Response Spectra Analysis of Base Isolated Building

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***Abstract*— Conventionally, seismic design of building structures is based on the concept of increasing the resistance capacity of the structure against earthquake by employing, for example, the use of shear walls, braced frames, or moment resistant frames. However, these traditional methods often results in high floor accelerations for stiff buildings, or large inter-storey drifts for flexible buildings. Because of this, the building contents and nonstructural components may suffer significant damage during a major earthquake, even if the structure itself remain basically intact. In order to minimize inter-storey drifts, in addition to reducing floor accelerations, the concept of base isolation is increasingly being adopted. Base isolation also been referred to as passive control as the control of structural motions is not exercised through a logically driven control system.**

This paper represents the analytical approach to find the response of the base isolated structures using concept of response Spectrum defined in IS: 1893 – 2002 (Part I). Because of the involvement of large parameters, use of software is inevitable for the solution of base isolated structures. However, this paper shows analytical way of solution for small SDOF building structure. The concept developed hereby can be extended further for large size building structures.

***Index Terms*—Base Isolated Structures, Mode shapes, Participation Factor, Response Spectrum for variable damping.**

I. Introduction

For structure in high seismicity regions, earthquake loading is considered the most significant and possibly the most destructive external load, particularly for low to medium rise buildings. Conventionally, seismic design of buildings is based on the concept of increasing the resistance capacity of the structures against earthquake by employing shear walls, braced frames or moment resisting frames. However, these methods of resistance often results in high floor accelerations for stiff buildings, or large inter-story drift for flexible building [1],[2].

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Modern buildings contain extremely sensitive and costly equipment that have become vital in business, commerce, education and health care. Electronically kept records are essential to the proper functioning of our society & this kind of contents are more costly and valuable then the buildings themselves. In addition, hospitals, communications and emergency centers, police stations and fire stations must be operational when needed most, immediately after an earthquake. The above mention fact spurs a question of - how to protect the important buildings? A simple logical answer to the question is - can the buildings be detached from the ground in such a way that the earthquake motions does not transferred to the building, or at the least greatly reduced ? This simple logic is feasible in the form of seismic base isolation of the buildings [3].

Seismic isolation consist essentially the installation of mechanisms which decouples the buildings, and/or its content, from partially damaging earthquake induces ground or support motions. This decoupling is achieved by increasing the flexibility of the system, together with providing appropriate damping to resist the amplitude of the motion caused by the earthquake. The concept of isolating buildings from the damaging effects of earthquake is not new, but gets momentum only after the invention of materials with the hybrid characteristics [4].

The advantage of seismic isolation includes the ability to eliminate or very significantly reduce structural and non-structural damage, to enhance the safety of the building contents and architectural facades, and to reduce seismic design forces. This potential benefits are greatest for stiff structures fixed rigidly to the ground such as low and medium rise building, nuclear power plants, bridges etc [5],[6].

II. Building Geometry

A fixed base single story building was considered for the response spectrum analysis of base isolated structures. The main aim behind this consideration was to keep problem upto SDOF system to avoid computational effort without compromising the insight of the problem.

The plan dimension of SDOF system was 3.0 m × 3.0 m. The height of building up to level of foundation support was 4.0 m. The slab thickness undertaken was 120 mm. The beams supporting slab on all four edges was of size 230 mm × 230 mm and four column supporting beams were also of same size. Because of higher in-plane stiffness of slab, it was assumed that it will act as rigid diaphragm.

The building was assumed to be in Ahmedabad city with seismic zone of III. It was also considered that the soil available beneath of building in medium stiff. The above mentioned parameter shall decide the seismic demand requirement for the building as per IS: 1893 – 2002 (Part-I). The building has OMRF frame for earthquake resistance. The importance of building was considered to be normal usage. The mass of the building was calculated to be 5448.53 kg.

The natural frequency and period of vibration for the building was:

$$\omega_n = \sqrt{\frac{k}{m}} = 28.33 \text{ rad/sec.}$$

$$T_n = \frac{2\pi}{\omega_n} = 0.223 \text{ sec}$$

III. RESPONSE SPECTRUM

The response spectrum curve with 5 % of critical damping for different types of soils specified in IS: 1893-2002 (Part-I) was used for the analysis. Two risk level of earthquake defined in IS:1893- 2002 (Part-I) was considered for the analysis namely, Design Based Earthquake (DBE) with 10 % probability in 50 years and Maximum Considered Earthquake (MCE) with 2 % of probability of being exceeded in 50 years. In addition, it was assumed that the acceleration spectrum is approximately equal to the pseudo acceleration spectrum at a critical damping ratio up to 20 % for the purpose of generating the displacement spectra.
The acceleration response spectra for different level of critical damping is generated and shown in Fig. 1 below.

