ᲡᲐᲥᲐᲠᲗᲕᲔᲚᲝᲡ ᲛᲔᲪᲜᲘᲔᲠᲔᲑᲐᲗᲐ ᲔᲠᲝᲕᲜᲣᲚᲘ ᲐᲙᲐᲓᲔᲛᲘᲘᲡ ᲛᲝᲐᲛᲑᲔ, ტ. 8, №2, 2014
BULLETIN OF THE GEORGIAN NATIONAL ACADEMY OF SCIENCES, vol. 8, no. 2, 2014

Geophysics

Coupling of Multiple Rayleigh Waves and Water Level Signals during 2011 Great Tohoku Earthquake Observed in Georgia, Caucasus

Tamaz Chelidze*, Ia Shengelia, Natalya Zhukova*, Teimuraz Matcharashvili*, Giorgi Melikadze*, Genadi Kobzev***

* *M. Nodia Institute of Geophysics, I. Javakhishvili Tbilisi State University, Tbilisi*
***Earth Science Institute, Ilia State University, Tbilisi*

ABSTRACT. The dynamic triggering due to the great Tohoku M 9 earthquake Japan (2011) was observed in local seismicity all around the globe. We presume that Tohoku EQ could also trigger local seismic events in Georgia (Caucasus), which is separated from Japan by 7800 km. It was discovered during integrated analysis of seismic and water level records in wells that besides S, L and R waves, multiple surface Rayleigh waves also induce water level oscillations. *© 2014 Bull. Georg. Natl. Acad. Sci.*

Key words: *Tohoku earthquake, water level, multiple surface Rayleigh waves*

Presently, there are a lot of observations on the significant impact of such small external forcings on the seismic regime, namely on the seismicity induced by wave trains of remote strong earthquakes (EQ). Many of such results still are the subject of intense scientific discussions, but nevertheless are quite logical in the light of undisputable strong nonlinearity of processes underlying seismicity. One of the main factors reducing local strength is the pore pressure of fluids, which is the scope of relatively new direction, so-called hydroseismology. The stresses imparted by teleseismic wave trains according to assessments are 10^5 times smaller than confining stresses at the depth, where the tremors are generated [1, 2]. Our laboratory data on stick-slip confirm the reality of triggering and synchronization under weak mechanical forcing [3]. According to [4-7] the dynamically triggered tremors (DTT) can be related to the fluid pore pressure change due to passage of wave trains from remote strong earthquakes; that is why we carried out integrated analysis of seismic and WL data.

The dynamic triggering due to the great Tohoku M 9 earthquake (2011), Japan was observed in local seismicity all around the globe [8-10]. We presume that Tohoku EQ could also trigger local seismic events in Georgia (Caucasus), which is a continental collision area, separated from Japan by 7800 km. The teleseismic waves' phases onsets at Tbilisi and Oni seismic stations (s/s) for the main shock are as following (UTC/GMT): *p* - 05 57 41, *S* - 06 07 26; Love -

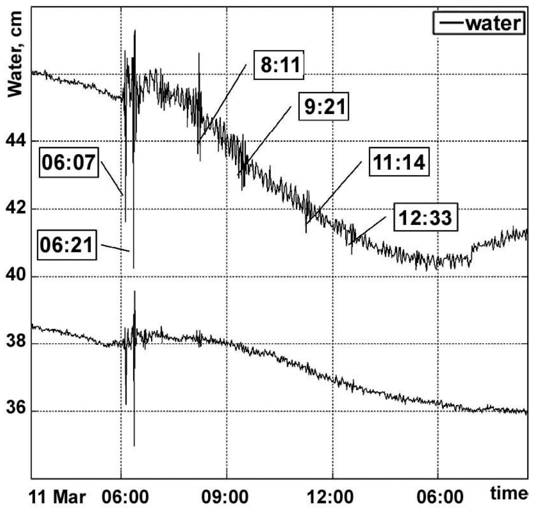

Fig. 1. Water Level change in Kobuleti (top) and Borjomi Park (bottom) before and during Japan M9 earthquake,11 March 2011 in conventional units (1/min sample rate): compressed 24 hour record. The lines with time data point to some late teleseismic surface (G-R) waves' onsets.

