# Seismic Response Analysis of a Shield Tunnel Connected to a Vertical Shaft

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**SUMMARY:**
This paper presents a seismic response analysis of a shield tunnel connected to a vertical shaft. The main objective is to investigate the influence of the torsional effects caused by the rocking of the vertical shaft on both the dynamic response and strain response of the tunnel connected to the vertical shaft. By using a three dimensional finite element analysis considering soil nonlinearities, three models are analysed herein: A jointed model considering the tunnel-shaft junction, a shaft-only model, and a tunnel-only model. The results of the dynamic response are shown by time-history responses of displacements and strains. Defining herein the shear distorsion as the relative displacement between the tunnel crown and invert, the analytical results show that in the proximity of the tunnel-shaft junction the strain response of the tunnel lining is influenced by the shear distortion of the tunnel caused by the torsional effects of the vertical shaft rocking.

*Keywords: shield tunnel, shaft, seismic response, torsion, finite element analysis*

## 1. INTRODUCTION

Nowadays, the construction of tunnels for water, sewage, electrical power and transportation systems requires the construction of shafts to interconnect tunnels and to provide exit to the ground surface. In many cases, the geometrical configuration of these tunnel-shaft systems must accomplish the use-restrictions of the underground space which may result in asymmetric three-dimensional underground structures subjected to the spatial variability of the ground motion and the soil-structure interaction effects during strong earthquakes. On these considerations, the structural safety and functional capability of these tunnel-shaft systems (JSCE, 1996) requires accurate prediction of their dynamic response which can be achieved by using three-dimensional models that take into account the complex boundary conditions and also the particular structural details of the tunnel-shaft junction.

To accomplish the above-mentioned requirements, this paper presents a three-dimensional dynamic finite element analysis of a shield tunnel connected to a vertical shaft which will be used to examine the influence of the torsional effects on the shield tunnel caused by the rocking of the vertical shaft. For a clear visualization of the dynamic response, a sine-wave input is used instead of an earthquake record. The results of this study show that the rocking of the vertical shaft influences significantly in the shear distortion and shear strains of the tunnel in the proximity to the tunnel-shaft junction.

## 2. TUNNEL-SHAFT MODEL CHARACTERISTICS

The geometrical characteristics of the tunnel-shaft model considered in this study are shown in Fig. 2.1, while Fig. 2.2 shows an schematic view of the geometry of the vertical shaft. In order to analyse effectively the influence of the shaft rocking on the dynamic response of the tunnel, No flexible materials are considered at the tunnel-shaft junction. The shield lining was designed according internal and grouting forces specified in the current Japanese standard for shield tunnelling.

The vertical shaft is rigidized with internal diaphragms transversal to the walls of the shaft. The external diameter of the tunnel is 6.0m and the thickness of the reinforced concrete shield segments is 0.3m. The reinforced concrete vertical shaft intersects the shield tunnel at 75m from both ends of the shield tunnel as shown in Fig. 2.1. The intersection of the tunnel with the shaft is located at Y=75m and Y=89m in global coordinates of the model.

