

Shear-Weight Ratio and Its Adjustment in Software SATWE

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ABSTRACT

The ground motion speed and displacement caused by earthquake dynamic effects have a greater influence on long-period structures, and the vibration mode decomposition response spectrum method is unable to make an accurate assessment. Therefore, we introduced the concept of shear-weight ratio. The relationships between the shear-weight ratio, the earthquake influence coefficient and the effective mass coefficient through simplifying the shear-weight ratio were also obtained. Through specific engineering examples, three adjustment processes of shear-weight ratio made by software SATWE of SATWE series based on the seismic code were shown. The study provides a novel method for the analysis of earthquake dynamic effects.

KEYWORDS: Vibration mode decomposition response spectrum method, Shear-weight ratio, Earthquake influence coefficient, Effective mass coefficient, SATWE software.

INTRODUCTION

The shear-weight ratio is an important parameter in seismic design. Article 5.2.5 in the Code for Seismic Design of Buildings (GB5001-2010) and article 3.1.13 in the Technical Specification for Concrete Structures of Tall Buildings have both explicitly put forward the requirements of the shear-weight ratio. Under various seismic fortification intensities, the horizontal seismic shear force " V_{Eki} " of each floor should not be less than the percentage of the representative value of weight load which includes the corresponding floor and the floors above it. The percentage " λ " is the shear coefficient, which has a relationship with the building system's fundamental period and seismic intensity. It is shown in Table 1 (Code for Seismic Design of Buildings, 2010).

The earthquake influence coefficient falls faster in long periods, but for long period structures, the

earthquake dynamic effects may have a greater influence on the structure damage, where the response spectrum analysis is unable to make an estimate (Stamatopoulos, 2014; Mevada et al., 2014; Liao et al., 2013; Butt and Piotr, 2014). Therefore, for security reasons, the specification states the minimum value of λ . If the value does not meet the requirements, the horizontal seismic effect on the structure should be adjusted according to λ . The relationship between shear-weight ratio and λ is that λ is the minimum value of shear-weight ratio.

Table 1. The value of λ

Type	7 degrees	8 degrees	9 degrees
Buildings with obvious torsion effect or with fundamental period of less than 3.5s	0.016 (0.024)	0.032 (0.048)	0.064
Buildings whose fundamental period is more than 5s	0.012 (0.018)	0.024 (0.032)	0.040

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Notes:

- (1) When the fundamental period is between 3.5s and 5.0s, the linear insert value method is allowed.
- (2) The value in parentheses is used in the design when the basic cycle of seismic acceleration is 7 (0.15g) or 8 (0.30 g).

BASIC CONDITIONS OF CONTROLLING THE SHEAR-WEIGHT RATIO

Summary

Before adjusting the shear-weight ratio, we must ensure that the structural modal participation factor reaches 90%, which can ensure that the vibration mode number is enough (Makoto et al., 2014; Zhang, 2012; Wang, 2013). Now, many complex structures need to consider the elastic deformation of floor slab, so we should find a more general way (Wei et al., 2014; Xiao et al., 2014). SATWE (Space Analysis of Tall-buildings with Wall-Element) software uses a general method to calculate the effective mass coefficient of each earthquake direction. It analyzes this problem from the angle of structure deformation energy. The specification requires that the effective mass coefficient is more than 90% (Xu et al., 2014). When the structure has many skip-floor columns and elastic nodes, this will lead the integrity of the structure to be poor and the local vibration to be obvious. This phenomenon often requires many vibration modes to make the effective coefficient of quality meet the requirements. The structure which has skip-floor and elastic nodes is shown in Figures 1-3.

