\Delta x) \times kf + Dnt(x, y) \times Mf(I,\Delta x) \times tf \qquad (9)$$

2.4 Death Toll Estimation in Terms of Temporal Variation

The key to discuss the optimum strategy for strengthening earthquake-resistant capacity of houses is to temporally follow the efficiency in countermeasures. In this study we regard minimizing the death toll as the principle of optimum strategy. For evaluating the simulation results of casualty procedure under every strategies, we propose the estimation method following the time variation of the death toll, the time variation of which origin is set at the present time, based on the above equations with considering both of such factors reducing casualties as the annual rate of seismic strengthening and of negative factor as material-aged of wooden house.

2.4.1 Temporal influence of material-aged upon structural scores

We investigate the temporal influence of material-aged of wooden houses upon the structural scores of buildings through the data on structural score surveyed by the Japan Wooden Housing Earthquake-Proof Reinforcing Businesses Cooperative (abbreviated to Mokutaikyo). Before revising the seismic diagnosis method for Japanese conventional wood house in 2004, the earthquake-resistant capacity was readily assessed, checking six major items of foundation combined with ground condition and five items of plan views *B-value*, placement of walls *C-value*, bracing details *D-value*, proportion of walls *E-value* and built year *F-value*. and integrating individual scores into one representative score, that is, the structural score. One of the individual scores *F-value* is related to material-aged, so that we can roughly estimate the temporal influence of material-aged by investigating the relation between F-value of the structural scores in old version and the passed year since it constructed. Figure 4 shows the results. The correlation between F-value and the building age is remarkable, and it shows that fifty year passed since a wood house has been built deteriorate about ten per cent of seismic strength of its structure. The temporal variation of structural scores can be functionalized simply as follows:

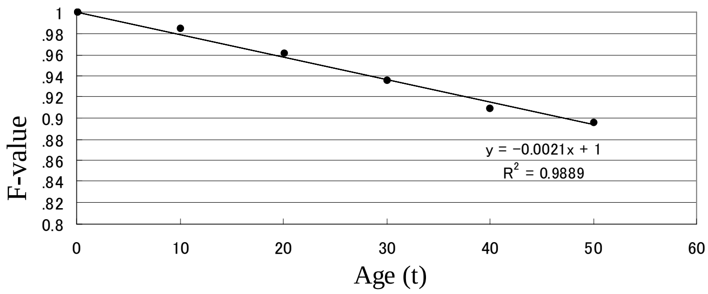


Figure 4 Relation between F-value in structural scores and building age

$$F(t') = -0.0021 \times t' + 1.0 \\ t' = q_0 - q + t \tag{10}$$

where $F(t')$ is a correction factor for structural scores s, q_0 is the present year, q is the year when a house was constructed, t is year passing from the present time, and t' means year passing since a house was constructed.

2.4.2 Temporal influence of natural trend with seismic strengthening execution

The distribution ratio of houses classified by built-year in a district is indicated by the item $T(q)$ in Equation (4). We deal with $T(q)$ as constant value in Equation (4) when we try to estimate the number of remained of houses, which were built in q-year, at present. For considering the time variation of the state, $T(q)$ should be transformed into $T(q,t)$. That is, $T(q,t)$ means the temporal change of distribution ratio of houses built in a specified year q . $T(q,t)$ is generally deteriorating with increasing t, because old houses are demolished in manner of rebuilding or repairing. $T(q,t)$ is estimated as follows:

$$T(q,t) = Ms(q,t) / \sum_q Ms(q,t) \tag{11}$$

where Ms(q,t) is the number of remained houses at t-years, houses that were built in q-years, and can be estimated as Table 3 by using a buiding census of Japan. Subtituting this equation into Equation (5), we can evaluate the influence of seismic strengthning execution upon the distribution of structural scores in a district.

