Understanding the ground motion of the Kocaeli earthquake, Turkey 1999

Comprendre les mouvements de sol du tremblement de terre survenu en 1999, à Kocaeli, en Turquie

B.Teymur – *Istanbul Technical University, Ayazaga, Turkey*
S.P.G.Madabhushi – *University of Cambridge, Cambridge, UK*

ABSTRACT: The Marmara region of Turkey was shaken by an earthquake with a magnitude of 7.4 and epicentre in Golcuk on August 17, 1999. In this paper the strong motion data acquired from this earthquake at one location is inspected using Fourier transform and a time-frequency technique using harmonic wavelets developed at Cambridge. Wavelet analysis enables us to see energy distribution in time-frequency plane. There is a need to simulate earthquake motions in laboratory conditions to study specific boundary value problems. Dynamic centrifuge modelling enables us to achieve this. The same technique of wavelet analysis can be applied to centrifuge test data. In this paper we show the occurrence of specific frequency shaking at different times both in real earthquake motion and centrifuge data. This could not have been detected using traditional FFT analysis.

RÉSUMÉ: Le 17 août 1999, la région de Marmara, en Turquie, a été secouée par un tremblement de terre d'une magnitude de 7,4 dont l'épicentre se situait à Golcuk. Dans cet article, les données de fort déplacement, acquises pour ce tremblement de terre à un emplacement donné, sont inspectées en utilisant la transformation de Fourier ainsi qu'une technique fréquence-temps développée à Cambridge qui utilise des wavelets harmoniques. L'analyse wavelet permet d'obtenir la distribution d'énergie dans le plan fréquence-temps. Il y a un besoin expérimental de simuler les mouvements de tremblement de terre en laboratoire pour étudier des problèmes avec des conditions aux limites spécifiques. La modélisation dynamique en centrifugeuse permet d'y aboutir. La même technique d'analyse wavelet peut être appliquée aux données acquises en centrifugeuse. Dans cet article, il est montré que l'occurrence d'une secousse de fréquence spécifique à des temps différents aussi bien pour des données de mouvement de tremblement de terre que pour des données acquises en centrifugeuse. Ceci n'aurait pas pu être détecté en utilisant l'analyse FFT traditionnelle.

1 INTRODUCTION

Kocaeli and the Marmara region of Turkey were shaken by an earthquake with a moment magnitude of 7.4 on the Richter scale on August 17, 1999. Peak lateral ground accelerations of 0.41g in EW was measured in Adapazari, and about 10km away from the epicentre at Yarimca Petrochemical Facility (YPT) as 0.32g in EW. In this paper the strong motion data acquired from this earthquake at YPT is inspected using a new time-frequency technique based on harmonic wavelets developed at Cambridge, Newland (1999 a, b). The advantage of harmonic wavelet analysis when dealing with non-stationary signals like earthquakes is that one can plot the signal in a time-frequency space enabling the energy distribution in the signal to be observed. The wavelet program used, computes the harmonic wavelet transform of the record and plots the result as the time-frequency map covering the whole frequency range from 0 to the Nyquist frequency. The energy of a signal can be broken into its constituents at different frequency bands and time locations via wavelet analysis, giving insight into the localised portions of the signal. This allows us to see the discontinuities within the signal and zoom in for closer inspection. Using the wavelets, it was observed that in the Kocaeli earthquake ground motions, accelerations with same frequency occurred at different time instants. The first part of this paper is dedicated to understanding ground motion in real earthquakes. The second part of the paper looks at correct modelling of the stress-strain conditions under laboratory conditions using dynamic centrifuge modelling.

