Time-variable gravity signal during the water impoundment of China’s Three-Gorges Reservoir

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[1] Beginning in 2003, China’s Three-Gorges Reservoir will start water impoundment in phases. By 2009, it will be holding 40 km\textsuperscript{3} of water, flooding a stretch of middle Yangtze River about 600 km in length. The water impoundment process represents a geophysical “controlled experiment” offering a unique opportunity for detailed studies of a classical forward/inverse modeling problem of surface loading. While Wang [2000] studied the large loading effects on a local scale, we aim for longer spatial scales upwards from several hundred km, specially on the time-variable gravity signals that can be detected by the newly-launched GRACE satellite mission, whose 5-year lifetime (until 2007) will span the major impoundment period. Our results using the Green’s function method adopting the PREM elastic Earth model indicate that the per-year geoid height increase is above the GRACE observational sensitivity out to harmonic degree 20, and to degree 50 (corresponding to a wavelength of 800 km) when integrated over the 5-year period. INDEX TERMS: 1223 Geodesy and Gravity: Ocean/Earth/atmosphere interactions (3339); 1227 Geodesy and Gravity: Planetary geodesy and gravity (5420, 5714, 6019); 1243 Geodesy and Gravity: Space geodetic surveys.


1. Introduction

[2] China’s Three-Gorges Reservoir will be one of the world’s highest artificial dams. Standing 175 m, by 2009 it will hold 40 km\textsuperscript{3} of water, flooding a stretch of middle Yangtze River about 600 km in length, with a width of 1–2 km (Figure 1). The impoundment process will be implemented in phases starting in 2003.

[3] The impounded water represents a net transport of a large quantity of mass from the oceans onto a concentrated area on land. It will have geophysical impacts on spatial scales from local to global, lasting temporally from concurrent to many decades and beyond, not only by the “visible” resultant loading on land and unloading over ocean. Compared to the major reservoirs existing in the world today the Three-Gorges Reservoir would rank about 25 in capacity, hardly a largest [Chao, 1995]. However, the Three-Gorges Reservoir represents a geophysical “controlled experiment”, one that offers a unique opportunity for conducting detailed geophysical studies assuming the availability of a complete documentation of the water level and history of the water filling process aided with a continual monitoring of the lithospheric loading response (such as area gravity and deformation). One then has a classical forward/inverse modeling problem of surface loading, where the “input” and certain “output” are known. The invisible portion of the impounded water, i.e. underground storage, poses either added values as an observable or a complication as an unknown to be modeled.

[4] Geophysical monitoring programs at the surface are indeed taking place. This is mainly for earthquake risk assessment [Wang, 2000; Wang et al., 2002]. Wang [2000] has studied the possible loading effects on a local scale within about 100 km upstream from the dam. He calculated that, depending on the local rheology, the local peak changes are: 3.41 mGal in free-air gravity, 7.5 mm in surface geoid, up to 4.8 cm in surface subsidence, and 7.8 arcseconds east-west and 17.5 arcseconds north-south in the tilt.

[5] In this paper we focus on larger spatial scales, upwards of several hundred km, paying particular attention to the time-variable gravity signals that can be detected by satellite missions from low-Earth orbits. Launched in March of 2002, GRACE [Tapley, 1997] is able to detect mass change equivalent to a few mm of water-depth over an area of a few hundred km across [Wahr et al., 1998]. It is fortuitous that about two thirds of the Three-Gorges water impoundment (over 2003–2009) will take place during GRACE’s nominal lifetime of 5 years (2002–2007); the remaining impoundment and the long-term viscous relaxing response of the lithosphere will presumably continue to be observed by future gravity missions beyond GRACE [e.g., NRC, 1997; ESA, 1999; Watkins et al., 1999].

