ARTIFICIAL NEURAL NETWORKS APPLIED TO THE SEISMIC DESIGN OF DEEP TUNNELS

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ABSTRACT:

Seismic response of underground structures is controlled by the earthquake-induced ground strain field and its interaction with the structure. Focusing on the response of the cross section, for simple geometry several closed-form solutions are available in the technical literature to compute the earthquake-induced stress increment in the lining. All these solutions are functions of the shear strain field which is the cause of the ovaling of the cross section. Since no direct measure of the transient ground strain during earthquake are available, it is common practice to indirectly compute the peak ground strains through simplified formulas based on simple assumptions of plane wave propagation in a homogeneous medium. A careful review of the damages caused by the earthquakes to underground structures shows that most damaged tunnels were located in the vicinity of the causative fault. Under such conditions ground motion is affected by near-fault effects and the induced strain field is quite complex. Therefore the use of simplified formulas may lead to a severe underestimation of the ground maximum strain. The strain field at depth can be evaluated numerically through the computation of synthetic time histories, however this procedure is rather involved, time consuming and requires numerous seismological input parameters. This paper illustrates the result of a numerical study in which an Artificial Neural Network (ANN) has been trained to predict the shear strain field in a neighbourhood of a seismogenic fault. The strain field was computed through numerical differentiation of synthetic displacement time histories obtained using the extended kinematic source model by Hisada and Bielak (2003). The reactivation of a fault located in the *Sannio* region (Southern Apennines, Italy) has been selected as a case study, since the fault is placed in the vicinity of an existing deep rock tunnel which is part of an important railway line in Southern Italy. The training of the ANN was conducted for a seismic source with varying magnitude, geometry and focal mechanism. Observation points at different strike and depth from the ground surface were considered. The computed results show the capability of ANN to predict the earthquake-induced strain field at depth in near-fault conditions and for varying seismological parameters.

KEYWORDS: Earthquake-induced shear strain, Seismic design of deep tunnels, Artificial Neural Networks, Near-fault effects.

1. INTRODUCTION

The seismic response of tunnels and in general of underground structures is considerably different from that of above-ground facilities since the overall mass of the structure is usually small compared with the mass of the surrounding ground, and the stress confinement provides high values of radiation damping. Therefore, the seismic response is mainly controlled by the imposed strain field and its interaction with the structure and not by the inertial characteristics of the structure itself. For engineering purposes underground structures may be assumed to undergo three primary modes of deformation during seismic shaking (Owen and Scholl, 1981): "*compression/extension*", "*longitudinal bending*" and "*ovaling*".
The analysis of seismic behaviour of a tunnel is a complex task since it involves the interaction with several disciplines including soil, rock and structural dynamics, structural geology, seismotectonics and engineering seismology. So far, relatively little efforts have been dedicated to this subject mainly because underground structures are not considered particularly sensitive to earthquakes, so that tunnel engineers often omit the analysis of the tunnel performance under seismic conditions at the design stage (Corigliano et al., 2007).
In a recent study Corigliano et al. (2007) have shown the capability of closed-form solutions to estimate the

seismically-induced stress increment in the cross section of the tunnel lining. In their study Corigliano et al. (2007) carried out a comprehensive analysis of the seismic problem which involves simultaneous modelling of the seismic source, the propagation path, accounting for near-source geological conditions and the soil-structure interaction. The results obtained from advanced numerical analyses were compared with those evaluated with a closed-form solution proposed by Corigliano et al. (2006) concluding that the simplified approach gives reasonable results from an engineering point of view. There are other closed-form solutions widely used in engineering practice (e.g. Wang, 1993; Penzien, 2000). These solutions are based on the computation of the state of stress in the cross section of a lined circular tunnel in plane strain conditions. The rock mass is considered to be an infinite, elastic, homogeneous, isotropic medium. The soil-structure interaction effects depend upon the ratio between the relative stiffness of the ground with respect to the lining. Another aspect which significantly affects the response of the tunnel is represented by the shear stress transmission at the ground-lining interface. The solutions are usually derived for two extreme contact conditions: *full-slip* (no shear stress transmission) and *no-slip* (no relative shear displacement). The seismic stress increment in the lining is accounted for in the closed-form solutions (i.e. Wang, 1993; Penzien, 2000; Corigliano et al., 2006) by analyzing the response of the cross-section to an imposed uniform strain field using the pseudo-static approach. This is done for two reasons (Penzien, 2000):

- the dimensions of a typical lining cross-section are small compared with the wavelengths of the dominant ground motion producing the ovaling;
- the inertia effects in both the lining and the surrounding ground as produced by dynamic soil-structure interaction effects are relatively small.

