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SEISMIC RESPONSE OF ALLUVIAL VALLEYS

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ABSTRACT

A simple shape is used to approximate the irregular interface of alluvial valleys. An approximate numerical method is proposed to carry out the parametric study in order to determine the range within which there appears big difference between two-dimensional and one-dimensional wave motions, which is defined as that there is heterogeneity of alluvial valleys. Formulation of the heterogeneity is carried out in the determined ranges, and a heterogeneity index, which is defined as the response spectral ratio of two-dimensional wave motion to one-dimensional wave motion, is proposed to consider the effect of heterogeneity. The index is proposed to be directly encoded into the current seismic design code to consider the effect of heterogeneity of alluvial valleys.

KEYWORDS

Heterogeneity; heterogeneity index; seismic wave motion; alluvial valleys; seismic response, seismic design, approximate numerical method.

INTRODUCTION

With the massive accumulation of seismic records and the development of numerical methods, the effect of heterogeneous underground interface on seismic wave motion has become one of the major research subjects in earthquake engineering. This effect has been observed repeatedly during the damage investigation of past earthquakes. Whereas, this effect has been totally ignored in the current seismic design code due to many reasons. One of the reasons has been that this effect is quite difficult to quantity, and another has been that there does not exist a synthetic parameter which can be used to quantify this effect. In order to quantify this effect, we first propose a simple numerical method to calculate the two-dimensional wave motion inside an alluvial valley. Second, we propose an index, which is the response spectral ratio two-dimensional wave motion to one-dimensional wave motion and defined as the heterogeneity index in this study, to approximate the effect of heterogeneous effect of alluvial valleys. Third, a great amount of parametrical study is carried out to quantify this index. Finally, a simple methodology is proposed to encode this effect into the current seismic design code.

A SIMPLE ANALYTICAL METHOD

A large number of numerical methods have been proposed to calculate the seismic wave motions inside alluvial valleys(Takenaka, 1993). The emphasis of almost all these methods has been on the accuracy of the numerical results, while the speed and simplicity of the method, which are two important factors to be considered in engineering, have been ignored, which result in the difficulty in massive amount of calculation encountered in parametrical study. In order to carry out the massive amount of calculation, a simple numerical method is proposed by the author (Wang, 1994) based on the improvement of an analytical method proposed by Aki and Larner (1970). A brief description of the method can be summarized as the following. The wave motion inside an alluvial valley is approximated as the summation of harmonic waves with unknown amplitudes. A least square method is used to find out the unknown amplitudes by matching the stress and displacement continuity conditions at the surface and interface between layers. A transmitting boundary (Liao and Wong, 1984) is applied at the boundary of the numerical model of calculation, which eliminates the non-practical assumption made in the original method by Aki and Larner, which is that the real space should be considered as an infinite repetition of the numerical model for the calculation. The elimination of this assumption leads to the following simplification of the numerical method. The number of unknown amplitudes is not restricted by the size of the numerical model, neither by the frequency of the wave motion. Therefore, the number of unknown amplitudes can be chosen so that a predetermined accuracy criterion (say, 1%) is met. A number of comparisons of the numerical results by the proposed method with those by other numerical methods have been finished to validate the efficiency of the proposed method, which verify that the number of unknown amplitudes can be chosen between 20~30 even at high frequency domain (Wang, 1993, 1994). Numerical comparisons have also demonstrated that the proposed method only takes about one fifth of the CPU time by the original method.

HETEROGENEOUS AREA

Definition of Heterogeneous Area

For the simplicity of the analysis, we only take one layer and assume that the shape of an alluvial valley can be generally depicted by Fig.1. Our first step is to determine the areas where there appears big difference between the motions calculated by one-dimensional method (1-D motion) and the two-dimensional method proposed by the author (2-D motion). Even with a model like the one shown in Fig.1, the number of parameters which could potentially influence the two-dimensional result is so big that it is impossible to consider all the parameters. Whereas, the following parameters are genearlly considered much more important than others, which should be considered in the study. They include 1) the relative depth of the valley, H/R, where H is the depth of the valley, R is the half width of the valley, 2) the relative length of the inclining portion, W_L/R, where W_L is the length of the left inclining portion, 3) impedance ratio of the valley, $\alpha = \frac{\rho_1 c_1}{\rho_2 c_2}$, where ρ is the density, c is the shear wave velocity, subscripts 1 and 2 are for upper and lower layer, respectively, 4) relative distance from the center of the valley, X/R, where X is the distance from the center of the valley. Based on the shape of alluvial valley in reality, we assume the ranges for the above parameter to be as: 1) H/R: 0.01~0.50, 2) α : 1/2~1/12, 3) W_L/R: 0.1~1.0. The range of X/R will be constrained to the area where there appears big difference between 1-D and 2-D motion. This area is called " heterogeneous area" in this study.

