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SEISMIC GROUND RESPONSE AT LOTUNG (TAIWAN)

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Abstract. *In this paper the ground response of the Lotung experiment site during the strong-motion LSST7 occurred on May 1986 is simulated using two different numerical schemes: a simple equivalent-linear visco-elastic and a fully-coupled non-linear approach. The fully-coupled includes an advanced elasto-plastic soil model which has been calibrated against resonant column data and in-situ cross-hole measurements. The two horizontal components of the input motion are applied separately at bedrock level. The results of the simple and advanced numerical simulations are compared with the down-hole motions recorded in-situ during the investigated seismic event in terms of acceleration time histories and response spectra. The comparison between predicted results and in-situ measurements highlights the limitations of the frequency-domain approach and demonstrates the good performance of the advanced numerical scheme. Further investigation is needed to improve the numerical predictions of the observed ground response, in particular the peak ground acceleration in the N-S direction.*

1 INTRODUCTION

Experience from historical and recent strong earthquakes has demonstrated the significance of local soil conditions on the seismic ground response. The changes in amplitude, frequency content and duration of the seismic motion during its propagation in soil deposits, commonly referred to as site effects, have a crucial impact on the response of buildings and infrastructures during earthquakes [e.g. 1].

Site response analysis methods allow geotechnical engineers to quantify the effects of soil deposits on the propagation of waves from bedrock to ground surface. These methods can be divided into frequency-domain schemes (using equivalent-linear methods) and time-domain schemes (usually performed with finite element procedures). The equivalent visco-elastic approach has been widely adopted in engineering practice during the past thirty years, although its limitations have been highlighted in the literature [e.g. 2, 3]. Alternatively, time-domain finite element (FE) schemes are nowadays available to solve the ground response more accurate accounting for the solid-fluid interaction by means of a coupled effective stress formulation [e.g. 4]. In these schemes, the behaviour of soil can be described by non-linear constitutive models with different level of complexity. From the validation point of view, the performance of the different numerical approaches to simulate the complex wave propagation process has been tested over the last decades using real vertical array data and/or laboratory data obtained from centrifuge models [e.g. 5-8].

This paper presents a validation study of the Lotung Large-Scale Seismic Test (LSST) site in Taiwan using the recordings from accelerometer arrays. In particular, the prediction of the free-field response at Lotung during the event recorded in May 1986 is investigated using a simple equivalent-linear visco-elastic and a fully-coupled non-linear approach.

In the first part of the paper the geological and geotechnical properties of the LSST site are briefly described. Then, the numerical models adopted for the frequency-domain and the time-domain dynamic simulations are summarised along with the calibration against in-situ and laboratory data of the soil constitutive model used in the advanced analyses. Finally, the direct comparison between predicted and recorded motions at different depths within the soil deposit is presented. The predictions obtained with the advanced non-linear approach are particularly successful, although further improvements are still necessary to better capture the observed free-field response.

2 THE LARGE-SCALE SEISMIC TEST AT LOTUNG

The Large-Scale Seismic Test (LSST) is located in one of the most seismically active region in the North-East of Taiwan, and has been originally established in the 80’s to study the dynamic behaviour of two scaled-down nuclear plant containment structures [9]. The site response has been monitored by a number of surface and down-hole accelerometer arrays, together with pore pressure transducers. The down-hole accelerometers have been installed at depths of 0, 6, 11, 17 and 47 m, oriented in N-S, E-W and vertical directions. Figure 1 shows the elevation and plan views of the instrumentation. Of particular interest here is the vertical array named DHB in Figure1(a) which has been considered as representative of the free-field response at Lotung.

The site geology consists of recent alluvium and Pleistocene materials over a Miocene basement. The upper alluvial layer, 30 to 40 m thick, consists mainly of clayey-silts and silty-clays [10]. The water table is located approximately at a depth of 1 m. The local geological profile shows a first layer of grey silty-sand and sandy-silt about 20 m thick underlain by about 10 m of more gravelly layer resting on a thick deposit of silty clay, as indicated by the SPT log profile reported in Figure 2(a).

