Effect of Vertical Ground Motion on Seismic Response of Steel Tower of Cable-Stayed Bridges

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1. Introduction

In the analysis and design of earthquake resistant structures, and particularly bridge structures, the vertical ground motion component tends, in general, to be ignored or underestimated in current seismic structures analysis, since it is retained that most of the damage is due to the horizontal component, and that the vertical acceleration is small. The current seismic codes recommend a vertical spectrum with values, which vary from half to three quarters of that of the horizontal spectra. This approach seems to be un-conservative in light of measurements of ground motion during recent earthquakes, which indicate that the vertical acceleration could reach values even higher than that of the horizontal acceleration. Moreover, in a near field region, the peak of vertical to horizontal spectral ratio is even larger the ratio of the peak ground acceleration, especially at short periods[1)]. Also field observations proved that many structures and bridges experienced significant damage attributable to high vertical forces. Some studies[2, 3)] presented a wide compendium of field evidence supported by analytical considerations, which confirmed that certain failure modes are correlated with the high axial forces due to the vertical motion. The analysis of the behavior of structures subjected to horizontal and vertical motion was considered only recently by many researchers[4)]. Where, the response of bridge columns and piers subjected to vertical and horizontal excitation was analyezed with the inelastic plane stress elements, and the results displayed unstable hysteresis loops and little energy dissipation.

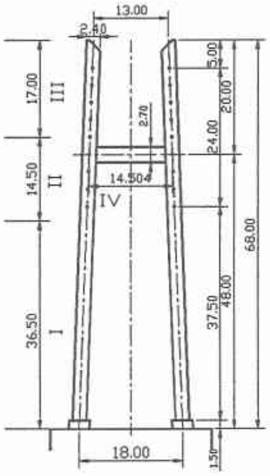
This study aims at clarifying the characteristics of the effects of vertical ground motions upon earthquake responses of steel tower of cable-stayed bridges subjected to strong ground motion records. It is performed in order to comprehend the influence of the vertical motion on the various aspect of the structural response. A comparison of the response with and without the vertical component is performed. The results confirmed that the vertical excitation could have a detrimental effect on the various aspects of tower seismic response.

2. Finite element model

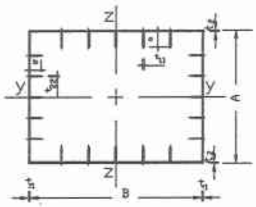
Based on the total incremental equilibrium equations, large displacement three-dimensional beam-column element formulation is carried out, where the tangent stiffness matrix and nodal point force vectors considering both geometrical and material nonlinearities can be determined. In this study, the implicit Newmark step-by-step integration method is used to directly integrate the equation of motion. The equation of motion 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. As the incremental displacement is determined, the response acceleration and velocity components of the tower can be determined. In addition, attenuation of the structure adopted the viscous damping of mass proportional type with damping coefficient to the first fundamental natural vibration mode is 5 % as standard.

The steel tower of Iwamizawa cable-stayed bridge located in Hokkaido, Japan is considered in this study. The steel tower is taken out of the cable-stayed bridge and modeled as three-dimensional frame structure characterized by a fiber flexural element. The model invoked large displacement using a Total Lagrangian formulation; the Hermitian cubic interpolation is used to describe bending deformation and linear interpolation to specify axial and torsional displacements. The tangent stiffness considers geometrical and material nonlinearities. The material behavior is modeled by a bi-linear elastic-plastic constitutive model incorporating a uniaxial yield surface criteria and kinematic strain hardening flow rule, the yield stress and the modulus of elasticity are equal to 353 Mpa and 200 GPa, respectively; the plastic region strain hardening is 0.01.

The nonlinear behavior of cable elements is idealized by using the equivalent modulus approach, in this approach each cable is replaced by a truss element with equivalent tangential modulus of elasticity used to take account of the sag effect. This cable-stayed bridge has nine cables in both sides of the tower. The dead load of the stiffening girder is considered to be equivalent to the vertical component of the pretension force of cables and acted vertically at the joint of cables. The inertia forces acting on the tower from the stiffening girders is neglected. For the numerical analysis, the geometry and the structural properties of the steel tower is shown in Fig. 1, where this tower has rectangular hollow steel section with internal stiffeners, which has various dimensions along the tower height and its horizontal beam as shown in Table 1.