The earthquake loading is modelled as a uniform, quasi-static strain field simulating a pure shear deformation as shown in Figure 1.

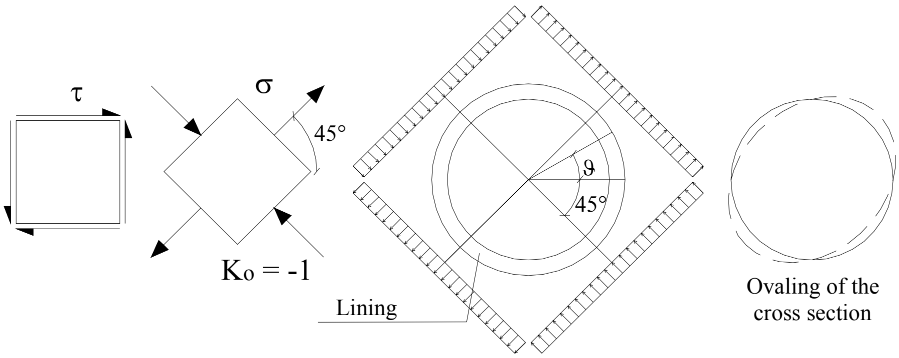

Figure 1 State of stress around a tunnel corresponding to a uniform, pure shear deformation

As a matter of fact underground facilities are in general less vulnerable to earthquakes compared with above-ground infrastructures. However there are exceptions as numerous tunnels worldwide have been severely damaged by ground shaking. Recent examples include among the others the 1995 Kobe (Japan), 1999 Chi-Chi (Taiwan) and 2004 Niigata (Japan) earthquakes. A careful review of the seismic damages suffered by underground facilities shows that most tunnels were located in the vicinity of causative faults. The characteristics of ground motion in the vicinity of the source can be significantly different from that of the far-field. Ground motion close to an active fault may be characterized by strong, coherent (narrow band) long period pulses and is severely affected by the rupture mechanism, the direction of rupture propagation relative to the site, and possible permanent ground displacements resulting from fault slip. These latter two phenomena are usually referred to respectively as "*rupture-directivity*" and "*fling step*" effects.

The previous considerations pointed out that the capability of closed-form solutions to predict the seismic response of underground structures is strictly related to the capability of assessing the earthquake-induced shear strain in the ground. Unfortunately, these quantities are usually not directly measured by the seismic networks. From dense seismic arrays the strain field can be computed through numerical differentiation based on spatial

interpolation of the recorded displacement field (Paolucci and Smerzini, 2008). However this kind of approach can be used to evaluate the strain tensor at the free surface. Moreover, close to the seismic source the strain field is strongly affected by near-fault effects.
A possible approach to estimate the strain field at depth in the vicinity of a causative fault in free-field conditions is by means of numerical differentiation of displacement time histories calculated using numerical methods for the simulation of synthetic seismograms. One of these methods is represented by the semi-analytical technique proposed by Hisada and Bielak (2003). The paper by Corigliano et al. (2007) shows an application of this method for the seismic design of rock tunnels. However, this procedure is rather involved, time consuming and furthermore it requires a large number of seismological and geological/geotechnical data. Therefore it is not suitable for engineering applications in the design practice. The objective of this paper is to illustrate a simplified though rigorous approach to predict the strain field in the vicinity of a seismogenic source based on the application of Artificial Neural Networks (ANN). The fundamental idea is to use the semi-analytical technique proposed by Hisada and Bielak (2003) to train an ANN for a variety of seismological scenarios so that eventually it will be able to predict the strain field at depth in the vicinity of a seismogenic fault for an arbitrary geometry, magnitude and focal mechanism. Availability of a well-trained ANN will dramatically reduce the complexity of the task of calculating the strain parameters not to mention the computational time required to perform the analyses. The idea has been applied to a fault located in the *Sannio* region (Southern Apennines, Italy) since it is positioned in the vicinity of an existing deep rock tunnel which is part of an important railway line in Southern Italy. Several analyses have been carried out accounting for different magnitude, fault geometry (dip angle), and focal mechanism (rake angle). Observation points at different strike and depth from the free surface have been considered.

