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SOIL STRUCTURE INTERACTION EFFECTS ON SEISMIC DESIGN OF BASE-CONNECTION FOR CABLE-STAYED BRIDGE TOWERS

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ABSTRACT

An incremental iterative finite element technique for a more realistic dynamic analysis of nonlinear soil-foundation-superstructure-anchor bolts system subjected to earthquake ground motion is developed. The objective of this investigation is to assess the effects of soil-structure interaction including column base anchor bolts on the seismic response and dynamic performance of the cable-stayed bridges tower with spread foundation. A three-dimensional frame model with a consistent mass model has been adopted for Eigen value and modal analyses. The results of this study show that the including of the soil-foundation-superstructure-anchor provides pronounced reduction in the reaction force and moment responses analysis due to the degradation of soil stiffness underneath and flexibility of the tower structure in dissipating the energy through the soil. The base plate deformation has a great effect by soil-structure interaction. Soil-structure interaction effect leads to the anchor bolt tensile force decrease significantly and doesn't reach the yield point of anchor bolt while it remains around the amount of anchor bolt pre-tension force. The uplift force at the anchor between superstructure and pier and effects of soil structure interaction is underestimated.

Keywords: Cable-stayed bridge towers, soil-structure interaction, anchor bolts, seismic response

INTRODUCTION

Serious damages in steel structures are ascribed to the failure of the column bases that was clearly observed in the Hyogoken-Nanbu earthquake 1995 in Japan as the anchor bolts came out or ruptured, the base plates bent out of shape, or the base mortar being crushed. Column base behavior has a strong effect on the overall behavior of the steel frames, hence avoiding failure in the column base connections is most important, so a more attention should be paid to the proper modeling and right construction. Analytical and experimental investigations (S. E. Abdel Raheem and et al; 2003a) which carried out proved that the assumption of pinned or fixed column-bases is not correct, especially when cyclic loading is applied to the structure where as the semi-rigid column base presence.

Column bases of steel frames are often designed as base plates welded at the bottom end of the column and fixed by anchor bolts embedded in the concrete. Ductile anchor bolts are mostly recommended to use for column bases in steel structures. The ductile anchor bolts have to be sufficiently embedded into the concrete so as to ensure that their failure occurs by excess of tension stress in the net section, when the anchor bolts are activated in tension, the base plate is subjected to tensile forces and deform in bending while the anchor bolts elongate. The failure of the tensile zone may result from the yielding of the plate, from the failure of the anchor bolts or from a combination of both phenomena. The performance of the base connection depends on the cyclic performance of the anchors and the

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surrounding concrete foundation. Much research work is needed in order to better understand the seismic behavior and to formulate improved design procedures. The steel frames behavior could only be accomplished through nonlinear dynamic analyses of complete frame systems with actual support condition.

The safe and economic seismic design of bridges depends directly on the understanding level of the seismic excitation and the influence of the supporting soil on the structural response. The long span bridges such as cable-stayed bridges structural synthesis provide a valuable environment for the nonlinear behavior due to material and geometrical nonlinearities of the relatively large deflection of the structure on the stresses and forces. So it is highly desirable in bridge engineering to develop accurate procedures that can lead to a through understanding and a realistic prediction of the structural response.

The dynamic interaction between the pier-foundation and soil has a significant effect on the earthquake response of bridges. The dynamic characteristics of soil-structure interaction system change due to materials and geometrical nonlinearity during a severe earthquake. This nonlinearity is sometimes treated by equivalent linear model. But the dynamic characteristics of soil structure interaction system, such as the shape of the peak of frequency transfer function change are depending on the stress level of the surrounding soil during a severe earthquake.

For long span bridges, steel towers are preferred because of their efficient utilization of structural materials, improved speed of construction, earthquake resistance, and so on. The fundamental period of soil-foundation-superstructure-anchor bolts system is one of the most crucial design factors, in order to understand base connection and anchor bolts effects on the seismic response of tower structure.

