Influence of the Hohenwarte reservoir on tilt and strain observations at Moxa

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Abstract

The Geodynamic Observatory Moxa is located around 4 km to the north of the Hohenwarte reservoir, a medium-sized artificial reservoir, holding on average 182 Mill. m^3 of water. The data of the installed seismometers and strainmeters at Moxa are successfully used for studies of the Earth's interior structure and properties. It is possible to observe tilt changes in the range of 10^{-9} rad and displacement changes of 10^{-9} strain.

We explore the possibility that registrations of the seismometers and strainmeters are influenced by deformation changes induced by lake-level fluctuations of the Hohenwarte reservoir, both on a short-term seasonal time scale and a long-term decadal time scale. We use the Finite Element method to calculate deformations in vicinity of the Hohenwarte reservoir. We show that the influence of lake-level fluctuations of up to 30% to tilt and strain registrations at the observatory is larger than the resolution of the instruments, with differences of at most 48 nrad for the tilt and 6 nstrain for the strain. Thus, at the location of Moxa, the influence of lake-level changes on the registrations is significant.

1 Introduction

Artificial reservoirs are important for flood protection, for providing drinking water and for the generation of electricity. Besides that, the filling of reservoirs with water induces a load on the Earth's surface, deforming the crust and mantle and producing tilt and strain deformations. These deformations have been studied extensively in the literature (see Steffen & Kaufmann, 2006, for a review).

The Hohenwarte reservoir in the southeast of Thuringia is the 3rd largest reservoir in Germany with a volume of 182 Mill. m^3, covering an area of 7.3 km^2. The

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dam was built between 1936 and 1943, and put into operation in 1941. The balance reservoir is the Eichicht reservoir in the west with a volume of 5.21 Mill. m^3 and an area of 0.71 km^2 (Fig. 1). In 4 km distance to the reservoir, the Geodynamic Observatory Moxa is situated, equipped with sensitive seismometers and strainmeters. With these instruments it is possible to observe tilt changes in the range of 10^{-9} rad and displacement changes of 10^{-9} strain. We explore the possibility that registrations of the seismometers and strainmeters are influenced by deformation changes induced by lake-level fluctuations of the Hohenwarte reservoir. We therefore use the Finite Element (FE) method to calculate the deformations in vicinity of the Hohenwarte reservoir.

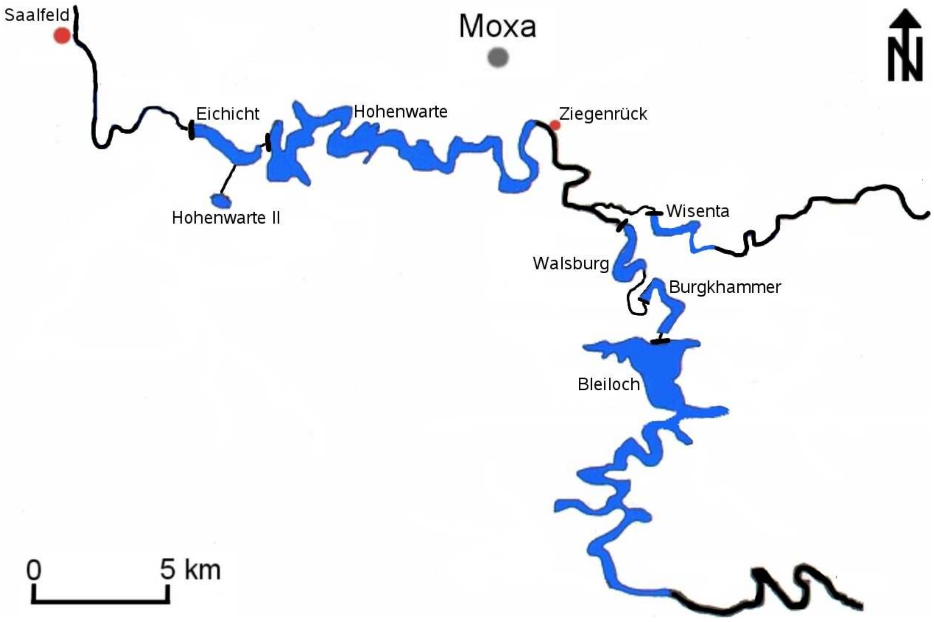

Figure 1: Overview of the reservoirs along the river Saale in the southeast of Thuringia, Germany, and the location of the Geodynamic Observatory Moxa.