2. EARTHQUAKE-INDUCED GROUND SHEAR STRAIN AT DEPTH

As previously pointed out, a key parameter for the seismic design of underground structures is the earthquake-induced strain field. Focusing on the transversal response of the tunnel, the most critical mode of deformation is the ovaling of the cross section due to the shear strain in the ground. The main difficulties in the application of closed-form solutions is related with the selection of the strain field parameters.

Newmark (1967) proposed a simplified method for calculating free-field ground strains caused by a 1D harmonic wave propagating at a given angle of incidence in a homogeneous, isotropic, elastic medium. St. John and Zahrah (1987) used Newmark's approach to develop an analytical procedure for estimating the free-field longitudinal, normal and shear strains as well as the curvature, due to propagating P, S, and Rayleigh waves. Shear strain induced by body waves can be calculated through the following relationships:

$$\gamma_P = \frac{V_P}{C_P} sen\phi \cos\phi \tag{2.1}$$

$$\gamma_S = \frac{V_S}{C_S} \cos^2 \phi \tag{2.2}$$

where V_P and V_S are the particle velocities of P and S waves respectively, C_P and C_S are the speed of propagation of P and S waves respectively and ϕ is the direction of propagation. Based on the previous approach longitudinal, normal and shear strains due to different kind of waves (P, S or Rayleigh) can be grouped into a simple formula which relate the Peak Ground Strain (PGS) to Peak Ground Velocity (PGV) and a suitable measure of the apparent propagation velocity (C) as follows (Paolucci and Pitilakis, 2007):

$$PGS = \frac{PGV}{C} \tag{2.3}$$

Equation (2.3) is widely used in engineering practice since it provides an easy way to estimate a design strain. Despite its simple formulation, Equation (2.3) requires a series of input data that are not easy to determine (e.g. angle of incidence, apparent velocity of propagation, prevailing wave type, etc.) and it can be used only if the assumptions of its derivation are satisfied (e.g. 1D plane harmonic wave propagation in homogeneous media). In addition to the features of wave propagation there are effects which are not accounted for in Equation (2.3) such as spatial incoherency, site effects, and near-fault effects (Bolt et al., 2004; Paolucci and Smerzini, 2008).
Recently, Paolucci and Smerzini (2008) proposed a methodology to experimentally determine transient ground strains from displacement records obtained by dense seismic arrays using a spatial interpolation technique. Although this approach provides a reliable measure of the strain field, such estimation is limited to the strain tensor at the free surface and it cannot be extended at depth. Moreover, in their paper Paolucci and Smerzini (2008) have shown the strong azimuth dependency of the Peak Ground Strain at the free surface. This feature can be also more pronounced in near-fault conditions.
In order to estimate the strain field at depth in a way that also accounts for near-fault conditions, Corigliano et al. (2006) proposed to calculate the earthquake-induced shear strain field (i.e. γ_{xz}, γ_{xy}, and γ_{yz}) in the vicinity of a causative fault through numerical differentiation of displacement time histories *u(x,y,z,t), v(x,y,z,t)* and *w(x,y,z,t)* at six points around the observation point (see Figure 2) as shown by the following relationships:

$$\begin{aligned}
\gamma_{yz} &= \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \cong \frac{1}{2\Delta z}\left[v\left(y_0, z_0 + \Delta z\right) - v\left(y_0, z_0 - \Delta z\right)\right] + \frac{1}{2\Delta y}\left[w\left(y_0 + \Delta y, z_0\right) - w\left(y_0 - \Delta y, z_0\right)\right] \\
\gamma_{xy} &= \frac{\partial u}{\partial x} + \frac{\partial w}{\partial y} \cong \frac{1}{2\Delta x}\left[u\left(y_0, x_0 + \Delta x\right) - u\left(y_0, x_0 - \Delta x\right)\right] + \frac{1}{2\Delta y}\left[w\left(y_0 + \Delta y, x_0\right) - w\left(y_0 - \Delta y, x_0\right)\right] \qquad (2.4) \\
\gamma_{xz} &= \frac{\partial u}{\partial x} + \frac{\partial v}{\partial z} \cong \frac{1}{2\Delta x}\left[u\left(z_0, x_0 + \Delta x\right) - u\left(z_0, x_0 - \Delta x\right)\right] + \frac{1}{2\Delta z}\left[v\left(z_0 + \Delta z, x_0\right) - v\left(z_0 - \Delta z, x_0\right)\right]
\end{aligned}$$

in which the partial derivatives are evaluated using the second order central finite difference operators. The largest value of the shear strains calculated at a point is called henceforth Peak Ground Shear Strain (PGSS).

