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APRIL 2002 EPICENTRAL EARTHQUAKE IN TBILISI, GEORGIA

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SUMMARY

The capital of Georgia, Tbilisi, with the population of 1.5 million is one of the oldest large cities in the world. It is situated on terraces of the river Mtkvari with abrupt coasts that caused linear configuration of the city along the river with sizes about 40 x 5 km in plan. On April 25, 2002 at 22h 41m local time the city was struck by an earthquake with epicenter within its limits. The destructive effect of the earthquake by macroseismic data can be estimated as intensity 7 by MSK-64 scale because of small focal depth and surface effect amplified due to local soil conditions, characteristics of the earthquake as well. The earthquake was accompanied by a series of foreshocks and aftershocks, the strongest of which have been analyzed. In the paper, information on seismic regime of the territory, on the building stock is presented. General statistical data, information on behavior of different structural types are given. The building stock of the city, its vulnerability and typical damages are classified, the influence of construction quality, ageing rate and existing damages on the manifested effect of the earthquake are analyzed. The results of numerical analyses of soil seismic response on the territory of Tbilisi with compiled maps are presented and analyzed. Results of the analyses of the EQ records, seismological parameters, dynamic coefficient curves are presented as well.

The work has been performed according to scientific activity of the Institute and in framework of the ongoing Project "Seismic Risk in Large Cities of Caucasus. Tools for Risk Management" (NATO SfP 974320).

INTRODUCTION

General Information
An earthquake occurred in Tbilisi, Georgia on April 25, 2002 at 22h 41min local time with epicenter in the central part of the city. Main seismological parameters are the following. Magnitude M=4.5,

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coordinates of the epicenter 41°44′ latitude North, 44°50′ longitude East; depth about 3km. The earthquake was accompanied with a set of foreshocks and aftershocks of different intensity.

The records were obtained in seismic observatory of the Institute of Geophysics, Georgian Academy of Sciences, on bedrock (Fig. 1) at a distance of 6km from the epicenter using strong motion instruments SMACH SM1. Dominant frequency of the records is 4-5Hz. Direct losses exceeded 180 million USD. 7 people died and 30 injured. Immediately after the earthquake a temporary seismic network was organized with the help of Armenian colleagues, that allowed to record a set of aftershocks on different types of soils.

By this time the most complete information on the earthquake is presented in the report "Tbilisi Earthquake of April 25, 2002. Earthquake damaging effects and recommendations for implementation of rehabilitation programme and seismic protection. Tbilisi-Skopje, June 2002", prepared by Prof. Jakim Petrovski, UNDP Consultant, who visited Tbilisi in May-June, presented uniform methodology and procedure for earthquake damage assessment of buildings, helped local experts in their activity. The technical report on the earthquake is under preparation in ISMEE as well.

The capital of Georgia, Tbilisi, with population of 1.5 million is one of the oldest large cities in the world. It is situated on terraces of the river Mtkvari with abrupt coasts that caused linear configuration of the city along the river with sizes about 40x4 km in plan (Fig. 2).
Historically for more than 1500-year period the city did not subject to so intensive seismic impact. As a rule, epicenters of past earthquakes located at a distance of 20-100km from the territory of the city, and their intensity did not exceed 6. Till 1991 seismicity of the city territory was VII (MSK-64). After the destructive Spitak (1988) and Racha (1991) earthquakes, increased seismic activity and that fact, that seismic faults with potential M=6-6.5 locate in immediate proximity from the city, the territory of the city was referred to background seismicity VIII. According to probabilistic maps of seismic hazard, compiled in 1999 in the Inst. of Geophysics, some part of the city territory also relates to intensity VIII.

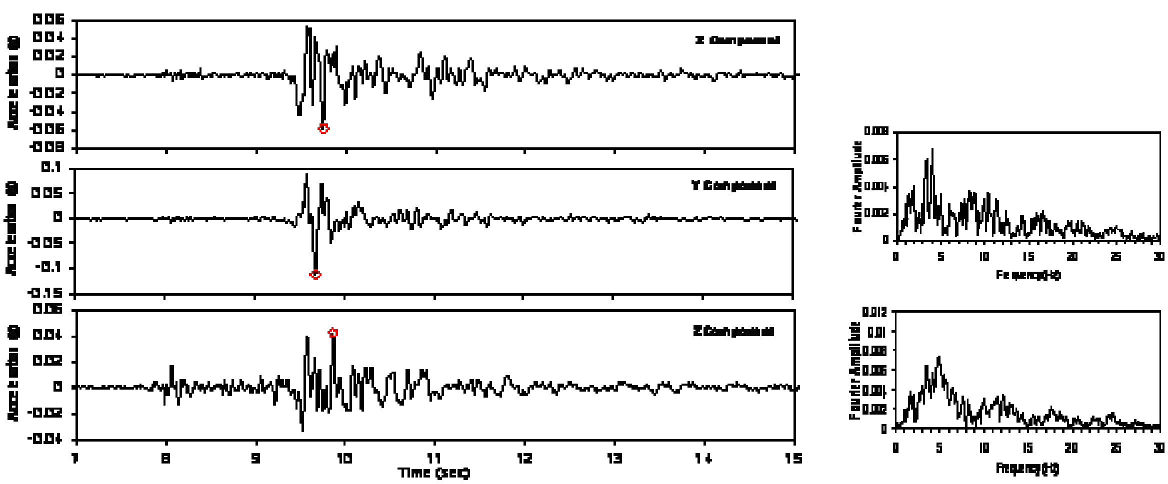


Fig.1. Record of the main shock of Apr 25, 2002. Seismic observatory, rocky basement. Fourier spectra of horizontal components (right).

