STRONG MOTION PREDICTION USING STOCHASTIC GREEN'S FUNCTION METHOD AND EVOLUTIONAL DAMAGE PREDICTION BASED ON NONLIENAR STRUCTURAL MODELS

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ABSTRACT :

We hypothesized that the scale of the predicted Nankai Earthquake will increase gradually year by year as the time passes from the last occurrence in December 1946, and then we estimated strong motions chronologically from 2009 to 2060 for western Japan based on the up-to-date strong motion prediction method, i.e., the so-called Stochastic Green's function method with hierarchical source heterogeneities. Next, we input the calculated chronological strong motions into a set of nonlinear response analysis models proposed by Nagato and Kawase and estimated building damage ratios for different structure types and numbers of floors. When we compare the evolutional damage ratios of buildings in the target areas with those for the reference case (corresponding to the scenario that will happen in 2036), we found that for every 10 years of delay in occurrence of the Nankai trough event we must expect 40% of increase in building damage, mainly in the epicentral areas.

KEYWORDS: Chronological Strong Motion Prediction, Evolutional Damage Prediction, Nankai earthquake, Damage Ratios, Nonlinear Response Analysis Models

1. INTRODUCTION

Predicted earthquakes will occur in the future and the buildings damaged by those earthquakes may not be the same as those that exist now. As the return period of the earthquake in question becomes longer, not only does its scale change, but we can also hypothesize that the seismic capacity of existing buildings will decrease and the total number and proportions of different types of buildings will also change greatly. On the other hand, even now, a common technique is to use vulnerability functions from experienced damage based on past earthquake damage ratios and to estimate building damage using past and present statistical building data. However, even if damage predictions are made, no matter how precise the technique is, if the model parameters are not adequate, the actual damage may differ greatly. Obviously, this could greatly undermine earthquake countermeasure planning and the rationality of countermeasures that are based on those damage predictions.

In this research, we focused on the Nankai Earthquake, which is feared to occur within the next several decades. First, we hypothesized that the scale of the predicted Nankai Earthquake will increase gradually year by year as the time from the last occurrence in December 1946 lengthens, and then we estimated strong motion chronologically from 2009 to 2060 for western Japan, particularly the island of Shikoku(Call it Chronological Strong Motion Prediction). We then compare these chronological strong motions with the non-chronological strong motions calculated from a fixed earthquake scale model based on an ordinary earthquake scale determined from past earthquake data.

Next, we input the calculated chronological strong motions into nonlinear response analysis models and estimated building damage ratios for the period from 2009 to 2060 by different structure types and numbers of floors(Call it Evolutional Damage Prediction). in the same way, we conducted comparative investigations of the results of chronological (evolutional) and non-chronological damage predictions.

2. CHRONOLOGICAL STRONG MOTION PREDICTIONS FOR THE NANKAI EARTHQUAKE

2.1. Chronological strong motion prediction technique

The average return period of Japan's subduction-zone earthquakes is short, ranging from several decades to hundreds of years[1)], in contrast to thousands or tens of thousands of years for inland earthquakes. Therefore, considering the dispersion of the return periods of earthquakes, chronological evaluation of strong motions should be conducted for subduction zone earthquakes, and countermeasures should be taken in response. In this paper, taking the Nankai Earthquake, which occurs at roughly 90–150 year intervals[1)], as an example, we determined the magnitude by assuming that its scale changes with the length of the return period. We determined that the maximum likelihood of occurrence is in January 2037 by using the standard occurrence interval (90.1 years), as provided by the Headquarters for Earthquake Research Promotion[1)] (HERP) and the occurrence of the last one in December 1946. For convenience in calculations, we adjusted the predicted occurrence to December 2036 and made it as the standard (2036) model. Although the occurrence year estimation obviously include errors depending on the past earthquake scale evaluation and 2036 assumption corresponds to the shortest recurrence time in history, we took this as the most-likely scenario at this time. Based on this prediction, we evaluated how the strong motion waveforms of the Nankai Earthquake would change relatively if it occurs before or after 2036 for the period from 2009 to 2060.