2 Model description

We model the water impounded in the Hohenwarte reservoir as surface load on a flat, viscoelastic earth by means of the FE method. The Earth model is a cube with 100 km side length, consisting of a 25 km thick crust and the 75 km thick upper mantle. For the crust a linear, elastic rheology and for the upper mantle a viscoelastic rheology is used. The viscosity for the upper mantle is set to 5 x 10^{20} Pa s, taken as an average of upper-mantle viscosities beneath Europe (Steffen & Kaufmann, 2005). Thus, this model allows the relaxation of stress in the upper mantle. The material parameters and the dimensions for the element layers are summarised in Steffen & Kaufmann (2006). The model is meshed with 130000 hexahedra elements. The central area, between 40 and 60 km in each horizontal direction, is meshed using elements with a horizontal side length of 250 m. The remaining 10 element rows of the 40 km wide peripheral frame have a variable side length from short side lengths near the center to long side lengths for the outer elements.

The full water load of 182 Mill. m^3 for Hohenwarte and of 5.21 Mill. m^3 for Eichicht is applied uniformly over the shape of each reservoir (Fig. 2), which is approximated by 135 (Hohenwarte) and 14 (Eichicht) element surfaces of the central area. Thus, the reservoir areas correspond to 8.44 km^2 and 0.88 km^2, respectively. The load is generated by dividing the water volume of each reservoir by the modelled area, multiplied with water density (1000 kg/m^3) and gravity (9.81 m/s^2). The full load of the Hohenwarte and the Eichicht reservoir corresponds to constant water columns of 22 m and 6 m, respectively.

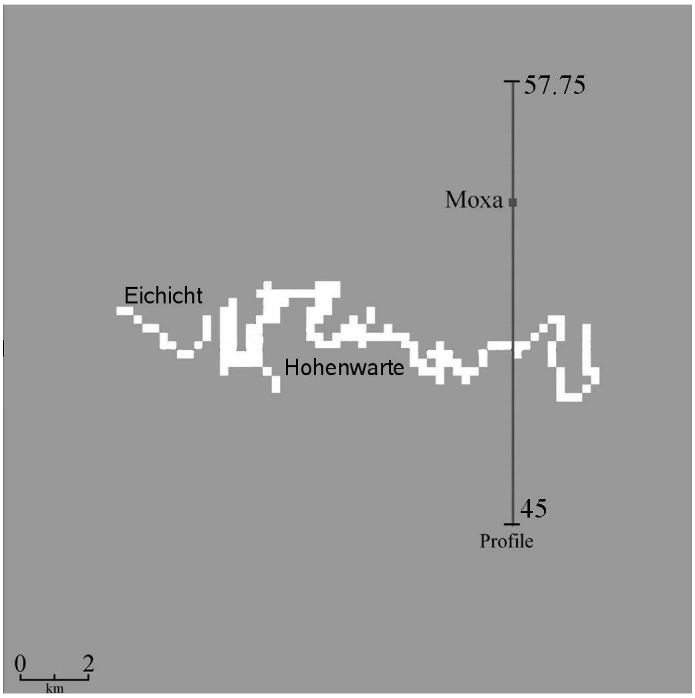

Figure 2: Top view of the model center (20 km x 20 km) with the shape of the reservoirs (white) and the profile for the deformations. The location of the observatory is marked. Numbers indicate locations in km relative to the entire grid of 100×100 km used.

The load initially increases linearly over 2 years, after the dam was closed in 1941. This simulates the filling of the reservoir starting at 0% of water volume and ending after 2 years with a maximum water volume of 100%. Then, two cycles of lake-level changes simulating the annual hydrological cycle follow (Fig. 3). Within 6 months, the reservoir volume is reduced to 70% (summer) and after another 6 months increased again to 100% (winter). After the two cycles the load is kept constant at 100% till the year 2011. With this approximation, it is possible to both study seasonal changes and to save computations time for the long-term evolution until the present.

