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Prediction Formula of Superstructure for Isolated building Based on 2DOF

Part 1: Equivalent Height of 2DOF Model

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MDOF Model, 2DOF Model, Isolated building,
Mass distribution, Eigen analysis

1. Introduction

The base-isolated building showed the benefits of restraining the damage of the mainframe and being easy to repair after an earthquake comparing with the seismic structure. Therefore, base-isolated buildings are increasing these years. In general, the period of superstructure is short obviously comparing with the period of isolation layer, therefore superstructure could be regarded as rigid body. However, when the period of superstructure is long (e.g., warehouse or high building), the effect of superstructure is considered necessary.

Fu et al. [1] proposed a prediction equation of superstructure for base-isolated building with steel dampers considering equivalent period ratio between the isolation layer and the superstructure T_{eq}/T_U. Li et al. [2] verified Fu's prediction equation could be used for base-isolated building with oil dampers. However, in Fu et al.[1]'s equation, the effect of the mass ratio between superstructure and isolation layer, the mass distribution, and the number of mass points for superstructure are not considered.

In this paper, a prediction formula of superstructure for isolated building considering the period ratio and mass ratio between superstructure and isolation layer is proposed. In the part 1, the equivalent height of two-degree-of-freedom (2DOF) model of isolation building is investigated. In the part 2, the prediction formula by 2DOF model is proposed. And the application range of Fu's prediction equation is confirmed.

2. Analysis Model and Mass Distribution

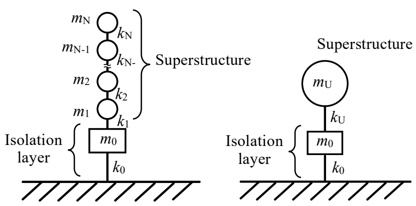
Fig. 1 shows the analysis models, (a) is multi-degree-of-freedom (MDOF) model of the base-isolated building, where the superstructure has N lump-masses m_i (i =1~N), and the isolation layer has a lump-mass m_0. k_i (i =1~N) and k_0 shows the stiffness of i story and isolation layer, respectively. (b) is two-degree-of-freedom (2DOF) model of the base-isolated building considered in this study, where the superstructure is considered as a whole lump-mass m_U and the isolation layer has a lump-mass m_0. k_U is the stiffness of superstructure.

Fig. 2 shows the mass distribution of superstructure for MDOF model, 4 cases ((a)~(b) = Case A ~ Case D) mass distribution are adopted in this paper. Case A is rectangular distribution. The others are trapezoidal distribution. Case B of mass distribution ratio m_N/m_1 = 1/3. Case C of mass distribution ratio m_N/m_1 = 1/6. And Case D of mass distribution ratio m_N/m_1 = 3. Fig. 3 shows the 1st mode eigenvector of superstructure for MODF model. And the 1st eigenvalue of i story ${}_1\phi_i = i$ (i =1~N).

Eq. 1 shows the stiffness of superstructure k_i (i =1~N). Eq. 2 shows the stiffness of isolation layer k_0.

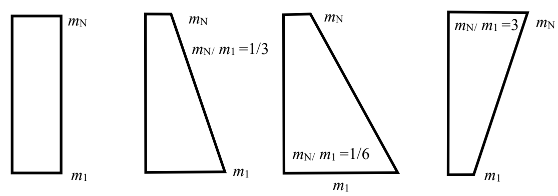
$$k_i = \frac{{}_1\omega^2 \cdot m_i \cdot {}_1\phi_i + \left({}_1\phi_{i+1} - {}_1\phi_i\right) \cdot k_{i+1}}{{}_1\phi_i - {}_1\phi_{i-1}}, \quad k_0 = \frac{4\pi^2}{T_0^2}\Sigma m \qquad (1, 2)$$

Where, ${}_1\omega$ is 1st circular frequency of superstructure, ${}_1\omega = 2\pi / T_U$. T_U is period of superstructure. Σm total mass of building, $\Sigma m = m_U + m_0$. T_0 is period of isolation layer.



