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Irregular index of mountain step-terrace frame structure

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Abstract: In order to study the influence of the irregularity of the step-terrace structure on the seismic performance of the structure, according to the difference between the internal force distribution of the step-terrace structure and the regular structure, this paper puts forward a new irregular index according to the difference between the lateral stiffness distribution of the step-terrace structure and the regular structure through the internal force analysis of the step-terrace structure. The nonlinear analysis of 12 step-terrace structures under rare earthquakes is carried out, and the relationship between the maximum inter-story displacement angle and the irregular index under rare earthquakes is analyzed. The results show that the irregularity of the structure increases with the increase of the number of spans and layers of the structure, and the influence of the number of spans on the irregularity of the structure is greater than that of the number of layers. With the increase of the irregular index of the structure, the seismic performance of the structure is worse.

1. Introduction

China has a vast area, of which the mountainous area accounts for about 69.86 % of the total land area [1]. With the development of urbanization and the gradual growth of population in China, the demand for construction land has further increased, and mountains have been gradually used. In order to better adapt to the mountainous terrain, many towns are built on the mountain, forming scattered mountain buildings, such as Hong Kong, Chongqing, Sichuan Panzhihua and other places. Mountain architecture refers to the structure built on the slope, and the constraint parts of the bottom lateral force resisting components are not on the same horizontal plane and cannot be simplified into the same horizontal plane. According to the grounding type, it can be divided into hanging foot structure, falling layer structure and so on [2]. The step-terrace structure is a natural vertical irregular structure. If the regularity index of ' Code for Seismic Design of Buildings ' is used to evaluate the step-terrace structure, it is generally evaluated as seriously irregular. However, according to its seismic failure mechanism and damage strength, it does not reach the expected severity of the regularity index.

At present, for irregular structures, national design codes use regular indicators to ensure their seismic performance. The structural regularity index can reflect the distribution characteristics of mass, stiffness and bearing capacity of the structure, and generally reflect the seismic performance of the structure. Scholars at home and abroad have put forward various irregular indexes for vertical irregular structures and carried out seismic performance of mountain buildings.

T L Karavasi [3] l is to study the seismic inelastic deformation requirements of indented frames. The irregularity caused by the existence of indent is described and quantified by a simple geometric index, and the influence of geometric irregularity on the seismic damage of indented frames is considered. In order to quantify the upper indented building frame, Pradip Sarkar et al. [4] proposed an irregular index based on the dynamic characteristics (mass and stiffness) of the structure, and verified various indented buildings to obtain a quantifiable upper indented frame building. In order to study the progressive collapse resistance of irregular structures, He [5] derived the irregular index based on the bending yield mechanism (provided by plastic hinge and plastic hinge line) and the large value of the bearing capacity of the tensile membrane mechanism, and used this index to quickly identify the most unfavorable column removal mode. S. Varadharajan [6] In order to determine the influence of indenting on the deformation of inelastic demand, an irregularity index is proposed to quantify the indented irregular buildings based on the dynamic characteristics of the frame. Wang Li ping [7] proposed that the control index (layer stiffness ratio and shear bearing capacity ratio) of the irregular elevation of the falling part and the upper ground layer of the falling layer structure in the current specification has failed, and the concept of ' in-layer stiffness ratio ' is proposed. Suggestions are given for the control of layer stiffness ratio and intra-layer stiffness ratio, and the determination method of weak layer of step-terrace structure is given. Xu Jun [8] In order to ensure the seismic performance of the step-terrace structure, based on the in-layer stiffness ratio and the layer stiffness ratio, the average stiffness ratio of the upper layer is proposed according to the seismic failure mechanism of the step-terrace frame. In order to evaluate the collapse risk of the step-terrace structure, [9] proposed an irregular index: period ratio, and observed that the shear failure risk of the upper grounding column showed a good correlation. Mitesh Surana [10] used nonlinear dynamic analysis method to analyze the seismic response and vulnerability of RC buildings on slopes in the Himalayas of India and other parts of the world, and concluded that the average damage of mountain buildings is higher than that of regular structures. In order to study the seismic response and failure mechanism of mountain step-terrace structure, Tang et al. [11] carried out a shaking table experiment on a six-story step-terrace frame model. It was observed that the integrity of the step-terrace structure was good under rare earthquakes, but the upper grounding column was seriously damaged. Xu et al. [12] also made a vulnerability analysis of the mountain step-terrace, and proposed that the step-terrace structure with improvement measures can enhance the seismic performance of the structure.