06 18 00, Rayleigh - 06 21 30. Besides looking for seismic DT events from Tohoku EQ [11], our goal was to compare the possible tremor signals with anomalies in water levels (WL) in deep wells' network in Georgia, operated by the M. Nodia Institute of Geophysics. Regular monitoring by this network is going on for several decades. It was important to find WL anomalous changes and compare them with teleseismic waves' phases as well as to assess pressure and stress changes of correlated seismic and WL signals: according to [4] the tremors can be triggered by fluid pore pressure change during teleseismic wave passage. It is documented that in the far field (which is our case) mainly correlated with seismic wave oscillations of WL are observed (hydroseismograms), sometimes accompanied with sustained WL change. As the seismic impact is instantaneous, it is expected that pore water has no time to flow, which in turn means that the WL response is undrained [5].

In Fig.1 we show water level respond to a series of Japan earthquakes 11 March 2011 with following *p*-wave arrival times of the main shock and aftershocks: a) M 9; time - 05: 57; b) Mw7.4, time - 06.19; c) Mw=7.9, time – 06: 26; d) Mw=7.7, time – 06: 36. As the WL values in different wells change in a very wide range in order to show their reactions on the same plot, the signals from the *i*-th borehole (WL_i) are plotted in conventional units, namely, they are shifted along y-axis according to the expression: $(WL_i) = WL_o$–[min(WL_i)]+offset; where WL_o is the observed WL, [min(WL_i)] is a minimum WL in borehole for the year 2011 and the offset is a constant, needed to fit WL curves into the same plot. For example, in Fig. 1 the value of [min(WL_1)] for Kobuleti is 106 cm, the value of offset= 0; for Borjomi [min(WL_2)] is 523 cm; offset - 6 cm.

There is a very interesting detail on the WL plot for Borjomi well (Fig.1, trace for Z-component): clear delayed WL perturbations are registered at the following times: 08:11, 09:21, 11:14 and 12:33, which cannot be associated with aftershocks. The possible explanation of these anomalies is the passage of late teleseismic phases, namely multiple surface waves circling the Earth: according to [12] they also trigger seismic events. The most effective in delayed triggering of microearthquakes are the first three groups

Table. 1. Seismic and hydraulic response to the multiple surface waves (R2, R3, R4, R5 and G2, G3, G4, G5) of Tohoku, M9, EQ in Kobuleti, Georgia

Site name	$\Delta(WL)_{mR}$ cm	ΔP_{mR} KPa	$\Delta(WL)_{mG}$ cm	ΔP_{mG} KPa	v_G cm/s	$\Delta\sigma_G$ KPa	v_R cm/s	$\Delta\sigma_R$ KPa	χ m/(m/s)
Kobuleti	3.20	0.32	-	-	G2 – 0.030	3.0	R2 - 0.020	2.0	160
	1.65	0.17	-	-	G3 – 0.015	1.5	R3 - 0.018	1.5	90
	1.26	0.13	-	-	G4 – 0.007	0.7	R4 - 0.008	0.7	160
	0.90	0.09	-	-	G5 – 0.003	0.3	R5 - 0.006	0.5	150

