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# Evaluation of NBCC 1990 seismic force reduction factors

W.K. Tso[I] and N. Naumoski[II]


## ABSTRACT

The seismic force reduction factors proposed in the seismic provisions of the National Building Code of Canada 1990 (NBCC 1990) are examined using ground motion records from two recent Canadian earthquakes. The displacement ductility demands are analyzed for structural systems with different ductility capacity. It is found that the NBCC 1990 force reduction factors, which are period independent, lead to a very high ductility demand for short period structural systems. To avoid this, two types of period dependent force reduction factor for short period structures are investigated. The results show that the linearly varying period dependent reduction factor represents a viable means to resolve the high ductility problems associated with short period structural systems.


## INTRODUCTION

For economic reasons, the design strength specified in building codes to allow for the effect of earthquake motions is considerably smaller than the strength demand of the structure if it remains elastic. Therefore, structures so designed are expected to be deformed into the inelastic range when subjected to strong ground shaking. The permissible level of the strength reduction from elastic strength in codes is based on, among other considerations, observation of the seismic performance of structures during major earthquakes. In general, a larger strength reduction is permitted for structural systems capable of sustaining larger inelastic deformation without failure. One important task in seismic code specification is to ensure that the minimum specified strength is not reduced far in excess from the elastic strength in the sense that the resulting ductility demand of the structure when subjected to the design ground motions does not exceed its ductility capacity. This implies that evaluation should be carried out on the base shear specification of the building codes.

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I Professor, Department of Civil Engineering and Engineering Mechanics, McMaster University, Hamilton, Ontario, Canada, L8S 4L7

II Research Engineer, Department of Civil Engineering and Engineering Mechanics, McMaster University, Hamilton, Ontario, Canada, L8S 4L7

In this paper, an attempt is made to evaluate the base shear expression of the Canadian seismic code provision (Section 4.1.9, NBCC 1990) (Associate Committee on the National Building Code 1990). There are three reasons that an evaluation is appropriate at this time. First, unlike the previous edition, the seismic design strength in NBCC 1990 is explicitly expressed in terms of the elastic strength. In other words, the reduction factor R*, defined as the ratio of elastic strength to actual strength, can be obtained from the Code without ambiguity. Second, ground motion records are now available from two strong earthquakes recently occurred in Canada, which can be used as representative input for this evaluation. Third, the design and detailing requirements for the different structural systems covered in NBCC 1990 are much more specific than in the previous edition of NBCC. Each structural system mentioned in the code has to be designed and detailed according to the requirements of the current Canadian material design codes and standards. In other words, this is a direct linking between the seismic loading on one hand, and detailing requirements on the other, for each of the structural systems covered.

## STRUCTURAL MODEL AND DESIGN STRENGTH SPECIFICATION

For buildings in the short to moderate period range, the higher modal contributions to the base shear are not significant and the major seismic response is from the fundamental mode. Single-degree-of-freedom (SDOF) systems are convenient structural model representations for these buildings, and they are used as structural models in this study.

The yield strengths of the SDOF systems are specified based on the base shear provision of the NBCC 1990. The minimum base shear, V, for a building structure is given as

$$V = (V_e/R)U \qquad (1)$$

where $V_e$ is the equivalent lateral seismic force representing elastic response. R is a force modification factor with assigned values between 1 for nonductile structural systems, to 4 for ductile structural systems. U is a factor representing a level of protection based on experience, with an assigned value of 0.6. To understand the implication of Eq.1 it is useful to rearrange it in the following form:

$$V(1/U) = V_e/R \qquad (2)$$

The factor (1/U) can be considered as an overstrength factor. It has been observed that buildings designed using a base shear value of V have a lateral strength that is substantially higher than V. The factors that contribute to the overstrength include the higher material strength realised than the nominal values specified in design, the many nominal or minimum design requirements in material codes irrespective of strength demand, the contributions to the lateral strength of elements such as stair and floor slabs, and the force redistribution effect due to the redundancy of most structural systems. The product of the base shear V and the overstrength factor (1/U) leads to an estimate of the actual lateral strength of the building. Equation 2 simply states that the actual lateral strength of the building should be equal to the elastic strength demand $V_e$, reduced by a factor R which is a function of the ductility capacity of the structural system concerned.