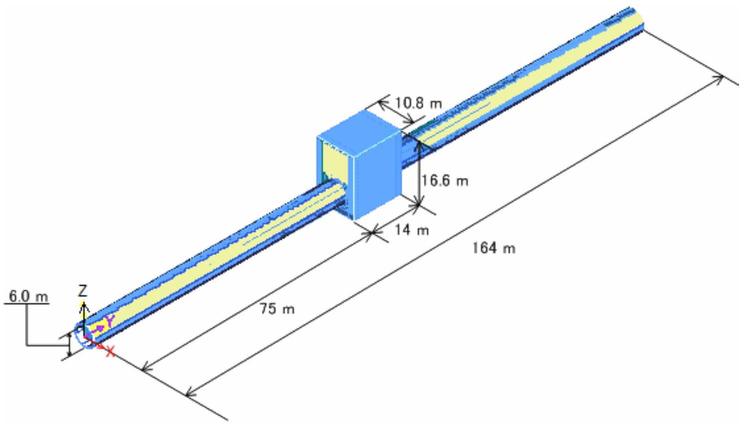



**Figure 2.1.** Geometrical characteristics of the tunnel-shaft model for the time-history response analysis

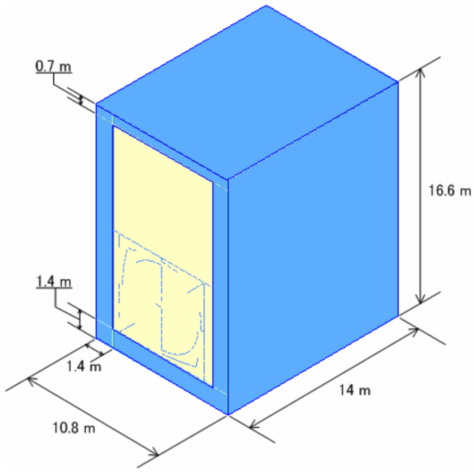



**Figure 2.2.** Geometrical characteristics of the shaft model for the time-history response analysis

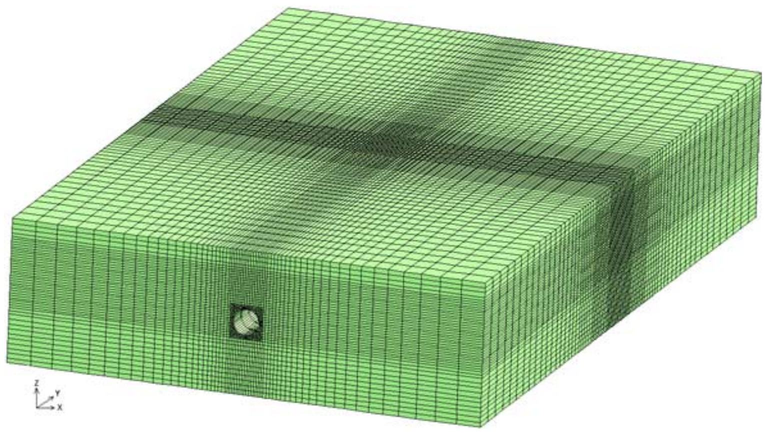
## 3. FINITE ELEMENT ANALYSIS

### 3.1. Methodology of the analysis

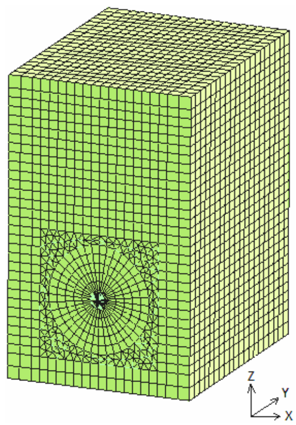
The three-dimensional finite element models showed in Fig. 3.1 represent the analysis cases used herein to examine the dynamic response of the tunnel-shaft system. The dynamic analysis is performed independently for each model. The results of each independent analysis are compared to examine the influence of the shaft in the dynamic response of the shield tunnel. The analysis models are:

- Tunnel-only (tunnel itself embedded in the ground)
- Jointed model (tunnel connected to the vertical shaft embedded in the ground)
- Shaft-only (vertical shaft itself embedded in the ground)
- Free-field (absence of underground structure)

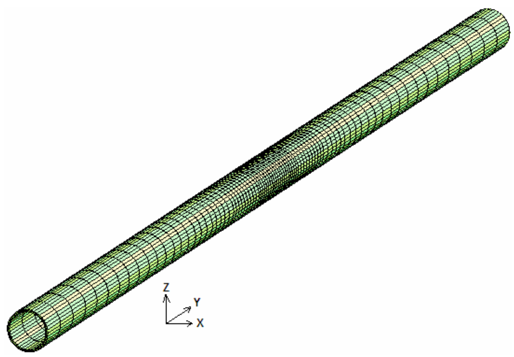
The Finite element analysis is carried out by using an in-house fortran source-code developed for soil-structure interaction analysis considering the nonlinear behaviour of soil material as elasto-plastic under the Drucker-Prager model. It can be seen in Fig. 3.1 that for all models, 8-node hexahedral elements are used in the zones of uniform geometry while 6-node prism elements are used in the proximity of the boundaries of the tunnel-shaft connection. The tunnel lining was modelled by solid plate elements, no-slip at the lining-ground interface is considered.



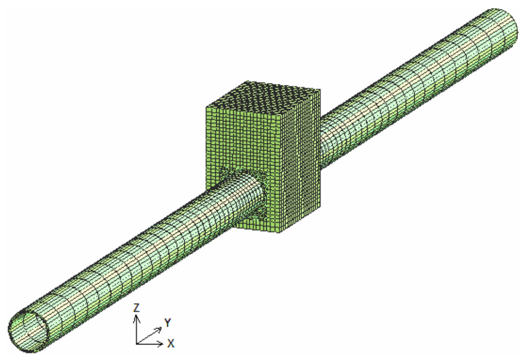
**(a)** Entire tunnel-shaft model



(b) Shaft model



**(c)** Pipe only model



(d) Tunnel-shaft model

**Figure 3.1.** Finite element models for dynamic response analysis (models are embedded in the ground)

## 3.2. Mechanical and dynamical properties of materials

The effect of dynamic soil-structure interaction depends on the stiffness and mass properties of the structure, the stiffness of the soil, and the damping characteristics of both soil and structure (Wolf, 1976). On this basis, an homogeneous soil-layer with the properties indicated in Table 3.2 is used in this study. In order to reduce the computational effort one soil-layer instead of a multi-layered soil is considered. The material properties of the shield lining and shaft used in the analysis are indicated in Table 3.2.

**Table 3.2.** Geomechanical characteristics and material properties

| | Soil | Shaft | Shield lining |
|---|---|---|---|
| Unit weight | 17.66 | 24.03 | 24.03 |
| Poisson ratio | 0.49 | 0.167 | 0.167 |
| Shear wave velocity (m/sec) | 200 | 2050 | 574 |
| Elastic modulus (kN/m$^2$) | $2.45 \times 10^7$ | $2.45 \times 10^7$ | $1.92 \times 10^6$ |
| Rayleigh damping coeff. $\alpha$ | 0.516 | | |
| Rayleigh damping coeff. $\beta$ | 0.0037 | | |

### 3.3. Input motion

The input motion used for the analysis is shown in Fig. 3.3, it is applied simultaneously in the transverse direction (X-axis) and axial direction of the tunnel (Y-axis) as indicated in Fig. 4.0. The sine-wave is chosen as input motion because it is computationally simple and because the superposition of harmonic responses of the models for comparative purposes can be better visualized than earthquake-excitation responses especially when the results of the analysis cases do not differ so much.