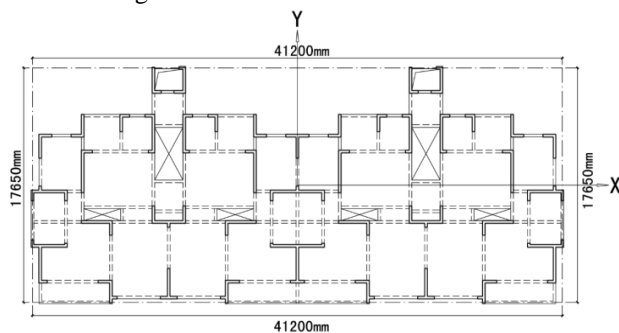


Figure (1): Structure layout of standard layer

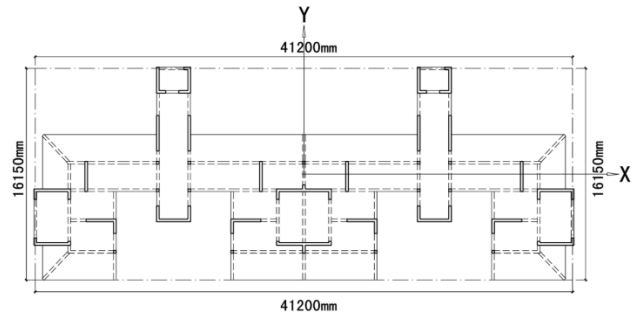


Figure (2): Structure layout of the top floor

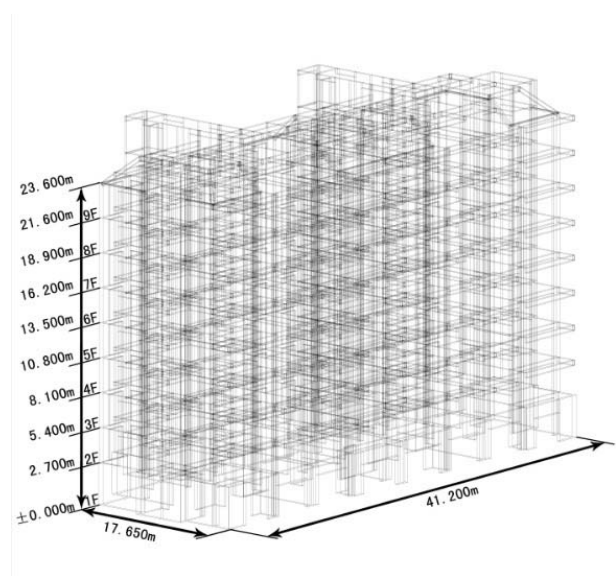


Figure (3): Frame structure 3D model

Table 2. Model data contrast analysis

Reasonable mode number	Shear-weight ratio	Effective mass coefficient
30	1.6%	50.14%
60	3.21%	96.90%

From Table 2, we can see that when the vibration mode number is 30, the effective mass coefficient is 50.14%, which does not meet the requirements of the specification. The shear-weight ratio is 1.6%, which is less than the requirements of the specification. But, when the vibration mode number reaches 60, the effective mass coefficient and the shear weight ratio both meet the requirements of the specification.

Theoretical Derivation

The formula of the horizontal seismic load for the j^{th} vibration mode and the i^{th} node according to the response spectrum analysis is:

$$F_{ji} = \alpha_j \gamma_j X_{ji} G_i \quad (1)$$

α_j — the influence coefficient of the j^{th} vibration mode.

γ_j — modal participation factor of the j^{th} vibration mode.

X_{ji} — the displacement of the j^{th} vibration mode in the i^{th} node.

G_i — the weight of the i^{th} node.

The formula of the modal participation factor for the j^{th} vibration mode is as follows:

$$\gamma_j = \frac{\sum_{i=1}^n G_i X_{ji}}{\sum_{i=1}^n G_i X_{ji}^2} \quad (2)$$

The formula of the earthquake force of the j^{th} vibration mode is:

$$F_j = \sum_{i=1}^n F_{ji} = \sum_{i=1}^n \alpha_j \gamma_j X_{ji} G_i = \alpha_j \gamma_j \sum_{i=1}^n X_{ji} G_i \quad (3)$$

Then,

$$\begin{aligned} F_j &= \alpha_j \frac{\sum_{i=1}^n G_i X_{ji}}{\sum_{i=1}^n G_i X_{ji}^2} \sum_{i=1}^n X_{ji} G_i \\ &= \alpha_j \frac{(\sum_{i=1}^n G_i X_{ji})^2}{(\sum_{i=1}^n G_i X_{ji}^2)^2} \sum_{i=1}^n G_i X_{ji}^2 \end{aligned} \quad (4)$$

The formula of the modal participation in quality of the j^{th} vibration mode is:

$$m_j = \frac{(\sum_{i=1}^n G_i X_{ji})^2}{(\sum_{i=1}^n G_i X_{ji}^2)^2} \sum_{i=1}^n G_i X_{ji}^2 \quad (5)$$