2. Modeling of Three-Gorges Loading Effects

[6] The Three-Gorges dam is presently near completion; the water impoundment will start in 2003. The water volume will increase quickly at first, and then continue to increase in phases. The average water levels are 54 m (above sea level) at the dam site, 135 m in 2003, 156 m in 2006, and 175 m in 2009. This latter figure corresponds to the nominal capacity of the Three-Gorges Reservoir at 3.93 × 10\textsuperscript{13} kg in mass [Wang, 2000]. Note that as far asGrace is concerned it is the difference between given epochs that will be the observable.

[7] In modeling the Three-Gorges loading effects in surface deformation and geoid, we assume a spherically symmetric, non-rotating, elastic and isotropic (SNREI) Earth model by adopting PREM elastic parameters [Dziewonski and Anderson, 1981]. Thus only the instantaneous, elastic loading response in the lithosphere is treated, which follows
and accumulates over the history of the water impoundment. Any viscous response should have only minimal effect, at least over the short period of several years under consideration here [e.g., Wahr et al., 1998; Tromp and Mitrovica, 1999]. In any case, a forward modeling of the viscous effect would be infeasible without sufficient knowledge about the local rheology of the upper mantle and crust, and the problem should be treated as an inverse problem equipped with sufficient ‘input-output’ knowledge.

[8] We use the classical Green’s function approach of Farrell [1972]. In general the surface loading effects are given by the following formulas in terms of the three load parameters, \( h'_{n}, \ell_{n}, \) and \( k'_{n} \): the vertical displacement is:

\[
\Delta H(\theta, \lambda, t) = \int \frac{GH(\psi) \delta \sigma(\theta', \lambda', t)}{P_{\text{Earth}}} \sin \theta \, d\theta' \, d\lambda' \tag{8}
\]

with the Green’s function for vertical displacement:

\[
GH(\psi) = \frac{3}{4\pi\nu} \sum_{n=0}^{\infty} h'_{n} P_{n}(\cos \psi). \tag{9}
\]

The horizontal displacement is:

\[
\Delta T_{\text{NS}}(\theta, \lambda, t) = \int \frac{\text{GT}(\psi) \cos \delta \sigma(\theta', \lambda', t)}{P_{\text{Earth}}} \sin \theta \, d\theta' \, d\lambda' \tag{10}
\]

for the north-south component, and:

\[
\Delta T_{\text{EW}}(\theta, \lambda, t) = \int \frac{\text{GT}(\psi) \sin \delta \sigma(\theta', \lambda', t)}{P_{\text{Earth}}} \sin \theta \, d\theta' \, d\lambda' \tag{11}
\]

for the east-west component with the Green’s function for tangential displacement:

\[
\text{GT}(\psi) = \frac{3}{4\pi\nu} \sum_{n=0}^{\infty} \cos \psi \frac{\partial P_{n}(\cos \psi)}{\partial \psi}. \tag{12}
\]

The geoid height variation is:

\[
\Delta N(\theta, \lambda, t) = \int \frac{GN(\psi) \delta \sigma(\theta', \lambda', t)}{P_{\text{Earth}}} \sin \theta \, d\theta' \, d\lambda' \tag{13}
\]

with the Green’s function for geoid height:

\[
GN(\psi) = \frac{3}{4\pi\nu} \sum_{n=0}^{\infty} \left(1 + k'_{n}\right) P_{n}(\cos \psi) \tag{14}
\]

where \( P_{n}(\cos \psi) \) is the Legendre polynomial of degree \( n \), \( \rho_{\text{e}} \) is the mean Earth density, \( \psi \) and \( \alpha \) are respectively the angular distance and the azimuth between the field point \((\theta, \lambda)\) and surface integral element \((\theta', \lambda')\). The time-variable surface mass density \( \delta \sigma \) is linked to water height \( h \) assuming a constant water density \( \rho_{w} = 1000 \, \text{kg m}^{-3} \), \( \delta \sigma(\theta', \lambda', t) = \rho_{w} h(\theta', \lambda', t) \). The \( h'_{n}, \ell_{n}, \) and \( k'_{n} \) are respectively the radial, horizontal, and potential load Love numbers; they are functionals of Earth’s elastic property and given as a function of the spherical harmonic of degree \( n \) in an SNREI Earth model.

