Vertical Seismic Response Analysis of Large Span Isolated Structures under Multi-Dimensional and Multi-Support Excitations

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Abstract. The multi-point random ground motion is artificially synthesized based on the triangular series method. Then the variation law and damping effect of vertical seismic response of large span isolated structures with different spans are studied respectively, under the action of both frequent earthquake and rare earthquake. The results show that in some areas of large span isolated structures, the vertical seismic responses are larger than those of non-isolated structures, under the multi-dimensional multi-point seismic input. The damping effects of large span isolated structures under rare earthquake are better than those under frequent earthquake. The area that is near the supports is prone to a large increase in response after isolation, so there should be strengthened during the engineering design.

1. Introduction

With the continuous enhancement of national strength and the improvement of people’s living standard, we need to build more and larger space buildings to meet the needs of life and commerce. This is a huge opportunity for domestic structural field. Once the large span space structure is damaged or even collapsed under the action of earthquake, it will bring huge economic losses and casualties. Due to the intensive natural vibration frequency and complex vibration mode of the large span structure, large structural vibration and large structural deformation often occur during the earthquake. The spatial effect of ground motion will lead to obvious differences in the seismic excitation of each supporting point. Therefore, multi-point input needs to be considered when the vertical seismic response of the large span structure is studied (Ding Y. et al. 2007; Jiang Y. et al. 2010). The calculation of the response of the large span structure under multi-dimensional and multi-point seismic input has been well studied in theory and application aspects. However, the behavior of the large span isolated structure under multi-dimensional and multi-point seismic input is very complex, and the laws of seismic activity have not been fully understood and mastered by the humankind. In most seismic design or analysis of structures, the influence of vertical ground motion is not considered. But for the buildings in the areas with high seismic intensity, especially those large span isolated structures, the effect caused by vertical earthquake cannot be ignored usually. Therefore, it is of great significance and value to strengthen the research on vertical seismic response of large span isolated structures in seismic safety assessment.

In this paper, the multi-point random ground motion is synthesized artificially at first (Ou J.P. et
al.1991; Ai X.Q. & Li J 2009). Based on that, the variation law and the damping effect of the vertical seismic response of the large span orthogonal grid isolated structures with different spans under the multi-dimensional and multi-point seismic input are studied, so as to provide some useful references for the rationality and safety when design the large span spatial structures.

2. Models and Seismic Input

2.1. Structural Models
In this paper, three different large span isolated structures are selected for calculation and analysis. The roofs are all quadrangle flat grids with orthogonal normal position, and the peripheral supporting models are adopted. The spans, heights and grid sizes of the models are shown in the Table 1. The lower part is a two-layer frame structure, and each layer has a height of 5m. The geometrical sizes and reinforcement of the beams and columns are all designed according to the specification requirements. The rest design parameters are detailed in the reference (Gu Z.Y. et al. 2017). The configuration of structural members has already been statically optimized before the isolation layer is set. The seismic isolation is arranged at the bottom of the columns. A plurality of lead rubber bearings are arranged at the bottom of the supporting columns, while the ordinary rubber bearings are set at bottom of the remaining frame columns. It is assumed that the grid nodes are in an ideal articulated state, and the effect of the wall on the overall structural stiffness is neglected.

| Table 1. The Geometry size of the models. |
|------------------------------------------|
| Plane size (m x m) | 30 x 60 | 60 x 120 | 90 x 180 |
| Grid height (m) | 1.7 | 3.5 | 5.2 |
| Grid size (m) | 3 x 3 | 6 x 6 | 6 x 6 |

2.2. Structural natural frequency
Table 2 shows the first ten natural vibration frequencies of the three structural models. It can be seen from the analysis results that all the fundamental frequencies of the large span isolated models are less than 1.0 Hz. Compared with the ordinary non-isolated grid of the same design conditions, the former is obviously more flexible. The fundamental frequency is closely related to the span of the grid and increases as the span becomes larger. In addition, the support form of the large-span isolated grid has a certain influence on the fundamental frequency of the structure. In this paper, the surrounding supporting is adopted in every large span isolated structure, so the boundary constraint of the structure is strong and structural fundamental frequency is high.