We assume that the scale of the earthquake is proportional to the average slip of the Nankai Earthquake epicenter fault. From the average slip given in HERP documents[1)] and the return interval, the average annual slip is 6.3 cm (570/90.1). This value is within the relative movement speeds between the Philippine and Eurasian plates of 5–7 cm/year[2)], so it seems appropriate. We adjusted slips in proportion to the interval between the Showa Nankai Earthquake and the predicted occurrences. Figure 1 shows the chronological change of the average slips for the asperities and the background domain for a hypothetical Nankai Earthquake.

2.2. Standard source model for the Nankai earthquake and locations of estimated sites

Based on the source model (case 2) proposed by HERP[1)] for calculations using a standard technique considering both global and local source characteristics, as well as the Kamae model[2)], we established a standard model that consists of three large asperities and the background area as shown in Figure 2. In addition to the first order heterogeneity of asperities, we also considered another smaller-scale heterogeneity to the slip within asperities in order to match the radiated energy in the relatively long (~ a few seconds) period to the observed. Namely, we make the slip 1.5 times larger for 22% elements inside the asperity (elements marked with crosses in Figure 2), while we make the average slips of the remaining elements smaller to preserve the seismic moment[3)]. We only scaled the slip (=the seismic moment) when we consider chronological strong motion prediction, not the spatial extent at all. We use the so-called Stochastic Green's function method. The locations analyzed were K-NET, KiK-Net, and JMA Shindokei network observation sites within 400 km of the center point of the asperities and the background area of the hypothetical Nankai Earthquake as shown in Figure 2 as open circles.

2.3. Calculation of chronological strong motion

We predict strong motion for the Nankai Earthquake. Occur in 2036 year. Using Stochastic Green's function method[4) 5)]. Stochastic Green's function to use for waveform synthesis is effective for broad-band range[6)]. In conducting waveform synthesis. We also considered the saturation characteristics of strong motion in near source area. We incorporated the lower limit of fault distance into an attenuation equation to use for waveform synthesis in this study. We set lower limit of fault distance is 8 km[7)].

Changing the calculated strong motion for the average slip of the predicted earthquakes with respect to the standard model, we estimated strong motion in the target area for occurrences in 2009 year, 2018 year, 2027 year, 2045 year, 2054 year and 2060 year. Figure 3 shows peak ground velocity (PGV) and acceleration (PGA) ratios with respect to the standard model in 2036. If the Nankai Earthquake occurrence shifts 10 years from the 2036 year, the maximum value would be 1.1 times larger or smaller. Figure 4 shows the PGV and PGA for the strong motion occur in 2036 year and the attenuation equation by Si and Midorikawa (1999)[8]. The calculated PGV and PGA almost coincided with the empirical attenuation equation. Red curves show averaged PGV and PGA values of but should not refer to for the long distance range close to the 400km limit.

Figure 5 shows the JMA Seismic Intensity scale (Hereafter JSI) levels for the Nankai Earthquake occur in 2018 year, 2036 and 2054 year, together with the trial calculation results for the hypothetical Nankai earthquake at prefectural capitals from HERP documents[2]. For all of the Shikoku island, Wakayama Prefecture, and other regions near the source, the JSI level would be greater than 4 in most places in 2018, while it would be a 5- (V minus) or greater in 2036 and it would be a 5+ (V plus) or greater in 2054. As seen in this figure, if the hypothetical Nankai Earthquake return period changes, the JSI level changes at certain numbers of sites. The JSI level may have a possibility to change ±1 when the period changes 18 years in regions near the source. Note that our 6- (VI minus) and 6+ (VI plus) JSI or greater levels correspond to the HERP highest JSI rank of 6- or greater and that other JSI levels appear to be almost the same, too. Although around Wakayama City, evaluations were a little smaller than the HERP results, it is clear that overall our 2036 results coincide with the HERP ones.