Since the reduction factor $R^*$ is defined as the ratio of elastic strength to actual strength, according to NBCC 1990,

$$R^* = R^*_{90} = R \qquad (3)$$

The subscript 90 denotes the reduction factor based on NBCC 1990. Since $R^*_{90}$ depends on the structural system only, and is not a function of the period of the building, the reduction factor adopted by NBCC 1990 is period independent.

The yield strength $F_y$ of the SDOF systems is taken equal to the actual strength, namely

$$F_y = V/U = V_e/R \qquad (4)$$

The equivalent elastic lateral seismic force, $V_e$, is specified as

$$V_e = vSIFW \qquad (5)$$

where, v is the zonal velocity ratio, S is the seismic response factor, I is the importance factor, F is the foundation factor, and W is the dead load. The zonal velocity ratio, "v", is defined as the ratio of the horizontal ground velocity to a reference velocity of 1 m/sec. In this study, "v" is taken as 0.2 in the strength calculation and all input ground motion records in the calculation are scaled to a peak ground velocity of 0.2 m/sec. For a rock site (F=1) and building of normal importance (I=1), the yield strength of the SDOF system model becomes

$$F_y = 0.2\ SW/R \qquad (6)$$

The responses of three classes of structural systems are studied, having an R value equal to 4, 3, and 2. The more ductile structural systems with specified R values of 4 and 3, are modelled by SDOF systems having bilinear hysteretic force displacement relationship. The strain hardening stiffness of the system is taken to be 3% of the initial stiffness. The less ductile systems with an R value of 2, are represented by SDOF systems having a stiffness degrading hysteretic behaviour. Among a number of available stiffness degrading models, the Q-hysteretic model is adopted in this study. For all structural models, a 5% critical viscous damping is assigned to each SDOF system to represent other non-hysteretic form of energy dissipation during the earthquake shaking.

## GROUND MOTION INPUT

The two sets of strong ground motion records available from two recent Canadian earthquakes are used as input. The first set was obtained in 1985 from the earthquakes which occurred in the North Nahanni river area of the North Western Territories of Canada. Six records (12 horizontal components) were recorded on rock sites from four earthquakes, with the strongest earthquake of magnitude $M_s$ = 6.9. The records are characterized by extremely high peak acceleration, A, to peak velocity ,V, (A/V) ratios, which range from 1.2 to 10 (Heidebrecht and Naumoski 1988).

The second set of records was obtained from the 1988 Saguenay earthquake of magnitude $M_s$ = 5.7 which occurred in the province of Quebec. Ten records (19 horizontal components) were recorded on rock sites during this earthquake at epicentral distances between 36 and 177 km. The records also have high A/V ratios which range from 1.62 to 9.68 (Tso and Naumoski 1990).

Figure 1 shows comparison of the 5% damped mean acceleration response spectra of the Nahanni and Saguenay earthquake records with the $Z_a>Z_v$ branch of the seismic response factor S used in NBCC 1990, all scaled to peak ground velocity of 0.2m/sec. This comparison is meaningful because the $Z_a>Z_v$ branch of the seismic response factor is recommended for regions where seismic ground motions are expected to contain major energy in the short period range. The mean spectra of both sets of records far exceed the $Z_a>Z_v$ branch of the seismic response factor in the short period range.

## EVALUATION OF THE FORCE REDUCTION FACTORS

Since all input motions have high A/V ratio, and have their energy in the short period range, they are considered to be representative of ground motions that may occur in regions where $Z_a>Z_v$ in the Canadian seismic zoning maps (NBCC 1990). To be consistent, the strength of the SDOF systems used are calculated using the $Z_a>Z_v$ branch of the S curve. The mean displacement ductility demands for the three classes of structural systems having R=2, 3 and 4, subjected to the Nahanni and the Saguenay set of records are shown in Fig. 2. For all three classes of structural systems, the ductility demand decreases with increase of structural period. In view of the mean elastic response spectra of these two earthquakes as shown in Fig. 1, such a trend can be expected. Of more concern is the very high ductility demand of short period (say < 0.3 sec) structures, exhibited in all these plots.