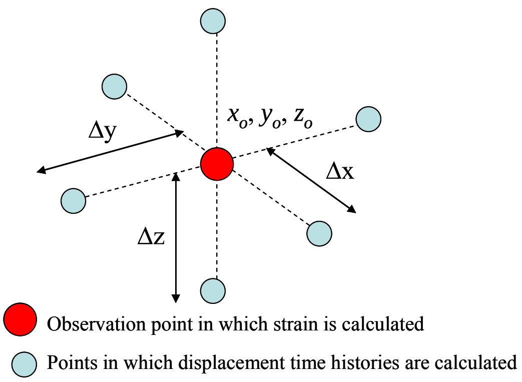

Figure 2 Spatial scheme used to calculate shear strain using finite difference operators

Displacement time histories were calculated using the semi-analytical method proposed by Hisada and Bielak (2003) which allow to perform a 3D simulation of the seismic source and associated wave propagation. The semi-analytical method developed by Hisada and Bielak (2003) is based on an extended kinematic source model and allows to investigate the effects of *fling step* and *rupture directivity* on the computed near-fault ground motion. This method is based on the computation of static and dynamic Green's functions of displacements and stresses for a viscoelastic horizontally layered half space. It takes advantage of an analytical expression for the asymptotic solutions of the integrands of the Green's functions, stemming from the generalized R/T reflection and transmission coefficient method and of the stress discontinuity representations for boundary and source conditions respectively. For the case under study only the dynamic contribution of the Green's functions will be taken into account.

The Hisada and Bielak (2003) method, as well as other procedures which compute synthetic ground motions, requires a wide range of input data composed by geophysical, geological and seismotectonics parameters, therefore such type of methods are not always suitable for the engineering practice. To simplify the procedure for the estimation of a design strain parameter based on the PGSS calculated with the previous approach, an Artificial Neural Network was trained with the purpose to predict the shear strain in a neighbourhood of a seismogenic fault. The method has been applied to an area located in the Northern sector of Southern Apennines ("*Sannio*" region, Italy), which is among the most active seismic regions in Italy. In fact, the Southern Apennines are characterized by a narrow seismic belt, with NW-SE striking and about 30 to 50 km width following the axis of the mountain range (Improta et al., 2000). In this area five large earthquakes with I_{MCS}>X occurred in 1456, 1688, 1702, 1735 and 1805, causing several victims and severe damage. A long seismic quiescence since1805 event makes the area highly susceptible to a new earthquake.

The Hisada and Bielak (2003) method requires definition of a crustal model for the region of interest. The geological structure of the "*Sannio*" region is rather complex and characterized by strong lateral heterogeneities in the upper 4 km of the earth crust. Improta et al. (2000) give an interpretation of the crustal seismic refraction data from the Northern Sector of the Southern Apennines thrust belt. Geophysical data were acquired along a 75 km seismic array parallel to the Apennines mountain range. This allowed the definition of a detailed two-dimensional P-wave velocity model of the upper crust. The velocity model is well constrained by sonic velocity logs obtained from oil wells located in close proximity to the seismic array and gravity data. This profile has been adopted as a generalised crustal model for the "*Sannio*" region. Since this model is too rough in the shallow part of the earth crust (due to the fact that only two layers in the first 5 km from the free surface are used), it has been adapted to fit the soil profile proposed by Cotton et al. (2006) based on the V_{S30} parameter. In this case it was selected a value of V_{S30} = 600 m/s to gradually merge with the V_S profile at greater depths. The adopted S-wave profile is shown in Figure 3. Since the active fault considered in this study reaches a depth of 25 km and the adopted crustal model is defined only down to 13 km depth, the latter has been extended in depth following the less detailed model proposed by other authors (i.e. Chiarabba and Amato, 1997).