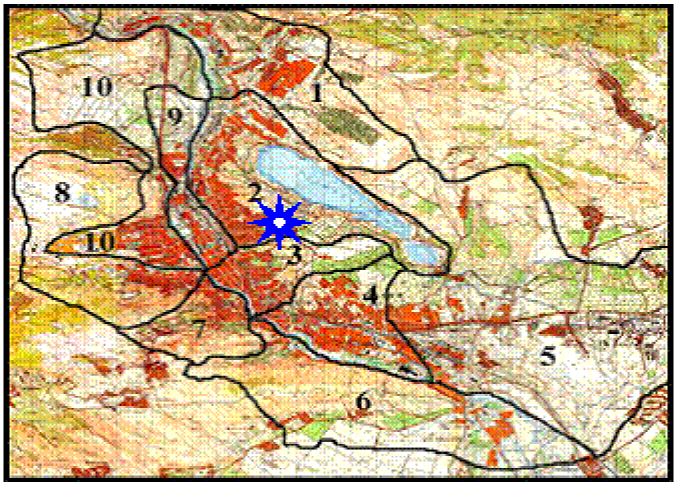


Fig. 2. Map of the city with the epicenter and districts

Building stock of the city

Since 1900 the population of the city increased approximately up to 10 times. At the end of 19 century out of 8000 mainly brick houses only 24 were of four story, 430 three story, others - one-two story. Now, according to municipal data, in the city there are more than 45000 residential houses of different construction type constructed on clay, sand, rocky and semi-rocky soils. Height of buildings as a whole does not exceed 16. As a rule, the mass antiseismic construction takes place since the late fifties. But there are examples of buildings with RC belts constructed in forties. The most widespread construction types are presented in Tab. 1. The feature of the building stock of the city is presence of large number of aged brick and masonry low rise residential houses constructed without antiseismic measures. The occurred earthquake was a serious test for these types of buildings.

In Tab. 1 types of buildings are: 1: 1-3 story with brick walls; 2: 4-8 story of brick; 3: 5-9 story large-block; 4: 5-12 story large-panel; 5: 5-16 story prefabricated & cast in place RC frame; 6: 5-16 story cast in place reinforced concrete. Numbers of district correspond to shown in Fig. 2.

Table 1. Distribution of buildings by structural types

District	Number of buildings in % by structural type							
	1	2	3	4	5	6	Other	Total Number
1. Gldani	77	2	11.2	8	1.5	0.2	0.1	2630
2. Nadzaladevi	89.9	4	5	1	0.1	-	-	10500
3. Chugureti	99.5	0.38	0.09	-	0.03	-	-	5227
4. Isani	93	1	2.8	3	0.2	-	-	8075
5. Samgori	74.3	11	8	6	0.2	-	0.5	3685
6. Krtsanisi	96.5	1.3	2	-	0.2	-	-	3100
7. Mtatsminda	95	4	0.8	-	0.2	-	-	3000
8. Vake	82.7	10.3	5.5	0.3	1	-	0.2	3564
9. Didube	80	3.2	10	5	1.8	-	-	1390
10. Saburtalo	79	10.1	7	2.4	0.5	-	1	3810

CONSEQUENCES

General Statistics

Epicentral zone of the earthquake encompasses a large part of the territory of districts Didube, Nadzaladevi, Chugureti, Mtatsminda, Krtsanisi. The influence of high-frequency content caused selective damage of low rise brick and stone buildings. Multi-story brick, large-block and frame RC buildings, with rare exception, have received lesser level of damages.

The total number of buildings inspected by groups of specialists are more than 16000. In all regions of the city the large part of damaged buildings are low rise ones with brick walls. Many of them were constructed without antiseismic measures. Many buildings before the earthquake had a definite level of damages caused by non-uniform settlements of foundations. The main reason of bad soil conditions is damaged water supply and sewage systems, infiltration of atmospheric water in foundation soil through damaged pavement, ground water. The earthquake has increased existing damages, caused mass appearance of inclined and vertical cracks in walls, partitions, fail of plaster, damage of connections between walls, partial destruction of masonry and brick lintels, mass fail of chimneys etc. In buildings with antiseismic measures typical damage is shift of prefabricated roof slabs as well. The proximity of epicenter caused destruction of cantilever eaves.

On the basis of the data collected in Ministry of Urbanization and Construction of Georgia, some statistical information on behavior of buildings of different types and destination is presented below.

Out of inspected 15500 apartment houses 3983 (25 %) have received damage grade 1; 6730 (43 %) - damage grade 2; 4696 (30 %) - damage grade 3; 107 (0.7 %) - damage grade 4. These data correspond to intensity VII (MSK-64).

Public buildings – educational institutions, hospitals, clinics, kindergartens received considerable material losses more than 15 million USD, that makes more than 10% of total direct material losses. All school buildings, most part of hospitals, clinics, kindergartens have been investigated after the earthquake by efforts of teams of engineers.

Data on damages of residential buildings are presented in Tab 2.

Table 2. Damages of residential buildings

##, District	Damage grade				
	1	2	3	4	5
1,2. Gldani-Nadzaladevi	1934	2779	1936	63	-
3,4. Didube-Chugureti	692	1536	1022	15	-
5,6. Isani – Samgori	863	1102	851	12	-
7,8. Krtsanisi-Mtatsminda	273	933	775	17	-
9,10. Vake-Saburtalo	221	370	112	-	-
Total	3983	6720	4696	107	-

All 202 schools in the city have been investigated by engineers. Building vulnerability class, damage grade, existing damages were identified; amount of necessary finances calculated. Total material losses make approx. 8 million USD. Average amount is 20,000-80,000 USD per school. Most part of schools are 3-4 story brick buildings. Most of them were constructed before 1950 – without antiseismic measures. Some were constructed in 1950 – 1990, when background seismicity of the territory of the city was VII

(MSK-64) (since 1991 background seismicity is VIII). Some schools of brick masonry were reinforced before the earthquake mainly with steel bars. That gave good results at the earthquake.
Main structural defect of old school buildings is large distance between capital transversal walls. Another serious danger represent massive plaster in upper part of walls and on the ceilings of especially old buildings, high massive parapets.