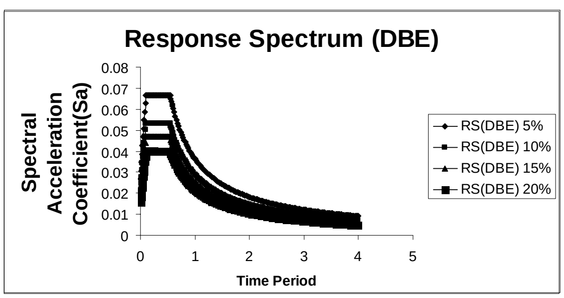

Fig. 1 Spectral Acceleration Response Spectra

The displacement spectra based on above generated acceleration spectra was derived and shown in Fig. 2, below.

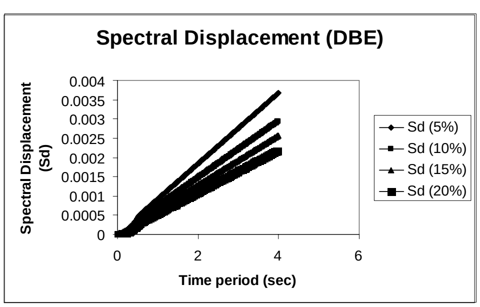

Fig. 2 Spectral Displacement Response Spectra

Similarly, the acceleration response spectra for different level of critical damping was generated for MCE and shown in Fig. 3, below.

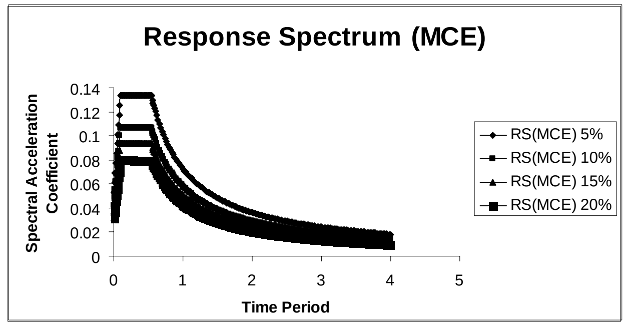

Fig. 3 Spectral Acceleration Response Spectra

Based on above spectral acceleration response spectra spectral displacement spectra for different level of damping was generated and shown in Fig. 4, below.

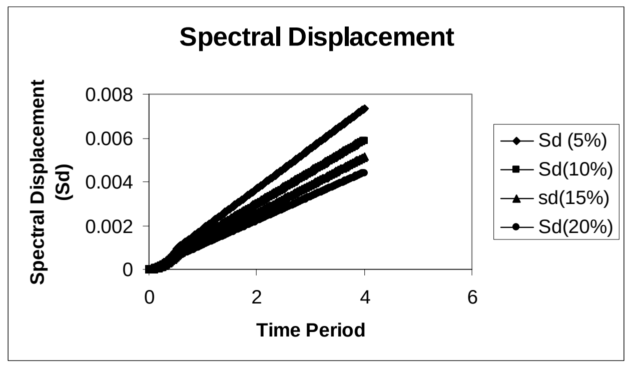

Fig. 4 Spectral Displacement Response Spectrum

IV. ANALYTICAL FORMUALTION

Response of building with calculated time period with the help of spectral acceleration and spectral displacement were obtained first. Therefore, the linear response of the building for the design based earthquake is,

$$\max\left[x(t)\right] = S_d = 8.18\times10^{-5}\text{ m}$$

$$\max\left[\ddot{y}(t)\right] = S_a = 0.06675\text{m/sec}^2$$

$$\max\left[V(t)\right] = mS_a = 363.69\text{N}$$

$$\frac{V}{W} = 0.0068$$

Table 1 indicates the values of maximum displacement response, maximum acceleration and base shear for different level of damping.

