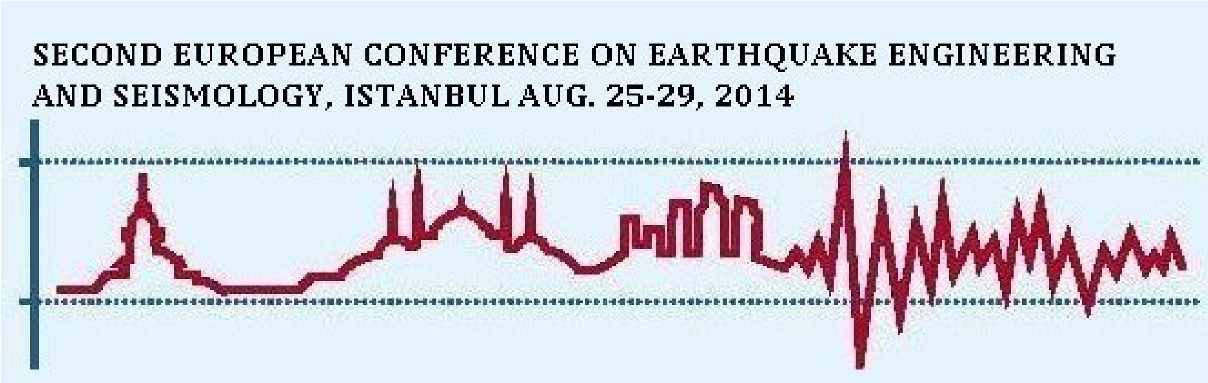

PHYSICAL MECHANISMS OF HIGH PEAK GROUND ACCELERATIONS (> 1G) IN STRONG GROUND MOTION (TOHOKU EARTHQUAKE OF MARCH 11, 2011 AS AN EXAMPLE)

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During March 11, 2011 Tohoku earthquake (M_w=9.0), 19 stations of strong-motion seismograph networks of Japan K-net and Kik-net reliably recorded accelerations higher than 1g (maximum ~3g), and acceleration time histories possessing the highest PGA resembled impulses with sharp peaks in one or two groups of waves at both horizontal and vertical components.

To understand physical mechanisms of generation of these high PGA, I studied the behavior of soils at Kik-net sites (vertical arrays) in the upper ~100-500 m (down to the location of the deepest device) in near-fault zones of the Tohoku earthquake (altogether, at ~50 sites recorded the highest PGA, 250-1335 Gal, at epicentral distances ~137-350 km). I applied the method of processing records of seismic vertical arrays suggested by Pavlenko and Irikura (2003) to construct models of soil behavior during the Tohoku earthquake, such as, time-dependent vertical distributions of stresses and strains in soil layers from the surface down to ~100-500 m.

In contrast to previously obtained models of soil behavior in strong earthquakes, such as, the 1995 Kobe earthquake (M_w= 6.8), 2000 Tottori earthquake (M_w= 6.7), and 1999 Chi-Chi (Taiwan) earthquake (M_w= 7.3), where we found strong nonlinearity of soft soil behavior in near-fault zones and shear moduli reduction during strong motion and their following recovery at the end of strong motion (Pavlenko and Irikura, 2002, 2003; Pavlenko and Irikura, 2006; Pavlenko, 2008), during the Tohoku earthquake soil behavior was quite different, “atypical”.

At the majority of the studied Kik-net stations recorded the highest PGA, shear moduli sharply increased to their maxima at the moments of the highest intensity of the strong motion, indication soil hardening, and then they decreased with decreasing the intensity of the strong motion. Such behavior was observed at many Kik-net stations possessing various soil conditions, and soil behavior was virtually linear. At soft soil stations, reduction of shear moduli was accompanied by step-like decrease of the predominant frequencies of the strong motion. Only few soil stations possessed “typical” nonlinear soil behavior and shear moduli reduction due to the strong motion and their recovery at the end of the strong motion. Japanese seismologists found that amplification of the strong motion in soil layers was noticeably higher during the mainshock of the Tohoku earthquake than during its aftershocks. The highest PGA recorded in the near-fault zones do not agree with the empirical attenuation relationship accepted for Japan (Si and Midorikawa, 1999).

If we compare all available models of soil behavior during recent strong earthquakes (the 1995 Kobe earthquake, 2000 Tottori earthquake, 1999 Chi-Chi earthquake, and 2011 Tohoku earthquake) based on records of seismic vertical arrays, we conclude that with increasing the magnitude of a strong earthquake, deeper layers become involved in the strong motion. The degree of the nonlinearity of soft soil response should increase with increasing the magnitude of an earthquake, and therefore, nonlinear damping should also increase. At the same time, in strong earthquakes we definitely record high accelerations sometimes exceeding 1g.