In order to define the heterogeneous area, we set up three criteria: 1) the difference of area below transfer function is above 10% in the frequency range of (0~5)f_1 (where f_1 is the 1-D predominant frequency at the center of the valley), 2) the difference of predominant frequency for 1-D and 2-D motion is above 10%, 3) difference of 1-D and 2-D transfer functions is above 15% at more than 50% of all the points where transfer function is calculated. Based on the above criteria, we define that the area which satisfies all the above three criteria is called heterogeneous area (shown as area 1 in Fig.1 and 2-a) of Fig.2), area which satisfies none of the above criteria is shown as area 3 of Fig.1 and 2-c) of Fig. 2, which needs no further study, area which satisfies one and/or two of the above three criteria is shown as area 2 of Fig.1 and 2-b) of Fig. 2 where there is heterogeneity, but not as big as in area 1, which will not be considered in this study.

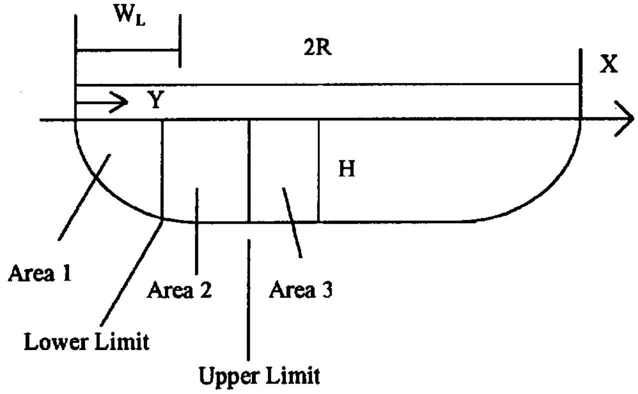
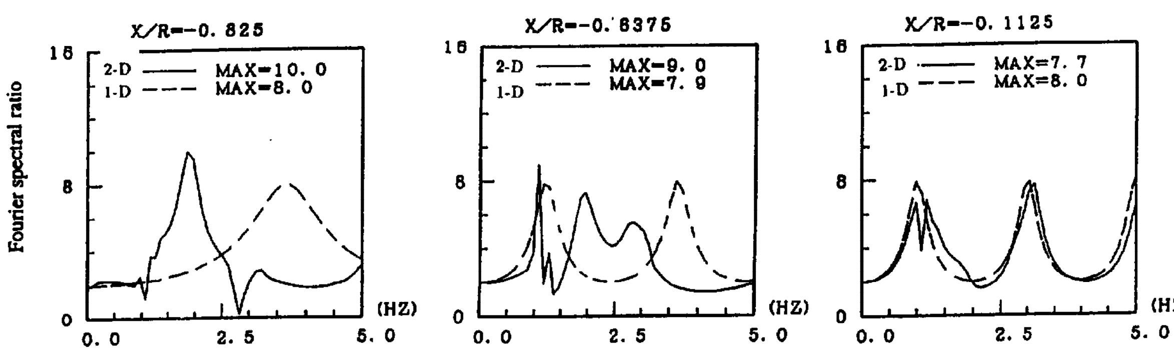


Fig. 1 A model for soft alluvial valleys

There are cases where H/R is big enough so that all the valley become heterogeneous area, a phenomena also observed by Bard and Bouchon (1985) in their study of the change of wave motion amplitude inside sediment-filled valleys. We define this H/R as critical shape ratio for the valley, which is found to be only a function of impedance ratio, depicted as (Wang, 1984)