Dynamic centrifuge modelling involves testing of reduced scale models in the increased gravity field of a geotechnical centrifuge and requires special boundary conditions in order to minimise the boundary effects on soil models. This has lead to the development of the Equivalent Shear Beam (ESB) model container, which reduces boundary effects by means of flexible, laminated end-walls, the shear stiffness of which is matched to that of the soil. Ideal boundary conditions for a dynamic model test are to minimise the container wall interference on the soil response, therefore it would involve no reflection of stress waves from the boundaries of the container. This implies that end wall displacements must be matched to those of the soil column and complementary shear stresses induced by base shaking must be sustained by the end walls. Special features of ESB model container include inextensible friction sheets attached to each end-wall, which were roughened by gluing sand onto them to transfer the shear stresses to the base of the container to overcome the overturning moment created in compression and extension.

A series of centrifuge tests involving dry and saturated models of homogeneous horizontal sand layers have been carried out, and measurements taken to quantify the effects of the boundaries on soil behaviour. Miniature CPT tests were conducted in flight, before and after earthquake loading at different locations to investigate boundary effects on the densification of sand near the end walls during dynamic loading and arching of soil and shear transfer to the walls. The influence of boundary effects will be shown based on centrifuge test data by comparing CPT profiles adjacent to the end walls with those taken near the centre of the model container. This paper will discuss the recent experiments, which are important in quantifying the effectiveness of the ESB model container. The results from these experiments are important to simulate dry and saturated soil conditions observed in Turkey. For the former it is important to establish the settlement characteristics of loose, dry sediments and for the latter to quantify liquefaction phenomena for soils that are below ground water level. The results from the experiments show that there is a difference in the soil stiffness before and after the earthquake loading due to the presence of rough shear sheets placed at the end walls. The rough sheets at the end walls are providing arching in the soil following earthquake loading, when rest of the soil samples undergoes settlement.

2 THE TURKEY EARTHQUAKE OF 1999

The earthquake caused structural damage of various degrees and lasted for 45-50 seconds. The peak ground accelerations at YPT were 0.32g in EW, 0.23g in NS and 0.24g in UD. A simplified geological map of the key features of the Marmara Region can be seen in Figure 1. The Adapazari city is located on an alluvial plain, which overlies Quaternary Age alluvial deposits with alternating layers of gravel, sand, silt and clay. The groundwater level is shallow and is between 0.5m to 3.0m below ground level. Izmit is located on the northern and eastern side of Izmit Bay, on a coastal plain with a gentle slope to the south, towards the sea. It is underlain by Quaternary age deposits with alternating layers of clay, silt, sand, gravel and dense silty fine sand (Kocaeli Earthquake Report, EEFIT, 2000).

The location of the strong motion station YPT chosen for this paper is as shown in Figure 1. The reason the station is chosen is due to its proximity to the epicentre. The EW record obtained for YPT strong motion station is shown in Figure 2. The acceleration-time history is only for the first 80 seconds of the earthquake and the sampling rate of the signal was 200Hz.

Figure 1. Simplified geological map of earthquake affected area. (after Kocaeli Earthquake Report, EEFIT, 2000).

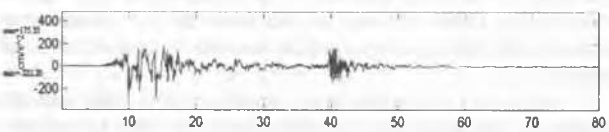

Figure 2. The acceleration time history of YPT signal-EW component. *(http://www.boun.edu.tr)*.

3 METHODS OF ANALYSIS

Time and frequency domains constitute two alternative ways of looking at a signal. In the time domain, signals can be analyzed in the form of the time histories and identifying signal peaks. In the frequency domain, time information is lost and it does not provide time localization of spectral components, it only shows the overall frequency distribution. Using the wavelet method it is possible to spot details of the signal, which would not be recognized by any other method. For example, if a time signal had the same frequency of vibrations at two distinct times, such information will show up as a single peak in the DFFT plots, but wavelets show these as peaks at different times. Frequency analysis using DFFT method was carried out on EW component of YPT signal showing various frequencies between 0-10 Hz as seen in Figure 3 with the first peak at 0.125Hz. The graph shows that there is no one dominant single frequency in the signal.