The behavior of steel framed structures depends on the performance of their connections. The design of base connection should capable of spreading the load so as to maintain the bearing pressure under the allowable values and connecting the base plate and column to the concrete foundation. But strong earthquake lateral forces can induce base overturning moments that exceed the available overturning resistance due to gravity loads causing base connection anchor bolts lift-off.

The objective of this investigation is to assess the effects of soil-structure interaction including column base anchor bolts on the seismic response and dynamic performance of the cable-stayed bridges tower with spread foundation. A three-dimensional frame model with a consistent mass model has been adopted for eigenvalue and modal analyses. An incremental iterative finite element technique for a more realistic dynamic analysis of nonlinear soil-foundation-superstructure-anchor bolts system subjected to earthquake ground motion is developed. Particular attention is directed to the tower structure, which are modeled as beam-column finite element with both material and geometric nonlinearities, while the soil and anchor bolts are idealized by nonlinear springs and dashpots uniformly attached along most of the embedded length of the pier and tower base. Further the soil-structure-anchor bolt interaction has been studied.

GENERAL SOLUTION PROCEDURE

Based on the total incremental equilibrium equations, finite displacement three-dimensional beam-column element formulation is carried out. The governing nonlinear dynamic equation of the tower response can be derived by the principle of energy that the external work is absorbed by the work of internal, inertial and damping for any small admissible motion that satisfies compatibility and boundary condition. By assembling the element dynamic equilibrium equation for the time $t+\Delta t$ over all the elements, the incremental FEM dynamic equilibrium equation can be obtained as:

$$[M]\{\ddot{u}\}^{t+\Delta t} + [C]\{\dot{u}\}^{t+\Delta t} + [K]^{t+\Delta t}\{\Delta u\}^{t+\Delta t} = \{F\}^{t+\Delta t} - \{F\}^{t} \quad (1)$$

where $[M]$, $[C]$, and $[K]^{t+\Delta t}$ are the system mass, damping and tangent stiffness matrices at time $t+\Delta t$, the tangent stiffness considers the material nonlinearities through bilinear stress strain relation for the beam column element, and the geometrical nonlinearities for the case of in-plane, out-plane bending deformations and linear torsional deformations. $\ddot{u}$, $\dot{u}$, and Δu are the accelerations, velocities, and incremental displacements vector at time $t+\Delta t$, respectively, $\{F\}^{t+\Delta t}$ - $\{F\}^{t}$ is the unbalanced force vector. It can be noticed that the dynamic equilibrium equation of motion takes into consideration the different sources of nonlinearities both geometrical and material nonlinearities, which affect the tangent stiffness and internal forces calculations.

The implicit Newmark step-by-step integration method is used to directly integrate the equation of motion and then it is solved for the incremental displacement using the Newton-Raphson iteration method where the stiffness matrix is updated at each increment to consider the geometrical and material nonlinearities and to speed the convergence rate. In addition, the tower structure damping mechanism is adapted to the viscous damping of Rayleigh's damping type with equivalent damping coefficient to equal to 2% for steel material of tower superstructure elements and 10% for concrete material of embedded pier substructure elements at vibration periods of 2.5 sec and 0.50 sec, to represent a broad range of high participation modes and the softening that takes places as the columns and soil yield. A common design approach of maintaining elastic behavior in the substructure to avoid inelastic behavior below the ground surface is considered, where the damage would be difficult to detect or to repair.

