PROPOSAL AND VERIFICATION OF PULSE-SEISMIC-DESIGN FOR BUILDING STRUCTURES

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SUMMARY

In this paper, the authors show a new seismic design method for the earthquake in near-source-region using pulse-response-analysis and show the application for actual buildings damaged in Hyogoken-Nambu Earthquake 1995 to verify the validity of the new method. In the verification, the authors also employ time history response analysis of multi-mass systems. As a result, the authors show that the velocity pulse wave causes middle story collapse in reinforced concrete mid-rise buildings and that it can simulate the phenomena by using the pulse-response-analysis. The possibility of middle story collapse also exists in the buildings designed by the current code of Japan (after 1981) in the case of near-source earthquake.

INTRODUCTION

The earthquake is the phenomena that the distortion energy accumulated inside the earth explodes the earthquake wave by the rapid fault movement. Especially when the fault is located just underneath the urban area, the earthquake is called in Japanese “Toshi-Chokka-gata Jishin” (very big ground motion in the near source region), which causes the great damage despite its relatively small magnitude. It accords with “intra-plate earthquake” against “inter-plate earthquake”. In this paper, the area targeted by Toshi-Chokka-gata Jishin, namely the nearby area of the epicenter, is referred to as “near-source-region”.

Hyogoken-Nambu Earthquake 1995 and Northridge Earthquake 1994 are typical examples of near-source earthquake. As for Northridge Earthquake, it has been pointed out in US that the impulsive earthquake motion observed causes a great damage to the building [Heaton,1995]. As for Hyogoken-Nambu Earthquake, the research has been made that verifies the great damage caused by the exceeding long period pulse in the direction crossing the fault surface [Koketsu,1996]. Also in the case of near-source earthquake, it has been pointed out by the finite element model analysis that dynamic behavior during the rupture process generates the impulsive ground motion [Kawano,1995].

The degree of such ground motion that causes the desperate damage to the building sometimes goes far beyond the usual design level as to over 1000cm/sec^2 in acceleration, 100cm/sec in velocity. In Hyogoken-Nambu Earthquake 1995, even among the buildings which can be regarded to be uniform bar in height direction, there were a number of examples of instantaneous collapse at the middle stories. These damages were not expected by the conventional seismic design method that counts on hysteresis damping of the building to take earthquake resistance effect. To avoid such a dangerous damage in the near-source earthquake, further investigation is strongly required. This paper presents the new structural design and investigation method for the pulse wave input, and verifies the applicability of this method to the actual buildings which collapsed at the middle stories as well as the buildings designed under the Japanese seismic design code (after 1981).

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PULSE-SEISMIC-DESIGN

2.1 Design procedure

Pulse seismic design is aimed to investigate, with the coherent preciseness, the hypocenter model, the make-up of earthquake motion spectrum, and the judgment of the safety regarding the near-source earthquake. There are various ideas of ground motion including the hypocenter area, but in this paper, rather macro-approach is employed. The procedure shown in Figure 1 is to evaluate the seismic safety of the building according to the pulse-response-analysis. In the wave propagation analysis for uniform bar model, investigation is taken whether or not there is possibility of exceeding the elastic limit at the middle story of multi story building. Then if there is any such possibility, followed by the pursuit of the collapsing behavior by the pulse-response-analysis for mass system.