2.4.3 Equations to describe temporally death toll reduction with seismic strengthenning strategeis

With the consideration of such factors reducing casualties as the annual rate of seismic strengthening and of negative factor as material-aged of wooden house, the distribution of structural scores $g(s,t)$ on the time axis can be derived as follows under the assumption that the structural score of house satisfied with seismic strengthening and/or repairing is fixed at 1.0.

In case of s is not equivalent to 1.0:

$$\boldsymbol{g}(s,t) = \sum_q \left(\boldsymbol{g}\left(q, s \times F(t')\right) \times \left(T(q,t) - hs(q,t)\right)\right) \tag{12}$$

In case of s is equivalent to 1.0:

$$\mathbf{g}(1.0,t) = \sum_q \left(\mathbf{g}(q,1.0) \times \left(T(q,t) - hs(q,t)\right) + hs(q,t)\right) \tag{13}$$

where $F(t')$ is a correction factor of structural scores given in Equation (10) and $hs(q,t)$ *which means* the rate of execution of seismic strengthening houses built in q-years after t-years passed from the present time, is presupposed as an arbitrary value depending on seismic strengthening strategies.

Substituting the above Equations (12) and (13) to Equation (5), we obtain the excess probability of damage to building after t-years passed, and using Equations (8) and (9), we reach the simulation results of death toll when any seismic strategies are implemented.

Table 3 Fluctuation ratio a year of buildings built in a specified years

Built-years	Shizuoka Pref.	Aichi Pref.	Mie Pref.	Gifu Pref.
Before 1950	-2.21 %	-1.23 %	-2.62 %	-1.03 %
1951 – 1960	-7.45 %	-6.79 %	-6.08 %	-8.55 %
1961 – 1970	-6.29 %	-4.60 %	-3.48 %	-5.48 %
1971 – 1980	-4.02 %	-4.58 %	-3.77 %	-3.64 %
1981 – 1990	0.05 %	0.32 %	-0.19 %	0.86 %
After 1991	11.92 %	8.26 %	7.87 %	8.07 %
Whole area	0.03 %	0.12 %	0.24 %	0.08 %

3. APPLICATION FOR THE AREA OF FOUR PREFECTURES IN TOKAI DISTRICT

3.1 Hazard Maps on Seismic Input Motion

We are apprehensive that a Tokai-Tonankai Earthquake might occur in the near future and we wish to implement a speedy process of strengthening for non-seismic houses in the whole area. The assumable hazard map of the Tokai-Tonankai Earthquake is estimated by Kuse et al. (2003). In the left side of Figure 6 the hazard map is shown. The figure indicates the maximum seismic intensity in JMA scale is 7 in Shizuoka prefecture. According to the National Census Data of 2003 the total number of people living in Tokai district is around 15,000,000. The population exposed to seismic intensity defined by Nojima et al. (2004) are estimated and shown in the right in Figure 6. It is known that over fifty per cent of the population living in Tokai district is exposed in severely strong ground motions over 6 in JMA intensity scale.