As can be observed in Fig. 3.3, the input motion is a 100 gal-sine wave with a frequency of 1.67 Hz which is close to the value of the natural period of the free-field motion. Vertical motion is not considered in the analysis herein. The input motion is prescribed at the soil-layer bed.

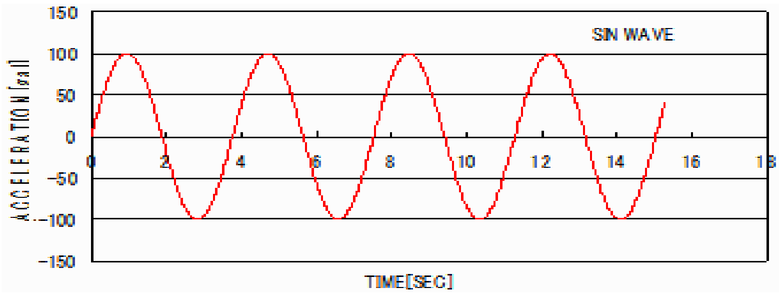



**Figure 3.3.** Input motions applied in the X-axis for the dynamic analysis

## 4. TIME HISTORY RESPONSES IN THE TRANSVERSE DIRECTION OF THE TUNNEL

In order to examine the dynamic response in the vicinity of the tunnel-shaft junction the time-history responses at locations $A, B, C,$ and $D$ indicated in Fig. 4.0 are considered. It can be seen that points $A$ and $B$ are on the tunnel crown and invert respectively. The separation distance between the tunnel-shaft junction and points $A$ and $B$ are 2.0m and 3.0m respectively. On the other hand, the points $C$ and $D$ are located on the shaft wall at very short distance of the boundaries of the tunnel-shaft junction.

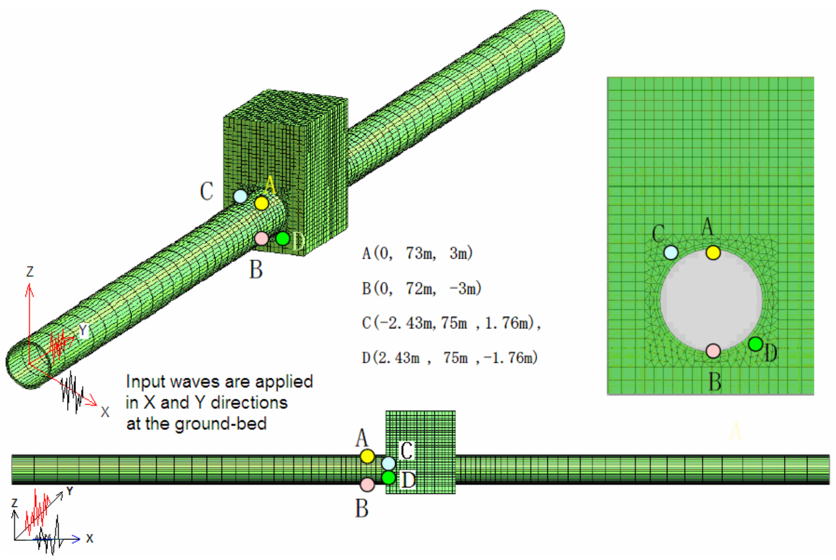



**Figure 4.0.** Selected locations to examine the time-history responses (All models are embedded in the ground)

In the following it will be examined the transversal displacements and shear strain responses at the tunnel crown and invert in the vicinity of the tunnel-shaft junction. In the legend of figures that show the time-history responses, the expression "jointed model" is referred to the tunnel connected to the shaft embedded in the ground, and, "tunnel-only" refers to the tunnel itself embedded in the ground.

### 4.1. Transversal displacements at the tunnel crown in the vicinity of the tunnel-shaft junction

From Fig. 4.1, it can be seen that for the jointed model the connection effect at the tunnel-shaft junction reduces slightly the transversal displacement of the tunnel-only model at the vicinity of the junction, it can be observed that the maximum transversal displacement of point $A$ at the tunnel crown obtained from the tunnel-only model reduces to 92% due to the connection effects of the junction.