Substituting (5) into (4) yields:

$$F_j = \alpha_j m_j \quad (6)$$

Because the modal maximum responses do not occur at the same time, the direct superposition of the modes' biggest reaction will cause the result to be larger (Haselton and Deierlein, 2008; Ermanno, 2014). By using random vibration theory, we can use the 'SRSS method' to estimate the biggest response for the structure, and then obtain better results. The formula is:

$$S = \sqrt{\sum S_j^2} \quad (7)$$

According to formula (7), the equivalent base shear value is:

$$V = \sqrt{\sum_{j=1}^m F_j^2} = \sqrt{\sum_{j=1}^m (\alpha_j m_j)^2} \quad (8)$$

If the structure weight is 'G', the shear-weight ratio of the lower floor is:

$$\lambda = \frac{V}{G} = \frac{\sqrt{\sum_{j=1}^m (\alpha_j m_j)^2}}{\sqrt{G^2}} = \sqrt{\sum_{j=1}^m \alpha_j^2 \left(\frac{m_j}{G}\right)^2} \quad (9)$$

where $\frac{m_j}{G}$ is the mass participation factor. From formula (9), we can notice that the shear-weight ratio has a relationship with the mass participation factor and the vibration mode influence factor.

ADJUSTMENT OF SHEAR-WEIGHT RATIO IN SATWE SOFTWARE

Automatic Adjustment

The SATWE software gives a control switch. By using it, the designer can adjust the shear-weight ratio. When the total shear force of the bottom floor does not

satisfy the requirements, if the switch is selected, the floor's shear will be adjusted according to the shear-weight ratio ruled in the specification. The basement will not be adjusted. For the weak layer of the vertical irregular structures, we should multiply the coefficient by 1.15 (Junwon, 2013; Shrabony, 2014). The calculation results in WNL.OUT file of SATWE are original values, but the results in the WWNL.OUT are the values adjusted.

In order to show the adjustment progress in the 'SATWE' software clearly, we give an example. The details of the project are: three underground levels, 26 floors, shear wall structure. The total height above the ground is 99.450m, and the seismic fortification intensity is 8 degrees (0.2g), II site. The total weight of the structure is 34320.012t, and the first layer plan and perspective of the structure are shown in Figures 4-6.