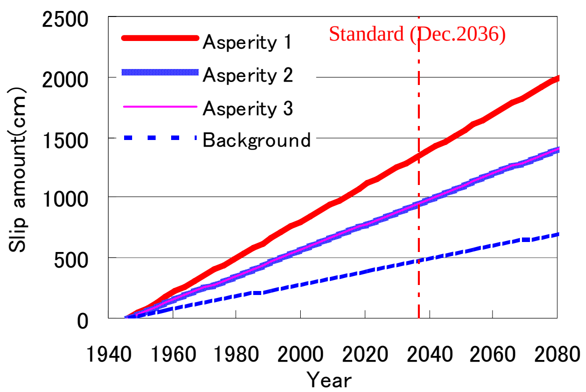

Figure 1. Average slip of the source model considering years of earthquake occurrence.

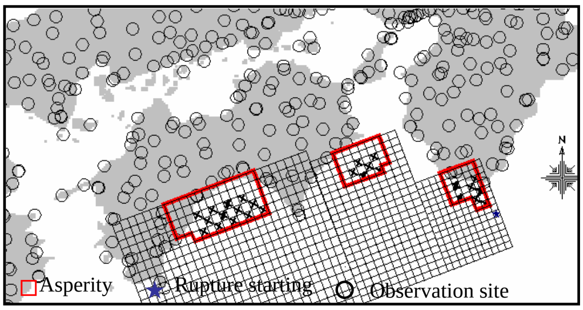

Figure 2. The assumed source model of the Nankai earthquake and estimated sites.

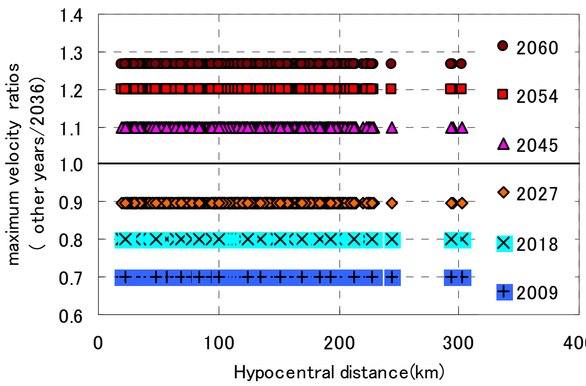

Figure 3. Chronological changes of predicted strong motions, for both PGV and PGV.

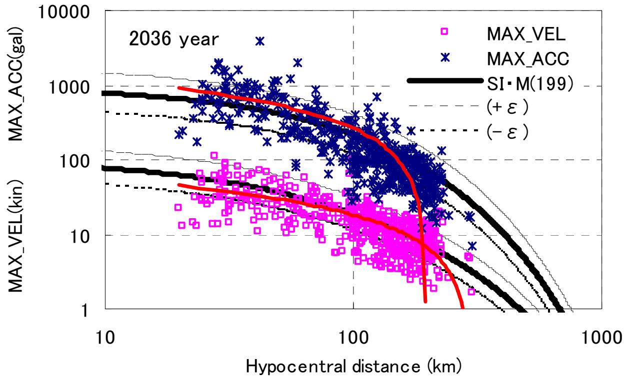

Figure4. Comparison between predicted strong motion using the standard model and empirical attenuation formula[7]

3. EVOLUTIONAL BUILDING DAMAGE PREDICTION TO THE NANKAI EARTHQUAKE

3.1. Input motion and building models

From past analyses and experiences, we know that PGA of 200 Gal or less will not cause serious damage to most buildings. For this reason, we selected K-NET, KiK-net, and JMA network observation sites within 400 km from the hypothetical Nankai Earthquake source where PGA would be more than 200 Gal and used them for the building damage prediction.

