Displacement-based Seismic Design in Bridge Engineering

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Abstract

Seismic design for structures is conventionally force-based. As the development of inelastic analysis and discovery of the design features of the structures that survived in serve earthquakes, structures are found to be able to carry the earthquake induced inertia forces much larger than the structural strength calculated by force-based seismic design. This paper briefly reviews the displacement-based seismic analysis and discusses its application in bridge engineering.

Keywords

Displacement, seismic design, bridge engineering.

1. Introduction

Engineering structures were not designed particularly to carry seismic loads until 1930's, when some major earthquake occurred: 1925 Kanto earthquake (Japan), 1933 Long Beach earthquake (USA), 1932 Napier earthquake (New Zealand). Experiences showed that structures designed for lateral wind force have better performances than those that were not designed for the lateral force. Therefore, many codes adopted the force-based design. As studies of structural dynamic characteristics became progressed in 1950's, researchers found that the majority of the structures that survived during the major earthquakes were designed for lateral wind loads. The earthquake induced inertia forces on these structures were much higher than their structural strengths calculated from force-based design. The ductility concept was then studied. In 1980's, the concept of ductility was further developed, and the capacity design was then introduced. Until 1990's, the performance-based design by considering the displacement was initiated [1]. Displacement-based structural design is considered as both safe and economical.

2. Displacement-Based Design

Displacement-based seismic design is focusing on the displacement demand of the structure. It induced by earthquake ground motion. The general requirement for a bridge withstanding through a major earthquake is the displacement demand not exceeds the displacement capacity.

$$Displacement\ Demand < Displacement\ Capacity \tag{1}$$

Both displacement demand and displacement capacity are at the global level. However, the failure of the structural component(s) may lead to the global collapse. Besides, structures are found to be able to carry the earthquake induced inertia forces much larger than the structural strength. Therefore, the structural components shall be evaluated for their ductility characteristics,

$$Ductility\ Demand = \frac{Displacement\ Demand}{Yield\ Displacement} \tag{2}$$

$$Ductility\ Capacity = \frac{Displacement\ Capacity}{Yield\ Displacement} \tag{3}$$

The seismic force used to calculate the displacement demand is determined based on a site specific acceleration response spectrum, Fig. 1. If a site specific acceleration response spectrum is not available, then a modified acceleration response spectrum developed from the spectrum provided AASHTO LEFD Specification shall be used. The acceleration response spectrum is developed according to the statistical analysis of a series of ground accelerations recorded from the historical major earthquakes. It is plotted in terms of earth gravity, g, in vertical axis, and structure natural period as horizontal axis.

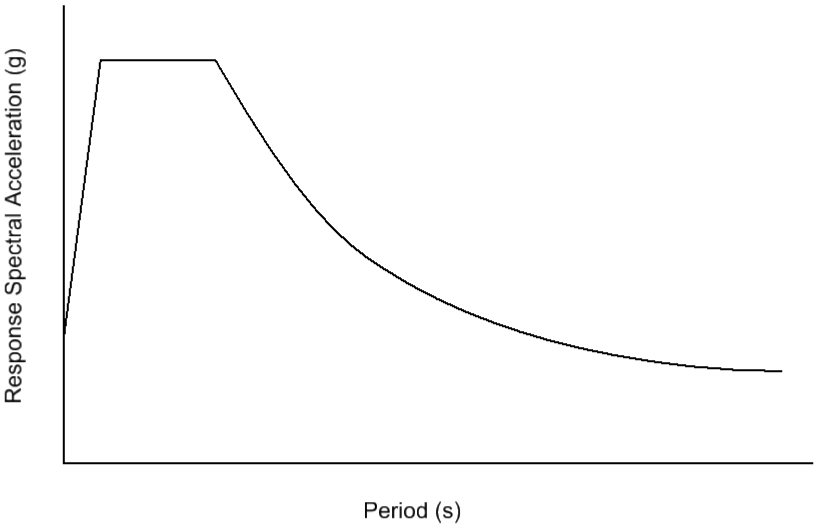


Fig. 1. Acceleration Response Spectrum

To find the ground motion at a target location, the structure natural period is used to find its corresponding ground acceleration. For single degree of freedom (SDOF),