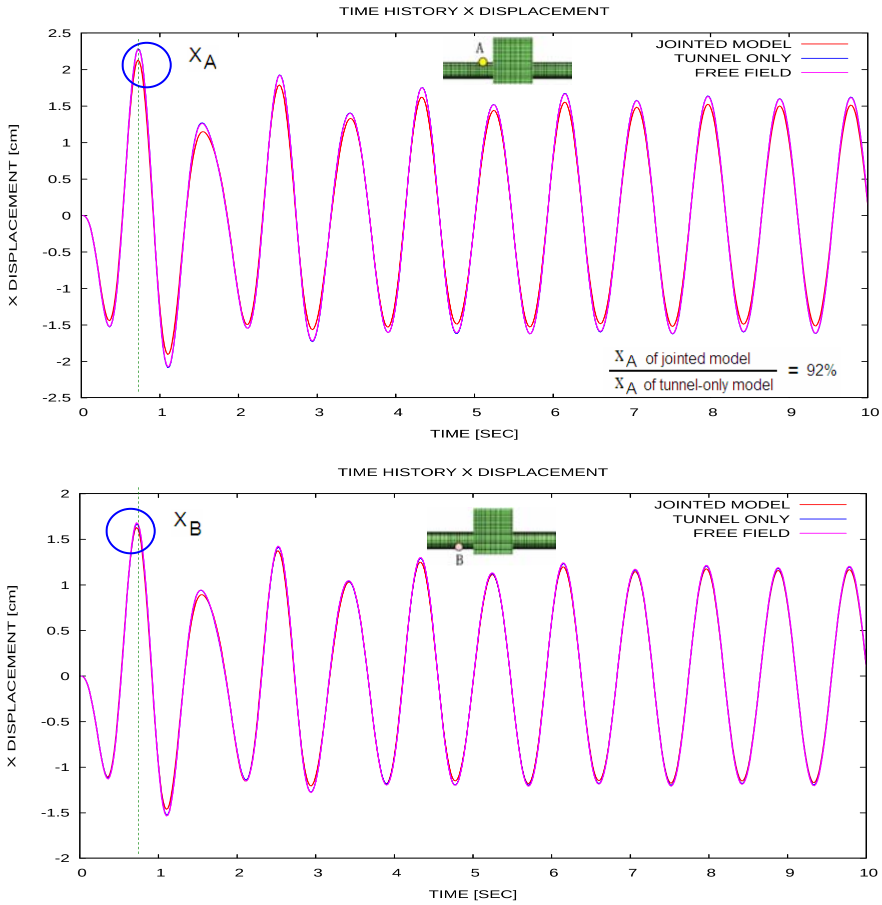



**Figure 4.1.** Absolute transversal displacement responses $x_A$ and $x_B$ at the tunnel crown and invert (points A and B), 2m and 3m away of the tunnel-shaft junction

Fig. 4.1 also shows that in the proximity of the junction, the transversal displacement time-history responses have the same "phase of motion". The maximum displacements at the crown $x_A$ and invert $x_B$ are 2.36cm and 1.7cm respectively.

### 4.2. Shear strain response at the tunnel crown in the vicinity of the tunnel-shaft junction

Fig. 4.2 shows that for the jointed model the time-history responses of shear strains at the tunnel crown and invert in the proximity of the tunnel-shaft junction have almost the same amplitudes but opposite "phase of motion", in other words, $x_A \approx -x_B$ which demonstrates that torsion occurs in the tunnel in the proximity of the tunnel-shaft junction during ground motion. The maximum transversal displacements of points $A$ and $B$ at the tunnel crown and invert are shown in Fig. 4.2.