$$(H/R)_{cr} = \frac{1.02\alpha}{1.62\alpha + 0.28} \tag{1}$$



2-a) Big difference   2-b) Some difference   2-c) Little difference

Fig. 2 Transfer functions for a valley of H/R=0.1, W_L/R=0.5, α=1/4

Determination of Heterogeneous Area

In order to determine the actual range of heterogeneous area, two terms need to be firstly defined. One is the upper-limit of the heterogeneous area, which is the boundary of area 2 and 3 in Fig.1, expressed by relative distance $(Y/R)_U$, where Y is the distance from the end of the valley. This implicates that when Y/R is bigger than $(Y/R)_U$, there is no heterogeneity. The other term is called lower-limit of the heterogeneous area, which is the boundary of area 1 and area 2, expressed by $(Y/R)_L$. This implies that Y/R below $(Y/R)_L$ is the area we need to study. From a large number of numerical results as those shown in Fig.2, we can read $(Y/R)_U$ and $(Y/R)_L$, which are plotted in Fig. 4 and 3, respectively. The horizontal axis is the relative depth divided by critical shape ratio of the valley, because when H/R is over $(H/R)_{cr}$, all the valley becomes the heterogeneous area. Empirical formula are found to fit the data shown in Fig. 4 and 3, which are

$$\left(\frac{Y}{R}\right)_U = 0.00 + 0.72\frac{W_L}{R} + \sin\left(\frac{(H/R)\pi}{2(H/R)_{cr}}\right); \quad \left(\frac{Y}{R}\right)_U \le 1.0 \tag{2}$$

$$\left(\frac{Y}{R}\right)_L = 0.02 + 0.55\frac{W_L}{R} + 0.47\left(\frac{(H/R)}{(H/R)_{cr}}\right)^2; \quad \left(\frac{Y}{R}\right)_L \le 1.0; \quad \left(\frac{Y}{R}\right)_L \le \left(\frac{Y}{R}\right)_U \tag{3}$$

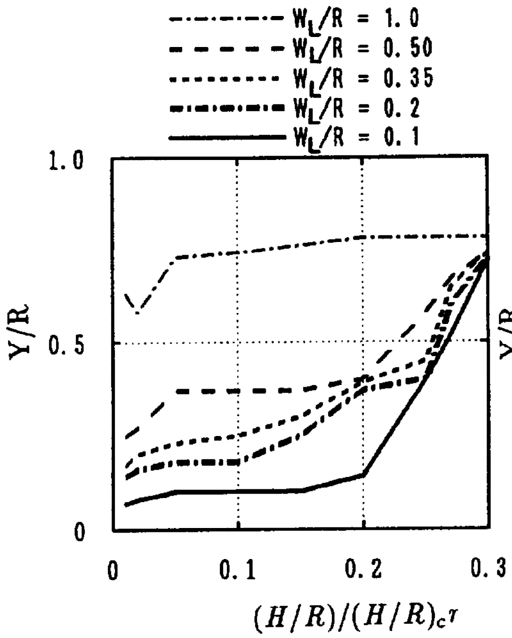


Fig. 3 Lower limit $(Y/R)_L$

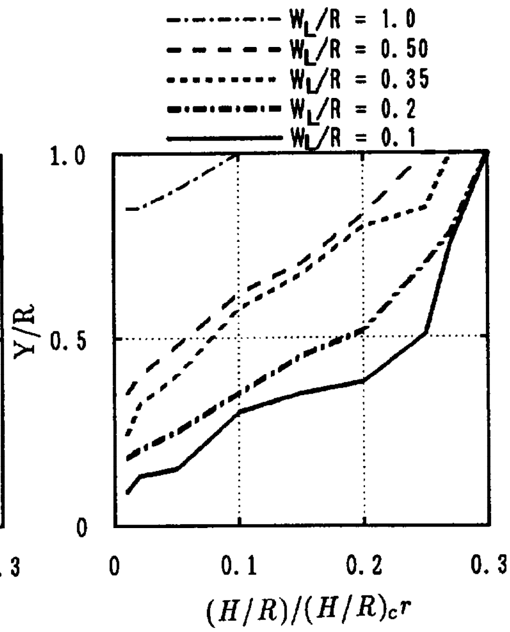
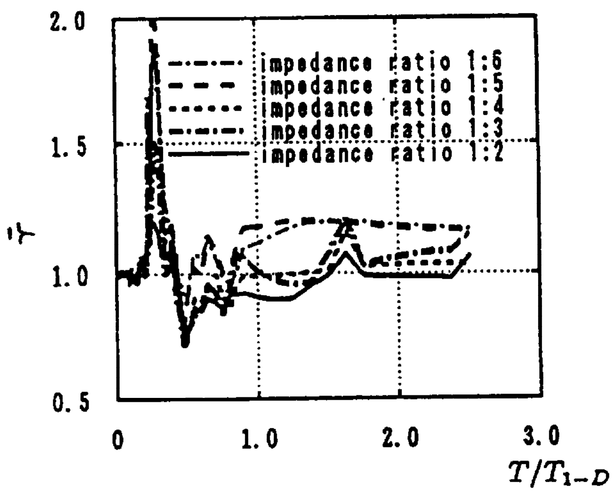


