An integrated analysis of geophysical data for landslide risk assessment

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SUMMARY

In May 2014, a severe storm caused substantial damage in the Balkan area by floods and landslides. As a contribution of geophysicists and geotechnical engineers to the effort of prevention of further damage, a Geoscientists *without* Borders (GwB) project was organised by Association of Geoscientists and Environmentalists of Serbia to assess the potential of further occurrence of landslide in the region supported by SEG and many other organisations, governments and individuals of many countries. Local and international experts conducted field data acquisition with students from four countries. The project benefited the students to get practical experience in geophysical fieldwork, local governments received information of landslide risk in their area and the residents of the area were made aware of landslide potential of around their home land.

Geophysical surveys with seismic and electric methods were carried out in three phases, June and September 2015 and June 2016, in six locations in Serbia and Bosnia and Herzegovina. About 7000m of seismic data are acquired in the sites where landslide potential is considered high. Lesser amount of electric survey was conducted in the same locations.

This paper presents some of the result of the geophysical surveys of some of the project areas comparing seismic reflection, MASW and electric resistivity methods, and subsequent assessment of risk of landslide. This information is used by the engineers of local government in their plan of mitigation of disasters.

Key words: Landslides, Disaster mitigation, MASW, Reflection, Resistivity.

INTRODUCTION

Heavy rain in May 2014 caused extensive damage to the Balkan area, which include over one thousand landslides in the catchment of River Sava, particularly in Serbia and Bosnia and Herzegovina. Amongst many international aides, a Geoscientists *without* Borders project funded by SEG Foundation on landslide risk assessment was launched in 2015 (Komatina, *et al.*, 2016). The Association of Geoscientists and Environmentalists of Serbia organised the project with supports from several municipal governments and local communities in Serbia and Bosnia and Herzegovina. The project involved geophysical experts from seven countries, students from four countries. Students gained practical experience in geophysical surveys from practicing geophysicists and academics, local government received valuable results of the geophysical surveys for designing recovery from the disaster and mitigation planning for further occurrence and residents of the survey areas received insight into the underground composition on their own land (Figure 1).

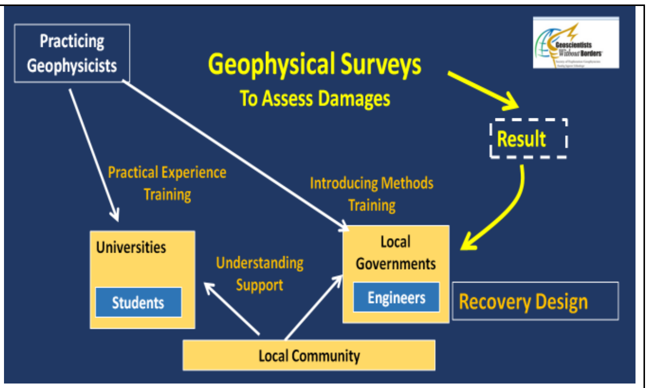

Figure 1. Participants and benefits of the GwB project.

The project included seismic and electric surveys in eleven locations in six municipalities in Serbia and Bosnia and Herzegovina (Figure 2; Table 1). The field data acquisition took place in three phases in 2015 and 2016. The resistivity survey was not carried out at all the locations due to availability of the equipment at the time of the field work.

