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Combined seismic methods for 3D modeling of quarternary deposits: Application to Skopje sedimentary basin

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Abstract

The large number of catastrophic earthquakes that have occurred worldwide and their consequences point out the fact that the seismo-geological structure of the terrain represents an amplitude-frequency modifier of the seismic effect. The unconsolidated sediments lying upon the bedrock as well as the variations of the bedrock topography may increase the amplification potential of the seismic effects depending on their physical properties and thickness. From this aspect, there arises the need for obtaining as realistic as possible insight into the structure of the terrain, i.e., definition of the geometry of the sedimentary basins. Particular attention in this study was paid to definition of thickness variation of alluvial unconsolidated deposits that constitute the Skopje sedimentary basin, reaching a depth of down to 200 m, as well as the topography of the Neogene sediments present in the terrain base. For that purpose, preliminary 3D geological modelling was done by interpolation of a number of boreholes made in the urban area of Skopje city. Geophysical surveys were performed by application of active and passive seismic methods as are seismic refraction, seismic reflection, Multichannel Analysis of Surface Waves (MASW), Refraction Microtremor (REMI) and Horizontal-to-Vertical Spectral Ratio (HVSR) for the purpose of defining the variation of the shear-wave velocity Vs through different lithological layers as well as upgrading and improving the accuracy of the 3D model. Of particular importance for this survey was the implementation of fast, economical and efficient procedure by using the combined seismic methods approach, which enabled seismo-geological modeling to different scales as well as comparative analysis of the results and verification of their accuracy.

Key words: combined seismic methods, quaternary deposits, 3D model

1 Introduction

The main objective of this study was modelling of the thickness of the quaternary deposits, which represent the upper surface layers of the Skopje sedimentary basin [1].
For that purpose, preliminary 3D stratigraphic modelling was done by interpolation of a total of 63 boreholes made in the urban area of Skopje city, with different maximum depth and irregular distribution [2].
Based on geological data obtained from the boreholes, three stratigraphic units were distinguished, namely, Quaternary, and Neogene-Pliocene and Miocene sediments.
Geophysical investigations were performed by application of active and passive seismic methods, i.e., seismic refraction, seismic reflection, Multichannel Analysis of Surface Waves (MASW) and Horizontal-to-Vertical Spectral Ratio (HVSR) for the purpose of defining the variation of the Vs velocity of shear waves through different geological media, as well as upgrading and improving the accuracy of the 3D model [3, 4, 5].
Geophysical surveys play a very important role in definition of local soil conditions, which are of a great importance when it comes to seismic risk assessment [6, 7]. A number of geophysical techniques have been developed and advanced in recent years in order to increase the quality and accuracy of site characterization. The surface seismic methods represent non-invasive, widely accepted geophysical methods for near-surface characterization and definition of parameters that have a direct influence on the site response during an earthquake.
In this study, particular attention was paid to the use of the integrated seismic methods approach to near-surface characterization. The most practical, cost and time effective way to perform in-situ measurement and processing by using different active and passive seismic methods as are seismic refraction, seismic reflection, MASW and HVSR method is presented in this paper through the results from the surveys performed at 2 characteristic locations. Each of these methods has some advantages and limitations, but their application in an integrated approach enables the results to be compared and complement each other, reducing thus the likelihood of making errors in interpretation and providing a higher accuracy subsurface modelling [8, 9].

2 Geological characteristics

The investigated sites are part of the Skopje depression, which was formed during the Cenozoic tectonic evolution. This evolution consisted of two periods of extension, the earlier in the Paleogene period and the later in Neogene. The last period of extensional deformation, which is still ongoing, began in early to Middle Miocene. It is marked by deposition of Middle Miocene strata in the deepest basins.
The current formation of the Skopje depression is associated with differential vertical tectonic movements along the older reactivated and the newly formed normal faults. The Skopje depression is bounded by a network of normal faults that strike NW-SE and

NE-SW to E-W. They produced the first uplifted horsts and subsiding grabens that became sites of freshwater lakes.