FINITE ELEMENT OUTLINE

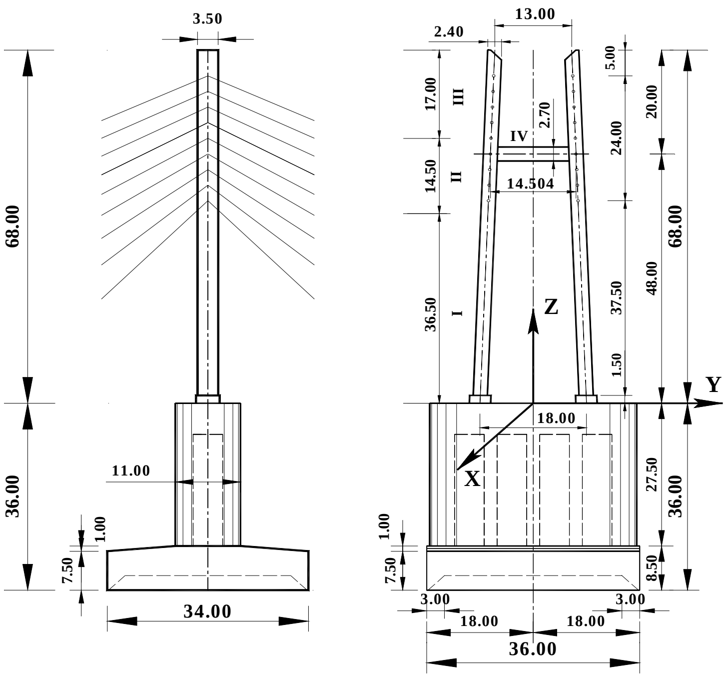
Tower structure model

The tower of Tappu cable-stayed bridge located in Hokkaido, Japan is considered. Since the cable-stayed bridges are not structurally homogeneous, it is concluded from previous study that the tower, deck and cable stays affect the structural response in a wide range of vibration modes. The tower is taken out of the cable-stayed bridge and modeled as three-dimensional frame structure. A fiber flexural element (S. E Abdel Raheem and et al; 2002) is developed for the tower characterization, the element incorporates both geometric and material nonlinearities, a cubic displacement field is employed for the transverse displacement and linear displacement field is employed for the axial and torsional displacements. The stress-strain relationship of the beam element is modeled as bilinear type. The yield stress and the modulus of elasticity are equal to 355 MPa (SM490) and 200GPa, respectively; the strain hardening in the plastic region is 0.01. The nonlinearity of inclined cable stays is idealized by using the equivalent modulus approach. The nonlinearity of the cable stays originates with an increase in the loading followed by a decrease in the cable sag as a consequence the apparent axial stiffness of the cable increases. In this approach each cable is replaced by a truss element with equivalent tangential modulus of elasticity E_{eq} that is given by Ernst as:

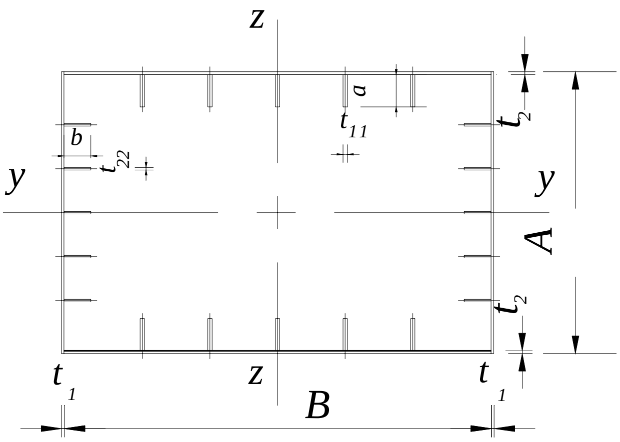
$$E_{eq} = E / \{1+ EA (wL)^2 / 12T^3 \} \qquad (2)$$

where E is the material modulus of elasticity, L is the horizontal projected length of the cable, w is the weight per unit length of the cable, A is the cross sectional area of the cable and T is the tension force in the cable.

This cable-stayed bridge tower has nine cables in each side of the tower. The stiffening girder dead load is considered to be equivalent to the vertical component of the pretension force of the cables and acted vertically at their joints, and two vertical components at stiffening girder-tower connection at substructure top level. For the numerical analysis, the tower geometry and the structural properties of the steel superstructure and concrete substructure are shown in Figure. 1. The tower steel superstructure has rectangular hollow steel section with internal stiffeners, which has different dimensions along the tower height and its horizontal beam as shown in Table 1.