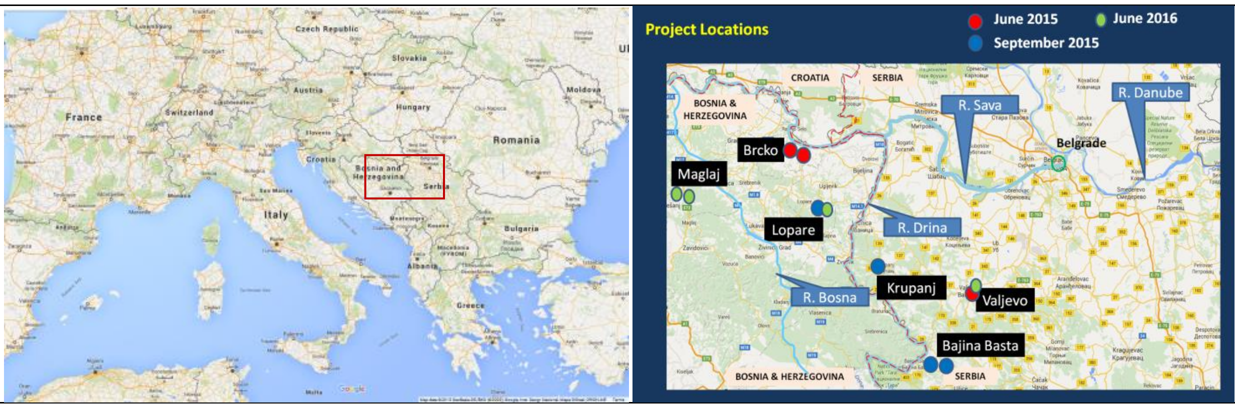

Figure 2: GwB Project locations

A few reports have been presented from this project (Urošević, *et al.*, 2016; Suto, *et al.*, 2016; Petrović, *et al.*, 2017; Burazer and Urošević, 2017; Suto, *et al.*, 2017). This presentation focuses on the survey results from the Valjevo area, wester Serbia. This is the first area of comprehensive results: Suto, *et al.* (2016a) described the MASW analysis, Petrović, *et al.* (2017) mainly showed the seismic reflection, and Burazer and Urošević (2017) focussed on the electric method.

This presentation summarises these three method and examine the consistency of the result and demonstrates the merit of combining multiple geophysical methods in a survey for landslide risk assessment.

Table 1 : Geophysical Surveys carried out at each location

Site 2015	Seismic			DC resistivity 42 el. - 4 el.		Laser scans	Drilling, logs&lab
	Reflection	MASW	Refraction				
Valjevo	2D (5)	+	+		+		+
Celic	2D (2)	++	+	+		+	
Vrazici	3D	+*	+	+		+	
Krupanj	2D (3)	+	+	+			
Bajna Basta	2D (4)	+	+	+			
Lopare	2D (3)	+	+	+			
Site 2016	Seismic			DC resistivity 42 el. - 4 el.		Laser scans	Drilling, logs&lab
	Reflection	MASW	Refraction				
Valjevo (TL)	2D (5)	+	+/-	2(TL)			+
Lopare (TL)	2D (2) 3D-Swath	+	+/-	TL			
Bradic	2D	+					
N.Seher	2D (2)	+					

SURVEY AREA

Municipality of Valjevo is situated in the western Serbia. It is in the valley of River XXX, a branch of River Drina. The survey area is about 2km north of Valjevo city centre in a hilly country. The hill is developed for orchard of plums, apricots and cherries, and the area is sparsely populated with farmhouses.

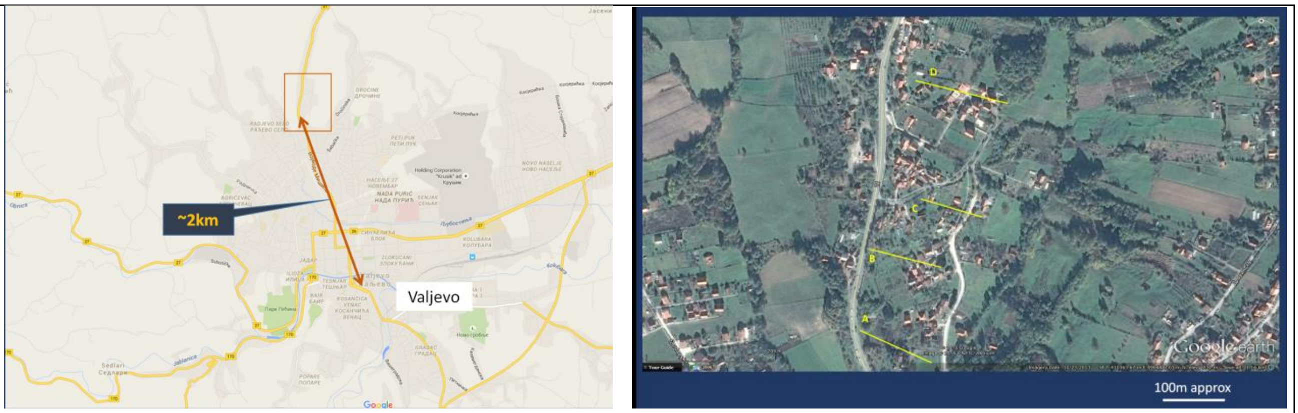

Figure 3. Valjevo location and the survey site. (Google map)

The 2014 rainfall caused some damage to the river bank near the city, and landslide and erosion occurred in the surrounding hills. Some landslides are very close to the houses; cracks on the walls of the houses due to the movement of the soil were commonplace. (Figure 4).