The sediments in the Skopje depression were developed during deposition in this lake. The depression is filled with Neogene lacustrine sediments and alluvial deposits on the surface, with a maximum thickness of over 2,500 m. Their base is represented by old Paleozoic crystalline shales, quartzite and marble. The transgressive basal conglomerate, gravel and sandstone contain clasts from the underlying rock units. The Miocene formations contain intermittent strata of gravel conglomerates, sandstone and siltstone, marl, marly claystone, and upper sandstone and siltstone. The younger Pliocene formation consists of cemented coarse-grained deposits, mainly gravel, gravelly sandstone and sandstone. On the top of the sedimentary sequence are found the most recent Quaternary sediments, mainly alluvial deposits of gravel, sand and clay [1].

3 3D geological modelling

Stratigraphic modelling of part of the urban area of Skopje city was done by application of the Rockworks software whereat the engineering-geological map and the research boreholes from the investigations after the catastrophic 1963 Skopje earthquake were used as the main source of geological data [10, 11]. A total of 63 boreholes made in the urban area of Skopje city, with different maximum depth and irregular distribution were used for the preliminary 3D stratigraphic modelling. The spatial distribution of the boreholes is shown in Fig.1.

Figure 1. Spatial distribution of research boreholes

3D modelling consisted of interpolation of individual stratigraphic units and their stacking into a 3D model. The interpolation was done by application of the Inverse Distance methodology according to which, the greatest influence upon prediction of the value for a non-measured location is exerted by the values measured at the closest points whereat the effect of the surrounding points upon prediction of the value is reduced with the increase of distance [12, 13].

The last step consisted of correction of the spatial distribution of the model for the purpose of removal of parts for which there were no data as well as correction of the topography by adding the USGS DEM (30 m) model.

The final 3D model provides a complete insight into the structure of the terrain, the distribution of each stratigraphic unit in the investigated area as well as the presence of variations and discontinuities. The variations of thickness of the Quaternary unconsolidated sediments were mapped with a good resolution, which was of a great importance in modeling the Skopje basin (Fig.2).

The Quaternary was generated upon the entire surface of the model. It is characterized by considerable variations in thickness. Its greatest depth is mapped in the southeast and the northwest part of the location, whereat, in the southeast part, the thickness of the Quaternary is about 50-60M. Toward northwest, the thickness in the central part is reduced to 10 – 20 m, whereas in northwest direction, it reaches the maximum depth of 100 m. This phenomenon points to a fault structure stretching in that direction.

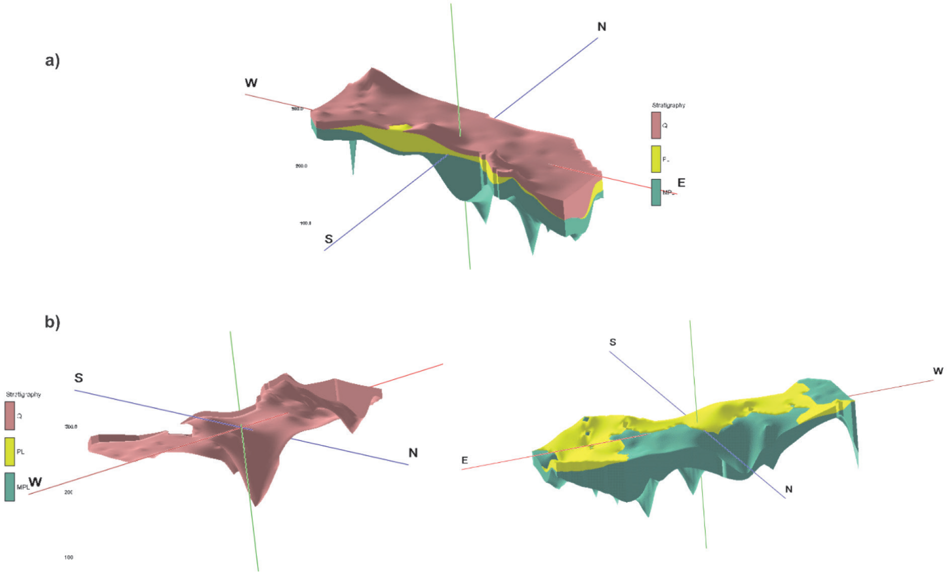

Figure 2. a)3D Stratigraphic solid model. b) Left - 3D thickness variation of quaternary deposits, right - Neogene sediments topography

4 Geophysical survey

Geophysical surveys by application of active and passive surface methods were done for the wider urban area of Skopje city for the purpose of definition of parameters that have a direct influence upon the seismic response of ground in conditions of earthquakes like depth and seismic velocities of unconsolidated sediments as well as topography of the seismic bedrock.