(a) Tower geometry



(b) Cross section

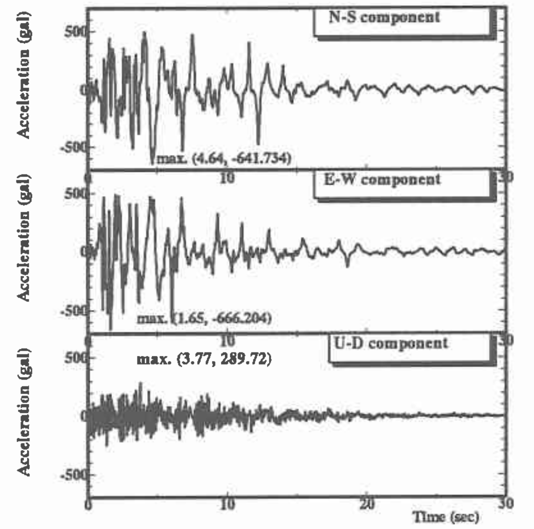
Fig. 1 Steel tower of Iwamizawa cable-stayed bridge

Table 1 Cross section dimension of different tower region

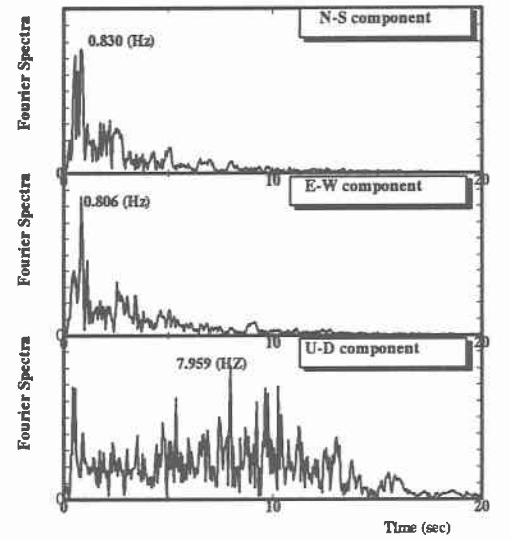
C. S. Dim. (cm)		Outer dimension				Stiffener dimension			
		A	B	t_1	t_2	a	b	t_{11}	t_{22}
Tower parts	I	240	350	2.2	3.2	25	22	3.6	3.0
	II	240	350	2.2	3.2	22	20	3.2	2.8
	III	240	350	2.2	2.8	20	20	2.8	2.2
	IV	270	350	2.2	2.6	31	22	3.5	2.4

3. Vertical Ground Motion Component

Generally the vertical ground motion attenuates more rapidly than the horizontal motion, and the vertical motion effects are more evident in the near earthquake field In fact it was observed that the vertical to horizontal peak ground acceleration ratio tends to assume greater values in the near field and to decrease as the epicenter distance increases[5]. Moreover, another aspect was not taken in consideration is the frequency content of the vertical motion, which was noticed to be significantly higher than that of the horizontal motion. Therefore the vertical component may be more dangerous as it was retained, since it may be close to the vertical frequencies of free vibration of many structures. There are a lot of records of instrumented structures, especially from the Northridge and the Kobe earthquakes, which show a great amplification of the vertical motion. The frequency content of the vertical motion is often higher than that of the horizontal motion, and could include the frequency range of vertical vibration of structures, thus causing great vertical amplification. The horizontal and the vertical accelerations recorded at the station of JR Takatori observatory[6] during Hanshin/Awaji earthquake 1995, with the corresponding frequency contents obtained with the Fast Fourier Transform are reported in Fig. 2. The previous mentioned ground motion with the largest intensity of acceleration is used as an input to assure the seismic safety of bridges. The acceleration time history recoded at JR Takatori Station is suggested for analysis of the steel tower of Iwamizawa cable-stayed bridge at Type II of soil condition. The earthquake force of E-W wave was put into the bridge axis direction, and N-S wave to the right angle to the bridge axis.