(a) MDOF　　(b) 2DOF

Fig. 1 Analysis Model



(a) Case A　(b) Case B　(c) Case C　(d) Case D

Fig. 2 Mass Distribution of Superstructure

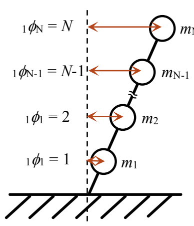


Fig. 3 1st Eigenvector

3. 1st Mode Period Ratio and 1st Mode Shape Ratio

When the periods of 2DOF and MDOF are close, meanwhile the ratio of top eigenvalue between 2DOF and MDOF is stable, the 1st mode shape of 2DOF could be used to predict 1st mode of MDOF. Furthermore, the prediction equation of superstructure could be proposed. (Part 2)

3.1. 1st Mode Period Ratio

Fig. 4 shows relationship between mass ratio m_U/m_0 and 1st mode period ratio ${}_1T_{2DOF}/{}_1T_{MDOF}$. ${}_1T_{2DOF}$ is calculated by Eq. 10 of part 2 and ${}_1T_{MDOF}$ is calculated by eigen analysis. (a)~(d) are various number of mass points (5, 15, 30 and 50DOF). (1)~(4) are various mass distribution of superstructure (case A~D). Horizontal axis is m_U/m_0 and vertical axis is ${}_1T_{2DOF}/{}_1T_{MDOF}$. For legend, solid lines are various T_0/T_U from 1.0 s to 5.0 s. With T_0/T_U increases, the gradient color become from red to bule. The dotted line means $T_0/T_U = 2.0$.

According to Fig. 4, when number of mass point of superstructure, mass distribution pattern, and mass ratio m_U/m_0 are same, with the period ratio T_0/T_U increases, the 1st mode period ${}_1T_{2DOF}/{}_1T_{MDOF}$ decreases. And when $T_0/T_U \geq 2.0$ s (general base-isolated building [3], [4]), ${}_1T_{2DOF}/{}_1T_{MDOF} < 1.057$. In other words, the periods of 2DOF and MDOF models are mostly same for general isolated building. Moreover, when number of mass point of superstructure is same, the 1st mode period ${}_1T_{2DOF}/{}_1T_{MDOF}$ of case D < case A < case B < case C, namely with the building centre-of-gravity position decreases, the 1st mode period ${}_1T_{2DOF}/{}_1T_{MDOF}$ increases. In addition, when mass distribution of superstructure is positive trapezoidal distribution, with the mass ratio T_0/T_U increases, the 1st mode period ${}_1T_{2DOF}/{}_1T_{MDOF}$ tends to increase and then decrease. Lastly, the effect of mass point on 1st mode period ${}_1T_{2DOF}/{}_1T_{MDOF}$ is very small.