Approximately 100 buildings were constructed by standard projects during last 40 years. They can be related to vulnerability class **B** and **C**. Large part of **B** class has received second damage grade, and **C** class - first damage grade that corresponds to intensity VII.

Most of old school buildings had accumulated damages (deformations, settlements) caused by changed soil conditions.

Today only small part of schools are rehabilitated because of lack of funds. There is no rehabilitation concept, guidelines for this procedure. There is no appropriate control and expertise of design documentation. Data on damages are shown in Tab. 3.

Table 3. Damages in school buildings in different districts

District	Damage grade				
	1	2	3	4	5
1,2. Gldani-Nadzaladevi	31	16	7	-	-
3,4. Didube-Chugureti	16	7	6	-	-
5,6. Isani – Samgori	17	21	12	-	-
7,8. Krtsanisi-Mtatsminda	12	13	4	1	-
9,10. Vake-Saburtalo	22	11	6	-	-
Total	98	68	35	1	-

160 buildings of kindergartens have been investigated. Total losses make 3,500,000 USD. Many of kindergartens are in residential 2-3 story brick houses. Some of new constructed RC frame buildings received damages in infill walls, between columns and walls. In some infill walls silicate white brick is used (with low cohesion with mortar). Statistical data on damages are shown in Tab. 4.

Table 4. Damage of kindergartens – distribution by districts.

District	Damage grade				
	1	2	3	4	5
1,2. Gldani-Nadzaladevi	15	18	16	-	-
3,4. Didube-Chugureti	19	10	7	-	-
5,6. Isani – Samgori	13	9	7	-	-
7,8. Krtsanisi-Mtatsminda	13	5	4	-	-
9,10. Vake-Saburtalo	17	4	3	-	-
Total	77 (48.1%)	46 (28.8%)	37 (23.1%)	-	-

120 buildings of hospitals have been investigated. Total direct losses make more than 4,000,000 USD. Statistical data on damages are presented in Tab. 5.

Table 5. Damages of hospitals and clinics

District	Damage grade				
	1	2	3	4	5
1,2. Gldani-Nadzaladevi	7	8	6	1	-
3,4. Didube-Chugureti	9	6	8	2	-
5,6. Isani – Samgori	8	8	12	4	-
7,8. Krtsanisi-Mtatsminda	5	3	1	-	-
9,10. Vake-Saburtalo	21	7	3	1	-
Total	50 (41.7%)	32 (26.7%)	30 (25.0%)	8 (6.7%)	-

Out of approximately 530 public buildings (schools, kindergartens, high educational institutions, hospitals and clinics) 21% received damages of grade 3-4. Out of other 740 public buildings 29% received damage grade 1; 45% - damage grade 2; 25% - damage grade 3.

Some reinforced concrete frame buildings designed for intensity VII, received severe damages. The main reason was the usage of low-quality materials, errors in design (Fig. 3).

By expert estimations, more than 75000 people lived in buildings which received damage grade 3; more than 1200 people lived in buildings received damage grade 4.

After the earthquake till now thousands buildings are not inspected yet. Their analysis may adjust data on damages and material losses.

The earthquake has created worsened difficult economic situation in the country, severe social and economic problems, which are not solved one year later. Many thousand people are without shelter, thousands buildings remain unserviceable. The minor funds were spent for rehabilitation of schools and separate buildings. Due to absence of the conforming normative documents, concept of recovery, poor coordination and control, the efficiency of measures is insufficient.

MACROSEISMIC INTENSITY

According to different criteria, earthquake intensity can be evaluated differently. Intensity of the earthquake by seismological parameters can be evaluated as VIII. Calculated intensity of the earthquake $I_0=3+1.54*M-3.5*\log(h)$, for M=4.5 and h=3.5 makes $I_0=8.02$. PGA of the main record is 0.11g (at a distance of 6km from the epicenter) that corresponds to intensity VII (MSK-64). Sliding and overturning of monuments in the grave yards correspond to intensity VIII. These phenomena took place in cemeteries in the pantheon of Didube, Kukia, in Nadzaladevi district. Calculated PGA on the surface give the values 0.1-0.25g. Calculated max. velocities on the surface are 10-25 cm/s.

a) b) c)

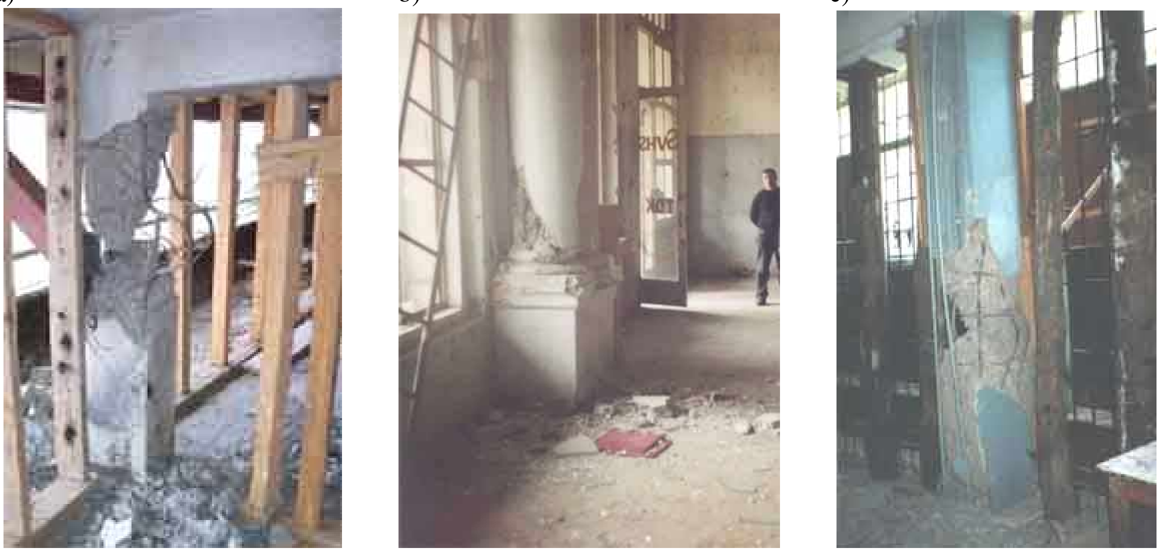


Fig. 3. Damage of columns. Inst. of Mathematics (a); Residential building in Kostava str. (b); Column of first RC floor of large-block building in Nadzaladevi District (c).