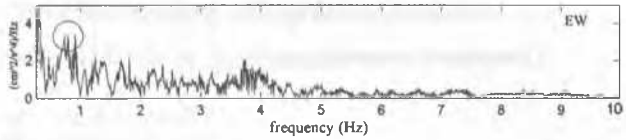

Figure 3. Fourier analysis of YPT EW signal.

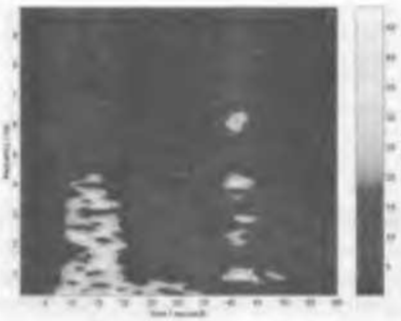

Figure 4. Wavelet analysis of EW component-YPT signal.

3.1 *Harmonic Wavelet Analysis*

The theory of harmonic wavelets has been described in previous papers by Newland (1999a, b). In wavelet analysis, the signal is broken into a series of local basis functions called wavelets. Wavelets occupy different times and have different frequency compositions so that combined together they completely represent the signal being analysed. By using wavelets, variations in frequency components with time can be observed. Harmonic wavelets have been found to be particularly suitable for vibration and acoustic analysis because their harmonic structure is similar to naturally-occurring signal structures and therefore they correlate well with experimental signals. They can also be computed by a numerically-efficient fft-based algorithm.

Time-frequency maps plotted here are the two-dimensional contour diagrams of the three-dimensional surface plots created from the harmonic wavelet transforms. The axes of the map are time plotted horizontally and frequency plotted vertically. Different grey shades represent the various contour levels. Figure 4 shows the results of harmonic wavelet analysis for the EW signal from YPT station. In the EW direction the first peak had a peak frequency of 0.125Hz and 1Hz at 10 and 42 seconds respectively. Same frequency present at different times and secondly, the presence of various frequencies at the same time can also be observed which cannot be distinguished by FFT. When one looks at the EW, component of YPT signal, two significant time bands involving various frequencies can be seen. The first one is between 8-20 seconds and then between 40-48 seconds. The frequencies of shaking in the first pulse are well distributed from 0 to 4Hz. The frequencies of shaking in the second pulse are concentrated at 1, 2, 4 and 6 Hz. These were not visible with the FFT graph seen in Figure 3.

4 DYNAMIC CENTRIFUGE MODELLING

Geotechnical centrifuge modelling is a physical modelling technique that enables us to create realistic full-scale stress states with uniform and measurable soil properties. Dynamic problems such as earthquakes, blasts, vibrations of structures, pile-driving and wave-induced cyclic loading can be modelled by using the geotechnical centrifuge. It has been extensively used in the last two decades to model seismic events to observe the dynamic behaviour of various soil-structure problems subjected to earthquake loading. In a centrifuge, space available to model real situations is not infinite and it is necessary to enclose the model within the finite boundaries provided by the container. Even though the principles of the earthquake model experiments are well explained in literature (Schofield, 1981), the boundary effects created by artificial boundaries of a model container need attention. This has lead to the development of the Equivalent Shear Beam (ESB) model container, which matches the container stiffness to that of the soil column (Zeng and Schofield, 1996). The dimensions of the ESB container are 560mmx250mmx223mm built with alternating rectangular layers of dural and rubber. Dynamic loading was simulated by the Stored Angular Momentum (SAM) earthquake actuator, developed at Cambridge (Madabhushi et al, 1998).

The key features observed in Turkey earthquake need to be reproduced, so that this powerful experimental technique can be used to study specific boundary value problems. In this paper we aim to understand the prevailing ground stiffness in centrifuge models before and after earthquakes, so that this technique can be applied with confidence to dry and saturated sites in Turkey where buildings or other infrastructure suffered damage. Further, the same wavelet analysis (see section 3) will be used to look at ground motions within centrifuge models.