Figure 4. Valjevo: Recovery effort after the damage near the City (Left); Erosion near a house (Right).

METHODS, DATA ACQUISITION AND PROCESSING

Seismic Methods

Four seismic lines were surveyed along the hill; each line about 200 to 250m long. Elevation drops about 20m over 200m (Figure 5). The data were primarily acquired for seismic reflection analysis in high-resolution mode with a short (1m) geophone interval. All the geophones were laid on the ground and hammer blow was made between every two geophones. The data acquisition parameters used are listed in Table 2. MASW (Park, *et al.*, 1999) processing was applied to the same dataset. The natural frequency of geophones, 10Hz, was confirmed adequate for this survey for shallow target by an experiment comparing with another dataset acquired using 4.5Hz geophones (Suto, *et al.*, 2016a).

Table 2. Data acquisition parameters

No. of channels	240 max
Natural frequency of geophones	10Hz
Receiver interval	1m
Source	Sledgehammer 5kg
Source interval	1m
Sampling interval	0.5 ms
Record length	2s

This is a rare example of application of the seismic reflection analysis for landslide survey (Petrovic, *et al.*, 2017). All the geophones up to 240 channels were laid on the ground and sourced by a 5kg sledgehammer between every two geophones. Geophones were rolled along so that the number of fold does not drop below 60. Data processing sequence included DMO and FD migration. A particular attention was paid to topography effect of the seismic section to produce the same surface profile as resistivity tomography and MASW sections. To compare with other sections, the depth conversion was done using the migration velocity (Urošević, *et al.*, 2016).

The MASW (Park *et al.*, 1999) method was applied to the same data as collected for the reflection analysis. SurfSeis 4 by Kansas Geological Survey was used for data processing. For MASW, fewer traces are required and locating the source in the middle of an array makes processing awkward. Therefore a subset of 31 traces with offsets 6 and 36m are extracted from the record for analysis. Every sixth shot records were analysed in this project (Figure 6).

Figure 5: A typical seismic line at data acquisition.

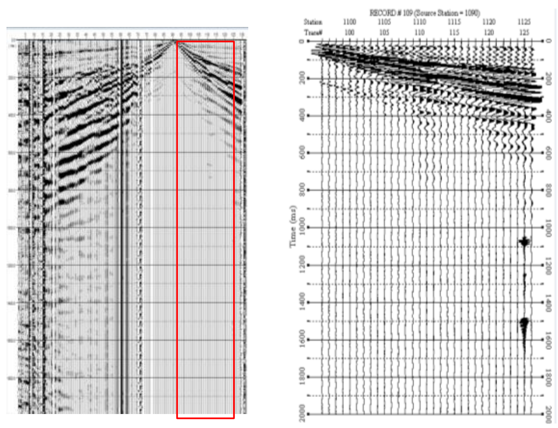

Figure 6: Selection of 31 traces for MASW analysis from a shot record collected for reflection processing.

Electric Resistivity Tomography

The electric resistivity survey data were collected using ABEM Terrameter LS system. For data acquisition, twenty-one electrodes were placed at a 3m interval, and rolled along four times with three segments overlapping. The protocol was set to Wenner, dipole-dipole and multiple gradient arrays. The multiple gradient arrays is considered to achieve good vertical and horizontal resolutions for this survey for limited depth. The applied current intensity was 100 mA.

The data collected in the field were processed using RES2DINV software, which automatically subdivide the subsurface into a number of blocks, and then least-squares inversion scheme was used to determine the appropriate resistivity values for each block in 2-D. Burazer and Urošević (2017), further introduced cooperative inversion, in which the structural model is constrained by information from the analysis of reflection seismic data and used to refine resistivity model.

Drilling

Two boreholes, B-3 and B-4, were drilled on Line 4 to the depth of 25m and 10m respectively. The ground is made of Neogene to Quarternay sediments with various degree of weathering. This presents two possible potential slip surfaces: tops of the two weathering crusts (top of yellow and top of pink in Figure 7).