Fig. 4 Upper limit $(Y/R)_U$

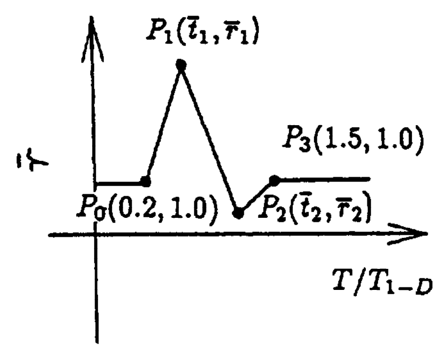
HETEROGENEITY INDEX

Formulation of Heterogeneity Index

Heterogeneity index is defined, in this study, as the response spectral ratio of 2-D wave motion to 1-D wave motion. A damping ratio of 5% is taken into account in the response spectrum calculation. The NS component of the ground motion recorded at El Centro is used as the input ground motion (further study demonstrated that input ground motion has little effect on the heterogeneity index). In order to maintain the generality of the result, the natural period is normalized by the predominant period of 1-D motion at the center of the valley, which is shown as $\bar{t} = T_{2\text{-}D} / T_{1\text{-}D}$. The effect of the parameters on heterogeneity index is summarized as following. 1) The index is almost proportional to the impedance ratio; 2) the effect of H/R can be generally divided into 3 groups (H/R=0.01~0.05, 0.10~0.20, 0.25~0.30), within each group, there seems to be little difference of the index caused by the change of H/R; 3) the effect of W_L/R can be eliminated in the following way. At the point with same depth, the index does not change even when W_L/R changes. Therefore, W_L/R is fixed to 0.5 in this study. Effect of other W_L/R values can be considered by changing the value of Y/R to match the depth at the point of consideration. Further explanation will be given in the following section of this study.



5-a) Calculated result of the index



5-b) General shape of the index

Fig. 5 Heterogeneity index

The H/R group of 0.01~0.05 is taken as an example to formulate the heterogeneity index. A typical result of the calculated heterogeneity index is shown in Fig.5-a). A large amount of calculation shows that the shape of the index does not change much even though the input parameters are changed. The shape can be generally expressed by the one shown in Fig.5-b). The horizontal axis of Fig. 5 is the normalized natural period $\bar{t}$ and the vertical axis is the heterogeneity index, which is expressed as $\bar{r}$ in this study. Calculation of the index demonstrates that even when all the parameters are changes, the only change in this shape is the position of point P_1 and P_2, while the position of P_0 and P_3 seldom changes, which is fixed at (0.2, 1.0) and (1.5,1.0), respectively. The reason for this phenomenon is that at the range which is far from the predominant period, the amplification of the valley becomes so small that the effect of heterogeneity can not appear to be large. But in the period range which is near the predominant period, the amplification becomes large, the effect of heterogeneity can appear as large as it could be. Therefore, the remaining problem is how to define the two points, P_1 and P_2. The coordinates of P_1 and P_2 are defined as $(\bar{r}_i, \bar{t}_i)$ $(i = 1,2)$. Reading of $\bar{t}_i$ $(i = 1,2)$ from the calculated heterogeneity index is shown in Fig. 6, which shows no effect from other parameters, except Y/R. It is understood from this figure that $\bar{t}_i$ $(i = 1,2)$ increases with the increase of Y/R, but the ratio of $\bar{t}_1 / \bar{t}_2$ is almost a constant. An empirical approximate formula for Fig. 6 can be expressed by

$$\bar{t}_2 = 0.88 + 0.31\frac{Y}{R}; \quad \bar{t}_1 / \bar{t}_2 = 0.45 \tag{4}$$

The estimated $\bar{t}_2$ by the above equation is also shown by a bold dashed line in Fig.6.