[9] We assume that all the water impounded in the Three-Gorges Reservoir comes ultimately from the ocean via atmospheric processes (the impact of the reservoir on global atmospheric water content is presumably negligible). The surface integral is therefore performed over two parts of the globe — the reservoir area where water mass is added (or loaded) and the ocean area therefrom corresponding water is extracted (or unloaded). The former is a near “delta function” in space; we expect it to be the dominant term and its associated spherical harmonic decomposition to be near “white”, spreading over a broad spectrum. The latter is included to ensure consistency in the sense of conserving the water mass during the process. Here we simply assume a uniform sea level drop over the entire ocean; its effect is hence spectrally red following the ocean function determined by the ocean geography [cf. Chao and O’Connor, 1988]. The Three-Gorges water impoundment corresponding to a drop of the eustatic sea-level by 0.11 mm [cf. Chao, 1991], this “ocean correction” is relatively small in magnitude (see below) because of the wide spread of the ocean function.

[10] When local topography information is needed to determine the flooded area as a function of the water level during impoundment, we use the topography provided by GTOPO30 [USGS, 1996], see Figure 1, which is gridded 2 degrees by 5 degrees in size, while assuming a constant width of 1 km for the Reservoir.

3. Results

[11] Our computed results for local areas near the Three-Gorges dam are, not surprisingly, very similar to those of Wang [2000] and Wang et al. [2002]. In below we report our results for much larger spatial scales in which we are interested. Figure 2 shows the geoid height change \( \Delta N \) induced by the filling of the Three-Gorges Reservoir, for three epochs relative to “zero mass” before the filling. Depending on the epoch, the geoid will be elevated by a

Figure 1. Schematic topography map of the Three Gorges area of the Yangtze River (GTOPO30 data).

Figure 2. Shaded contour maps showing regional geoid elevation (in mm) due to water impoundment of the Three-Gorges Reservoir at three given epochs.
fraction of one millimeter out to well over a thousand kilometers distance. Figure 3 shows the same induced geoid height change but in the more tell-tale spectral domain, in terms of per-degree amplitude as a function of the spherical harmonic degree. The top curve is the geoid change for the entire water impoundment (till 2009). Because of the small spatial extent of the reservoir, the spectral amplitude decreases slowly with the harmonic degree. The degree 0 and 1 terms are anomalous because we have not considered the load Love number of degree 0 (we assume $k_0 = 0$) and because of the choice of the center-of-mass reference frame. The thicker curve is the geoid change due to average “per-year” water impoundment. Compared with the jagged curve which is a simulated GRACE sensitivity spectrum for the recovered geoid (S. Bettadpur, personal communication, 2002, and scaled by the square root of the observing length assuming the same scaling for all harmonic degrees), one sees that yearly changes will be observable up to about degree 20. For the entire GRACE lifetime of 5 years, the observability will be $5x\sqrt{5} \sim 11$ times greater (with 5 times more mass and the GRACE sensitivity $\sqrt{5}$ times better than the “per-year” curve shown in Figure 3), and the geoid change will be observable by GRACE out to degree above 50, corresponding to a wavelength of 800 km. The bottom curve is the ocean correction term (the unloading effect) for the total water mass extracted from the ocean. Included here to account for the conservation of mass, the values are below GRACE sensitivity and barely discernable even for the lowest-degrees under the GRACE lifetime observability, but anyway ought to be accounted for in interpreting GRACE data.

[12] The vertical crustal displacement field at the three epochs is shown in Figure 4. The deformation should be observable only close to the dam using geodetic surveys such as GPS and surface leveling measurements which are conducted for seismic risk assessment [Wang, 2000]. Farther from the dam, the deformation is too small to be detectable. For example, at the closest regional IGS (International GPS Service) [Beutler et al., 1987] stations at distances of a few

Figure 4. Same as Figure 2, but for the regional vertical crustal depression (in mm).