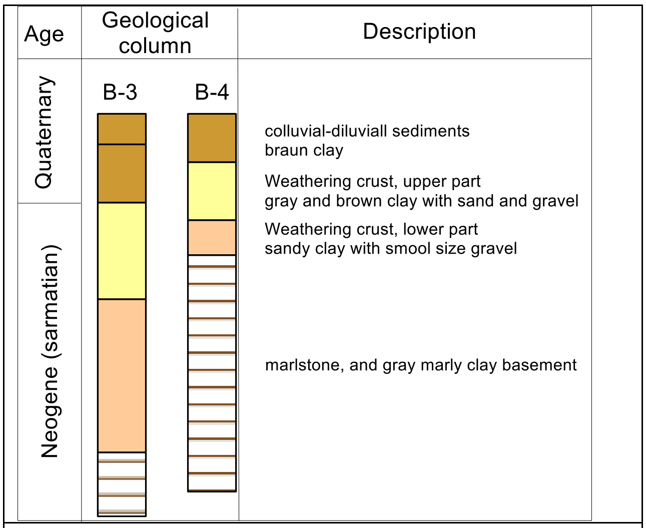

Figure 7: Geological Columns from two boreholes

RESULTS AND DISCUSSION

The result of the geophysical surveys are shown in Figures 8 and 9: Figure 8 compares the results of three array configurations of electric survey, seismic reflection (DMO section) and MASW processing, while Figure 9 compares the results of three inversion methods with the seismic analyses.

Among the three electrode arrays tried on Line 2, the gradient array gives more detailed resistivity distribution than other two arrays (Figure 8). The geometrical features of the horizons with resistivity contrast generally agree with the major reflective horizons of the reflection section, and the reflection section shows finer details and deeper features. The horizons are shown somewhat smoother on the MASW section. This may be due to its process uses a range of traces with 30m lateral extent to calculate each S-wave velocity profile. The S-wave velocity information on this section is a parameter of mechanical strength. It shows a high S-wave velocity layer about 5 to 10m below the ground. This seems to correspond to the upper weathering crust.

In the comparison of the inversion processes (Figure 9), the cooperative inversion, incorporating the geometry of the geological units interpreted from reflection seismic section, shows more detailed resistivity structure, while Smooth and Robust inversions present simpler layered structure. Faults are more clearly observer in the reflections section of Line 4 than Line 2. By inputting this geometry, detailed resistivity structure is revealed. The S-wave velocity section similarly shows faulted structure but in somewhat smoother fashion. The agreement in geometry between resistivity and S-wave velocity is noted: the low resistivity of the Tertiary sediments generally corresponds to the low S-wave velocity; and high resistivity basement to high S-wave velocity. Fault patterns between the reflection section and the S-wave velocity section are consistent but the reflection section shows better clarity. The geometry generally agrees between resistivity and S-wave velocity sections, but the values do not always correspond to each other in some places. High resistivity areas are not always high S-wave velocity and vice versa. This may be due to some difference in kind of soil as well as its condition such as porosity, moisture content, grain size, compaction, etc. This still remains unsolved until further drilling. However, the depth and shape of the potential slipping surface are similar in those sections. Those potential slipping surface are characterised by sharp change of resistivity, but not uniquely high to low or low to high. On the other hand, S-wave velocity section shows the slipping surface as a boundary of low S-wave velocity layer above high S-wave velocity layer at about 250 to 350m/s.

The geological description of top soil and residual soil underlain by weathered rocks and depth of the potential slip surface, this landslide area can be classified as “earth slide or earth flow” of Vames’ classification (1978). This is a common type in the area (Suto, *et al.* 2016b).