Fig. 4. Damaged brick building of hospital, A.Kazbegi str (left); Damaged column. State historical museum (right).

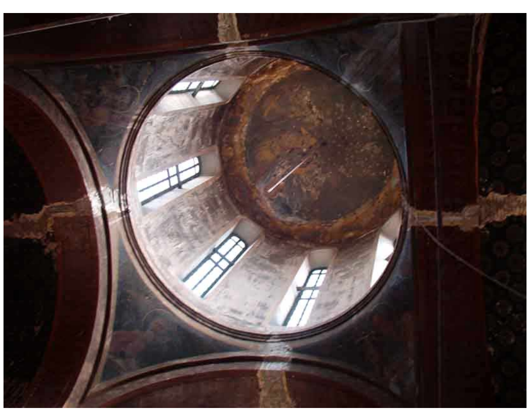


Fig . 5. Repaired symmetrical cracks, 300 Aragveli church. Fig. 6. Shifted and overturned monuments in grave yards

Fig. 7. Failed chimneys in Chugureti District

Fig. 8. Failed brick wall

Fig. 9. Alexander Dumas str. Before the EQ, March 2002 (left); after the EQ (right)

Fig. 10. Chaikovski str. Brick building before the EQ, March 2002 (left); after the EQ (right)

By macroseismic estimations – behavior of buildings, in considerable territory of the city intensity was VII. As to geological indications – cracks, landslides etc. phenomena (which can be observed even at intensity VI), there are no appropriate data in the city territory.

The most part of the population in Didube, Nadzaladevi, Chugureti, Mtatsminda, Krtsanisi, Isani, Saburtalo districts were frightened and leaved their houses that corresponds to intensity VII.

In Fig. 11 the map of macroseismic intensity is presented constructed on the basis observed data and calculated using equation (1).

$$I_0 = 1.5M - 3.5\lg\sqrt{r^2 + h^2} + 3 \qquad (1)$$

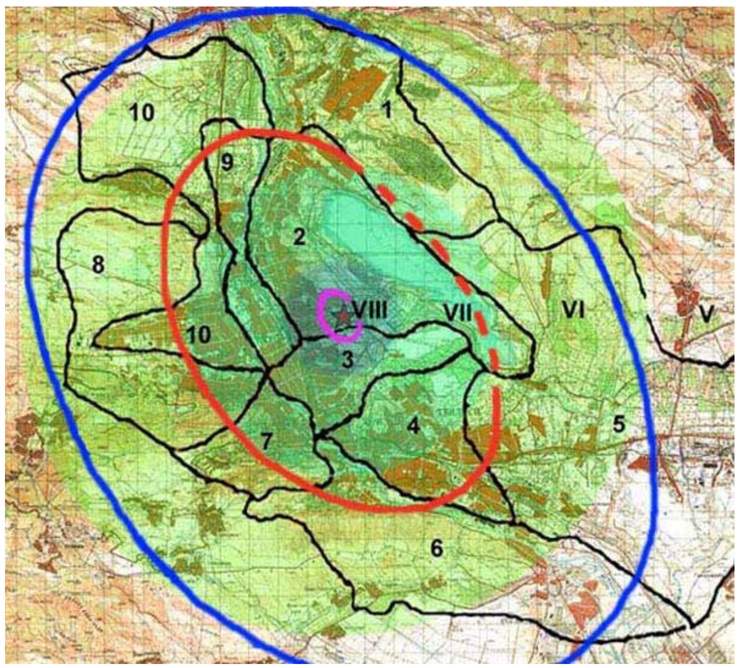


Figure 11. Macroseismic intensity of the April 25, 2002 earthquake on the observed and calculated data.

All above stated can be summarized in Tab. 6.

Table 6. Macroseismic intensity by different criteria

Criteria	Macroseismic Intensity
Equation I_0=3+1.54*M-3.5*log (h)	VIII
PGA on baserock	VII
PGA on the surface	VII-VIII
Max velocities on the surface	VII-VIII
Spectral intensity	VI
Macroseismic data (brick/stone buildings)	VII
Macroseismic data (grave yards)	VIII
Geological effects	<VI

Duration of the earthquake
One of important factors influencing on the damage effect (and not presented in macroseismic scales), is earthquake duration. Fortunately, duration of the Tbilisi earthquake was short that played positive role in response of all types of buildings, in particular, of buildings having initial damages (Fig. 9, 10). For transversal component the bracketed duration is 0.2s (calculated between the first and the last excursions of 5% of PGA level); the uniform duration is 0.1s (calculated as the total time during which the acceleration is larger then a value 5% of PGA); significant duration is 2.4s (calculated as the interval of time between the 5% and 95% thresholds of the total accumulated Arias intensity.

Another reason of good behavior of this type of buildings is high energy dissipation. It is also expected that far earthquakes with low frequency content would more dangerous for this group of buildings.

CALCULATED SOIL SEISMIC RESPONSE

Approach
In this part some results of calculations of soil response in the territory of Tbilisi using software EERA (Equivalent-linear Earthquake site Response Analysis), Bardet, Ichii, Lin (2000) are presented. The software represents the modern version of computer program SHAKE, Schnabel et al. (1972), widely used for calculations of soil response with parallel layers. A linear-equivalent model of cyclic behavior of soils is used at vertical seismic wave propagation from rocky basement. The program is integrated into MS Excel. Different nonlinear dependences of shear modulus, shear strains and damping coefficients are used (Fig. 12). In the present work the software has been updated with some features: calculation of duration of active part of earthquake record, values of spectral intensity, dynamic coefficient, graphical representation of superposed input-output accelerograms and Fourier spectra, dynamic coefficient, response spectra at different damping, released seismic energy etc. parameters and their graphical representation, Lomidze at al. (2003).