Damping	x(t) in m	$\ddot{y}(t)$ in m/sec^2	V(t) in N	$\frac{V}{W}$
10%	6.55×10^{-5}	0.0534	290.91	0.00544
15%	5.73×10^{-5}	0.04673	254.61	0.00476
20%	4.91×10^{-5}	0.04005	218.21	0.00408

The linear response of the fixed-base structure for the maximum considered earthquake is,

$$\max[x(t)] = S_d = 0.00016 \text{ m}$$

$$\max\left[\ddot{y}(t)\right] = S_a = 0.13325 \text{m}/\sec^2$$

$$\max[V(t)] = mS_a = 726.06\text{N}$$

$$\frac{V}{W} = 0.0136$$

Table 2 indicates the values of maximum displacement, maximum acceleration and base shear for different levels of damping.

Damping	X(t) in m	$\ddot{y}(t)$ in m/sec^2	V(t) in N	$\frac{V}{W}$
10 %	0.000131	0.1066	580.81	0.0109
15 %	0.000114	0.09328	508.24	0.0095
20 %	9.8×10^{-5}	0.07995	435.61	0.00815

As base isolators should provide the flexibility at the base of the structures along with it's axial load carrying capacity. Therefore, the stiffness of base isolator should be less compared to the stiffness of fixed base structures. General value for base isolator stiffness is about 1/10 the stiffness of the fixed base stiffness.

In this case, $\alpha = 0.1$ and it leads,

$$\omega_1 = \sqrt{\frac{\alpha+2-\sqrt{\alpha^2+4}}{2}}\ \omega_n = \sqrt{\frac{0.1+2-\sqrt{(0.1)^2+4}}{2}}\ (28.33) = 6.255 \text{ rad/s}$$

$$\omega_1 = \sqrt{\frac{\alpha+2+\sqrt{\alpha^2+4}}{2}}\ \omega_n = \sqrt{\frac{0.1+2+\sqrt{(0.1)^2+4}}{2}}\ (28.33) = 40.57 \text{ rad/s}$$

$$T_1 = \frac{2\pi}{\omega_1} = \frac{2\pi}{6.255} = 1.005 \sec$$

$$T_2 = \frac{2\pi}{\omega_2} = \frac{2\pi}{40.57} = 0.155 \sec$$

$$r_1 = \frac{\alpha+\sqrt{\alpha^2+4}}{2} = \frac{0.1+\sqrt{(0.1)^2+4}}{2} = 1.05$$

$$r_2 = \frac{\alpha-\sqrt{\alpha^2+4}}{2} = \frac{0.1-\sqrt{(0.1)^2+4}}{2} = -0.95$$

$$\phi_{roof(1)} = \begin{Bmatrix} 1/1.05 \\ 1.0 \end{Bmatrix} = \begin{Bmatrix} 0.95 \\ 1.0 \end{Bmatrix},\ \phi_{roof(2)} = \begin{Bmatrix} -1/0.95 \\ 1.0 \end{Bmatrix} = \begin{Bmatrix} -1.05 \\ 1.0 \end{Bmatrix}$$

and mode participation factors can be calculated as,

$$\Gamma_{roof(1)} = \frac{\begin{Bmatrix} 0.95 \\ 1.0 \end{Bmatrix}^T \begin{bmatrix} 1.0 & 0.0 \\ 0.0 & 1.0 \end{bmatrix} \begin{Bmatrix} 1.0 \\ 1.0 \end{Bmatrix}}{\begin{Bmatrix} 0.95 \\ 1.0 \end{Bmatrix}^T \begin{bmatrix} 1.0 & 0.0 \\ 0.0 & 1.0 \end{bmatrix} \begin{Bmatrix} 0.95 \\ 1.0 \end{Bmatrix}} = 1.024$$

$$\Gamma_{roof(2)} = \frac{\begin{Bmatrix} -1.05 \\ 1.0 \end{Bmatrix}^T \begin{bmatrix} 1.0 & 0.0 \\ 0.0 & 1.0 \end{bmatrix} \begin{Bmatrix} 1.0 \\ 1.0 \end{Bmatrix}}{\begin{Bmatrix} -1.05 \\ 1.0 \end{Bmatrix}^T \begin{bmatrix} 1.0 & 0.0 \\ 0.0 & 1.0 \end{bmatrix} \begin{Bmatrix} -1.05 \\ 1.0 \end{Bmatrix}} = -0.024$$