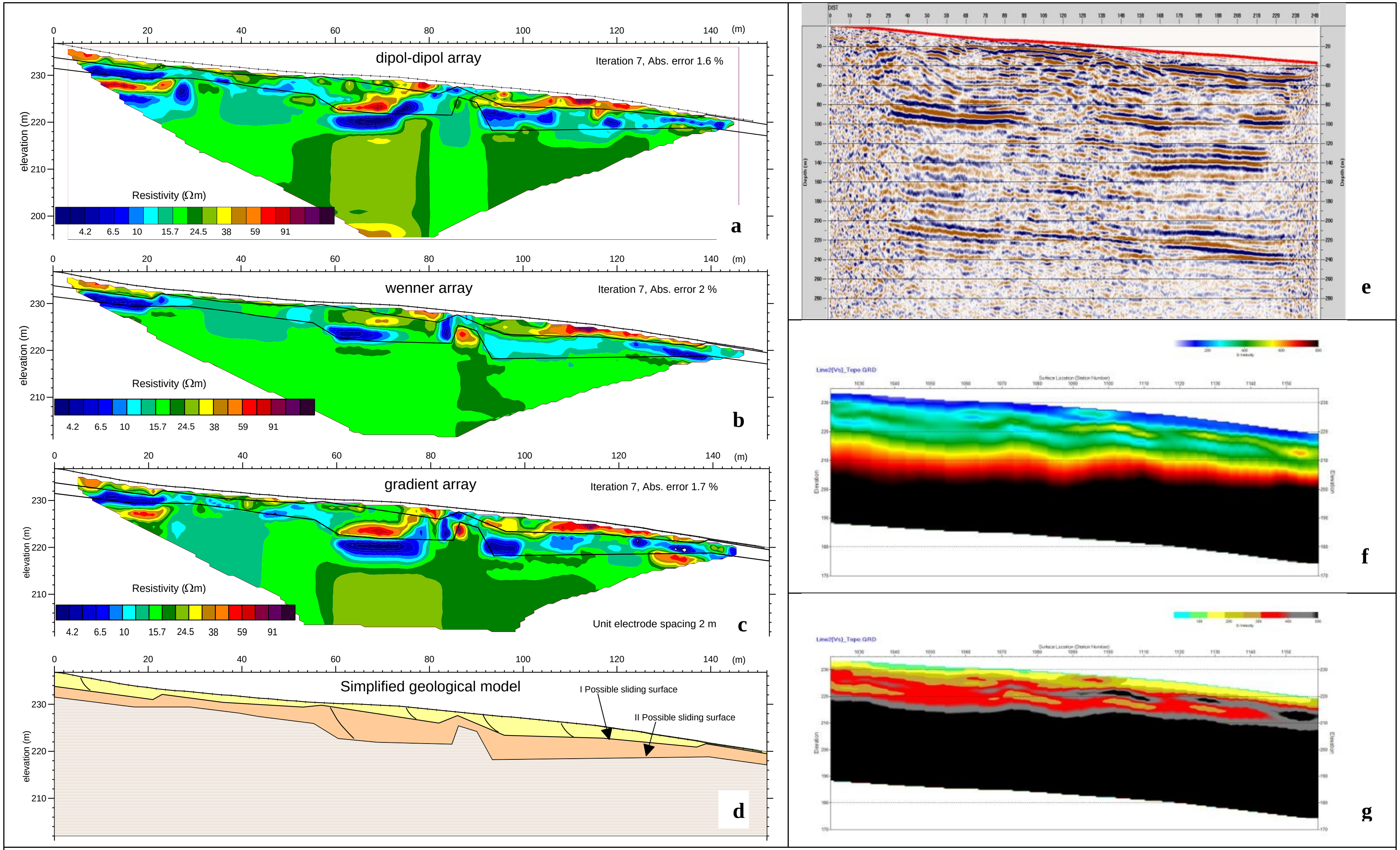

Figure 8: Line 2- (Left) Three different electrode arrays were used in resistivity measurement. a) dipole-dipole; b) Wenner and c) multiple gradient; d) Geological interpretation from cooperative inversion seismic-resistivity data. (Right) e) DMO section; f) Vs section by MASW; g) Vs section blocked at every 50m/s.