Out of the active seismic methods, the seismic refraction, seismic reflection and MASW methods were applied.

The same seismic equipment and, in most of the cases, the same acquisition parameters were used, enabling time and cost-effective survey for subsurface characterization. The choice of these parameters was not random. Experimental research was carried out for a long period using the above-mentioned seismic methods to define the optimal parameters for successful application of an integrated technique in future research.

The most time and cost-effective passive method for estimation of shear-wave velocities of deeper layers is the single station microtremor HVSR method [14]. Recording of microtremors by application of Tromino3-componental seismometers was done at certain locations where Quaternary deposits reach a depth of over 100 m. The analysis of data in combination with the results from the active seismic methods enabled computation of the Vs velocity in deeper layers and definition of depth of the seismic base.

The results from these surveys will be used in further analysis for upgrading and improving the accuracy of the 3D model.

In this paper, two case studies from the geophysical surveys are presented. The first case study refers to the part of the Skopje urban zone area where the thickness of the quaternary sediments is lower than 30 meters and the second one refers to the part of the city were the thickness can reach a depth of 100 meters and higher. Certain site-specific details regarding the "in situ" measurements were as follows.

Case study 1:

Seismic refraction measurements were performed along seismic spread of 17 channels by using the following acquisition parameters: spacing between geophones - 3m, near off-set (minimal source to receiver distance) of 3m, excitation step of 12m at 5 points through the seismic spread, duration of seismic record of 0.5s and sampling frequency of 512 Hz.

2D MASW vs Seismic Reflection Joint Acquisition was performed along seismic spread of 17 channels by using the following acquisition parameters: spacing between geophones of 2m, excitation step of 2m, near off-set 6 m, duration of seismic record 0.5s and sampling frequency of 512 Hz. The total number of source-receiver configuration displacements for the roll-a-long measurements was 13.

Case study 2:

Single station microtremor measurements were performed by using 3-componental Tromino seismometer, with recording length of 20 min.

MASW vs Seismic Refraction Joint Acquisition was performed along seismic spread of 17 channels by using the following acquisition parameters: spacing between geophones of 5m, near off-set 5 m, duration of seismic record 0.5s and sampling frequency of 512 Hz.