5 CPT RESEARCH ON SAND MODELS

Miniature CPTs are often used in centrifuge tests to obtain information on the homogeneity of sand models and the strength distribution. In this paper we study the effect of the earthquake loading and the proximity of end-walls on the measured cone resistance. Therefore measurements were taken before and after the earthquake at the centre of the container and near the end-walls of dry and saturated sand models. The CPT was used for comparison of the results and hence only total penetration resistance is measured.

The miniature CPT device has a 6mm diameter rod fitted with a 60° conical tip connected to the piston of the cylinder. A load cell is placed at the top of the rod to measure the total force. The hydraulic cylinder has 200mm penetration distance and the valves were set so that the penetration rate is 2mm/s. The experimental procedure is to perform two CPTs in flight at known distance from the end-walls at the same penetration rate before the earthquake load. Then, an earthquake is simulated and the CPTs are repeated at two other locations. The heights of the sand models in the tests were 178 and 217mms corresponding to 8.9m and 10.85m for saturated and dry models in prototype scale respectively. The LB100/170 sand used in the tests has a median grain size, D_{50} of 0.120mm, specific gravity, G_s of 2.65, minimum void ratio of 0.502 and maximum void ratio of 1.060. The saturated model had a void ratio, e=0.76 (I_D=53.76%) and the dry model void ratio of 0.79 (I_D=48.39%). The models were prepared by using a sand hopper and the saturation was done under vacuum using 50cS silicone oil. This high viscosity pore fluid ensures that the rate of dissipation of pore pressure in the fluid is same as would be seen in an equivalent prototype.

5.1 *Earthquake Effects on the Soil Models*

The penetration resistances have very similar curves before the earthquake in saturated and dry models confirming the model to be uniform. The boundary had little effect on the penetration resistance prior to the earthquake loading in both models. As seen in Figure 5 after the earthquake the resistance at the end and the centre starts to deviate at 60kPa vertical effective stress. Up to that depth the soil layer became uniform as the arching effect observed before the earthquake has been destroyed. Beyond this effective stress (i.e. at greater depths) the effect of shear stresses due to arching on penetration resistance is seen. The earthquake loading clearly caused an increase in penetration resistance at the centre, while near the end wall the penetration resistance has dropped as was observed in the dry model. The reason for this behavior may be that the soil layer does not have the same settlement as the end wall and the rough boundary caused by the shear sheets would be holding the sand up causing boundary

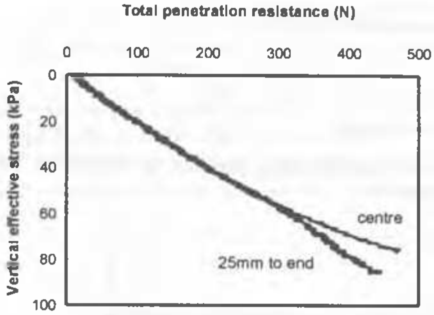

Figure 5. Penetration resistances after the earthquake saturated sand model.

effects to be observed. The concept of shear sheets was developed with the view of generating complementary shear stresses being generated at the boundaries in sympathy with the lateral shaking at the base, there by avoiding any dynamic moment being generated about the centroid of the soil model, Madabhushi et al (1995). The results from the current study show the effects of the complementary shear sheets prior to and after the earthquake loading. Clearly the rough sheets at the end walls are providing arching in the soil following earthquake loading, when rest of the soil samples undergoes settlement.

6 HARMONIC WAVELET ANALYSIS OF ACCELERATION SIGNALS ACQUIRED FROM THE SAND MODELS

The centrifuge model tests were conducted to simulate a semi-infinite dry or saturated horizontal sand layers. Accelerations were monitored for each test during the strong motion application. As shown in Figure 6, the accelerometers were placed vertically in two shear beam columns, one 10mm away from the end-wall, one at the centre. The duration of the shaking was 0.5s in model scale. Even though signals were acquired at all the places shown in the figure, only measurements at certain locations are used in this paper. There were six pore pressure transducers (PPTs) placed in the model to monitor the excess pore pressure build-up.