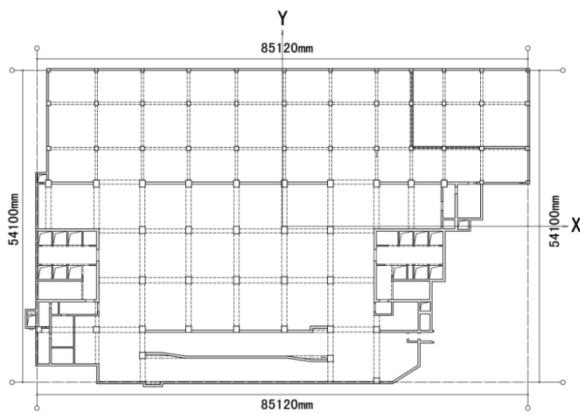


Figure (4): Structure layout of the first layer

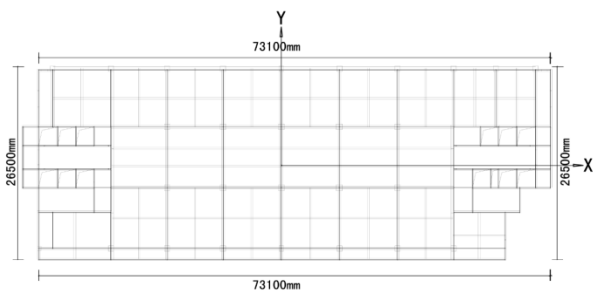


Figure (5): Structure layout of standard layer

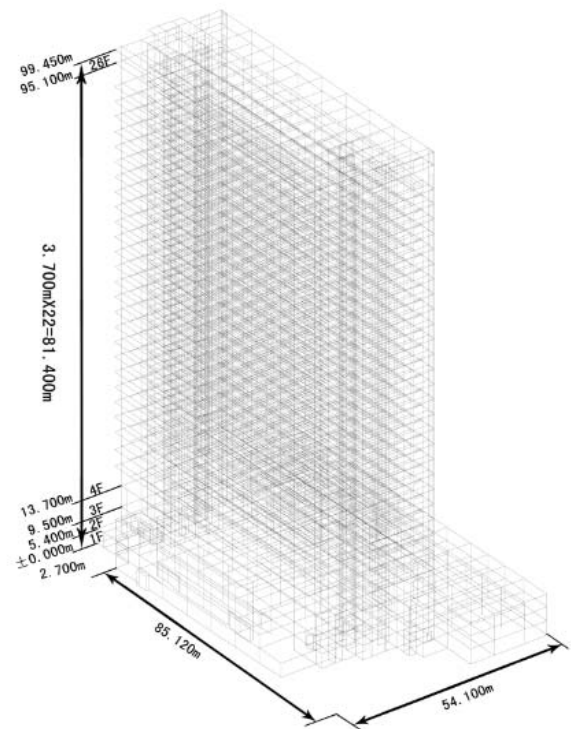


Figure (6): 3D model of the structure

The structure's cycle, the shear force and the shear-weight ratio are shown in Tables 3-5.

Table 3. The cycle of the three main modes

Vibration modes	Cycle (s)	Translational coefficient	Torsion coefficient
1	2.2785	1.00 (0.00+1.00)	0.00
2	2.1010	0.99 (0.99+0.01)	0.01
3	1.8929	0.01	0.99

Table 4. Earthquake shear force and shear weight of x- direction in SATWE output

Floors	$F_x (kN)$	$V_x (kN)$	Shear-weight ratio
36	272.96	272.96	8.23%
35	582.72	855.51	7.91%
3	91.74	8716.85	3.12%
2	82.47	8769.81	3.00%
1	75.51	8817.87	2.57%

Table 5. Earthquake shear force and shear weight of y-direction in SATWE output

Floors	$F_y (kN)$	$V_y (kN)$	Shear-weight ratio
26	375.20	375.20	11.32%
25	773.21	1148.23	10.62%
3	121.34	9598.01	3.43%
2	114.07	9684.48	3.31%
1	137.64	9788.16	2.85%

After selecting the control switch, we can obtain the adjustment coefficients which are shown in Table 6.

Table 6. Shear-weight ratio adjustment coefficient of each floor (according to the seismic code (5.2.5))

Floors	Coefficient of x	Coefficient of y	Yes/No
1	1.000	1.000	No
2	1.067	1.000	Yes
3	1.067	1.000	Yes
4	1.067	1.000	Yes
5	1.067	1.000	Yes
25	1.067	1.000	Yes
26	1.067	1.000	Yes

The adjustment process of the shear-weight ratio is as follows: the total weight of the structure is 34320.012t; the quality produced by the constant load of the first layer is 4818.1t; the quality produced by the live load of the first layer is 260.4t; the quality produced by the constant load of the second layer is 1182.3t; the quality produced by the live load of the second layer is 84.1t. The shear of the first layer is $V_{1x} = 8817.87k, V_{1y} = 9788.16kN$. So, the shear-weight ratio of this layer is:

$$\lambda_{1x} = \frac{V_{1x}}{\sum_{j=1}^{26} G_j} = \frac{8817.87}{34320.012 \times 10} = 0.02596 .$$

$$\lambda_{1y} = \frac{V_{1y}}{\sum_{j=1}^{26} G_j} = \frac{9788.16}{34320.012 \times 10} = 0.02852 .$$

The results above are the same as the output of the software.

The second layer's shear:

$$V_{2x} = 8769.81kN, V_{2y} = 9684.48kN.$$

So, the shear-weight ratio of this layer is:

$$\lambda_{2x} = \frac{8769.8}{[34320.012 - (4818.1 + 260.4)] \times 10} = 0.02999 \approx 3.00\%$$

$$\lambda_{2y} = \frac{9684.48}{[34320.012 - (4818.1 + 260.4)] \times 10} = 0.03311 \approx 3.31\%$$

The results are the same as the output of the software.

The structure's translational period is less than 3.5s, and its seismic fortification intensity is 8 degrees (0.2g). So, the minimum shear-weight ratio is 0.032. The first floor is the basement, its shear-weight ratio needs not be adjusted. Because the second floor's shear-weight ratio in the x direction does not satisfy the requirements, we should adjust the shear-weight ratio of this floor and the floor above it. The adjustment coefficient is $\frac{0.032}{0.030} \approx 1.067$. This coefficient should be adopted by all the floors above the basement of this building. The second floor's shear-weight ratio in the y direction satisfies the requirements, so it should not be adjusted. All of the results are the same as the output of the SATWE software.