Using mostly earthquake records from California to evaluate the inelastic responses of SDOF systems, the studies by Blume (1970) and Newmark and Hall (1973, 1982) showed that the overall ductility demand bears a simple relationship to the reduction factor, as can be expressed by

$$\mu \approx R^* \tag{7}$$

In other words, the ductility demand of the system is similar in value to the reduction factor used to specify the strength of the system. This relationship provides an important link between the design strength on one hand, and the maximum inelastic deformation demand on the other. In NBCC 1990, $R^*_{90}$=R. Therefore, this simple relationship can be represented by the line μ=R shown in each of the ductility demand plots. It can be seen that the ductility demand of short period buildings designed based on NBCC 1990 is much higher than that implied by Eq.7. Such high ductility demand may be beyond the ductility capacity of the structural systems. One alternative to reduce this very high ductility demand for short period structures is to cut down the reduction in strength from elastic strength for short period structures by adopting a period dependent reduction factor.

## PERIOD DEPENDENT FORCE REDUCTION FACTOR

To reduce the high ductility demand for short period structures, two forms of period dependent reduction factor will be considered herein. The first form is that proposed by Newmark and Hall (1973, 1982). If R is the value of the reduction factor for medium and long period structures, their concept of period dependent reduction factor, denoted by $R^*_{N\text{-}H}$ in this paper, can be written as

$$
\begin{aligned}
R^*_{N\text{-}H} &= R && \text{for } T > 0.5 \text{ sec} \\
&= \sqrt{2R-1} && \text{for } 0.125 < T < 0.5 \text{ sec}
\end{aligned}
\qquad (8)
$$

and $R^*_{N\text{-}H}$ varies linearly from unity to a value of $\sqrt{2R-1}$ when T varies between 0.03 and 0.125 sec.

The second form of reduction factor is the linearly varying period dependent reduction factor, $R^*_L$. It takes the value of R for period longer than 0.5 sec. For period below 0.5 sec, it decreases linearly as the period decreases from 0.5 sec and has a value of unity at T=0 (rigid structure). Mathematically, it can be written as

$$
\begin{aligned}
R^*_L &= R && \text{for } T > 0.5 \text{ sec,} \\
&= 1+(R-1)T/0.5 && \text{for } 0 < T \leq 0.5 \text{ sec.}
\end{aligned}
\qquad (9)
$$

This form of reduction - period variation is similar to that proposed by Berrill et al. (1980). The period dependency of these two forms of reduction factor together with the period independent reduction factor $R^*_{90}$, is graphically illustrated in Fig. 3.

The mean ductility demands of SDOF systems designed based on the three forms of reduction factor $R^*$, subjected to the set of scaled ground motion records from the Saguenay earthquake are shown in Fig. 4. The plots represent ductility demands of structural systems designed corresponding to R=2, 3, and 4. The horizontal line representing the simple relationship $\mu = R$ is included in each of the plots. The Newmark-Hall type of period dependent reduction factor leads to some reduction of ductility demand from that associated with the period independent reduction factor. However, only the linearly varying period dependent reduction factor $R^*_L$ leads to ductility demand which is below R for ductile structural systems (R=3 or 4), and slightly over R for systems with nominal ductility (R=2) in the very short period range.

The ductility demand of SDOF systems designed based on the linearly varying reduction factor when subjected to the set of ground records from the Nahanni earthquake follows a similar trend, as shown in Fig. 5. Therefore, the linear reduction factor $R^*_L$ represents a viable means to resolve the high ductility demand problems associated with short period structural systems, when their strength is designed based on NBCC 1990.