| Table 2. The natural vibration frequency of the models. |
|--------------------------------------------------------|
| Natural frequency (Hz) | Model plane size (m x m) | 30 x 60 | 60 x 120 | 90 x 180 |
|------------------------|---------------------------|---------|---------|---------|
| 1                      |                           | 0.623   | 0.671   | 0.753   |
| 2                      |                           | 0.635   | 0.671   | 0.754   |
| 3                      |                           | 0.685   | 0.679   | 0.761   |
| 4                      |                           | 2.134   | 1.453   | 1.121   |
| 5                      |                           | 2.664   | 1.85    | 1.43    |
| 6                      |                           | 2.782   | 2.927   | 2.246   |
| 7                      |                           | 3.129   | 3.78    | 2.868   |
| 8                      |                           | 3.146   | 3.881   | 3.075   |
| 9                      |                           | 4.489   | 4.285   | 3.251   |
| 10                     |                           | 5.705   | 4.572   | 3.383   |
2.3. Artificial ground motion synthesis
Assuming that the intensity of the site fortification is 7 degree, the site category is class II and the damping ratio is 0.05. The apparent wave velocity is 50 m/s. The self-power spectrum adopts the C-P spectrum model proposed by Clough and Penzien, which has a certain safety reserve for the long-period structures such as large span structures, and the parameters are determined according to the seismic intensity, the site conditions and the parameter fitting results in the reference (Li Q., 2015). The hysteretic coherent function uses the Harichandran and Vanmarcke model (Harichandran R. S. & Vanmarcke E. H. 1986). The power spectrum model of multi-point ground motion which considers each dimension of ground motion as independent component is adopted according to the reference (Huang B., 2013). The time history of multi-dimensional multi-point ground motion is simplified as the synthesis of three one-dimensional multi-point ground motions, and the random phase angle of each dimension is kept independent during the synthesis process. Considering the non-stationary characteristics of ground motion, its envelope function is given by Equation (1) (Amin M. & Ang A. H. S., 2015), and the corresponding parameters are: \( t_1 = 0.8 \), \( t_2 = 7 \), \( c = 0.35 \). The time histories of multi-dimensional multi-point seismic acceleration with a 7-degree frequent intensity and rare intensity at all the supports are synthesized.

\[
f(t) = \begin{cases} 
(t/t_1)^{t_1} & 0 \leq t \leq t_1 \\
1 & t_1 \leq t \leq t_2 \\
\exp[-c(t-t_1)] & t_2 \leq t 
\end{cases}
\]  
(1)

3. Results and Discussions
Take the 90m×180m large span isolated structure as an example, and the distribution positions of the nodes of the grid roof with larger vertical responses can be shown in Figure 1.

![Figure 1. The location of members with larger vertical responses(90m×180m).](image)

3.1. Vertical acceleration response
Figure 2~ Figure 7 give the cloud charts of vertical acceleration responses for both the upper chord layer and lower chord layer of large span isolated structures with three spans, under multi-dimensional and multi-point input of earthquakes with a 7-degree frequent occurrences (35gal) and a 7-degree rare occurrences (220gal), respectively, where the apparent wave velocity is 50 m/s. It can be concluded from the figures that for the large span isolated structures, the maximum vertical acceleration
responses of the grid roof in the case of frequent earthquake and rare earthquake occur near the surrounding supports, while the acceleration responses at other places of both the upper chord and the lower chord are much smaller. The maximum accelerations of the grid roof increase significantly with the increase of the peak value of the ground motion, and have a tendency to grow with the increase of the structural span as a whole.

(a) The upper chord layer
(b) The lower chord layer

Figure 2. Vertical acceleration of grid roof with the size of 30m×60m under 35gal earthquake (m/s²).

(a) The upper chord layer
(b) The lower chord layer

Figure 3. Vertical acceleration of grid roof with the size of 30m×60m under 220 gal earthquake (m/s²).