It is of great significance to determine the regularity evaluation index which can reasonably reflect the overall irregular characteristics and control the force transmission mechanism and failure mechanism of its special force components under earthquake action for the grounding irregular structure which is different from the flat irregular structure. In order to study the influence of the number of layers and spans on the whole structure, according to the difference of internal force distribution between the regular structure and the step-terrace structure, based on the average stiffness ratio of Xu Jun, a new irregular index is proposed according to the difference between the lateral stiffness of the step-terrace structure and the regular lateral stiffness, and the irregular index is used to evaluate the seismic performance of the step-terrace structure.

2. Lateral stiffness calculation method

2.1. Common methods for calculating the lateral stiffness of components

The common methods of approximate calculation of internal force under horizontal load are inflection point method, D value method and S-C method.

2.1.1. D value method and inflection point method

The D value method [13] is an improved inflection point method, which mainly considers the influence of frame joint rotation and the change of inflection point position on the basis of its inflection point. In the inflection point method, the lateral stiffness of the column is:

$$i_c = \frac{12i}{h^2} \quad (i = \frac{EI}{h}) \tag{1}$$

This assumption has little error for structures with beam-column linear stiffness ratio greater than 3. However, in most cases, the linear stiffness ratio of the beam to the column is generally between 0.5-3. In order to reduce the error, the influence of the rotation of the frame joint should be considered. Therefore, the lateral stiffness of the column is calculated as follows:

$$D = \alpha \frac{12EI}{h^3} \tag{2}$$

α reflects the influence of beam-column linear stiffness ratio on column lateral stiffness.

$$\alpha = \frac{K}{2+K} \text{ (General layer)}$$

$$\alpha = \frac{0.5+K}{2+K} \text{ (Bottom layer)}$$

$$K = \frac{\sum i}{2i} \tag{3}$$

2.1.2. S-C method

The Smith-C method is the abbreviation of the Smith and Coull method. The S-C method considers that the lateral displacement between the layers of the frame is caused by the double curvature bending deformation of the beam, the double curvature bending deformation of the column and the axial deformation of the column under the horizontal load. The lateral displacement of the structure is larger, close to the actual situation, the error between the actual value and the actual value is small, and the calculation workload is small. According to the research results of S-C method, when the aspect ratio of the frame structure is less than 4, it is considered that the influence of the axial deformation of the column can be ignored. The lateral stiffness of each layer except the bottom layer is [13]:

$$\sum D = \frac{12}{h_i^2\left(\frac{1}{\sum i_b + \sum i_c}\right)} \tag{4}$$

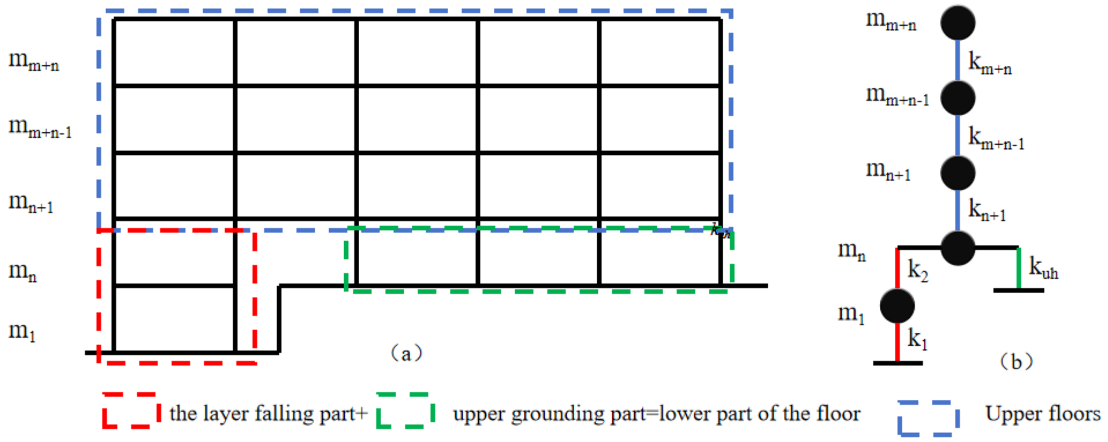
The lateral stiffness of the bottom layer is:

$$\sum D_i = \frac{12}{h_i^2} \cdot \frac{\left(1 + \frac{\sum i_c}{6\sum i_b}\right)}{\left(\frac{2}{3\sum i_b} + \frac{1}{\sum i_c}\right)} \tag{5}$$

The common ordinary uniform frame structure is calculated by D value method under the assumption that the height of each layer is equal, the span is equal, the linear stiffness of each layer is equal, the rotation angle of each layer is equal and the interlayer displacement is equal. However, for the step-terrace structure with the bottom column at different elevations, when the height difference is large, the rotation angle at the top of the column is quite different. At this time, the assumption that the rotation angles of each layer of beam-column joints are equal in the D-value method is obviously not established. If the D-value method is used to calculate the lateral stiffness of the bottom in the step-terrace structure, it is bound to produce a large error, and the S-C method is more concise than the D-value method. In this paper, the lateral stiffness is calculated by the S-C method.

2.2. Mechanics distribution and lateral stiffness of the split-foundation RC frame

For the typical step-terrace frame structure, it can be divided into two parts: the upper floor and the lower floor according to its structural geometric layout characteristics. Among them, the lower floor can be divided into the falling part and the upper grounding part according to the different strata. According to the geometric arrangement of the step-terrace frame structure and the characteristics of shear deformation, it can be simplified into a multi-degree-of-freedom lumped mass model, as shown in Figure 1.



(a) Structural prototype (b) lumped mass model

Figure 1: Simplified model of the layer-down framework

Figure 1(a) is a frame structure with m(upper floor)+n(lower floor) floor, k(step-down part)+l(upper grounding part)+1(left and right connection part, upper grounding beam) span. Figure 1(b) is the equivalent lumped mass model obtained by simplifying the prototype structure shown in Figure.1 (a) by the above method. It should be noted that in order to clarify the relationship between different parts of the structure and the characteristics of static and dynamic response, this paper does not divide the upper and lower floors of the structure according to the traditional architectural significance, but according to the characteristics of the structure, that is, the upper stratum is also divided into the lower floors. The layers of the falling part are in series; the falling part and the upper grounding part are in parallel relationship; the upper floors are in series with each other; the falling part, the upper grounding part and the upper floor are connected together by the upper stratum, and the stiffness relationship can be calculated according to the series-parallel relationship:

$$K_{dh} = \frac{1}{\sum \frac{1}{k_i}} \tag{6}$$

Lower floor:

$$K_{ls} = K_{uh} + K_{dh} \tag{7}$$

3. Irregular formula derivation

3.1. Layer stiffness ratio and upper grounding stiffness ratio

The vertical irregularity caused by the discontinuity of vertical lateral force resisting members, the sudden change of story height, local indentation or protrusion can be evaluated by the 'Code for Seismic Design of Buildings'. The step-terrace structure also belongs to the vertical irregular structure, but the vertical irregularity of the step-terrace structure is closely related to the existence of different grounding methods due to its vertical irregularity. In addition, it is affected by various reasons such as the change of the bottom grounding height difference and the lateral constraint at the bottom. The vertical irregularity evaluation standard of 'Building Seismic Code' cannot be applied to the step-terrace structure. It is necessary to propose a new irregular index to evaluate the step-terrace structure. Based on the irregular index proposed by Wang Li ping and Xu Jun, this paper proposes a new irregular index.