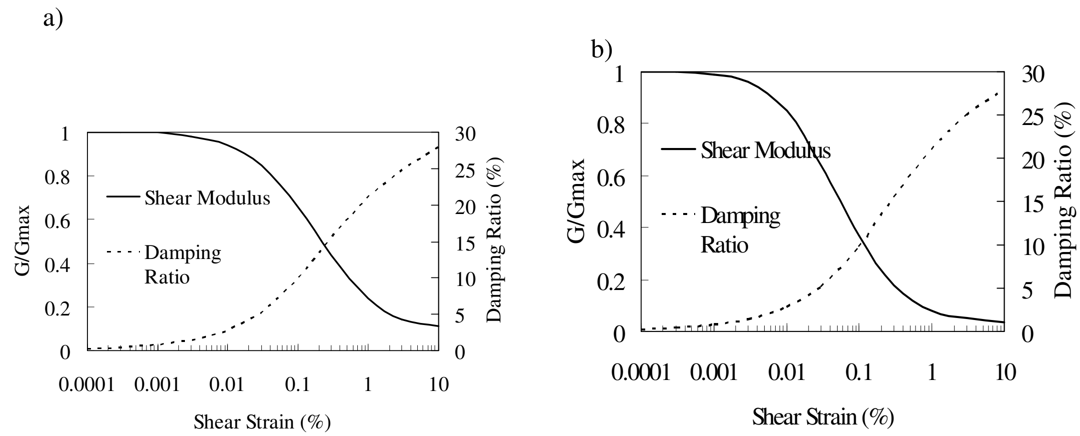


Figure 12. Dependences of soil parameters used in calculations: a) Modulus for clay, Seed, Sun (1989) upper range, damping for clay and sand, Idriss (1990); b) Modulus for sand, Seed, Idriss (1970) upper range and damping for sand, Idriss (1990).

Initial parameters are the data of soil profiles of the city territory collected and stored in the form of updatable database on the basis of results of engineering-geological investigations. In the calculations parameters of soil of 100 boreholes data have been used. Given number of boreholes is enough only for general idea about distribution of studied parameters on the territory of the city. In Fig. 12 statistical characteristics of soil conditions on the territory of the city are shown on the basis of analysis of database content. Major soil types are rocky and semi-rocky (weathered and not weathered), gravel, clays, loams, sand loams (dense and subsident), silty clay, lacustrine, swampy fill soils and others. The depth of boreholes is mainly 5-25m, fundamental period 0.1-0.3 sec, weighted average shear wave velocity in general is 400-700 m/s, the same parameter for upper 5m layer thickness is 100-300 m/s (Fig. 13).

Records of the main shock of the April 25, 2002 Tbilisi limits were used as an input excitation. Initial parameters for the calculation are: soil material type (diagram), thickness of layer, unit weight, shear wave velocity.

Main results

For each soil profile response on the surface has been calculated – acceleration, velocity, displacement for horizontal components of acceleration records of main shock of the earthquake. Amplitude Fourier spectra, amplification ratios, response spectra for periods of 0.1-1.2sec, values of spectral intensity (average spectral velocities in diapason 0.1-2.5sec) have also been calculated. On the basis of calculations a table of data was generated, related to corresponding files of calculation results, which was imported to GIS software ArcView. Maps of distribution of soils according to shear wave velocity have been compiled according to soil classification in new seismic Code of Georgia.

In Fig. 13-16 the maps of distribution of different parameters for the territory of Tbilisi are shown: spectral intensity, spectral acceleration, fundamental period of soil vibration.