3.2 Estimation of Death Toll for Four Prefectures in Tokai District

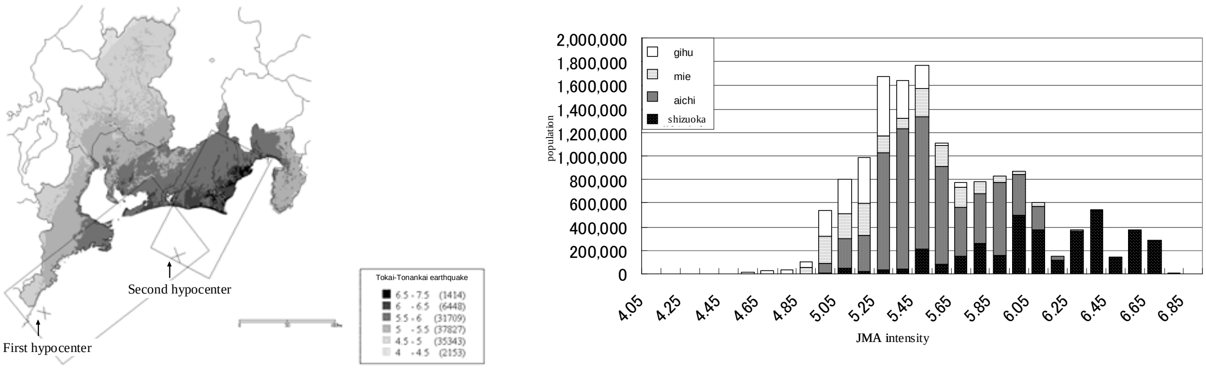


Figure 6 Seismic hazard and population exposure to the JMA intensity

Following the proposed method through Equations (5) to (9) we tried to calculate the death toll in the affected wooden dwelling houses. We estimated the number of damage to dwelling houses as well as human casualties at every unit of 500 m^2, amounting 20,000 units due to the limited size of unit summing up statistical data as population and the number of houses etc. The estimation results about death toll by the occurrence of The Tokai-Tonankai Earthquake are as Table 4.

Table 4 Estimated ddeath toll by arisen from The Tokai-Tonankai Earthquake

Prefecture	Shizuoka Pref.	Aichi Pref.	Mie Pref.	Gifu Pref.
Death toll	8,516	680	167	48

3.3 Discussion of Seismic Strengthening Strategies

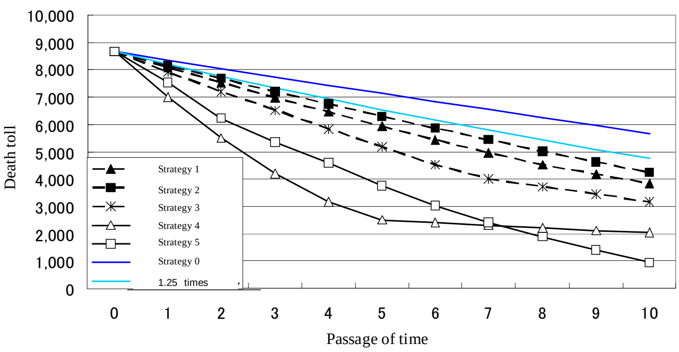
3.3.1 Seismic strengthening strategies proposed

The death toll in expectation is depending upon nation policy on seismic strengthening for non-seismic houses. The policy only says that such an insufficient percentage of seismic strengthened houses as three quarters of Japanese conventional houses at present should increase to 90 percentages in a decade, so that rebuilding a year should be increased 1.25 times as many as current rebuilding and repairing houses a year should be increased twice; but does not mention the process of decision-making on which houses should be prior to be strengthened. We propose several kinds of strategies on seismic strengthening under the assumption that the rate of rebuilding speed is fixed as following the nation's policy because of constancy of labor power in Japan, and try to compare with the influence of each other's strategies on reduction of death toll.

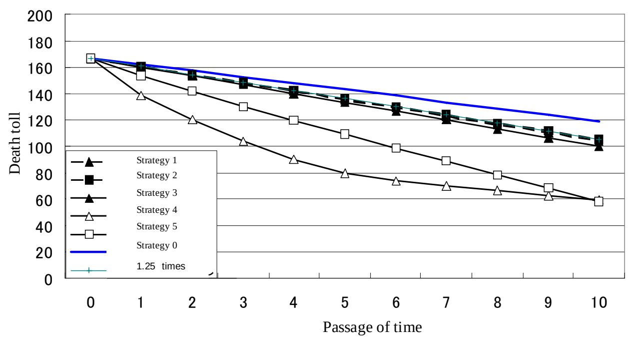
In case without strategy (Strategy 0):

Strategy 0 is the most primitive measures, that is, we execute the simulation under the situate that the fluctuation of number of building follows the natural trend as shown in Table 3 without considering of seismic strengthening.