Wang Li ping [7] proposed that the general structure is still in an elastic working state at a certain level through the matching of strength and stiffness. Ductility is to ensure that the structure still has a certain elastic-plastic deformation capacity under the condition that the bearing capacity attenuation is not obvious after the large earthquake, and the damage degree is reduced to a minimum. Strength, stiffness and ductility, as the characteristics of the structure, essentially determine the seismic performance of the structure, that is, the control of the seismic performance of the structure is the grasp of the three. Therefore, when the strength and stiffness mismatch caused by the uneven stiffness distribution of the structure, the elastic-plastic deformation of a layer or a part of the structure is too large, and then a weak layer is formed, resulting in the collapse of the structure. Therefore, the stiffness distribution of the structure should be controlled in advance in the structural design, and the ductility measures should be guaranteed. This characteristic is precisely the characteristics of the step-terrace structure. The significant difference between the structure and the ordinary structure is mainly manifested at the bottom. Therefore, if the influence law of the seismic performance of the step-terrace structure is grasped from the stiffness distribution characteristics, such as the influence on the sudden change of the interlayer displacement angle and the position of the weak layer. Then the control of the vertical irregularity of the structure and the location of the weak layer can be carried out by quantifying the stiffness distribution. Furthermore, the irregular index layer stiffness ratio a and the in-layer stiffness ratio a are proposed.

Furthermore, the irregular index layer stiffness ratio r_c and the in-layer stiffness ratio r_n are proposed. The elastic-plastic analysis of the step-terrace frame structure is carried out to study the law between the irregular and the maximum interlayer displacement angle and the yield ratio. The layer stiffness ratio is the layer stiffness ratio, which is the ratio of the total lateral stiffness of the lower floor to the lateral stiffness of the second floor. The stiffness ratio of the inner layer is the stiffness of the inner layer, which is the lateral stiffness of the upper grounding part and the total lateral stiffness of the lower floor.

$$r_c = K_{ls} / k_{n+1}$$

$$r_n = k_{uh} / K_{ls} \tag{8}$$

Wang Li ping [6] proposed that r_c should not be less than 0.5, and when r_n is greater than or equal to 0.5, the following formula can be used to determine the location of the weak layer of the drop layer structure and the seismic force of the weak layer multiplied by the increase coefficient of 1.15 for reinforcement design

$r_n < 0.7$ The weak layer is located in the upper ground layer 1.

$r_n \geq 0.7$ The weak layer is located in the upper grounding layer 1 and 2. (9)

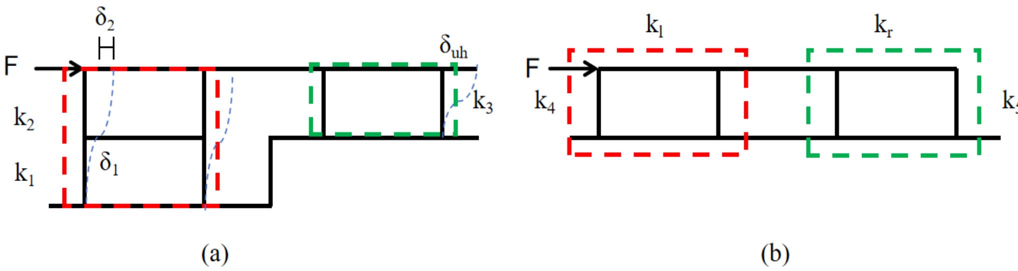
On the basis of Wang Liping 's stiffness ratio in the layer, Xu Jun [8] obtained the average lateral stiffness ratio index of the upper ground component (referred to as 'the average stiffness ratio of the upper ground') according to the basic criterion of internal force distribution and force transmission mechanism between different vertical lateral force resisting components in the lower floor of the step-terrace structure, and according to the normalization idea, the upper ground stiffness and the total stiffness of the lower floor are divided by the number of the above ground columns and the total number of the upper ground columns, respectively.

$$\bar{\gamma}_{uh} = \frac{k_{uh} / (n_{uh} + 1)}{K_{ls} / (n_b + 1)} \tag{10}$$