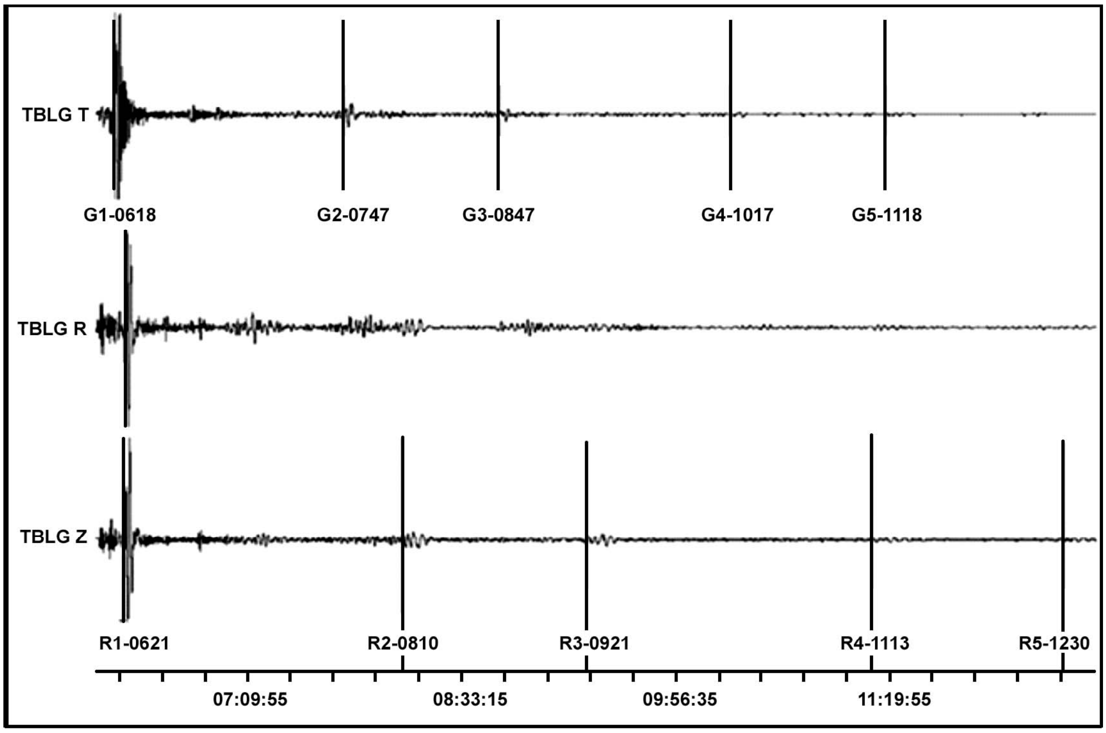

Fig. 2. Seismogram with arrivals of multiple surface G and R waves at Tbilisi s/s. Water level perturbations (Fig.1) coincide with arrival of multiple surface waves R2 (08.10), R3 (09.21), R4 (11.13) and R5 (12.30), which travelled correspondingly 289, 431, 649 and 791 degrees

of multiple surface waves (G1-R1, G2-R2, etc). Indeed, the analysis of seismograms shows that exactly at above mentioned times of WL perturbations arrive multiple surface waves R2 (08.10), R3 (09.21), R4 (11.13) and R5 (12.30), which travelled correspondingly 289, 431, 649 and 791 degrees [13]. Thus, we show that multiple surface R waves can generate not only local microseismicity, but also significant WL signals.

On the other hand, WL does not respond to the arrival of G-group Love waves (G1, G2 etc) (Figs. 1, 2). Thus the WL signals, recorded at 08:11, 9:21, 11:14 and 12:33 are definitely triggered by passing multiple surface R-waves.

Table 1 summarizes corresponding seismic and WL data. We can conclude that though the stress change imparted by multiple surface waves of both G and R-groups are comparable (Table 1), the WL responds strongly only to R-waves impact. This result is in agreement with the statement that for WL change porous space should consolidate or dilate; Rayleigh waves give rise to volumetric strain what satisfies this model [4]. S and L waves do not have volumetric component and accordingly they should not affect WL, but the recent data [5, 6] as well as our results show that S and SS waves also significantly change WL. The mechanisms suggested for explanation of the latter observation include permeability enhancement of fractured rocks due to removal of blocking elements by oscillating fluid [5] or just strong anisotropy/heterogeneity of aquifer rocks, which can add volumetric component to a shear displacement [4]; of course, such effects are absent in isotropic homogeneous material.

Another confirmation of suggested mechanism is following: after Tohoku EQ in the spectrum of WL oscillations several spikes appear around frequencies 2.4 10^{-3}; 4.0 10^{-3}; 4.9 10^{-3}; 6.2 10^{-3}; 7.2 10^{-3} Hz, which seem to be harmonics of the first mode with a multiplier approximately 1.3. The intensity of harmonics is especially high during the first 30 min after the EQ. The reverberations are absent in the spectrum for the 10th March. The spectrogram of the same WL record also shows intensive signals around above frequencies. The observed reverberations in WL hardly can be explained by the excitation of the so-called Kraukis waves which propagate back and forth along fluid-filled fractures of the aquifer, emitting periodic seismic signal [14] (Tary et al, 2014). The frequency of Krauklis wave depends on the fracture width, shear modulus of the solid, fluid density and the ratio of shear and longitudinal waves: in order to be in the observed range, the system should contain unrealistically long and thin cracks.

The most probable explanation of WL oscillations with periods 2-7 min is the impact of mantle surface waves (Love and Rayleigh), which can excite seismic signals with periods up to about 500 s (Bormann, 2012), which fits the observed WL oscillations' frequency range $2.4\ 10^{-3}$ - $7.2\ 10^{-3}$ Hz. Thus, spectral data confirm suggested model of coupling WL signals with multiple surface R-waves.

Conclusion

Our new observation obtained by integrated analysis of seismic and water level records (hydroseismograms) document, for the first time, that multiple surface R waves generate not only local microseismicity [12], but also significant synchronous WL signals (unlike less efficient multiple surface G waves).