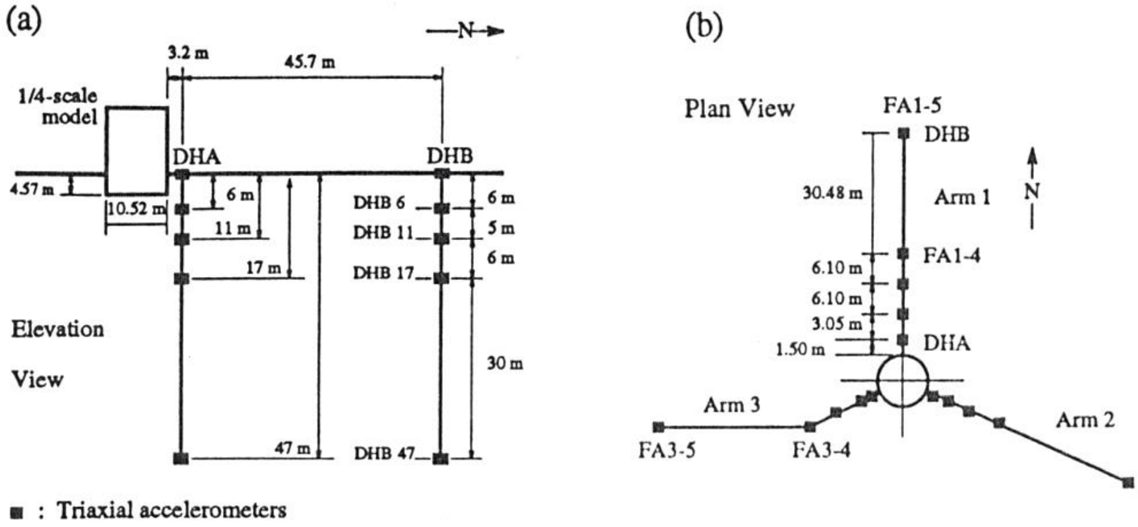

Figure 1: Instrumentation at the LSST site: (a) down-hole arrays; (b) surface arrays [11].

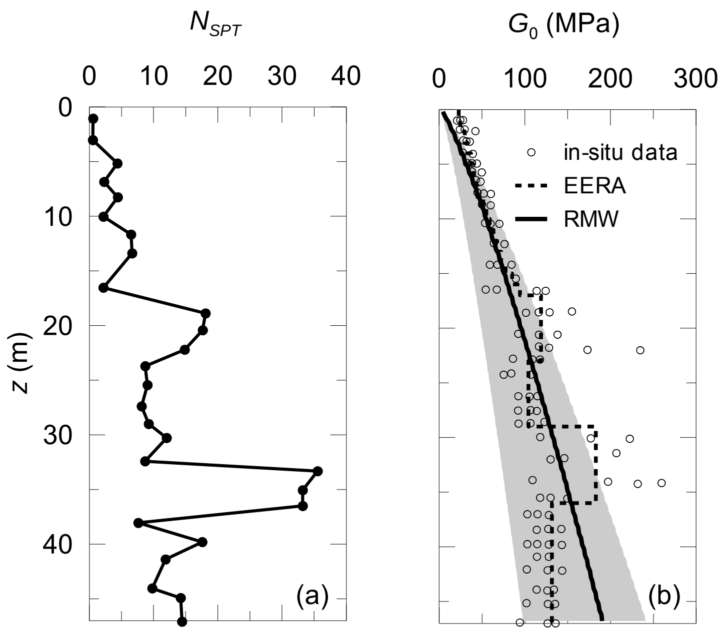

Figure 2: Local soil profile at the LSST site: (a) SPT log; (b) elastic shear modulus.