In the formula, n_b is the total number of spans, and n_{ub} is the number of spans of the upper ground layer. Because it is composed of the grounding stiffness K_{ls} on k_{uh} and the stiffness k_{dh} of the falling part, it evolves into the following formula:

$$\bar{\gamma}_{uh} = \frac{k_{uh}}{(k_{uh} + k_{dh})} \cdot \frac{(n_b + 1)}{(n_{uh} + 1)} \tag{11}$$

However, the above irregular means only consider the lateral stiffness distribution of the step-terrace structure, and do not consider the difference between the regular structure and the step-terrace structure. This paper introduces the regular structure and compares it with the step-terrace structure to analyze the difference between the internal force distribution of the step-terrace structure and the regular structure, as shown in Figure 2.



(a) step-terrace structure (b) regular structure

Figure 2: Bottom diagram of cliff-Structure and rule structure

According to the seismic design code, the calculation formula of inter-story displacement is:

$$\delta = \frac{V}{K} \tag{12}$$

According to the distribution characteristics of the force of the falling structure, the structure is divided into the falling part and the upper grounding part. In order to facilitate the analysis of the internal force distribution of the falling structure and the regular structure, the regular structure is also divided into two parts: left and right.

$$k_{dh} = \frac{k_1 k_2}{k_1 + k_2} \tag{13}$$

Because $k_2 < k_1$ so $k_{dh} < k_l$ and $k_{dh} < k_{uh}$

Therefore, when the step-terrace structure and the regular structure are the same in all aspects, the stiffness of the step-terrace structure is always smaller than that of the regular structure. The bottom of the step-terrace structure is regarded as a whole, and the same force F is applied to the step-terrace structure and the regular structure. Because of Equation (13), the step-terrace structure has a larger interlayer displacement than the regular structure, and it is easier to be destroyed under earthquake. The internal force analysis of the step-terrace structure is carried out, and the interlayer displacement of the step-terrace part is analyzed:

$$V_{uh} = \frac{k_1 k_2}{k_1 k_2 + k_1 k_3 + k_2 k_3} F$$

$$V_{dh} = \frac{k_1 k_3 + k_3 k_2}{k_1 k_2 + k_1 k_3 + k_2 k_3} F$$

$$\delta_1 = \frac{k_1}{k_1 k_2 + k_1 k_3 + k_2 k_3} F$$

$$\delta_2 = \frac{k_2}{k_1 k_2 + k_1 k_3 + k_2 k_3} F$$

$$\delta_{uh} = \frac{k_2 + k_1}{k_1 k_2 + k_1 k_3 + k_2 k_3} F \tag{14}$$

In the formula, δ_{uh} refers to the displacement of the upper grounding part δ_1 refers to the displacement of the first layer of the drop layer δ_2 refers to the displacement of the second part of the drop layer. Since the stiffness is positive, $\delta_{uh} > \delta_1 > \delta_2$ can be obtained. It can be seen that in order to improve the seismic performance of the step-terrace structure, it is mainly to enhance the stiffness of the upper grounding part.

According to the irregular reference index of lateral stiffness in the vertical irregular index of 'Code for seismic design of buildings'[14], the lateral stiffness of this layer is less than 70 % of the adjacent upper layer. Because the step-terrace structure cannot accurately judge the irregularity of the step-terrace structure according to this rule, but the regularity of the step-terrace structure can be determined by comparing the bottom of the step-terrace structure with the bottom of the regular structure. According to Table 4, except for KJ511, the rest are less than 0.7 K_g

Therefore, this paper takes the proportion of the difference stiffness between the step-terrace structure and the regular structure as the index to evaluate the frame of the step-terrace structure, and introduces the normalization idea to propose the irregular index of the step-terrace structure:

$$\gamma = \frac{\left(K_g - K_{ls}\right)}{K_g} \tag{15}$$

K_g is the total stiffness of the regular structure, and K_{ls} is the total stiffness of the lower floor of the step-terrace structure.