(a) Ground motion acceleration components



(b) FFT of acceleration components

Fig. 2 Strong ground motion measured at JR Takatori observatory

4. Investigation on Effects of Vertical Ground Motion

The principal effect of the vertical motion is the generation in tower legs of fluctuating axial forces uncoupled from the lateral forces. These axial forces are added to the axial forces correlated with the in plane moments and greater level of compression and tension could be reached in tower legs than with the horizontal motion alone. The vertical motion could have a detrimental effect on structural behavior of the steel tower if it produces significant axial forces simultaneously with the horizontal components peak effects. The effects of the vertical motion on tower seismic response are studied with the tower model described before. Two cases analyses for the input ground motion are considered, the first under the horizontal components alone, the second under both the horizontal and the vertical components. In order to observe directly some of the effects of the vertical motion, the axial force time histories of the tower base and uplift forces at the tower base are shown in the Figs. 3 and 4, respectively. It is evident the superposition of the axial force variations induced by the vertical motion with that due to the horizontal motion, which has a lower vibration period, and how great could be there the extreme values reached by the axial force with the vertical motion. The maximum compression axial force at the tower base with and without consideration of vertical ground motion becomes, in fact, 4.06, 2.85 times the initial axial force due to gravity loads, while the maximum tension axial force becomes 2.22, 1.30 times the initial axial force, respectively.

It can be concluded, that the main effect of the vertical motion is the axial forces generation, which are uncoupled to that due to lateral forces and have a lower vibration period corresponding to the vertical period of the structure. The axial forces at tower bas due to the overturning moments are significant and the contribution of the vertical motion to the total axial force can be comparable, to that of the horizontal motion, since the extreme compression and tension values of axial forces in the tower base are reported that the contribution of the vertical motion increases and it reaches, the 42.5, 71.25% of the total axial force for that case without consideration of vertical ground motion, respectively. From Figs. 3 and 4, it results that not only greater values of compression are obtained, but also significant tensile axial forces, indicated with the negative sign. The great values of compressive and tensile axial forces can lead also to the possibility of direct failure in compression or tension.

The moment-curvature diagram of the tower base, obtained with and without the vertical motion Fig. 5, shows the characteristics of the column behavior under coupled axial and lateral force variation, as for example, the strength asymmetry and moment curvature diagram shift due to fluctuating axial force effect. The diagram obtained with the vertical motion reveals an unusual and irregular shape with significant fluctuations in strength and stiffness, which reflect, through the axial force-moment interaction, the effects of the vertical vibration. The maximum curvatures reached by the loops in first case are about 75% of those reached in second case, and this indicates the lower dissipation capacity considered with the vertical motion. However this is not the only reason of the lower dissipated energy, since also in tower, which experience greater curvatures, the hysteresis energy resulted lower, and probably another important cause is the irregular shape of the loops. The damage caused by the horizontal motion is similar to that caused by the vertical and horizontal motions.

It is appeared that the detrimental influence of the vertical motion on maximum tower top acceleration, as shown in Fig. 6, the tower top horizontal acceleration is resulted to increase of a non negligible amount with the vertical motion, due to the inelastic behavior of the structure, and probably also to the P- Δ effects in presence of high compression forces. The extreme in-plane acceleration values at the tower top are reported that the contribution of the vertical motion increases and it reaches, the 100% of that for case without consideration of vertical ground motion.