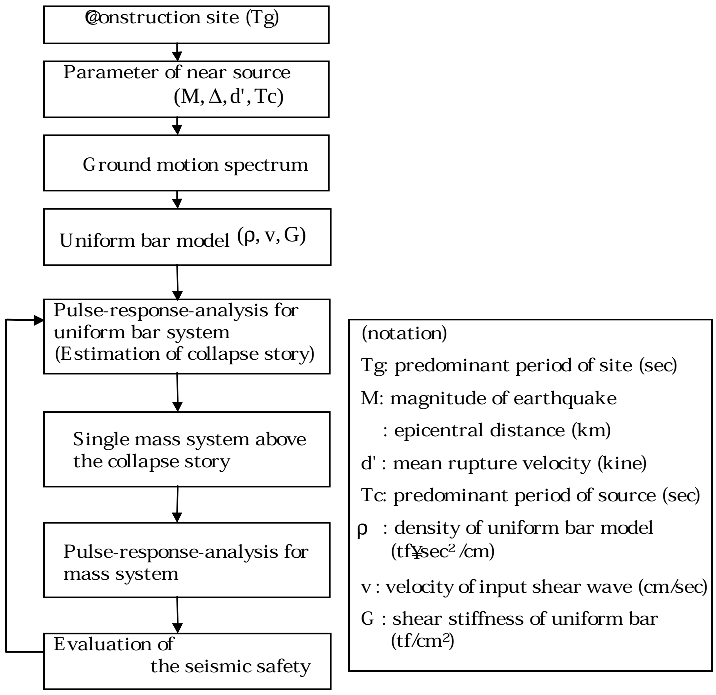


Figure1: Procedure of the seismic design using pulse-response-analysis

2.2 Near source region

Near source region is defined to be located within the radial Δb, centering around the epicenter of active fault with high activity. This circular field is called “effective near source region”. The radial Δb is given by the following equation according to the magnitude M [Kawamura,1982].

$$\log \Delta b = 0.5\,M - 2.1 \tag{1}$$

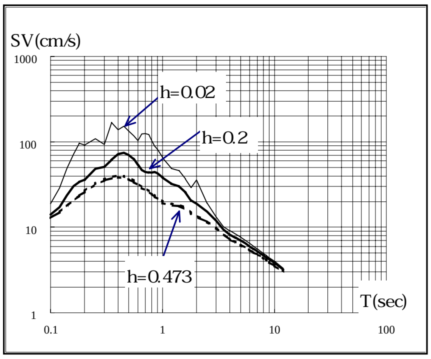
2.3 Input earthquake motion and design criteria

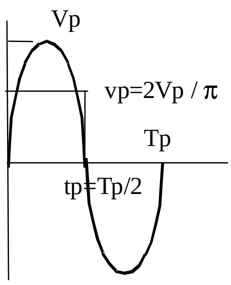
The maximum velocity amplitude (Vp) of ground motion in the near source region depends on predominant period (Tg) of the site ground and mean rupture velocity (d’) at the hypocenter. It can be obtained from the following equation [Kawamura,1982].

$$Vp = (\pi/2) \times (Tg) \times (d') / 0.15 \tag{2}$$

Here, assuming mean rupture velocity (d’) to be 50cm/sec, then Vp=500/Tg (d’=15-50cm/sec is employed for the general investigation, and d’=50cm/sec for the safety side). The ground motion spectrum in the near source region almost accords with 20% damping spectrum of the observation site. When applying JMA-Kobe ground motion spectrum of Hyogoken-Nambu Earthquake to the above equation, it has been verified that it shows almost the average value given d'=15cm/sec, and shows the maximum value given d'=50cm/sec.

As a result of the investigation in numerical value on the buildings damaged by Hyogoken-Nambu Earthquake [Katagihara et.al.,1996], it has become clear that the usage of "velocity pulse response" where not considering the input loss matches the situation. The input wave used for the analysis is modelled on sine wave (1 cycle) or rectangular wave as shown in Figure 3. As input wave for the verification, there are also rectangular or triangle waves, the latter has been used by Heaton,T.H.et.al. (1995) for their various studies. However, in this paper, sine wave is used since it is easy to be handled in terms of the numerical value.