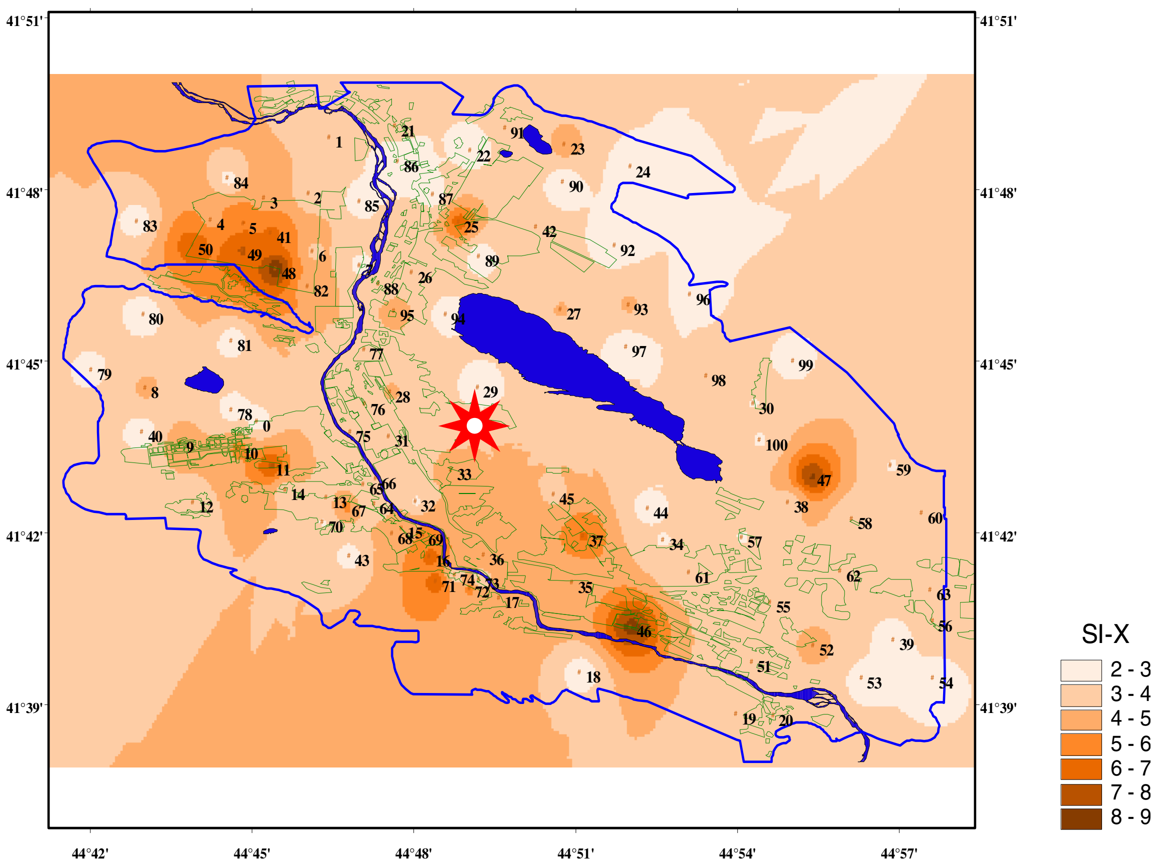


Figure 13. Epicenter of the earthquake. Spectral intensity (cm/s), X component, 5% damping.

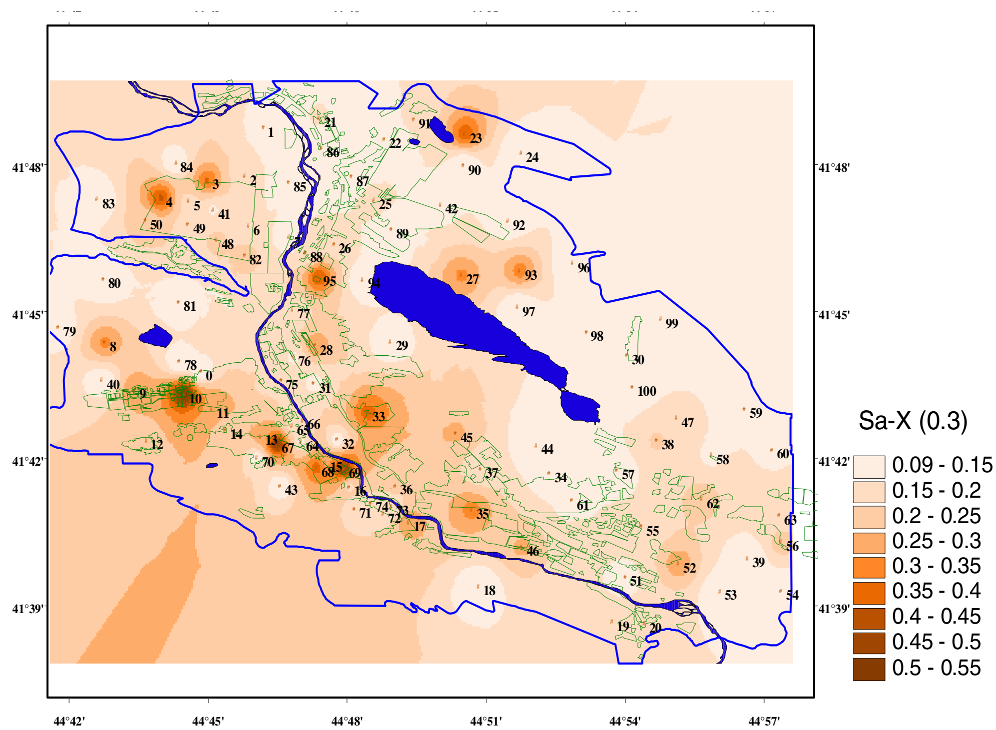


Figure 14. Spectral acceleration, X component; T=0.3s at 5% of critical damping.

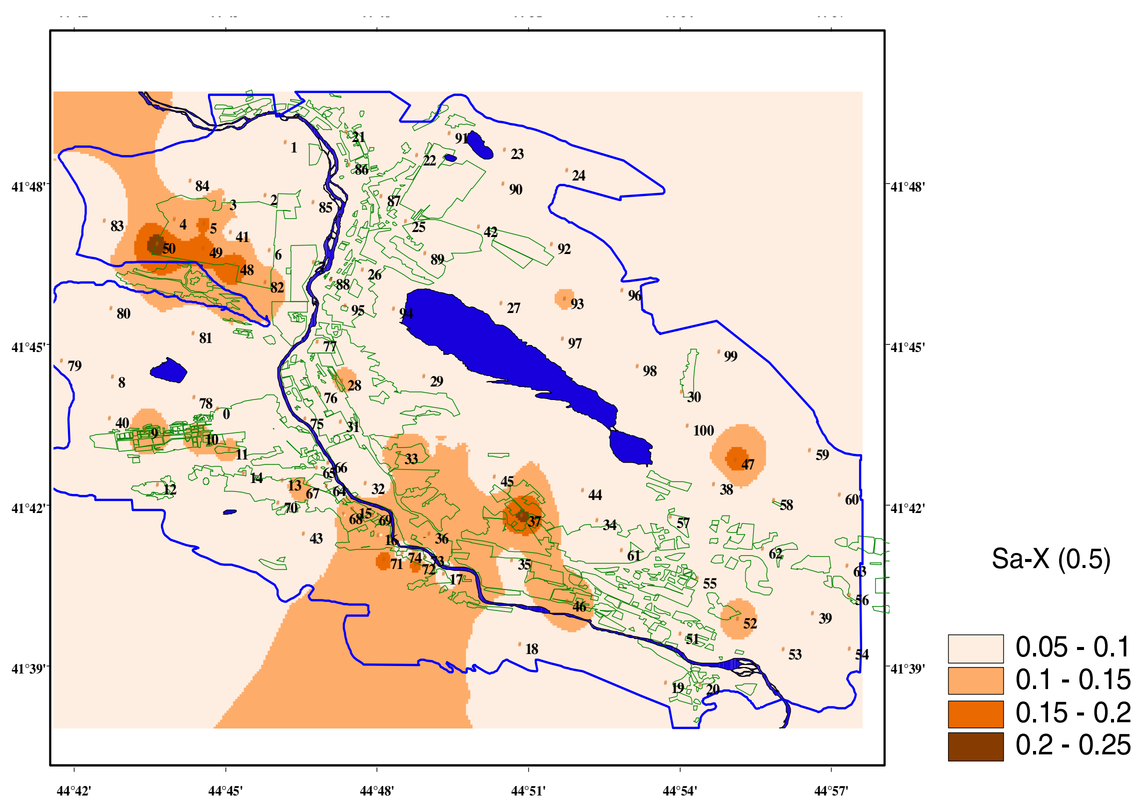


Figure 15. Spectral acceleration, X component; T=0.5s at 5% damping.