The displacement of the floors can be calculated using the modal superposition method. Therefore, first mode response is,

$$X^{(1)} = \max \begin{Bmatrix} x_1^{(1)}(t) \\ x_2^{(1)}(t) \end{Bmatrix} = \phi_{roof(1)} \Gamma_{roof(1)} S_d(T_1, \varsigma_1)$$

$$X^{(1)} = \begin{Bmatrix} 0.95 \\ 1.00 \end{Bmatrix} (1.024) S_d(T_1, \varsigma_1)$$

$$\ddot{y}^{(1)} = \max \begin{Bmatrix} \ddot{y}_1^{(1)}(t) \\ \ddot{y}_2^{(1)}(t) \end{Bmatrix} = \phi_{roof(1)} \Gamma_{roof(1)} S_a(T_1, \varsigma_1)$$

$$\ddot{y}^{(1)} = \begin{Bmatrix} 0.95 \\ 1.00 \end{Bmatrix} (1.024) S_a(T_1, \varsigma_1)$$

and the second mode response is,

$$X^{(2)} = \max \begin{Bmatrix} x_1^{(2)}(t) \\ x_2^{(2)}(t) \end{Bmatrix} = \phi_{roof(2)} \Gamma_{roof(2)} S_d(T_2, \varsigma_2)$$

$$X^{(2)} = \begin{Bmatrix} -1.05 \\ 1.00 \end{Bmatrix} (-0.024) S_d(T_2, \varsigma_2)$$

$$\ddot{y}^{(2)} = \max \begin{Bmatrix} \ddot{y}_1^{(2)}(t) \\ \ddot{y}_2^{(2)}(t) \end{Bmatrix} = \phi_{roof(2)} \Gamma_{roof(2)} S_a(T_2, \varsigma_2)$$

$$\ddot{y}^{(2)} = \begin{Bmatrix} -1.05 \\ 1.00 \end{Bmatrix} (-0.024) S_a(T_2, \varsigma_2)$$

The base isolator carries characteristic of less stiffness and high damping. Considering higher level of damping about 20% the spectral displacement & spectral acceleration response is as follows, in case of design based earthquake,

$$S_d(T_1 = 1.00, \varsigma_1 = 20\%) = 0.000552\text{m}$$

$$S_a(T_1 = 1.00, \varsigma_1 = 20\%) = 0.0218 \text{m}/\sec^2$$

Based on above values, displacement & acceleration response are,

For the first mode,

$$X^{(1)} = \begin{Bmatrix} 0.95 \\ 1.00 \end{Bmatrix} (1.024)(0.000552) = \begin{Bmatrix} 0.00054 \\ 0.00057 \end{Bmatrix} \text{m}$$

$$\ddot{y}^{(1)} = \begin{Bmatrix} 0.95 \\ 1.00 \end{Bmatrix} (1.024)(0.0218) = \begin{Bmatrix} 0.0212 \\ 0.0223 \end{Bmatrix} \text{m}/\sec^2$$

The variation into base shear because of this response is,

$$V^{(1)} = (5448.53)(0.0212) + (5448.53)(0.0223) = 237.011\text{N}$$

$$\frac{V^{(1)}}{W} = 237.011/53.45\times10^3 = 0.00443$$

For the second mode,

$$S_d(T_1 = 0.155, \varsigma_1 = 20\%) = 2.6\times10^{-5} \text{ m}$$

$$S_a(T_1 = 0.155, \varsigma_1 = 20\%) = 0.04 \text{m}/\sec^2$$

$$X^{(2)} = \begin{Bmatrix} -1.05 \\ 1.00 \end{Bmatrix} (-0.024)(0.000552) = \begin{Bmatrix} 0.139\times10^{-4} \\ -0.132\times10^{-4} \end{Bmatrix} \text{m}$$

$$\ddot{y}^{(2)} = \begin{Bmatrix} -1.05 \\ 1.00 \end{Bmatrix} (-0.024)(0.04) = \begin{Bmatrix} 0.001008 \\ -0.00096 \end{Bmatrix} \text{m}/\sec^2$$