$$T_n = 2\pi\sqrt{\frac{m}{k}} \tag{4}$$

T_n is structure natural period. m is structure mass. k is structure stiffness. The displacement demand induced by seismic ground motion is calculated by the Hook’s Law,

$$u = \frac{F}{k} \tag{5}$$

where u is the displacement in the direction of ground motion. F is seismic force. k is structure stiffness. Then seismic displacement capacity and yield displacement of a structure needs to be determined. Plastic hinges are expected to take place during the cyclic seismic inertia force. A structure fails when all its design plastic hinges are formed. The location and the stress-strain relationship of the plastic hinges are defined based on the properties of seismic-load carrying components, e.g. bridge columns. Pushover analysis and time-history analysis are the two major approaches to calculate the plastic displacement of a structure.

3. Bridge Seismic Design

In bridge engineering, multimode spectrum analysis is commonly used for calculation of displacement demand. It is a linear elastic dynamic analysis. This method is used to calculate the seismic response of the entire bridge. The linear elastic dynamic procedures are not able to consider the nonlinear response of bents, columns, expansion joints, soil behavior, and so on. The interior bents then are designed to deform plastically during a seismic design. The effective stiffness of the two adjacent bents, Fig. 2, should satisfy

$$\frac{k_s \cdot m_s}{k_l \cdot m_l} \geq 0.75 \tag{6}$$

k_s is the smaller effective stiffness. m_s is the smaller tributary area supported by the bents with k_s. k_l is the larger effective stiffness. m_l is the smaller tributary area supported by the bents with k_l.

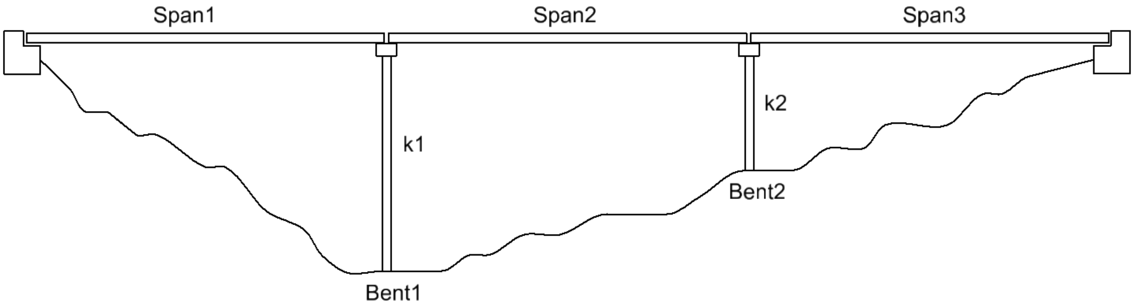


Fig.2.Bridge Elevation

The total stiffness, k_{total}, of the substructure to be considered to determine the seismic displacement including the pile/column stiffness, k_{pile}, backwall stiffness, $k_{backwall}$, and abutment stiffness, $k_{abutment}$.

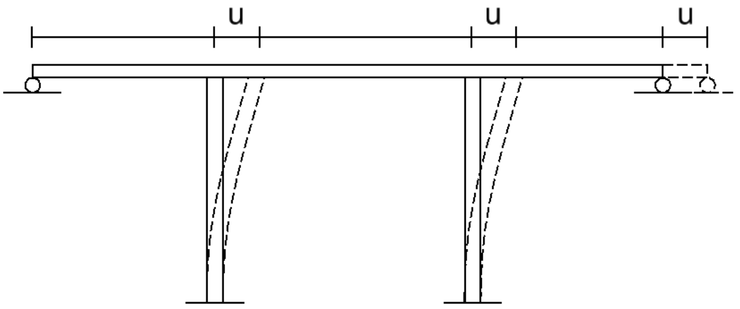
$$k_{total} = k_{pile} + k_{backwall} + k_{abutment} \tag{7}$$

The longitudinal and transverse elastic displacement demands of the entire bridge system thus can be calculated by Hook's Law. The pile length is calibrated by adjusting the height of the piles/columns, in order to move the pile point of fixity up and down along the vertical pile to meet the engineering requirements. The point of fixity of a column can be determined in several methods, one of which is using the moment diagram of the column/pile.