3.2. Example analysis

In order to study the influence of the irregularity of the step-terrace structure on the seismic performance of the structure, according to the ' Code for Seismic Design of Buildings ', PKPM was used to design the 5-7 story step-terrace structure and the four-story regular structure respectively. In order to ensure that the regular structure has no other factors, the column section, load and structural fortification intensity of the regular structure are the same as those of the step-terrace structure. The upper floor is four floors, the falling part is 1-3 floors, and the number of spans is 1-4. The longitudinal (y direction) of the structure is 5 spans, and the transverse (x direction) is 6 spans. The layer height is 3.3 m. The fortification intensity of the structure is 8 degrees (0.2g), the site category is Class II, and the design earthquake group is the first group. The basic wind pressure is 0.4kN/m^2, and the ground roughness is class B. The standard value of floor dead load is 5.0kN/m^2 (including floor weight), the standard value of live load is 2.0kN/m^2, the standard value of roof dead load is 6.0kN/m^2 (including floor weight), the standard value of live load is 0.5kN/m^2, the standard value of partition and retaining wall load is 8.0kN/m, the standard value of top floor parapet wall is 3.5kN/m, the thickness of floor is 100mm, and the roof is 120mm. C35 is selected as structural concrete, HRB400 is selected as beam-column longitudinal reinforcement, and HPB300 is selected as stirrup. In order to ensure that the regular structure is not affected by other factors, the column section, load and structural fortification intensity of the regular structure are the same as those of the step-terrace structure. In the structural design of the example, in order to reflect the influence of different structural arrangements on the seismic performance of the step-terrace structure, the influence of other factors is ignored as far as possible. The component size and reinforcement method are as follows:

Table 1: Structural model information

<table>
<tr><th>Model number</th><th>column cross-section /mm</th><th>girder cross-section /mm</th></tr>
<tr><td>KJ511</td><td rowspan="4">1-2 floor
550×550
3-5 floor
500×500</td><td rowspan="13">main beam:300×550
secondary beam:250×450</td></tr>
<tr><td>KJ512</td></tr>
<tr><td>KJ513</td></tr>
<tr><td>KJ514</td></tr>
<tr><td>KJ621</td><td rowspan="4">1-3 floor
550×550
4-6 floor
500×500</td></tr>
<tr><td>KJ622</td></tr>
<tr><td>KJ623</td></tr>
<tr><td>KJ624</td></tr>
<tr><td>KJ731</td><td rowspan="4">1-4 floor
550×550
5-7 floor
500×500</td></tr>
<tr><td>KJ732</td></tr>
<tr><td>KJ733</td></tr>
<tr><td>KJ734</td></tr>
<tr><td>GZ4</td><td>1 floor
550×550
2-4 floor
500×500</td></tr>
</table>

(1) The structure with the same number of vertical anti-lateral force components at the upper and lower grounding ends (such as 5-span structure, 2-span structure is selected) is the basic model. By adjusting the size of the components and the material label (if necessary), the basic model is close to

the lower limit of the specification, that is, the elastic inter-story displacement angle is close to 1/550. The other example structures with the number of layers are realized by increasing or decreasing the number of layers of the basic model. In this process, the geometric size and material of the components are kept unchanged. When the maximum elastic inter-story displacement angle exceeds the specification limit, no further adjustment is made. The section size of the frame beam column is shown in Table 1, and the size of the secondary beam is 250mm×450mm.

(2) The reinforcement of the cross section of the component is realized by PKPM software. When the structure of the model is special, such as the number of the upper grounding anti-lateral force components is significantly less, the cross section will inevitably be over-reinforced. At this time, the maximum allowable reinforcement ratio of the cross section is taken as the reinforcement ratio of the cross section, the beam section is 2.5%, and the column section is 5%.

The index results of the regularity index of the structure are located in Table 2. According to Table 2, it can be seen that the irregularity of the structure increases with the increase of the number of spans and layers of the structure, and the number of spans has a greater influence on the irregularity of the structure than the number of layers.