We used the building models for damage prediction created by Nagato and Kawase[9) 10)]. They created a total of 15 nonlinear response analysis models for buildings to reproduce the actual damage ratios observed during the 1995 Hyogo-ken Nanbu earthquake disaster. Their models include one 2-story wooden (W) model regardless of the construction age, both new and old models for 3-story (including 2 and 4 stories), 6-story (including 5 and 7 stories), 9-story (including 8 and 10 stories) and 12-story (including 11 and 13 stories) reinforced concrete (RC) buildings, and new and old models for 3, 4, and 5-story steel-frame (S) buildings. For the wooden building model, if the maximum inter-story drift angle becomes 1/10 rad. or more, serious damage or total collapse is assumed to occur. In the RC and S building models, if the maximum inter-story drift angle becomes 1/30 rad. or more, serious damage or total collapse is assumed to occur regardless of the construction age.

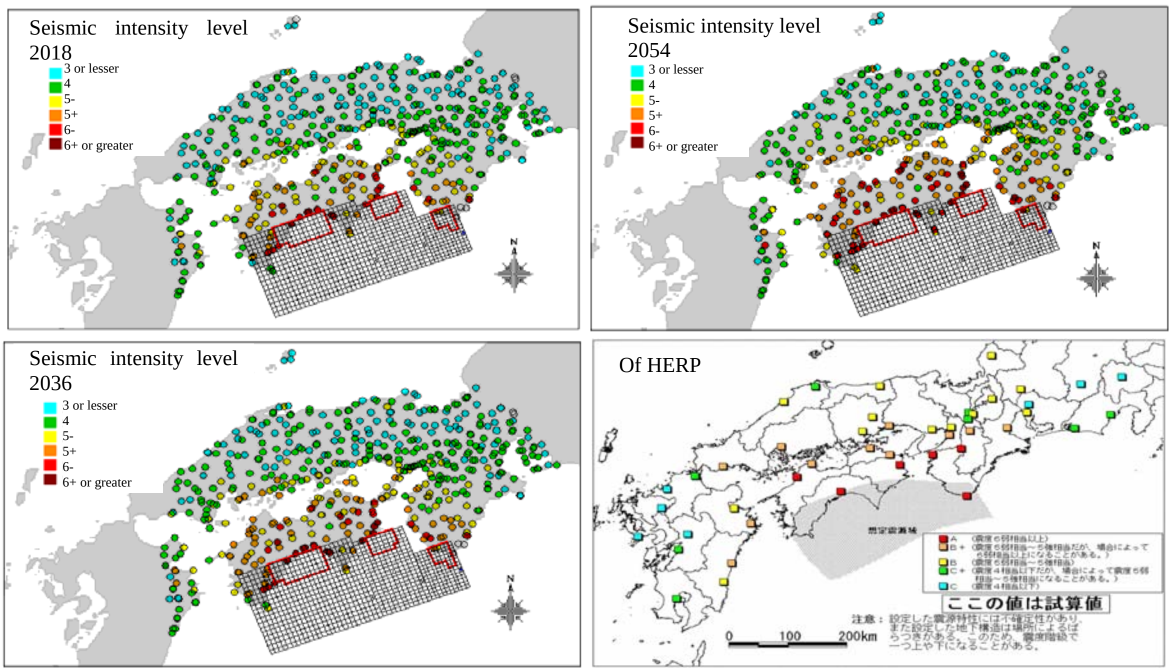

Figure 5. Comparison of seismic intensity level (JMA Seismic Intensity scale) calculated by our three chronological models with the result of HERP at prefectural capitals and other locations (right bottom panel).

