Numerical modelling of site effects – Influences of groundwater level changes

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Abstract: In the past decades the necessity for detailed earthquake microzonation studies has been recognised worldwide. Therefore different approaches were established and applied. Unfortunately, the majority of these approaches is not based on existing field data but requires extensive geophysical measurements and investigations. Further these approaches cannot take seasonal or long-term changes of groundwater level into account.

For this purpose, notably numerical models are most suitable. These models require a good knowledge of the local geological conditions (especially of the uppermost Quaternary layers), information about the geotechnical parameters of these layers and a hydrogeological model of the investigated area. Most of these information can be obtained from geotechnical investigations and surveys which have already been carried out in these mostly densely populated areas.

It can be shown that groundwater and groundwater level changes have a very important influence on site effects. If confined aquifers exist near the surface liquefaction can take place. Under certain conditions one can benefit from the existence of liquefied layers as they attenuate the propagation of shear waves.

Key-Words: Numerical modelling, Site effects, Microzonation, GIS, Visco-hypoplasticity, Geotechnical parameters, Groundwater level change, Liquefaction, Bucharest

1 Introduction

In order to elaborate building codes for earthquake-endangered cities it is very important to know local site effects or to have a detailed earthquake microzonation map. Site effects can be investigated either directly by measuring response spectra for many sites (this requires additional extensive geophysical measurements and investigations) [e.g. 1, 2], by applying probabilistic methods (combination of seismic registrations and modelling) [e.g. 3] or indirectly by calculating response spectra based on a (hydro-) geological model [e.g. 4, 5]. The first approach has the disadvantage that in most cases measurement results can only be obtained for weak motion and not for the more relevant strong earthquakes. Furthermore, influences of seasonal or long-term groundwater level changes (i.e. maximum and minimum groundwater level) cannot be taken into account sufficiently as the duration of the geophysical investigations in most cases is limited to a few weeks.

On the other hand, if enough geological and geotechnical data are already available (which applies to the most modern cities), the latter approach enables us to calculate the response spectra both for weak motion and for strong motion by using constitutive laws, which take as well non-linearity into account. Additionally, in combination with a detailed hydrogeological model the influence of groundwater level (changes) can also be studied accurately [e.g. 6, 7].

This work is being carried out within the German Collaborative Research Center 461: “Strong Earthquakes: A Challenge for Geosciences and Civil Engineering”. Within the framework of this interdisciplinary research center scientists and engineers co-operate to investigate the seismotectonic characteristics of the Vrancea earthquakes, to analyse the seismic hazard for Romania, and to implement strategies to minimise future damages and losses in case of another strong Vrancea earthquake.

2 Geological situation

2.1 Geology

The present-day geological situation of Romania is closely connected with the Carpathian orogenesis. Bucharest, the capital, is situated within a thick Molasse basin. During the Upper Tertiary and the Quaternary this basin was developed above a continuously subsiding basement [8]. The Tertiary formations of the Bucharest area reaches about 700 m thickness.

The Quaternary units around Bucharest consist of poorly consolidated, undisturbed gravels, sands and clays. The total thickness of the Quaternary succession varies between 200 m in the south and 300 m in the north. Based on the lithology of the Quaternary deposits, a classification into seven main units was established for the Bucharest area [9].

2.2 Hydrogeology

Two main aquifer systems exist in the uppermost 50 m. The first aquifer is about 1–10 m below the surface. Over the last 30 years, the phreatic groundwater level within this aquifer has shown seasonal and long-term variations up to 3–4 m [10]. This upper aquifer is partly confined.

The second aquifer is about 25–55 m below the surface. The thickness varies between 5 and 30 m. This lower aquifer is always confined.

2.3 Seismotectonics

Bucharest belongs to Europe's cities with the highest seismic risk. The seismicity is caused by the rupture of the subduced East-European plate in the south-eastern part of the Carpathians. During the 20th century four major earthquakes (M_W = 6.9–7.7) occurred in the 80–200 km deep seismogenic volume. They caused a few thousand of casualties and serious damages. The epicentral region of these earthquakes is confined to the Vrancea region, a 30 km wide and 70 km long area about 160 km north of Bucharest [11].