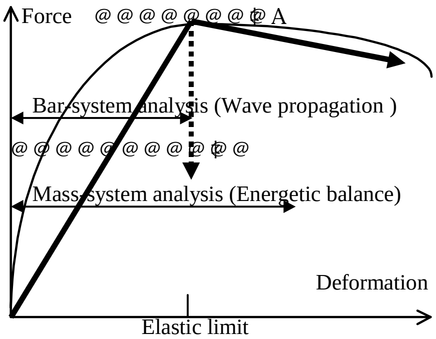


Figure 3: Pulse wave input

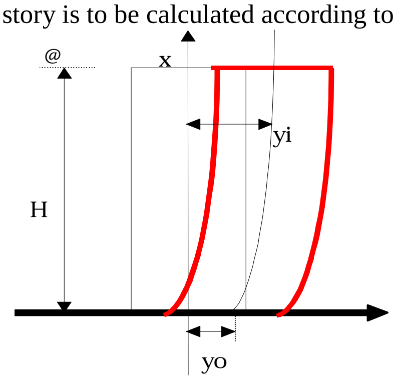
Figure 2: Earthquake spectrum (JMA-KOBE 1995)

Figure 4: Restoring force characteristic

Pulse-response-analysis is aimed to undertake piece-wise linear analysis to realize the simplified calculation, thus its main focus is to estimate the collapsing point of the structure. Therefore, it does not make essential change if the hysteresis characteristics are drastically simplified in a small deformation (elastic) range as shown in Figure 4. This being said, the hysteresis characteristics used for the pulse response analysis are expressed in the bi-linear model whose curving point corresponds with the story yield point. Two types of the curve are shown in Figure 4; brittle structure controlled by shear collapse or buckling, ductile structure where the deformation capacity can be expected after reaching the story yield.

2.4 Pulse response analysis

As shown in Figure 1, it is first judged whether or not each story reaches yield or collapse according to "pulse-response-analysis for uniform bar system" (Figure 5). If it is confirmed that the deformation capacity is expected when facing the story collapse, the amount of the ultimate response deformation of the estimated collapse story is to be calculated according to "pulse-response-analysis for single mass system" (Figure 6).



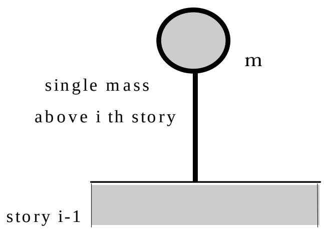


Figure 5: Model for uniform bar system

Figure 6: Model for single mass system

2.4.1 Pulse-response-analysis of uniform bar system

The equation of the wave theory is given by (3), and the propagation velocity of shear wave v is by (4).

$$\frac{\partial^2 y}{\partial t^2} = v^2 \frac{\partial^2 y}{\partial x^2} \qquad (3) \qquad\qquad v = \sqrt{G/\rho} \qquad (4)$$

When the ground motion to be yo(t), deformation of the bar is given (5), and the shear distortion (γ) is (6).

$$y = y_o(t - \frac{x}{v}) \qquad (5) \qquad\qquad \frac{\partial y}{\partial x} = -\frac{y_o'(t - \frac{x}{v})}{v} \qquad (6)$$

Here, yo' is dyo(t)/dt, representing the velocity wave of the ground motion (Vp sin ϖ t). The input shear wave (sine wave with one cycle) corresponding with the velocity amplitude Vp and the period Tp goes ahead of the foundation of the bar, and reflects at the top and foundation. The reflecting wave turns the mark the other way around (reflection coefficient = -1.0) at the top, free end, and runs the same mark (reflection coefficient = 0.5) at the foundation, fixed end. The input wave is composed with those reflecting waves, and the shear distortion γ at each part of the uniform bar per time can be calculated.

The analysis is undertaken following the above procedure. In this procedure, the story which is estimated to collapse is where the deformation generated either by the original wave or the synthetic wave composed of input and reflecting waves reaches δ yi at each story most quickly. Basically the estimated collapse story is obtained according to Tp and Vp, but the collapse story cannot be limited to the only one considering the preciseness of the assumption terms.

2.4.2 Pulse-Response-Analysis for mass system

Regarding the dynamic movement, the system is judged to be single mass at the estimated collapse story (Figure 6), and the response of the mass to be monotonic deformation. The earthquake movement is the random wave given by the spectrum and the lasting time. However, in the wave propagation analysis the input sine wave accords with the amplitude Vp and the lasting time Tp, but in the mass system we employ rectangular wave of 1/2 cycle (c.f. Figure 3). Therefore, the code Vp stands as vp (=2Vp/ π), Tp as tp (=Tp/2).