Tower geometry



Cross section

Figure1. Steel tower of Tappu cable-stayed bridge

Table 1 Cross section dimension of different tower region

C. S. Dim.		Outer dimension			Stiffener dimension				
		A	B	t_1	t_2	a	b	t_{11}	t_{22}
Tower parts	I	240	350	2.2	3.2	25	22	3.6	3.0
	II	240	350	2.2	3.2	22	20	3.2	2.8
	III	240	350	2.2	2.8	20	20	2.8	2.2
	IV	270	350	2.2	2.6	31	22	3.5	2.4

Base connection components modeling

In recent decades, long span bridges such as cable-stayed bridges have gained much popularity. For these bridges, steel towers are preferred because of their efficient utilization of structural materials, improved speed of construction, earthquake resistance, and so on. Steel towers are usually fixed by multiple bolts to large anchor frame embedded in a concrete pier/footing, Figure 2 shows sketch and details of tower base connection design drawings and the frame anchorage system, which provides a reliable and durable anchorage system.

The column base connection consists of 24 anchor bolts arranged outside the tower leg flanges. To have sufficient weld to transmit the flange force into the base plate, additional weld is used through welding vertical plates to the flange and lengthening the anchor bolts. The complex nature of bolted base connections requires that advanced analysis techniques be used for seismic design. Finite element models of the connection components and their interaction have been developed. The sub-models enable a full nonlinear elasto-plastic analysis of the connection to be performed. A component spring model for base connections is proposed. This model incorporates deformations from tension bolt elongation, bending of base plate and concrete bearing underneath base plates.

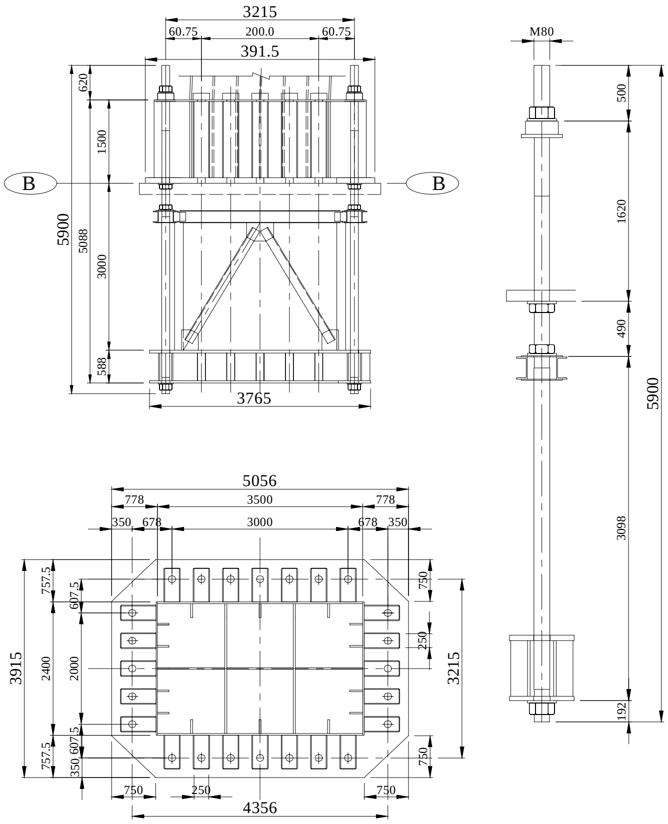


Figure2. Details of steel tower base connection (mm)