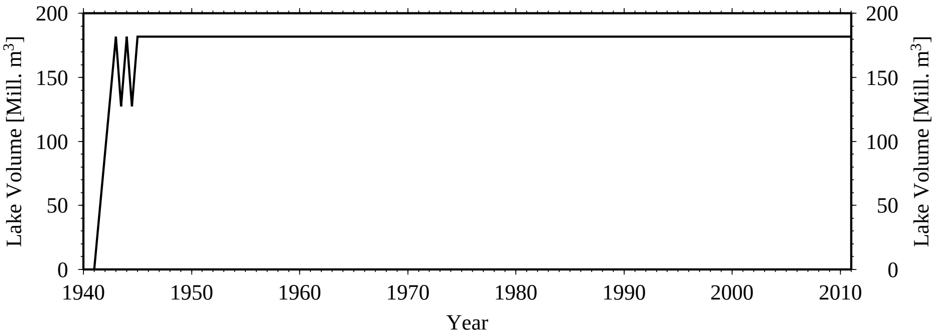

Figure 3: Lake volume as function of time.

3 Results

An extensive study of the deformations in vicinity of the Hohenwarte reservoir can be found in Steffen & Kaufmann (2006). In this study, we focus on the results for Moxa observatory.

The deformation of the model by the time-dependent water load is calculated, and strains and tilts are shown along the profile of Fig. 2. The profile starts south of the reservoir and runs in NS–direction. The location of Moxa observatory is at 54.25 km on the profile.

3.1 Short-term seasonal variations

Tilt: Fig. 4 shows on top the tilt in the NS– and EW–component at different load times. To compare the results, the tilts at different times of an annual cycle are taken when the reservoir is filled-up (winter, solid) and 70%-filled (summer, dotted). The tilt changes on the profile reflect the location of the reservoir and which reservoir border is tangent to the profile. The tilt only shows eye-catching changes when the reservoir is crossed at 50 km. The amplitude is affected by the load sum in the vicinity of each point and is in winter at most 3 μrad northward in the NS–component. Between winter and summer significant differences in the amplitude of the tilts are found. The tilt difference between winter and summer is at most 30% of the full load in winter and therefore a result of the elastic behaviour. Changes in the direction of the tilt are not observed.

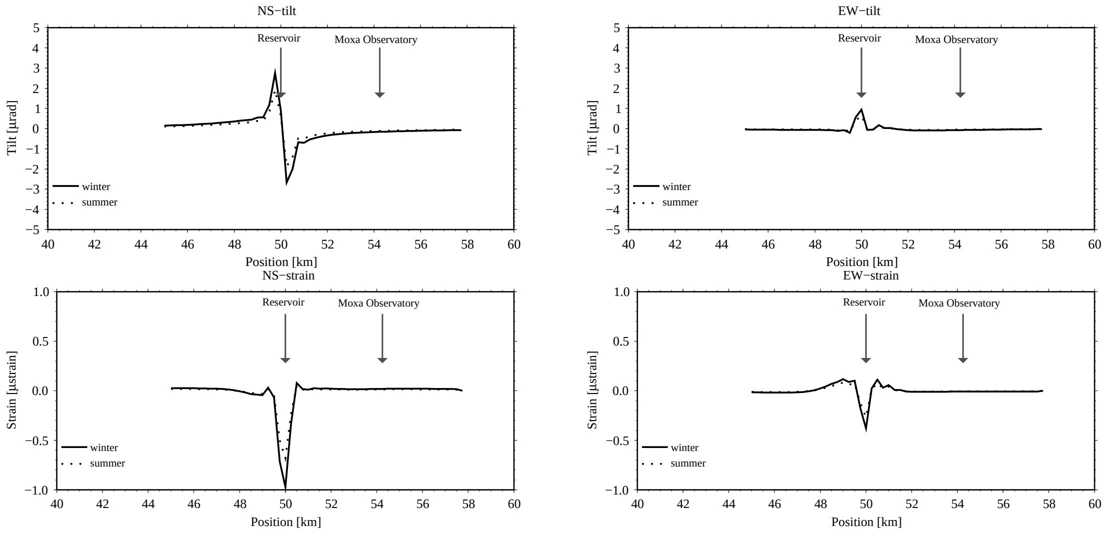

Figure 4: Top: Tilt in the NS– component (left) and EW–component (right) obtained at different load times. Tilt northward and eastward positive. Bottom: Strain in the NS–component (left) and the EW–component (right) obtained at different load times. Extension positive.