## CONCLUSIONS

For many short period structures which are designed with some ductility reserve, and hence are allowed to have lower strengths than the specified elastic strengths, it is shown in the present study that they may be exposed to a very high level of ductility demand if the reduction factor used is period independent, as exemplified by $R^*_{90}$. It is shown that the period dependent reduction factor, and in particular, the linearly varying period dependent reduction factor $R^*_L$ represents a viable means to resolve the high ductility problems associated with short period structural systems. Using available Canadian earthquake records and realistic modelling of ductile systems, it is shown herein that $R^*_L$ reduces the ductility demand of short period structures to such a level that the maximum ductility demand $\mu$ is approximately equal to the R factor in NBCC 1990. With this reduction factor, the ductility demand for buildings of all periods can be estimated using the relation $\mu$=R.

This paper is focused on the evaluation of the reduction factors of NBCC 1990 for regions where $Z_a > Z_v$. Presently, it is not possible to carry out similar evaluation for other seismic regions where $Z_a = Z_v$, or $Z_a < Z_v$ because there are no strong motion records from Canadian earthquakes to provide appropriate excitation for such evaluation.

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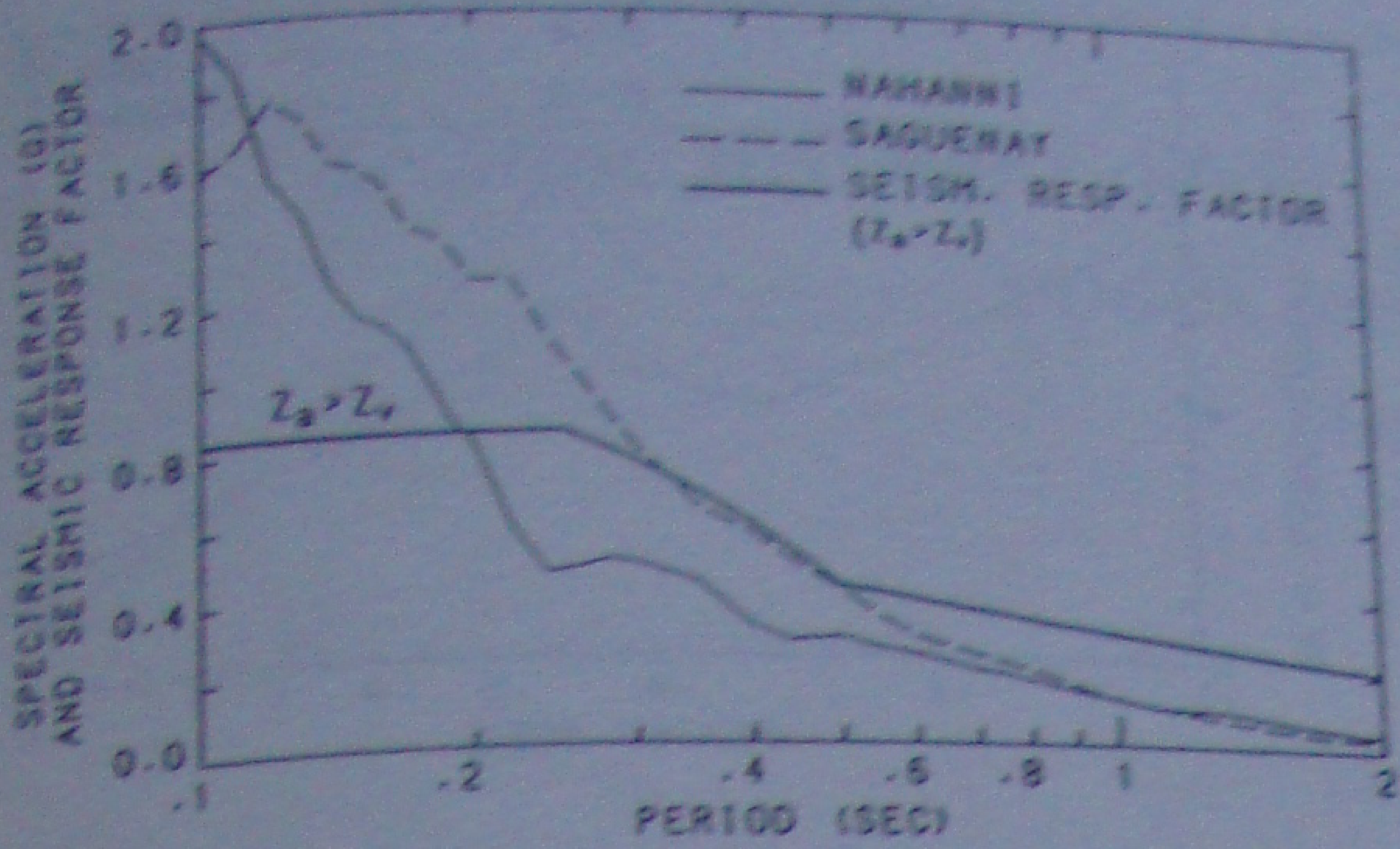