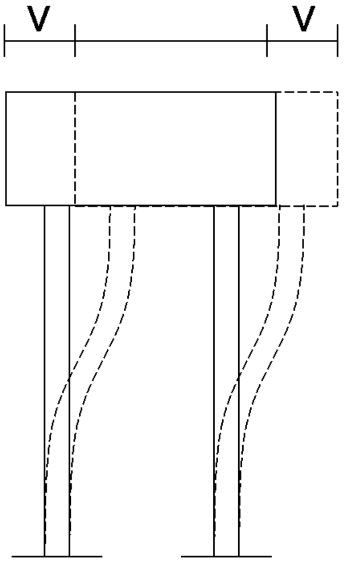
$$\Delta_i = \frac{P_{seismic}}{k_{total}(H)} \tag{8}$$

Δ_i longitudinal or transverse displacement of the entire bridge using elastic response analysis, Fig. 3. $P_{seismic}$ is the site specific seismic load calculated based on structural natural frequency, structure mass, and the acceleration response spectrum. $k_{total}(H)$ is the total stiffness of bridge substructure including bridge pile bents/columns, backwall, and wing wall. $k_{total}(H)$ can be adjusted by moving the point of fixity along the vertical length of the piles/columns. H is the height of the piles/structures. After trial and error, the bridge global displacements demand Δ_d in both transverse and longitudinal directions are determined.

A displacement capacity that is larger than the displacement capacity which provided shall be fulfilled for a bridge experiencing a major earthquake without catastrophic damage. Bridge bent piles or columns shall be designed as ductile components, meaning that they are able to deform inelastically without significant failure. The bridge substructure behavior is affected by the soil properties, Fig. 4. The surrounded soil should provide the resistance to the passive earth pressure and the piles or columns embedded. To mathematically involve the soil influence on the bridge substructure, a series springs are defined along the height of the substructure. The interior bent is usually considered alone instead of the entire bridge system. The bent fails is plastic hinges are formed in all the piles/columns with the bent. The property and location of plastic hinges shall be defined. The plastic hinges, Fig. 5, shall be located according to the substructure movement direction, and for the accessibility of inspection.



(a)



(b)

Fig.3 Horizontal displacement induced by seismic ground motion (a)Longitudinal and (b) transverse

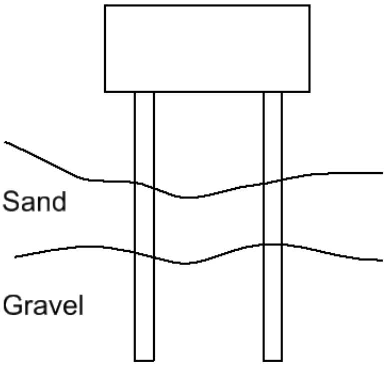


Fig. 4 Soil Profile

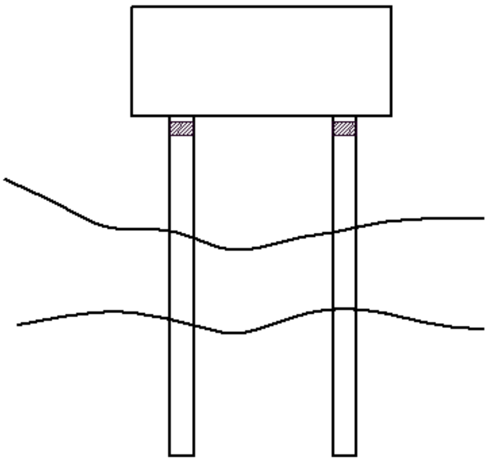


Fig. 5 Plastic hinge

The total displacement, Δ_{total}, includes elastic yielding displacement, Δ_y, and plastic displacement, Δ_p, Fig. 6.