A series of geophysical seismic tests have been performed to measure shear and compression wave velocities at the LSST site. Figure 2(b) shows the elastic shear modulus data obtained from seismic cross-hole tests [12]. The bedrock formation can be assumed to be at a depth of 47 m. Shear modulus and damping ratio curves have been measured through resonant column and cyclic torsion tests on undisturbed specimens [12, 13]. Alternatively, Zeghal *et al.* [14] have proposed to back-figure the in-situ moduli ratio curves for Lotung soil based directly on its seismic response recorded along the down-hole arrays during 18 earthquakes which occurred between 1985 and 1986. In particular, different sets of G/G_0 and D-γ curves have been developed for the depths of 0-6, 6-11 and 11-17 m, producing for each depth a least-square best fit (SF) as well as an upper (UB) and a lower bound (LB) curve indicative of the possible variations in the material dynamic properties (Figure 3). The shear modulus and damping ratio curves of the soil between 17 and 47 m have been assumed to be the same as those from 11 to 17 m.

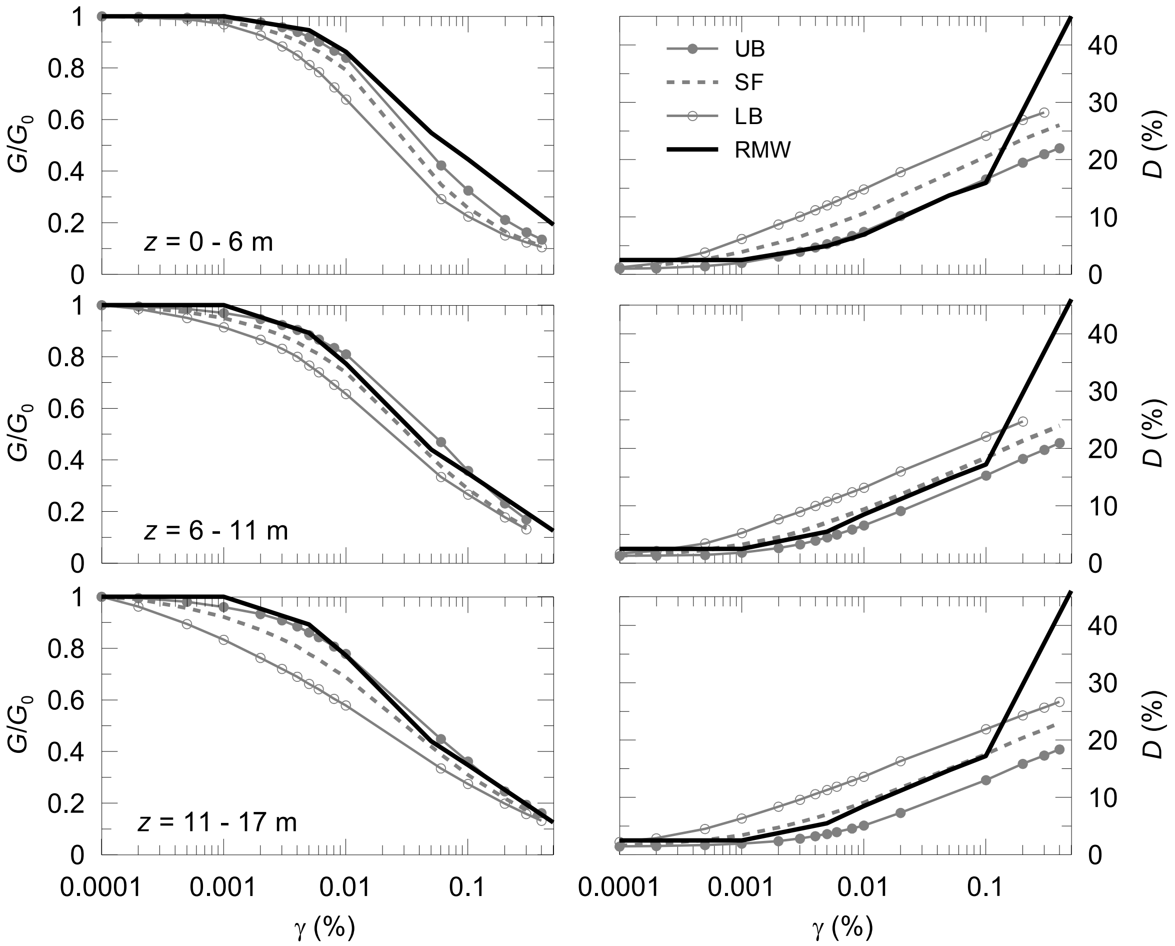

Figure 3: Shear modulus and damping curves developed by Zeghal *et al.* [14] and RMW predictions.

3 NUMERICAL MODEL

The ground response analyses of the Lotung site during the LSST7 event occurred on May 1986 have been performed using the equivalent-linear visco-elastic code EERA [15] and the FE code SWANDYNE II [16]. The earthquake, characterised by maximum accelerations of 0.16 g and 0.21 g respectively in the E-W and N-S direction, has been selected due to its strong-motion characteristics. The two horizontal components of the seismic event have been applied separately as input motions at the bedrock level (i.e. at 47 m).

3.1 Equivalent-linear visco-elastic model

The code EERA is based on the assumption of equivalent-linear visco-elastic soil behaviour. The approach makes use of the exact continuum solution of wave propagation in horizontally layered visco-elastic materials subjected to vertically propagating transient motions [e.g. 17]. The non-linear variation of soil shear modulus, G, and damping, D, with shear strain is accounted for through a sequence of linear analyses with iterative update of stiffness and damping parameters. For a given soil layer, G and D are assumed to be constant with time during the shaking. Therefore, an iterative procedure is needed to ensure that the properties used in the linear dynamic analyses are consistent with the level of strain induced by the input motion in each layer.