Several analyses were carried out considering two focal mechanisms i.e. strike-slip (dip=90°; rake=0° and 180°) and dip-slip (dip=50 and 70°; rake=0°, 90° and 230°), and for each of them three values of moment magnitude (6.4, 6.9 and 7.4). For all the analyses the strike of the fault has been kept fixed and equal to 277°. Observation points at different strike and depth from the free surface have been considered for a total of 384 cases for which the shear strain was computed at 3072 points. Not all the results of numerical simulations were used to train the ANN. Some data were used to check the prediction capabilities of the ANN.

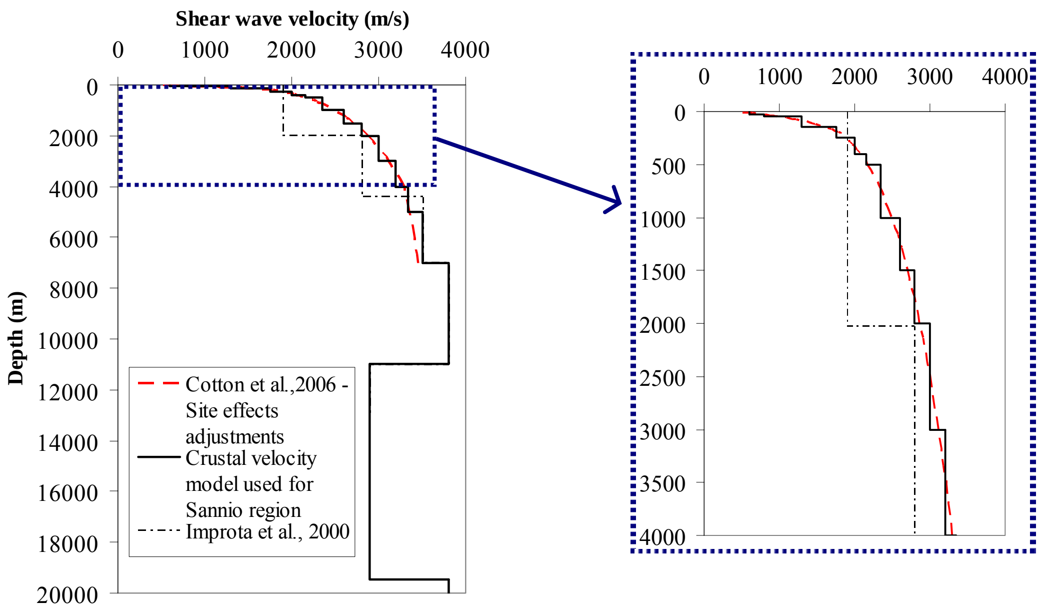

Figure 3 Crustal velocity profile adopted for the *Sannio* region (Southern Apennines, Italy)

3. ARTIFICIAL NEURAL NETWORKS (ANN)

ANN is a mathematical tool that can be used to model complex relationship between available and relevant inputs and outputs parameter. The architecture of ANN consists of interconnected groups of artificial neurons in different layers. The learning process begins with the presentation of an input pattern to the network. Then this input pattern is propagated through the entire network with first random weights until an output pattern is produced. The generalized delta rule, an error-minimization process, determines the error between computed output and target result, and this error would be sent back to update the connecting weights in each hidden layer, and the process is repeated for the next input-output pattern. The whole learning process would be stopped when the total computed error is less than ten percent, or when no further error reduction can be achieved at particular numbers of cycles. A new network architecture would be introduced to find the best optimized relationship between input and output data. After a number of trial and error simulations, a standard two hidden layer neural networks with 50 neurons inside each hidden layer have been found to give the best results. For each magnitude (M_W 6.4, 6.9, and 7.4) the 512 training input-output datasets have been given to train ANN, whereas the other 512 testing datasets have been used to verify the capability of ANN. There are six input patterns for ANN, the dip and rake angles of the fault trace, the depth, the Peak Ground Velocity (PGV) at the observation point, the azimuth angle referred to the north and the rupture distance (r_{rup}) (see Figure 4).