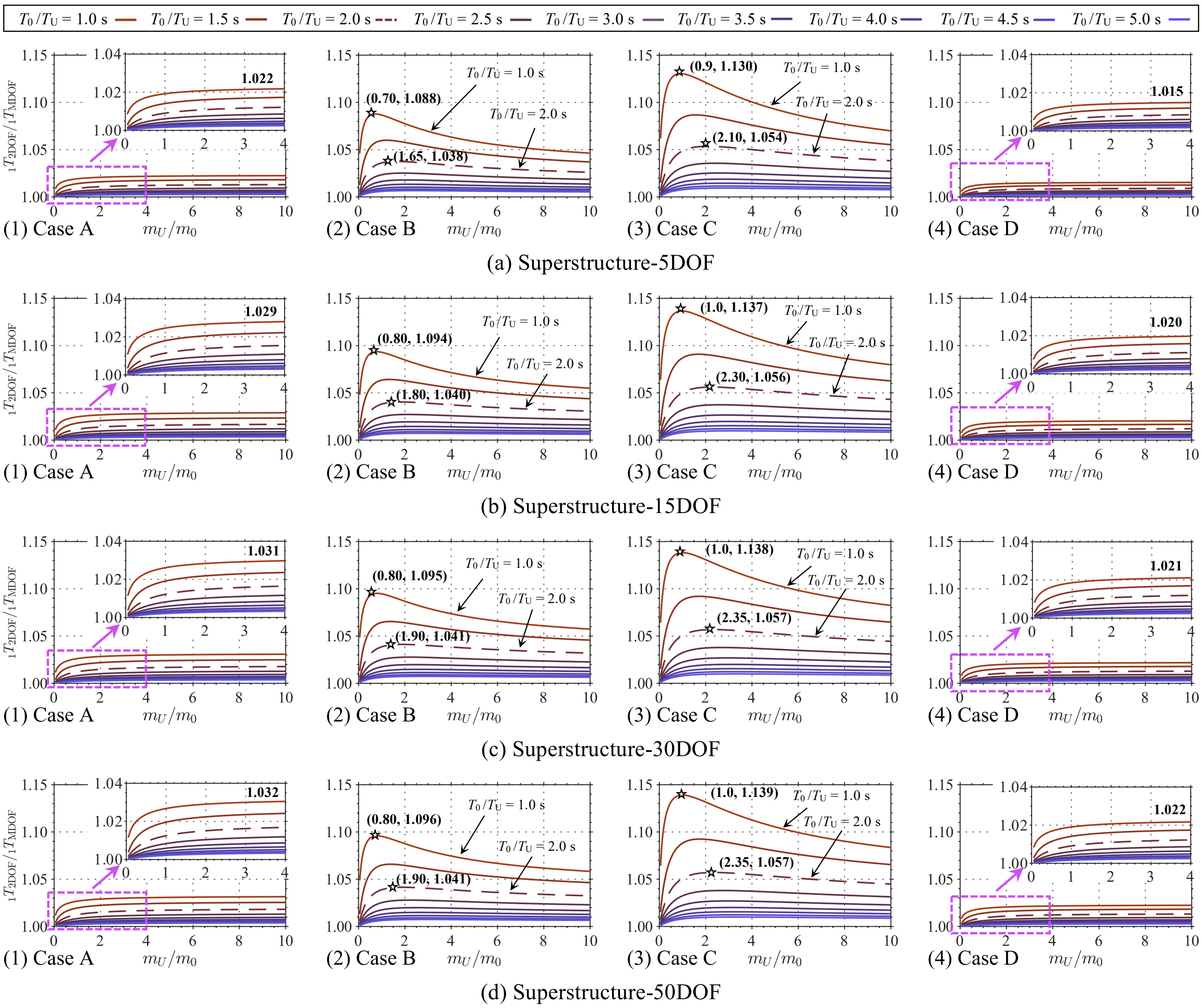


Fig. 4 1st Mode Period Ratio

3.2. 1st Mode Shape Ratio

Fig. 5 shows the relationship between the mass ratio m_U/m_0 and 1st mode shape ratio ${}_1\phi_{U,2DOF}/{}_1\phi_{N,MDOF}$. Where ${}_1\phi_{U,2DOF}$ (calculated by Eq. 12 of part 2) and ${}_1\phi_{N,MDOF}$ (calculated by eigen analysis) are corresponding values when ${}_1\phi_{0,2DOF}$ = ${}_1\phi_{0,MDOF}$ = 1 for 2DOF and MDOF models, respectively. (a) ~ (d) are various number of mass points for superstructure. (a) ~ (d) are 5, 15, 30 and 50DOF. (1) ~ (4) are various mass distribution of superstructure (case A ~ D). Horizontal axis is mass ratio m_U/m_0 and vertical axis is 1st mode shape ratio ${}_1\phi_{U,2DOF}/{}_1\phi_{N,MDOF}$. For legend, solid lines are various period ratio T_0/T_U. With T_0/T_U increases, the gradient color become from red to bule. The dotted line means T_0/T_U = 2.0.