3 Geotechnical investigations

At the beginning thickness and depth of the seven main Quaternary units in Bucharest was determined for more than 1000 existing drillings. These data were interpolated to develop a 3D geological model of Bucharest [12]. Consequently, a 3D hydrogeological model was developed and combined with the geological model.

For some of the already existing drillings results from laboratory tests were available. These data were completed with specific in-situ tests to investigate shear wave velocity, density and other geotechnical properties. For this purpose Vertical Seismic Profile- (VSP-), Seismic Piezocone Penetration Test- (SCPTu-) and special seismic Crosshole-measurements were performed at different sites in Bucharest [13, 14, 15]. These parameters were assigned to one of the seven main Quaternary units according to their depth and lithology.

4 Numerical modelling

4.1 Methodology

For the numerical modelling a novel computer programme developed by Osinov was used [16], that allows to analyse ground response and also liquefaction of layered soils. Herein, the constitutive behaviour of the soil is governed by a hypoplastic constitutive model for cohesionless soil and by a visco-hypoplastic model for cohesive soil [17, 18].

In a first step, ground responses were calculated for selected sites, where the necessary (visco-)hypoplastic parameters were investigated. Synthetic seismograms of different magnitudes, obtained with a stochastic approach [19], were used as excitation at the base of the soil profiles.