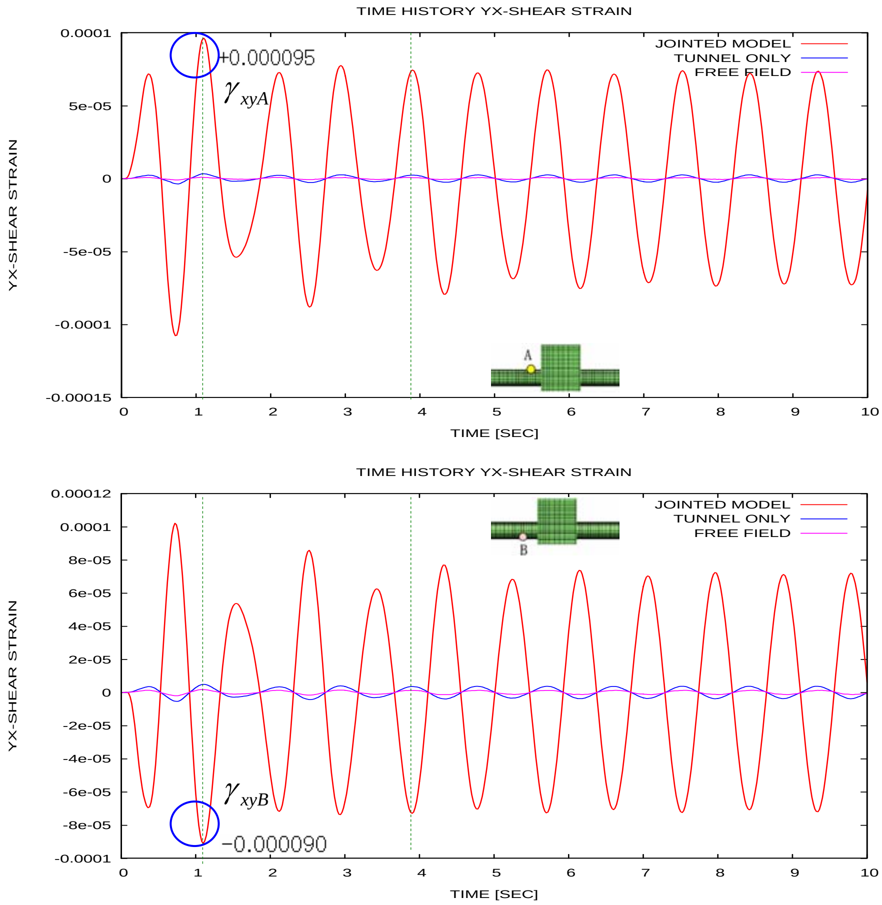



**Figure 4.2.** Shear strain responses $\gamma_{xyA}$ and $\gamma_{xyB}$ at the tunnel crown and invert (points A and B) respectively, 2m and 3m away of the tunnel-shaft junction

## 4.3. Shear strain response of the shaft wall just above and below the tunnel-shaft junction

As shown in the time-history responses of shear strains of Figs. 4.3 and 4.4, for the jointed model, the locations just above and below the tunnel-shaft junction (points $C$ and $D$) sustain shear strains in opposed directions during a ground motion. By comparing Figs. 4.3 and 4.4, it can be observed that , the shear strain amplitudes of the jointed model are opposed to the ones of tunnel-only model and shaft-only model.

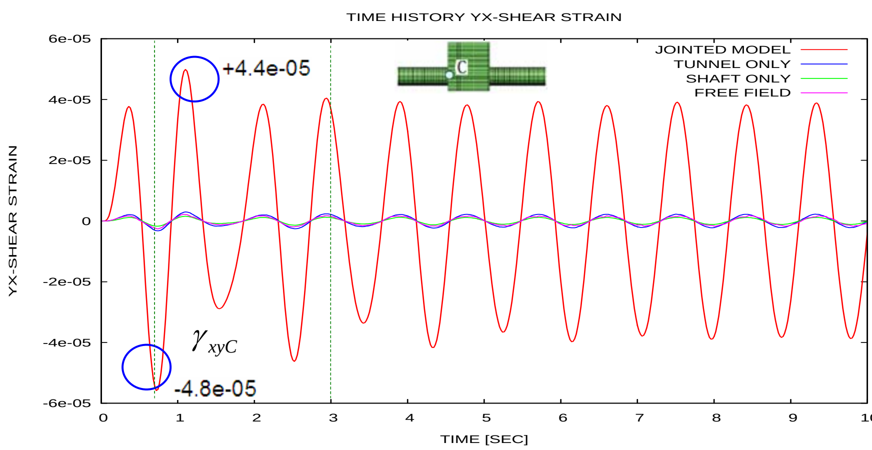



**Figure 4.3.** Shear strain responses $\gamma_{xyC}$ at the tunnel-shaft junction (see point C)

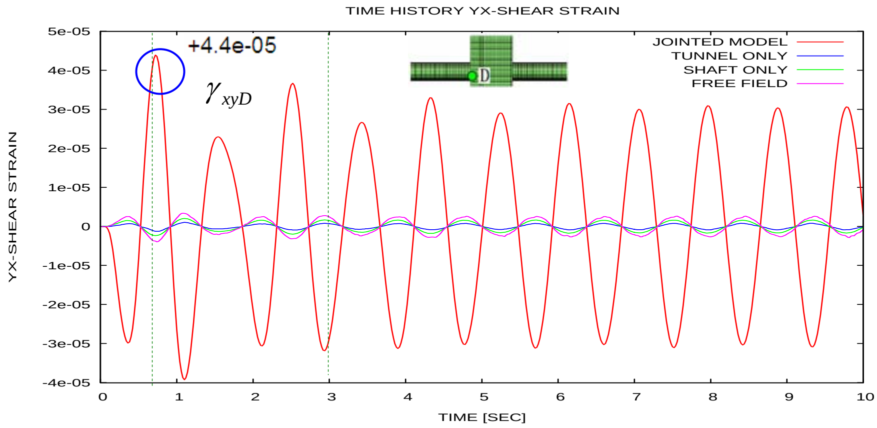



**Figure 4.4.** Shear strain responses $\gamma_{xyD}$ at the tunnel-shaft junction (see point D)

## 5. TIME HISTORY RESPONSES IN THE AXIAL DIRECTION OF THE TUNNEL (Y-AXIS)

In order to examine the dynamic response of the jointed model, tunnel-only model and shaft model the points $A, B, C$, and $D$ indicated in Fig. 5.0 are selected, as can be seen in this figure, the selected points are located in the tunnel and shaft at tunnel crown and invert levels.

