Abstract for the 3rd DNVA-RSE Norway-Scotland Waves Symposium, Oslo 16-17 September 2013. http://folk.uio.no/johng/waves13/

Seiches in Norwegian fjords generated by distant earthquakes

by

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In a recent paper we reported seiches in fjords in western Norway after the Tohoku earthquake (magnitude M_w 9.0) in Japan 11 March 2011 based on recordings from cell-phone and surveillance cameras (Bondevik et al. 2013). From analysing the unique film clips and numerical simulations we were able to identify which part of the seismic wave train was responsible for the generation of the seiches. At the Wave Symposium a review of observational data will be presented together with a more thorough discussion of the modelling aspect.

The wave motion were observed on several locations in Sognefjorden and Hardangerfjorden and the recorded film clips provides an unique opportunity, previously not available, to determine the period, amplitude, and duration of the wave motion. The observations show maximum trough-to-peak amplitudes of 1.0-1.5 m and periods of 67-100 s. Simultanous records of ground displacement and accelerations are available from the long periodic seismic station SUE located at the mouth of Sognefjorden. Horizontal ground acceleration of about $8{\cdot}10^{-5}$ m/s^2 (8 milliGal) occurred in a powerful long periodic S-wave group with period 50-90 s. The seiches appeared a few minutes after the arrival of the S-wave group and the fjord seiching continued for up to three hours in some locations.

Seiches in Norwegian fjords and have been observed previously after historic large earthquakes i.e. Lisboa 1755, Assam 1950 (Kvale 1955). Kvale also reported oscillations in some water reservoirs in England after the 1950 event. Observations of seiches on the west coast of North America and Alaska after powerful earthquakes are analysed by McGarr and Vorhis (1968), and Barberopoulou (2008). The mechanism of seiche generation by seismic waves was investigated in an early paper by McGarr (1965).

Although the generation mechanism is well understood in principle, it remains to identify which part of the seismic wave train is responsible for the generation of seiches, why the seiches appear within a relatively short time after the arrival of the first seismic waves, and why the seiches attain relatively large amplitudes in certain locations.

By analysing the unique data set from Sognefjorden during the Tohoku 2011 event and by numerical modelling and simulations we were able to shed more light on these questions.

Norwegian fjords are sensitive to seiching because they are deep. The larger Norwegian fjords are typically 100 km long, 5 km wide, and 500-1000 m deep. This implies that the period for the gravest mode transvers eigen-oscillation is 100-140 s, i.e. comparable to the period of the longest seismic waves from a powerful earthquake. At near resonance condition the amplitude η of cross

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fjord eigen-oscillations will increase linearly in time t according to the formula

$$\eta = \frac{2ah}{\pi\sqrt{gh}}t$$

where a is the horizontal acceleration of the ground and h is the depth of the fjord. This shows that the deeper the fjords are, the more rapidly the amplitude of seiches will increase with time. With typical values for a and h given above, seiches amplitudes of about 15 cm will occur after only 5 min. Near shore wave amplification and runup will be important for generation of larger seiches. Numerical simulations show that cross fjord oscillations will generate edge wave modes with increasing amplitude and decreasing wave length as the waves propagate towards the shallow regions at the fjord head (see figure). The waves will also amplify in certain location where the near shore depth profile is favorable, as discussed for example by Didenkulova et al. 2009. Interference between different wave modes may also lead to seiches with higher amplitude. By using a numerical fjord model with horizontal grid resolution of 25 m, and with the observed ground acceleration as forcing, we were able to simulate time series of the seiching which correspond resonable well with observations from Flåm located at the head of an inner arm of Sognefjorden.

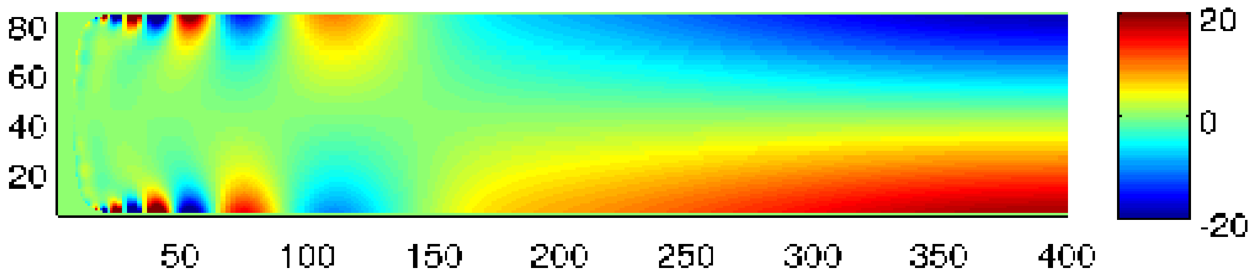

Figure 1: Generation of edge waves by cross fjord eigen-oscillations at the head of an idealized fjord. Simulated sea surface displacement with cross fjord ground acceleration $a = 8\ mGal$, and period $T = 90\ s$. Colour scale in cm at right. Units on the axis are grid size $\Delta x = \Delta y = 50\ m$.

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