This analytical method is based on the principle of "select maximum response" [Kawamura,1981]. In order to make energetic balance between the input and the absorption by the system, vp-tp relation is selected having the contact with ground motion spectrum, and the maximum response deformation (δ p) is obtained as shown in Figure 7. When receiving single rectangular-velocity-pulse, initial conditions are given as equations (7) and (8), from the equation of energy balance, vp-tp relation is given as (9);

$$t = 0, \quad \delta(0) = 0, \quad \frac{d\delta(0)}{dt} = vp \qquad (7) \qquad\qquad t = tp, \quad \delta(tp) = \delta p, \quad \frac{dx}{dt} = 0 \qquad (8)$$

$$\int_0^{\delta p} \frac{d\delta}{\left(vp^2 - \frac{2}{m} A(\delta)\right)^{\frac{1}{2}}} = \int_0^{tp} dt = tp \qquad (9)$$

Here, we can refer to the equations for analysis of various restoring force characteristics on [Fujitani et.al.,1986].

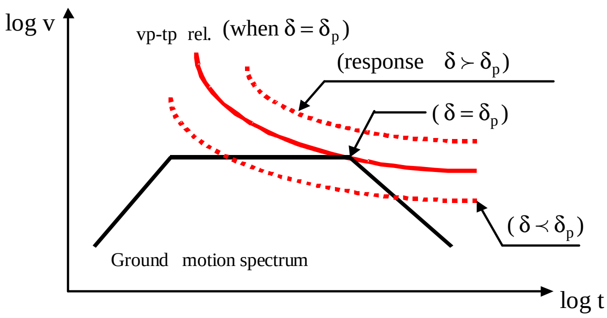
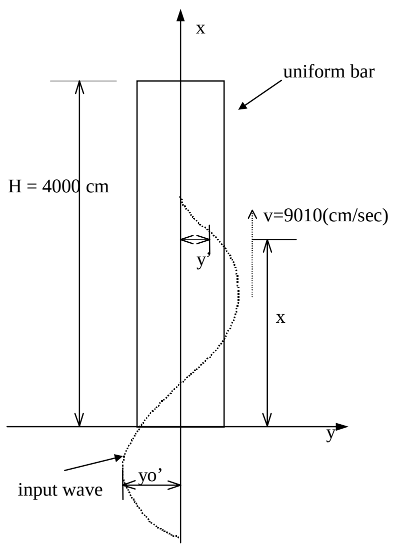


Figure 7: Earthquake ground motion spectrum and the vp-tp relations

APPLICATION TO BUILDING STRUCTURES

3.1 Analysis of idealized 14 stories building

3.1.1 Pulse-response-analysis for uniform bar



Structural properties of the model

Total height : H = 4000 (cm)

Story height : h = 285 (cm)

Yield shear force: Qy = 1,600 (tf)

Shear stiffness : G = 5.33 x 10^{-2} (tf / cm^2)

Density : ρ = 6.56 x 10^{-8} (tf sec^2 / cm^4)

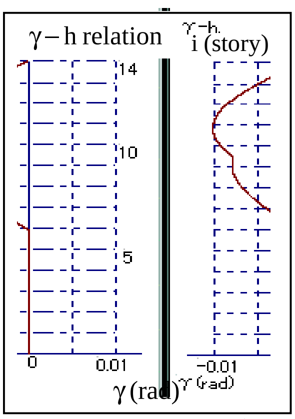
Figure 8: Propagation of shear strain wave

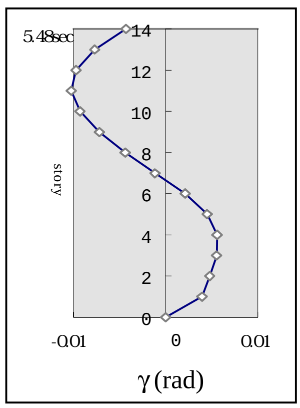
Following are the terms of assumption for the analysis based on wave theory:

1) The system is a shear-type uniform bar; hence no bending nor twisting to be considered.
2) The analysis targets the performance within the elastic range.
3) The structure has uniform weight distribution.
4) The structure has uniform stiffness distribution.