Accelerometers numbered *a1* from the central column and *b3* in the soil column near the boundary were chosen for the analysis in this paper. The acceleration-time histories for these can be seen in model scale in Figure 9. The input acceleration for this test was 10.2%g at 50g corresponding to 50.03m/s^2. Uniformity across the horizontal plane in the model was observed, but the acceleration traces showed an amplification of acceleration at the centre of the model as we go up in the soil column. However near the end-wall, an attenuation of the peak acceleration is observed as we move up. In Figure 7, long term excess pore pressure time trace of the bottom PPT is shown. The liquefaction ratios which were calculated from excess pore-pressure traces are 50% at the bottom and in the middle increased to 100%. These ratios indicate the softening of the soil as excess pore pressures are built up.

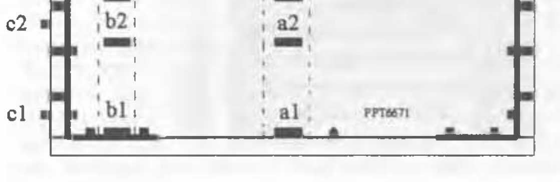

Figure 6. Instrumentation layout for test BT-6, saturated loose sand experiment.

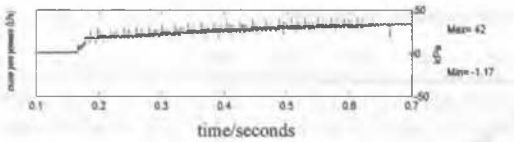

Figure 7. Long term excess pore pressure-time history of PPT6671 on the bottom of the container.

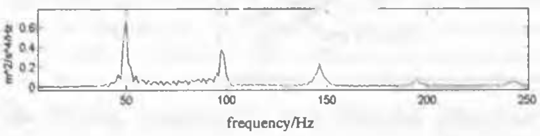

Figure 8. Fourier analysis of the input acceleration signal for *c1*.

The Fourier responses for each accelerometer were similar showing peak amplitude at the fundamental frequency of 50Hz and significant second and third harmonics (see Figure 8). As we go up towards the surface of the model the third harmonic increased in amplitude as well.

Figure 9 shows the results of harmonic wavelet analysis for the signals from the loose saturated sand model. When we look at the wavelet maps of *a1* and *b3*, the increase in energy at higher harmonics as we go up the model can be seen. This is consistent at the centre, end-wall and on the model container. This behaviour can be related with the changing properties of the soil model as a result of the shaking. The vibration motion has the same energy in the fundamental frequency around 50Hz as could be seen from the same time bandwidth of the signals with constant frequency width. The first three harmonics has significant energy compared to the higher harmonics of the motion.

The movement at the fundamental frequency near the end-wall suggests that energy is being lost as we go up. Considering liquefaction ratios this suggest that the bottom of the soil layer near the end-wall even though has more energy, this energy is not transferred to the soil above to be liquefied. Instead it is being lost in the friction between the end-wall and the sand. With dry model, since the end-walls have better match with soil stiffness, the difference with the centre of the model and the boundary was not observed. However with saturated models, the boundary of the ESB does not function well compared with dry models.