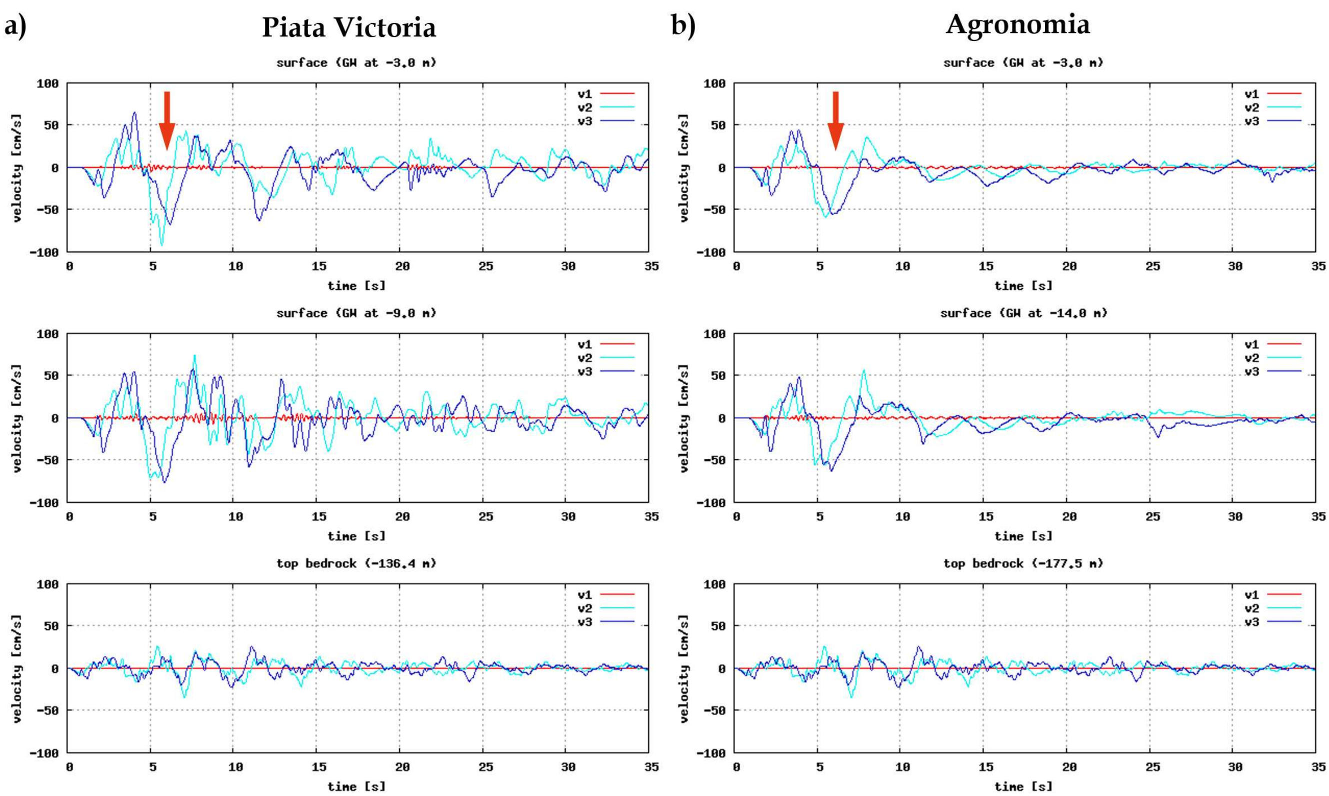

Fig. 1: Calculated ground responses for a synthetic M_W = 8 Vrancea earthquake *(bottom)* for minimal *(middle)* and maximal *(top)* groundwater level **a)** at site Piata Victoria and **b)** at site Agronomia. The arrows indicate the moment when attenuation of the shear wave starts by liquefaction of the upper aquifer (v1 = vertical, v2, v3 = horizontal).

4.2 Input data
To exemplify the modelling results two different sites were selected. The lithology of the two sites is shown in Table 1.

Table 1: Soil profile of the two sites Piata Victoria and Agronomia [depth of the lithological boundaries in m].

	Piata Victoria	Agronomia
Silt and Clay	3.1	4.4
Sand and Gravel	9.5	14.4
Clay and Silt	34.0	23.2
Sand	40.0	54.6
Silt and Clay	136.4	177.5

Whilst the thickness of the lower aquifer is minimal at one site (“Piata Victoria”; thickness 6.0 m) it is maximal at the other site (“Agronomia”; thickness 31.4 m). To investigate the influence of groundwater level changes the calculations were done both for minimal and maximal groundwater level at each site. The values for maximal, mean and minimal groundwater level for both sites are given in Table 2.

Table 2: Groundwater level at the two sites Piata Victoria and Agronomia [m below surface].

	Piata Victoria	Agronomia
Maximal GW level	3.0	3.0
Mean GW level	5.0	7.5
Minimal GW level	9.0	14.0