(a) The upper chord layer
(b) The lower chord layer

Figure 4. Vertical acceleration of grid roof with the size of 60m×120m under 35 gal earthquake (m/s²).

(a) The upper chord layer
(b) The lower chord layer

Figure 5. Vertical acceleration of grid roof with the size of 60m×120m under 220 gal earthquake
Figure 6. Vertical acceleration of grid roof with the size of 90m×180m under 35 gal earthquake (m/s²).

(a) The upper chord layer
(b) The lower chord layer

Some typical nodes are selected from the upper chord layer and the lower chord layer of the grid respectively. The nodes numbered from 1 to 6 are on the upper chord layer, while the nodes numbered from 7 to 12 are on the lower chord layer, as shown in Figure 8.

Under the seismic input of multi-dimensional and multi-point 7-degree frequent earthquake (35gal) and 7-degree rare earthquake (220gal), the vertical acceleration response peaks of both large span non-isolated structures and the isolated structure are calculated respectively, where the apparent wave velocity is 50 m/s. The damping effects are shown partially in figure 9 to figure 11.

Figure 7. Vertical acceleration of grid roof with the size of 90m×180m under 220 gal earthquake (m/s²).

(a) The upper chord layer
(b) The lower chord layer

Figure 8. The key points layout of grid roof (90m×180m).
It can be concluded from the figure that: (1) for the vertical acceleration response of the isolated structure with the span of 60m, the damping effects of the measured points at the upper and lower chord layer of the grid roof under frequent earthquake are -30%~48% and 47%~71%, respectively, while the damping effects are -24%~68% and 60%~71% respectively under this circumstance of rare earthquake; (2) for the isolated structure with the span of 120m, the damping effects of the measured points of the upper and lower chord layer under frequent earthquakes are -64%~48% and 27%~50%, respectively, while the damping effects are respectively -51%~46% and 44%~52% under this circumstance of rare earthquake; (3) for the isolated structure with the span of 180m, the damping effects of measured points of the upper and lower chord layer under frequent earthquake are -383%~20% and -144%~50%, respectively, while the damping effects are respectively -64%~28% and -104%~51% under the action of rare earthquake. It shows that some nodes of the grid roof of the large span isolated structure have a certain vertical damping effect, and the damping effect is slightly better under rare earthquake than under frequent earthquake. Besides, vertical damping effect decreases with the increase of span in general; (4) for some corner points and midpoints on the edge spans of the upper chord layer of the 60m-span and 120m-span isolated structures, their vertical acceleration responses increase greatly after isolation. As the span increases, such nodes are more widely distributed. Such situation occurs to some corner points, midpoints of edge spans, and geometrically centric points on the upper chord layer and the entire lower chord layer of the 180m-span isolated structure.

3.2. Vertical displacement response

Figure 12 to Figure 17 show the cloud charts of vertical displacement response of the upper chord layer and lower chord layer of large span isolated structures, under the multi-dimensional and multi-point input of 7-degree frequent earthquake (35gal) and rare earthquake (220gal) respectively, where the apparent wave velocity is 50 m/s.

Figure 12. Vertical displacement of grid roof with the size of 30m×60m under 35 gal earthquake (m).

(a) The upper chord layer

(b) The lower chord layer
(a) The upper chord layer  
(b) The lower chord layer

Figure 13. Vertical displacement of grid roof with the size of 30m×60m under 220 gal earthquake (m).

(a) The upper chord layer  
(b) The lower chord layer

Figure 14. Vertical displacement of grid roof with the size of 60m×120m under 35 gal earthquake (m).

(a) The upper chord layer  
(b) The lower chord layer

Figure 15. Vertical displacement of grid roof with the size of 60m×120m under 220 gal earthquake (m).