Segment Adjustment

According to the instructions of the SATWE software, when the moving displacement scaling factor is 0, we should adjust the shear-weight ratio according to the section controlled by acceleration. When the moving displacement scaling factor is 1, we should adjust the shear-weight ratio according to the section controlled by displacement. When the moving displacement scaling factor is between 0 and 1, we should adjust the shear-weight ratio according to the section controlled by speed. The characteristic period of the above example is 0.35s, so we should adjust the shear-weight ratio according to the section controlled

by displacement; that is to say, the moving displacement should be 1.0. The output results calculated by the SATWE software are shown in Table 7.

Table 7. Shear-weight ratio adjustment coefficient of each floor after segment adjustment (according to the seismic code (5.2.5))

Floor	Coefficient of x	Coefficient of y	Yes/No
1	1.000	1.000	No
2	1.067	1.000	Yes
3	1.064	1.000	Yes
4	1.063	1.000	Yes
5	1.062	1.000	Yes
6	1.060	1.000	Yes
7	1.059	1.000	Yes
8	1.058	1.000	Yes
25	1.025	1.000	Yes
26	1.024	1.000	Yes

The process of adjustment of the shear-weight ratio is as follows:

The first floor is the basement, which does not need to be adjusted. The second floor's shear-weight ratio is:

$$\lambda_{2x} = \frac{8769.8}{[34320.012 - (4818.1 + 260.4)] \times 10} = 0.02999 \approx 3.00\%$$

$$\lambda_{2y} = \frac{9684.48}{[34320.012 - (4818.1 + 260.4)] \times 10} = 0.03311 \approx 3.31\%$$

From the results above, we should adjust the x direction's shear-weight ratio only. Because the moving displacement factor of the x direction is 1.0, we can adjust the ratio according to the same coefficient, which is $\Delta\lambda_0 = 3.2\% - 3\% = 0.2\%$.

The second floor's increment of the x direction is:

$$\begin{aligned} \Delta F_{Ek2} &= \sum_{j=2}^{26} G_j \times \Delta\lambda_0 \\ &= 0.2\% \times [34320.012 - (4818.1 + 260.4)] \times 10 \\ &= 584.83kN \end{aligned}$$

The second floor's adjustment coefficient is:

$$\lambda_{2x} = \frac{V_{2x} + \Delta F_{Ek2}}{V_{2x}} = 1.0666 \approx 1.067$$

The results are the same as the output of the software.

The third floor's shear is $V_{3x} = 8716.85kN$, so the corresponding shear increment value is:

$$\begin{aligned} \Delta F_{Ek3} &= \sum_{j=3}^{26} G_j \times \Delta\lambda_0 \\ &= 0.2\% \times [34320.012 - (4818.1 + 260.4) - (1182.3 + 84.1)] \times 10 \\ &= 559.5kN \end{aligned}$$

The third floor's adjustment is:

$$\lambda_{3x} = \frac{V_{3x} + \Delta F_{Ek3}}{V_{3x}} = 1.0642 \approx 1.064$$

The results are the same as the output of the software.

Other floors' results are the same as those of this floor.

It should be noticed that when the moving displacement factor is 0.5, the 'SATWE' software does not adjust the horizontal seismic force according to clause 5.2.5 in the seismic code. The software just adopts the average value of the shear-weight ratio adjustment when the moving displacement factors are "0" and "1".

CONCLUSIONS

The shear-weight ratio is an important parameter for long period structures. It can make up for the shortage that the specification is unable to make an accurate assessment to long period structures. We explored the influence factors of shear-weight ratio and the relationship between shear-weight ratio and its influence factors. After the introduction of the shear-weight ratio, we introduced the adjustment of the

shear-weight ratio in SATWE software through an example. The following conclusions can be drawn:

- (1) In order to prevent the building's local damage caused by the reason that vibration mode number is too little, we must fully consider the control conditions of the shear-weight ratio.
- (2) If the shear-weight ratio is too small, we should adjust the structure type. We should not only adjust the shear-weight ratio to meet the requirements of the specification.
- (3) When using the method of the segment adjustment to adjust the shear-weight ratio, we should judge the phases of construction cycle and then adjust it according to the specification.
- (4) When the moving displacement factor is 0.5, the 'SATWE' software does not adjust the horizontal seismic force according to clause 5.2.5 in the seismic code. It just adopts the average value of the shear-weight ratio adjustment when the moving displacement factors are "0" and "1".

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