Figure 1. Comparison of the mean spectra of the Nahanni and Saguenay earthquake records with the $Z_a>Z_v$ branch of the seismic response factor; V = 0.2 m/s, 5% damping

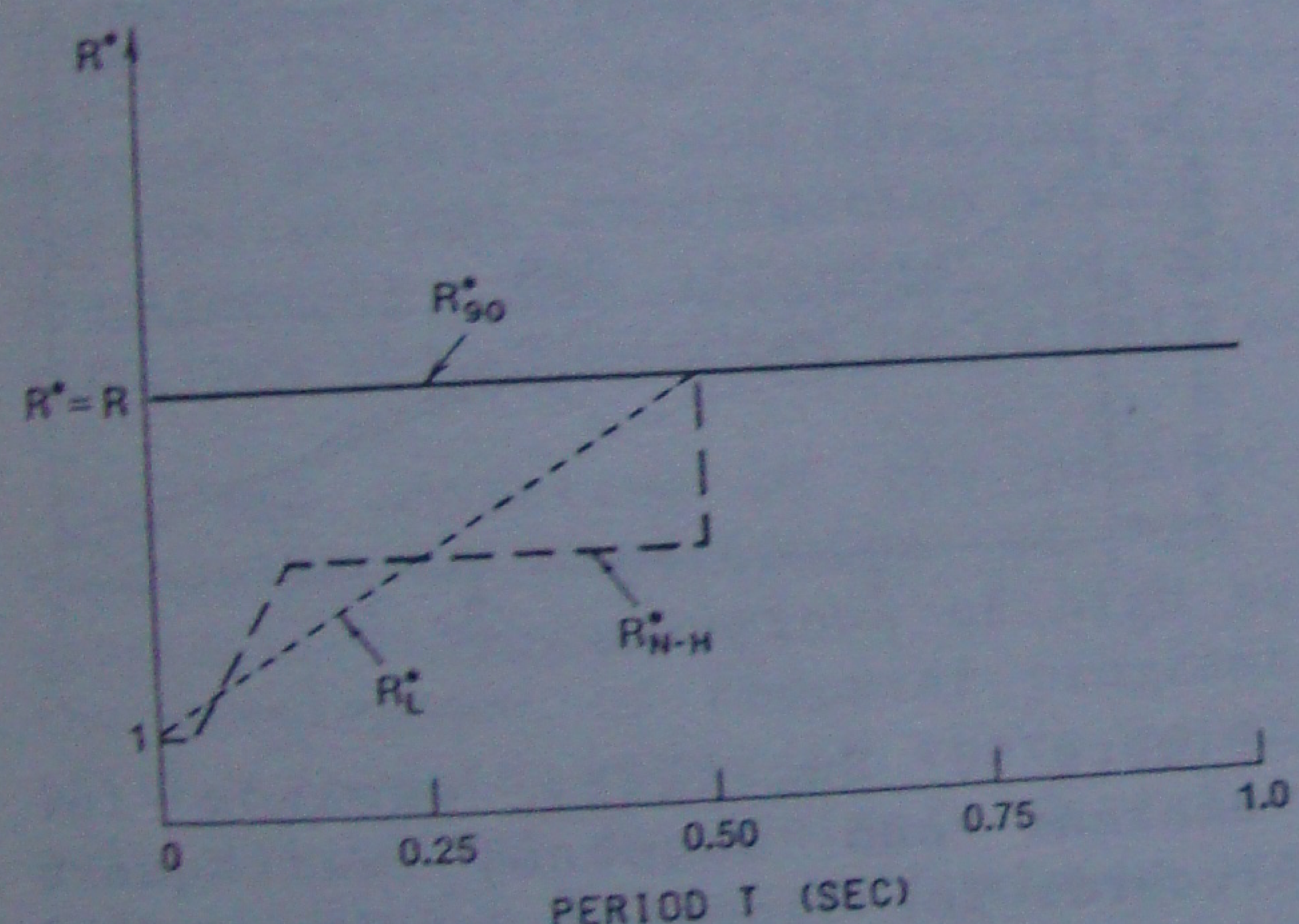