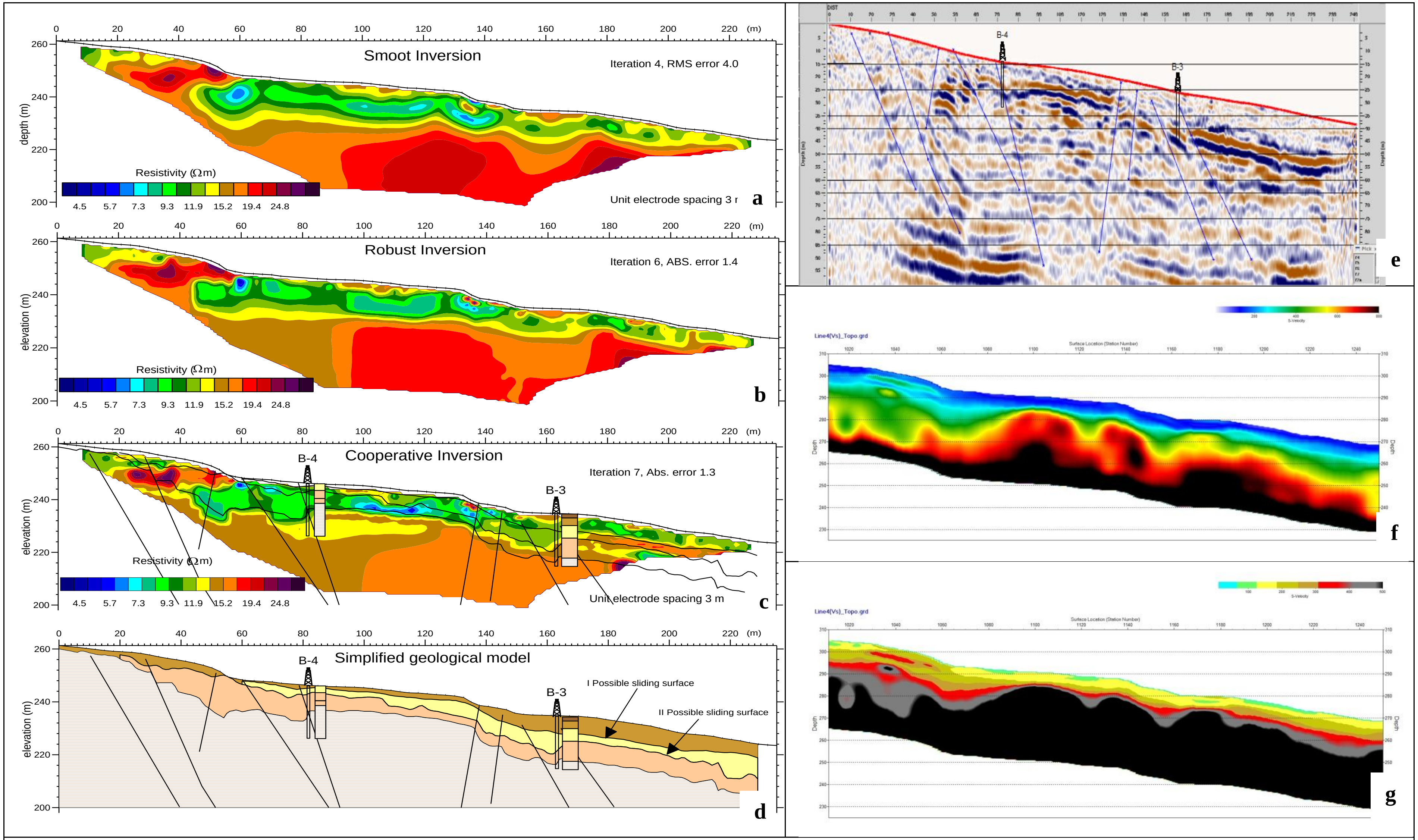

Figure 9: Line 4 (Left) Models from different inversion methods. a) smoothness-constrained least-squares optimization method b) blocky or robust inversion method c) The boundaries mapped from reflection seismic incorporated into the resistivity inversion; d) Geological interpretation. (Right) e) DMO section; f) Vs section by MASW; g) Vs section blocked at every 50m/s.

CONCLUSIONS

Three geophysical methods, electric resistivity, seismic reflection and MASW, were applied to a steep sloped area near Valjevo, Serbia. They show general agreement in the underground geological structure inferred. Two drill holes identified two lithology boundaries as top of potential slip surfaces. The S-wave velocities are slower above the potential slip surfaces indicating some loose material. It does not uniquely correspond to high or low electric resistivity; it depends on material and conditions. In geotechnical terms, this area is classified as Vernes' "earth slide or earth flow". The result is provided to the engineers of local government for designing a disaster mitigation plan.

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