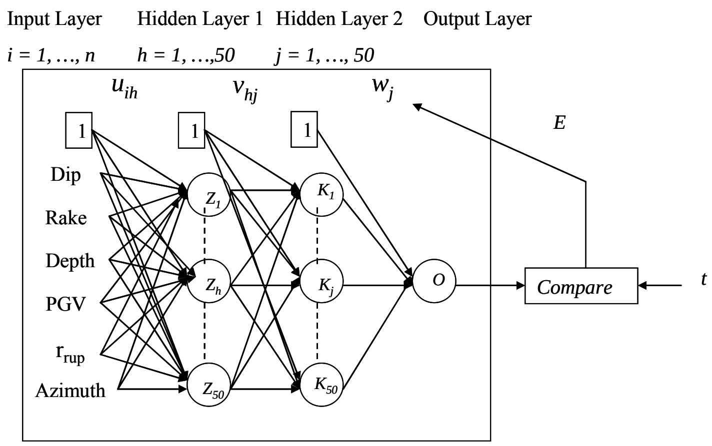

Figure 4 The architecture of the Artificial Neural Network (ANN)

PGS data from each observational point from four different directions (0˚, 90˚, 180˚, and 270˚) were used to train the ANN. Subsequently, the trained ANN is expected to be able to determine the PGS for all observational points at different strike directions (45˚, 135˚, 225˚, and 315˚ strike degrees) with a reasonable accuracy. Figure 5 shows the location of the observation points used to train and check the capability prediction of ANN.

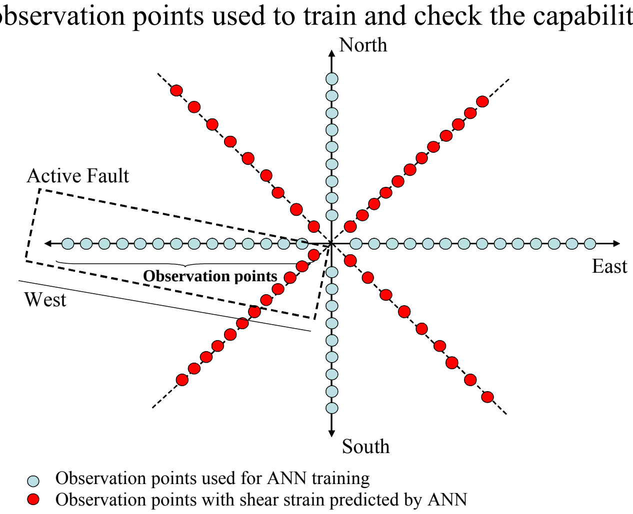

Figure 5 General outline of seismic source and observation points

Figure 6 shows an overall comparison of PGSS/PGV ratio between Hisada and Bielak (2003) computation and predicted values by ANN for all the considered cases for M_W=6.9, while Figure 7 shows a comparison for different magnitude, dip, rake angle and depth. In general the predictions of ANN can be considered satisfactory.

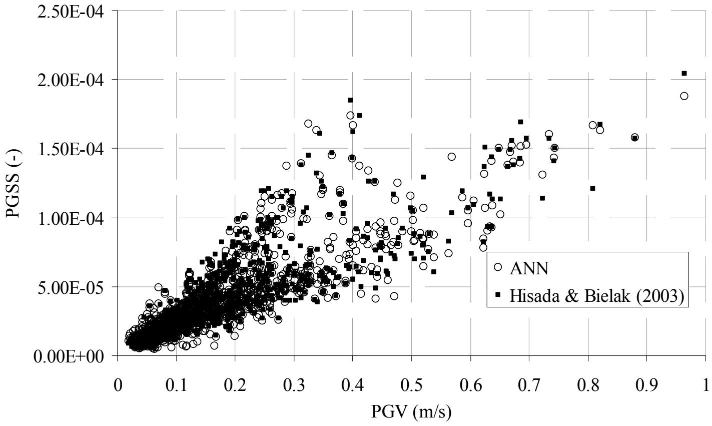

Figure 6 Comparison of PGSS/PGV ratio between Hisada and Bielak (2003) computation and predicted values by ANN for M_W=6.9