Figure 3. Period dependency of different types of reduction factor

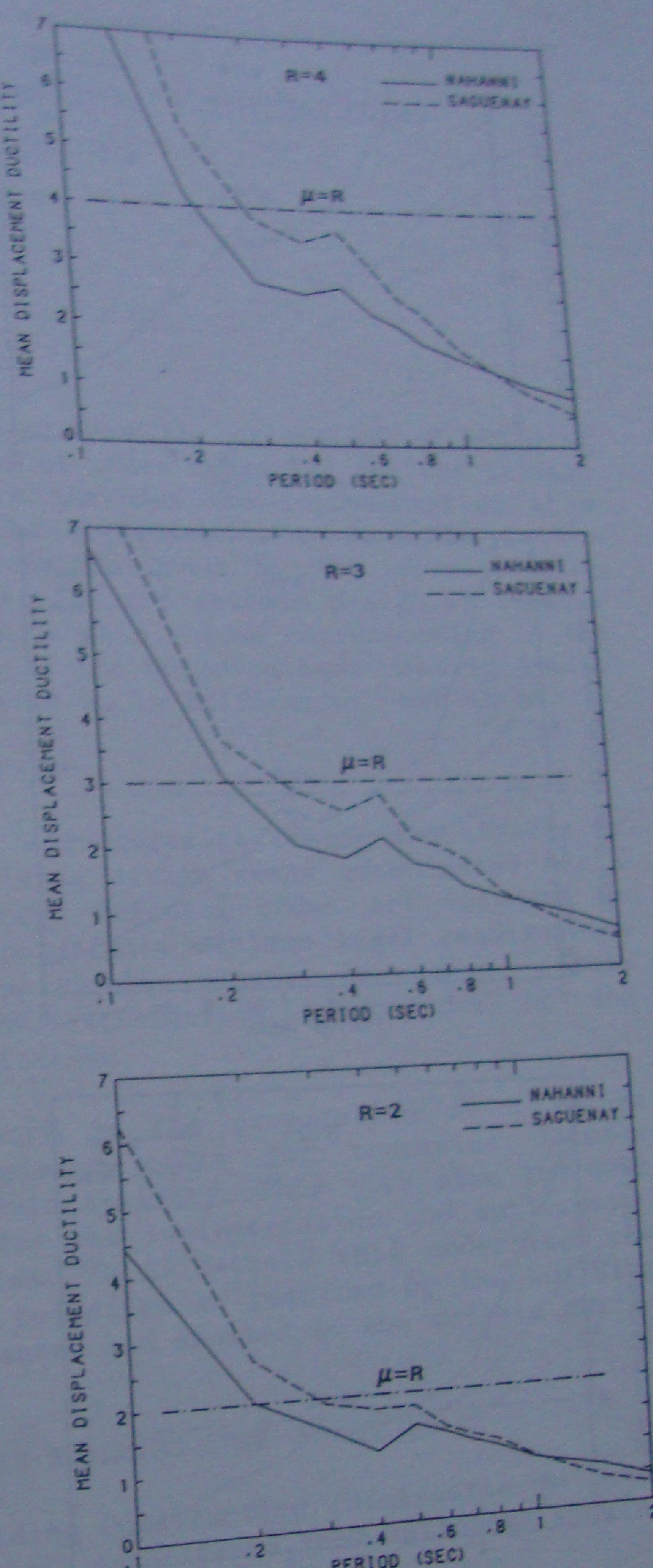


Figure 2. Ductility demands for Nahanni and Saguenay earthquake records for period