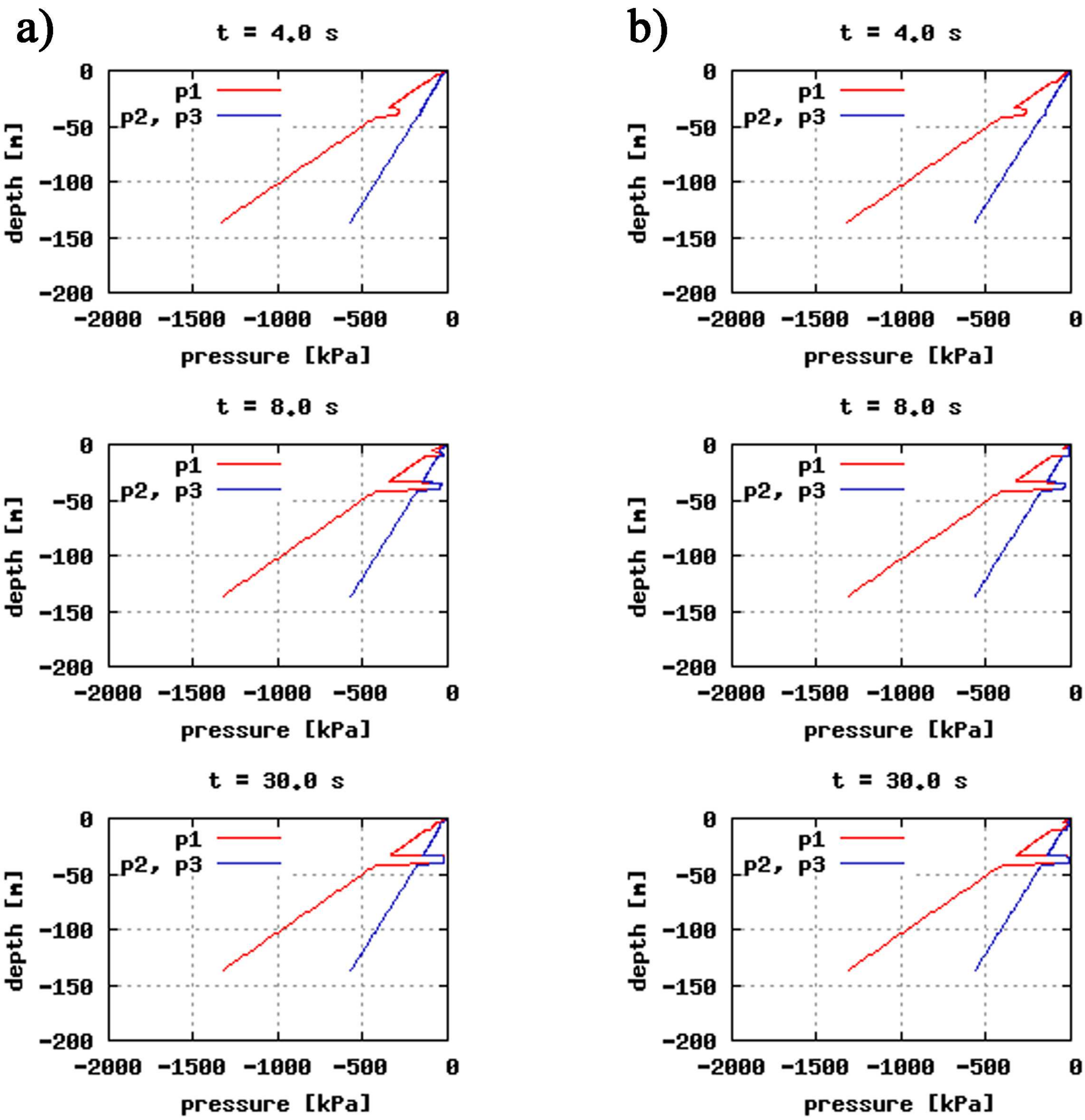

Fig. 2: Effective pressure at site Piata Victoria after 4, 8, and 30 seconds for **a)** maximal groundwater level (3.0 m below surface) and for **b)** minimal groundwater level (9.0 m below surface).

4.3 Results and discussion

The calculated ground responses for the two sites for a synthetic $M_W = 8$ Vrancea earthquake are shown in Fig. 1.

During the first 6 or 7 seconds, important amplifications by factor 2-3 can be observed for both sites and both maximal and minimal groundwater level. But, later for both sites significant differences between the ground response for maximal and minimal groundwater levels can be seen. This effect corresponds to an increase in pore water pressure and an decrease in effective stress in the upper sandy and gravely aquifer. This effect is only observed at maximal groundwater level, when both aquifers are completely saturated and confined (see also Figs. 2 and 3). It is interpreted as beginning liquefaction. The almost complete loss of effective stress and liquefaction of this shallow layer leads to attenuation of the shear waves. In the lower sandy aquifer a decrease of effective stress can be observed as well. But it takes much longer (about 30 seconds) to reduce the effective stress in this lower aquifer almost completely. At this moment the strongest part of the earthquake signal has already passed.

Apparent differences between the ground responses of the two sites can be observed in Fig. 1 as well. At site Piata Victoria, where the lithology is dominated by thick cohesive and comparatively thin cohesionless layers, the ground response is much bigger than at site Agronomia, where the lithology is characterised by comparatively thick cohesionless layers.