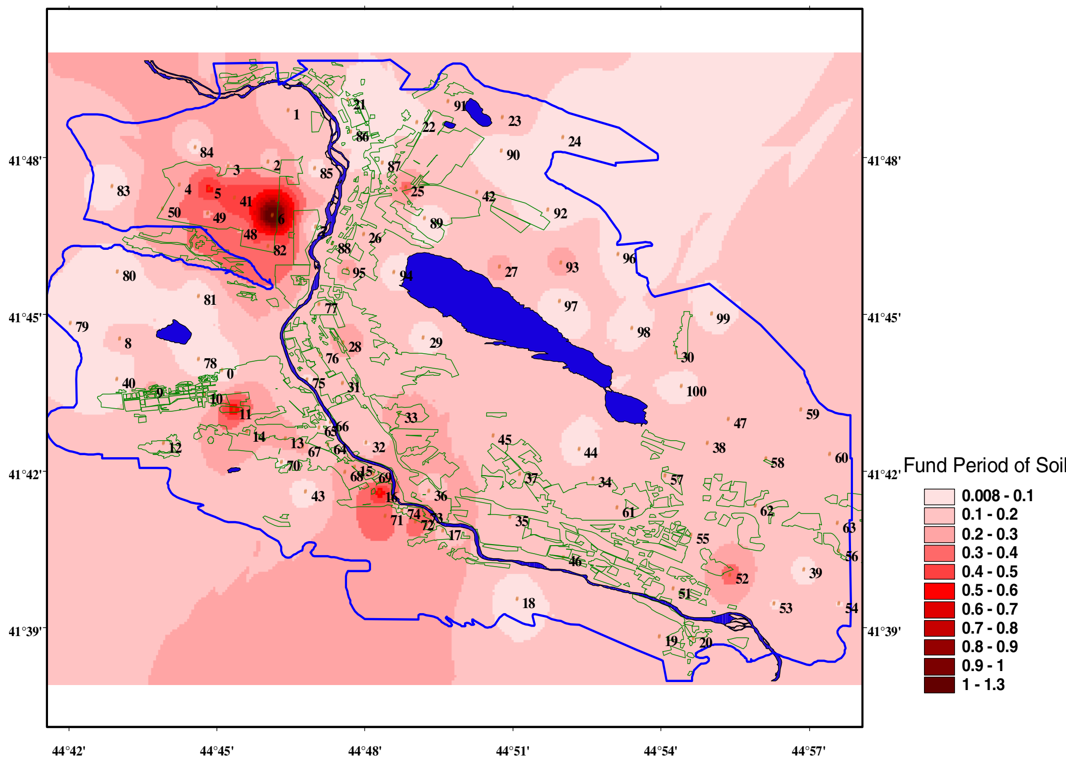


Figure 16. Natural period of soil vibration.

As an example some results of calculated parameters using soil data of borehole #77 are given below (Tab.7, Fig. 17). The value of spectral intensity is 3.5 cm/s while spectral acceleration is very high; peak acceleration on the surface is 0.25g.

Table 7. Soil profile, borehole #77

	Layer number	Soil material type	Thickness of layer (m)	Maximum shear modulus G_{max} (MPa)	Total unit weight (kN/m^3)	Shear wave velocity (m/sec)
Surface	1	1	2.5	15.2	15.00	100
	2	1	2.5	111.4	17.50	250
	3	3	1.5	402.5	19.50	450
	4	3	2.0	733.9	20.00	600
	5	3	2.0	733.9	20.00	600
	6	3	2.0	2115.9	23.00	950
	7	3	2.0	2115.9	23.00	950
Bedrock	8	0		3522.9	24.00	1200

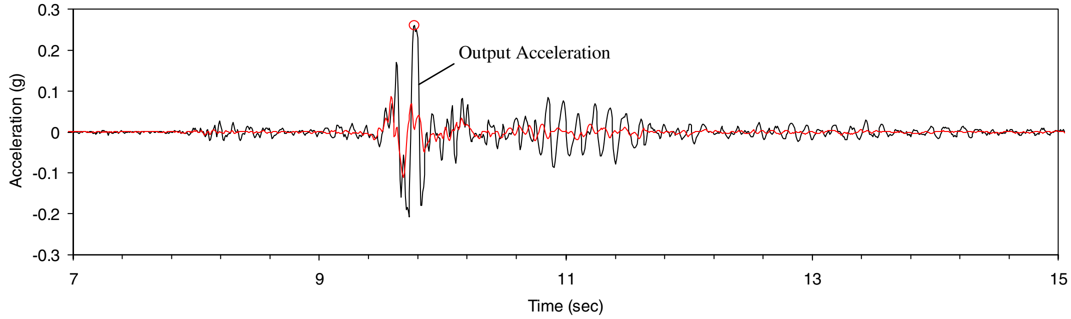
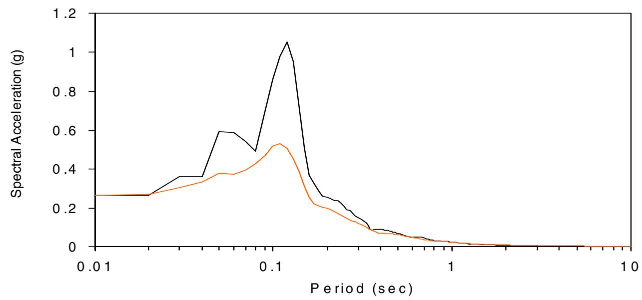
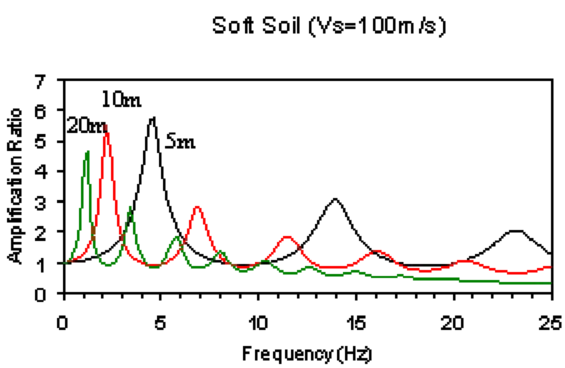