Figure 5. Same as Figure 2, but for the regional North-South horizontal crustal deformation (in mm). (The corresponding maps for the East-West deformation not shown.)
hundred km and longer (Wuhan, Shesan, Kunming and Lhasa), the induced surface displacements are smaller than 10^{-2} mm/yr, far below the accuracy of the sensitivity of GPS. Figure 5 gives the horizontal north–south deformation at the three epochs; the corresponding east–west deformation (not shown) is similar but having the E–W pattern. The magnitude of the tilt is comparable to the vertical displacement.

[13] Globally, the 3.93 \times 10^{13} kg of water mass amounts to about 0.7 \times 10^{-11} times that of the total Earth mass. Chao [1995] has computed the global geodynamic impacts at the longest wavelengths due to world's major reservoirs from the past. Using the same formulation, we find that when filled, the Three-Gorges Reservoir would cause an overall change in Earth's dynamic oblateness \( J_2 \) by \(+3.0 \times 10^{-13}\), \( J_3 \) by \(+2.4 \times 10^{-12}\), and Earth’s rotation by only \(+0.06 \mu s\) in length-of-day, but as much as 0.64 milliarcsecond in polar motion excitation toward the direction away from the longitude of the Three-Gorges.

4. Discussions

[14] The Three-Gorges water redistribution is far above the GRACE sensitivity on the scale of GRACE's spatial resolution. On long wavelength part of the spectrum, our results show clearly that the per-year geoid height increase due to the Three-Gorges water impoundment is above the GRACE observational sensitivity out to harmonic degree 20, and to degree 50 when integrated over the whole 5-year GRACE lifetime, corresponding to wavelengths longer than about 800 km. This means that the mass loading of the reservoir cannot be neglected in interpreting gravity variations recovered by GRACE missions at least for wavelengths longer than about 800 km.

[15] In evaluating the overall effects, we have assumed zero water mass before the impoundment, which in actuality may be as much as 10% of the total capacity [H. Wang, personal communication, 2002]. This amount is uncertain until detailed survey data are available, but it does not really matter as far as GRACE observations are concerned because only differences between epochs are of concern. On the other hand, detailed survey data for river channel topography such as the digital model used by Wang et al. [2002] are still required to construct the precise history of water impoundment given the water level record. For that purpose topography data with a sampling of about 0.1 km may be needed, compared to the sampling of GTOPO30 [USGS, 1996] at around 1 kilometer as used here. However, this uncertainty should be consequential only close to the dam, and insignificant under GRACE's spatial and temporal resolutions.

[16] A fundamental assumption we have made is that all other geophysical contributions to the time-variable gravity signal than the Three-Gorges Reservoir are known to the extent that they can be separated out from the observation. These include mass redistribution and associated loading effects by the atmospheric pressure system, regional land hydrology, and solid Earth deformation due to tectonics and glacial isostatic adjustment in the area. While some are better monitored and modeled than others, these contributions have very distinct signatures both in time history and spatial pattern than those of the Three-Gorges Reservoir given in Figure 2, and hence readily separable.

[17] We have modeled Earth's elastic loading deformations using a spherically-symmetric Earth model (PREM). This should be adequate for long-wavelengths (continental sizes); but for a more precise evaluation of intermediate (regional effects) and shorter wavelengths (local effects), more realistic elastic parameters would be needed, for example, a laterally heterogeneous model. By the same token, regional lithospheric rheology model is required to model any visco-elastic behavior which is ignored in our study. Although relatively small, the viscous effect will last for decades to come and remain observable by future time-variable gravity measurements.

[18] Another possibly significant unknown is the amount of underground water storage change induced by the Reservoir depending on the local geology. Its gravity effect may not be readily separable from those of the local lateral heterogeneity and rheology discussed above. These in fact are what GRACE data would be valuable for in conjunction with independent ground measurements and modeling.

References