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It was shown in (Pavlenko and Irikura, 2005; Pavlenko, 2008) that the nonlinearity of soft soil response was rather high during the earthquakes of magnitudes Mw= 6.7-7.3. During the Kobe and Tottori earthquakes, the contents of nonlinear components in the soil response was up to ~60% of the whole intensity of the response, and during the Chi-Chi earthquake, it was up to ~80%. As known from nonlinear acoustics, the limiting case of the highest nonlinearity of the medium is represented by shock waves. Therefore, during the Tohoku earthquake we can expect the highest nonlinearity and shock waves, and I think that the most probable cause of these high PGA recorded during the Tohoku earthquake (Mw=9.0) are shock waves radiated by the earthquake source.

According to their definition, shock waves are characterized by abrupt changes in characteristics of the medium, such as pressure, density, and others, at the wave fronts. Such changes in the characteristics of the medium can be seen in spectral-temporal diagrams of the acceleration time histories of the Tohoku earthquake: at soft soil Kik-net sites, we observe step-like decrease of the predominant frequencies of the strong motion from ~4-5 Hz down to ~2 Hz just after passing the most intense waves. This can be interpreted as consolidation of soil at the wave front and its tension behind the wave front.

As known, maximum PGA induced by the Tohoku earthquake were recorded in two main areas in Japan, such as, in Sendai area and to the west (where acceleration time histories contain two groups of intense waves) and along the west coastal area to the north of Tokyo (Mito) (where acceleration time histories contain one group of intense waves). These shapes of acceleration time histories, containing one or two groups of intense waves (in high-frequency and low-frequency domains) are explained by the earthquake source mechanism (NIED, 2011, Hayes, 2011, Fujii et al., 2011, Noguchi, 2011). Evidently, the source contained at least two main ruptures: the first one propagated to the north from the hypocenter, and the second one occurred approximately one minute later and propagated in the southern direction. Thus, high PGA in the near-source zones can be produced by shock waves radiated by two these ruptures in the earthquake source.

Shock waves effectively propagate in the air, whereas, in the earth, they are rather quickly attenuated with distance. Based on records of Kik-net stations located at various epicentral distances, I traced the propagation of groups of intense waves (probably, shock waves) from the two main ruptures of the earthquake fault and estimated the attenuation distance of the intense waves, i.e., the epicentral distances, at which "typical" soil nonlinearity is observed. It is less than the dimensions of the fault, which agrees with the theory of shock waves in solids. Records of Kik-net stations located at various epicentral distances show us the transition from the "shock wave" areas to the areas of "typical" soil nonlinearity.

The conclusion that shock waves can be generated in the near-fault zones of the earthquakes is partially supported by rather not-rare observations of earthquakes, besides Tohoku (they can be easily found in Japanese strong-motion databases K-net and Kik-net), in which unusually high PGA (substantially higher than those predicted by empirical attenuation curves) were recorded near the faults, for example, 722 Gal at *r*=5 km and 44 Gal at *r*=26 km (13.08.1996, Mw= 5.0); 408 Gal at *r*=6 km and 27 Gal at *r*=28 km (2.06.1996, Mw= 4.3); 248 Gal at *r*=6 km and 31 Gal at *r*=20 km (7.03.1997, Mw= 4.3); 325 Gal at *r*=0 km and 83 Gal at *r*=24 km (16.12.1999, Mw= 4.1); 235 Gal at *r*=9 km and 24 Gal at *r*=14 km (26.03.1997, Mw= 4.0); 444 Gal at *r*=3 km and 93 Gal at *r*=13 km (22.08.1999, Mw= 3.8); 224 Gal at *r*=6 km and 21 Gal at *r*=18 km (10.01.2000, Mw= 3.6), etc. As seen from these data, abnormally high PGA were recorded at the closest to the fault sites, whereas at more distant sites they look like "normal" ones matching attenuation relationships.

Note that the shapes of the acceleration time histories of the Tohoku earthquake possessing the highest PGA resemble the shapes of shock waves produced, for example, by supersonic aircrafts.

Accounting for all the observed features, I assume that "shock wave" mechanism is the most possible cause of "atypical" soil behavior during the Tohoku earthquake and high PGA values recorded in the near-fault zones. Thus, it is not site effect, but it is source effect.

Anyway, the whole patterns of soil behavior in near-fault zones of strong earthquakes prove to be more complicated than we thought before. In addition to zones of strong nonlinearity of soil response around the earthquake sources, areas of shock-wave generation can occur just near the sources. Large scattering of PGA values in near-fault zones, sometimes reported for some earthquakes, can be explained by such effects, i.e., by the generation of shock waves under certain conditions.

As far as this is source effect, to predict PGA in some area, we should study the features of earthquake sources in this area, such as, regional types of slip distributions over the fault planes, released stresses, source spectra, etc.

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