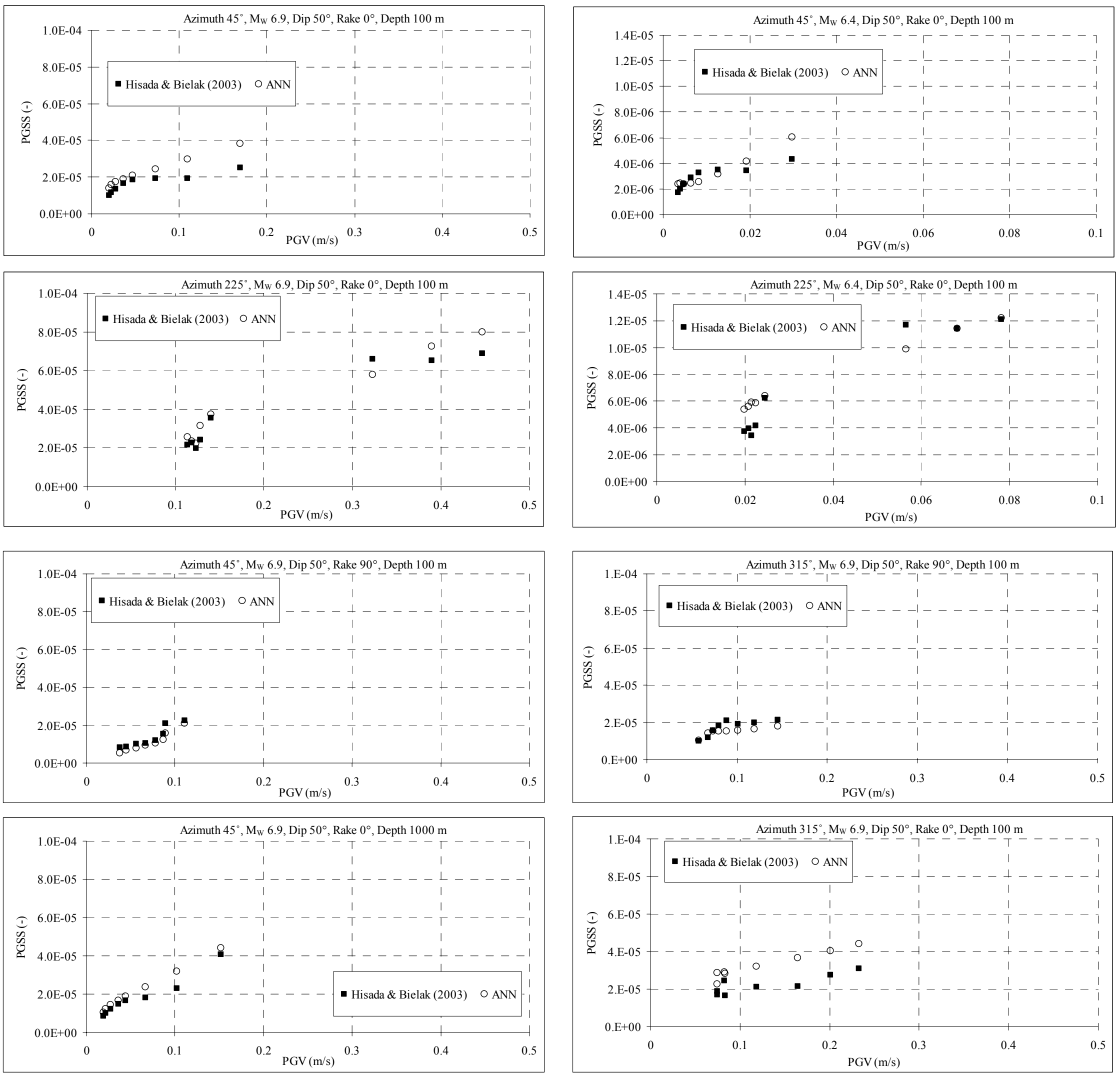

Figure 7 Comparison of PGSS/PGV ratio between Hisada and Bielak (2003) computation and predicted values by ANN for different Magnitude, dip, rake and depth

4. CONCLUSIONS

The paper illustrated the result of a numerical study in which an Artificial Neural Network (ANN) has been trained to predict a strain design parameter required for the computation of earthquake-induced stress increments in underground structures through the use of closed-form analytical solutions. The proposed approach allows to consider the most important features of near-fault ground motions without the recourse of complicated numerical simulations of the fault rupture. At the same time the method overcomes some of the limitations of widely spread simple formulas based on the assumption of plane wave propagation in homogeneous media. The obtained results have shown the capability of ANN to satisfactory predict the earthquake-induced strain field.

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