The process of the analysis is to judge the system to be a cantilever of uniform bar (Figure 8). The authors undertake analysis according to the wave theory by the pulse motion input from the foundation, and then identify the disadvantageous response (i.e. whether or not to reach the elastic limit distortion) for the system.

Assuming h=0.2 in JMA Kobe-NS 1995, the ground motion spectrum obtained from the Hyogoken-Nambu Earthquake, what is judged to be input ground motion is the sine wave of 1 cycle having the velocity amplitude Sv =yo' (Figure 2). Following the principle of "select of maximum response", it is required to cover all t and yo' (=Sv) appearing on this spectrum curve. In this study, however, some are dispersively chosen among them according to the situation.





(t=0.45 sec, vp = 74 cm/sec)

Figure 9: Output of wave propagation analysis **Figure 10: Result of time history response analysis**

Figure 9 is the output of shear distortion analysis. Figure 10 shows the strain distribution when any story reaches at the yield distortion point by time history analysis. In this analysis, the story having the yield shear distortion γy=0.01 appears under such condition that the period Tp is 0.25-0.65(sec) or 1.2-1.6(sec) in JMA Kobe-NS

1995, it does not appear in any other conditions. Whereas in the time history analysis, Figure 10 shows the distortion of all the stories of the time when a certain story reaches the yield distortion γy. In this situation, it can be observed that it reaches shear strain of 0.01 first (among other stories) around the10th and 11th stories.

3.1.2 Pulse-response-analysis for single mass system

Regarding the result of the velocity pulse-response-analysis, the case of degrading after yield by 5% type is shown in Table 1 (as the wave reflecting at the top has influence on the middle stories, so analysis is to be undertaken where the amplitude is doubled). The output data of the analysis is less than that of the time history response analysis, i.e. when vp=48.469x2cm/sec (the estimated collapse story is the13th story), and vp=50.933x2cm/sec (the estimated collapse story is the12th story). Apart from that, especially near vp=74.605x2cm/sec (the estimated collapse story is the 11th story) which has the maximum velocity amplitude, the output data is larger than that of the time history response analysis, however, the error is considered to be slightly small.

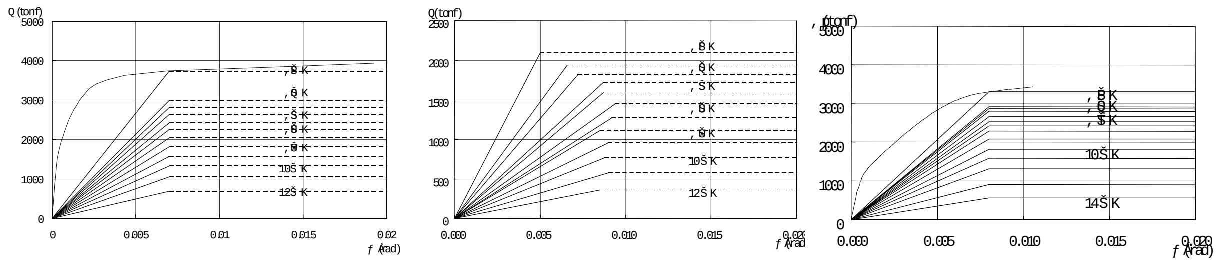
Table 1: Results of pulse-response-analysis for mass system

vp (cm/sec)	collapse story	γp (cm)	time history analysis.(cm)
48.469*2	13	2.232	2.41
50.933*2	12	3.023	3.08
61.968*2	12	3.663	3.08
72.055*2	11	5.951	3.32
74.605*2	11	6.08	3.32
70.789*2	11	5.322	3.32
63.282*2	10	5.603	2.96
54.169*2	10	4.269	2.96
46.851*2	9	4.093	2.64

3.2 Analysis of existing buildings

3.2.1 The outline of the target buildings for verification and the hysteresis characteristics

The buildings targeted to verify the application are two RC middle-high-rise buildings in Chuo-ku, Kobe, which were designed according to former code (before 1981) and damaged at their middle stories. One more building of the similar scale that was designed according to the current design code in Japan is analyzed.