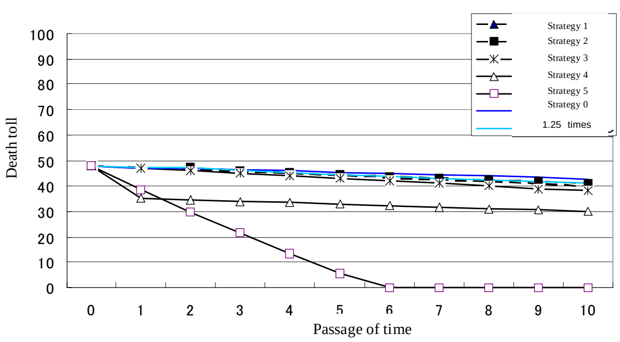
In case of following the national policy (Strategy 1, 2, and 3):
As mentioned in the first part of this section, it is a strategy increasing percentage of seismic strengthened houses to 90 per cent of all Japanese houses in a decade.
Strategy 1 has no rule of the prior selection of straightening houses in random order with keeping the strengthening rate a year, which is the national policy itself.
Strategy 2 is that seismic strengthening is prior to be executed in newly building order with keeping the strengthening rate a year.
Strategy 3 is that seismic strengthening is prior to be executed in older building order with keeping the strengthening rate a year.
In case of pay attention to the damage state of houses (Strategy 4 and 5):
After the 1995 Kobe Earthquake, many researchers have indicated that human casualties are strongly related to the damage state of buildings in which they lived, and most deaths occurred especially at seismic incidence over 0.8 in damage index scale of building [for example, Ohta et al. (2003), Tabata et al. (2004)]. Paying attention to the fact, we simulate in Strategy 4 and 5.
Strategy 4 gives priority in seismic strengthening order to housing of which assumable damage is over 0.8 (total collapse) in damage index scale.
Strategy 5 gives priority in seismic strengthening order to housing of which assumable damage is over 0.6 (severe damage) in damage index scale.
3.3.2 Result of simulation
In Figure 4 the simulated results in each prefecture are shown. Notice that death toll appears to decrease linearly with increasing time. Because, even in the case of strategy 0 with no specialized strengthening strategy, the death toll is decreasing as a result of rebuilding only older houses. In comparison with six kinds of strategies about the time variation of death reduction, it should be emphasized that the time variation of death reduction are widely different in spite of the same number of strengthening in all the strategies. No matter whether you follow the national policy on strengthening execution, it is no use of reduction of death toll in case of seismic strengthening action plan not based on the optimal strategy. As a result of this simulation it is proven that the optimal strategy is Strategy 4 which means giving the priority to non-seismic houses.



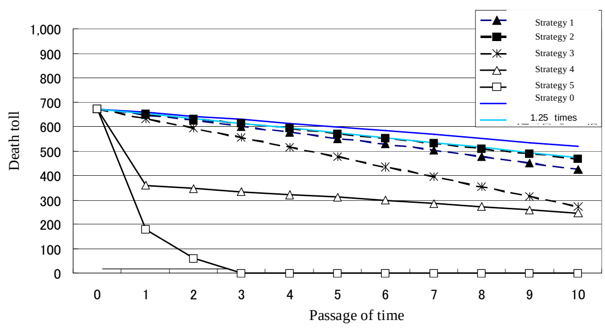
(a) The time variation of death reduction in Shizuoka



(b) The time variation of death reduction in Mie



(c) The time variation of death reduction in Gifu



(d) The time variation of death reduction in Aichi

Fig 7 Estimate the time variation of death reduction

In case of Shizuoka Prefecture where much hazardous input will probably attack, the simulation teaches us that in the early stage we should adopt Strategy 4 which precede houses presumable to be totally destroyed, and after around 6 years we should change the strategy from 4 to 5 which wider the target houses presumable to be slightly damaged.

4. CONCLUSION

These results indicate that the effective to decrease the death toll is variation of seismic strengthening strategy. The result of this study contributes to the decision-making on practical strategy of seismic strengthening in municipal unit.

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