In the presented EERA analyses, the profile of small-strain stiffness shown in Figure 2(b) with a dashed black line has been discretised by constant stiffness sub-strata of 1 m thickness.

The statistical fit (SF) curves reported in Figure 3 have been adopted in the visco-elastic simulations for the top layers (i.e. between 0 and 17 m). From 17 to 47 m the same curves as those relevant to the depth between 11 and 17 m have been considered.

3.2 Non-linear finite element model

The ground response analysis of the Lotung experiment site has been also undertaken using the two-dimensional fully-coupled finite element code SWANDYNE II. The code allows to perform linear and non-linear dynamic analyses, using the Generalised Newmark method [18] for time integration. In particular, the values of the Newmark parameters selected in all the FE analyses illustrated in this note are β_1 = 0.600 and β_2 = 0.605 for the solid phase and β_1^* = 0.600 for the fluid phase. These values ensure that the algorithm is unconditionally stable, while being dissipative mainly for the high frequency modes [e.g. 4]. A 5 m wide, 47 m high FE mesh composed by 235 isoparametric quadrilateral finite elements with 8 solid nodes and 4 fluid nodes has been used in the dynamic simulations. The base of the mesh has been assumed to be rigid, while equal displacements have been imposed to the nodes along the vertical sides (i.e. tied-nodes lateral boundary conditions). Base and lateral hydraulic boundaries have been assumed as impervious, while drained conditions have been imposed at the top of the mesh. A small amount of viscous damping, equal to 3%, has been introduced into the model through a standard Rayleigh formulation [e.g. 19] to reduce the high frequency spurious spikes.

In order to investigate the effects of soil non-linearity on the wave propagation process, plasticity has been implemented in the FE simulations through the advanced elasto-plastic model (RMW) developed by Rouainia and Muir Wood [20]. The RMW model allows to reproduce some of the key features of the cyclic behaviour of natural soils as the decay of the shear stiffness with strain amplitude, the corresponding increase of hysteretic damping and the related accumulation of excess pore water pressure under undrained conditions. The model has been implemented in SWANDYNE II with an explicit stress integration algorithm adopting a constant strain sub-stepping scheme. RMW has been successfully employed to simulate both static [21, 22] and dynamic geotechnical problems [23, 24]. For more details on its formulation and implementation the reader is referred to Rouainia and Muir Wood [20] and Zhao *et al*. [25].