Fig. 7 shows the reading of $\bar{r}_2$ from the calculated heterogeneity index. Since there is little effect caused by impedance ratio, we just take the average of all the values, which is shown in a bold solid line in Fig.7. Fig. 8 is the result of $\bar{r}_1$, which shows a big effect caused by changeing the impedance ratio. The approximation of $\bar{r}_1$ in Fig.8 can be expressed as

$$\overline{r}_1 = a + b\alpha \qquad (5)$$

where a, b are the coefficients, which are functions of Y/R. Derivation of a,b from Fig.8 is shown in Fig.9.

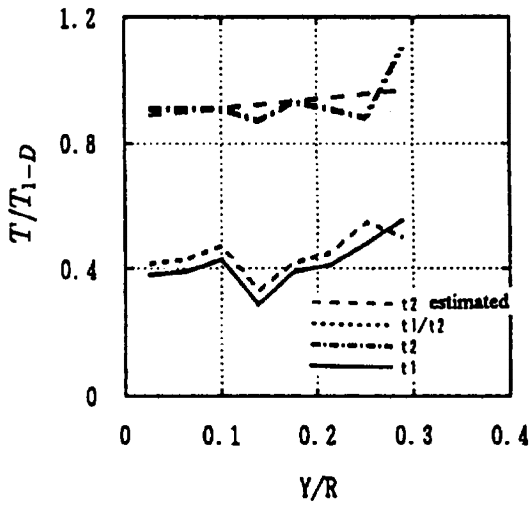


Fig. 6 Values of t_1 and t_2

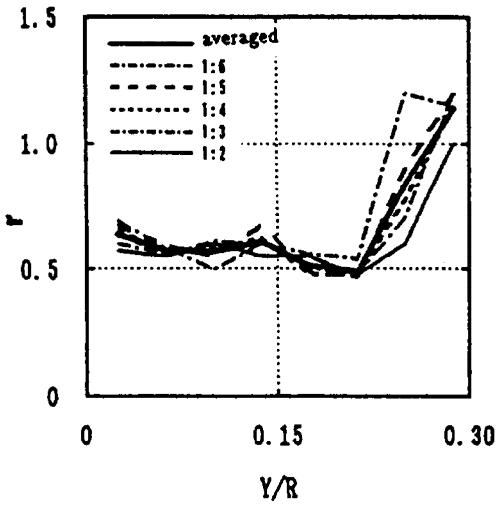


Fig. 7 Values of r_2

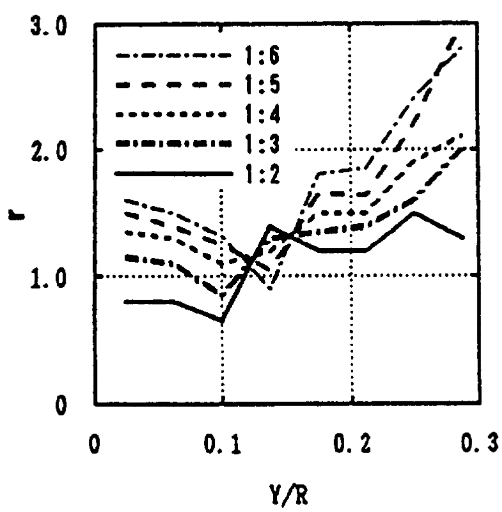


Fig. 8 Values of r_1

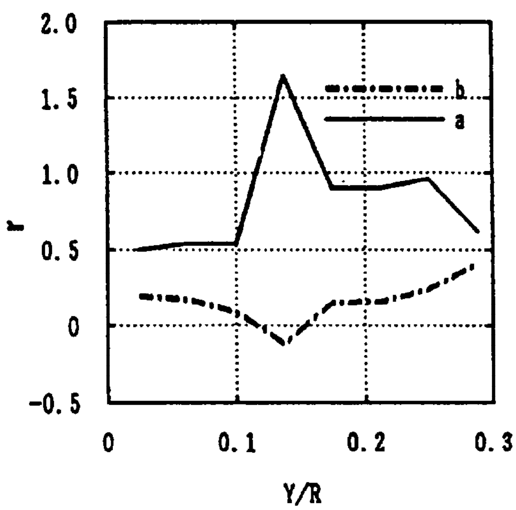


Fig. 9 Values of a, b for r_1

To test the results by all these empirical formulas, a test case is selected, with $\alpha = 1/3$, Y/R = 0.175 and 0.250. From Eqs.(4, 5) and Figs. 7, 9, we can get the values of $(\overline{r}_i, \overline{t}_i)$ $(i = 1,2)$, then the result of heterogeneity index. On the other hand, direct calculation of the heterogeneity index can also be obtained. All these results are plotted together in Fig. 10. From Fig. 10, we can conclude that the estimated heterogeneity index and the directly calculated results match quite well, which implicates that the proposed formula can be applied in the simplification of considering the heterogeneous effect of alluvial valleys.