$$\Delta_{total} = \Delta_y + \Delta_p \tag{9}$$

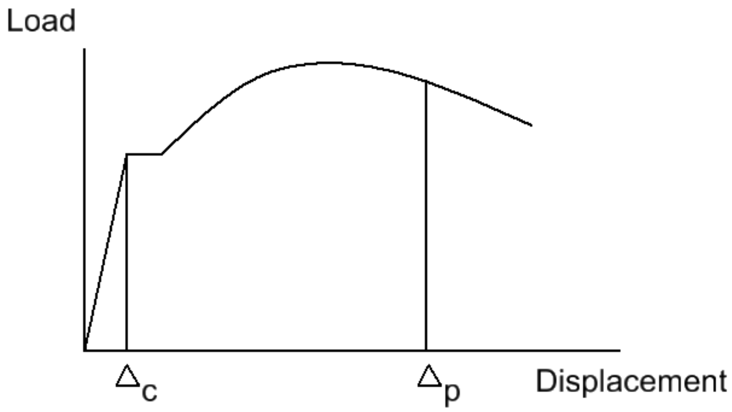


Fig. 6 Load-displacement relationship

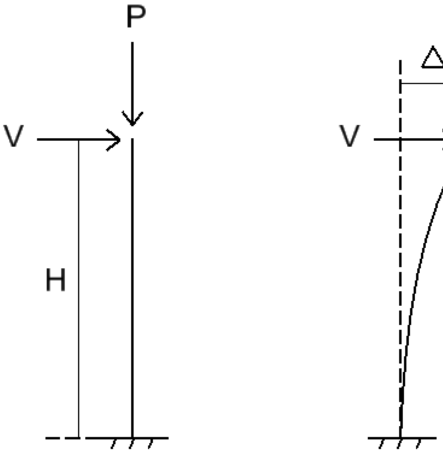


Fig. 7 P-Δ effects

Pushover analysis is a common analysis method to calculate the non-linear behavior of the bridge substructure. The secondary effect, P- Δ effect is included, Fig. 7. By static pushing the structure, it gradually increases the lateral displacements of the piles/columns until the plastic deformation occur and finally collapse. As discussed previously, failure of one or more structural components can cause the entire bridge failure. To prevent bridge collapse, both global displacement and local components ductility shall be examined.

At global level,

$$\Delta_d < \Delta_c \tag{10}$$

at local level,

$$\mu_d = \frac{\Delta_d}{\Delta_y} \tag{11}$$

$$\mu_c = \frac{\Delta_c}{\Delta_y} \tag{12}$$

Δ_d is displacement demand, calculated by the elastic multimode spectrum analysis. Δ_c is displacement capacity, calculated by static pushover analysis or dynamic time-history analysis. Δ_y is yield displacement, calculated from the force-displacement relationship of the structural component. μ_d is ductility demand. μ_c is ductility capacity. In bridge seismic design, values of μ_d and μ_c are given based on the engineer experience and test results. Then the vertical and lateral load capacities of the structure under design can be adjusted.

4. Conclusion

Bridges located at a high-seismic zone are designed inelastically for the economical consideration. Displacement-based method is often used for bridge seismic design instead of force-based method, because structures are found to be able to carry the earthquake induced inertia forces much larger than the structural strength. In general, seismic design of bridge structures includes three main steps: 1. Calculation of global displacement demand; 2. Calculation of global displacement capacity; 3. Check the substructure member ductility. To prevent bridge collapse during the major earthquakes, displacement demand shall not exceed displacement capacity at a global level. Local component ductility shall be examined to meet certain requirement, since one or more structural member failure can cause a bridge collapse while the overall displacement demand remains under bridge displacement capacity. Bridge substructure is allowed to form plastic hinges, while the location of the plastic hinge shall be considered for the easement of inspection.

Acknowledgements

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