In previous versions of the model a classical hypoelastic formulation was employed for the determination of the bulk and shear moduli, K and G_0. In this work, the well-known equation proposed by Viggiani and Atkinson [26] for the small-strain shear modulus has been implemented to reproduce the dependency of G_0 on the mean effective stress (p) and the overconsolidation ratio (OCR):

$$\frac{G_0}{p_r} = A\left(\frac{p}{p_r}\right)^n OCR^m \tag{1}$$

where p_r is the reference pressure (equal to 1 kPa). The non-dimensional parameters A, m and n depend on the properties of the soil and can be determined as function of the plasticity index. In the initialisation of the FE model, a higher overconsolidation ratio has been assumed for the upper part of the FE column (from 0 to a depth of 6 m), with an average OCR equal to 4, while a constant OCR of 2 has been imposed for the remaining part of the model. The assumed variation of OCR with depth is deemed to be realistic in accordance with the G_0 data shown in Figure 2(b), where a non zero elastic shear modulus of about 25 MPa can be observed near the ground surface (corresponding to a measured shear wave velocity of about 100 m/s). Once the FE model has been initialised, a range of possible elastic shear modulus profiles, reported in Figure 2(b) with the shaded area, have been investigated and the final G_0 profile adopted in the FE dynamic simulations is shown in the same figure with a solid black line.

Numerical simulations of undrained cyclic simple shear tests have been carried out with RMW in order to produce normalized shear modulus and damping curves. The secant shear modulus and the damping ratio for each shear strain amplitude have been assessed after 500 load cycles, a number sufficient to reach steady-state condition. The results of the single element tests performed with the RMW model are reported in Figure 3 with a solid black line for each depth and compared with the corresponding curves presented by Zeghal *et al*. [14]. Table 1 summarises the RMW model parameters adopted for the different soil layers.

Depth	λ^*	κ^*	M	R	B	ψ	r_0
0-17 m	0.03	0.0015	0.922	0.08	0.60	1.0	1.0
17-23 m	0.03	0.0015	1.096	0.08	0.60	1.0	1.0
23-29 m	0.03	0.0015	0.814	0.08	0.60	1.0	1.0
29-37 m	0.03	0.0015	0.941	0.08	0.60	1.0	1.0
37-47 m	0.03	0.0015	0.730	0.08	0.60	1.0	1.0

Table 1: Material parameters for the RMW model.

4 RESULTS AND DISCUSSION

The results of the EERA simulations are shown in Figure 4 with a dashed black line in terms of acceleration time histories recorded at depths 0 and 11 m. The corresponding downhole motions recorded in-situ during the earthquake along the DHB array [27], named FA1-5 and DHB-11, are reported in the same figure. The comparison shows that EERA is able to predict the E-W motion very well, particularly at the depth of 11 m both in terms of peak acceleration and zero crossing. The peak acceleration at ground surface in the E-W direction is slightly over-estimated. On the contrary, a poorer prediction can be obtained by applying the N-S component at bedrock level: the equivalent-linear analysis under-predicts the peak acceleration significantly both at ground surface and at the depth of 11 m. Moreover, a time shift in the acceleration peak between the recorded and predicted motions can be observed at surface. A similar performance of the equivalent-linear visco-elastic approach has been observed by Borja *et al*. [5] and Amorosi *et al*. [8].