According to Fig. 5, when number of mass point of superstructure, mass distribution pattern, and mass ratio m_U/m_0 are same, with the period ratio T_0/T_U increases, the 1st mode shape ${}_1\phi_{U,2DOF}/{}_1\phi_{N,MDOF}$ trends to close 1. Moreover, when number of mass point of superstructure, mass distribution pattern, and mass ratio T_0/T_U are same, with the mass ratio m_U/m_0 increases, 1st mode shape ratio ${}_1\phi_{U,2DOF}/{}_1\phi_{N,MDOF}$ trends to increase. And when $T_0/T_U \geq 2.0$ s (general base-isolated building [3], [4]), the effect of mass ratio m_U/m_0 on ${}_1\phi_{U,2DOF}/{}_1\phi_{N,MDOF}$ is not obvious. In other words, the effect of mass ratio m_U/m_0 on 1st mode shape ratio ${}_1\phi_{U,2DOF}/{}_1\phi_{N,MDOF}$ is not considered necessary for general base-isolated building. In addition, when number of mass point of superstructure, mass ratio and period ratio are same, the 1st mode shape ${}_1\phi_{U,2DOF}/{}_1\phi_{N,MDOF}$ of case D > case A > case B > case C, namely with the centre-of-gravity position decreases, the 1st mode shape ratio ${}_1\phi_{U,2DOF}/{}_1\phi_{N,MDOF}$ increases. Lastly, the effect of number of mass point on 1st mode shape ${}_1\phi_{U,2DOF}/{}_1\phi_{N,MDOF}$ is very small .