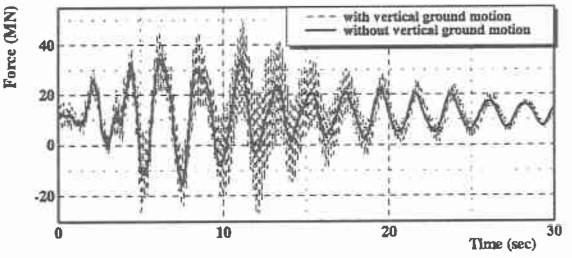


Fig. 3 Vertical force time history at tower base

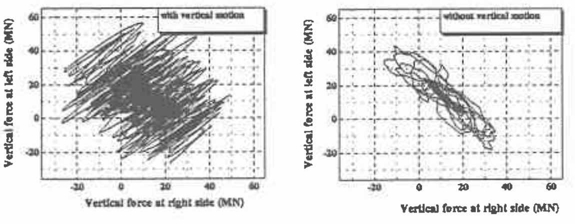


Fig. 4 Uplift force relationship at the tower bases

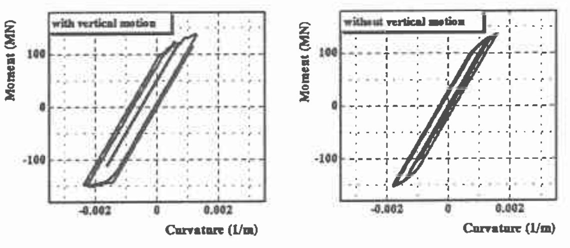


Fig. 5 Moment-curvature diagrams at tower base.