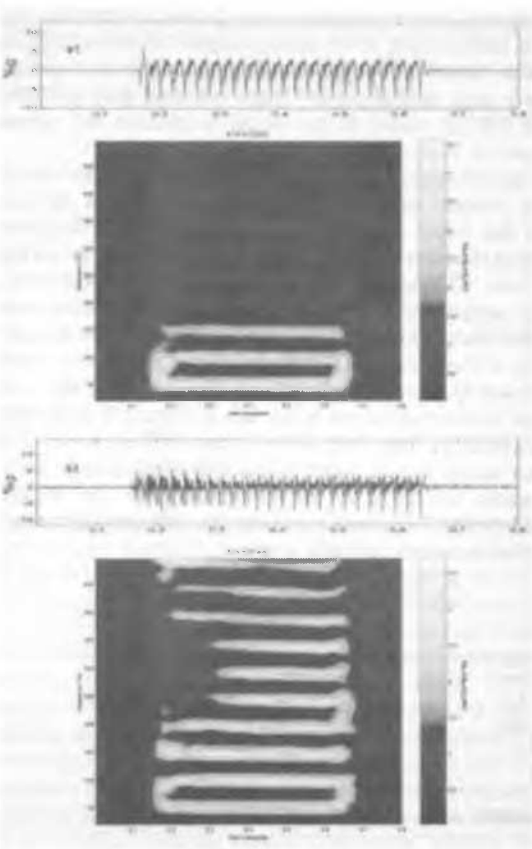

Figure 9. Acceleration-time histories and harmonic wavelet analysis of the acceleration signals of *a1* and *b3*.

7 CONCLUSIONS

Using the wavelets, it was observed that in the Kocaeli earthquake ground motions, acceleration with same frequency occurred at different time instants. This could not have been observed by traditional DFFT methods. Acceleration traces showed two significant peaks suggesting two distinct rupture events occurred. Most frequencies concentrated between 10-20 seconds of the earthquake for YPT signal. The frequencies of shaking in the first pulse are well distributed from 0 to 4Hz. The frequencies of shaking in the second pulse are concentrated at 1, 2, 4 and 6 Hz. In this paper, we analysed ground stiffness in centrifuge models with the aim to compare these with site conditions in Turkey. The results show the uniformity of the soil model prior to earthquake loading, and the penetration resistance changes after earthquake loading. In case of loose saturated and dry models, more densification occurred at the centre of the model relative to the boundary region. Due to the stiffness of the wall not matching the soil and also differential vertical settlements between the soil and the wall, shear stresses are produced. These shear stresses decrease the total penetration resistance measured by the CPTs. The results suggest that the complementary shear sheets cause differences in the soil behaviour between the centre and the end-walls.

The stiffness of the soil decreases with increase in pore fluid pressure as the earthquake progresses. This effect is due to the volumetric changes the soil undergoes when subjected to cyclic shear stresses. With harmonic wavelets, the change in the frequency response of the model over the course of the shaking motion can be identified. Thus the same wavelet technique used to analyse real earthquake data from Turkey, was useful in providing better understanding of centrifuge test data. These observations could not have been made by analysing either the time histories or the Fourier analysis.

ACKNOWLEDGEMENTS

The authors are greatly indebted to Prof. D. E. Newland for providing the harmonic wavelet program and his guidance in its usage.

REFERENCES

Kocaeli Earthquake Report 2000. EEFIT Report, I.Struct.E., London.

Madabhushi, S.P.G, A.N. Schofield and X. Zeng, 1995. Complementary shear stresses in dynamic centrifuge modelling, Dynamic geotechnical testing II, ASTM STP 1213, USA, 346-359.

Madabhushi, S.P.G, A.N. Schofield and S.Lesley, 1998. A new stored angular momentum (SAM) based earthquake actuator, Centrifuge 98, Tokyo, Japan, 111-116.

Newland D.E., 1999a. Harmonic Wavelets in Vibrations and Acoustics, Phil.Trans.R.Soc.Lond.A., Vol. 357: 2607-2625

Newland, D. E., 1999b. Ridge and Phase Identification in the Frequency Analysis of Transient Signals by Harmonic Wavelets, *J. Vib. and Acoustics*, Trans. ASME, Vol. 121.

Schofield, A.N., 1981. Dynamic and earthquake geotechnical centrifuge modelling. Proc. Int. Conf. Recent Adv. Geotech Earthquake Engng Soil Dyn. Rolla 3, 1081-1100.

Zeng, X. and A.N. Schofield, 1996. Design and performance of an equivalent-shear-beam container for earthquake centrifuge modelling, *Geotechnique*, Vol.46, No.1, 83-102.