independent reduction factors as specified in NBCC 1990

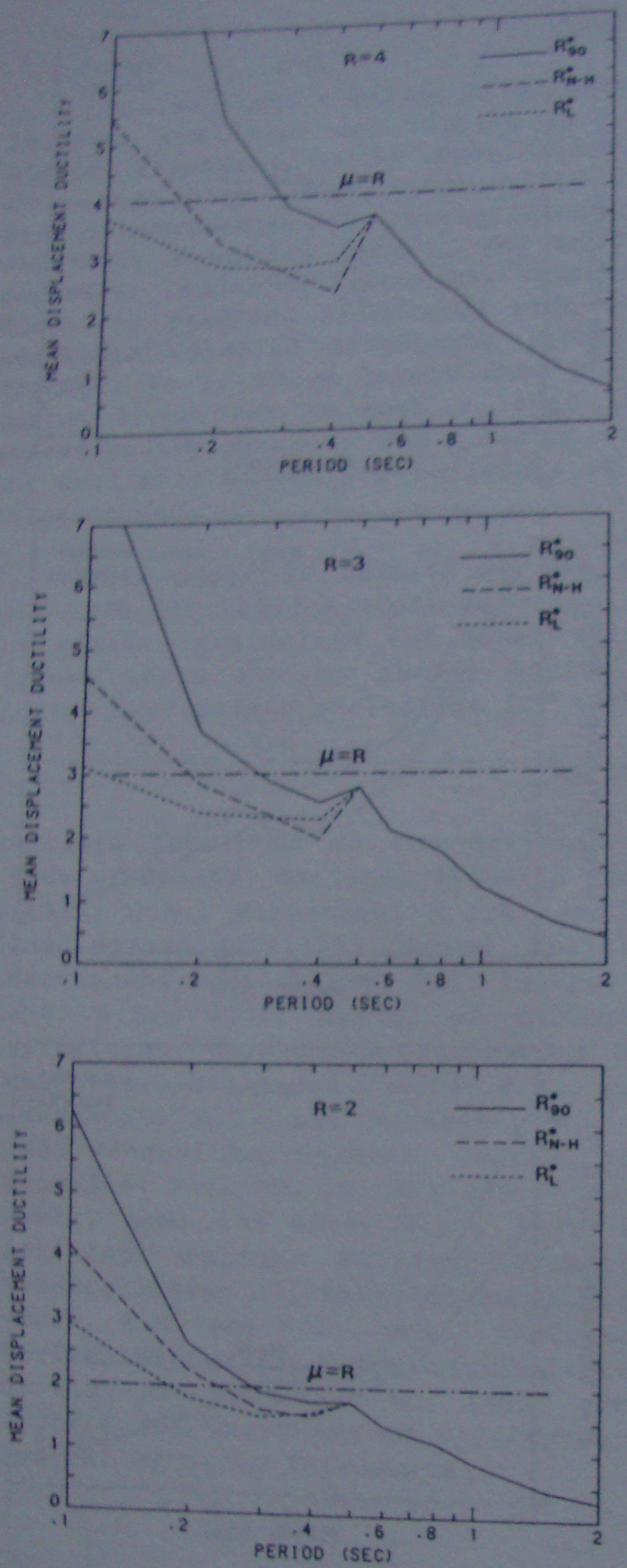


Figure 4. Ductility demands for Saguenay earthquake records for different types of reduction factor