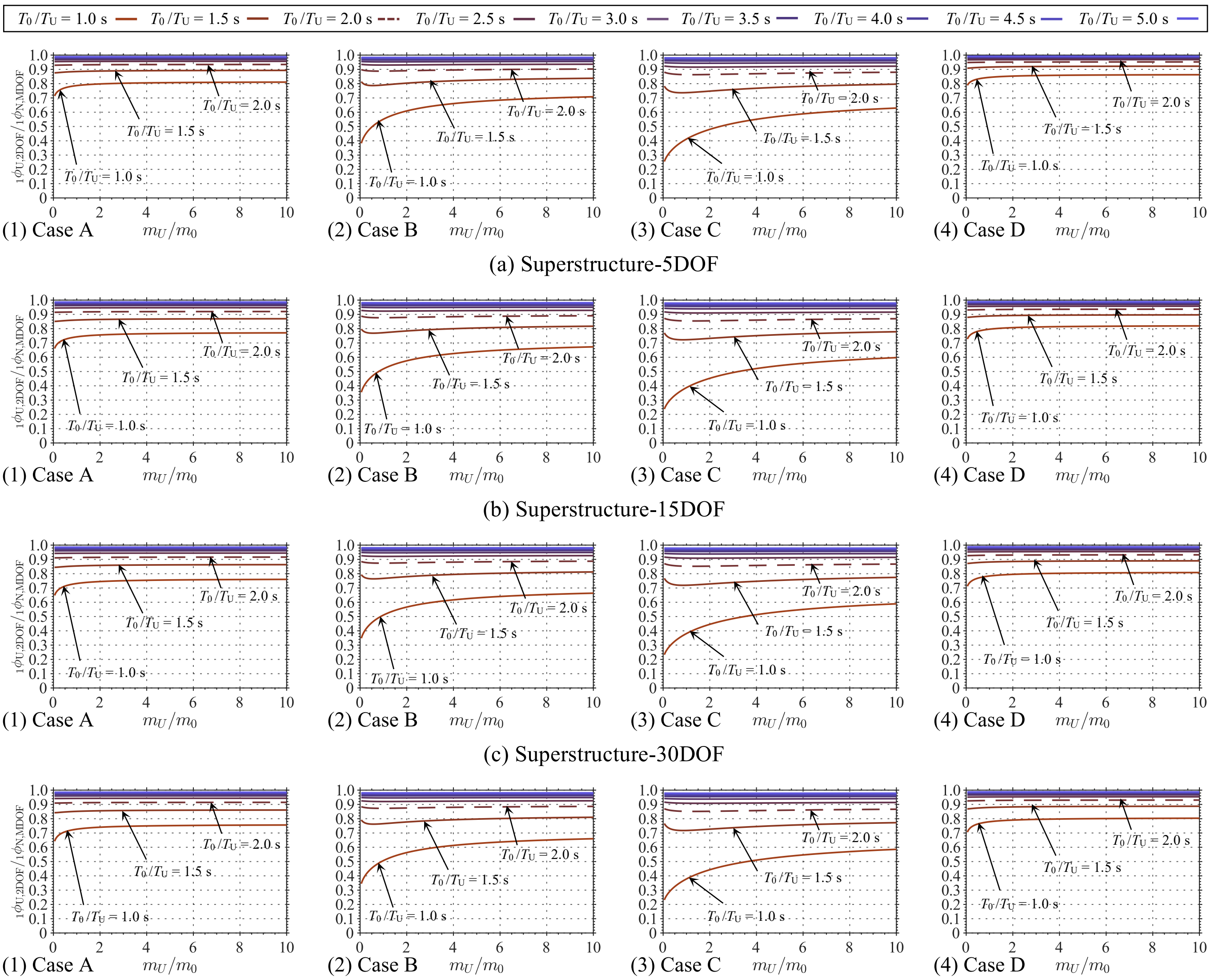


Fig. 5 1st Mode Shape Ratio

4. Equivalent Height

In this chapter the equivalent height ratio λ_{eq} is proposed. As shown in Fig.6, which is 1st mode eigenvector of isolated building, the equivalent height ratio λ_{eq} is the ratio between equivalent height of 2DOF model H_{eq} and the height of MDOF H. H_{eq} is corresponding height of MDOF model when corresponding eigenvalue are same (${}_1\phi_{U,2DOF}$ = ${}_1\phi_{eq,MDOF}$). Where, the eigenvalues of isolation layer of two type models are same and uniformly 1. And the equivalent height ratio λ_{eq} is shown in Eq. 3.

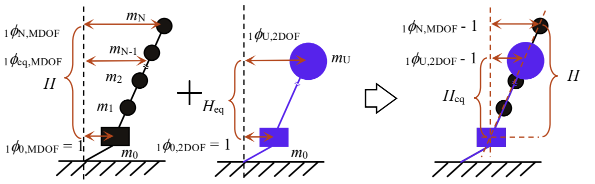


Fig. 6 1st Mode Eigenvector of Isolated Building

$$\lambda_{eq} = \frac{H_{eq}}{H} = \frac{{}_1\phi_{U,2DOF} - {}_1\phi_{0,2DOF}}{{}_1\phi_{N,MDOF} - {}_1\phi_{0,MDOF}} = \frac{{}_1\phi_{U,2DOF} - 1}{{}_1\phi_{N,MDOF} - 1} \quad (3)$$