3.2. Building damage ratio using chronological strong motions

First, we input acceleration waveforms at the observation points that would exceed 200 Gal in the occurrence of a hypothetical Nankai Earthquake in 2009, 2018, 2027, 2036, 2045, 2054 and 2060 into the Nagato-Kawase models (2002)[9) 10)] and calculated the ratios of serious damage or worse to buildings. Table 1 is a list of observation points where serious damage or worse would occur. In the results of the standard model, serious damage or worse would occur across a broad region centered at Shikoku and distributed from Osaka Prefecture to Oita Prefecture. Figure 6 shows the damage ratio distributions of wooden, RC and S buildings (constructed after 1982) in the standard model. The estimated damage ratios were high for locations that suffered relatively severe damage in the 1946 Nankai Earthquake. These include Kochi City, Aki City, and Shimanto City (which was called Nakamura-machi at that time and suffered an 80% collapse ratio of wooden houses) in Kochi Prefecture, Shingu City and Tanabe City in Wakayama Prefecture, Tokushima City and Anan City in Tokushima Prefecture and other places in the surrounding region. The bottom panel of Figure 6 shows the distribution of damaged buildings according to the Central Disaster Prevention Council[11]. In this figure, places where there are numerous damaged buildings also have high estimated damage ratios in the standard model.

Figure 7 shows the damage ratio distributions for new 3-story RC buildings for strong motions by 2018 and 2054 models, revealing differences from the standard model. Figure 8 and Table 2 shows the average damage ratios for all the observation points where serious damage or worse would occur for each subject building models and the ratios of different year models relative to 2036 model. We found that for every 10 years of delay in occurrence of the Nankai trough earthquake we must expect 40% of increase in building damage. Overall, as the earthquake occurs later, the average damage ratio becomes larger, and the average damage ratios of non-wooden buildings become remarkably larger for occurrences from 2036 and later. This trend is greater in new buildings than in old buildings. Moreover, the regions that show higher damage ratios to buildings are limited always to coastal areas near asperities, or riverside plain areas where ground is relatively soft. For building structural types the damage ratio decreases in the following order: low steel-frame, wooden, medium and low RC. For age, the damage ratio decreases naturally from old to new.

Table 1. Observation sites that receive serious damage or worse.

Prefectures	K-NET、KiK-Net、JMA subject points
Kochi	KOC001、KOC002、KOC003、KOC004、KOC005、KOC006、KOC007、KOC010、KOC011、KOC012、KOC013、KOC014、KOC015、KOCH03、KOCH05、KOCH07、F35、97A、598、599、97B
Tokushima	TKS001、TKS002、TKS003、TKS004、TKS006、TKS007、TKS008、TKSH02、F37、592、593、974、975
Wakayama	WKY002、WKY003、WKY005、WKY006、WKY008、WKY010、WKYH07、58A、58B、96B、__96A
Kagawa	KGW004、KGW005、KGW007、KGWH02、977、978、594、F33
Ehime	EHM003、EHM005、EHM008、EHM010、EHM016、EHMH03、EHMH04、EHMH06、EHMH08、EHMH09、979、595、F2F、F34
Osaka	OSKH01、OSK010、OSK004、OSK008
Hyogo	HYGH01、HYGH10、585、967、968、E82、HYG016
Nara	NARH01
Okayama	OKYH01
Hiroshima	HRS018、HRS019、EB6
Yamaguchi	YMG017、YMG018
Oita	5E8、OIT010、OIT013

Table 2. Ratios of serious damage ratio for each model relative to the standard model (2036)

Damaged ratios(other years /2036)							
Occurrence time(year)	2009	2018	2027	2036	2045	2054	2060
Wooden building	0.45	0.67	0.80	1.00	1.36	1.56	1.74
RC building (-1981)	0.22	0.40	0.55	1.00	1.38	2.05	2.50
RC building (1982-)	0.19	0.41	0.64	1.00	1.38	2.06	2.32
RC building (all)	0.21	0.40	0.58	1.00	1.38	2.05	2.43
Steel building (-1981)	0.37	0.55	0.75	1.00	1.29	1.65	1.76
Steel building (1982-)	0.41	0.60	0.75	1.00	1.43	1.58	1.78
Steel building (all)	0.39	0.57	0.75	1.00	1.35	1.62	1.77
All building	0.35	0.54	0.71	1.00	1.36	1.73	1.94