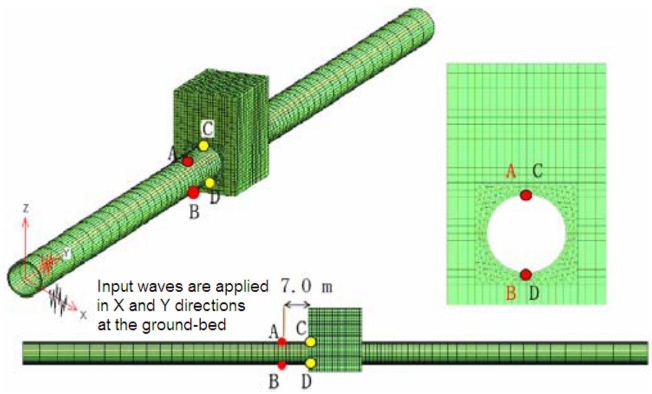



**Figure 5.0.** Selected locations to examine the time-history responses (All models are embedded in the ground)

### 5.1. Displacements at the tunnel crown in the axial direction of the tunnel

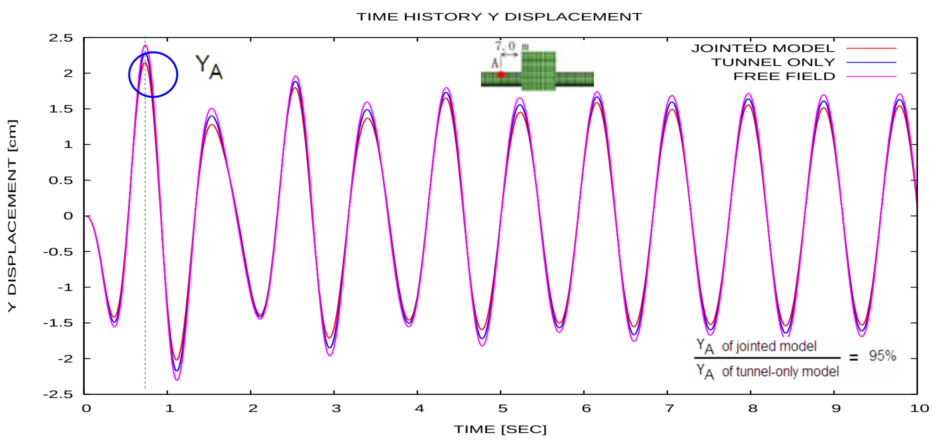



**Figure 5.1(a).** Absolute displacement responses $y_A$ at the tunnel crown 7m away of the tunnel-shaft junction (see point A)

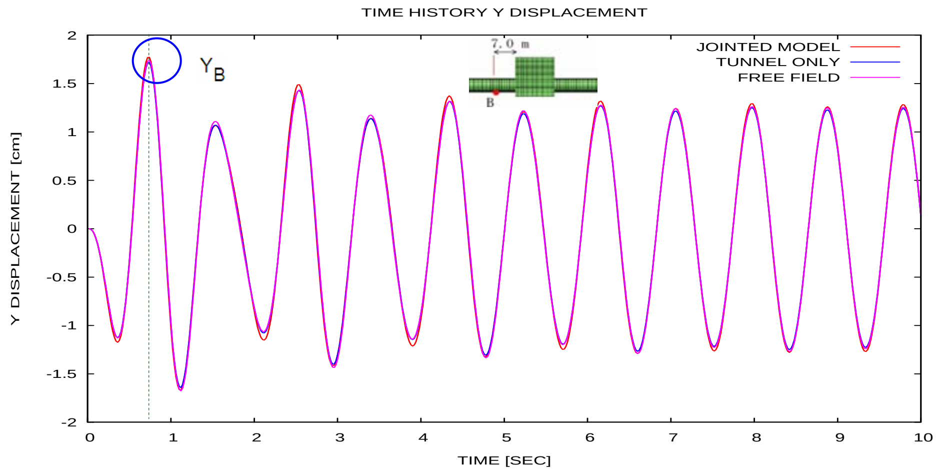



**Figure 5.1(b).** Absolute displacement responses $y_B$ at the tunnel invert 7m away of the tunnel-shaft junction (see point B)

The amplitude and phase of the time-history responses of displacements in the axial direction of the tunnel crown and invert are quite similar at 7m away from the tunnel-shaft junction which indicates that the displacements in the axial direction of the tunnel do not reveal the torsion effects produced in the tunnel-shaft junction during the ground motion. Similar conclusion arises from the time-history responses of lateral displacements of points $A$ and $B$ located 7m away from the tunnel-shaft junction.

### 5.2. Axial strain response at the tunnel crown 7m away from the tunnel-shaft junction

From Figures 5.2(a) and 5.2(b), it can be observed that for the jointed model the amplitude and phase of the time-history response of axial strains of the tunnel crown at point $A$ are opposite to the amplitude and phase of the tunnel invert at point B, it means that axial strains of the crown and invert have opposite sign. On the other hand, for the tunnel crown at point $A$, the time-history responses of axial strains of the jointed model have opposite phase of motion respect to the tunnel-only model. However, for the tunnel invert at point $B$, the time history response of axial strains of the jointed-model have the same sign of the axial response of the tunnel-model only.