Acknowledgement

The authors express their gratitude to the Shota Rustaveli National Science Foundation of Georgia (Project FR/567/9-140/12) for financial support.

გეოფიზიკა

საქართველოში დაფიქსირებული მრავალჯერადი რელეის ტალღების და წყლის დონის ანომალიების კავშირი 2011 წლის დიდი ტოჰოკუს მიწისძვრის დროს

თ. ჭელიძე*, ი. შენგელია, ნ. ჟუკოვა*, თ. მაჭარაშვილი*, გ. მელიქაძე*, გ. კობზევი***

** ი. ჯავახიშვილის თბილისის სახელმწიფო უნივერსიტეტი, მ. ნოდიას გეოფიზიკის ინსტიტუტი, თბილისი*
*** ილიას სახელმწიფო უნივერსიტეტი, დედამიწის შემსწავლელი ინსტიტუტი, თბილისი*

2011 წლის იაპონიის დიდმა ტოჰოკუს (M9) მიწისძვრამ მთელს დედამიწაზე გამოიწვია ლოკალური მიკროსეისმურობის გააქტიურება დინამიკური ტრიგერირების გზით. ჩვენ მიგვაჩნია, რომ ტოჰოკუს მიწისძვრამ საქართველოშიც, იაპონიიდან 7800 კმ დაშორებით, მოახდინა სუსტი ლოკალური სეისმური მოვლენების ტრიგერირება. სეისმური და წყლის დონეების ჩანაწერების ერთობლივი ანალიზის შემდეგ აღმოჩნდა, რომ გარდა S, L და R სეისმური ტალღებისა, წყლის დონეების რხევას იწვევს აგრეთვე მრავალჯერადი ზედაპირული რელეის ტალღები R2, R4, R4, R5.

REFERENCES

1. *D. Hill, Zh. Peng, D. Shelly* and *Ch. Aiken* (2013), Bull. Seis. Soc. America, 103: 1541–1550.
2. *S. Prejean* and *D. Hill* (2009), In: Encyclopedia of Complexity and Systems Science, R. A. Meyers (Ed.), Springer, pp. 2600-2621.
3. *T. Chelidze, T. Matcharashvili, O. Lursmanashvili, N. Varamashvili, N. Zhukova* and *E. Meparidze* (2010), In: Synchronization and Triggering: from Fracture to Earthquake Processes. Eds. V.de Rubeis, Z. Czechowski and R. Teisseyre, pp.123-164.
4. *E. Brodsky, E. Roeloffs, D. Woodcock, I. Gall* and *M. Manga,* (2003), J. Geophys. Res. 108, B8, 2390, doi:10.1029/2002JB002321,
5. *C.-Y. Wang, Y. Chia, P-L. Wang, D. Dreger* (2009), Geoph. Res. Lett., 36: L09404, doi:10.1029/009GL037330, 2009.
6. *C.-Y. Wang, M. Manga* (2010), Earthquakes and Water. Springer-Verlag Berlin Heidelberg.
7. *Y. Zhang* and *F. Huang* (2011), Bull. Seis. Soc. America, 101: 1531-1541.
8. H. Gonzalez-Huizar, A. Velasco, Zh. Peng and R. Castro (2012), *Geophys. Res. Letters.*, 39: L10302, doi: 10.1029/2012GL051015.
9. *K. Obara* and *T. Matsuzawa* (2013), Bull. Seismol. Soc. Am., **103**: 1551–1571.
10. *K. Chao, Z. Peng H. Gonzalez-Huizar, Ch. Aiken, et al,* (2013), Bull. Seis. Soc. America, 103: 1551-1571, doi: 10.1785/0120120171
11. *T. Chelidze, N. Zhukova, T. Matcharashvili,* SEISMOTOOL – an easy way to see, listen, analyze seismograms. *Seismol. Res. Letters* (in print).
12. *Z. Peng, C. Wu* and *C. Aiken* (2011), Geophys. Res. Lett., 38: L04306, doi:10.1029/2010GL046373.
13. *P.* (*Ed.*) *Bormann* (2012), New Manual of Seismological Observatory Practice (NMSOP-2), IASPEI, GFZ German Research Centre for Geosciences, Potsdam; http://nmsop.gfz-potsdam.de;
14. *J. B. Tary, M. van der Baan* and *D.W. Eaton* (2014), J. Geophys. Res. Solid Earth, 119. doi:10.1002/ 2013JB010904.doi:10.1002/2013JB010904.

Received June, 2014