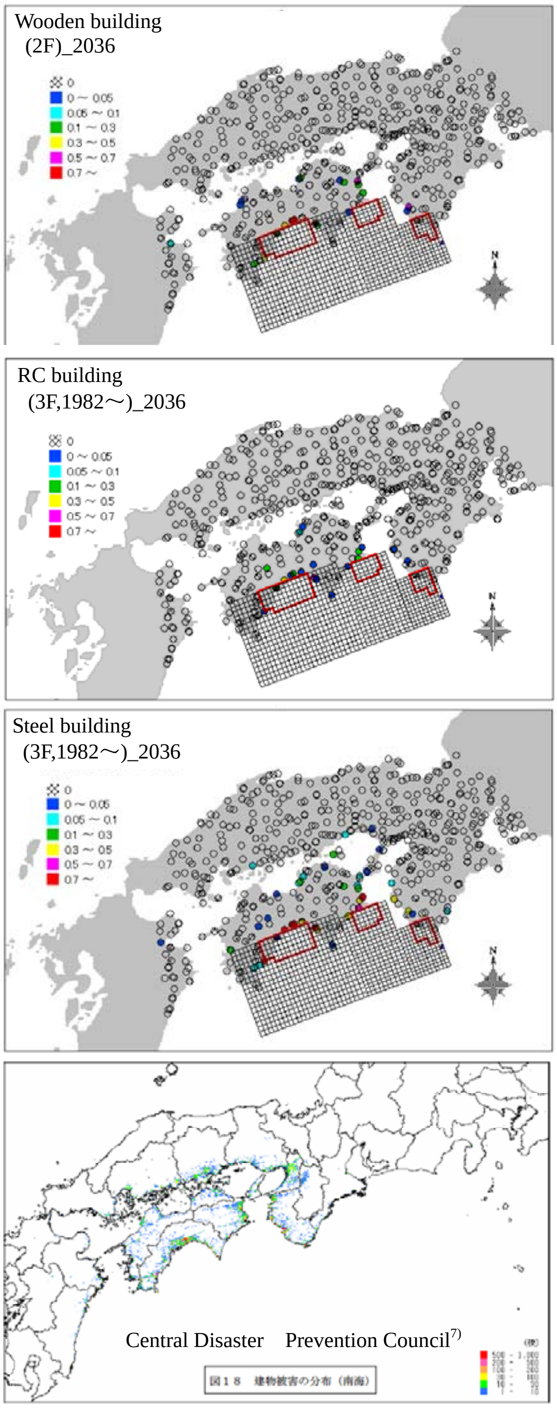

Figure 6. Comparison of building damage ratio distribution from the standard model and building damage distribution released from the Central Disaster Prevention Council [7]

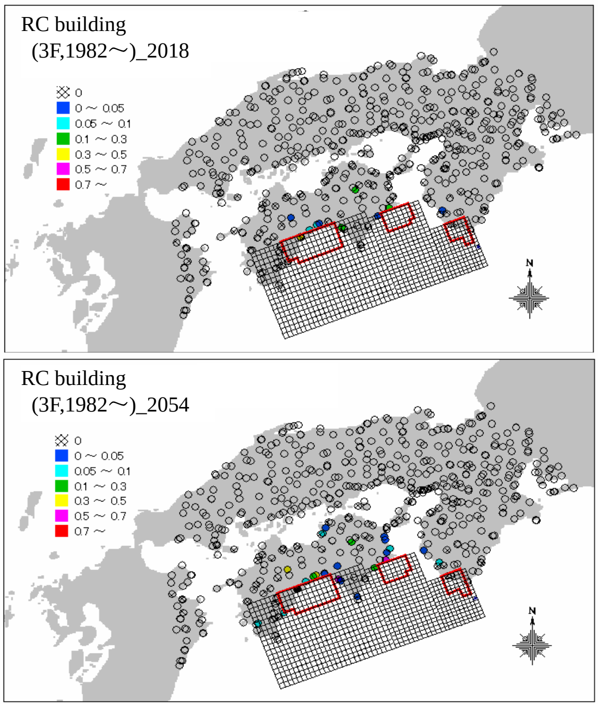

Figure 7. Building damage ratio distribution when Nankai Earthquake occurred in 2018 or 2054.