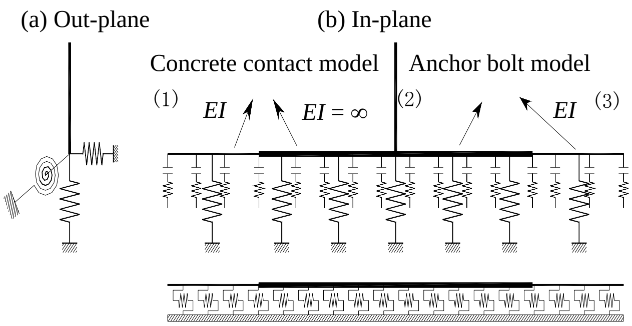
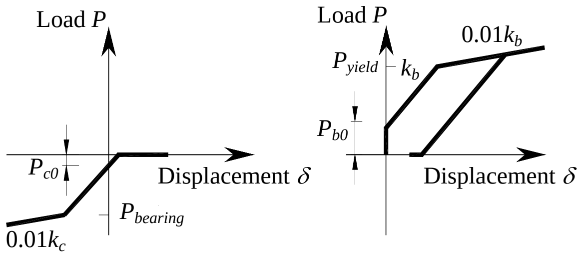


Figure3. Tower base connection mechanical model



(a) Concrete contact model **(b) Anchor bolt model**

Figure 4. Base connection components constitutive models

Table 2. Base connection components properties

Description	Properties value	
Anchor bolt	E_b	205.80 GPa
	Stiffness k_b	201.2 MN/m
	Yield force / stress	1.93 MN/ 440 MPa
	Pre-tension force	0.81 MN
	Shear stress	251.4 MPa
	Steel / Diameter	S45C / M80
Concrete foundation	E_c	24.50 GPa
	Stiffness k_c	19.852 GPa / m
	Bearing stress	20.58 MPa
	Friction coefficient	0.5
Base plate	Steel	SM490Y

The individual components of the connection are model by a nonlinear spring. Then each of these springs is added to the system and its stiffness is assembled into the final overall stiffness of the connection. Figure 3 shows mechanical model of the base connection. In this model, the constitutive components of the base connection are represented by means of springs system that includes extensional springs to simulate the anchor bolts tension deformation, extensional springs to simulate the concrete in compression under the base plate. Each of these springs is characterized by its own deformability curve as an individual component, as shown in Figure 4. The stiffness and resistance properties of the springs are calculated on the basis of the geometrical characteristics and the mechanical properties of the nonlinear constitutive material as given in Table 2. The stiffness of the concrete is determined by using an elastic half space. The anchor bolt pretension force and concrete compression pre-stress state as a result of self-equilibrium are considered.

Soil foundation model characterization

The interaction between the soil and the structure is simulated with nonlinear springs and dashpots system along the embedded depth of the pier (S. E. Abdel Raheem and et al; 2003b), and both of strain-dependent material nonlinearity and geometrical nonlinearity by base mat uplift are considered through nonlinear soil element connected in series with gap element springs system as shown in Figures 5 and 6. The spring constants in both bridge axis and right angle directions are calculated based on foundation geometry and soil profile of different layers underneath and along embedded depth of foundation. Hardin-Drnevich model is proposed to represent the soil material nonlinearity that is often used for its capacity to trace the degradation of stiffness. The spring coefficients are computed by the method suggested in Specification for Highway Bridges issued by Japan Road Association. Each spring consists of a gap element and a soil element. The gap element transmits no tensile stress, which can express the geometrical nonlinearity of base mat uplift.