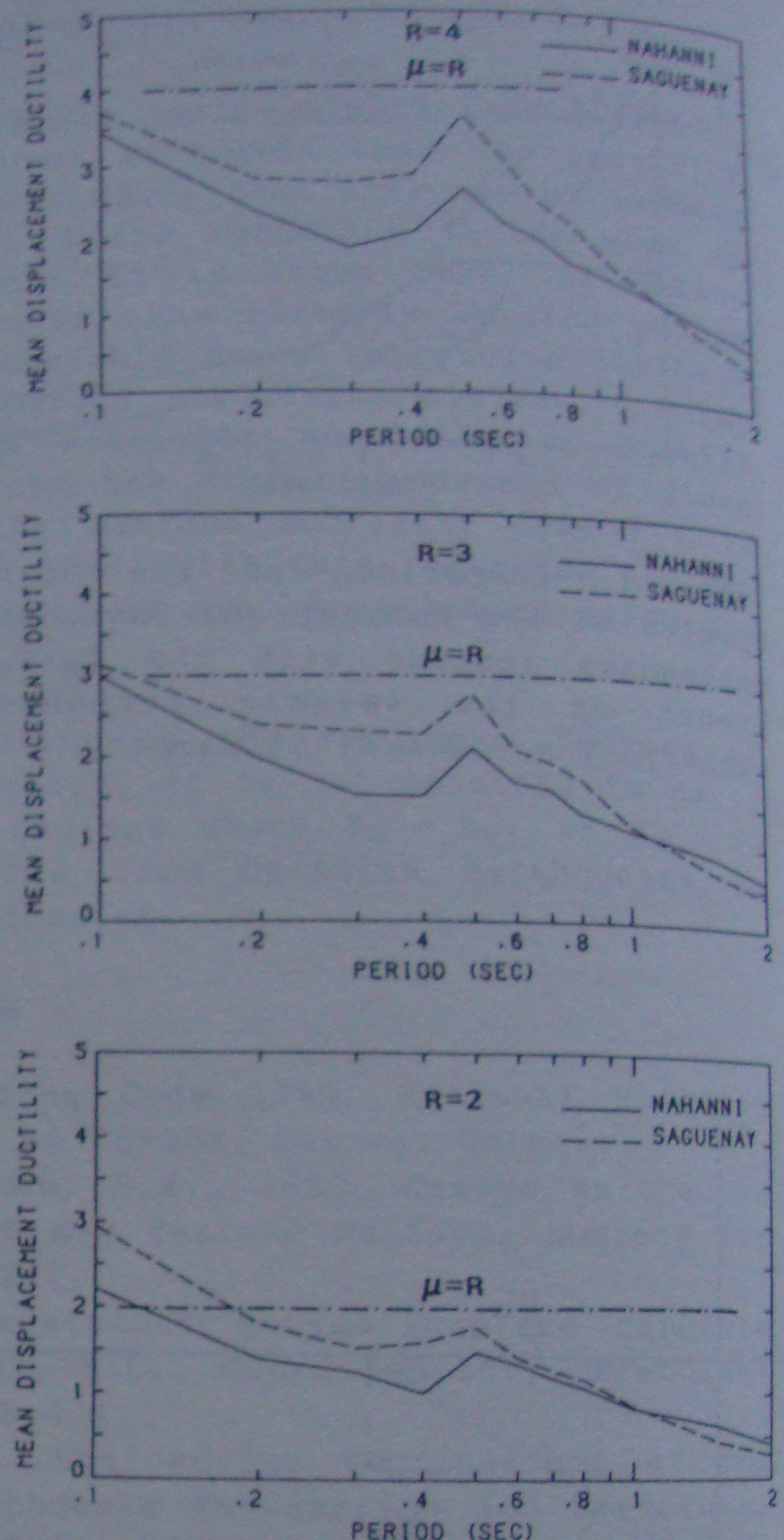


Figure 5. Ductility demands for Nahanni and Saguenay earthquake records for linearly varying period dependent reduction factor