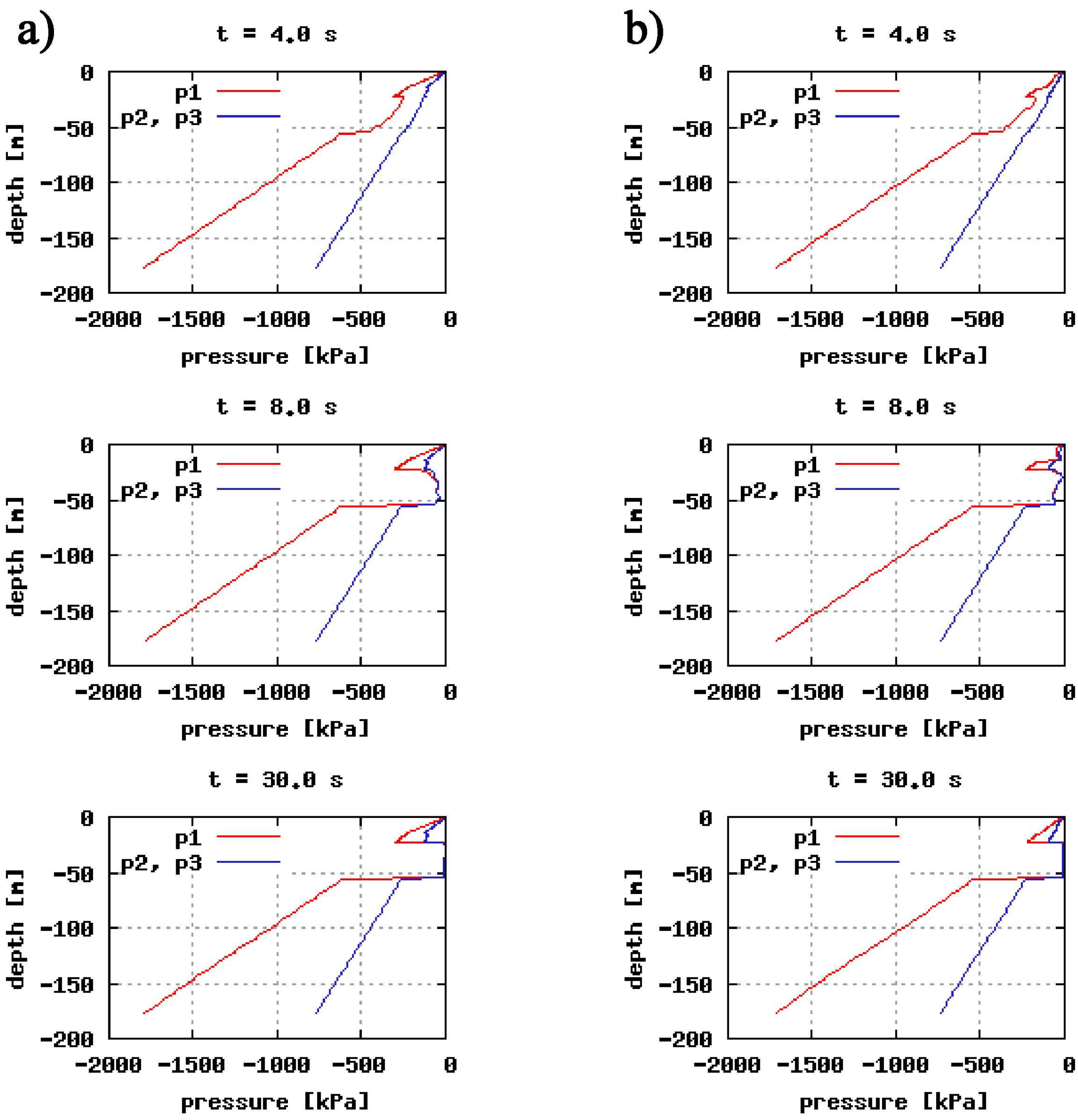

Fig. 3: Effective pressure at site Agronomia after 4, 8, and 30 seconds for **a)** maximal groundwater level (3.0 m below surface) and for **b)** minimal groundwater level (14.0 m below surface).

5 Conclusion

The approach described in the present paper enables us to calculate ground responses for every site, where the stratigraphic soft soil sequence is known from drillings or a detailed geological model and where the parameters of the sedimentary layers were investigated. Combined with a hydrogeological model it allows us to take liquefaction sufficiently into account.

Further it could be shown, that (changes of) groundwater level influences the ground response significantly and cannot be neglected for site effect analyses. In the presence of confined aquifers liquefaction can take place in the subsurface. This results in attenuation of the propagation of shear waves and can reduce the ground shaking.

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