(a) I public house **(b) M building** **(c) H public house**

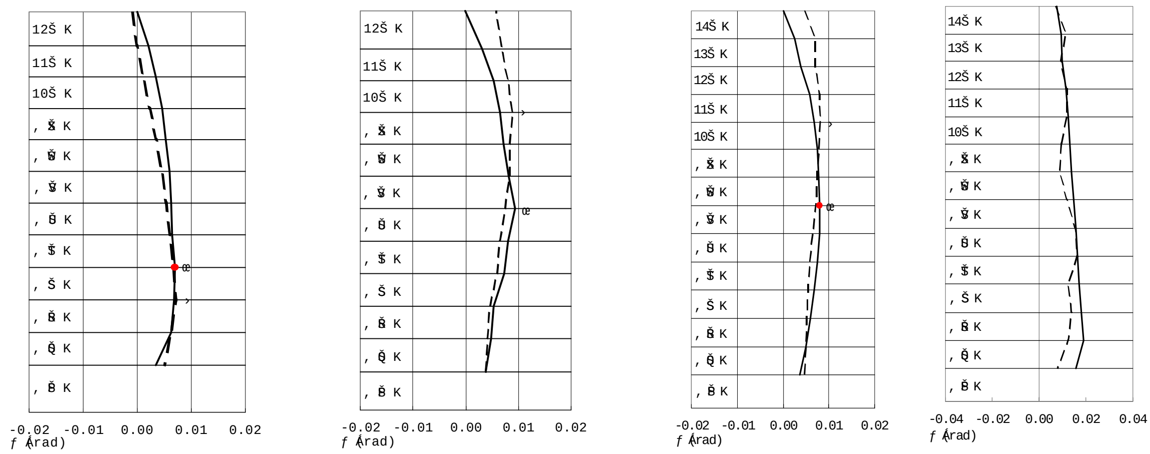
Figure 11: Restoring force characteristics of the building by incremental analysis

The public house “I” was the rental houses, 12 stories, SRC+ RC above 8th story, which was built in 1972 [Utsumi,1996]. The inside steel frames are of tie-plate type. During the Hyogoken-Nambu Earthquake, the stories above the 4th floor collapsed in longitudinal direction. The building “M” is an office building also located in Chuo-ku, Kobe, SRC, 12 stories, constructed before 1981 [Takayama,1996]. During the Hyogoken-Nambu Earthquake, all the 5th floor of this building was fallen down. The Public housing “H” is 14 story, high-rise RC building designed by the current code (after 1981), now under construction. To seek the hysteresis characteristics, the popular software on the market was used, and incremental analysis was undertaken considering the all slab-width to be effective. The turning point of each bi-liniar hysteresis curve refers to the moment of the story-yield (Figures 11(a), (b), (c)). The public house “I” and the building “M” had shear-collapse at many of their columns (or walls) at this moment. Therefore, the yield point is to be ultimate deformation. The public house “H” is considered to be ductile according to the incremental analysis.

3.2.2 Analytical results

Figures 12 (a)-(c) show the analytical results of each building respectively. In the figures (c-1 for the Figure 12), the solid lines show the degree of story deformation in the "wave propagation analysis", and ●s in the figures show the location where they first reach the story yield points. The dotted lines show the results of the time history response analysis of multi-mass system having the input of JMA-KOBE original wave, and the deformations of the moment when a certain story first yields (○) is shown for the purpose of comparison.

The solid lines of Figure 12(c-2) shows the result of "pulse response analysis for mass system". The model of single mass is established as each story, which support the load of its upper stories. The half-wave that accords with the maximum amplitude is replaced with the rectangular wave of the equal value, and then the response deformation amount is calculated according to the vp-tp relationship in Figure 7. Also the dotted line shows the maximum response value of the multi-mass system (analyzed by time history analysis) at the moment of first 1.5 cycle input for comparison.