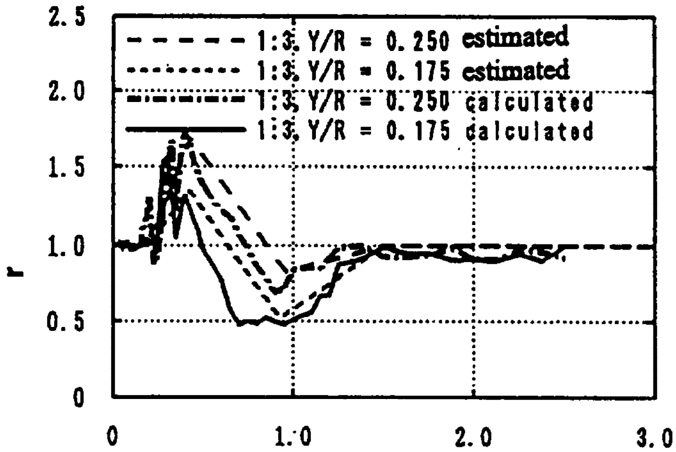


Fig. 10 Comparison of the heterogeneity index

Application of Heterogeneity Index

This section explains how to apply the proposed index in seismic design to consider the effect of heterogeneous underground structure alluvial valleys without the complicate calculation of seismic wave motions for the real alluvial valley. The steps are:

1) At the point of consideration, calculate impedance ratio α, H/R, $(W_L/R)_0$, $(Y/R)_0$, where subscript 0 stands for the original value calculated from the underground structure.

2) Calculate (H/R)cr from Eq.(1) by using α obtained in step 1).

3) Determine the heterogeneous area by Eqs.(2,3). If $(Y/R)_0$ is within the heterogeneous area, the effect of heterogeneity needs to be considered, otherwise, there is no need to consider the effect.

4) Calculate the 1-D predominant period which corresponds to the center of the valley, expressed as $T_{1\text{-}D}$.

5) Calculate Y/R which corresponds to a model in which the depth of the valley equals to the depth at the point of consideration, but W_L/R=0.50. For example, if the values obstained in step 1) are $(W_L/R)_0 = 0.25$, $(Y/R)_0 = 0.10$, at the same depth of a model with W_L/R=0.50 will result in a value of Y/R which is approximately 0.20.

6) Calculate $(\overline{r_i}, \overline{t_i})$ $(i = 1,2)$ from Eqs. (4,5) and Figs. 7, 9. Then a shape looks like Fig.5-b) will be derived. We express this as $\overline{R_{2\text{-}D}}$.

7) Multiple the horizontal axis of Fig. 5-b) by the value of $T_{1\text{-}D}$, which results in a horizontal axis which is the natural period. We express this multiplied value as $R_{2\text{-}D}$.

With the value of $R_{2\text{-}D}$, the design load for seismic design can be derived, which considers the effect of heterogeneity effect at the site of consideration. For example, if the coefficient C_i of shear force for seismic design is considered, the modified formula should be

$$C_i = Z \bullet (R_t \bullet R_{2\text{-}D}) \bullet A_i \bullet C_0 \quad (6)$$

where Z is the modifier which considers the effect of seismicity in different zones, R_t is the site amplifier before considering the effect of heterogeneity, A_i is the distribution of C_i along the height of the building, C_0 is the standard shear force coefficient for seismic design. If we simply replace the original R_t with (R_t*$R_{2\text{-}D}$), all the other calculation will remain the same as it is.

CONCLUSIONS

A simple model is used to approximate the shape of alluvial valleys. A thorough parametrical study by the proposed method is carried out to define and determine the heterogeneous areas, to formulate the equations for the proposed heterogeneity index. The application of the proposed heterogeneity index to the current seismic design code is proposed to include the effect of the heterogeneous effect of the alluvial valleys.

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