Table 2: Examples of structural irregularities

Upper floors	the number of the off-layer	the number of the off-across			
		1	2	3	4
4	1	0.29	0.41	0.54	0.59
	2	0.32	0.47	0.61	0.68
	3	0.33	0.49	0.64	0.73

4. Applicability of irregular index seismic performance

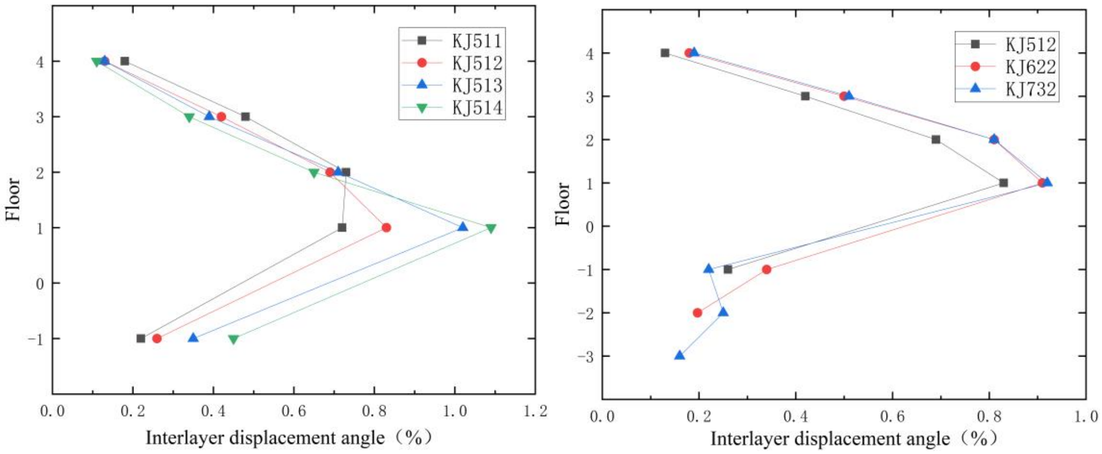
Table 3: The maximum inter-story displacement angle of the structure under rare earthquake

Upper floors	the number of the off-layer	the number of the off-across			
		1	2	3	4
4	1	0.73%	0.83%	1.02%	1.09%
	2	0.75%	0.91%	1.15%	1.81%
	3	0.76%	0.92%	1.60%	2.20%

Table 4: Bottom stiffness of step-down structure and regular structure

Step-down frame number	Total Stiffness of Lower Floor of Staircase Frame /104(N/mm)	0.7 rule frame bottom stiffness /104(N/mm)
KJ511	16.18	15.995
KJ512	13.42	
KJ513	10.605	
KJ514	9.479	
KJ621	15.5	
KJ622	12.18	
KJ623	8.868	
KJ624	7.219	
KJ731	15.23	
KJ732	11.683	
KJ733	8.137	
KJ734	6.281	

In the 'seismic design code', the inter-story displacement angle is usually used to represent the seismic performance of the structure, and the design concept of ' no damage under small earthquakes, repairable under medium earthquakes, and no damage under large earthquakes ' is proposed. The key to the evaluation of structural seismic failure mechanism is to accurately obtain the nonlinear response of the structure under rare earthquakes, which can usually be achieved by elastic-plastic time history analysis or static pushover analysis (Pushover). It is troublesome to select multiple seismic waves for elastic-plastic time history analysis. In this paper, static pushover is selected to analyze the nonlinear response of each step-terrace structure under rare earthquake. In order to test the practicability of the irregular index and the seismic performance of the step-terrace structure, 12 step-terrace structures are designed in this paper. The column section, load and earthquake conditions are the same as those above, as shown in Table 3 and Table 4.



(a) (b)

(a) The number of spans increases the interlayer displacement angle (b) The number of layers increases the interlayer displacement angle.

Figure 3: Inter-story displacement angle of step-terrace structure under rare earthquake

According to Figure 3(a), it can be observed that when the number of the same spans of the structure is gradually increased, the maximum inter-story displacement angle of the structure under rare earthquakes is gradually increased. According to Figure3 (b), it can be seen that when the number of spans in the falling part of the structure is the same but the number of layers gradually increases, the inter-layer displacement angle also gradually increases. At the same time, it can also be seen that the increase in the number of spans of the falling layer is more unfavorable to the seismic performance of the falling layer structure.