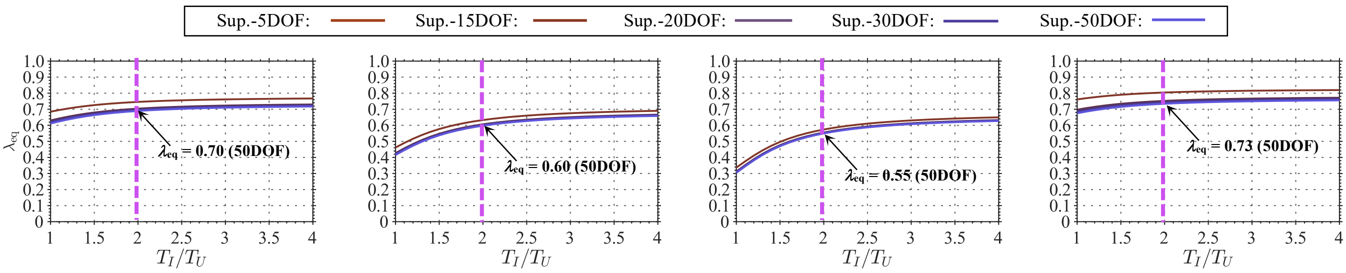
Fig.7 & 8 shows the relationship between period ratio T_0 /T_U and equivalent height ratio λ_{eq}. Fig. 7 shows the results when mass ratio m_U /m_0 = 2. Fig. 8 shows the results when number of mass points of superstructure is 50. (1)~(4) are various mass distribution of superstructure from case A to case D. For legend, solid lines are various number of mass points of superstructure (Fig. 7) or mass period (Fig. 8). With number of mass points of superstructure (Fig. 7) or mass period m_U /m_0 (Fig. 8) increases, the gradient color become from red to bule.

According to Fig.7, when mass distribution and period ratio T_0 /T_U are same, the effect of number of mass points on equivalent height ratio λ_{eq} are not significant. Moreover, when mass distribution and number of mass points are same, with T_0 /T_U increases, λ_{eq} is increase. In addition, when number of mass points and T_0 /T_U are same, λ_{eq} of case D > case A > case B > case C. In general, period ratio T_0 /T_U ≥ 2 s for isolated building, therefore, λ_{eq} ≥ 0.55 (case C).

Similarly, according to Fig.8, when mass distribution and period ratio are same, the effect of mass ratio m_U /m_0 on equivalent height ratio λ_{eq} are not significant. In addition, when number of mass points and T_0 /T_U are same, λ_{eq} of case D > case A > case B > case C = 0.55. In summary, for safety reasons, to let λ_{eq} = 0.50.

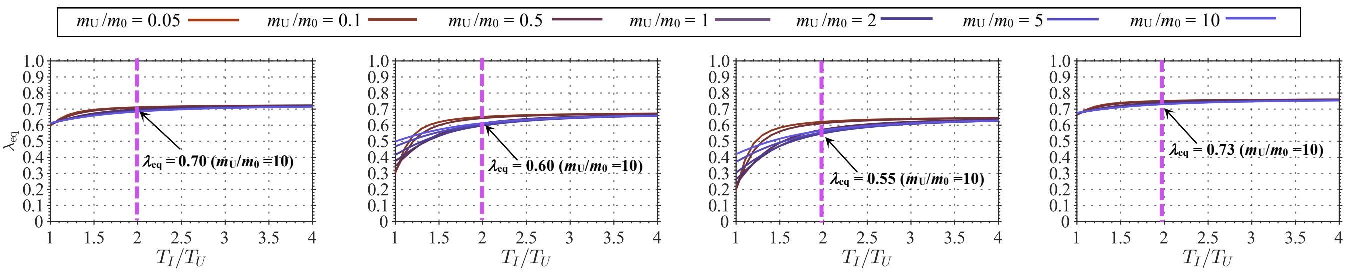
5. Conclusion

In this paper, a prediction formula of superstructure for isolated building considering the period ratio and mass ratio between superstructure and isolation layer was proposed. In this part 1, the periods of 2DOF and MDOF models were mostly same for general isolated building (period ratio T_0 /T_U ≥ 2 s) was verified. And the equivalent height ratio λ_{eq} (H_{eq}/H) = 0.5 was confirmed.



(1) Case A (2) Case B (3) Case C (4) Case D

Fig. 7 Equivalent Height Ratio (m_U /m_0 = 2.0)



(1) Case A (2) Case B (3) Case C (4) Case D

Fig. 8 Equivalent Height Ratio (Superstructure-50DOF)

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