Similarly, in case of maximum considered earthquake (very rare earthquake, the spectral displacement & spectral acceleration values are,

$$S_d(T_1 = 1.00, \varsigma_1 = 20\%) = 0.0011\text{m}$$

$$S_a(T_1 = 1.00, \varsigma_1 = 20\%) = 0.0435\text{m}/\sec^2$$

The displacement & acceleration response of buildings is,

$$X^{(1)} = \begin{Bmatrix} 0.95 \\ 1.00 \end{Bmatrix}(1.024)(0.0011) = \begin{Bmatrix} 0.00107 \\ 0.00112 \end{Bmatrix}\text{m}$$

$$\ddot{y}^{(1)} = \begin{Bmatrix} 0.95 \\ 1.00 \end{Bmatrix}(1.024)(0.0435) = \begin{Bmatrix} 0.0423 \\ 0.0445 \end{Bmatrix}\text{m}/\sec^2$$

and base shear value for the building is,

$$V^{(1)} = (5448.53)(0.0423) + (5448.53)(0.0445) = 472.93\text{N}$$

$$\frac{V^{(1)}}{W} = 472.93/53.45\times10^3 = 0.00885$$

For the second mode,

$$S_d(T_1 = 0.155, \varsigma_1 = 20\%) = 5.18\times10^{-5}\,\text{m}$$

$$S_a(T_1 = 0.155, \varsigma_1 = 20\%) = 0.08\text{m}/\sec^2$$

The displacement & acceleration response of the building is,

$$X^{(2)} = \begin{Bmatrix} -1.05 \\ 1.00 \end{Bmatrix}(-0.024)(5.18\times10^{-5}) = \begin{Bmatrix} 1.31\times10^{-6} \\ -1.24\times10^{-6} \end{Bmatrix}\text{m}$$

$$\ddot{y}^{(2)} = \begin{Bmatrix} -1.05 \\ 1.00 \end{Bmatrix}(-0.024)(0.08) = \begin{Bmatrix} 0.00202 \\ -0.00192 \end{Bmatrix}\text{m}/\sec^2$$

V. RESULT AND DISCUSSION

It was evident from the above analytical calculation that, the acceleration response of building with base – isolation reduces drastically compared to fixed base building, e.g. 0.06675 m/sec^2 to 0.0212 m/sec^2 for design based earthquake and 0.0423 m/sec^2 for maximum considered earthquake (very rare earthquake) for the fundamental mode of vibration only. Obviously, the second mode even reduces the response as reflected in the numerical values.

However, because of the flexibility of base-isolator displacement response was found to increase for base-isolated building compared to fixed based building e.g. 8.18×10^{-5} m to 0.000552 m for design based earthquake and 0.0011 for maximum considered earthquake for the fundamental mode of vibration.

It was clear from the values of base shear for fixed based building & base-isolated building that base shear is more in fixed based building compared to base-isolated building e.g. 363.69 N to 237.011 N for design based earthquake and to 726.06 N to 472.93 N for the fundamental mode of vibration of the building.

It was also brought out from the above mentioned calculation that base – isolated building has a high displacement at base because of the flexibility of base – isolators. But, eventually this reduced inter-storey drift drastically, e.g. $\Delta = 0.00057 - 0.00054 = 3\times10^{-5}\,\text{m}$, which was $8.18\times10^{-5}\,\text{m}$ in case of fixed based building. This reduction represents approximately a threefold reduction in column response amplitude.

The main cause behind above benefits obtained was an elongated time period of base – isolated building compared to fixed based building e.g 0.223 sec to 1.00 sec for the fundamental mode of vibration, which is a dominant mode of vibration as the building is a SDOF system.

VI. CONCLUSIONS

Based on above study following conclusions are made.

1. Analytical approach of response spectrum analysis of base – isolated building is fairly complex. It's handy for SDOF system but for solution of MDOF use of computational software is must.
2. The distinct advantage of providing base-isolator is an elongation of time period, which help in reducing base shear on the building. This was achieved numerically.
3. The elongation of time period also reduced acceleration response of building drastically, which was also achieved here.
4. Because of flexibility of base-isolator, displacement at base is more compared to fixed-base building, but eventually, storey drift was reduce by three times.
5. The above analytical solution in valid for SDOF system, but extension of same in the form of more degrees of freedom (DOF) is quite possible. Only it's required computational efforts.
6. The stiffness of base-isolator was reduced to 1/10th compared to fixed based building and damping assumed was 20 % for the solution, these values are quite practical, in view of base-isolator available in market.
7. The displacement, acceleration & base shear for design based earthquake is less compared to maximum considered earthquake, because of higher seismic demand of maximum considered earthquake.
8. The pilot study presented here can also be extended for MDOF and same sort of response may be obtained.

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