In addition to the EERA results, Figure 4 also shows the predictions obtained with the FE non-linear approach. The time-domain analyses, undertaken within the SWANDYNE II finite element code along with the RMW constitutive model, are in good agreement with the recorded data, especially at the depth of 11 m from surface, for both the E-W and N-S component. The predicted peak acceleration of the E-W motion at ground surface agrees well with the observed array data, while a slight under-estimation of the PGA can be seen in the N-S direction. A very good agreement with the array data is obtained in terms of zero crossing.

The response spectra (for 5% damping) of the acceleration time histories recorded during the EERA and SWANDYNE II simulations at ground surface and 11 m depth are presented in Figure 5. While the agreement with the array data obtained by both the visco-elastic and FE non-linear schemes is evident for the E-W component of the input motion, EERA is not able to correctly capture the frequency content of the N-S component both at 0 and 11 m depth. On the contrary, a significant improvement in the frequency prediction of recorded data is obtained by the advanced numerical approach. It should be noted that the wave signal arrives at the depth of 11 m already significantly damped from the deeper soil layers, for which a proper geotechnical characterization in terms of reduction in shear modulus and damping is not available.

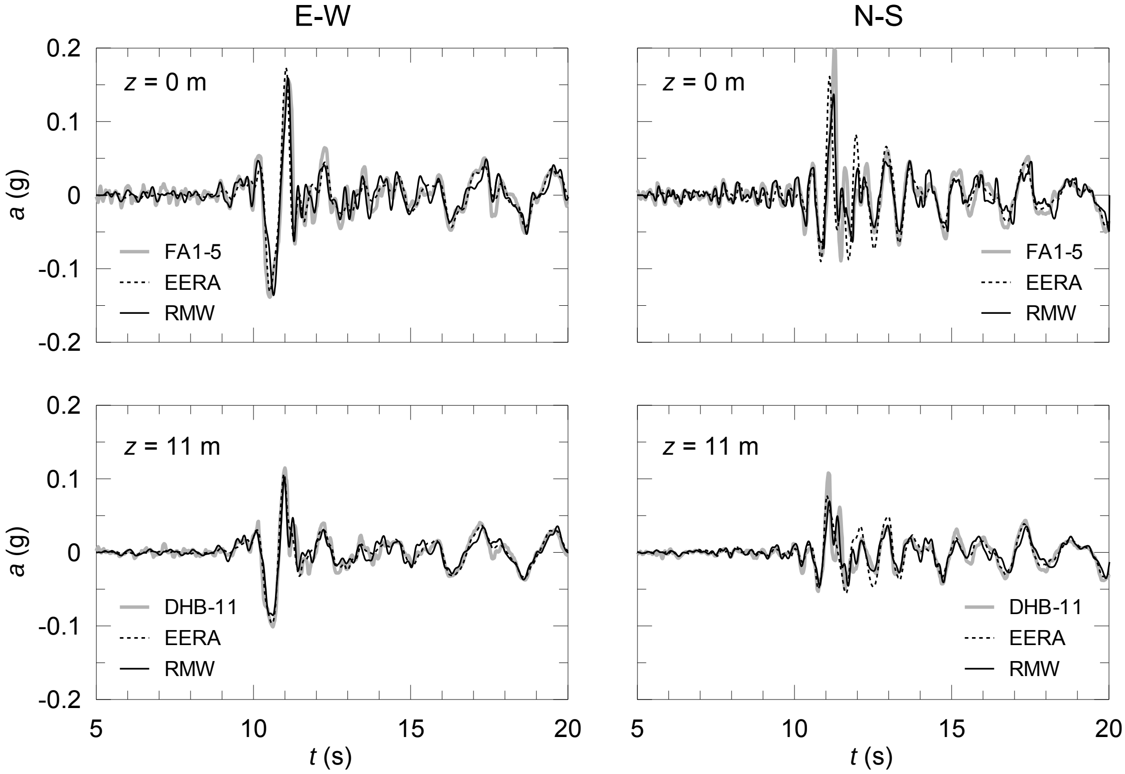

Figure 4: Comparison between predicted acceleration time histories and array data.