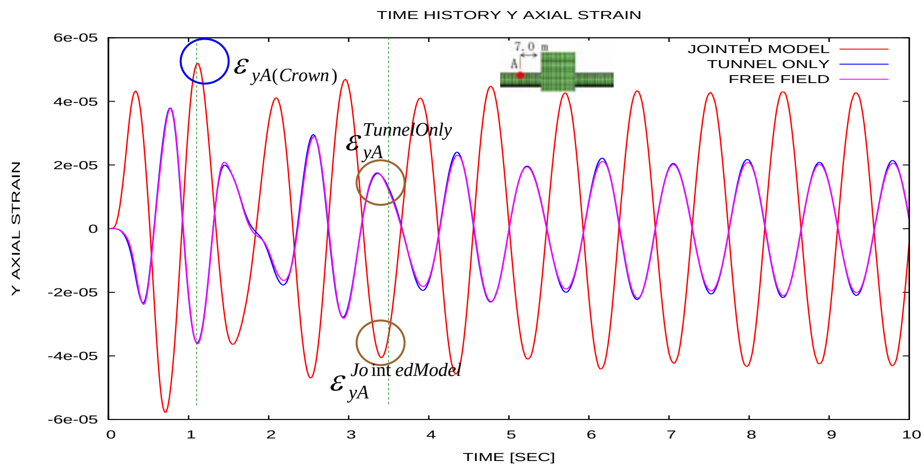



**Figure 5.2(a).** Axial strain responses $\varepsilon_{yA}$ at the tunnel crown 7 m away from the tunnel-shaft junction (point A)

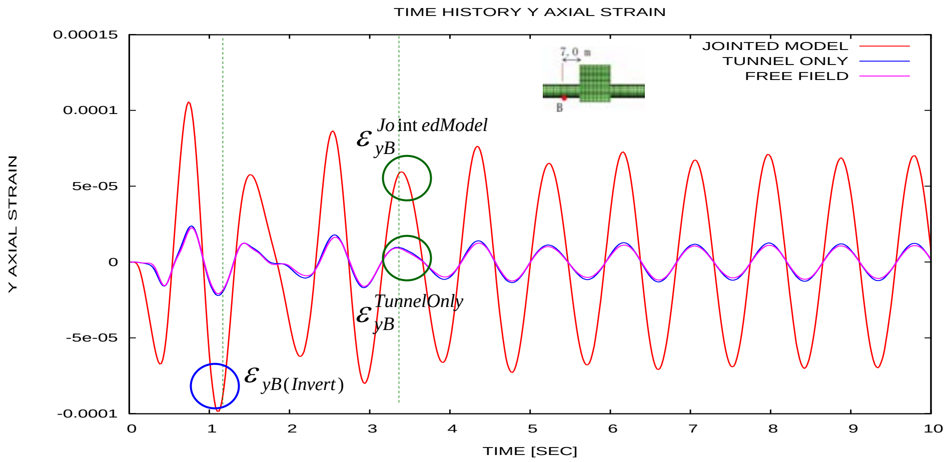



**Figure 5.2(b).** Axial strain responses $\varepsilon_{yB}$ at the tunnel invert 7m away from the tunnel-shaft junction (point B)

### 5.3. Axial displacements at the tunnel crown and invert at the intersection with the shaft

Fig. 5.3 shows that for the jointed model the axial displacements at the tunnel crown at the intersection with the shaft are slightly lower than the ones of the shaft-only model (0.97 times) and smaller than the ones of the tunnel-only model (0.96 times). On the other hand, the axial displacements of the jointed model at the tunnel invert at the intersection with the shaft are larger than those of the tunnel-only and tunnel-shaft models. The amplitude and phase of time histories of axial displacement of the tunnel at the intersection with the shaft are similar at the tunnel crown and invert.