Figure 17. Borehole #77: input and output accelerogram (above); spectral acceleration at 5 and 20% of critical damping (right).



In Fig. 18 calculated amplification ratios are shown for soft and average types of soil at different soil layer thickness, X component accelerogram of the earthquake.



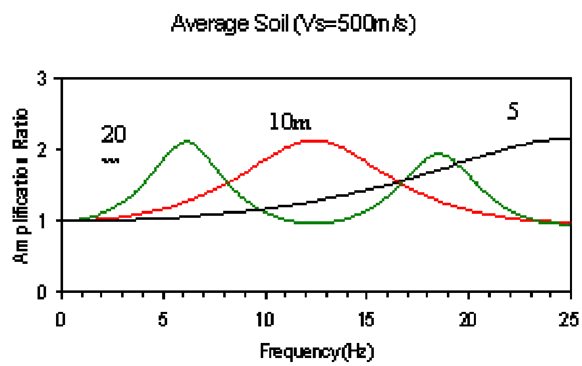
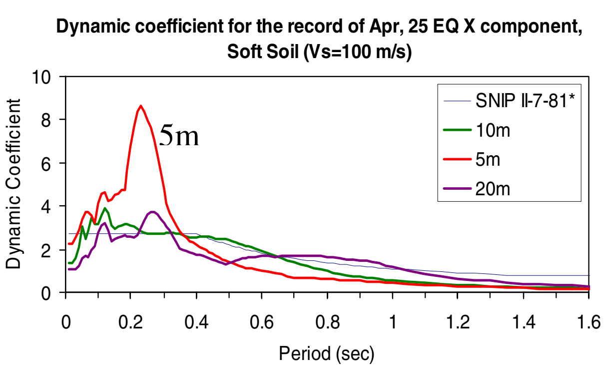
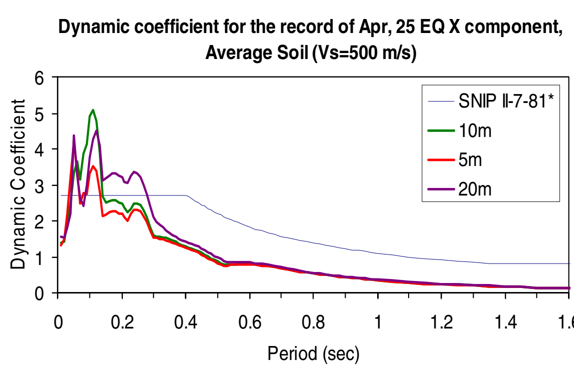


Figure 18. Amplification factor for soft and average soil at 5, 10, 20m soil layer thickness.





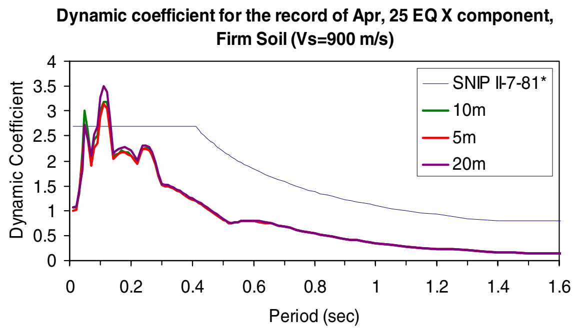


Figure 19. Dynamic coefficient curves for soft, average and firm soil at different layer thickness; normative curve from seismic Code SNIP II-7-81*.

CONCLUSIONS

The earthquake has raised serious social-economic problems. Lack of funds did not allow to rehabilitate most part of damaged essential facilities. Necessary normative documents must be developed urgently for effective realization of rehabilitation measures. Fortunately for the building stock, there was an epicentral earthquake with high dominant frequency. Fortunately, the shock was short term and hard, like an explosion and caused no resonance effects. Big part of the building stock (old 2-3 story brick/stone buildings with initial damages) has received additional damages and created over 18000 households with 69000 inhabitants of homeless population. Historical center of the city is now in critical condition. Mid rise (5-8 story) and high rise (9-16) buildings have received light damages of grade 1-2. Many historical monuments have received additional damages. Many of other high-risk groups of buildings (e.g. with added steel loggia) received damages and mainly are in critical technical condition. They require urgent reinforcement or demolition. The city is not ready for the next earthquake. The obtained results of soil dynamic response calculations as a whole agree with macroseismic data of the earthquake. Calculated peak values of spectral accelerations in some cases reach high level, about 0.6-0.8g and more at T=0.1-0.3sec. At the same time, values of spectral intensity are relatively small and much better correlate with actual level of damage of structures. This is due to small duration of the seismic impact, that caused respectively small magnitudes of spectral velocities and displacements, without perceptible resonance effects, decreased destructive effect. The level of ductility of a system insignificantly influences on the values of spectral displacement; more significantly changes spectral velocity and acceleration (0.1-0.15g in lieu of 0.26g in case of elastic system). Received data are used as basis for risk analyses of the urban territory. Calculated accelerograms can be used directly for calculation of buildings and structures, for geotechnical calculations.

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