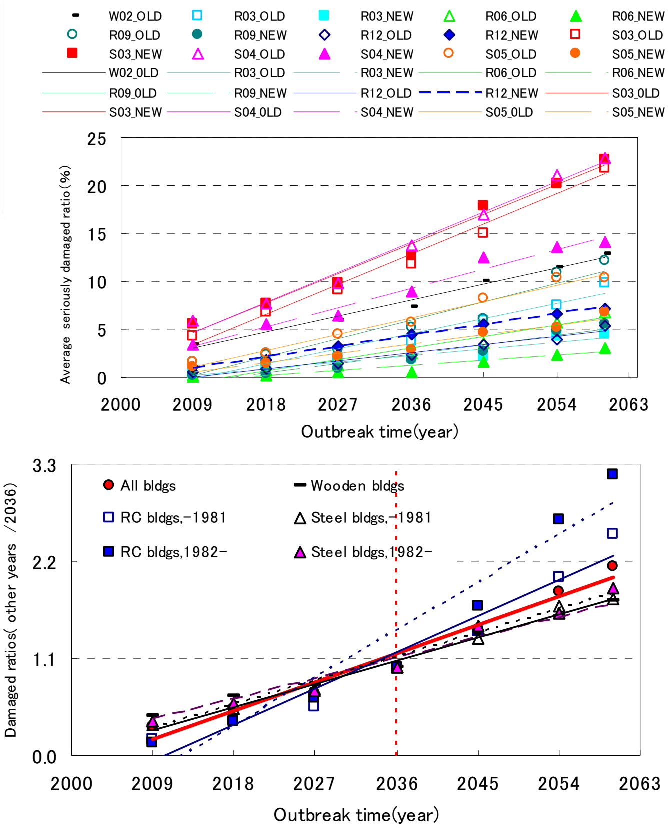

Figure 8. Average ratios of serious damage or worse and ratios relative to the standard model for each category of buildings.

4. CONCLUSION

First, we reflected the chronological change in the scale of the hypothetical Nankai Earthquake in terms of the average slip and calculated strong motions accordingly. If the occurrence shifts 10 years, the average slip, and hence the PGV and PGA values increase or decrease by about 1.1 times. As a result, as the occurrence of the Nankai Earthquake shifts from the currently predicted year of 2036, the JMA seismic intensity level also changes, with the possibility of ±1 change for the period change of 18 years in regions near the source.

Next, we conducted evolutional damage predictions by inputting six chronologically-determined strong motions for years between 2009 and 2060 into nonlinear building damage prediction models. As a result, we found that for every 10 years of delay in occurrence of the Nankai trough earthquake we must expect 40% of increase in building damage on the average. Note that the occurrence of serious damage or worse to buildings would be possible in coastal regions, riverside alluvial ground regions and other areas with relatively soft ground. This damage would be centered on Kochi, Tokushima, Wakayama and other areas near the source region. Furthermore, the damage ratio becomes smaller depending on building type in this order: steel-frame, wooden, RC. New buildings constructer after 1982 show smaller damage ratios than old buildings. If the occurrence of the Nankai earthquake is delayed, then the damage ratios for buildings, will increase quite rapidly so that we need to increase design levels for these relatively safe buildings as time goes by.

These results are based on the comprehensive evaluations by using strong motions that reflect the return period only in the average slip and standard building damage prediction models that produce severe damage or worse ratios. For truly "evolutional" damage impact prediction for Nankai trough event we will consider changes in regional population, changes in average floor areas per person, statistical building life-spans for different types of buildings, and needs of newly construction floor areas per year to predict building stocks in future and then chronologically estimate damaged building floor areas and their environmental, economical, and social impact for the foreseeable future.

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