(a) I public house (b) M building (Bar-model) (c-1) H public house (Mass-model) (c-2) H public house

Figure 12: Analytical results

VERIFICATION

4.1 The relation between the results of the analyses and the actual damage

Considering the analytical results on the public housing "I" (Figure 12(a)), the results of the wave propagation analysis and the time history response are similar, both having the 4th or 3rd floor yields first among other stories. Also they show similar results in terms of the time of the yielding, i.e. 0.8-0.9sec. This time refers to a moment when forward wave of the input pulse (1 cycle sine wave) reflects at the top to be synthesized with backward wave, and reaches the story yield deformation amount at the 4th floor. In the actual damage, half part of the 4th floor collapsed, which can be analyzed that the column of 4th floor was met by the shear collapse in the first hit, and collapsed before the input of the following maximum amplitude wave.

The result of the analysis of the building "M" (Figure 12 (b)) also shows the similar tendency to that of the public housing "I". In the wave response, it reaches the story yield at the 6th floor at 0.8 sec, and in the time history response, it starts to yield at the 9th floor at 0.9 sec. As for the overall deformation distribution, both analyses show the similar results at the stories lower than the 6th floor. As for the actual damage, the whole part of 5th floor was fallen down, whereas the 6th floor, though declined, kept standing without collapse (during the aftermath). Considering these factors, it can be estimated that the fall-down of the 5th floor occurred instantaneously, therefore, it is most likely that the vertical members were fallen down having also the shear collapse at the moment of story collapse. The public housing "H" is the high rise RC structure which was designed by the current code (after 1981). However, according to the result shown in Figure 12(c-1), the 7th story yields first due to the 1st pulse of JMA-Kobe (NB: 10F in the time history response analysis). This building had enough ductility to support the resistance even if it is met by the story yield. This being said, Figure 12(c-2) shows the calculation to trade the extent of the deformation caused by the pulse wave with the maximum amplitude which follows the first wave. According to the result, it is verified that the 2nd story reaches close to the story drift angle 1/50. As for the overall deformation, it does not differ much from the time history analysis (dotted lines in the figure).

4.2 Applicability of the wave propagation analysis

Tracing the transmission of velocity pulse wave input to the building, it repeats reflection at the top and foundation of the building even if the input wave has 1 cycle, and the wave pulse synthesized gives the bigger amplitude.

Whether or not it reaches the story yield in pulse response analysis can be estimated according to the equation (6). Since the maximum value in equation (6) is " γ max = Vp max / v mean", if input v mean = $\sqrt{(G/\rho)}$, γ max = Vp max / $\sqrt{(G/\rho)}$. Supposing (input) Vp = 100cm/sec, Vp max is possible to become double the (input) Vp, 200cm/sec by one reflection at the top. Checking the equation γ max = δ y / h = 250 / $\sqrt{(G/\rho)}$, for the normal RC structure, $\sqrt{(G/\rho)}$ ranges 10,000 - 20,000 cm/sec, and assuming 10,000cm/sec, the maximum story deformation angle (γ max) becomes over 200/10,000=1/50. So, it is said that when the structure has the story yield angle of 1/50 (rad.) or more, it may not yield by input of 100cm/sec pulse.

CONCLUSION

As the measures against the near source region earthquake, the seismic design method using the pulse-response-analysis is presented, applied to the buildings damaged by the Hyogoken-Nambu Earthquake in 1995, and verified quantitatively. In the process of verification, the multi-mass time history analysis is also employed for the purpose of comparison. As a result, it has been verified that the reason for the middle story collapse is biggest possible when subject to "amplitude increase by reflection" at the relatively initial stage caused by the velocity pulse wave which is characterized in the near-source earthquake. That phenomena can easily be simulated according to the wave propagation analysis shown in this paper.

Also, it has been verified that even for the building having been designed according to the current code in Japan, there is the possibility of the similar middle story collapse.

The method of pulse-seismic-design presented in this paper is more simple than conventional design methods, and is effective for the visual and instinctive judgment on the seismic safety.

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