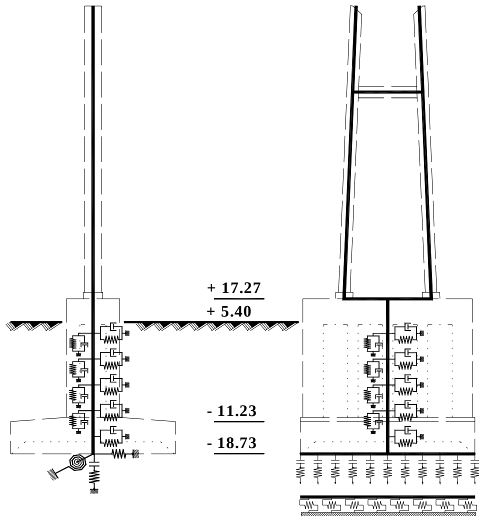


Figure 5. Mathematical model of soil foundation superstructure system

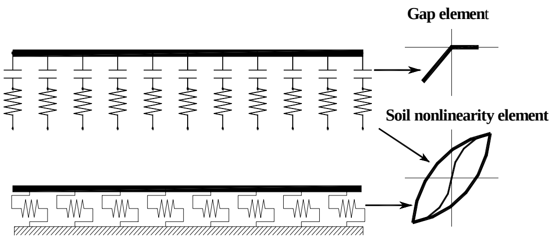


Figure 6. General concept of uplift and sliding modeling

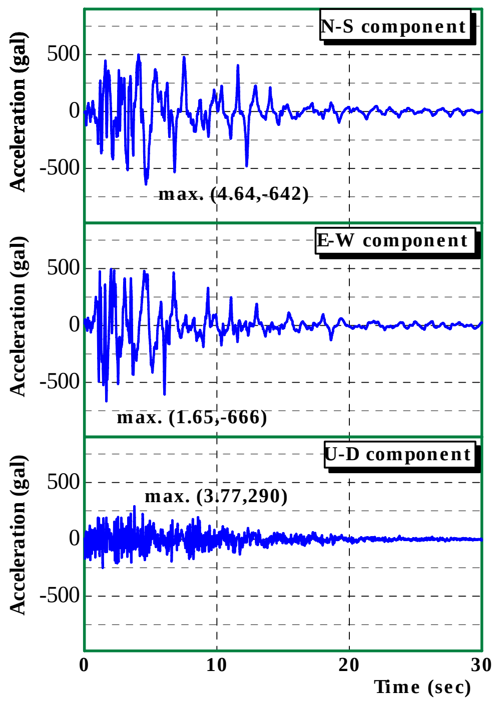


Figure 7. Strong ground motion measured at JR Takatori observatory

SELECTED GROUND MOTIONS

In the dynamic response analysis, the seismic motion by an inland direct strike type earthquake that was recorded during Hyogoken-Nanbu earthquake 1995 of high intensity but short duration is used as an input ground motion to assure the seismic safety of bridges. The horizontal and the vertical accelerations recorded at the station of JR Takatori observatory (Committee of Earthquake Engineering 1995), (Japan Road Association 1996), as shown in Figure. 7, are suggested for dynamic response analysis of the of cable-stayed bridge tower at type II of soil condition. It is considered to be capable of securing the required seismic performance during the bridge service life. The selected ground motion has maximum acceleration intensity of its components equal to 642 gal (N-S), 666 gal (E-W) and 290 gal (U-D).

NUMERICAL ANALYSIS

Soil-structure conditions are considered in the detailed base foundation with anchor bolts where base and dynamic response simulation is conducted by applying acceleration at the base of the soil deposit to study the effects of soil-structure interaction on the seismic behavior of the cable stayed bridges tower,: the following three different cases of soil idealization are analyzed
Case I: Seismic response of tower with more realistic model for the support conditions.
Case II: Seismic response of tower considering soil-structure interaction effect.
The including of the soil-structure interaction has a significant effect on the dynamic characteristics of the bridge tower structure with physical base model. It can be observed that the tower top acceleration and displacement responses have a big decrease in displacement amplitude with longer natural vibration, as illustrated in Figure 8. This may attributed to the degradation of soil stiffness underneath and flexibility of the tower structure in dissipating the energy through the soil.

By comparing the reaction force and moment time histories at the tower base for different cases of base condition, it is found that considering the soil-structure interaction provides pronounced reduction in the reaction force and moment responses compared to the original tower response as shown in Figure 9. Hence the analysis neglecting the soil-structure interaction leads to larger stress values, where the transverse bending moment at tower superstructure base could lead to over-conservative design.