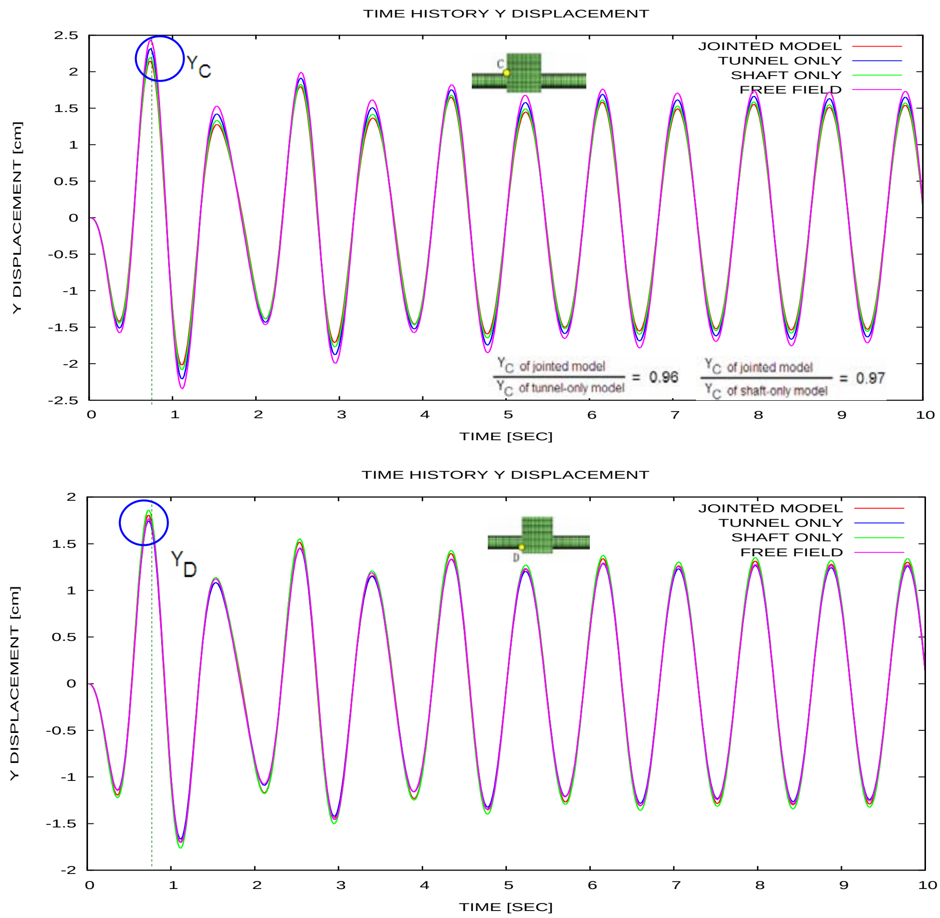



**Figure 5.3.** Axial displacement at the tunnel crown and invert at the intersection with the shaft, points C and D

### 5.4. Axial strain response of at the tunnel crown and invert at the intersection with the shaft

It is shown in Fig. 5.4 that the axial displacements at the tunnel crown and invert at the intersection with the shaft have large values for the tunnel-only model, medium values for the jointed model, and small values for the shaft-only model. For the tunnel crown the phase of the time-history responses of axial strain is similar for the three models. For the tunnel invert, the time-history response calculated from the jointed model have opposite phase and small amplitudes respect to the tunnel-only model.

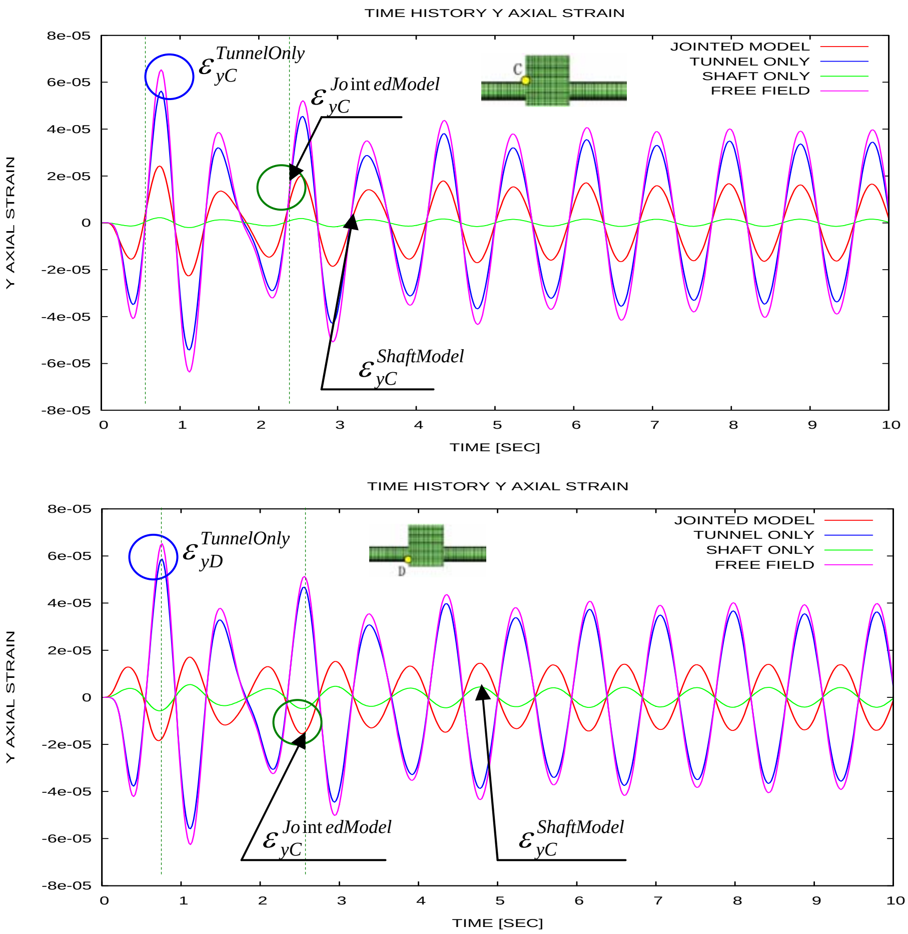



**Figure 5.4.** Axial strain at the tunnel crown and invert at the intersection with the shaft (points C and D)

## CONCLUSIONS

This paper has provided a background to understand the torsional effects produced in the proximity of a tunnel-shaft junction due to an excitation wave. It has been shown herein that for the jointed model (tunnel connected to the vertical shaft embedded in the ground) the time-history responses of shear strains and axial strains at the tunnel crown and tunnel invert have opposite phase of motion and increased values due to the rocking effects of the vertical shaft in the proximity of the tunnel-shaft junction. The significance of this paper relies in the procedure proposed to determine the shear strains (shear distortion) of the tunnel in the proximity to the tunnel-shaft junction by taking into account the torsional effects induced in the tunnel by the vertical-shaft rocking during ground motion

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