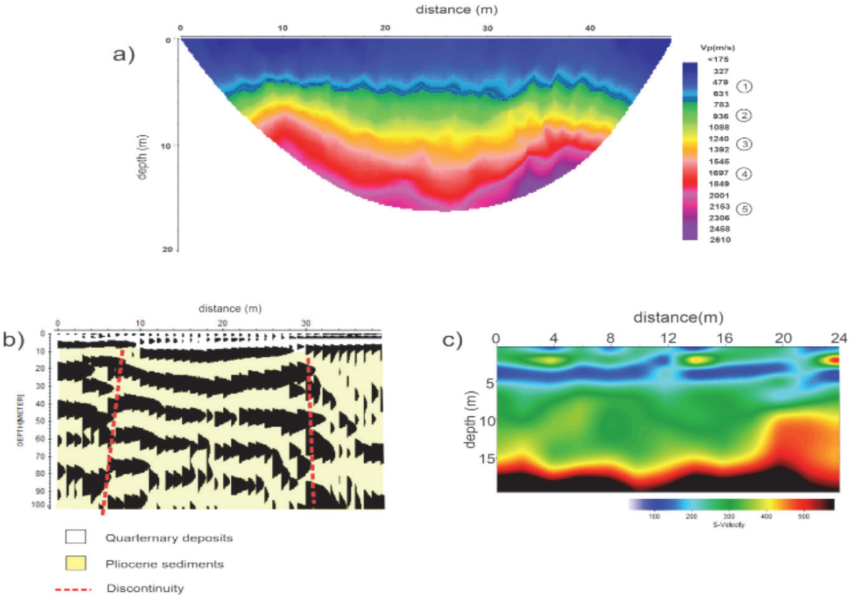

Figure 3. Case study 1: a) 2DVp seismic refraction tomography model. b) 2D Seismic reflection section. c) 2D Vs model as a result of the MASW survey

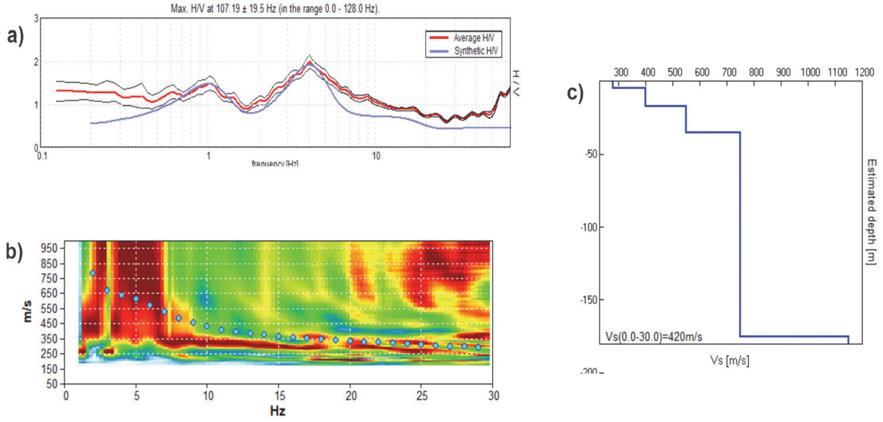

Figure 4. Case study 2: HVSR vs Dispersion curve joint analysis and inversion. a) HVSR experimental and synthetic curve. b) Dispersion curve. c) 1D Vs model

The seismic models, in combination with the geological data, reflect the seismo-geological characteristics of the site.

A survey by use of three different methods was performed along the same profile line for Location 1 (Fig. 3). The 2D MASW model refers to the position of 15-39m along the seismic refraction and reflection profile. According to the 2D Vp and Vs models, the thickness of the quaternary deposits, which are characterized by values of shear-wave velocities in the range of Vs=100-600m/s, varies in the range of 8m to 15m. The same variation of the quaternary thickness is interpreted at the seismic reflection 2D model.

The results from the surveys at the second location were a HVSR curve as a result of the microtremor measurements and a spectral analysis and dispersion curve as the result of the MASW measurements (Fig.4a, Fig.4b).

The HVSR curve shows clear peak frequencies at 1Hz and 4Hz. The first peak is related to a deeper layers (impendance contrast at the depth larger then 100m) while the second peak is related to the shallower surface layers.

The result from the joint inversion of the HVSR curve and the dispersion curve is the 1D Vs model, which clearly maps the contact between the Quaternary and Neogene sediments at depth of 170 meters (Fig. 4c).

5 Conclusions

The results obtained from the performed geological modelling point to the importance of the 3D approach to definition of the seismo-geological characteristics and the connection between different structures. 3D geological modelling in these surveys has been specifically performed in order to define the thickness of the Quaternary deposits, which are considered as unconsolidated according to the physical-mechanical characteristics.

The application of a combined approach involving different seismic methods enables mapping of the variation of the Vs velocity through different media with a high resolution, definition of the thickness of the Quaternary deposits as well as definition of the local deformation and disturbances in the terrain structure.

This paper shows the methodology and the results from the surveys carried out at 2 different, but specific locations. The main purpose was to show the importance of using a combined approach and adequate methods depending on the local site conditions.

The next step is reconstruction of the 3D stratigraphic model with the data from the geophysical investigations and its application for continuous coverage of the investigated area with the representative shear-wave velocity Vs.

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