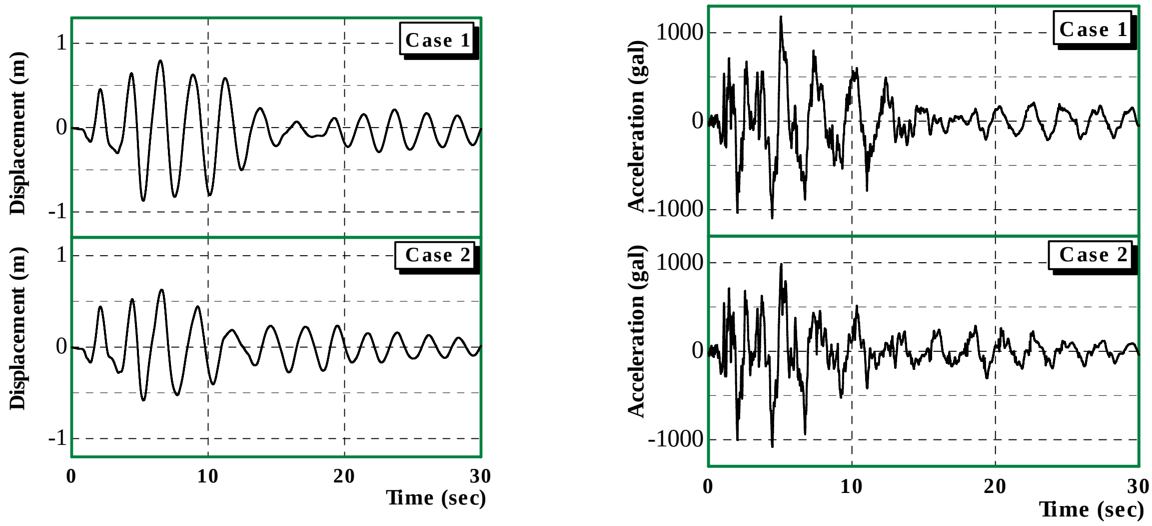


Figure. 8 Displacement and acceleration time histories at tower top

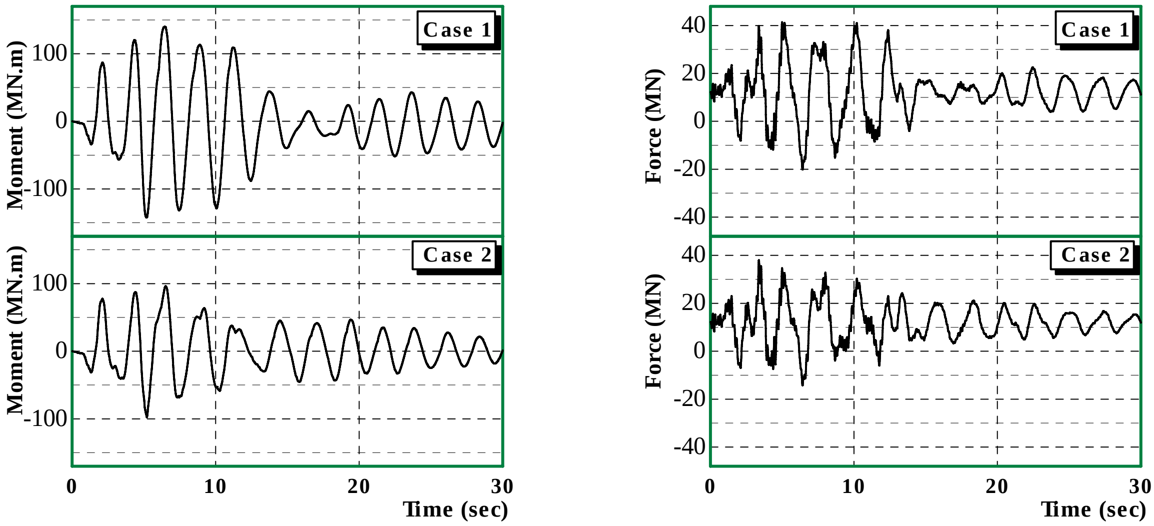


Figure. 9 Moment and reaction force time histories at tower base

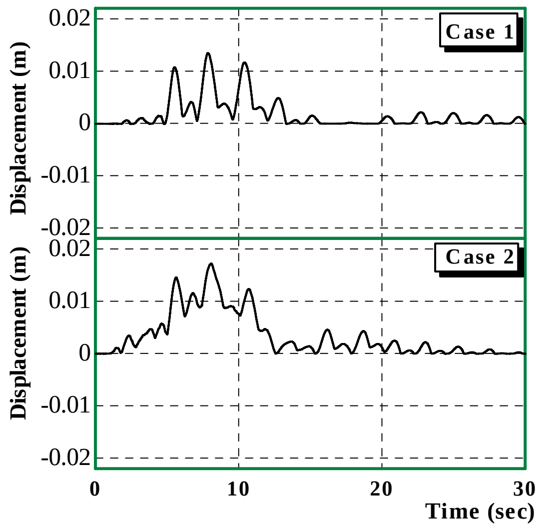


Figure. 10 Base plate deformation time history

The base plate analysis is so important in design where the base plates are responsible for transferring the primarily compression forces into concrete block. The compression part of the base plate designed for resistance of the concrete in crushing under the flexible base plate. The behavior of the tension part of the base plate is mostly guiding the column base resistance and stiffness in case of loading by bending moment. The base plate deformation time history at plate middle, Figure.10, is significantly affected by the including of soil-structure interaction effect under base plate and foundation which contribute in nonlinear increase of maximum base plate vertical deformation significantly. This increasing at base plate deformation comes from the appearance of rocking motion of foundation due to the high rigidity of the structure comparing to the rigidity of the underlying foundation soil.

To study the interaction effect between the soil -structure and anchor bolts, the anchor bolt bearing force as a function of time is shown in Fig. 11. The anchor bolt tensile force is affected by soil-structure interaction where it decrease significantly and doesn't reach the yield point of anchor bolt while it remains around the amount of anchor bolt pre-tension force.