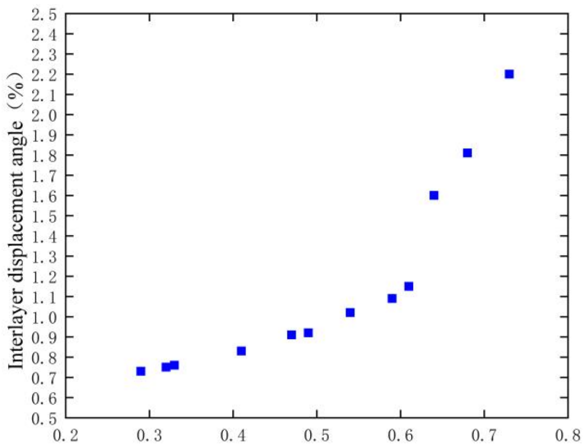


Figure 4: The relationship between irregular index and interlayer displacement angle

According to Figure. (4), it can be concluded that the interlayer displacement angle of the step-terrace structure increases with the increase of the irregular index, and the irregular index can be used to evaluate the seismic performance of the step-terrace structure.

5. Conclusion

(1) With the increase of the number of spans and the number of layers, the seismic performance of the structure decreases: and the influence of the number of layers on the structure is less than the influence of the number of spans on the structure.

(2) The irregularity index proposed in this paper reduces the seismic performance of the structure with the increase of the irregularity of the step-terrace structure, which can be used to evaluate the irregularity of the step-terrace structure.

References

[1] Announcement of National Bureau of Statistics of the People 's Republic of China [J]. China Statistics, 2018, (3): 21.

[2] Ministry of Construction of the People 's Republic of China. Mountain building structure design standard JGJ/T472-2020 [S]. Beijing: China Architecture Media Publishing.

[3] T. L. Karavasilis, N. Bazeos, D. E. Beskos. Seismic response of plane steel MRF with setbacks: Estimation of inelastic deformation demands[J]. Journal of Constructional Steel Research, 2008, 64 (64): 644-654.

[4] Pradip Sarkar,A. Meher Prasad, Devdas Menon. Vertical geometric irregularity in stepped building frames[J]. Engineering Structures, 2010, 32: 2175-2182.

[5] Xiao-Huang-Can He, Xian-Xun Yuan, Wei-Jian Yi. Irregularity index for quick identification of worst column removal scenarios of RC frame structures[J]. Engineering Structures, 2019, 178 (178): 191-205.

[6] S. Varadharajan, V. K. Sehgal, Babita Saini. Determination of inelastic seismic demands of RC moment resisting setback frames[J]. Archives of Civil and Mechanical Engineering, 2013, 13 (13): 370-393.

[7] Wang Liping. Ground motion input and lateral stiffness control method for mountain building structure design [D]. Chongqing University, 2010

[8] Xu Jun. Research on seismic failure mechanism of step-terrace reinforced concrete frame structure [D]. Chongqing University, 2019

[9] Liu Liu. Research on seismic collapse risk assessment and control method of step-terrace RC frame structure [D]. Chongqing University, 2021

[10] Mitesh Surana, Abdelghani Meslem, Dominik H. Lang. Analytical evaluation of damage probability matrices for hill-side RC buildings using different seismic intensity measures[J]. Engineering Structures, 2020, 207 (207): 110254.

[11] Li Yingmin, Tang Yangyang, Jiang Baolong, et al. Shaking table test of RC frame structure with step-terrace in mountain area [J]. Journal of Building Structures, 2020, 41 (8): 68-78.

[12] XU Gang, LI Aiqun, CHEN Sufang. Earthquake vulnerability analysis of mountain step-terrace frame structure [J]. Journal of Disaster Prevention and Mitigation Engineering, 2017.

[13] Meng Huanling, Liu Yang, Shen Pusheng. Comparison of three lateral displacement methods for hand-calculated frame structures [J]. Journal of Railway Science and Engineering, 2006, (3): 61-64.

[14] GB 50011-2010. Code for seismic design of buildings [S]. Beijing: China Construction Industry Press, 2010.