(a) The upper chord layer  
(b) The lower chord layer

Figure 16. Vertical displacement of grid roof with the size of 90m×180m under 35 gal earthquake (m).
It can be concluded from the figures that: (1) whether it is under the action of frequent earthquake or rare earthquake, the vertical displacement response distributions of large span isolated structures with the size of 30m×60m and 60m×120m are very similar. The maximum values are all near the bearings (the support where the multi-point seismic wave first arrives) at short sides, and gradually decrease along the propagation direction of the seismic wave. Vertical vibration of the members near the bearings is greater than that in the middle spans. However, the distribution of the response values of the 90m×180m isolated structure is completely different. The maximum value of vertical displacement response is shifted to the long side, and the response values are larger in the region near the middle of the plane; (2) the vertical displacement responses of the grid roof of the large span isolated structures under rare earthquake are one order of magnitude larger than that under frequent earthquake, which shows that the isolated layer of the isolated structure can not effectively absorb the energy of vertical component of ground motion even after it is fully deformed in rare earthquake.

Under the seismic input of multi-dimensional and multi-point 7-degree frequent earthquake (35gal) and 7-degree rare earthquake (220gal), vertical displacement response peaks of the large span non-isolated structures and isolated structures are calculated respectively, where the apparent wave velocity is 50 m/s. The damping effects are partially shown in figure. 18 to figure. 20.

It can be concluded from the figure that: (1) for the vertical displacement responses of the isolated structure with the span of 60m, the damping effects of the measured points of the upper and lower chord layer of the grid roof under frequent earthquake are -20%~25% and 0%~20% respectively, while the damping effects are -18%~29% and 0%~19% respectively under this circumstance of rare earthquake; (2) for the vertical acceleration response of the isolated structure with the span of 120m, the damping effects of the measured points of the upper and lower chord layer under frequent earthquakes are -75%~50% and -133%~50%, respectively, while the damping effects are -33%~33%...
and -110%~59% respectively under the action of rare earthquake; (3) for the vertical acceleration response of the isolated structure with the span of 180m, the damping effect of the measured points under frequent earthquakes are -500%~18%, -850%~350% respectively, while the damping effects are -405%~79% and -679%~352% respectively under the action of rare earthquake; (4) compared with the non-isolated structure, the vertical acceleration responses of some joints in the isolated structure increase greatly. Especially for the isolated structure of 180m span, the partial corner points of the upper chord layer, the midpoints of the edge spans, the geometrically centric points, and the responses of the entire lower chord layer increase severely. The vertical displacement response values of these areas are rather small in the case of non-isolated structures, then become strong vibration areas after isolation. These parts should be strengthened in the process of engineering design.

Compared with the non-isolated structures, the maximum vertical displacement responses of the isolated structures are not effectively reduced. Especially for the structure with the size of 90mx180m, after the isolation, the area of the roof where vertical vibration is strongly shifted. The response values of the area that has large vertical deformation become very small after isolation, which means a good vertical isolated effect. And the damping effects under rare earthquake are slightly better than those under frequent earthquake on the whole. There are also the cases in which the vertical displacement responses of some nodes of the isolated structures increase significantly. In the seismic design of large span structures, special attentions should be paid to the areas that are near the supports whose response values are very large in the case of non-isolated structures and increase significantly indeed after isolation.

4. Conclusions
(1) The vertical seismic responses of large span isolated structures with different spans are distributed differently under the action of both frequent and rare earthquakes, and the regions where the maximum values occur are different too. The maximum vertical responses of large span isolated structures under rare earthquake are about an order of magnitude larger than those under frequent earthquake, which indicates that the isolation layer can’t effectively absorb the energy of vertical component of earthquake ground motion after sufficient deformation under rare earthquake.

(2) After isolation, the areas of space truss roof that strong vertical vibration occurs have a shift. On one hand, the response values of the original non-isolated structures with large vertical deformation become very small, which means a good vertical isolation effect. On the other hand, the vertical response values in some areas are very small in the case of non-isolated structures, while they become areas with strong vibration after isolation and the increase magnitude of responses has a tendency to grow with the span increases.

(3) Vertical responses of large span isolated structures appear near the surrounding bearings. Vertical deformations near the bearings at the short side of the roof whose ground motion firstly arrived are rather large, and these parts are prone to the situation that the responses increase significantly after isolation, which should be strengthened in the process of engineering design.

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