Strain: Fig. 4 shows at the bottom the strain in the NS– and EW–component at the two different load times winter (solid) and summer (dotted). The maximum amplitude is found in winter with around 1 μstrain compression. The strain changes reflect the location of the reservoir in compression. The profile demonstrates this behaviour clearly when the reservoir is crossed around 50 km. As for the tilts, between winter and summer significant differences in the amplitude of the strains are found. At the location of the reservoir, the difference between winter and summer is at most 30% of the full load in winter and again a result of the elastic behaviour. No changes in the direction of the strain are detected.

Tilt and strain at Moxa: Tab. 1 summarises for the location of the Moxa observatory the differences in tilt and strain for both components between winter (100%–filled) and summer (70%–filled). The difference in the EW–component is around 22 nrad and in the NS–component around 48 nrad. The strain differences results for the EW–component in only around 2.5 nstrain and for the NS–component in around 6 nstrain. These differences between winter and summer should be observable with the sensitive instruments at Moxa (see Kroner et al., 2005, for a description), if lake-level variations are in the order of 30%.

3.2 Long-term variations

Fig. 5 shows the vertical deformation on the surface at Moxa for the load cycle (Fig. 3). The deformation at Moxa for a full reservoir in winter is about 0.85 mm, and 0.60 mm in summer, when the lake-level is 30% lower. There is clearly no big influence of

Table 1: Difference in tilts and strains in both components between winter and summer at the location of Moxa observatory.

	NS	EW
tilt [nrad]	48	22
strain [nstrain]	6	2.5

the viscoelastic mantle on the vertical deformation due to the loading period of the Hohenwarte reservoir. After 70 years, the viscoelastic part is only about 0.22 μm of vertical deformation. The differences in the vertical deformation induced by short-term load changes are caused by the elastic crust. There is no influence of the viscoelastic mantle on tilt and strain in this case.

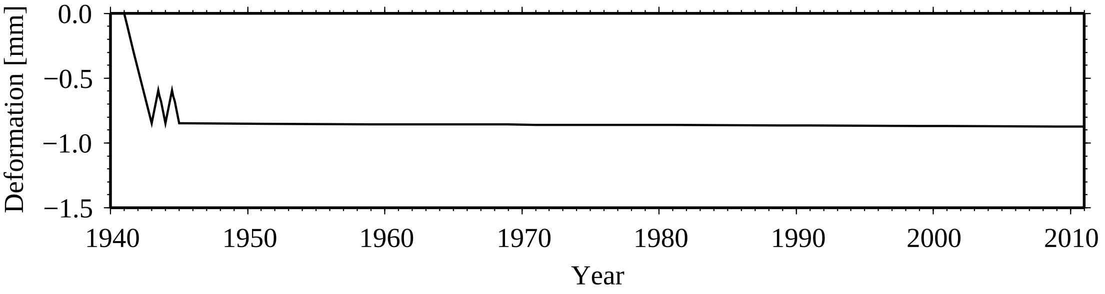

Figure 5: Vertical deformation over 70 years obtained at Moxa.

4 Conclusions

Artificial reservoirs such as the Hohenwarte reservoir in Germany induce additional loads on the Earth's surface. The resulting effects in tilt and strain deformations can be observed with sensitive instruments in the Geodynamic Observatory Moxa, which is located in a distance of 4 km to the reservoir. The influence of lake-level changes on the registrations is significant. For lake-level fluctuations up to 30% tilt and strain differences at the observatory are larger than the resolution of the instruments. Differences of at most 48 nrad for the tilts and 6 nstrain for the strains are established and should be observable. The vertical deformation is more affected by load changes with a difference of around 0.25 mm between winter and summer. The influence of the viscoelastic mantle after a long time-period is negligible.

Acknowledgements

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