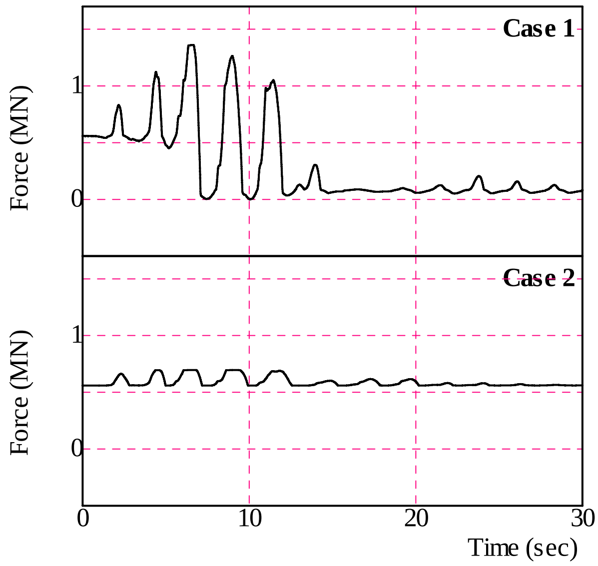


Figure. 11 Anchor bolt load time history

CONCLUSIONS

Numerical parametric study of the steel tower cable-stayed bridge has been conducted to investigate the dynamic behavior considering nonlinear soil-foundation-superstructure-anchor bolts system subjected to earthquake ground motion. The nonlinear finite element dynamic analysis demonstrates how soil-foundation-superstructure-anchor bolts system influence tower seismic response. From this study, the following conclusions can be drawn as (1) the including of the soil-foundation-superstructure-anchor provides pronounced reduction in the reaction force and moment responses analysis due to the degradation of soil stiffness underneath and flexibility of the tower structure in dissipating the energy through the soil, (2) the analysis neglecting the soil-structure interaction leads to larger stress values, where the transverse bending moment at tower superstructure base could lead to over-conservative design, (3)the base plate deformation has a great effect by soil-structure interaction, and (4) soil-structure interaction effect leads to the anchor bolt tensile force decrease significantly and doesn't reach the yield point of anchor bolt while it remains around the amount of anchor bolt pre-tension force.

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