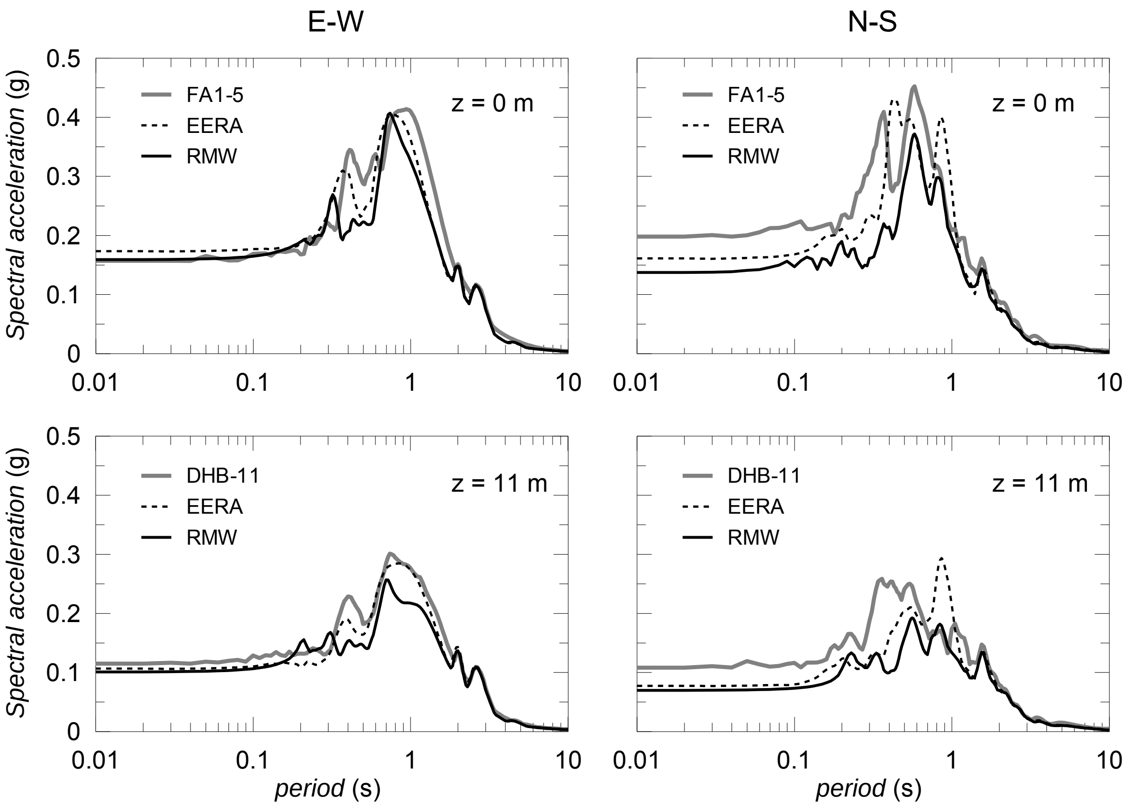

Figure 5: Comparison between predicted response spectra and array data.

5 CONCLUSIONS

The ground response analysis of the Large-Scale Seismic Test site in Lotung has been studied in this work using the simple equivalent-linear visco-elastic method and a fully-coupled non-linear FE approach The incorporation of plasticity through an advanced elasto-plastic model, which has been calibrated against laboratory and in-situ data, has allowed the effects of soil non-linearity on the wave propagation to be investigated. The comparison with recorded array data has enabled to assess the performance of the two numerical schemes, highlighting the limitations of the visco-elastic method and the advantages of the advanced approach. In particular, the results have shown how the frequency-domain approach is unable to capture the frequency content of the observed acceleration in the N-S direction at all investigated depths. In contrast, the fully-coupled simulations are in good agreement with the array data in terms of frequency, although a small under-estimation of the peak ground acceleration in the N-S direction has been observed. Further improvements are still necessary to better simulate the observed free-field response.

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