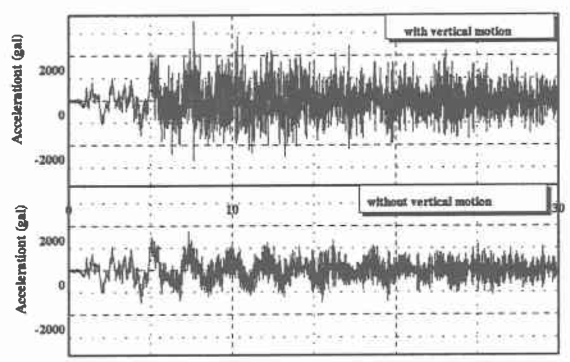


Fig. 6 In-plane acceleration time history of the tower top

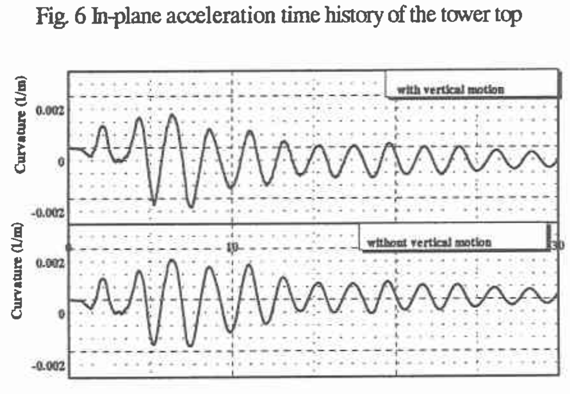


Fig. 7 In-plane curvature time history at tower base

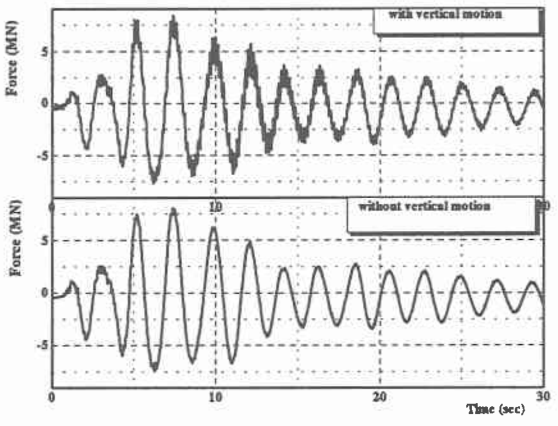


Fig. 8 In-plane shear time history at tower base

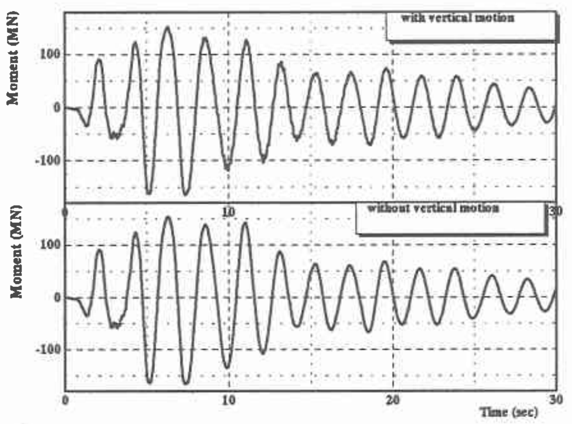


Fig. 9 In-plane moment time history at tower base

The curvature time history at the tower base, as shown in Fig. 7, reports the growth of the inelastic behavior, which can arise with the vertical motion, is due to the generation of new plastic zones caused by axial force fluctuation. A pronounced inelastic behavior increase is obtained with the vertical motion, and as a consequence, for the tower structure, there are various causes, such as the greater number of plasticized sections and the increment of the plastic curvature. The tower response with vertical ground motion shows slightly effects in the tower base shear reaction and in-plane bending moment, but high frequency response of the tower, which is appeared as waviness in the shear force and moment time history of the tower due to fluctuations in the axial force as a result of vertical motion effects, shown in Figs. 8 and 9. The tower overall flexural response in not significantly altered by the fluctuation in the axial force associated to the vertical ground motion, although moment curvature is affected by axial-bending interaction.

5. CONCLUSIONS

In this paper, the effects of the vertical motion on the seismic response of a steel tower frame of cable-stayed bridge are studied. The dynamic response analyses of the steel tower of Iwamizawa cable-stayed bridge have been performed for two cases of the input ground motions: the first case under horizontal motions only, and the second case under both the vertical and horizontal motions. The most detrimental is resulted to present a great peak vertical acceleration and a high frequency content of the vertical motion effects. For a representative tower and a selected earthquake ground motion, the conclusion of this study can be summarized as follows:

1) A significant axial force fluctuations as a result of vertical inertia forces due to the vertical motion affected the tower behavior and as a consequence the global structural response. Moreover, an inelastic behavior is obtained with vertical motion as a result of the plasticized regions increases and their extension increased at the tower base.
2) A slightly reduction in the energy dissipation due to the irregular shape and shifting of the moment-curvature loops is noticed.
3) The damage caused by the horizontal ground motion is similar to that caused by the vertical and horizontal ground motions, which may be attributed to the time lag between the large response to the vertical motion and that to the horizontal motion.
4) The tower overall flexural response is not significantly altered by the fluctuation in the axial force associated to the vertical ground motion, although moment curvature is affected by axial-bending interaction.
5) The results of this investigation show the vertical motion importance in the seismic analysis, and suggest improving the study of the vertical motion characteristics and of the structural behavior under this type of action.

References

1) Bozorgnia, Y., Niazi, M. and Cambell, K. W., Characteristics of free-field vertical ground motion during the Nothrige earthquake, *Journal of Earthquake Spectra*, Vol.11, No. 4, 1995.
2) Papazoglou, A.J. and Elnashai, A.S., Analytical and field evidence of the damaging effect of vertical earthquake ground motion, *Earthquake Engineering and Structural Dynamics*, Vol. 25, pp. 1109-1137, 1996.
3) Diotallevi, P. P., and Landi, L., Effect of the axial force and of the vertical ground motion component on the seismic response of R/C frames, *Proceedings of International Conference on Advanced Problems in Vibration, Theory and Application,* 2000.
4) Saadeghvaziri, M.A. and Foutch, D.A., Behavior of RC columns under non-proportionally varying axial loads, *Journal of Structural Engineering*, ASCE, Vol. 116, No. 7, pp. 1835-1856, 1990.
5) Kikuchi, M., Dan, K. and Yoshiro, K., Seismic behavior of a reinforced concrete building due to lare vertical ground motion in near source regions, *Proceedings of International Conference on Advanced Problems in Vibration, Theory and Application,* 2000.
6) Committee of Earthquake Engineering, *The 1995 Hyogoken-Nanbu Earthquake, Investigation into Damage to Civil Engineering Structures,* Japan Society of Civil Engineers, 1996.